Appendix E

Surface Water Report

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RUSSELL VALE COLLIERY WONGA EAST UNDERGROUND EXPANSION PROJECT SURFACE WATER MODELLING

Wollongong Coal Limited
May 2014

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For and on behalf of
WRM Water & Environment Pty Ltd

Michael Batchelor
Director

EXECUTIVE SUMMARY

This report describes the geometry of the catchments and streams potentially impacted by mining subsidence induced by the proposed underground expansion of the Wonga East workings of Russell Vale Colliery longwall mining project. It also outlines hydrological modelling undertaken to determine the relative contribution of the potentially affected catchments to runoff in the receiving waters.

The catchments of Cataract Creek, Bellambi Creek and Cataract River will potentially be affected by the Wonga East workings. The proposed Wonga East workings do not underlie the Cataract Creek, Bellambi Creek or Cataract River channels. However, the western end of the predicted subsidence associated with Panel 6 and Panel 7 approaches close to the eastern bank of the high water extent of the Lake Cataract backwater. The mine panels are to be laid out in accordance with the Sydney Catchment Authority (SCA) requirements for clearance from the reservoir.

Catchment Physical Characteristics

Catchment geometry and stream longitudinal profiles were extracted from an airborne laser scanning survey acquired over the Study Area on 20th October 2009, and are described below:

1. Cataract Creek is approximately 5.5km long from its headwaters to the upstream reaches of Lake Cataract. It is a 4th order stream for most of its length. The proposed Wonga East workings are located between Chainage 2,500 m and Chainage 4,500 m. Approximately 2.5 km of the stream reach is located upstream, 2.0 km within and 0.9 km downstream of the 20 mm subsidence zone. Channel invert elevations fall from approximately 340 m AHD to 285m AHD. Of the total Cataract Creek catchment area of 5.2 km^2, 1.9 km^2 is located upstream of the potential subsidence zone, and 3.2 km^2 has been identified as potentially subsided by the proposed workings.

2. Cataract River is approximately 6.7km long from its headwaters to the upstream reaches of the Lake Cataract storage. The proposed Wonga East workings and its associated 20mm subsidence zone do not underlie the Cataract River. The predicted 20mm subsidence zone runs adjacent to the Lake Cataract backwater for a distance of about 350m. It is a 3rd order stream upstream of the Link Road crossing and 4th order from the confluence just downstream of the crossing to the Lake Cataract backwater. Channel invert elevations fall from approximately 430m AHD to 285m AHD. Of the total Cataract River catchment area of 11.6km^2, 0.5km^2 has been identified as potentially subsided by the proposed workings with 11.1km^2 outside of the 20mm subsidence zone.

3. Of the total Bellambi Creek catchment area of 9.3 km^2, 8.9 km^2 is located downstream of the potential subsidence zone, and 0.4 km^2 has been identified as potentially subsided by the proposed workings.

4. Of the total Lake Cataract catchment area of 127.8 km^2, 4.4km^2 is identified as potentially subsided.

Swamps

Potentially affected swamps adjacent to the project make up around 0.9% of the Lake Cataract catchment, and 1.1% of the Cataract Creek catchment. Approximately 64% of the potentially affected swamps in the project area are within the proposed subsidence zone.

Catchment Rainfall

Rainfall in the study area is highly variable, with mean annual rainfall ranging from less than 1,000mm/a in the west of the Study Area to over 1,800mm/a on the eastern escarpment. Historical records show significant variations in rainfall from north to south during specific events.

Streamflow

While water levels are monitored in pools along Cataract Creek and Cataract River, insufficient data is available to derive long-term streamflow records for the potentially affected streams. However, streamflow data is available from gauges on headwater streams flowing into Lake Cataract: Bellambi Creek at South Bulli No. 1 (<5 years) and Loddon River at Bulli Appin Road (<19 years). The streamflow records from these two gauges show similar responses to rainfall– with persistent baseflow being a notable feature, but contributing a relatively small proportion of total runoff.

The SCA operated a streamflow gauge in the Cataract River at Jordon's Crossing over the period from August 1986 to July 2013. The streamflow at this location is heavily influenced by releases from water storages upstream of the gauge. Therefore, the data from this gauge is mostly unsuitable for the analysis of natural streamflow conditions in the Cataract River.

The streamflow records were extended by simulating catchment behaviour using the Australian Water Balance Model (AWBM) rainfall-runoff model and historical climate data. Given the limited availability of representative rainfall data, the AWBM gave a reasonable representation of the observed streamflow records.

Daily runoff from other catchments in the upper Study Area was estimated using the AWBM model, with the model parameters transposed from the adjacent Bellambi Creek catchment. The model reproduces similar baseflow behaviour to that observed in recently collected pool monitoring data. However, the Bellambi Creek data showed a number of historical cease to flow periods which did not occur in the Loddon River data and could not be replicated by the AWBM when calibrated to other features of observed runoff. This behaviour would be consistent with a loss of streamflow to seepage of approximately 0.3ML/d, but could also be due to inaccuracies in the flow data.

The adopted Bellambi Creek calibration shows no cease-to-flow events. This is consistent with recent observations in Cataract Creek (though recent conditions have not been as dry as the period of Bellambi Creek flow record). Based on catchment modelling, over the long term, baseflow makes up approximately 32% of total flow. Average daily streamflow is significantly larger than median daily due to the impact of a small number of large surface flow events. Modelled average daily streamflow at CC9 on Cataract Creek is 11.2 ML/d of which 3.5ML/d is baseflow. Median baseflow at this location is 2.2ML/d.

Lake Cataract Reservoir Behaviour

A simple daily timestep spreadsheet model of the Lake Cataract catchment was used to generate a historical time series of inflows to Lake Cataract. The spatial variability of rainfall across the catchment, make runoff modelling to the lake difficult. However, it was possible to simulate the historical behaviour of the reservoir during dry periods, including all inflows and outflows, using historical records of storage and release data provided by the SCA.

Impact Assessment – Streamflow

Subsidence induced cracking could potentially affect streamflow in the reaches overlying and downstream of the proposed workings. Other investigations have concluded that these impacts would normally be restricted to short reaches, where flow infiltrates into cracks in the bed, then remerges further downstream. Based on the available subsidence assessments, it is not possible to directly predict the magnitude of these losses or the lengths of streams likely to be impacted.

In the absence of long-term streamflow records on Cataract Creek, the impact of losses from the affected reaches due to mine subsidence was estimated by extracting a constant daily loss rate from the simulated streamflow record. The loss of low flows in Cataract Creek at the reporting locations just downstream of the proposed 20mm subsidence zone resulted in the following modelled changes to low flow characteristics:

A loss of 0.3ML/d would:

- reduce the frequency of flows greater than 1.0ML/d from around 78% to 72%.
- reduce the frequency of flows greater than 0.1ML/d from around 99% to 91%.
- increase the maximum cease to flow period length from 0 to 83 days.
- increase the median duration of cease to flow periods from 0 to 12 days.

A loss of 0.5ML/d would

- reduce the frequency of 1.0ML/d flows to 69%.
- reduce the frequency of 0.1ML/d flows to 86%.
- increase the maximum cease to flow period length from 0 to 101 days.
- increase the median duration of cease to flow periods from 0 to 9.5 days.

A potential mechanism for the loss of streamflow in Cataract Creek is the loss of flow to the underground workings via cracking in the tributary catchments overlying the subsidence area. The potential impact on Cataract Creek of losing flow in these 9 mapped unnamed tributaries was assessed by removing these areas from the catchment model and examining the effect on key streamflow characteristics at CC9 (which is located upstream of the Lake Cataract free surface level). Catchment areas downstream of the underground workings were left in the model to continue to contribute to streamflow in Cataract Creek. The impact of loss of streamflow in a tenth tributary, Tributary 10, was also examined separately (as its confluence with Cataract Creek is located well downstream of CC9).

The effect of catchment losses was assumed to be proportionally the same for all flows - the magnitude of losses is higher during large flow events. The following observations can be drawn from the modelling results:

- Loss of streamflow from the catchment areas of all mapped tributaries upstream of CC9 would reduce the median total flow rate by 0.9ML/d (from 2.54ML/d to 1.64ML/d). Median baseflow would reduce by 0.61ML/d (from 1.71ML/d to 1.10ML/d). The loss of all tributary streamflow to the underground workings via subsidence cracking is very improbable;
- The loss of streamflow from the catchment area of Tributary 1 makes up the bulk of this loss – with the median total flow rate reducing by 0.37ML/d (from 2.54ML/d to 2.17ML/d). Median baseflow would reduce by 0.25ML/d (from 1.71ML/d to 1.46ML/d);
- Loss of streamflow from the catchment areas of the individual tributaries 2-9 would be minimal as each of these tributaries make up less than 6.1% of the total catchment to CC9;
- The loss of streamflow from the catchment area of Tributary 10 would reduce the median total flow rate from this tributary by 0.04ML/d (from 0.08ML/d to 0.04ML/d). Median baseflow would reduce by 0.02ML/d (from 0.05ML/d to 0.03ML/d).

Impact Assessment – Reservoir Yield

The reservoir yield model was used to investigate the potential for additional catchment inflow losses to prevent the reservoir from supplying water demands under historical conditions. Additional losses would have had very little impact on historical Lake Cataract water levels.

The maximum modelled reduction in stored volume occurs in mid-2007 and ranges from 940ML for a loss of 0.5ML/d to 1,385ML for a loss of 10ML/d. Losses of 10ML/d would not have caused the Lake Cataract Reservoir water volume to fall below 10% of capacity. Such loss rates are very large, and unlikely to eventuate given the underlying geology and proposed mining method.

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1 INTRODUCTION

1.1 BACKGROUND

WRM Water and Environment was engaged by Wollongong Coal Limited to assist in assessment of the potential surface water impacts of the proposed expansion of the Russell Vale Colliery Wonga East underground operations.

This study describes the existing surface water hydrology of the potentially affected streams, and the hydrological modelling undertaken to quantify the potential impacts. The modelling has been undertaken to address components of the Director General's Requirements (DGRs) for the project relating to the potential impacts on flows in watercourses and the associated reliability of water supplies from Cataract Dam.

The study draws on estimates of the extent of mine subsidence and the potential for cracking of the ground surface along watercourses. This report focuses on surface water hydrology, whilst the potential impacts on other features of the streams and upland swamps are covered by associated studies.

1.2 UPDATED REPORT

The previous version of this document (Report No. 0637-07-A2 dated the 31st March 2014) was submitted to the New South Wales Department of Planning and Infrastructure as part of the Preliminary Residual Matters Report (Hansen Bailey, 2014) for the Russell Vale Colliery Underground Expansion Project. Since submitting this report, additional modelling has been undertaken to assess the potential impact of subsidence cracking in tributaries on the streamflow in Cataract Creek.

This report includes details on the methodology and results of this modelling in sections 8.2.3 and 8.3.3.

The results of the Cataract Creek streamflow loss impact have also been updated to include the full period of available climate data. The previous report quoted results from analysis of a truncated dataset that commenced in 1960. Updated results can be found in Section 8.3.2.

1.3 PROJECT DESCRIPTION

The proposed workings are contained within the Russell Vale Colliery in Consolidated Coal Lease 745 (CCL745) and Mining Lease 1575 (ML1575), which are located approximately 13km northwest of Wollongong. These areas are shown in Figure 1.1.

Coal will be extracted from the Wongawilli Seam by longwall extraction from 5 new panels in the Wonga East area.

1.4 STUDY AREA

The Study Area includes the catchments of potentially affected and adjacent streams in the vicinity of the project. As shown in Figure 1.1, the Study Area extends approximately 20km west from the Illawarra Escarpment and comprises the catchments of Lake Cataract.

Lake Cataract is a component of the Upper Nepean water supply scheme, and is managed by the Sydney Catchment Authority (SCA).

Figure 1.1 Study Area

1.5 SCOPE OF WORK

The following tasks were completed under the scope of this study:

- Delineate drainage catchments over the mine subsidence area,
- Produce longitudinal profiles over the proposed workings,
- Assess streams in terms of gradient, length, and order,
- Assess rainfall residuals for the nearest long-term rainfall gauge,
- Obtain streamflow from nearby streamflow gauges if relevant to the site catchments,
- Obtain hydrological data pertaining to Lake Cataract:
  - spill volumes,
  - stored volume,
  - water extractions, and
  - surface evaporation.
- Prepare and calibrate a rainfall-runoff model of the Lake Cataract catchment to generate a daily time series of inflows to the dam,
- Assess the contribution of the mine subsidence areas to the total runoff to Lake Cataract over a range of flow conditions,
- Assess the impact of the potential loss of flow due to subsidence-induced cracking on streamflow in the creeks crossing the proposed subsidence area.

2 CATCHMENT CHARACTERISTICS

2.1 LAKE CATARACT CATCHMENT

Ground surface elevations in the Lake Cataract catchment vary from 485m AHD near Mount Keira on the eastern escarpment to 150 m AHD at the confluence of Wallandoola Creek and the Cataract River, at the downstream (western) end of the Study Area. The underlying geology predominantly comprises Hawkesbury Sandstone, however the Bald Hill Claystone and Bulgo Sandstone are exposed in the valley floor of Cataract Creek. Steep rocky outcrops and cliffs are present in some areas, while some headwater streams drain upland headwater swamps on the higher eastern plateau via ephemeral gullies incised into the sandstone.

Cataract Dam has significantly altered streamflow from the upstream catchment since its construction in 1907. The dam has a capacity of 97,190 ML and controls a catchment area of 130km^2. Flows downstream of the dam are further regulated by Broughton's Pass weir, which diverts water supplies to the Macarthur Water Treatment Plant via Cataract Tunnel.

There has been a long history of coal mining under the Upper Nepean water supply catchments. Mining activities by previous owners of Russell Vale Colliery and the decommissioned BHP Billiton Cordeaux Colliery longwall as well as other old bord and pillar workings have caused adverse subsidence impacts in the Study Area. Longwall mining in the Appin, Westcliff and Northcliff workings approximately 2.5 km to the north of the Lease Area have also resulted in adverse impacts on surface water quality and quantity (Short, 2007).

Surface infrastructure associated with mining affects relatively small portions of the catchment, and as the SCA's Metropolitan Special Area is a restricted access area, the Study Area is otherwise largely undeveloped and in a natural condition.

2.2 WONGA EAST CATCHMENTS

The Wonga East area is predominantly drained by Cataract Creek, and to a much lesser degree, Bellambi Creek and the Cataract River. Cataract Creek joins the Cataract River within the impoundment of Lake Cataract.

As shown in Figure 2.1, parts of the upper catchments have been cleared for powerlines and access tracks. The Southern Freeway/Mount Ousley Road also crosses the eastern portion of these catchments. Three upland swamps are present in the Cataract River catchment.

Longwall mining of the Balgownie Seam as well as bord and pillar extraction of the Bulli Seam has previously been conducted under Cataract Creek. The most recent activities were associated with mining of Longwall Panels 4 and 5 to the south of Cataract Creek.

As shown in Figure 2.1, the proposed Wonga East workings underlie Cataract Creek. Figure 2.2 shows the western end of Panel 7 and its associated predicted 20 mm subsidence zone will encroach close to the eastern bank of the high water extent of the Lake Cataract backwater.

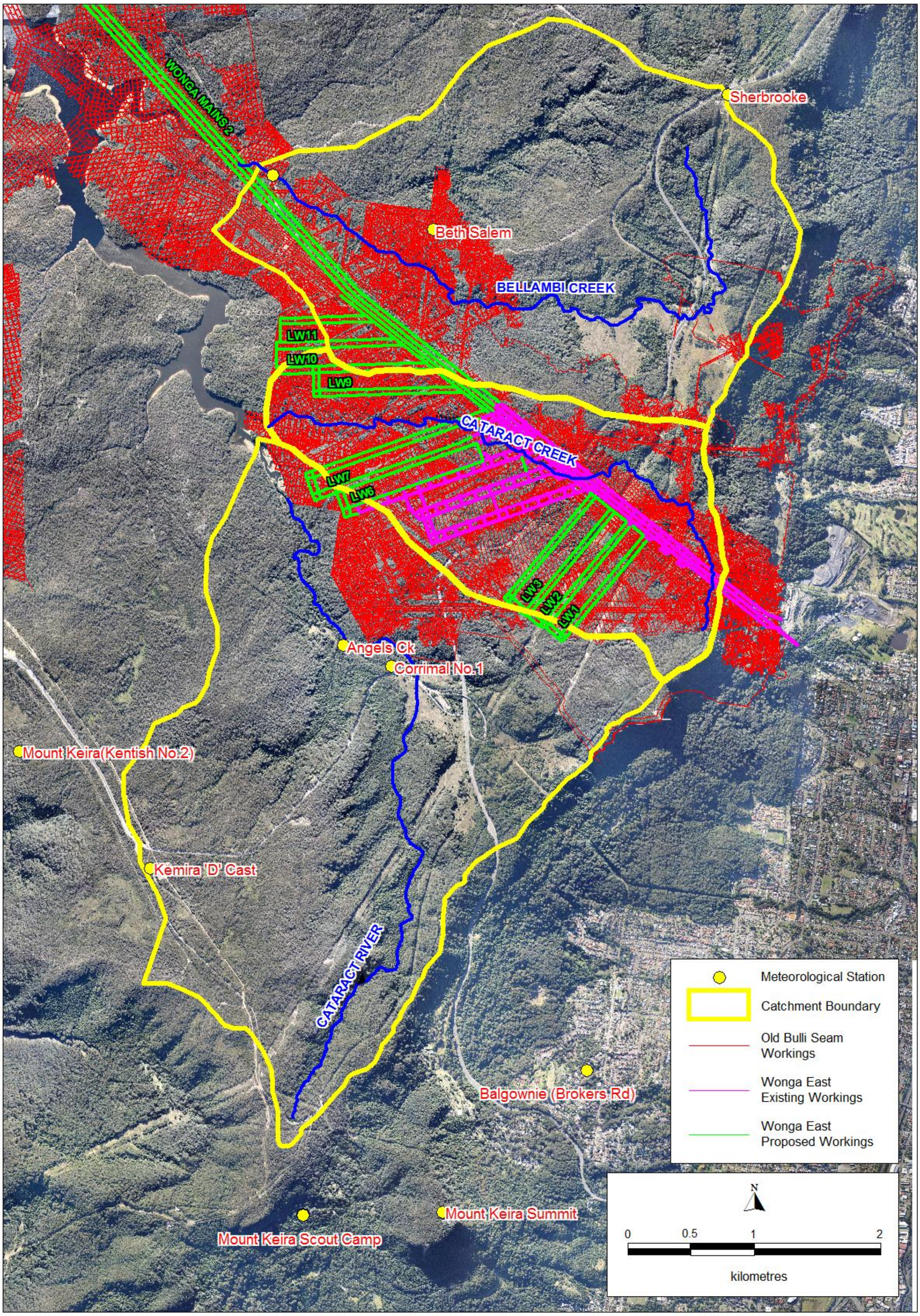


Figure 2.1 Cataract River and Cataract Creek Catchment Areas

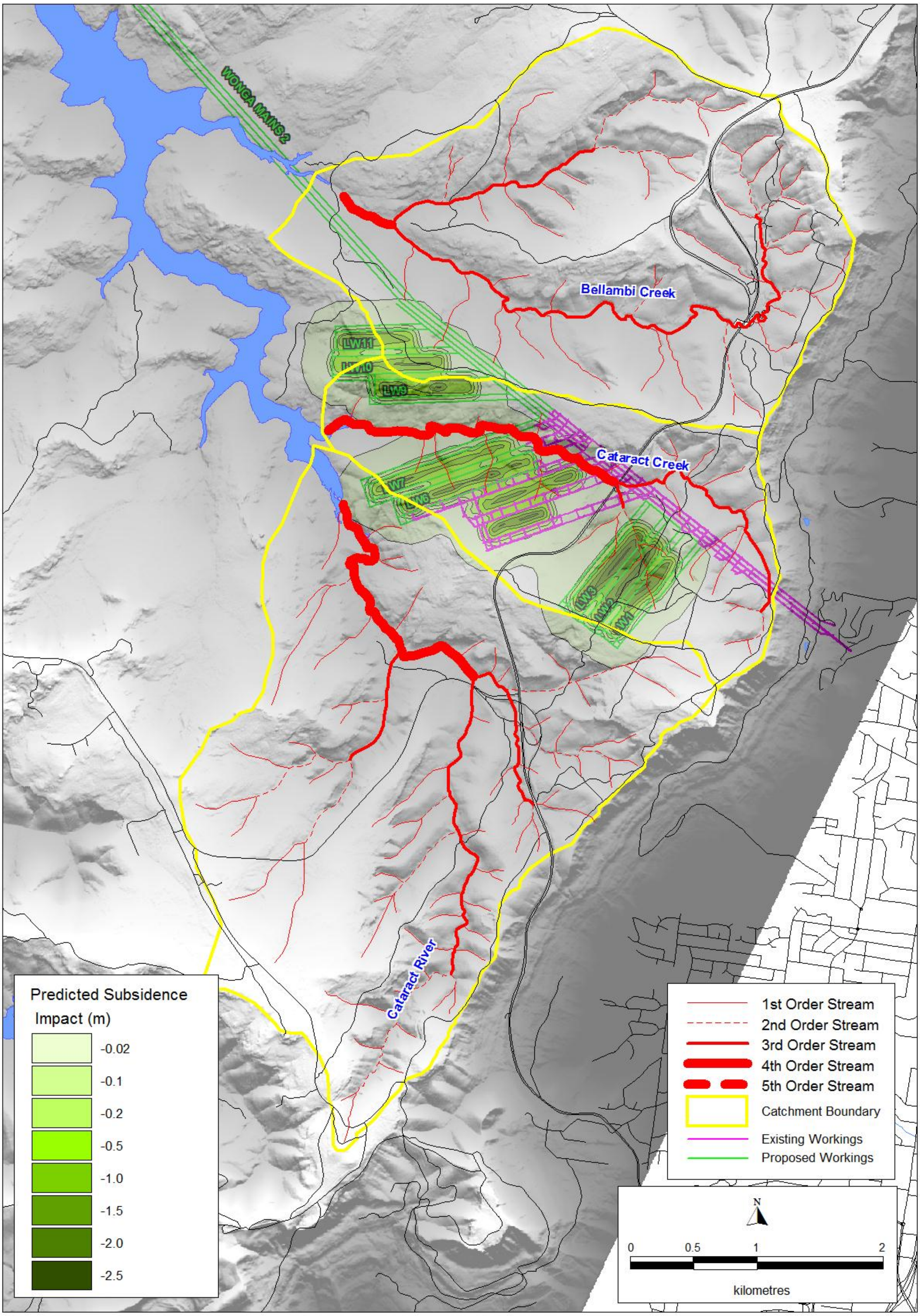


Figure 2.2 Stream Order – Cataract River, Cataract Creek and Bellambi Creek

3 STREAM GEOMETRY

3.1 GENERAL

Longitudinal profiles of each of the potentially affected watercourses were produced from a digital terrain model derived using airborne laser scanning (ALS) survey acquired over the Study Area on 20th October 2009. The accuracy of well-defined points in the survey data is quoted as better than 100mm, based on comparison with ground survey in cleared areas (AAM Hatch, 2009). Ground survey cross-sections were obtained at the Cataract Creek pool level monitoring locations by Southern Cross Surveyors in September 2013.

3.2 CATARACT CREEK

As shown in Figure 2.2, Cataract Creek is a 4th order stream for most of its length.

A longitudinal profile of Cataract Creek is shown in Figure 3.1 (its alignment is shown in Figure 3.3). Cataract Creek is approximately 5.5km long from its headwaters to the upstream reaches of the Lake Cataract storage. Channel invert elevations fall from approximately 340m AHD to 285m AHD. The channel is relatively gently sloping at a gradient of 0.9%, for most of its length - the exception being the steep upstream 0.5km reach, which slopes at 2.5%

The proposed Wonga East workings are located between Chainage 2,500m and Chainage 4,500m. Approximately 2.5km of the stream reach is located upstream, 2km within and 0.9km downstream of the 20mm subsidence zone.

Channel cross-sections at three locations along Cataract Creek are shown in Figure 3.2. The cross-section at Chainage 240m was created using ALS data only. The cross-sections at chainages 2,600 and 4,600 were created using a combination of ground survey and ALS data.

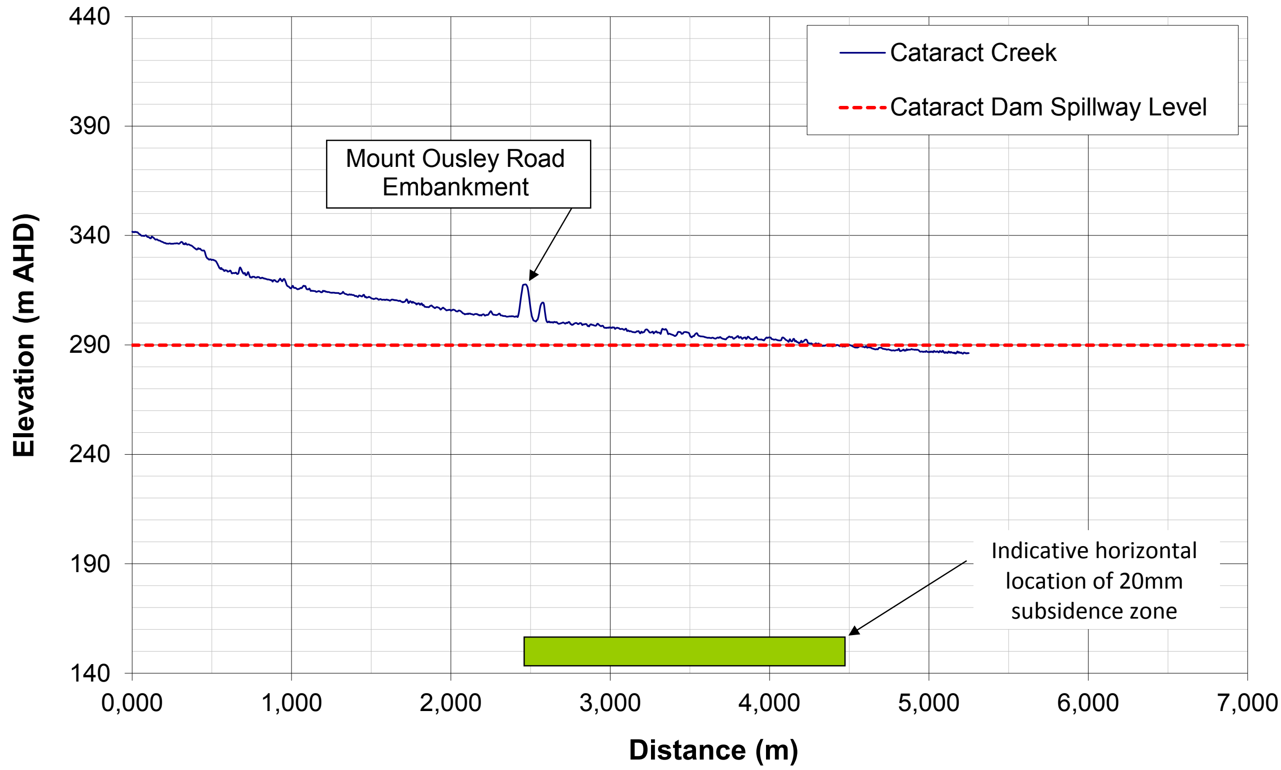


Figure 3.1 Longitudinal Profile Cataract Creek

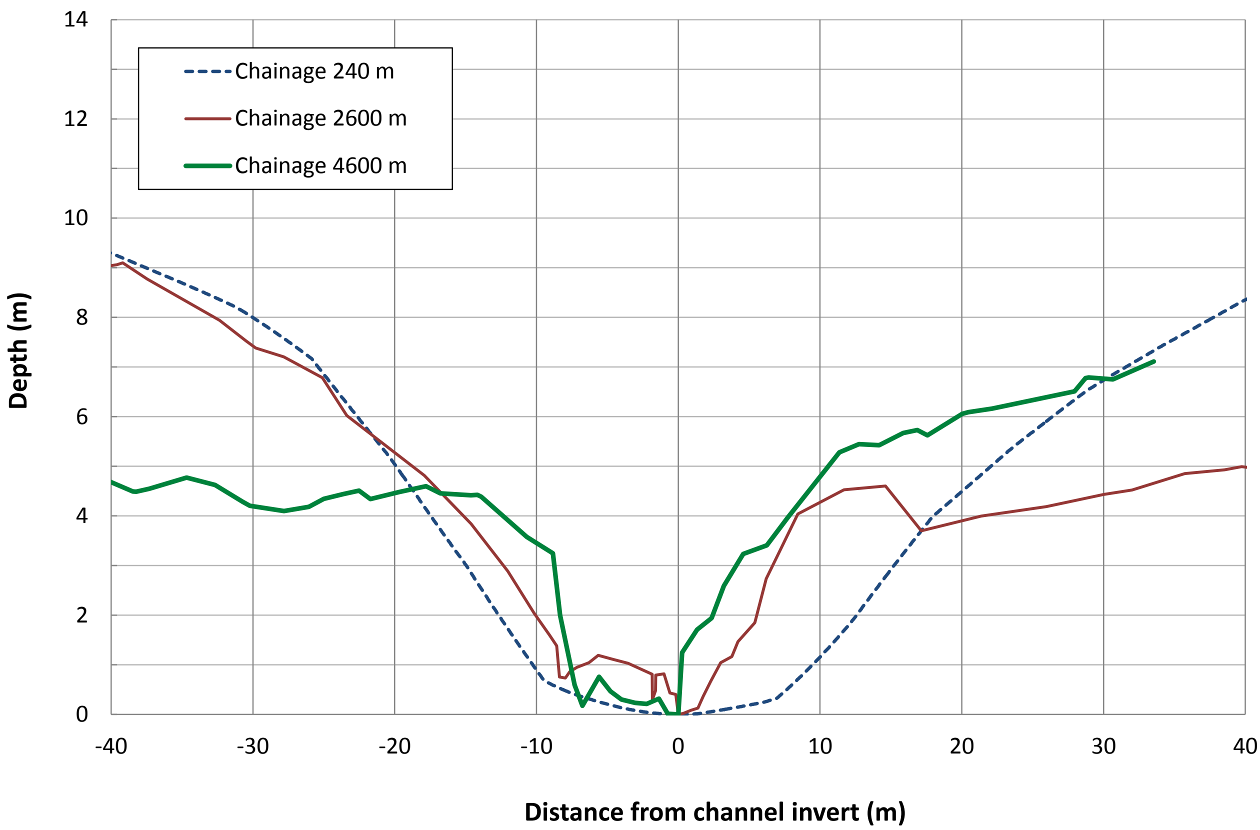


Figure 3.2 Cross-sections of Cataract Creek

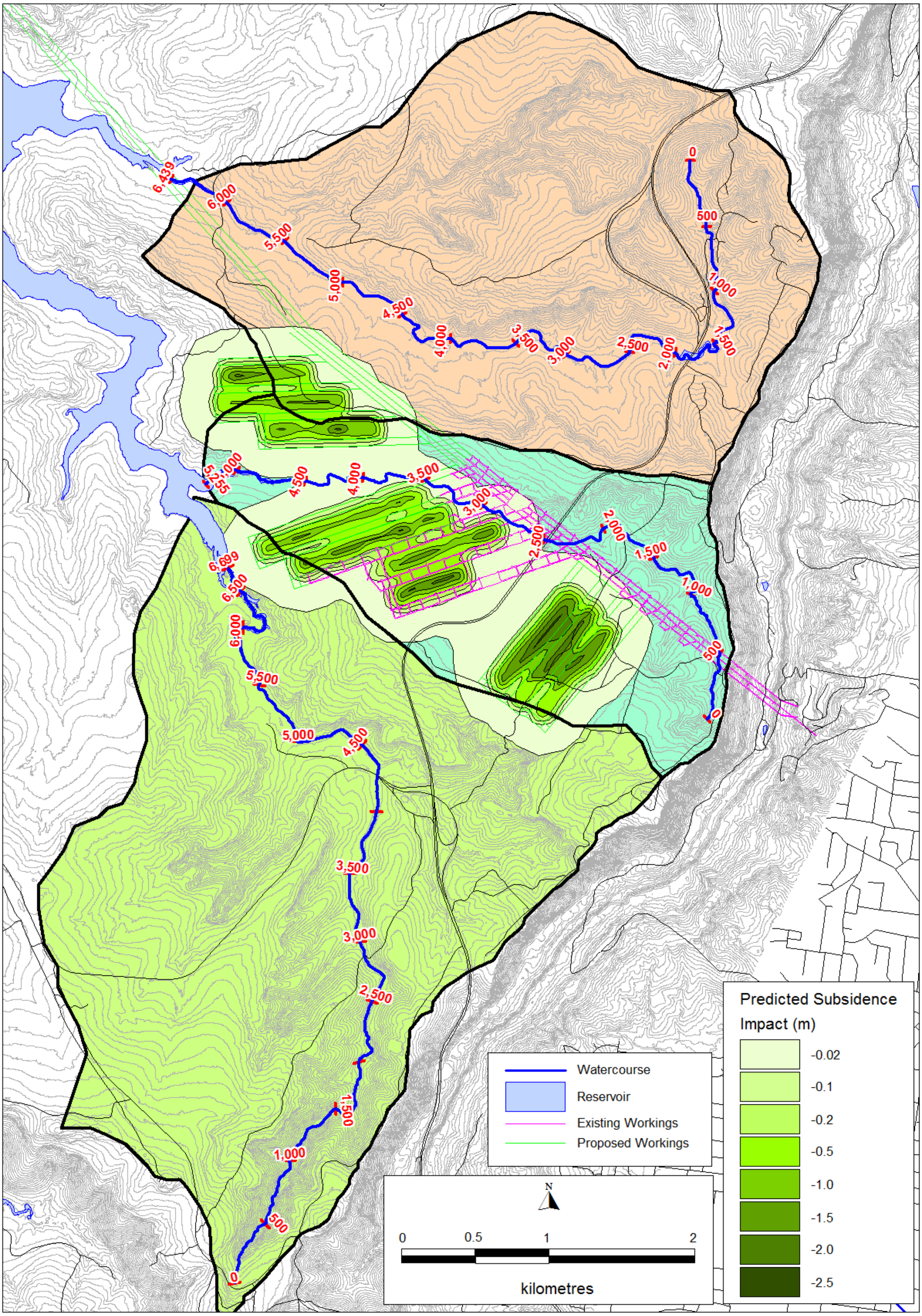


Figure 3.3 Alignments of Longitudinal Profiles of Cataract River, Cataract Creek and Bellambi Creek

3.3 CATARACT RIVER

As shown in Figure 2.2, Cataract River is a 3rd order stream upstream of the Link Road crossing, and 4th order from the confluence near the crossing to the Lake Cataract backwater.

Cataract River is approximately 6.7km long from its headwaters to the upstream reaches of the Lake Cataract storage. Channel invert elevations fall from approximately 430m AHD to 285m AHD. The channel is relatively gently sloping at a gradient of 0.5%, for much of its length - the exception being the steep upstream 0.5km reach, which slopes at around 17%.

The proposed Wonga East workings do not underlie the Cataract River. The mine panels are to be laid out in accordance with SCA requirements for clearance from the reservoir area.

Channel cross-sections at three locations along Cataract River are shown in Figure 3.5.

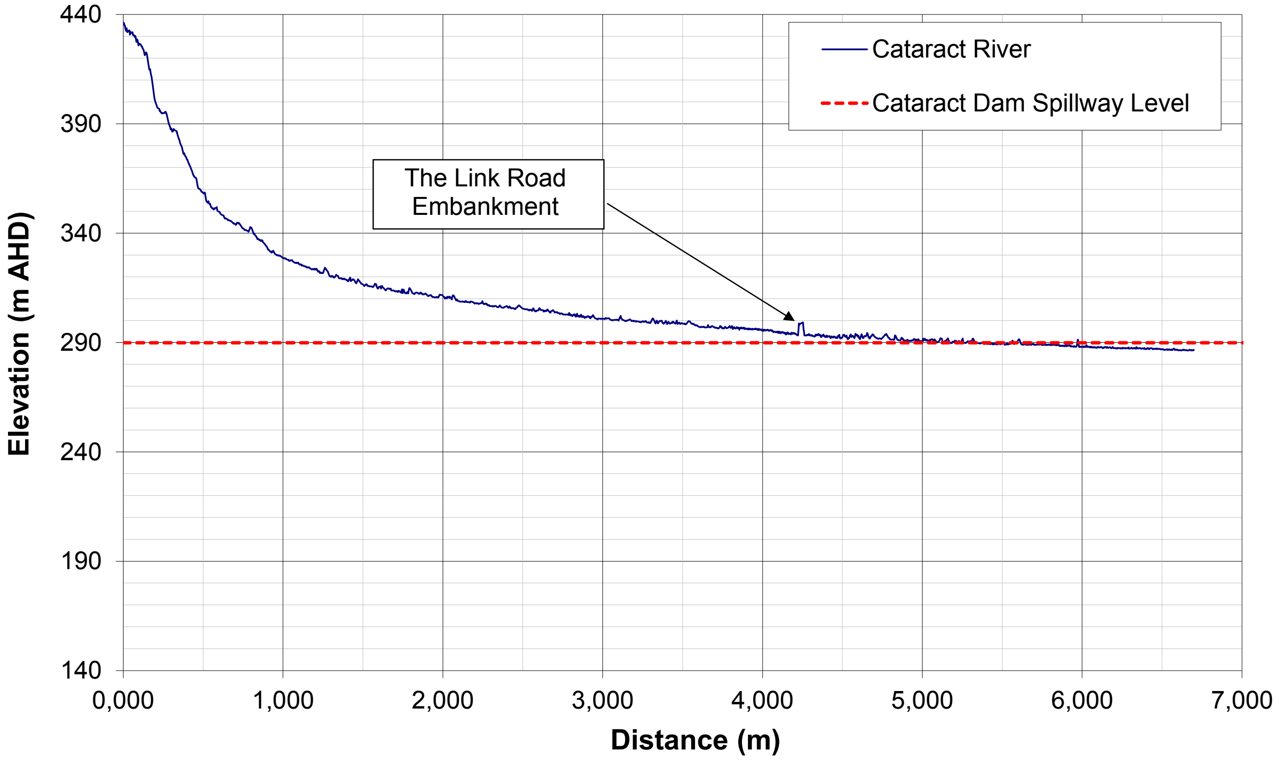


Figure 3.4 Longitudinal Profile Cataract River

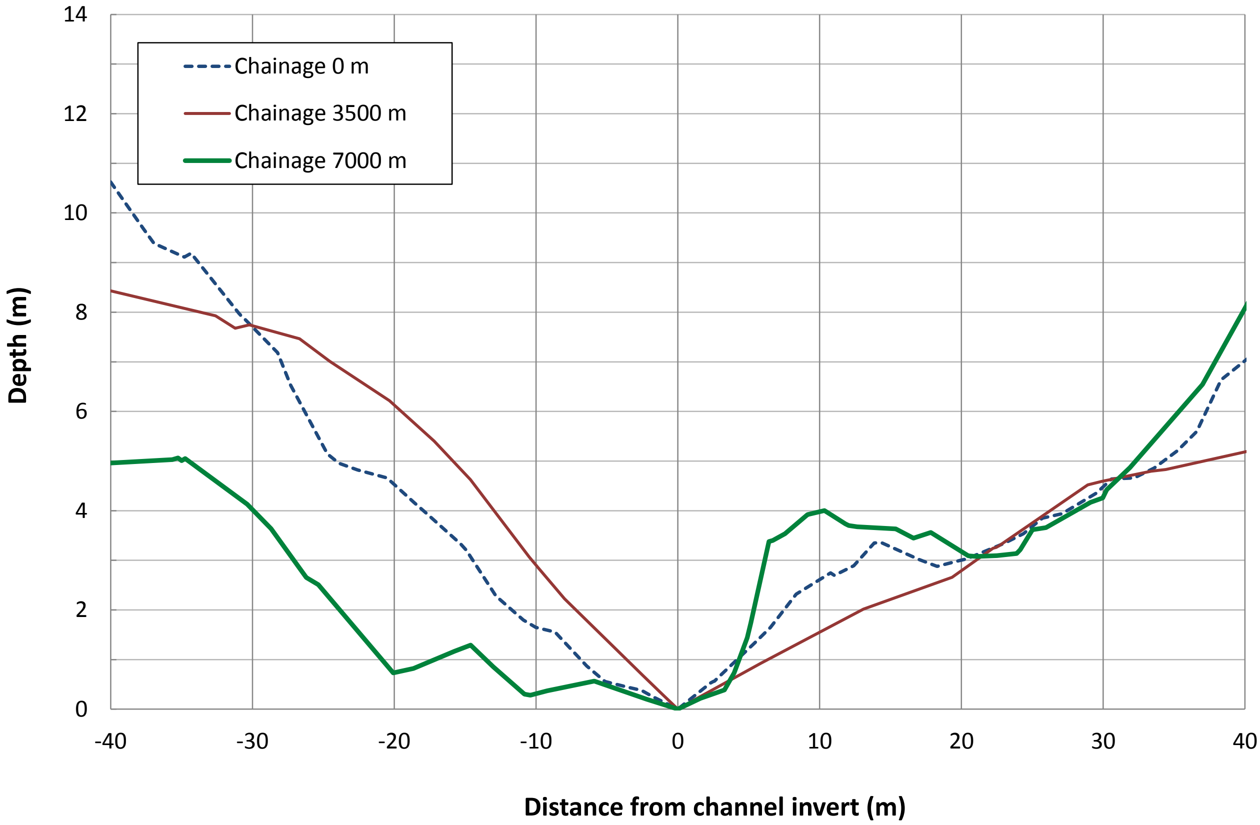


Figure 3.5 Cross-sections of Cataract River

3.4 BELLAMBI CREEK

As shown in Figure 2.2, Bellambi Creek is a 3rd order stream upstream of Chainage 5,500m, and 4th order from Chainage 5,500m to the Lake Cataract backwater.

Bellambi Creek is approximately 6.4km long from its headwaters to the upstream reaches of the Lake Cataract storage. Channel invert elevations fall from approximately 453m AHD to 286m AHD. The channel is relatively gently sloping at a gradient of 0.6%, for much of its length - the exception being the steep upstream 1.0km reach, which slopes at around 2.8%.

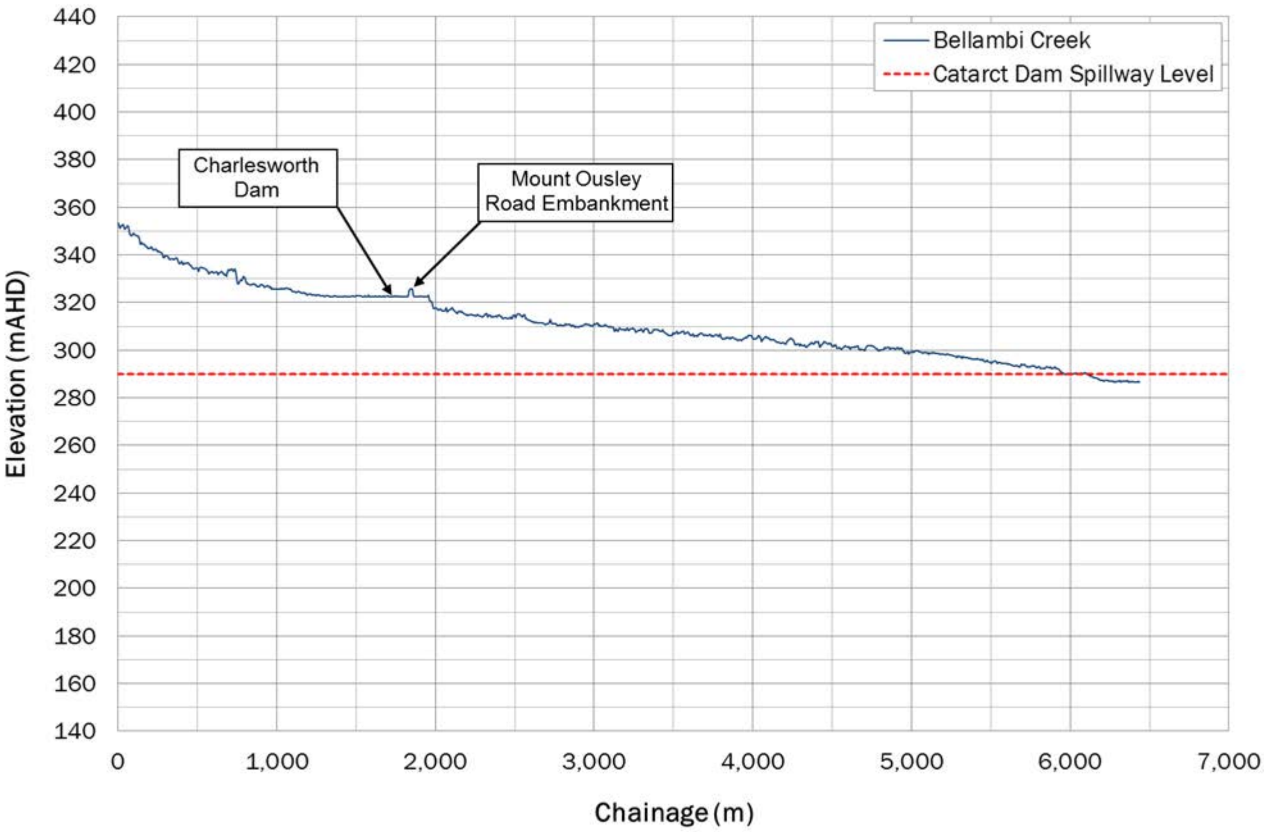


Figure 3.6 Longitudinal Profile Bellambi Creek

4 CLIMATE CHARACTERISTICS

4.1 RAINFALL

4.1.1 Available Data

Daily rainfall has been recorded by the Bureau of Meteorology (BOM) and the SCA and its predecessors. The nearby rainfall stations with the longest records are located at Cataract and Cataract Dam. These stations have good quality records extending from 1883 to 1966 and 1904 to 2014 respectively.

The BOM's SILO data service has prepared Patched Point Datasets (PPDs) from the Cataract and Cataract Dam records. Gaps in the records are infilled with data interpolated from other nearby stations to provide continuous records between 1889 and the present day (Jeffrey et al., 2001).

4.1.2 Temporal Variability

As shown in Figure 4.1, annual rainfall at Cataract Dam for the period 1889 to 2013 has varied from 480mm in 1944, to 2,293 mm in 1950. Mean annual rainfall over this period was 1,085 mm/a.

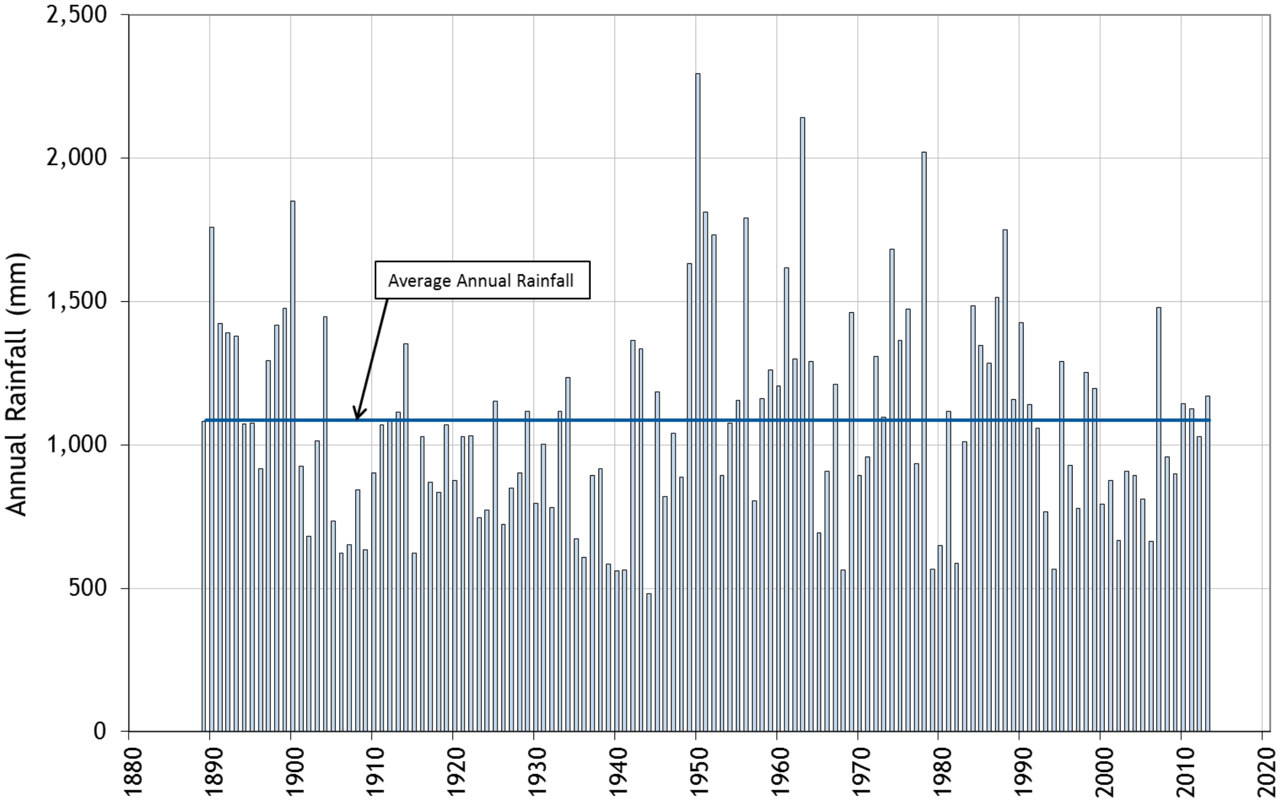


Figure 4.1 Annual Rainfall at Cataract Dam (Patched Point Dataset)

Cataract Dam rainfall is relatively consistent throughout the year. Rainfall is highest between January and June and lowest between July and December. This is illustrated in Figure 4.2, which shows mean monthly rainfall.

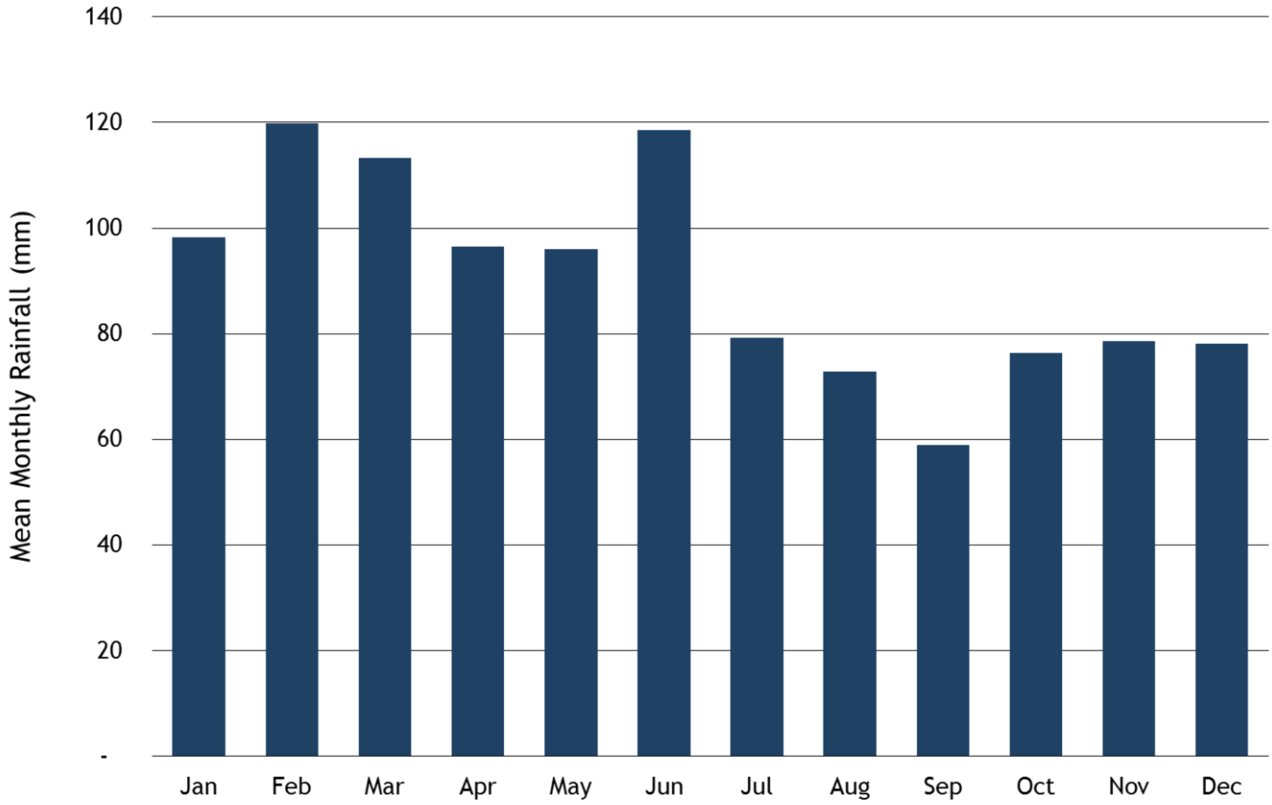


Figure 4.2 Variation in Mean Monthly Rainfall at Cataract Dam

Figure 4.3 shows a plot of rainfall residual at Cataract Dam for the period 1889 to 2013 (prepared using the PPD). The raw data for the station is overlaid on this line for comparison over the available period of record.

The rainfall residual shows departures from the long-term average (i.e. it has not been seasonally adjusted). Upward sloping lines indicate relatively wet periods, and downward sloping lines indicate relatively dry periods.

The figure shows that the period between 1905 and 1942, and the period since 1992 were relatively dry. The period from 1890 to 1900 and between 1950 and 1992 was generally relatively wet (with the exception of the late 1960s and the early 1980s). A plot of the SOI residual has been overlaid on the rainfall residual for comparison.

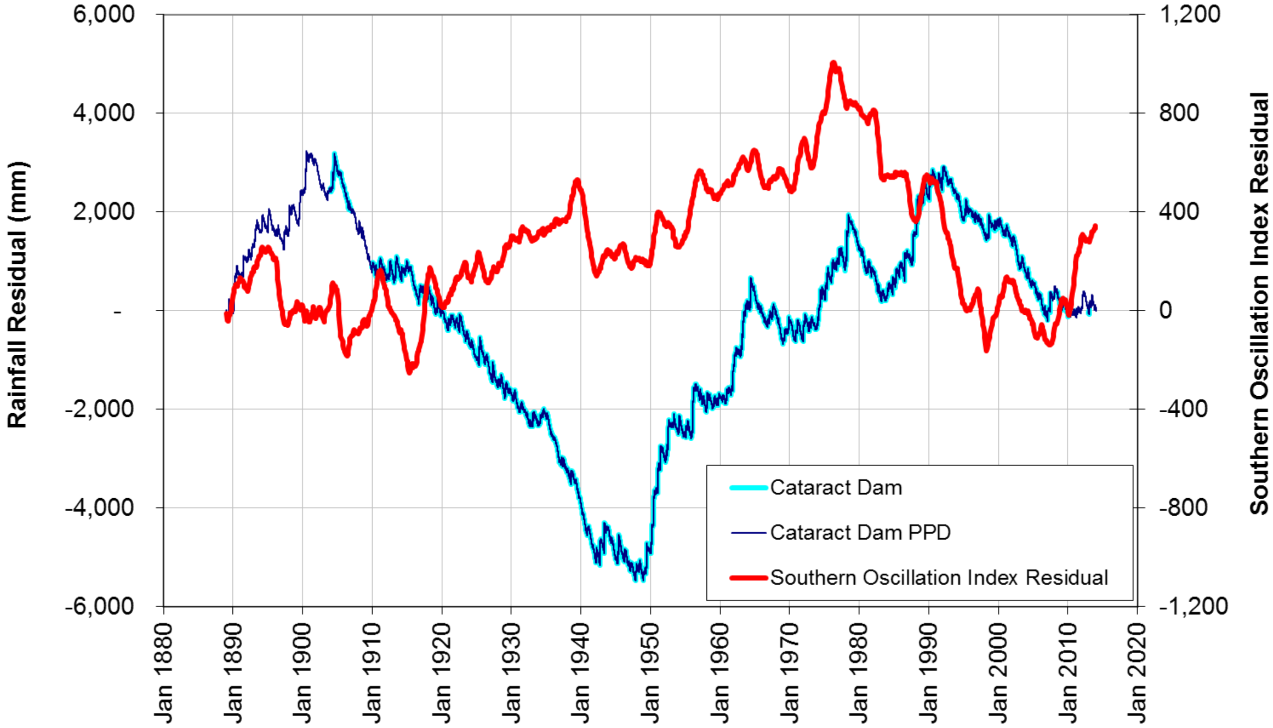


Figure 4.3 Rainfall Residual at Cataract Dam 1889-2013

4.1.3 Spatial Variability

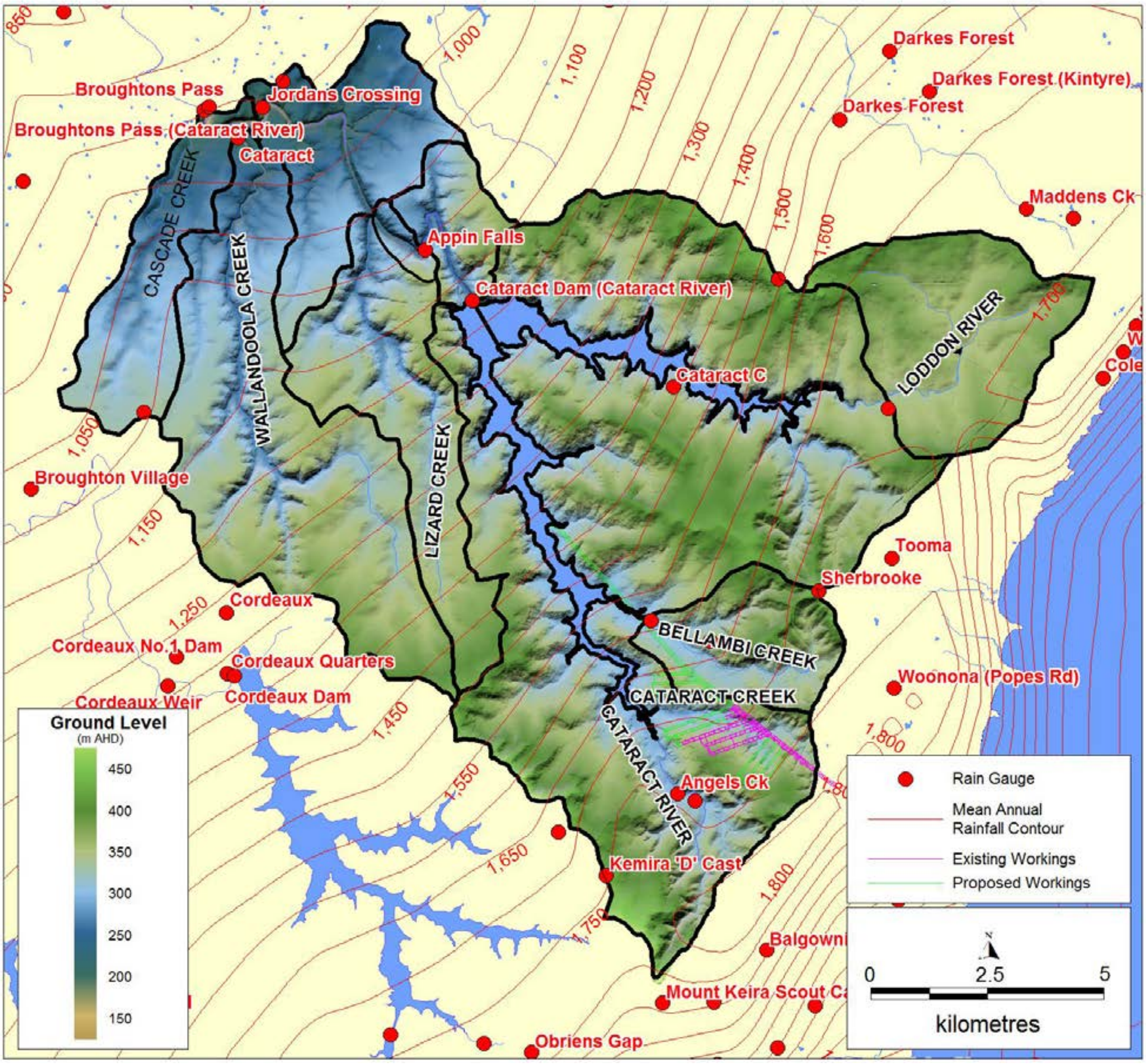
The locations of rainfall stations of interest are shown in Figure 4.4. Few stations have operated in the immediate vicinity of the proposed workings, and most are located near the Study Area boundary. Table 4.1 shows the period over which data was available from each of the gauges.

Table 4.1 Daily Rainfall Recording Stations in the Vicinity of the Study Area

Station Number	Station Name	Period of Record	
		Start	Finish
568004	Cordeaux Airstrip	08-Feb-1964	-
68020	Cordeaux Quarters	01-Jul-1945	-
68017	Cataract	30-Mar-1883	29-Dec-1966
68016	Cataract Dam	01-Jan-1904	-
568065	Letterbox Tower	06-Dec-1964	-
568067	Beth Salem	30-Aug-1966	-
68086	Mount Keira Scout Camp	30-Jan-1944	29-Jul-1992

The length and quality of records from these seven stations is variable. Continuous data from an overlapping data period is only available for the period 1984 to 1991. Figure 4.5 and Figure 4.6 compare mean annual and mean monthly rainfall at the gauges over this common period.

The figures show rainfall increases significantly across the study area from west to east. The eastern stations exhibit relatively high rainfall in February, March, April and June compared to the rest of the Study Area. This spatial variability of rainfall is also illustrated in Figure 4.4, which shows isohyets derived from gridded interpolated rainfall data over the Study Area prepared by BOM for the period 1969 to 1990.



(Source: BOM gridded data 1969-1990)

Figure 4.4 Mean Annual Rainfall Isohyets

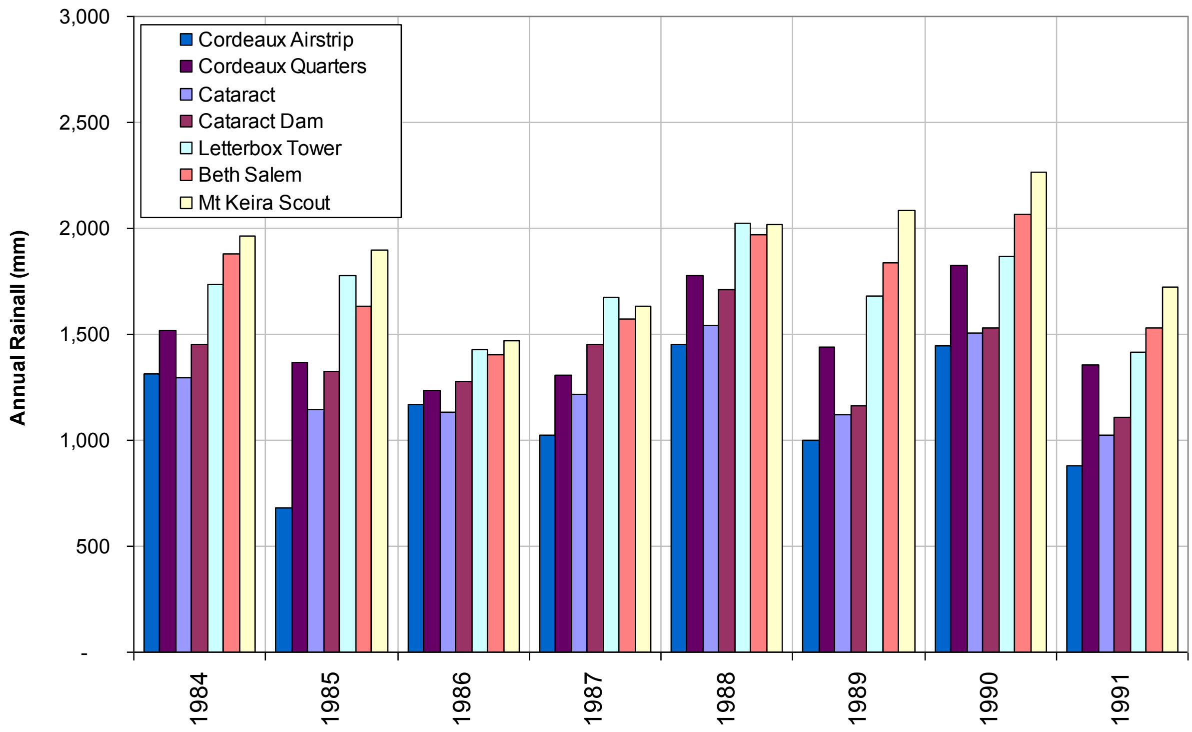


Figure 4.5 Variation in Mean Annual Rainfall across the Catchment (raw data 1984-1991)

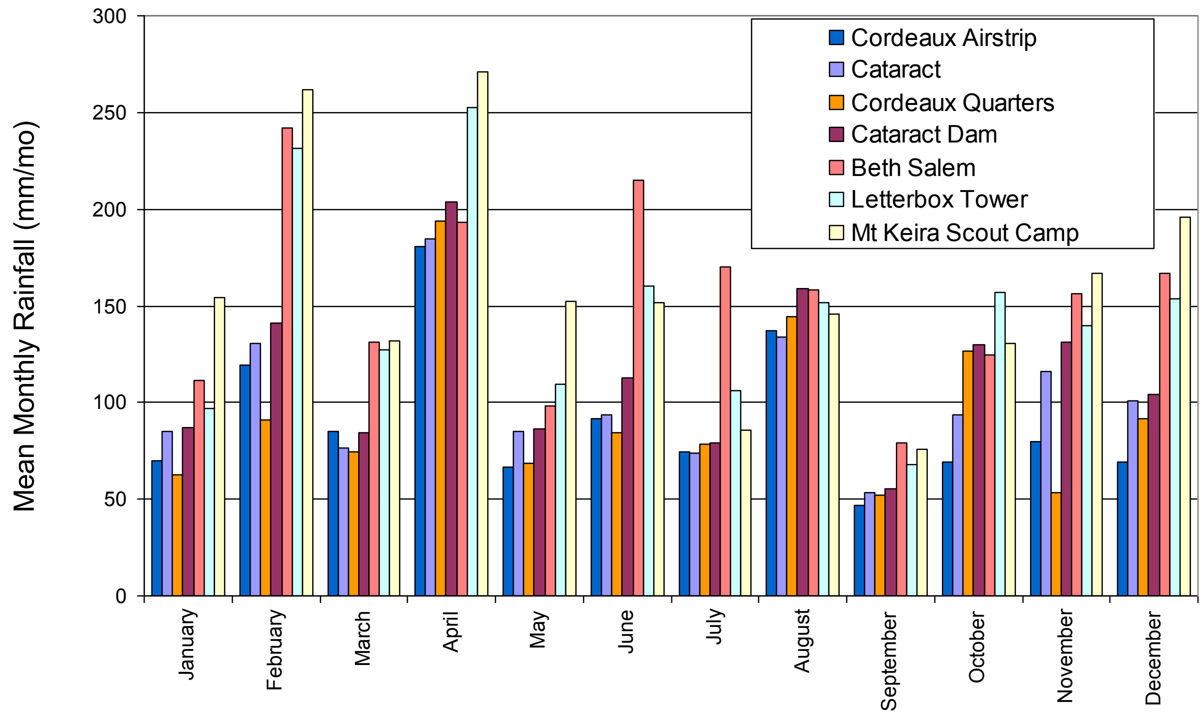


Figure 4.6 Variation in Mean Monthly Rainfall across the Catchment (raw data 1984-1991)

4.2 EVAPORATION

Daily Pan Evaporation has been recorded at the sites shown in Table 4.2 and Figure 4.7.

Table 4.2 Daily Evaporation Recording Stations in the Vicinity of the Study Area

Station	Location	Start	Finish
68017	Cataract		
668048	Cataract Dam	1908	
668049	Cordeaux Quarters	1-Jul-45	
668068	Upper Cordeaux	1973	31-Jul-96

Evaporation is relatively consistent across these gauges. Mean annual pan evaporation at Cataract Dam is approximately 1420 mm/a.

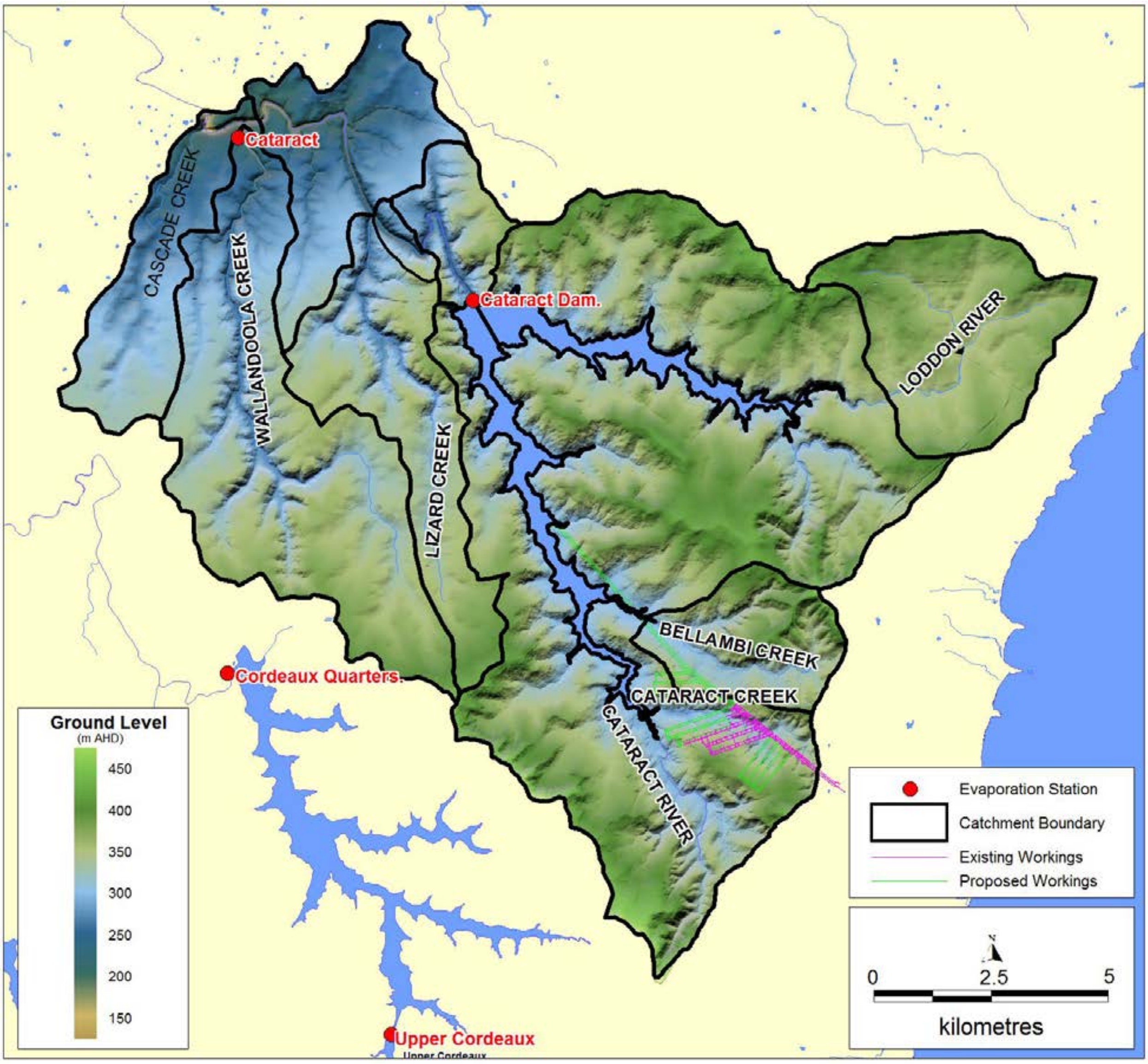


Figure 4.7 Daily Pan Evaporation Recording Stations

The monthly variation in pan evaporation at Cataract Dam is illustrated in Figure 4.8. Evaporation is highest in the summer months.

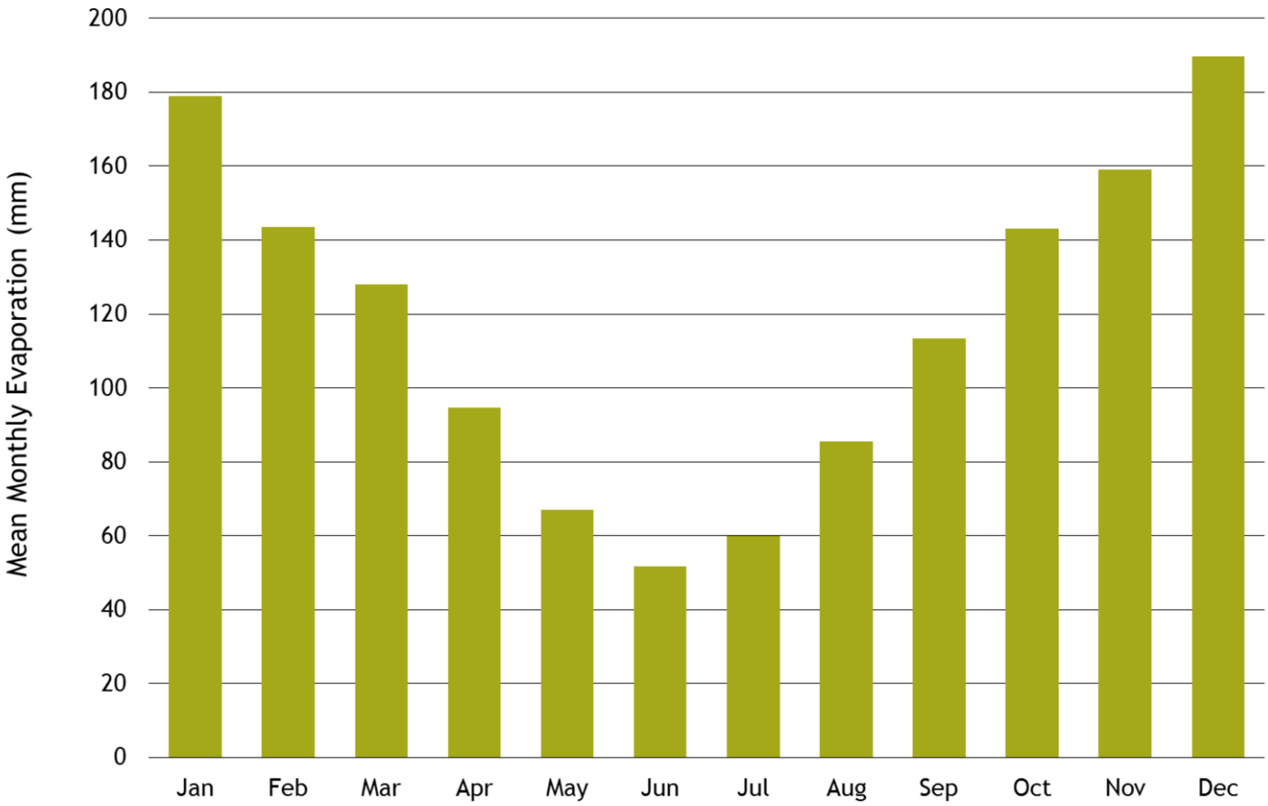


Figure 4.8 Monthly Pan Evaporation at Cataract Dam (PPD)

5 RUNOFF CHARACTERISTCS

5.1 STREAMFLOW DATA

Long term streamflow has been recorded in the Study Area at the gauges shown in Figure 5.1. Gauges in the immediate vicinity of the proposed workings used for this study are listed in Table 5.1. Both are in headwater streams flowing into Lake Cataract, and are not directly impacted by the predicted subsidence from the proposed workings.

The SCA operated a streamflow gauge in the Cataract River at Jordon's Crossing over the period from August 1986 to July 2013. Unfortunately the streamflow at this location is heavily influenced by releases from water storages upstream of the gauge. Therefore, the data from this gauge is unsuitable for the analysis of natural streamflow conditions in the Cataract River.

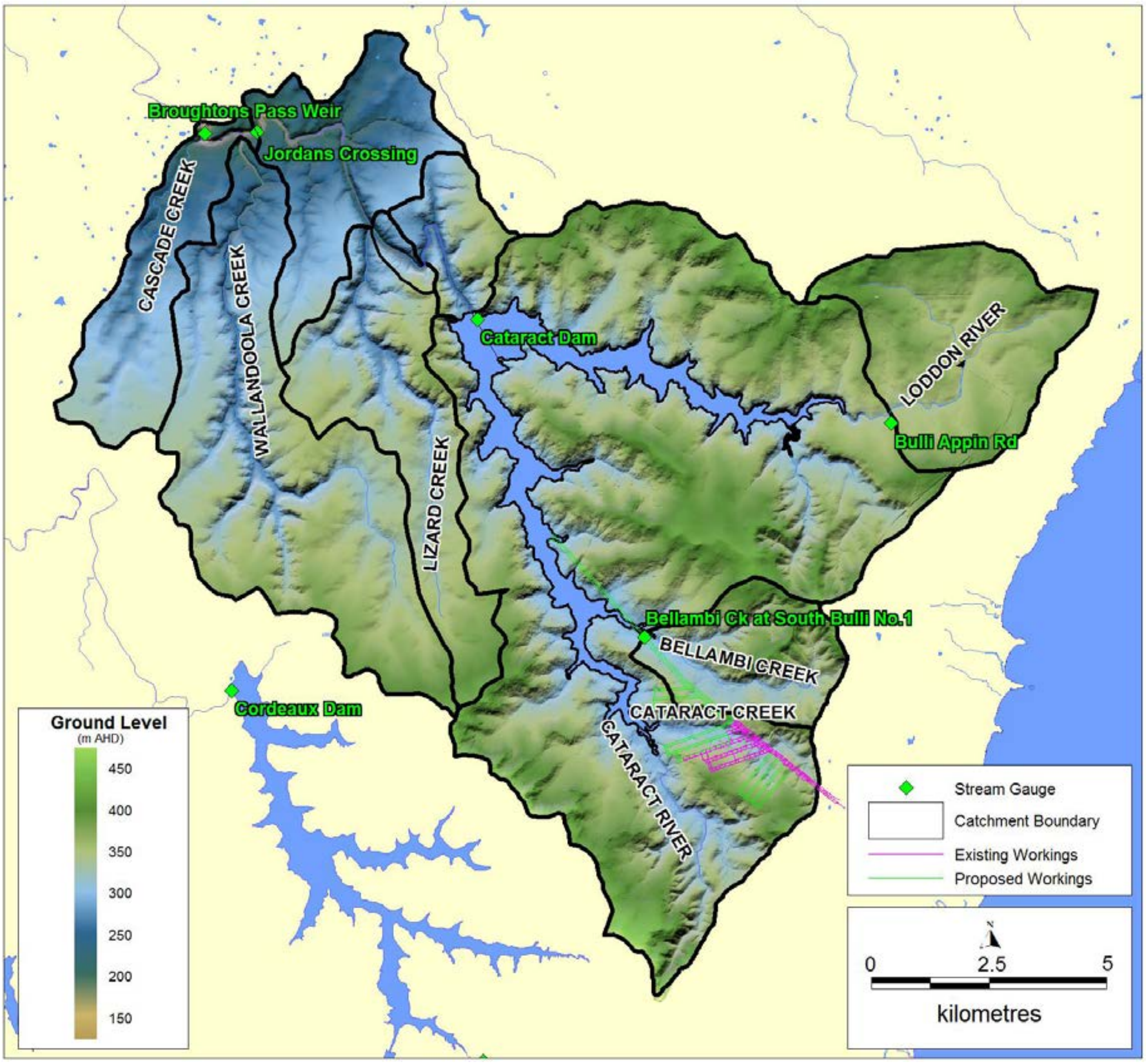


Figure 5.1 Streamflow Recording Stations in the Study Area

Table 5.1 Streamflow Recording Stations in the Study Area

Station Number	Station Name	Catchment Area (km²)	Mean Flow (ML/a)	Median Flow (ML/a)	Period of Record
2122321	Bellambi Creek at South Bulli No 1	9.3	2,608	1,194	01/01/1991-03/09/1995
2122322	Loddon River at Bulli Appin Rd	17.6	12,810	1,920	01/01/1991-08/11/2009

Streamflow is shown in Figure 5.2 for the overlapping period between 1991 and September 1995. The figure shows the catchments respond similarly, although much higher flows are generated from the Loddon River. Baseflow persists for extended periods after rainfall – and is similar in both streams, even though the Bellambi Creek catchment is much smaller. The flow frequency curves in Figure 5.3 and Figure 5.4 show that flow occurs more than 90% of the time, and flows exceeding 3ML/d occur 50% of the time.

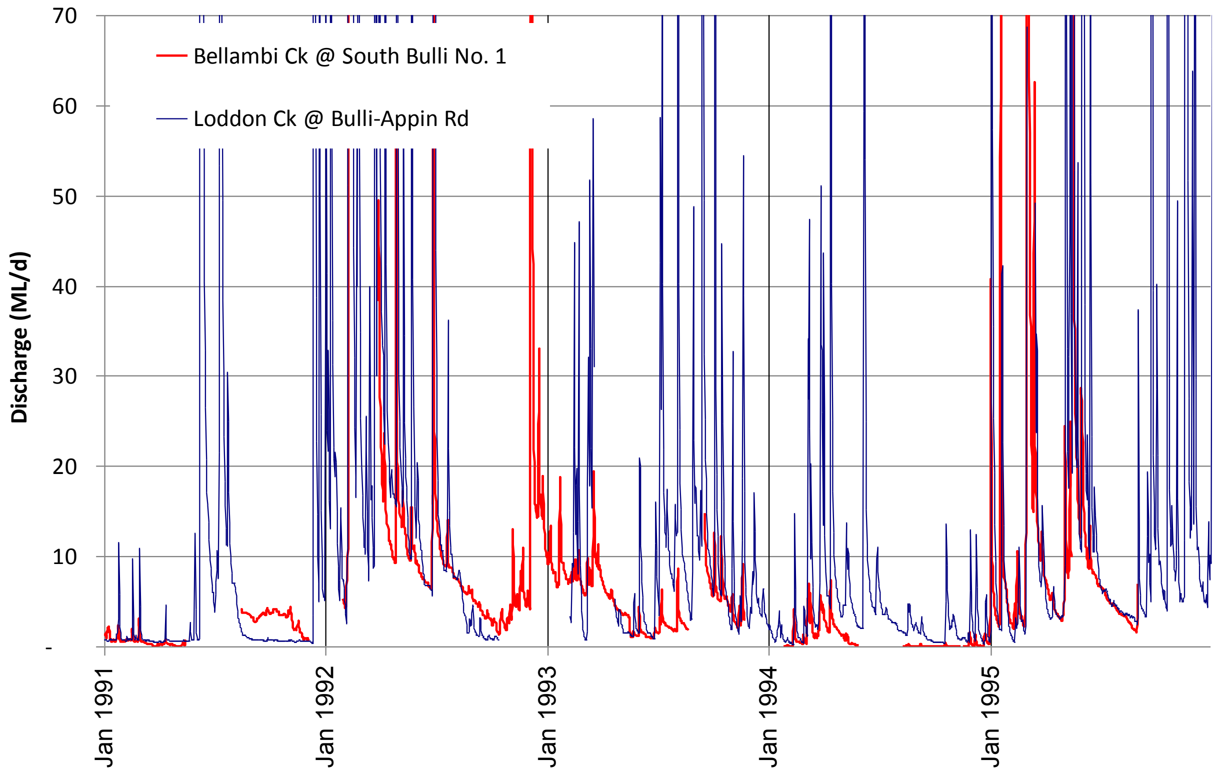


Figure 5.2 Sample Streamflow Record Bellambi Creek and Loddon River (1991-1995)

While persistent baseflow is a notable feature of the streamflow, it contributes a relatively small portion of total streamflow volume. The curves in Figure 5.5 show that over 90% of the total streamflow volume came from the largest 40% of daily flows. Flows of less than 3ML/d made up only 5% of total flow volume from both catchments.

There are however some periods when the flows are dissimilar – due probably to spatially variable rainfall. The Loddon River catchment exhibits a significantly higher runoff to rainfall ratio, as demonstrated in the table below, which compares total runoff (considering days when flow was recorded at both gauges only).

Table 5.2 Runoff Characteristics Loddon River and Bellambi Creek 1991-1995

Station Name	Mean Annual Flow (ML/a)	Runoff Depth (mm/a)
Bellambi Creek at South Bulli No 1	2,608	280
Loddon River at Bulli Appin Rd	9,239	525

Very low flows less than 1 ML/d occurred less frequently in Bellambi Creek. This could be a hydrological characteristic of this catchment. Alternatively, low flows may have been affected by historical streamflow loss through subsidence-induced cracking of Bellambi Creek. However, it is possible this characteristic is an artefact of inaccuracies in the height-discharge relationship of either or both of these streamflow gauges.

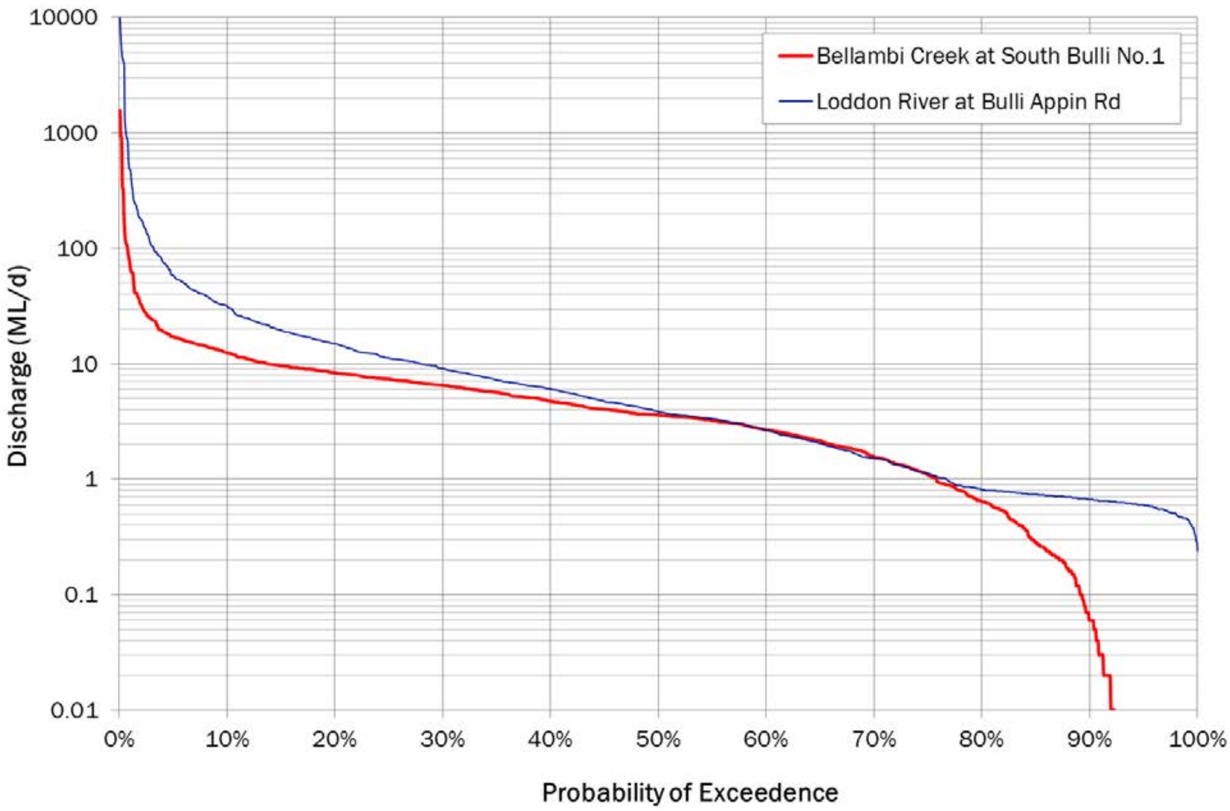


Figure 5.3 Flow Frequency Curves Bellambi Creek and Loddon River (1991-1995) - Discharge

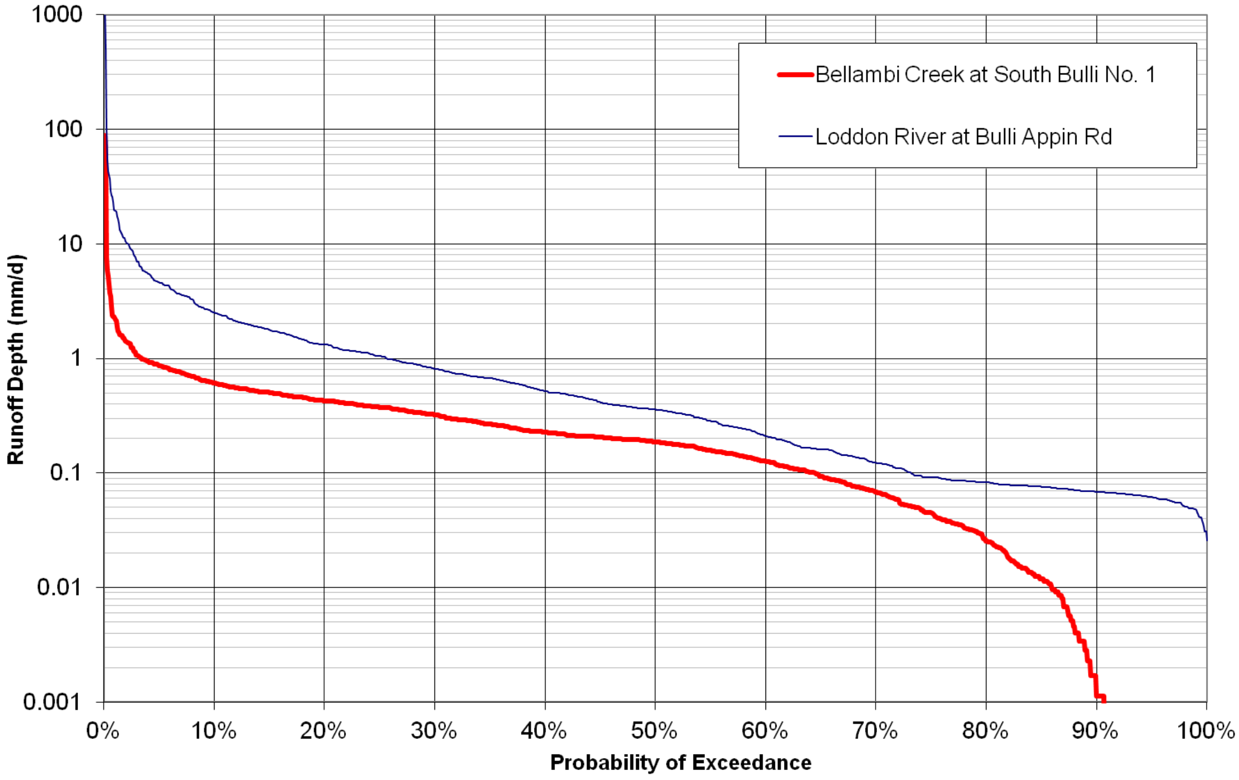


Figure 5.4 Flow Frequency Curves Bellambi Creek and Loddon River (1991-1995) – Runoff Depth

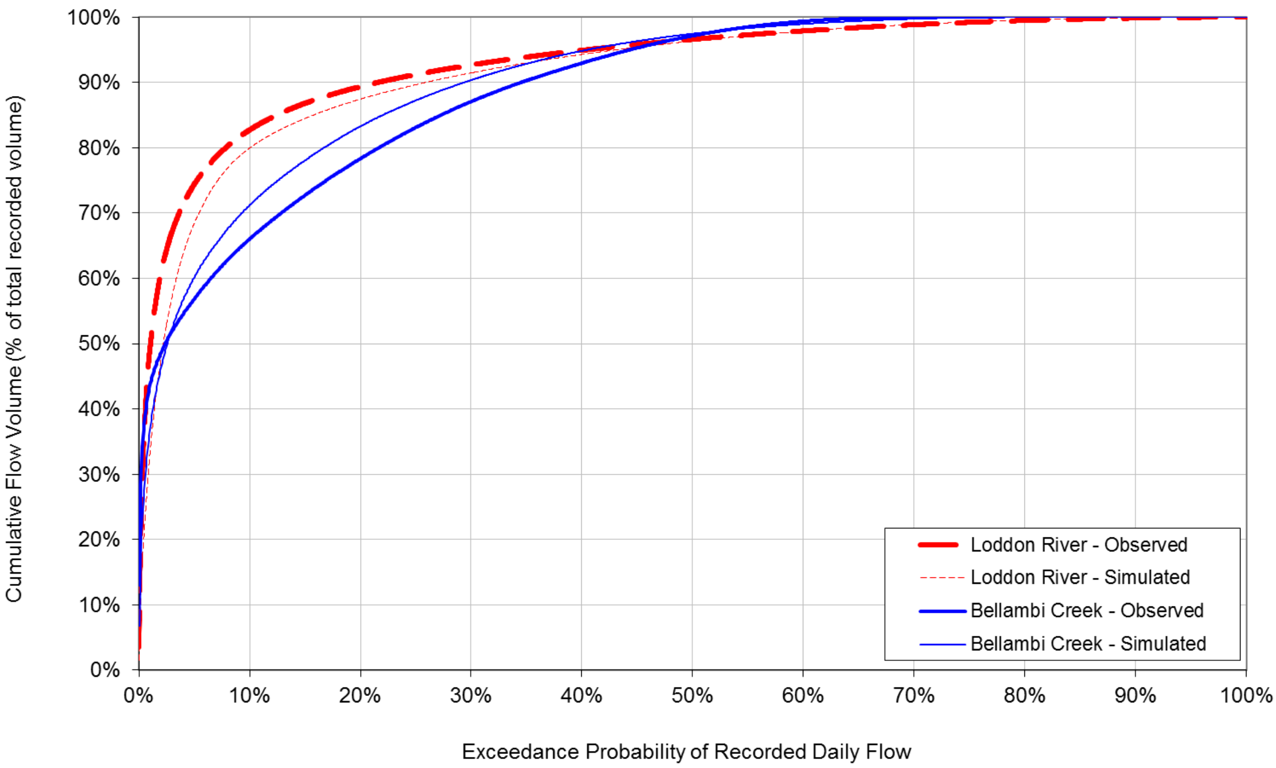


Figure 5.5 Cumulative Flow Volume Bellambi Creek and Loddon River

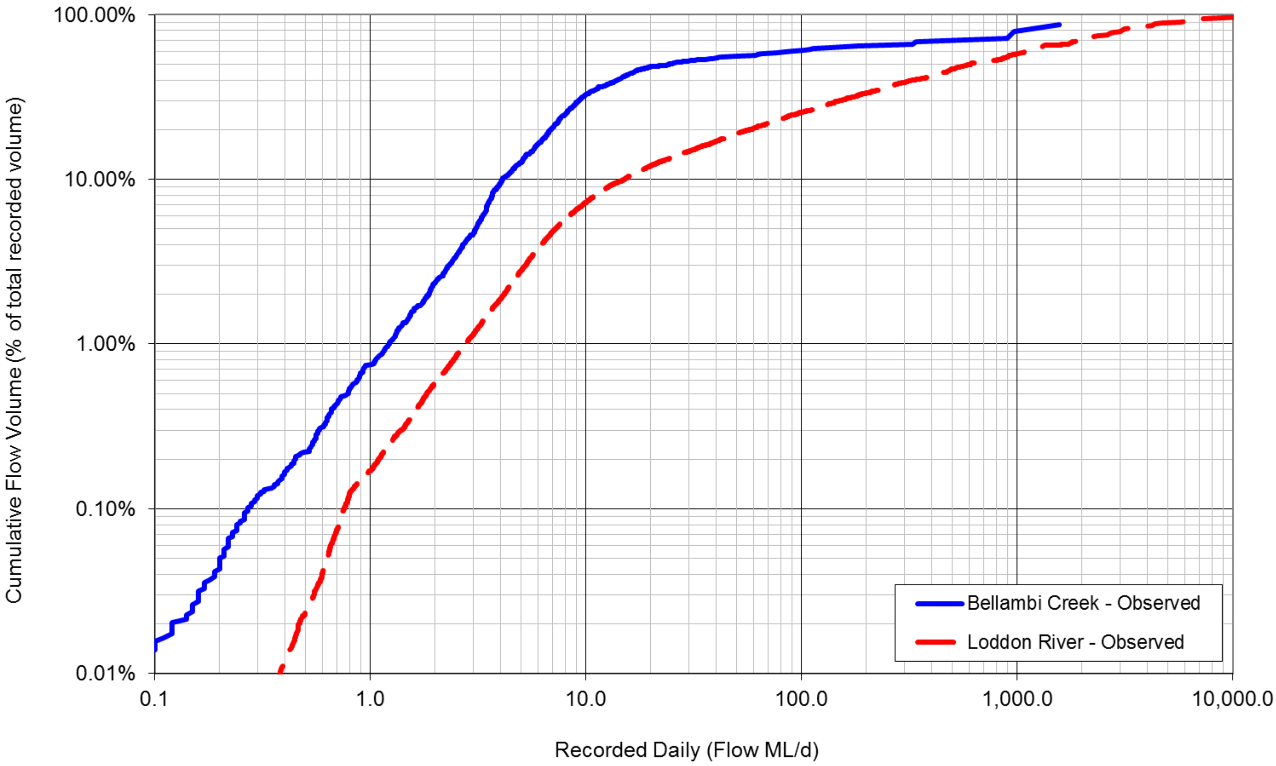


Figure 5.6 Cumulative Flow Volume Bellambi Creek and Loddon River

5.2 POOL LEVEL AND STREAM FLOW MONITORING

Pool water levels have been monitored in the study area since September 2009. Seven sites are located on Cataract Creek and three on the Cataract River as shown in Figure 5.7 below. There also two monitoring points on an upper unnamed, third order tributary of Cataract Creek. The downstream-most monitoring points on both streams are affected by Lake Cataract water levels, when stored volumes are high.

Figure 5.8 to Figure 5.10 show the recorded pool water levels in Cataract Creek and the Cataract River. Note that during the period 3/9/2011 to 2/12/2011 the logger at CC3 did not record any useable data.

Wollongong Coal periodically undertakes measurements of flow velocity across transects at Cataract Creek monitoring points. However, at the time of preparing the present study, insufficient data was available to develop full reliable rating curves, and flow-frequency relationships at the monitoring points.

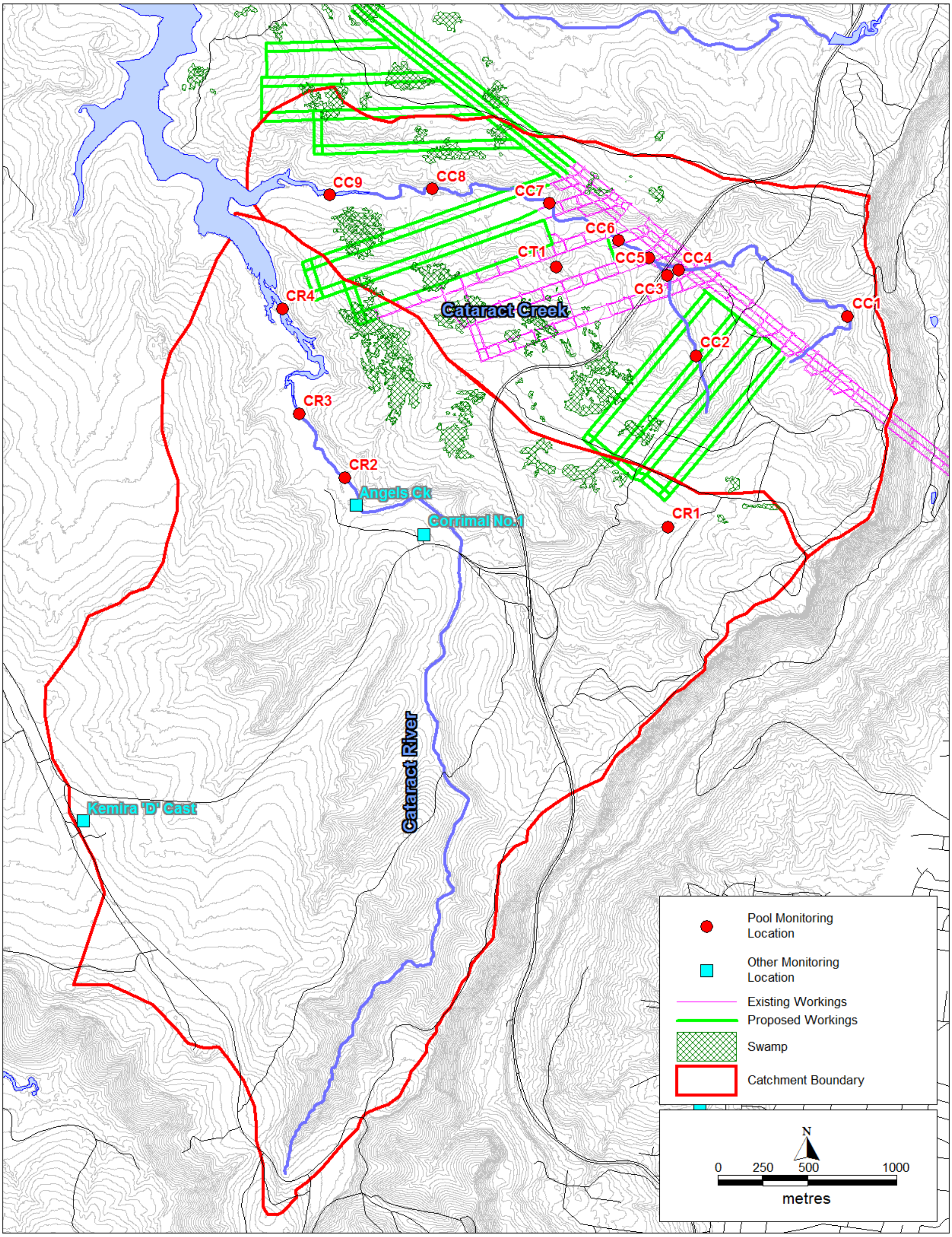


Figure 5.7 Pool Monitoring Locations, Wonga East

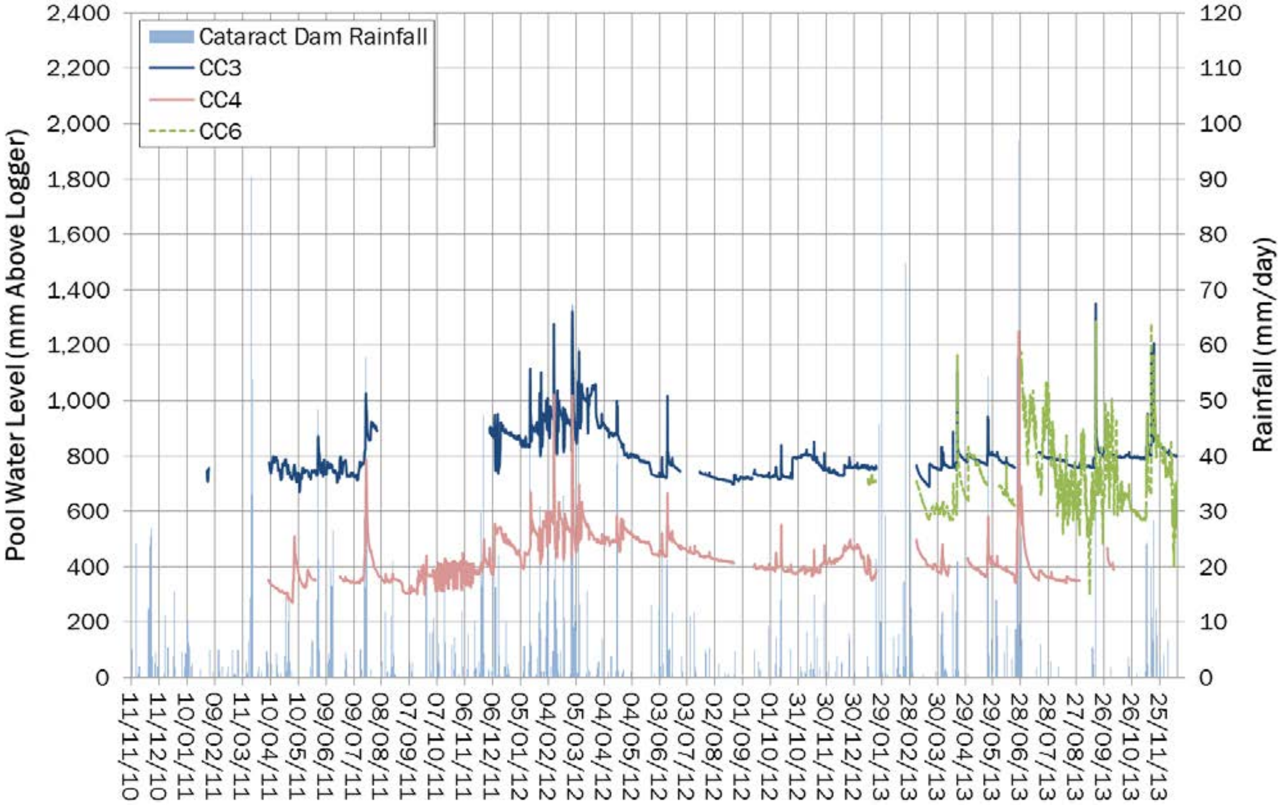


Figure 5.8 Cataract Creek Pool Monitoring Data

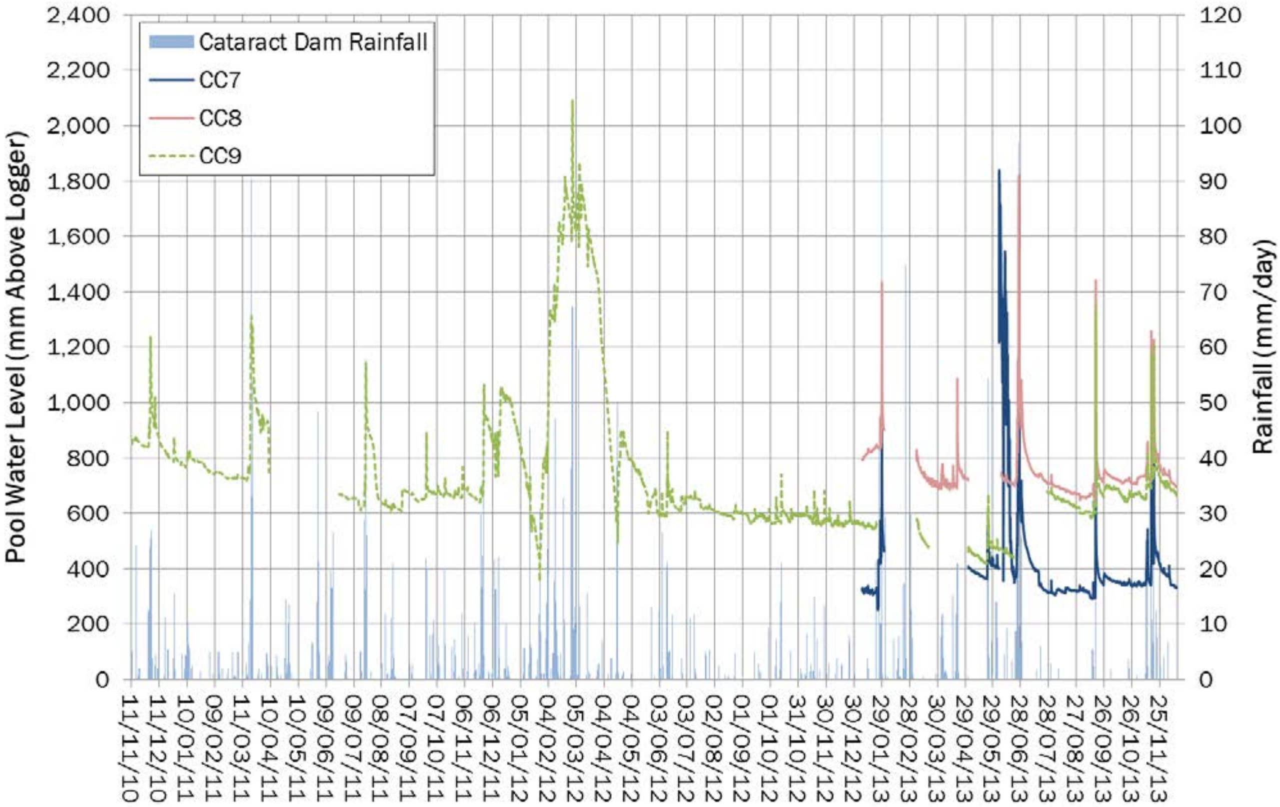


Figure 5.9 Cataract Creek Pool Monitoring Data

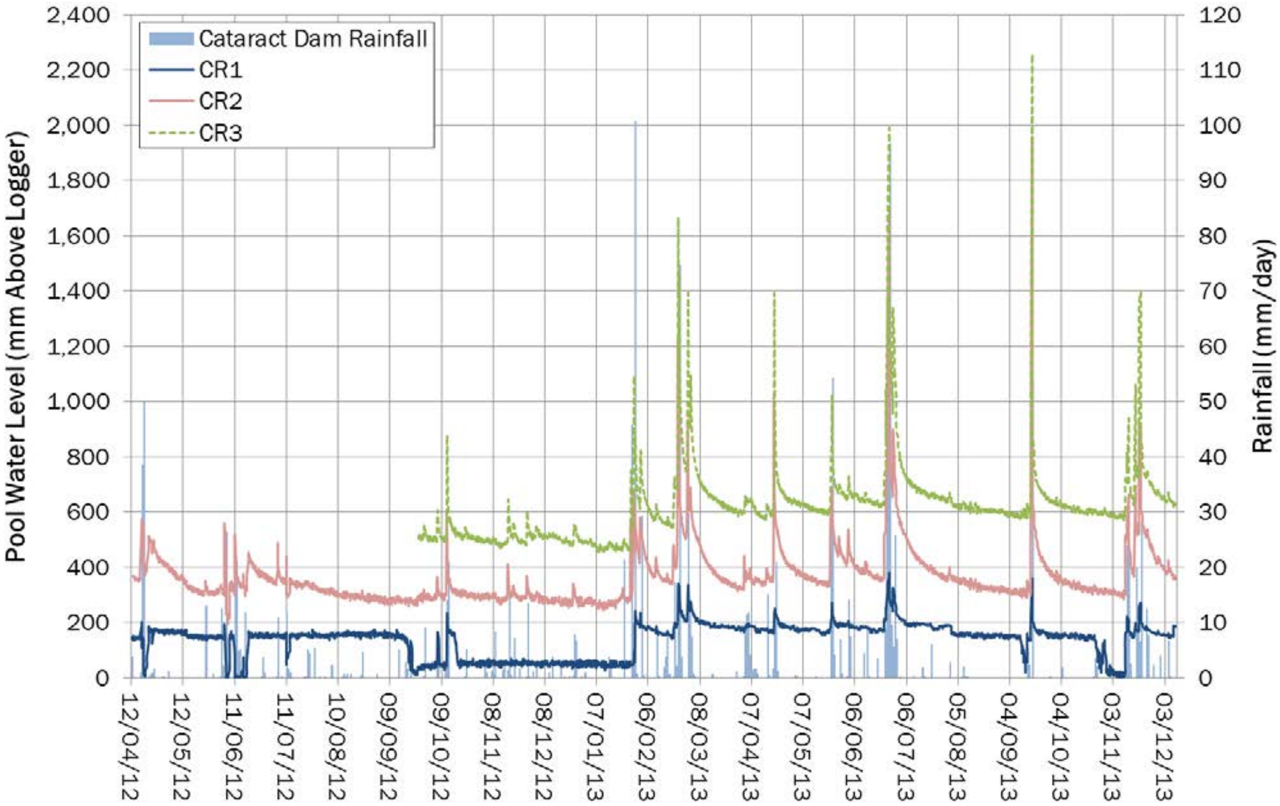


Figure 5.10 Cataract River Pool Monitoring Data

5.2.1 Streamflow Monitoring

Volumetric stream flow monitoring sites have been established on Cataract Creek at the Mount Ousley Road Crossing. Full stage-discharge relationships will be established once sufficient flow measurements have been taken and flow-frequency relationships will be developed. In addition, a number of pool monitoring sites are being investigated for their suitability as flow measurement points, taking into account the potential effects of:

- the presence of subsidence cracking in the creek bed resulting in disconnected stream flow during low flow periods due to mining subsidence over the Bulli Seam and Balgownie Seam workings dating back to the 1970s. The isolated cracked areas can enable transfer of overland stream flow to the shallow groundwater system under the creek bed. This means that not all of the total catchment flow in this reach is present as overland flow, and therefore a surface flow based monitoring system could under-report the actual volume of water flowing down the catchment and into Cataract Reservoir;
- overland flow diversions through natural bedding plane discontinuities which are washed out. It should be noted that this diversion is natural and is not due to subsidence cracking;
- baseflow though the hyporheic zone particularly in sandy channels during dry periods.

6 CATCHMENT MODELLING

6.1 MODELLING APPROACH

Rainfall-runoff models were created for the two gauged headwater catchments in the Study Area; Loddon River and Bellambi Creek. The models were calibrated to the daily streamflow records and used to extend those records to the length of available climate record.

The AWBM was selected for catchment modelling, as it has been successfully used in neighbouring catchments for similar studies. It uses a group of connected conceptual storages (three surface water storages and one ground water storage) to represent a catchment. Water in the conceptual storages is replenished by rainfall and is reduced by evaporation. Simulated surface runoff occurs when the storages fill and overflow. The model parameters define the storage depths, the proportion of the catchment draining to each of the storages, and the rate of flux between them (Boughton, 2003).

Daily runoff from other catchments in the Study Area was estimated using the AWBM, with model parameters transposed from the adjacent calibrated catchments. Climate data specific to each sub-catchment of interest was used to account for the spatial variability described in the previous sections.

6.2 INPUT CLIMATE DATA

Key climate data inputs for the AWBM are daily rainfall and daily evapotranspiration (this is different to most rainfall-runoff models, which use potential evapotranspiration) (Podger, 2004).

Rainfall data for the gauged catchments was obtained from nearby recording stations. The locations of these stations are shown in Figure 6.1 and Figure 6.2 respectively.

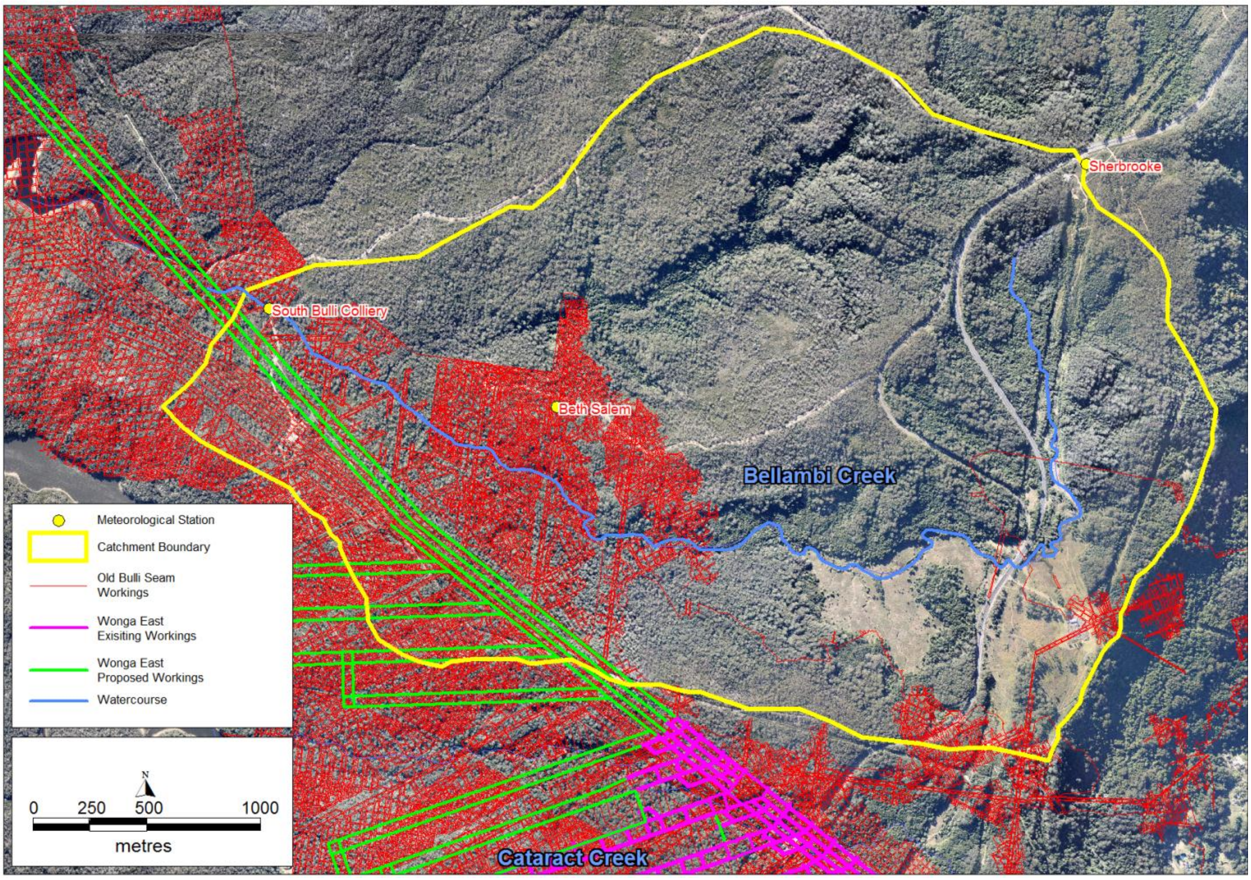


Figure 6.1 Bellambi Creek Catchment

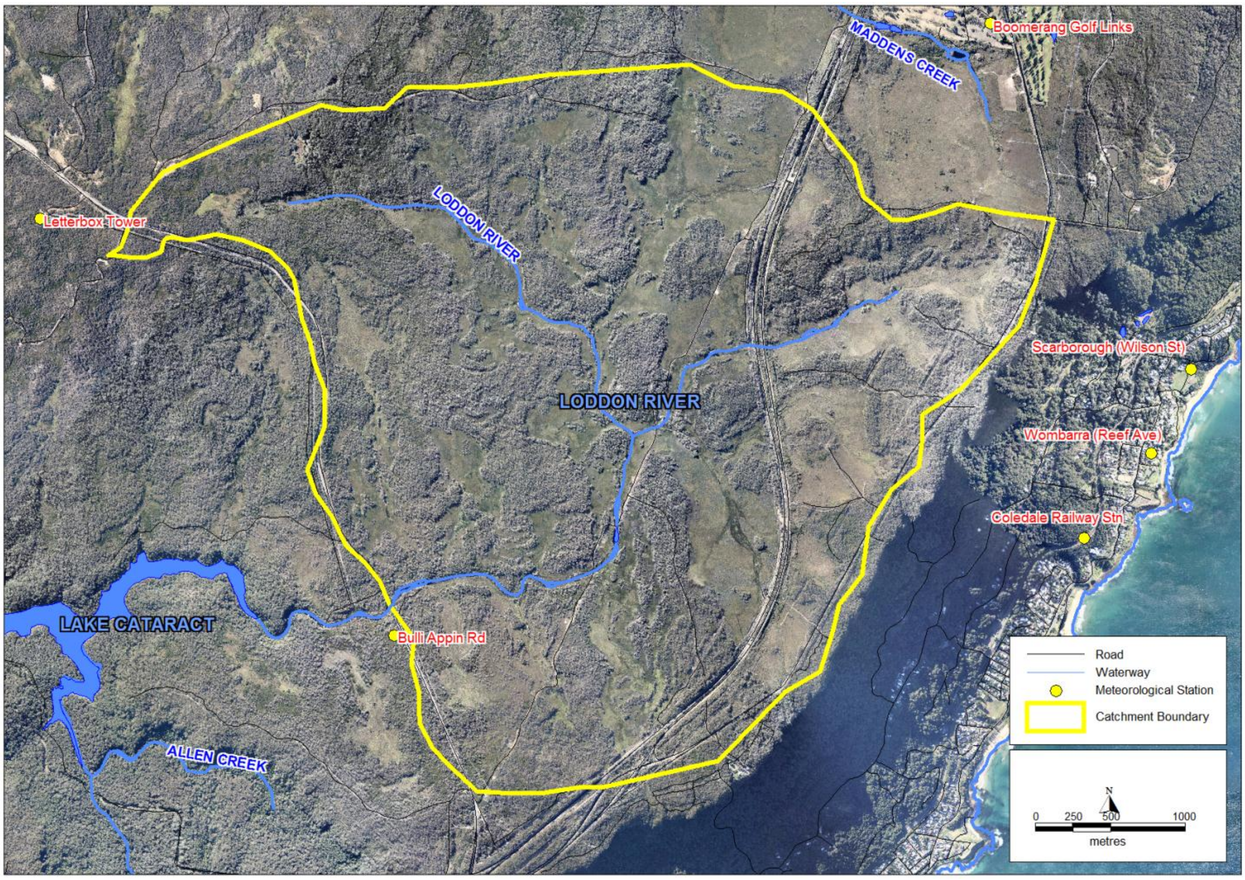


Figure 6.2 Loddon River Catchment

As pan evaporation has not been recorded in the immediate vicinity of the streamflow gauges, the BOM's SILO Data Drill service was used to derive inputs for catchment modelling. The Data Drill *"accesses grids of data derived by interpolating the Bureau of Meteorology's station records. Interpolations are calculated by splining and kriging techniques. The data in the Data Drill are all synthetic; there are no original meteorological station data left in the calculated grid fields. However, the Data Drill does have the advantage of being available for any set of coordinates in Australia"* (Bureau of Meteorology, 2006).

Data Drill data was used to infill and extend the datasets from the nearby recording stations where required. Details of the data used are summarised in Table 6.1. Daily rainfall derived using the Data Drill are compared to rainfall observations in Appendix A for nearby rainfall gauges.

While the Data Drill data is a synthetic dataset, and therefore needs to be used with caution, it can be useful for catchment studies where insufficient site-specific data is available.

Table 6.1 Input Data Sources for Catchment Modelling

Stream Gauge	Rainfall Data Source	Evapotranspiration Data Source
Bellambi Creek at South Bulli No.1	Beth Salem (Raw Data from SCA extend and with gaps in-filled using Data Drill at Beth Salem)	Data Drill at Beth Salem
Loddon River at Bulli-Appin Rd	Letterbox Tower (Raw Data from SCA extend and with gaps in-filled using Data Drill at Beth Salem)	Data Drill at Letterbox Tower

The recorded datasets are shown in the following four figures, which also show the duration and timing of rainfall data gaps that were infilled prior to calibration and the SCA quality codes assigned to the streamflow records. Descriptions of the corresponding quality codes are given in Table 6.2.

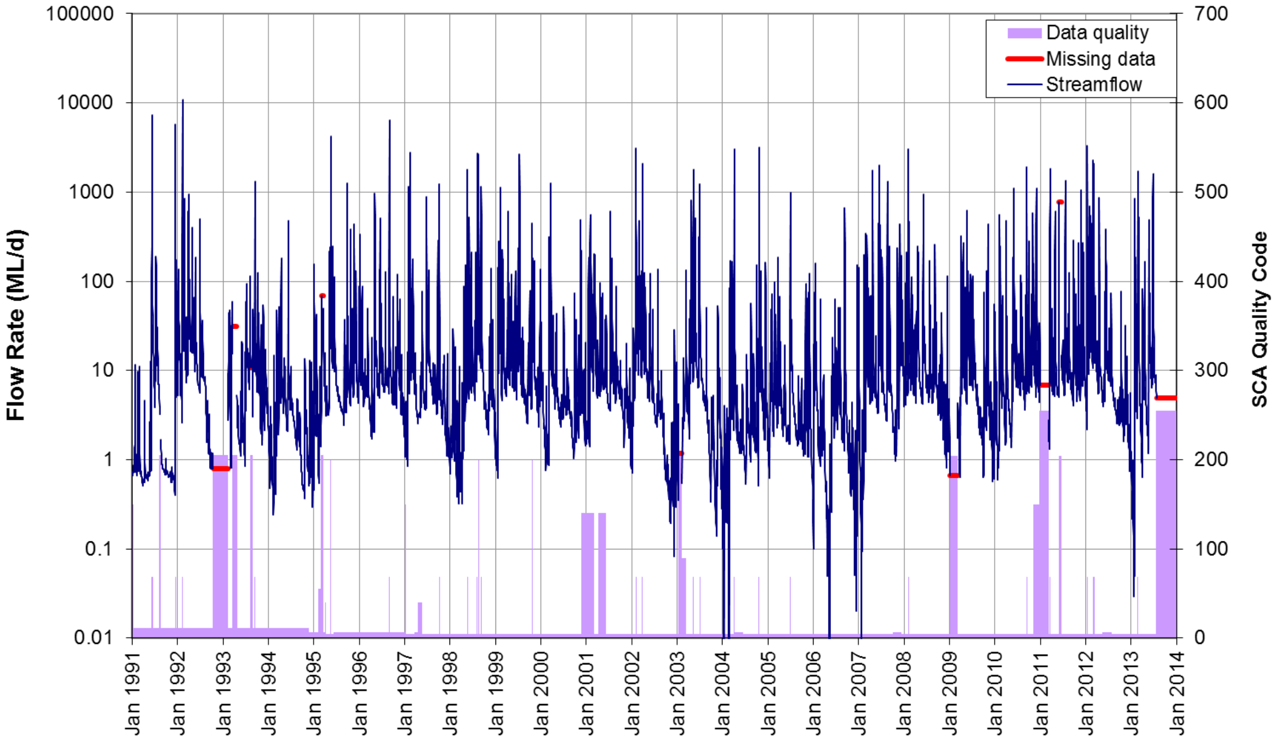


Figure 6.3 Streamflow Measured at Loddon River at Bulli Appin Road

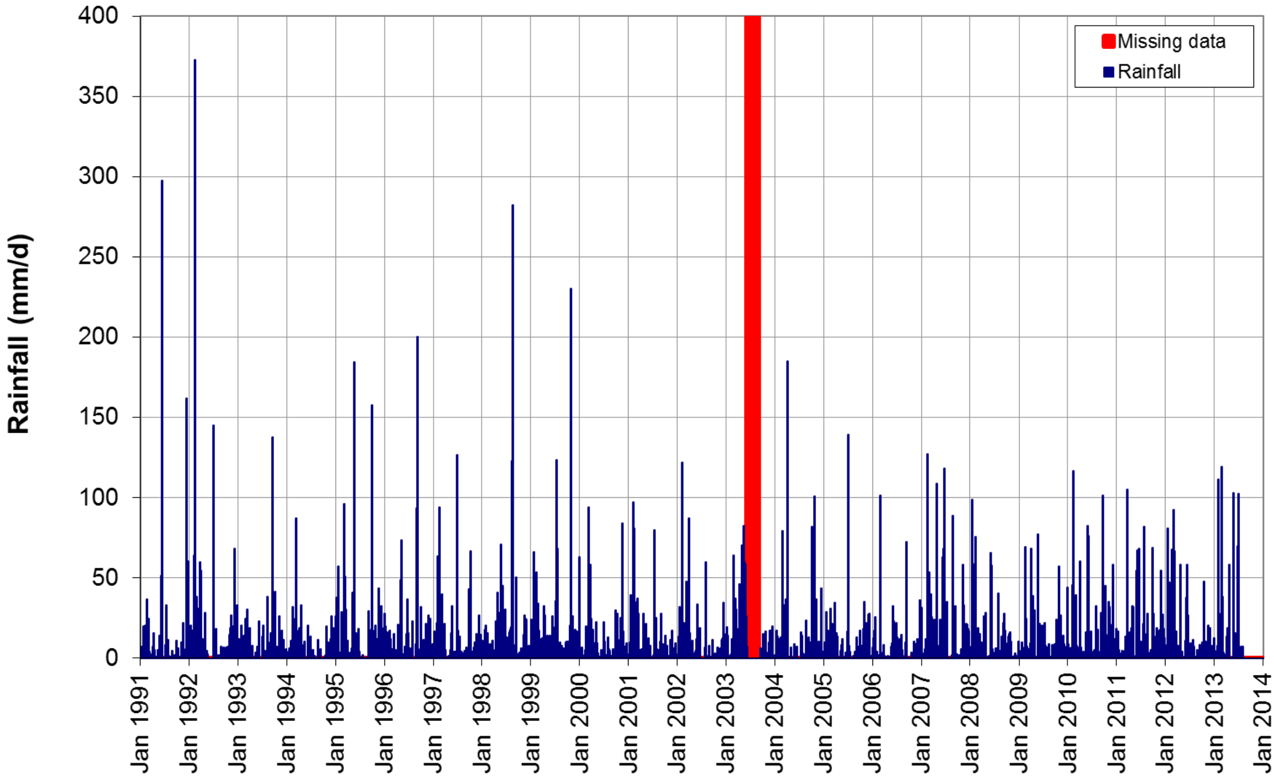


Figure 6.4 Rainfall Measured at Letterbox Tower over Loddon River Gauge Period

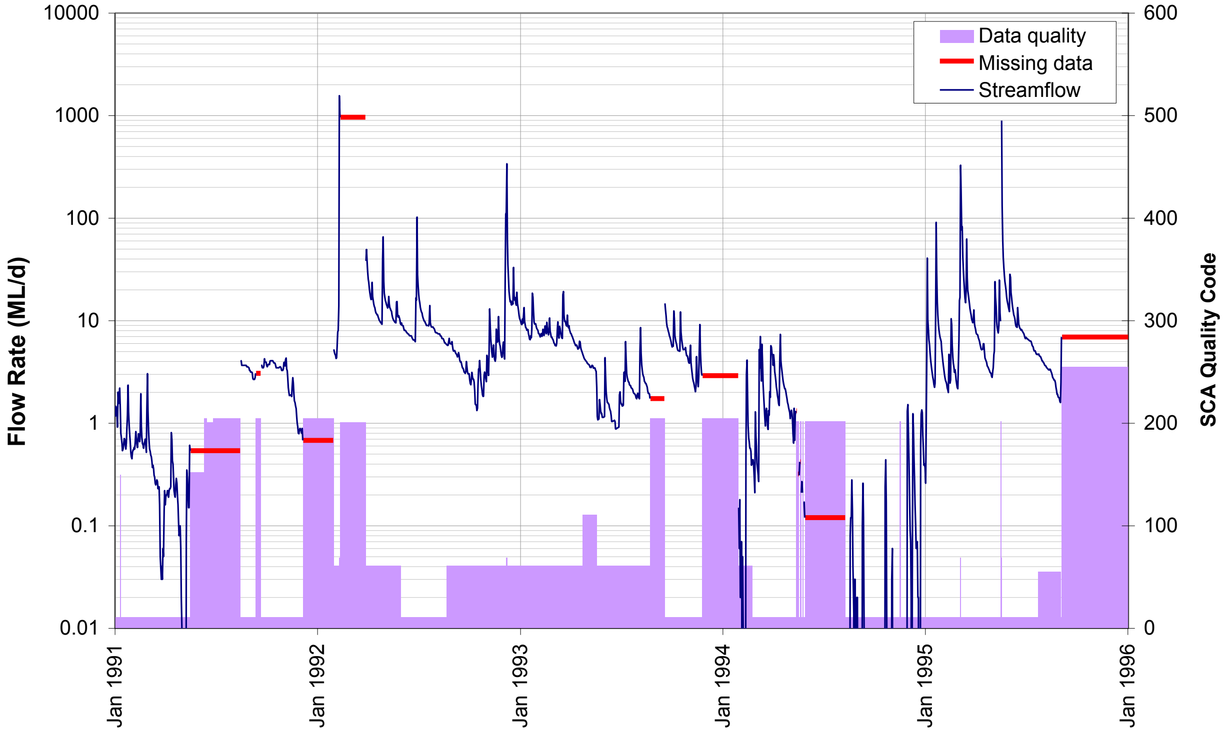


Figure 6.5 Streamflow Measured at Bellambi Creek at South Bulli No. 1

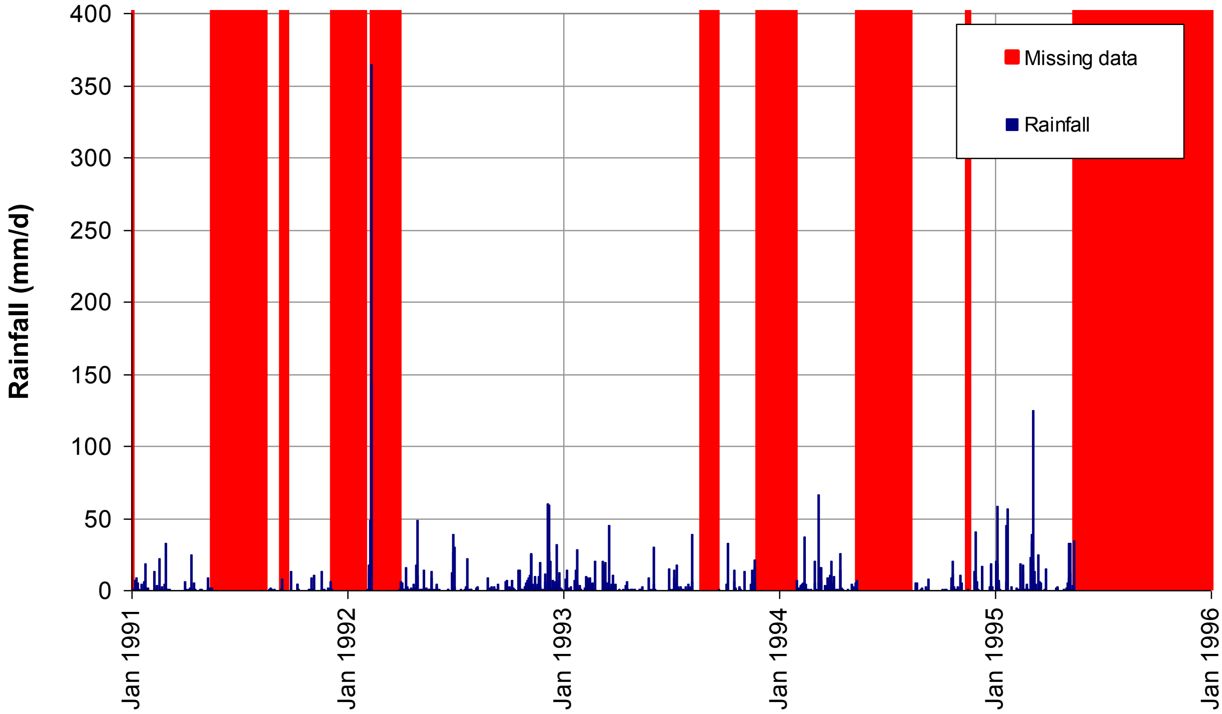


Figure 6.6 Rainfall Measured at Beth Salem Over Bellambi Creek Gauge Period

Table 6.2 SCA Quality Code Descriptions

Quality Code	Description
5	Good quality edited data
6	Reasonably good quality edited data
11	Good quality record processed pre 1995 and coded either 5 or 6
40	Good quality estimate (correlation or other reliable method)
55	Fair quality edited data
57	Fair quality contractor supplied data
61	Fair quality record processed pre 1995 and quality coded 55
69	Fair quality rating extrapolation
90	Fair quality estimation (correlation or other method)
105	Poor quality edited data
111	Poor quality records processed pre 1995 and quality coded 105
119	Poor quality rating extrapolation
140	Estimate that reasonably reflects the actual event with edit comments inserted to explain method of estimation
149	Contractors data supplied without quality codes
150	Data not yet quality coded
151	Backwater affected
152	Data for which quality
162	SENSOR OUT OF WATER WITH NO FLOW
201	Data not recorded - logger/sensor not installed
202	Data not available for release (e.g requires extensive editing)
204	Data lost due to vandalism
205	Data lost
255	Hydsys default - no data

6.3 CALIBRATION OF BELLAMBI CREEK CATCHMENT MODEL

The Bellambi Creek AWBM Model was calibrated over the period between the 1st January 1991 and the 1st September 1995. The adopted AWBM parameters are summarised in Table 6.3 below.

Table 6.3 Adopted AWBM Parameters – Bellambi Ck Catchment

Parameter	Value
A1	0.134
A2	0.433
BFI	0.317
C1	6
C2	94
C3	240
K_{base}	0.976
K_{surf}	0.632

It was not possible to perfectly replicate all streamflow features of interest (e.g. annual flow, flow frequency, monthly flow, daily flow, hydrograph shape, and baseflow) at all temporal scales. The calibration parameters were selected to achieve a compromise between matching the above characteristics.

Observed and simulated streamflow time series are compared in Figure 6.7. During the period from mid-1992 to mid-1993 the model underestimates baseflow, and during mid-1995 it overestimates baseflow. This is probably due to rainfall variability, with the earlier discrepancy due to differences between the rainfall recorded at Beth Salem compared to the rest of the catchment, and the latter due to the limitations of using Data Drill rainfall in areas of high rainfall gradient. The presence of Charlesworth Dam in the upper catchment will also tend to reduce flows during dry periods, and possibly slightly delay flow down the catchment.

Simulated mean annual runoff is 3,644 ML/a, compared to the observed mean annual runoff 3,279ML/a over the same period. The streamflow frequency curves in Figure 6.8 show a reasonable match, but flows between 10ML/d and 100ML/d tend to be overestimated by the model, and flows between 1ML/d and 10ML/d are underestimated. The model fit is reasonable given the limitations of the available data. The most significant discrepancy is that the model tends to underestimate the frequency of no-flow periods.

As mentioned in Section 5, very low flows less than 1 ML/d appear to occur less frequently in Bellambi Creek than in Loddon River. This could be due to rating curve errors, or be a hydrological characteristic of this catchment. Alternatively, low flows may have been affected by historical streamflow loss through subsidence-induced cracking of Bellambi Creek. The observed discrepancy would be consistent with a streamflow loss of 0.3ML/d.

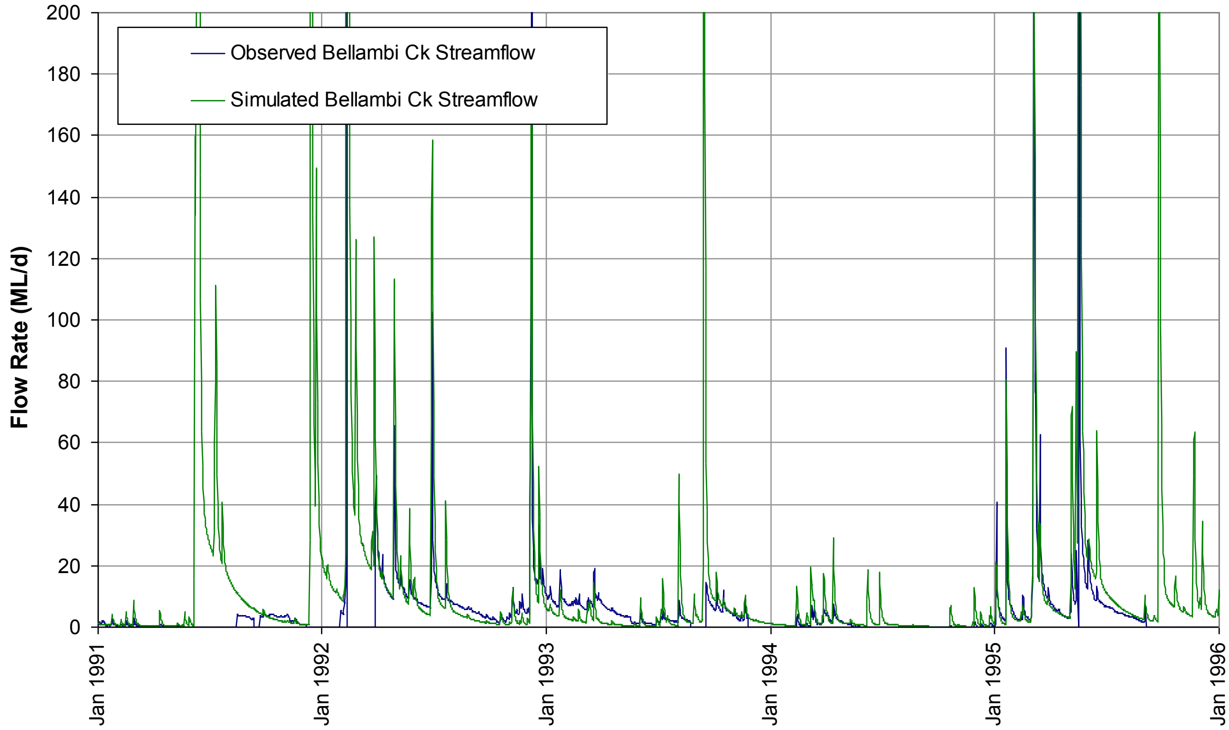


Figure 6.7 Observed and Simulated Streamflow – Bellambi Ck at South Bulli No. 1

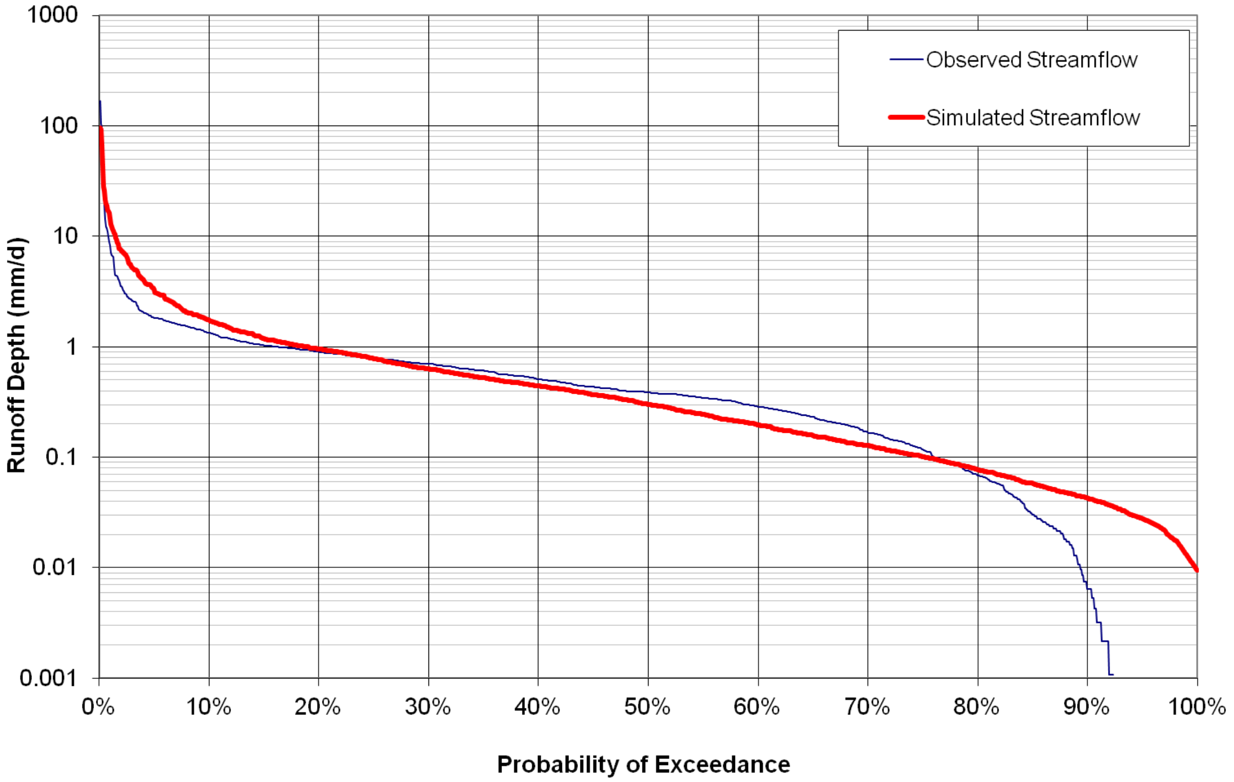


Figure 6.8 Observed and Simulated Streamflow Frequency Curves - Bellambi Ck at South Bulli No.1

6.4 CALIBRATION OF LODDON RIVER CATCHMENT MODEL

The Loddon River AWBM Model was calibrated over the period between the 1st January 1991 and the 8th November 2009. The adopted AWBM parameters are summarised in Table 6.4 below.

It was not possible to perfectly replicate all streamflow features of interest (e.g. annual flow, flow frequency, monthly flow, daily flow, hydrograph shape, and baseflow) at all temporal scales. The calibration parameters were selected to achieve a compromise. The calibration parameters were selected to achieve a compromise between matching the above characteristics, and tend to match the observed frequency of very low flows curve at the expense of matching the full baseflow recession curve for some flow events.

Table 6.4 Adopted AWBM Parameters – Loddon River catchment

Parameter	Value
A1	0.134
A2	0.433
BFI	0.200
C1	12.0
C2	39.4
C3	100.0
K_{base}	0.975
K_{surf}	0.200

Observed and simulated streamflow time series are compared in Figure 6.9 below.

Simulated mean annual runoff is 13,245 ML/a, compared to the observed mean annual runoff of 13,920 ML/a over the same period.

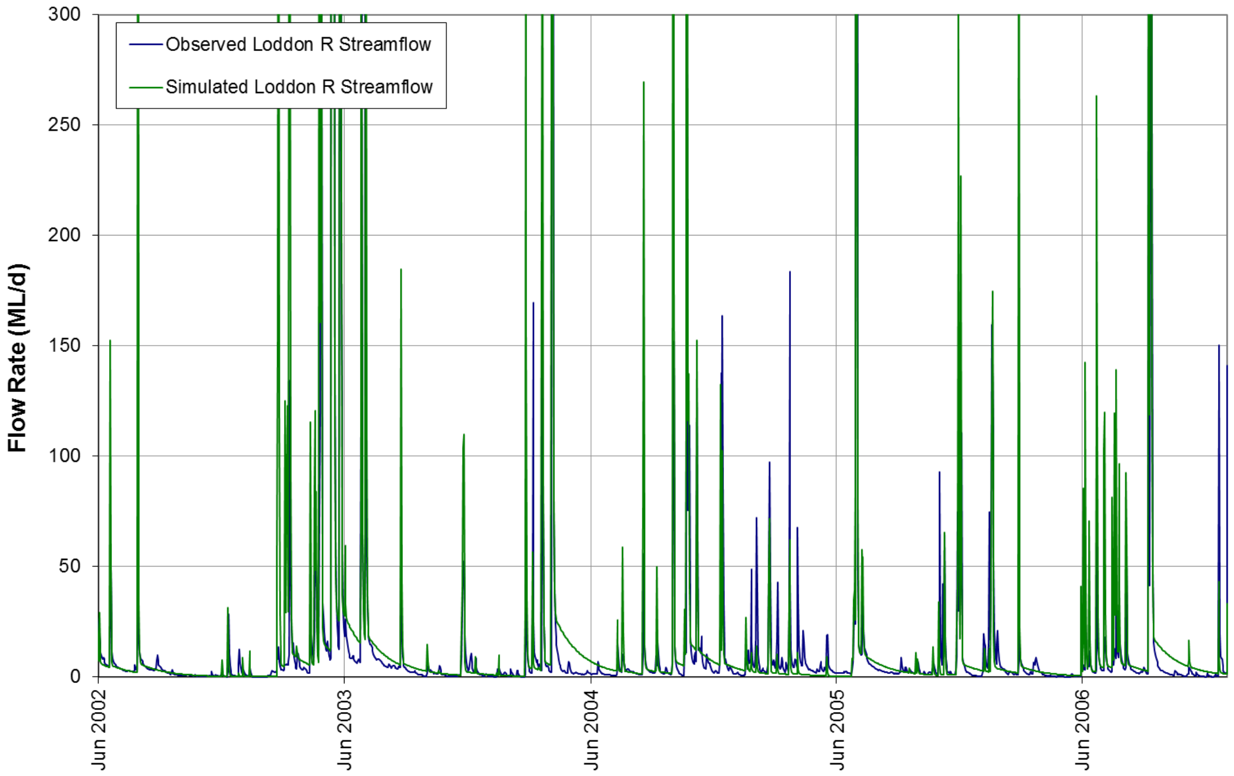


Figure 6.9 Observed and Simulated Streamflow – Loddon River at Bulli Appin Road – Sample of Record from June 2002 to December 2006

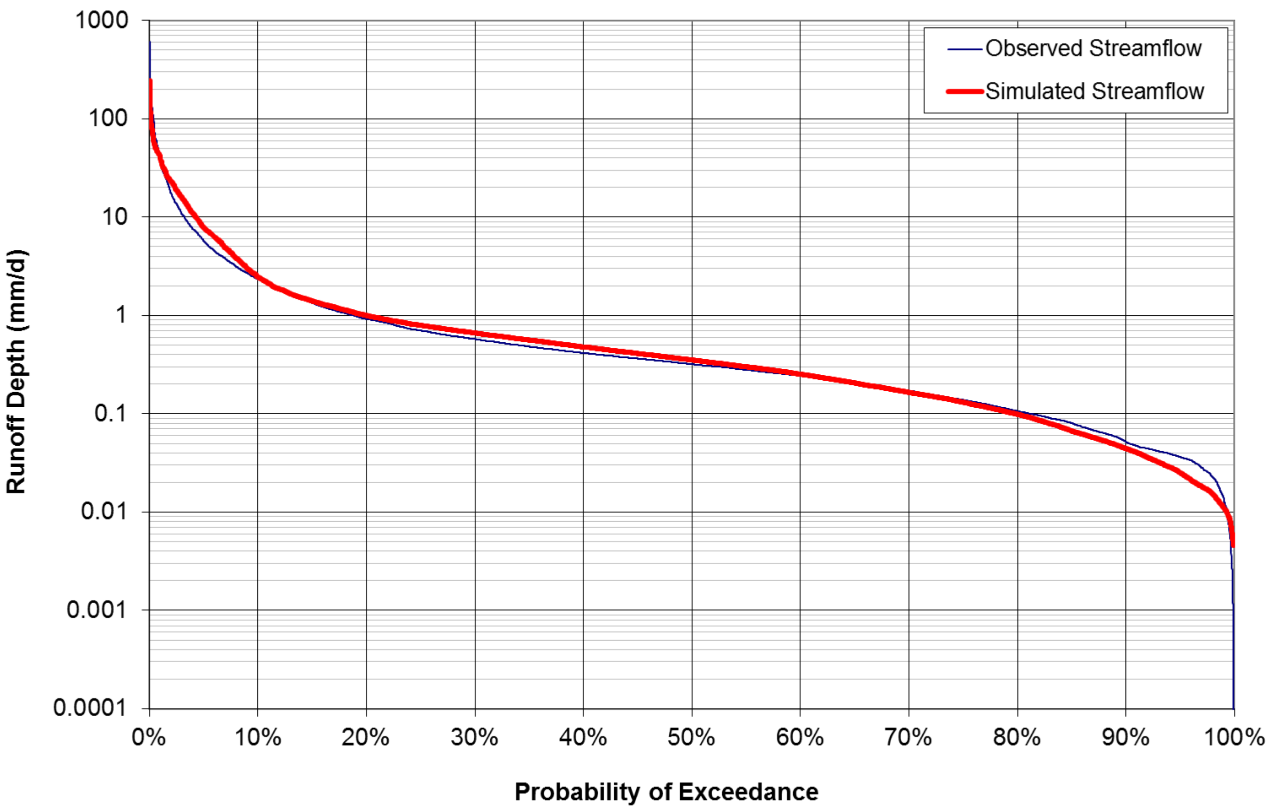


Figure 6.10 Streamflow Frequency Curves for Loddon River at Bulli Appin Road

6.5 STREAMFLOW IN AFFECTED CATCHMENTS

While insufficient information is available to derive accurate rating curves for monitoring sites, the water level observations can be used to verify the ability of the model to reproduce streamflow characteristics in the affected catchments.

Figure 6.11 below compares modelled daily streamflow to water levels observed every 12 hours at monitoring station CC4 between February 2012 and June 2012. The figure shows the model produces runoff at the same times as were observed, and also the persistence of baseflow over similar periods to what was observed.

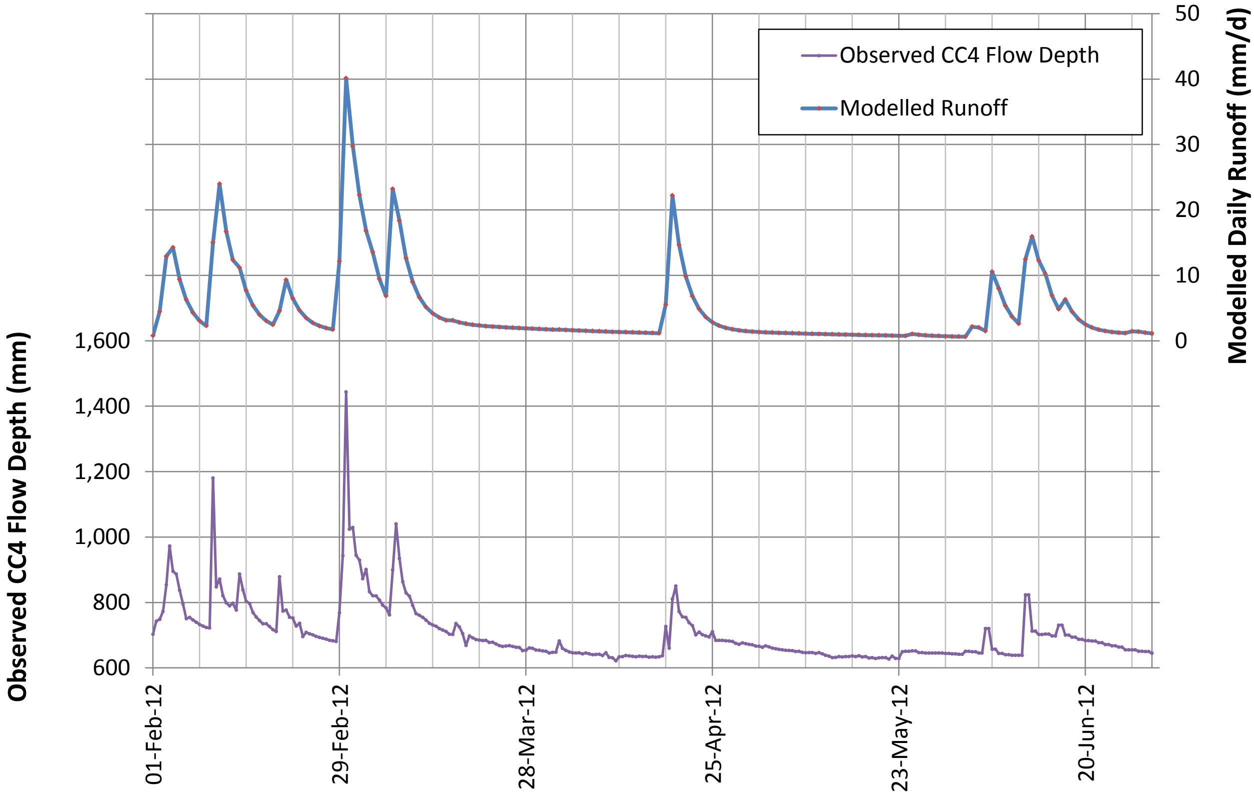


Figure 6.11 Comparison of Modelled Streamflow to Water Level Observations at CC4

Figure 6.12 shows the contribution that baseflow makes to total streamflow over this period. Based on catchment modelling, over the long term, it makes up approximately 32% of total flow. The relative contribution of baseflow to average streamflow varies seasonally, as shown in Figure 6.13.

Table 6.5 summarises the modelled surface runoff and baseflow at each of the monitoring points. The table shows that average daily streamflow is significantly larger than median daily due to the impact of a small number of large surface flow events. Average daily streamflow at CC9 on Cataract Creek is 11.2 ML/d of which 3.5ML/d is baseflow. Median baseflow at this location is 2.2ML/d.

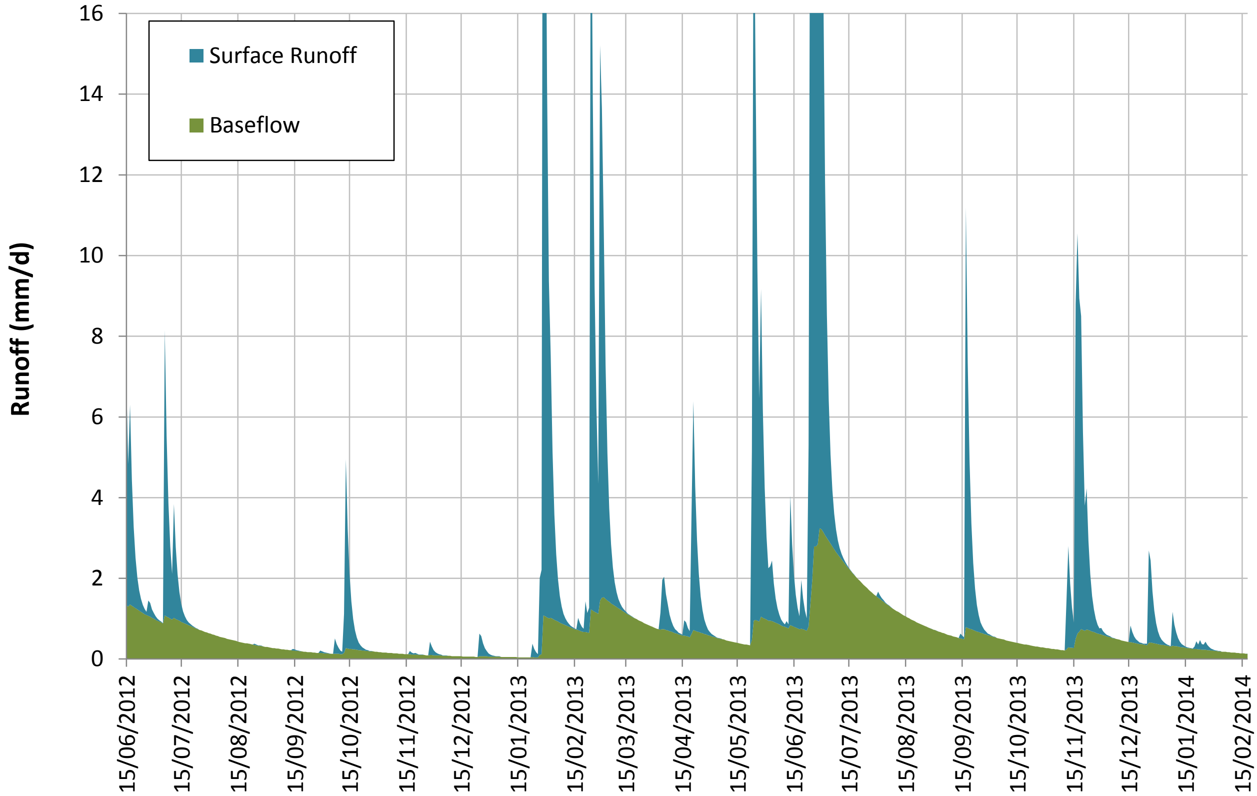


Figure 6.12 Modelled Cataract Creek Baseflow and Surface Flow Hydrographs

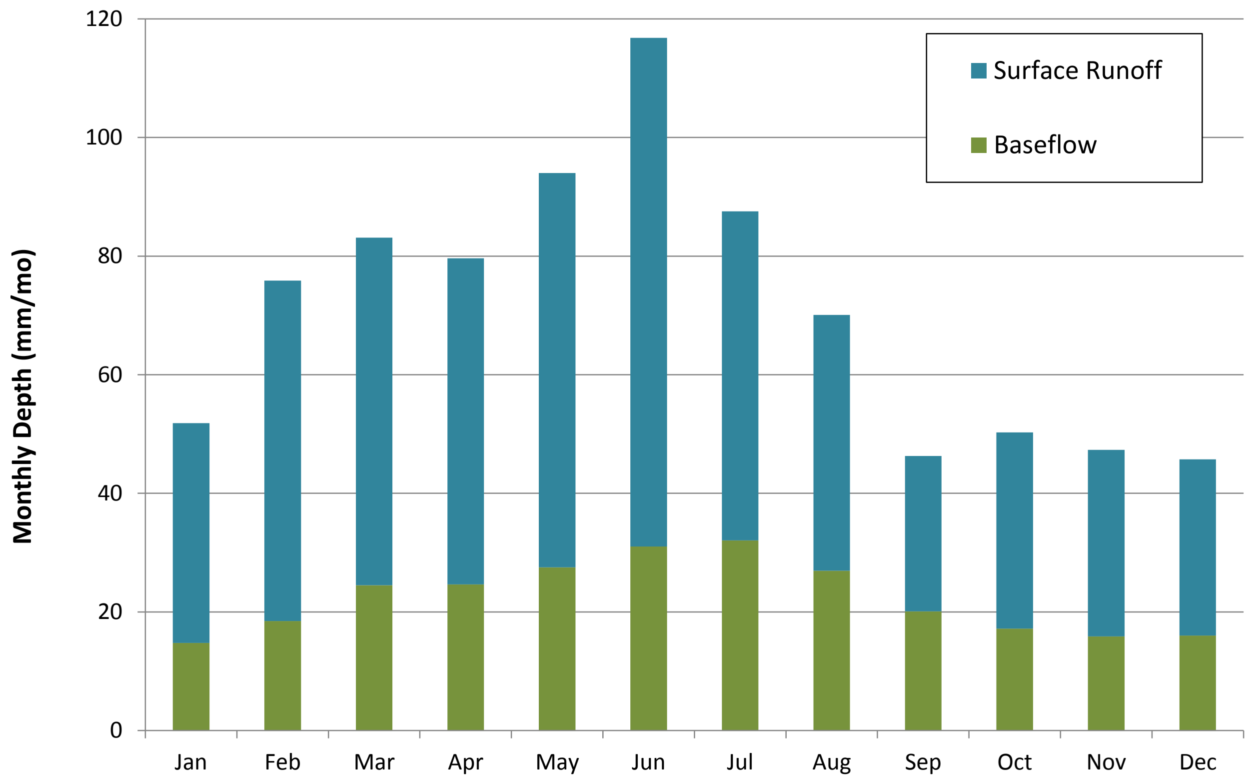


Figure 6.13 Modelled Cataract Creek Mean Monthly Baseflow and Surface Flow

Table 6.5 Contribution of Baseflow to Mean and Median Daily Modelled Flow at Monitoring Points

Catchment	Average Flow (ML/d)			Median Flow (ML/d)		
	Surface Runoff	Baseflow	Total Streamflow	Surface Runoff	Baseflow	Total Streamflow
Cataract Creek						
CC3	1.7	0.8	2.5	0.04	0.49	0.71
CC5	4.2	2.0	6.2	0.11	1.22	1.78
CC6	4.6	2.1	6.8	0.12	1.34	1.95
CC7	5.5	2.6	8.1	0.14	1.60	2.33
CC8	6.6	3.1	9.7	0.17	1.92	2.80
CC9	7.6	3.5	11.2	0.19	2.21	3.22
Cataract River						
CR2	15.4	7.1	22.5	0.39	4.46	6.49
CR4	17.5	8.1	25.6	0.44	5.07	7.39
Bellambi Creek						
BC4000	6.5	3.0	9.5	0.16	1.89	2.75
BC4500	7.7	3.6	11.2	0.19	2.23	3.24
BC5000	8.6	4.0	12.5	0.22	2.48	3.61

7 LAKE CATARACT RESERVOIR YIELD

7.1 OPERATIONAL DATA SUPPLIED BY SCA

The SCA provided data pertaining to the operation of Lake Cataract. The daily stored volume, controlled release (including regulated discharges and environmental releases) and spillway discharge information are shown in Figure 7.1. Releases are made from Cataract Dam for the purposes of meeting water supply requirements and providing environmental flows. Figure 7.2 shows the surface area and water volume characteristics of the lake.

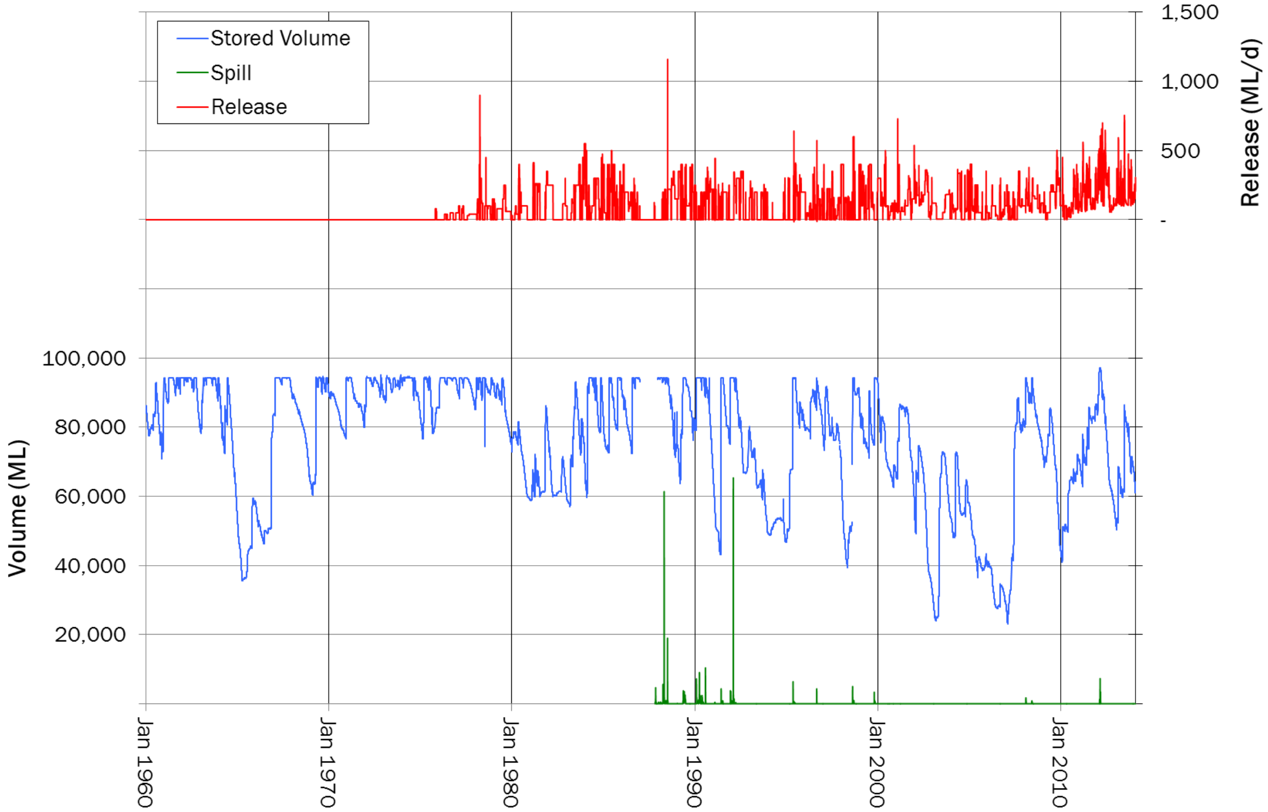


Figure 7.1 Lake Cataract Operational Data

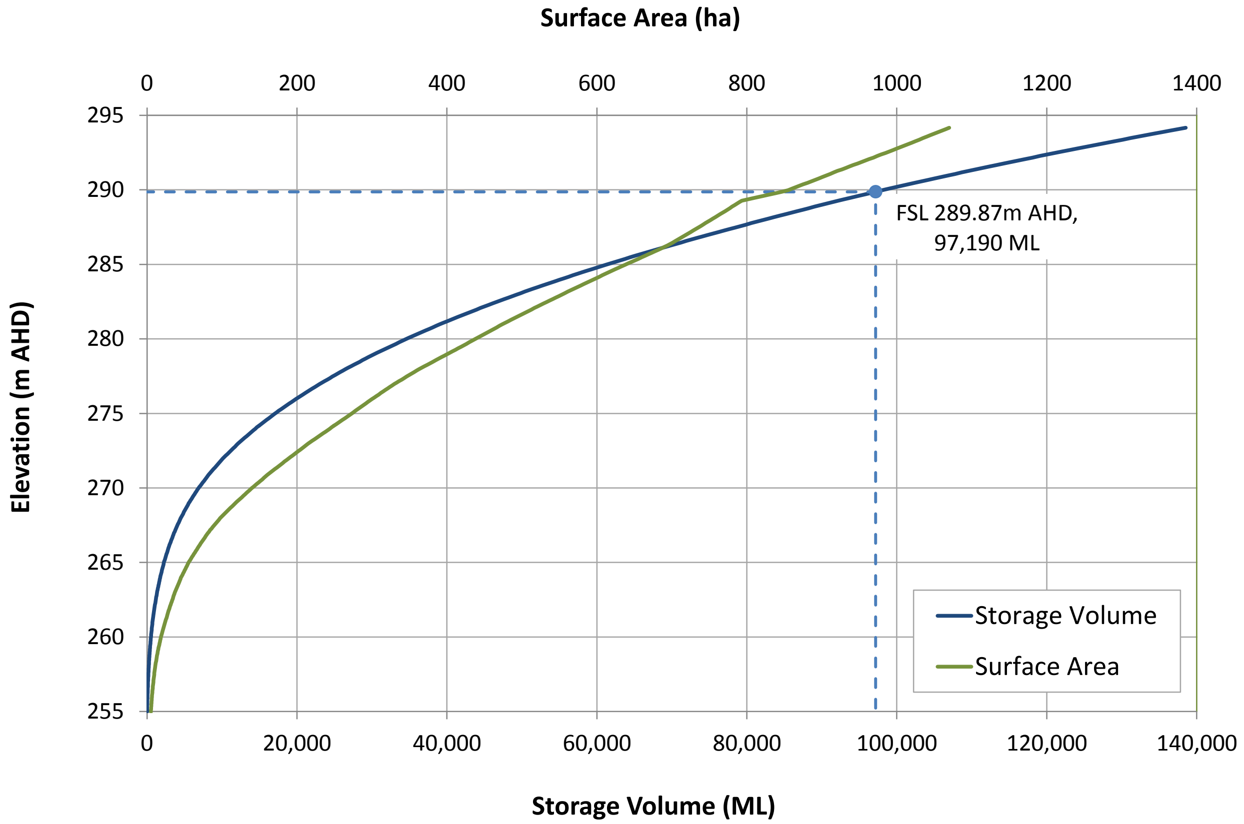


Figure 7.2 Lake Cataract Storage Curves

7.2 PURPOSE OF MODEL

A daily timestep water balance model of the Lake Cataract reservoir was developed with a view to deriving time series of inflows and outflows which replicate the historical behaviour of the reservoir.

These time series could then be used to develop a reservoir model to determine the impact of additional catchment losses on the potential for the storage to be drawn down completely under historical conditions. The focus of the analysis was therefore on reproducing behaviour during the longest dry spell on record, which occurred between 2002 and 2007.

7.2.1 Model Schematisation

The behaviour of Lake Cataract was simulated using a daily time step spreadsheet model comprising the following major components (shown schematically in Figure 7.3):

- Direct rainfall to the lake surface - a daily time series of rainfall depths was obtained from the SILO Patched Point Dataset for Cataract Dam. The rainfall depth was applied to the lake surface area estimated at each time step from the storage curve shown in Figure 7.2.

- Evaporation from the lake surface – a time series of lake evaporation rates was obtained from the SILO Patched Point Dataset for Cataract Dam. The pan evaporation rate (adjusted by a pan factor of 0.9) was applied to the lake surface area estimated at each time step from the storage curve shown in Figure 7.2.

- Releases from the dam – the daily time series of recorded releases provided by SCA were extracted from the storage.

- Spills from the dam – inflows exceeding the remaining water storage were treated as spills.

Each of the above inflows and outflows can be quantified relatively easily and accurately. The most challenging input to estimate is the catchment runoff - due to the lack of long-term streamflow records and the high spatial variability of rainfall in the catchment.

Catchment runoff was estimated using recorded streamflow in contributing tributaries, where available, and the AWBM rainfall/runoff model where it was not. The highly variable rainfall of the area necessitated subdividing the catchment into four subareas with different combinations of AWBM catchment parameters and input daily climate datasets (as summarised in Figure 7.3).

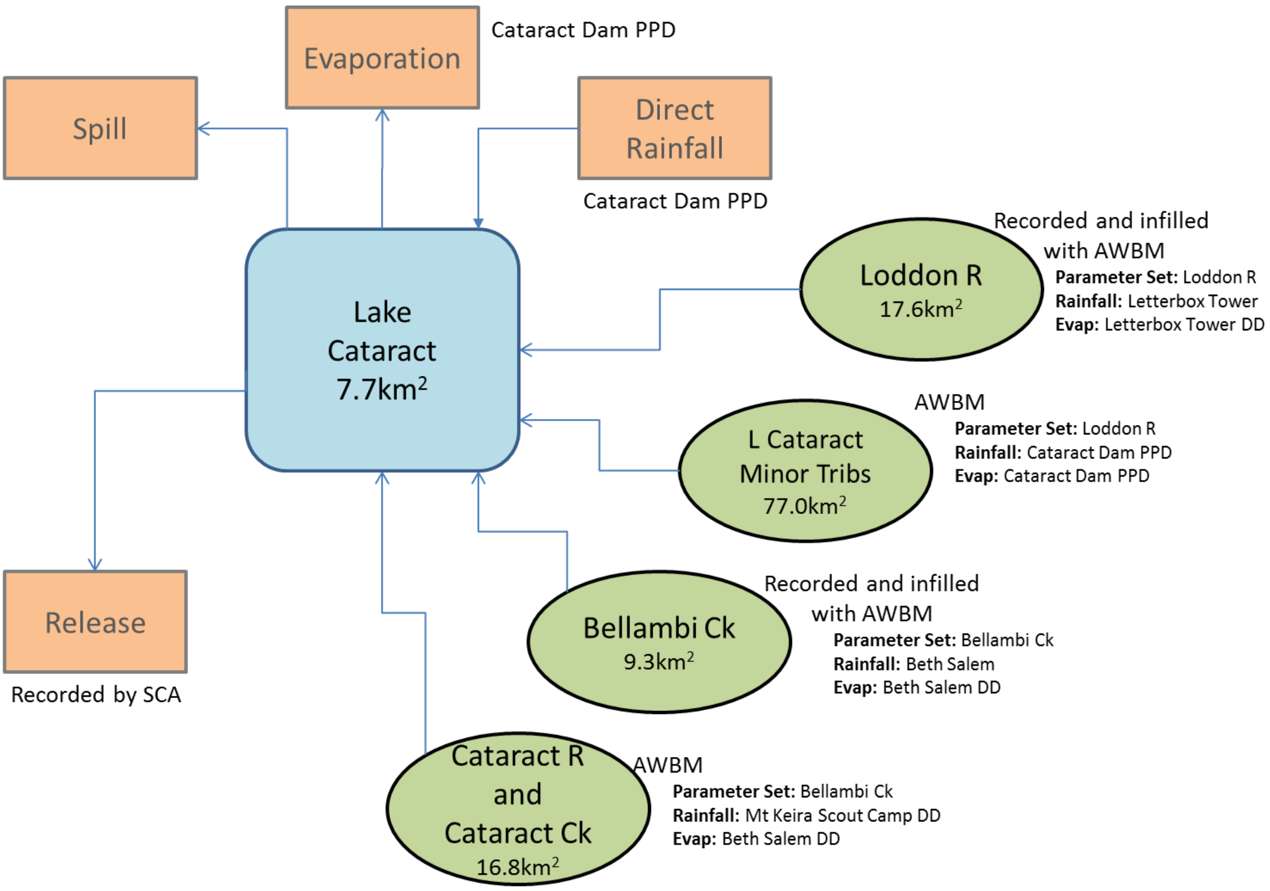


Figure 7.3 Lake Cataract Hydrological Model

Over the period of records since 1977, based on the results of the water balance modelling, the total water balance for the reservoir is estimated to be as follows:

Table 7.1 Lake Cataract – Average Annual Water Balance

Item	Flow (ML/a)
Catchment Runoff (including direct rainfall)	217
Surface Evaporation	25
Seepage to Groundwater	10
Releases (recorded)	120
Overflows	64
Change in Volume	-2

The above estimates should be used with some caution, because while the distribution of rainfall as defined in Figure 7.3, is likely to be generally representative of distributions over the catchment, it is not perfectly representative across all historical events. This is illustrated in Figure 7.4 which shows that over much of the historical record, the model gives a good representation of historical stored volumes, but there are discrepancies in the volume of runoff (and hence also overflows) generated during some inflow events.

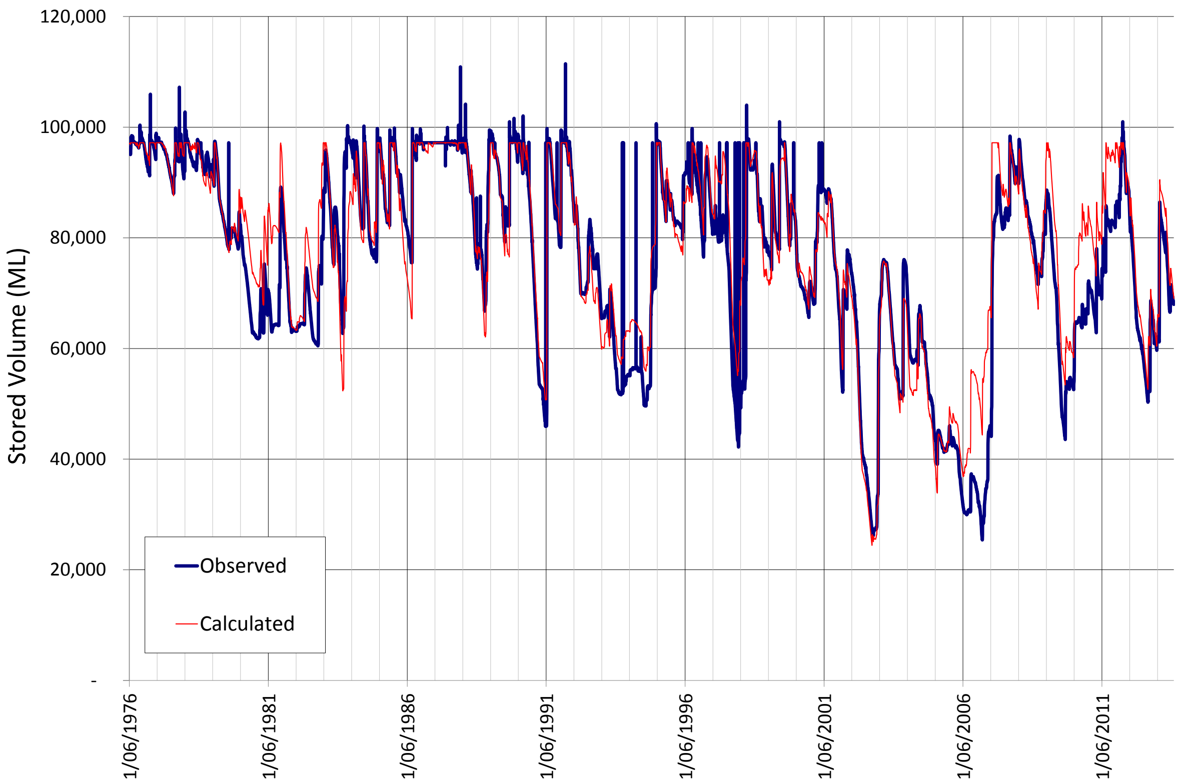


Figure 7.4 Observed and Modelled Volume at Cataract Dam from 1977

For the purpose of the yield impact assessment, a more accurate representation of historical inflows, runoff was estimated from the change in stored volume during wetter periods. The resultant time series of modelled stored volume is a good representation of the observed behaviour - as shown in Figure 7.5.

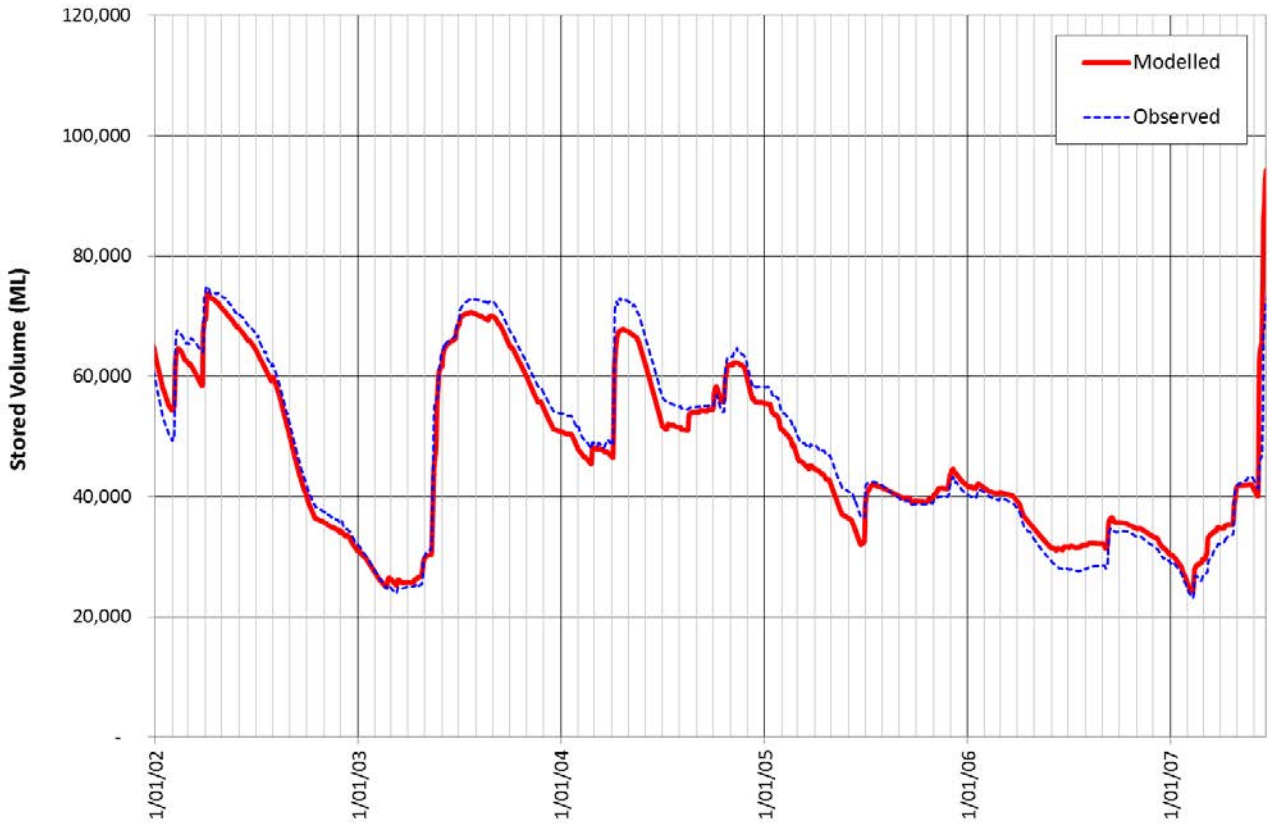


Figure 7.5 Observed and Modelled Dry Period Volume at Cataract Dam 2002-2007

The most rapid drawdown of the reservoir occurred between August 2003 and March 2003. Over this period, the stored volume fell from 88,780 ML to 26,190 ML26191 (62,590 ML) (by June 2003 - the dam stored over 67,000ML again).In 587 days - this equates to a 107ML/d loss – made up of:

- Releases to supply demand - 169ML/d;
- Evaporation - estimated to be approximately - 23.5ML/d;
- Seepage to groundwater of - 10ML/d;
- Runoff inflows - estimated from modelling to be 94.1ML/d

8 CONTRIBUTION OF CATCHMENTS POTENTIALLY AFFECTED BY SUBSIDENCE

8.1 POTENTIAL MECHANISMS FOR HYDROLOGICAL IMPACTS

The following potential hydrological risks have been raised as stakeholder concerns:

- **Reservoir yield** - the possibility that the quantity of water reaching Lake Cataract and Broughtons Pass Weir could be reduced,

- **Stream health** – the possibility that cracking of the stream beds draining into Cataract Dam and Broughtons Pass Weir may induce loss of overland stream flow and adversely affect stream water quality or stream health.

In its review of the Metropolitan Coal Project Environmental Assessment, the Planning Assessment Commission (PAC) Panel cited the following potential mechanisms whereby this may occur (NSW PAC, 2009):

1. Rainfall on the broader catchment, which previously found its way to watercourses by surface or subsurface flow infiltrates through fractures and is permanently lost to the surface water system.
2. Water in streams that are subject to fracturing is lost from the surface water system to the groundwater system and does not reappear.

The above potential risks are addressed in the following sections.

In its submission on the DGR's the Department of Water and Energy required this EA report *demonstrate the project is consistent with the spirit and principle of the NSW State Rivers and Estuaries Policy, Wetland Management Policy, including :*

1. *General description of channel form, river style or other descriptive category of any affected channel, including identification of key geomorphological indicators and conditions within the zone of influence for the proposal.*

2. *Hydrologic and geomorphic character of the riverine system, stream energy and stream power relationships, energy relationships at bankfull stage and at peak flow, and assessment of stream power and critical tractive stress for existing and any modified conditions for any rivers affected by the proposal, which provides details of:*
   - *long profile and cross sectional survey along the channel, and identification of at least the closest upstream and downstream controls on the channel*
   - *assessment of bed and bank material, identification of critical entrainment and destabilisation thresholds*
   - *assessment of the constriction and resultant change in afflux through, past or over the structure, and resultant changes in energy profiles involving the structure*

- *nature of bedload transport, and mechanism(s) to permit bedload transport through the structure*

3. *Procedures to develop stream relocation and reconstruction criteria which utilise best practice management, which must include the principles which underpin any embargoes currently in force under the Water Act, 1912, or operational rules of any Water Sharing Plan in force under the Water Management Act 2000 over the site*

4. *Methodologies by which proposed relocation or reinstatement of watercourses will be undertaken, and whether any proposed ecological offset provisions will provide adequate protection to any instream or groundwater dependent ecosystems which exist on the site*

5. *Mechanism to maintain long profile grade through the structure, or to provide energy dissipation through the structure at the re-entry point design volumes/velocity downstream*

6. *Nature of existing controls along all watercourses on the site, and proposed use of engineered and vegetation to provide long term control to the channel*

7. *Final configuration of any relocation, modification or other impact upon rivers and watercourses on or surrounding the site, including geomorphic character mimicking conditions of undisturbed rivers or watercourses adjacent to the proposal area*

The streams overlying the project area are not being relocated or reinstated, and no instream structures are proposed. The predicted subsidence impacts are expected to result in only small changes to the stream bed profile. As a result, localised reductions in bed gradients are not likely to cause significant additional ponding. Any localised increase in bed gradient is likely to be within the range of those occurring naturally, and as the stream bed material comprises competent rock, the resultant localised increases in stream power and tractive force are unlikely to cause bed scour. As a result, we have not undertaken a detailed assessment of bedload transport mechanisms or afflux.

The proposed workings will potentially disturb the following portions of the catchments in the Study Area.

Table 8.1 Potential Subsidence Areas Compared to Total Catchment Area

Stream	Catchment Area (km^2)						
	Total Catchment to D/S Confluence	Subsided by More Than 20mm	Percentage Subsided	U/S of Disturbance Envelope	% U/S	D/S of Disturbance Envelope	% D/S
Lake Cataract*	127.8	4.4	3.5%	1.9	1.5%	125.9	98.5%
Cataract Creek	5.2	3.2	61.3%	1.9	36.0%	3.3	64.0%
Cataract River	11.6	0.5	4.3%	0.0	0.0%	11.1	95.7%
Bellambi Creek	9.3	0.4	4.8%	0.0	0.0%	8.9	95.2%

*Lake Cataract disturbance includes disturbance area in Cataract Creek, Cataract River and Bellambi Creek.

8.2 ASSESSMENT METHODOLOGY

The PAC has previously noted that without special techniques and extensive quality control and checking, the normal accuracy of stream gauging measurements combined with staged measurements and the derivation of rating curves, precludes reliable detection of small absolute changes in stream flows from one location to the next (NSW PAC, 2009). This is further affected by the likelihood that in Hawkesbury Sandstone based waterways with natural (and potentially induced) bedding plane as well as jointing washouts and fractures, subsurface flow is present that can not be accurately measured, especially during low flow regimes.

In its review of the Metropolitan Coal Project Environmental Assessment, the PAC was of the view that because fracturing is likely to only occur in the surficial groundwater system, and that any increase in initial rainfall runoff losses would be temporary, any surface water losses would therefore be undetectable unless the surficial groundwater system intercepted a permeable subsurface stratum that bypassed the reservoir (NSW PAC, 2009).

The Southern Coalfield Inquiry was also of the view that there was no evidence that *"subsidence impacts have resulted in any measurable reduction in runoff to the water supply system operated by the Sydney Catchment Authority or to otherwise represent a threat to the water supply of Sydney or the Illawarra Region."* (DECC, 2007)

However, the PAC did make the case that the issue was not beyond doubt and recommended further investigation of catchment yield impacts.

The rate of water loss from pools affected by subsidence induced cracking has been measured in waterways overlying other projects in the Southern Coalfield (Gilbert, 2008). However, due to the lack and distribution of suitable overland stream flow monitoring sites within the Study Area, it is not possible to accurately determine the loss, if any of stream flow reporting into Cataract Dam.

The Wonga East area is different to others in the Southern Coalfields, as the main lithology in the creek bed is the Bald Hill Claystone/Newport/Garie Formations and Bulgo Sandstone. The Hawkesbury Sandstone is mainly only present in the upper headwaters. The significance of this is that the non-Hawkesbury Sandstone creek beds respond differently to subsidence. The uplifted sandstone sheets fractured sandstone diversions observed in Hawkesbury Sandstone based channels are not expected in this area (GeoTerra, 2012).

Given these uncertainties, it is not currently feasible to definitively quantify any overland stream flow losses that may, or may not, result from the potential loss mechanisms.

The catchment models developed for the study area have been used to describe how a range of modelled loss rates could impact on streamflow downstream of potentially affected subsidence areas. The Lake Cataract reservoir model has been used to estimate the impact on historical reservoir yield.

8.2.1 Potential Impact on Reservoir Yield

The Lake Cataract model was used to investigate the impact that various loss rates from the upstream catchment would have on reservoir yield.

Catchment and in-stream losses were applied by reducing the Cataract Creek/Cataract River inflow rate by a daily loss rate in ML/d (up to the daily flow rate). Loss rates of 0.5ML/d, 1ML/d, 5ML/d and 10ML/d were applied.

8.2.2 Potential Impact on Streamflow

Based on pool water level reduction rates, overland stream flow loss in the order of 0.5 ML/d have been estimated at other similar projects in the Southern Coalfields (Gilbert, 2008). Based on observations of groundwater inflows and piezometer behaviour in the area, the credible range of subsidence induced streamflow loss from Cataract Creek due to Wonga East operations is of the range 0.1-0.5ML/d (SCT, 2014), (Geoterra, 2012).

Daily flow rates at the reporting locations shown in Figure 5.7 were reduced by 0.1ML/d, 0.3ML/d and 0.5ML/d to indicate the effect on the hydrograph shape and the flow frequency curves.

8.2.3 Potential Additional Loss of Cataract Creek Streamflow due to Tributary Losses

A potential mechanism for the loss of streamflow in Cataract Creek is the loss of flow to the underground workings via cracking in the tributary catchments overlying the subsidence area.

Several unnamed tributaries of Cataract Creek will be impacted by subsidence cracking. Figure 8.1 shows the contributing catchment areas of the 10 mapped tributaries that will be affected by subsidence. The potential impact on Cataract Creek of losing subsidence affected tributary streamflow within, and upstream of, the extent of the underground workings was assessed by removing these areas from the catchment model and examining the effect on key streamflow characteristics at CC9 (which is located upstream of the Lake Cataract free surface level). Catchment areas downstream of the underground workings were left in the model to continue to contribute to streamflow in Cataract Creek. The impact of loss of streamflow in Tributary 10 was examined separately as the confluence with Cataract Creek is located well downstream of CC9.

The likelihood of losing all tributary streamflow to the underground workings via subsidence cracking is very improbable. The purpose of this modelling is to show the contribution of the tributaries to streamflow in Cataract Creek.

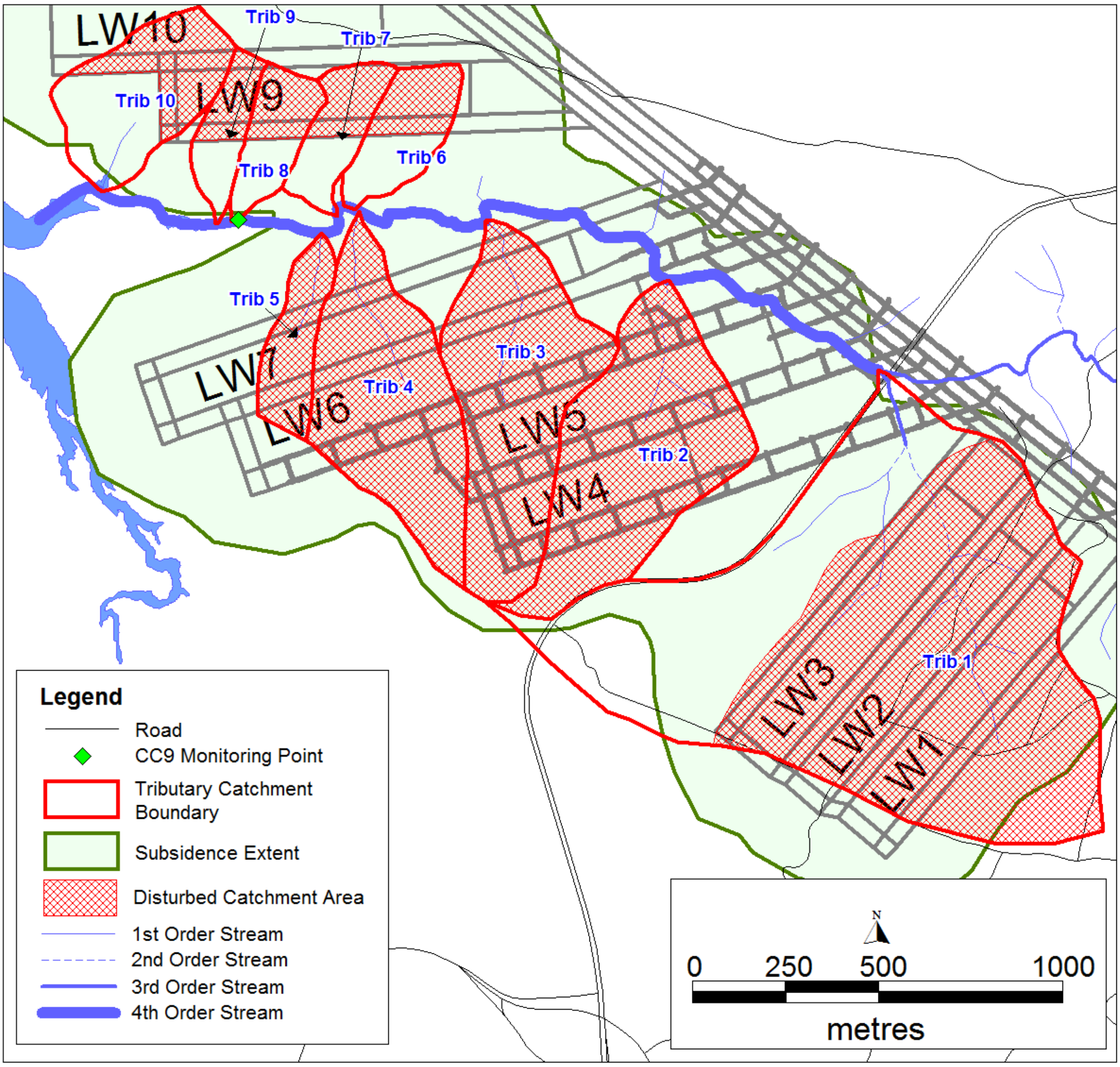


Figure 8.1 Cataract Creek Tributary Catchment Areas

8.3 MODEL RESULTS

8.3.1 Potential Impact on Reservoir Yield

Figure 8.2 below compares the simulated stored water volume with no subsidence losses to those simulated with catchment losses of increasing magnitude.

The overland stream flow loss rates were applied to the total Cataract River (including Cataract Creek) inflow. The results show that under historical water use and climate conditions recorded since 1976, losses of 1ML/d would have had very little impact on Lake Cataract water levels.

The maximum reduction in stored volume occurs in mid-2007 and ranges from 550ML for a loss of 0.5ML/d to 10,890ML for a loss of 10ML/d. Losses of 10ML/d would not have caused the Lake Cataract Reservoir water volume to fall below 10% of capacity. Such loss rates are very large, and based on previous experience and observations at similar coal mines in the Southern Coalfields (Gilbert, 2008) they are unlikely to eventuate given the anticipated and observed response of the stream bed to the predicted subsidence along with the proposed panel layout.

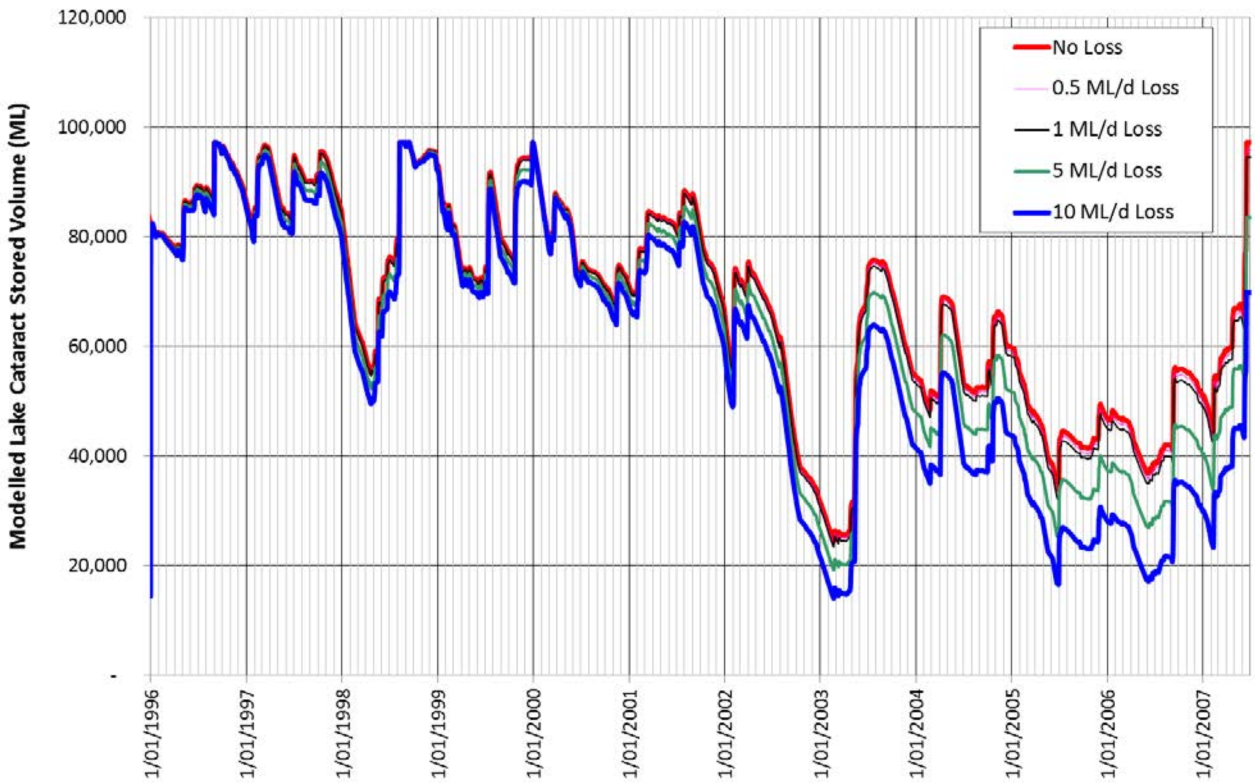


Figure 8.2 Impact of catchment loss on Lake Cataract dry period stored water volume

During a more significant drought which was severe enough to empty the reservoir (i.e. more server than in the reservoir historical record), additional loss created by the project would increase the period of time that water would be unavailable. The worst case scenario (in terms of size of the impact) would be where the reservoir was full at the start of a drought which was long enough to empty it (the length of the drought is not otherwise relevant because the drought-breaking inflow would be much greater than the losses – so supply would restart at the same time after rainfall regardless of the loss).

The table below illustrates the potential impact on supplies from the reservoir in terms of how much longer the dam would be empty because of the extra loss of water. The period of time is dependent on the rate of supply from the dam, as well as the loss rate. The table shows that over the range of likely release rates and loss rates, the impact is likely to be of the order of no more than a few days of no supply.

Table 8.2 Additional Days of No Supply During Reservoir-Emptying Drought

Loss Rate	SCA Release Rate (ML/d)						
ML/d	20	50	100	200	300	400	500
0.1	3.9	1.5	0.6	0.2	0.1	0.1	0.0
0.3	11.6	4.5	1.7	0.6	0.3	0.2	0.1
0.5	19.2	7.5	2.9	0.9	0.4	0.3	0.2
1	38.1	15.0	5.7	1.8	0.9	0.5	0.3
5	176.7	71.5	27.7	9.0	4.4	2.6	1.7
10	324.0	135.0	53.4	17.6	8.7	5.1	3.4

8.3.2 Potential Impact on Streamflow

The results of the analysis over the period January 1986 to January 1988 are illustrated in Figure 8.3 and Figure 8.4, which show modelled flow rates at the Cataract Creek pool monitoring stations CC5 and CC9 using the Bellambi Creek AWBM parameters. It should be emphasised that the model overestimates recorded low flows and there are no cease to flow periods in the modelled streamflow dataset.

The effect of losses of the magnitude considered would have a proportionally smaller impact on large flows. However, they could constitute a higher portion of baseflow under low flow conditions at the localised affected areas.

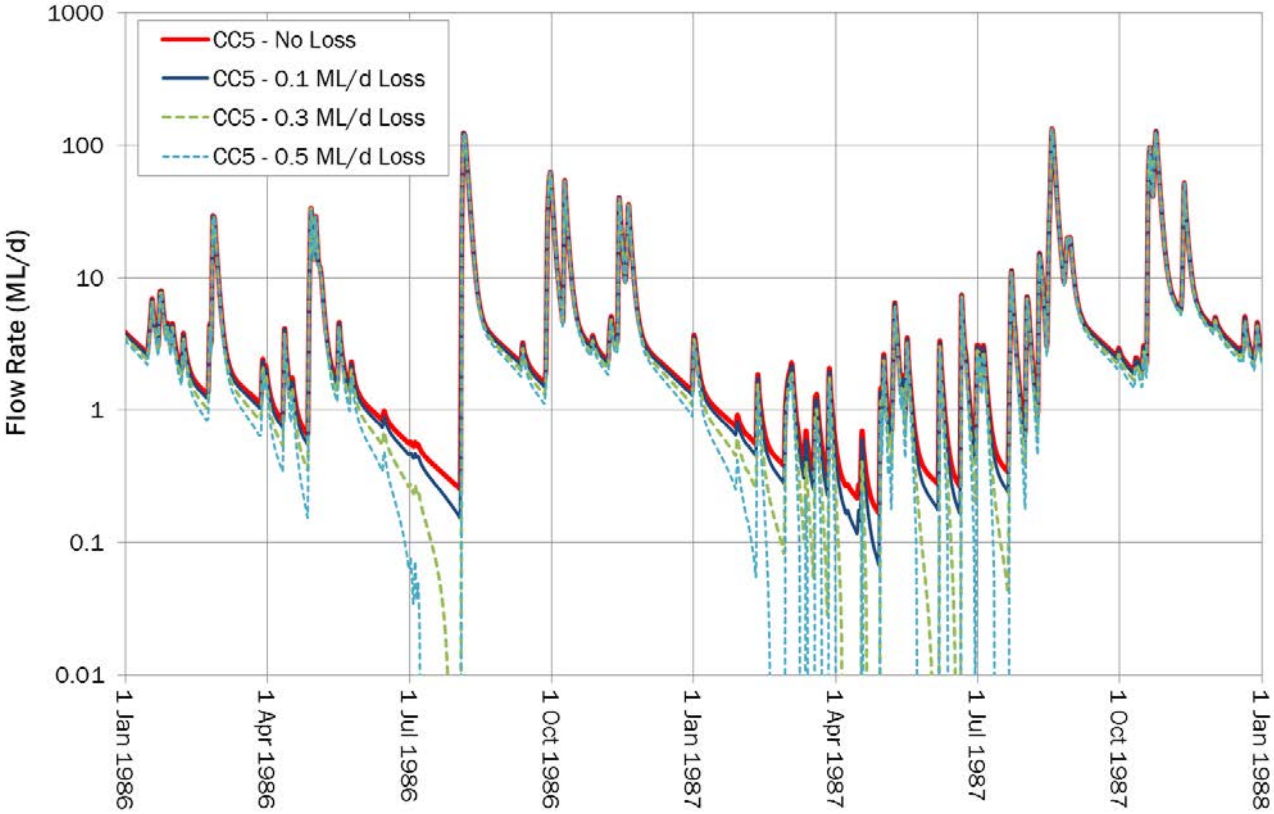


Figure 8.3 Example impact of flow loss on modelled hydrograph shape Cataract Ck at CC5

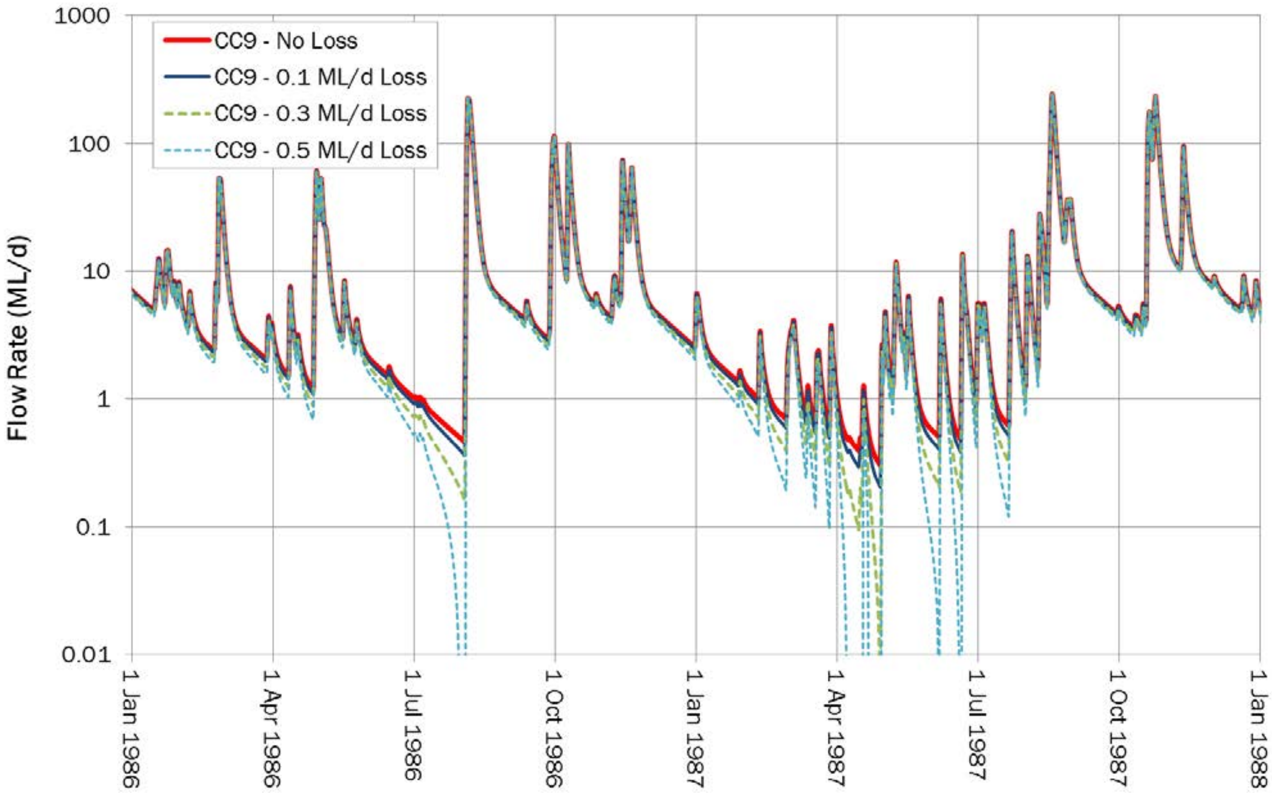


Figure 8.4 Example impact of flow loss on hydrograph shape Cataract Creek at CC9

The impact of the losses over the entire model period, between 1889 and 2014, is illustrated in Figure 8.5 and Figure 8.6. The following observations can be drawn from these results:

- At CC5, a loss of 0.3ML/d would reduce the frequency of flows greater than 1.0ML/d from around 65% to 58%. A loss of 0.5ML/d would reduce the frequency of flows greater than 1.0ML/d to 54%. The median duration of cease to flow periods would increase from 0 to 10 days, and the maximum cease to flow period length would increase from 0 to 78 days.

- At CC9, a loss of 0.3ML/d would reduce the frequency of flows greater than 0.1ML/d from around 78% to 73%. A loss of 0.5ML/d would reduce the frequency of flows greater than 0.1ML/d to 69%. The median duration of cease to flow periods would increase from 0 to 9 days, and the maximum cease to flow period length would increase from 0 to 69 days.

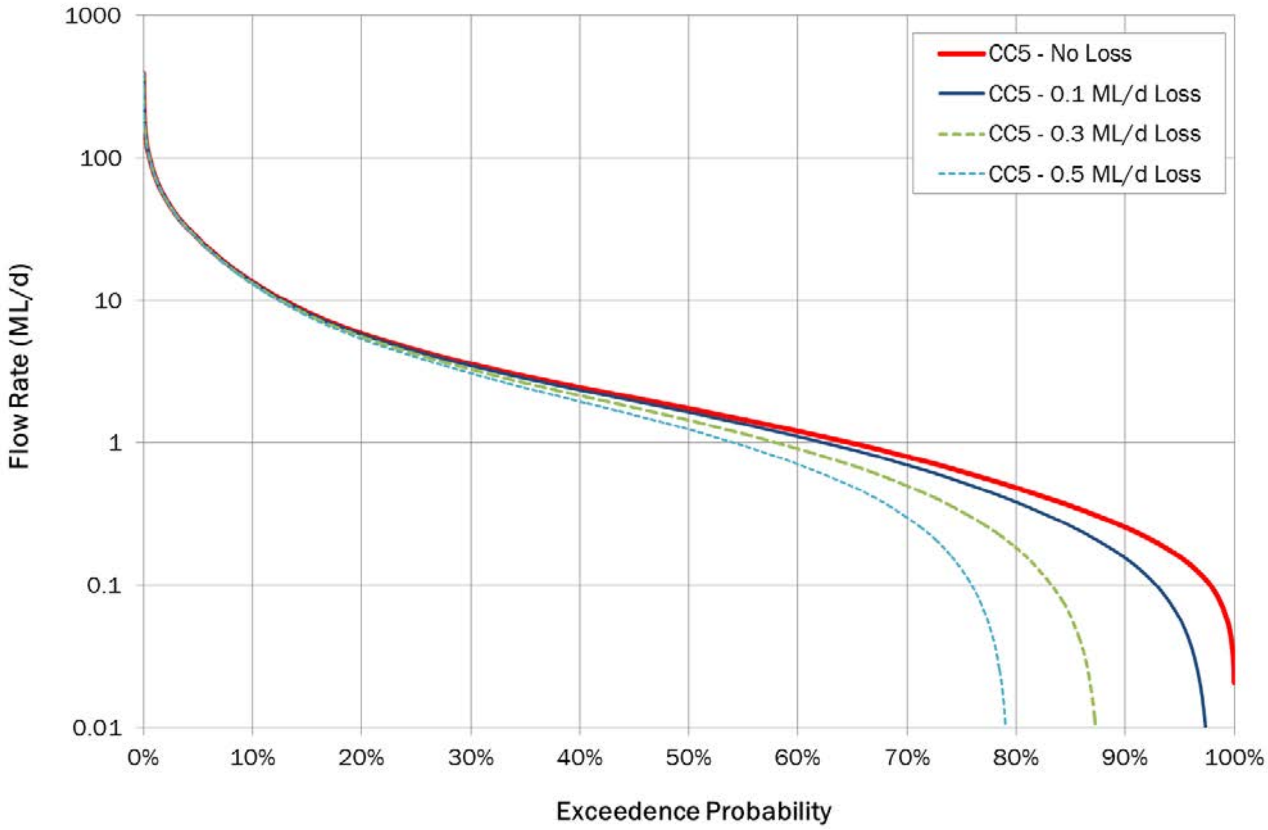


Figure 8.5 Impact of losses on Cataract Creek flow frequency curve at CC5

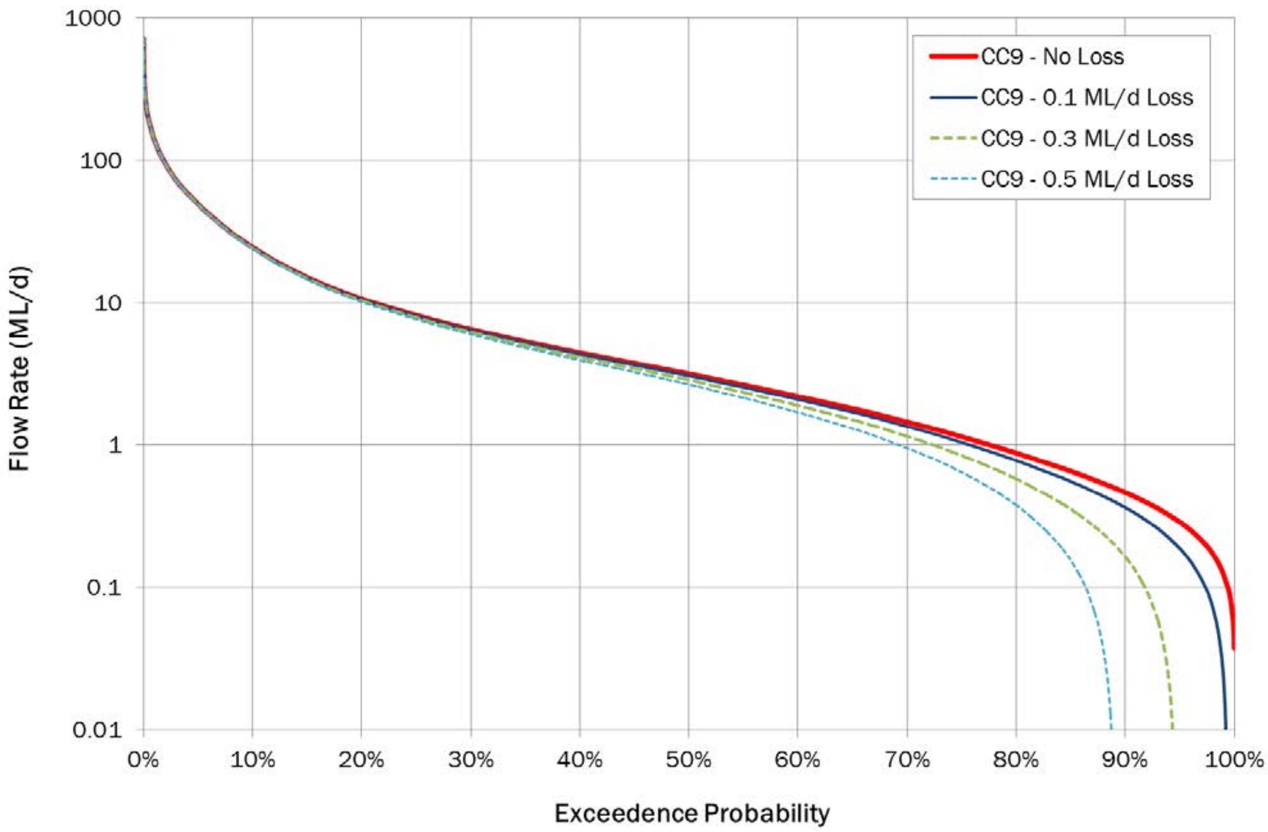


Figure 8.6 Impact of losses on Cataract Creek flow frequency curve at CC9

The AWBM model tends to underestimate the number of cease to flow periods in the Bellambi Creek dataset. While the modelled results appear to be consistent with a lack of no-flow periods observed in Cataract Creek, a sensitivity analysis was undertaken to determine the impact assuming Cataract Creek cease to flow periods were similar to Bellambi Creek. Appendix B shows the impact of streamflow losses on Cataract Creek using historical streamflow data at Bellambi Creek factored by the catchment areas upstream of CC5 and CC9. The following observations can be drawn from the results using historical streamflow data:

- At CC5, a loss of 0.3ML/d would reduce the frequency of flows greater than 1.0ML/d from around 67% to 61%. A loss of 0.5ML/d would reduce the frequency of flows greater than 1.0ML/d to 58%.
- At CC9, a loss of 0.3ML/d would reduce the frequency of flows greater than 0.1ML/d from around 88% to 78%. A loss of 0.5ML/d would reduce the frequency of flows greater than 0.1ML/d to 74%.

It should be noted that if flow losses occurred from a reach of the affected streams, it is thought that the flow would return to the channel further downstream. The impacts described above are therefore likely to affect only limited portions of the affected streams.

8.3.3 Potential Additional Loss of Cataract Creek Streamflow due to Tributary Losses

The results of the analysis over the period January 1986 to January 1988 are illustrated in Figure 8.7 and Figure 8.8, which show modelled flow rates at the Cataract Creek pool monitoring station CC9 using the Bellambi Creek AWBM parameters. Figure 8.10 shows the results of the analysis in Tributary 10.

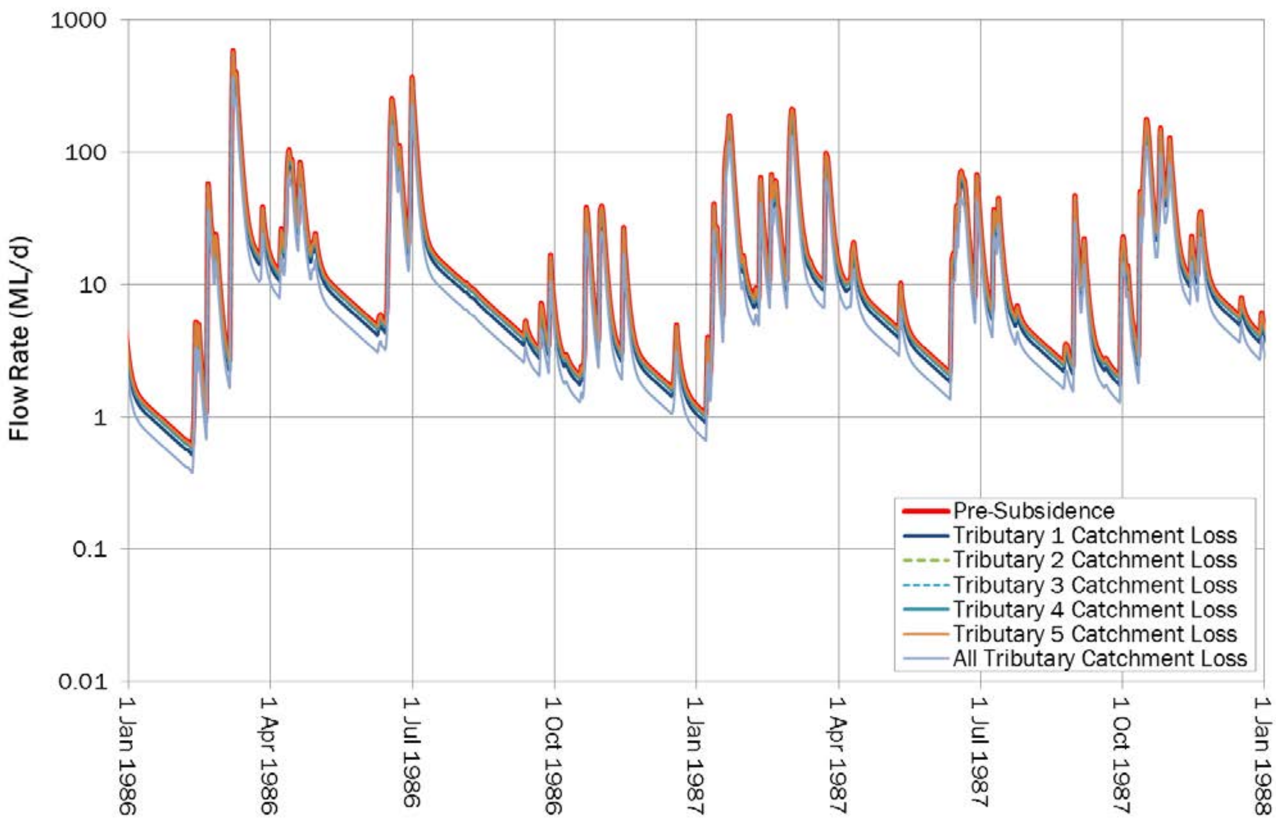


Figure 8.7 Example impact of tributary flow loss on hydrograph shape of Cataract Creek at CC9, Tributary 1-5.

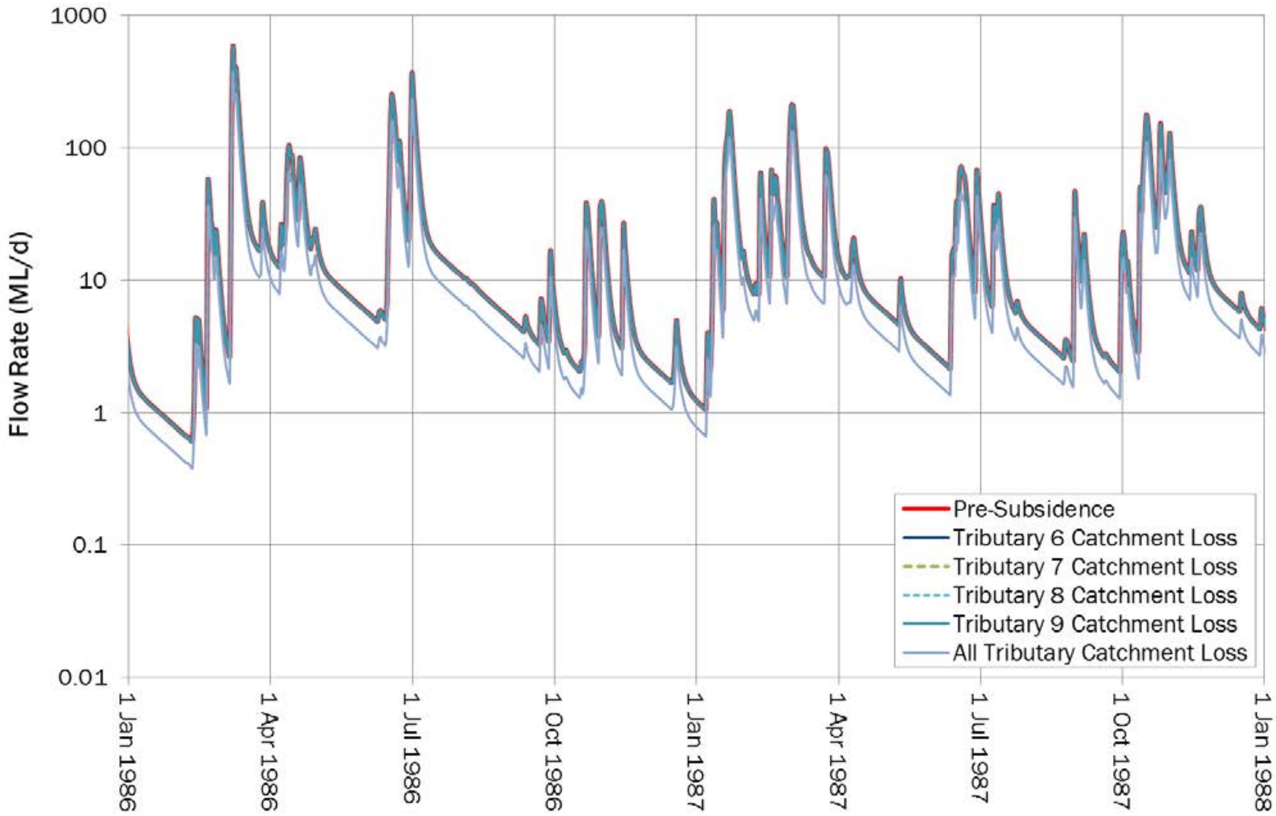


Figure 8.8 Example impact of tributary flow loss on hydrograph shape of Cataract Creek at CC9, Tributary 6-9.

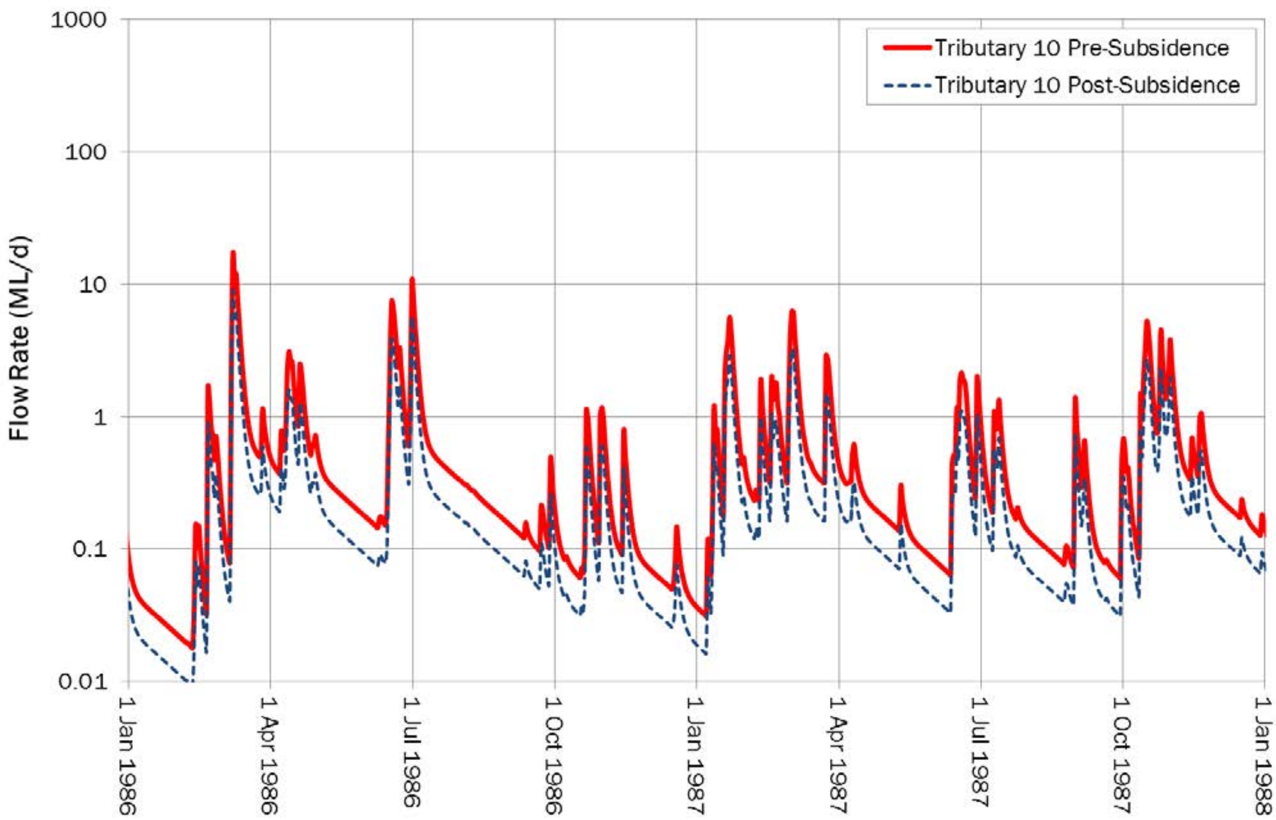


Figure 8.9 Example impact of tributary flow loss on hydrograph shape of Tributary 10.

The additional effect of catchment losses was assumed to be proportionally the same for all flows – with the magnitude of losses being higher during the large flow events. Table 8.3 shows the impact of catchment losses over a range of flows upstream of CC9 and in Tributary 10. The impact of the losses (in the absence of other in-stream losses) over the entire modelled period, between 1889 and 2014, for tributaries upstream of CC9 is illustrated in Figure 8.10 and Figure 8.11. Figure 8.12 shows the impact of catchment loss in Tributary 10.

The following observations can be drawn from these results:

- Loss of streamflow from the catchment areas of all tributaries upstream of CC9 would reduce the median total flow rate by 0.9ML/d (from 2.54ML/d to 1.64ML/d). Median baseflow would reduce by 0.61ML/d (from 1.71ML/d to 1.10ML/d);
- The loss of streamflow from the catchment area of Tributary 1 makes up the bulk of this loss – with the median total flow rate reducing by 0.37ML/d (from 2.54ML/d to 2.17ML/d). Median baseflow would reduce by 0.25ML/d (from 1.71ML/d to 1.46ML/d);
- Loss of streamflow from the catchment areas of the individual tributaries 2-9 would be minimal as each of these tributaries make up less than 6.1% of the total catchment to CC9;
- The loss of streamflow from the catchment area of Tributary 10 would reduce the median total flow rate from this tributary by 0.04ML/d (from 0.08ML/d to 0.04ML/d). Median baseflow would reduce by 0.02ML/d (from 0.05ML/d to 0.03ML/d).

Table 8.3 Impact of tributary losses on streamflow at CC9 and in Tributary 10

Scenario	Disturbed Area (km2)	Unaffected Area (km2)	Total Flow (ML/d)		Baseflow (ML/d)	
			Average	Median	Average	Median
Pre-Subsidence (to CC9)	0.00	4.75	9.71	2.54	3.08	1.71
Loss of:						
Tributary 1	0.70	4.05	8.28	2.17	2.62	1.46
Tributary 2	0.29	4.46	9.12	2.39	2.89	1.61
Tributary 3	0.27	4.48	9.16	2.40	2.90	1.61
Tributary 4	0.24	4.51	9.22	2.41	2.92	1.62
Tributary 5	0.06	4.69	9.58	2.51	3.04	1.69
Tributary 6	0.04	4.71	9.64	2.52	3.05	1.70
Tributary 7	0.03	4.72	9.65	2.53	3.06	1.70
Tributary 8	0.03	4.72	9.65	2.53	3.06	1.70
Tributary 9	0.03	4.72	9.66	2.53	3.06	1.70
All Tributaries (to CC9)	**1.69**	**3.06**	**6.26**	**1.64**	**1.98**	**1.10**
Tributary 10 Pre-Subsidence	0.00	0.14	0.29	0.08	0.09	0.05
Tributary 10 Post-Subsidence	0.07	0.07	0.15	0.04	0.05	0.03

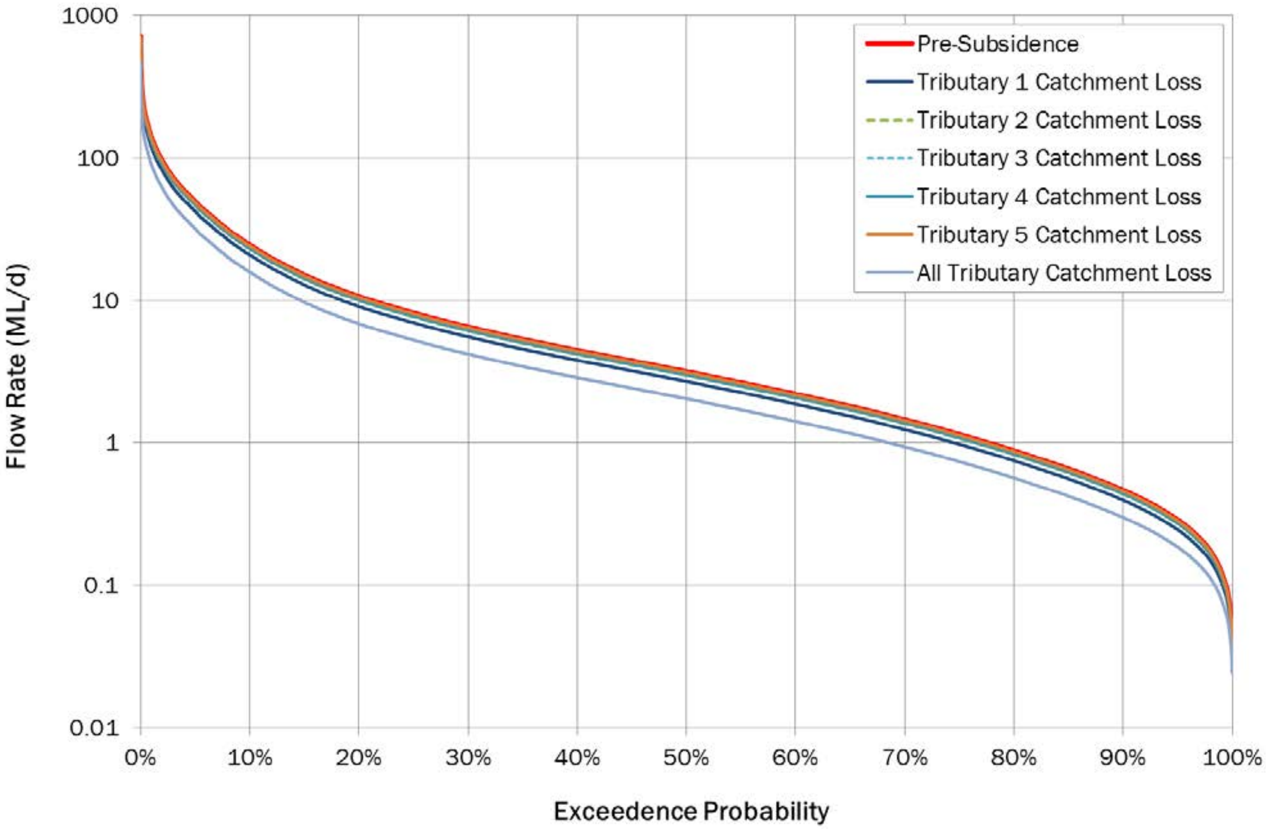


Figure 8.10 Impact of tributary losses on Cataract Creek flow frequency curve at CC9, Tributary 1-5.

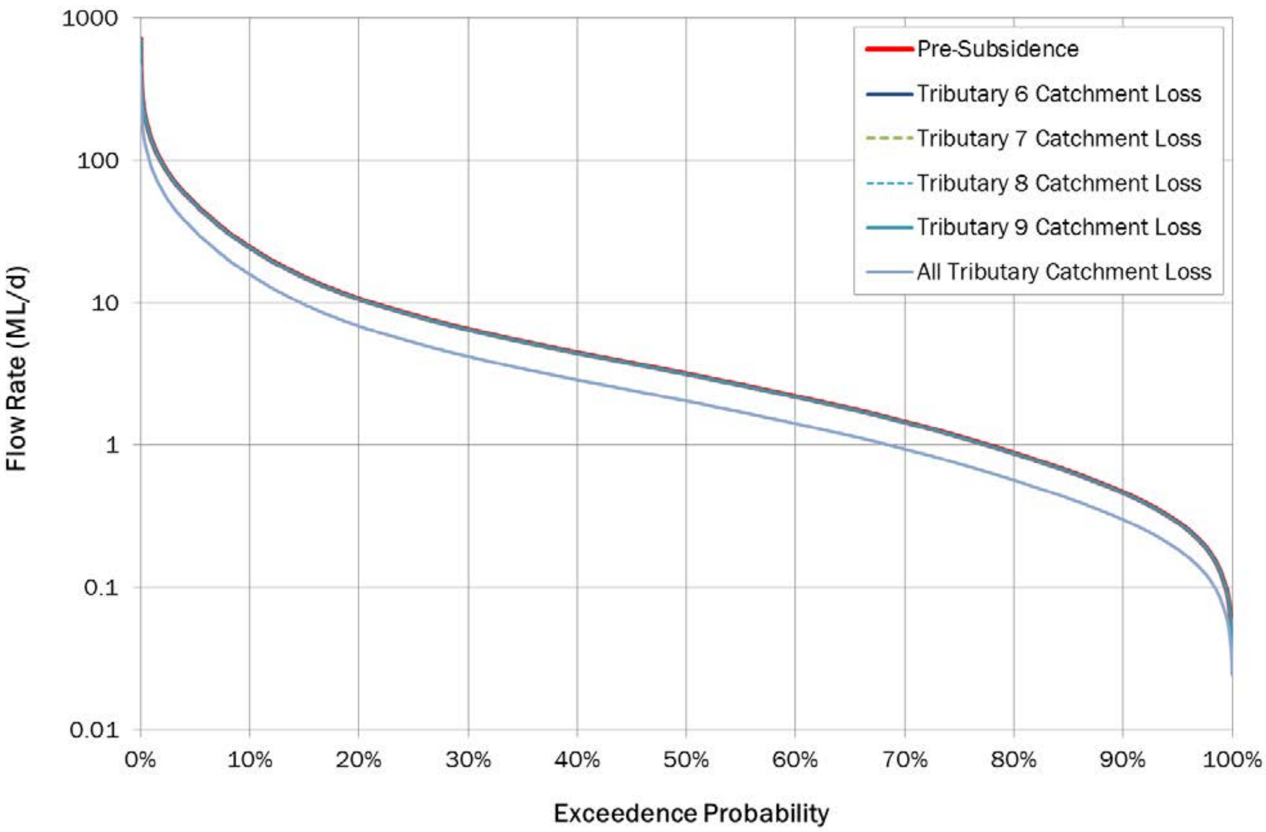


Figure 8.11 Impact of tributary losses on Cataract Creek flow frequency curve at CC9, Tributary 6-10.

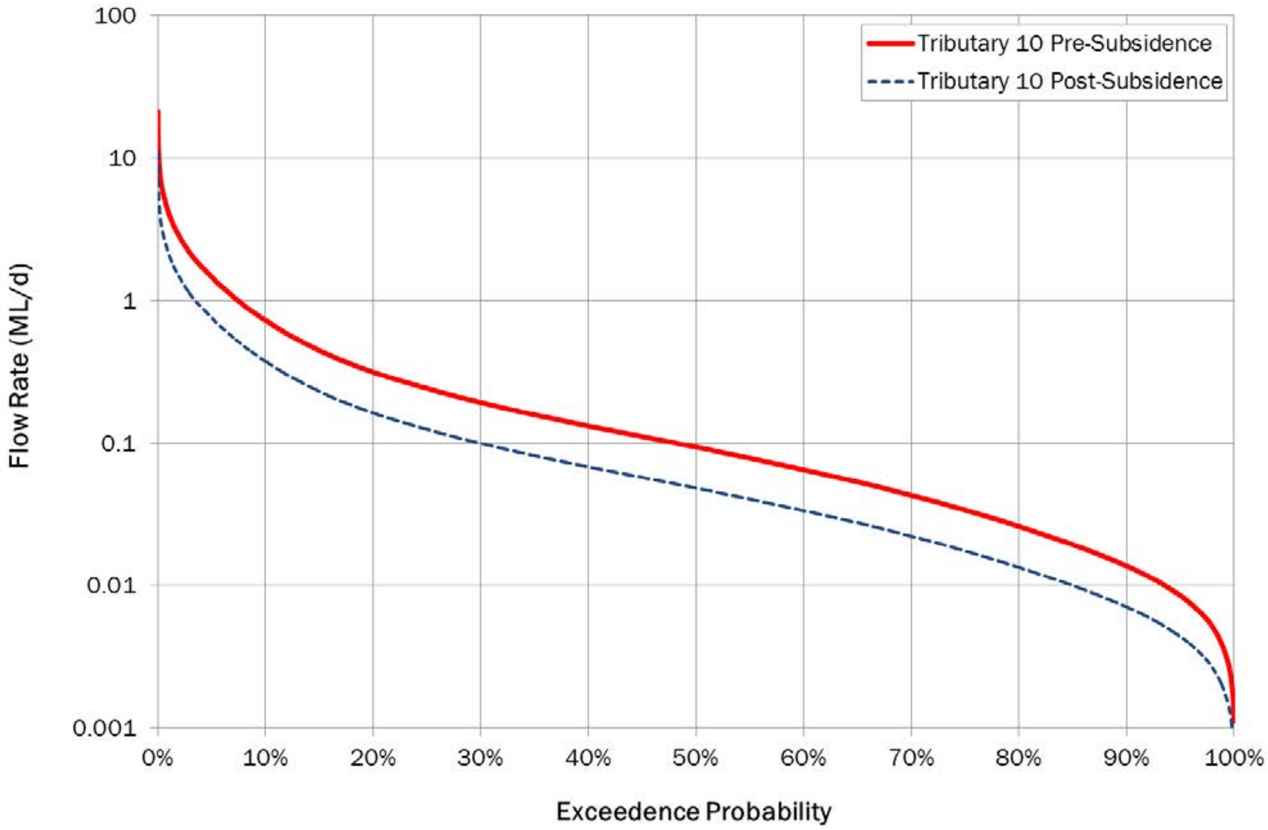


Figure 8.12 Impact of catchment losses on Tributary 10 flow frequency curve.

9 SUBSIDENCE IMPACT ON SWAMPS

9.1 LOCATION OF SWAMPS

The locations of potentially affected swamps in relation to catchments crossing the project area are shown in Figure 9.1 and Table 9.1. Swamps make up around 1.1% of the Cataract Creek catchment.

Table 9.1 Areas of Swamps in the Project Catchment Areas

Catchment	Total Catchment Area	Total Swamp Area	Proportion which is swamp
	ha	ha	%
Cataract River	2,088	16.5	0.8
Cataract Creek	1,928	21.4	1.1
Bellambi Creek	1,441	7.6	0.5
Lake Cataract		3.0	
Total Lake Cataract	**5,463**	**48.5**	**0.9**

Table 9.2 and Figure 9.1 show the proportions of these swamps within the 20mm subsidence zone. Approximately 64% of the potentially affected swamps in the project area are within the proposed subsidence zone.

Table 9.2 Proportions of Swamps Within Subsidence Zone

	Swamp Area Within Subsidence Zone	Unaffected Swamp Area	Total Swamp Area	Proportion Within Subsidence Zone
	ha	ha	ha	%
Cataract River	5.9	10.6	16.5	36
Cataract Creek	19.1	2.4	21.4	89
Bellambi Creek	4.4	3.3	7.6	58
Lake Cataract	0.5	1.2	3.0	29
Total Lake Cataract	**31.1**	**17.4**	**48.5**	**64**

Table 9.3 shows the contribution that swamps, and swamps within the proposed subsidence zone make to the catchment areas to each monitoring station. The table also shows the contribution of swamps to the catchment at key locations along Bellambi Creek.

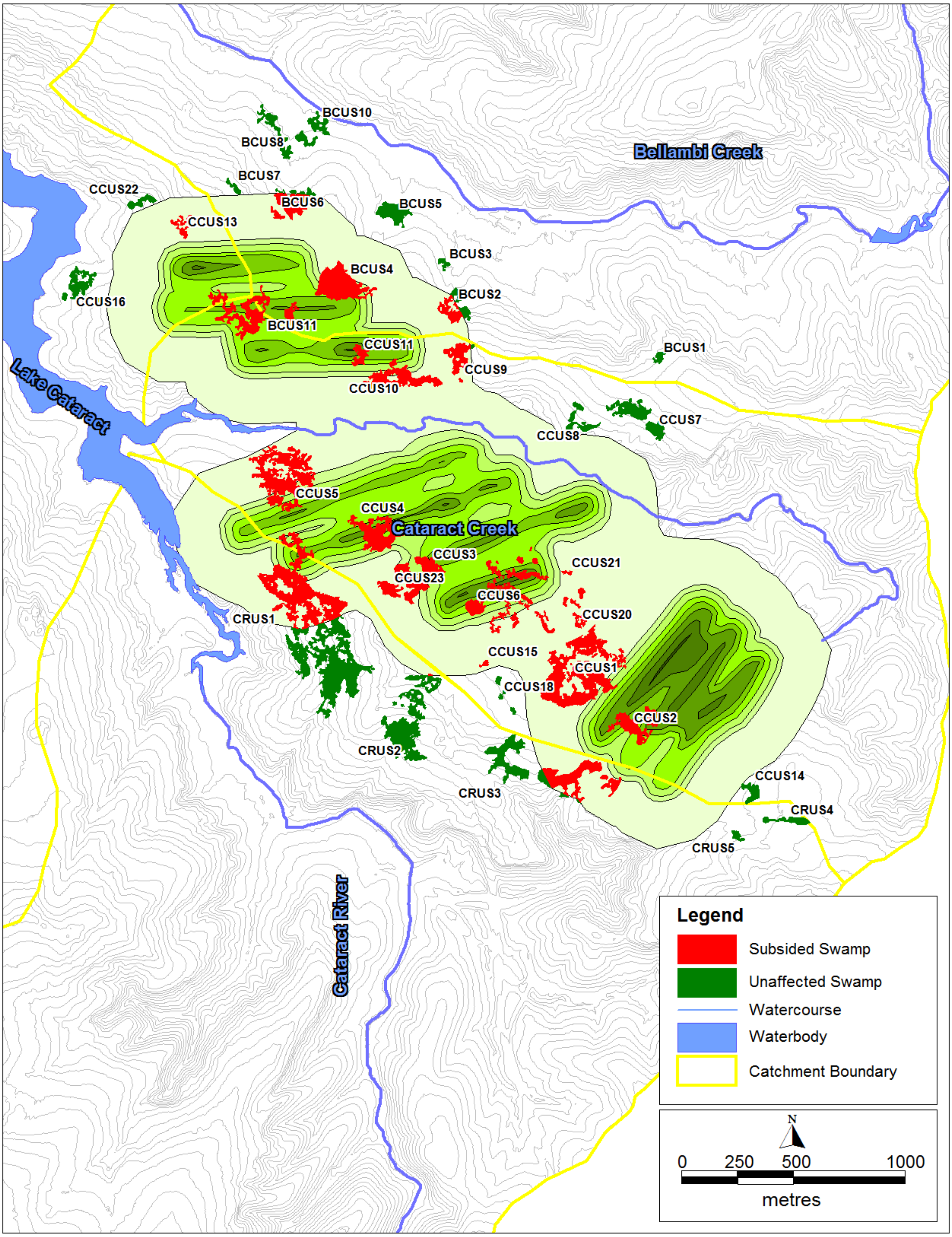


Figure 9.1 Locations of Potentially Subsided Swamps in the Vicinity of the Project Area

Table 9.3 Contribution of Swamps to Catchment Area at Monitoring Points (ha)

Catchment	Swamp Area			Non-Swamp Area	Total Catchment Area
	Undisturbed	Subsided	Total		
Cataract Creek					
CC3	0.5	6.1	6.6	99.5	106.1
CC5	0.5	6.6	7.2	257.8	265.0
CC6	0.9	6.6	7.5	283.5	291.1
CC7	2.3	8.7	11.0	336.4	347.5
CC8	2.3	11.3	13.6	403.8	417.4
CC9	2.3	19.1	21.4	458.5	479.9
Cataract River					
CR2	7.3	1.8	9.1	960.0	969.1
CR4	10.6	5.9	16.5	1085.8	1102.3
Bellambi Creek					
BC4000	0.2	0.0	0.2	410.1	410.2
BC4500	1.6	3.3	4.9	479.0	483.9
BC5000	3.3	4.4	7.6	531.5	539.1

10 CONCLUSIONS

The catchments of Cataract Creek, Bellambi Creek and Cataract River overlie areas anticipated to experience subsidence associated with the proposed expansion of the Wonga East underground workings. However, the proposed mine panel layout has been designed to limit the adverse effects on the potentially affected channels.

As a result, the Bellambi Creek channel will not be affected by subsidence induced by the proposed expansion. The predicted subsidence along the channels of Cataract Creek and Cataract River (including the reaches inundated by Lake Cataract) will be less than 20mm, as detailed below:

1. Cataract Creek. The proposed Wonga East workings are located between Chainage 2,500m and Chainage 4,500m. Of the total Cataract Creek catchment area of 5.2km^2, 3.2km^2 has been identified as potentially subsided by the proposed workings.

2. Cataract River. The proposed Wonga East workings do not underlie the Cataract River. The predicted 20mm subsidence zone runs adjacent to the Lake Cataract backwater for a distance of about 350m. Of the total Cataract River catchment area of 11.6km^2, 0.5km^2 has been identified as potentially subsided by the proposed workings. The western end of Panel 10 in the Wonga East workings extends under the high water extent of the northern bank of the Lake Cataract backwater in the Cataract River.

3. Bellambi Creek. Of the total Bellambi Creek catchment area of 9.3 km^2, 0.4 km^2 has been identified as potentially subsided by the proposed workings.

Subsidence- induced cracking could potentially reduce overland streamflow in reaches overlying the proposed workings.

Based on a catchment yield model calibrated to historical records since 1976, overland flow losses of 1ML/d would have very little impact on Lake Cataract water levels. The maximum reduction in stored volume occurs in mid-2007 and ranges from 940ML for a loss of 0.5ML/d to 1,385ML for a loss of 10ML/d. Losses of 10ML/d would not have caused the Lake Cataract Reservoir water volume to fall below 10% of capacity. Such a loss rate is very large, and unlikely to eventuate given the underlying geology and proposed mining method.

In the absence of long-term streamflow records on Cataract Creek, the impact of losses from the affected reaches on the persistence of baseflow has been estimated by extracting a constant daily loss rate from a simulated streamflow record. The model parameters were transposed from AWBM models calibrated to the adjacent Bellambi Creek catchment runoff records. The loss of low flows in Cataract Creek at the reporting locations just downstream of the proposed 20mm subsidence zone resulted in the following modelled changes to low flow characteristics:

A loss of 0.3ML/d would:
- reduce the frequency of flows greater than 1.0ML/d from around 78% to 72%.
- reduce the frequency of flows greater than 0.1ML/d from around 99% to 91%.
- increase the maximum cease to flow period length from 0 to 83 days.
- increase the median duration of cease to flow periods from 0 to 12 days.

A loss of 0.5ML/d would

- reduce the frequency of 1.0ML/d flows to 69%.
- reduce the frequency of 0.1ML/d flows to 86%.
- increase the maximum cease to flow period length from 0 to 101 days.
- increase the median duration of cease to flow periods from 0 to 9.5 days.

The additional effect of catchment losses from the unnamed tributaries of Cataract Creek was assumed to be proportionally the same for all flows - with the magnitude of losses being higher during the large flow events. The following observations can be drawn from the results of modelling the loss of tributary inflows (in the absence of other in-stream losses):

- Loss of streamflow from the catchment areas of all tributaries upstream of CC9 would reduce the median total flow rate by 0.9ML/d (from 2.54ML/d to 1.64ML/d). Median baseflow would reduce by 0.61ML/d (from 1.71ML/d to 1.10ML/d);
- The loss of streamflow from the catchment area of Tributary 1 makes up the bulk of this loss – with the median total flow rate reducing by 0.37ML/d (from 2.54ML/d to 2.17ML/d). Median baseflow would reduce by 0.25ML/d (from 1.71ML/d to 1.46ML/d);
- Loss of streamflow from the catchment areas of the individual tributaries 2-9 would be minimal as each of these tributaries make up less than 6.1% of the total catchment to CC9;
- The loss of streamflow from the catchment area of Tributary 10 would reduce the median total flow rate from this tributary by 0.04ML/d (from 0.08ML/d to 0.04ML/d). Median baseflow would reduce by 0.02ML/d (from 0.05ML/d to 0.03ML/d).

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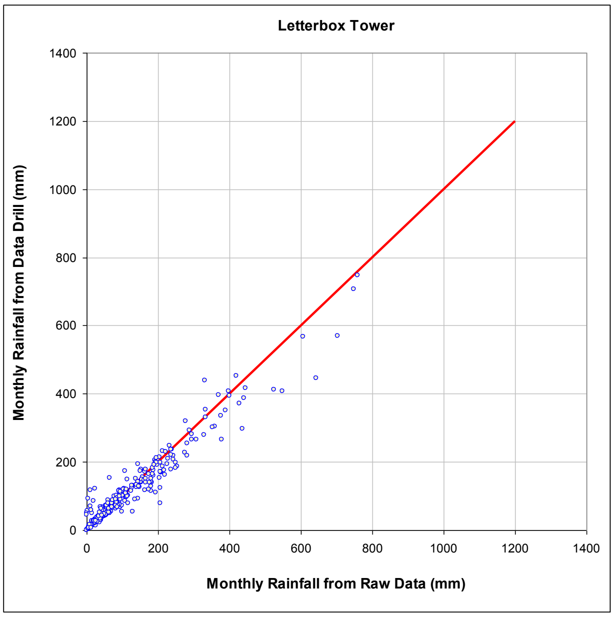
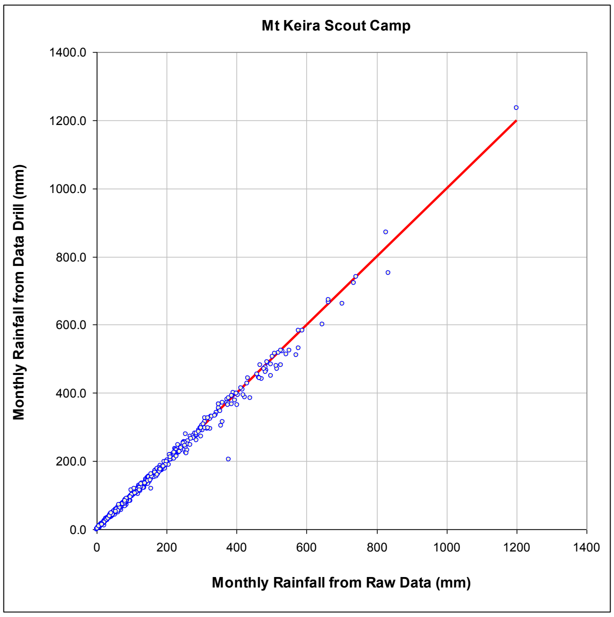
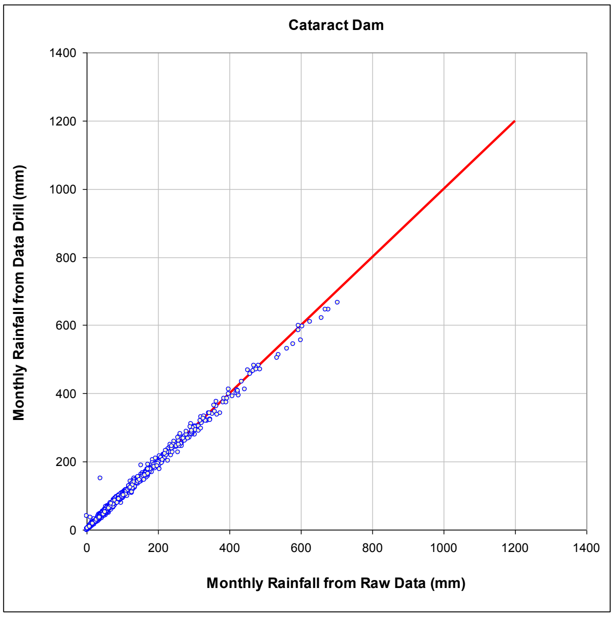
APPENDIX A

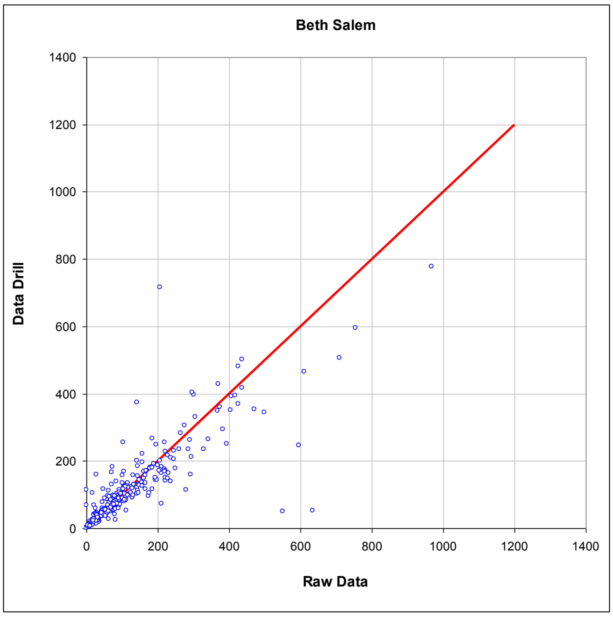
COMPARISON OF RAW RAINFALL DATA AND

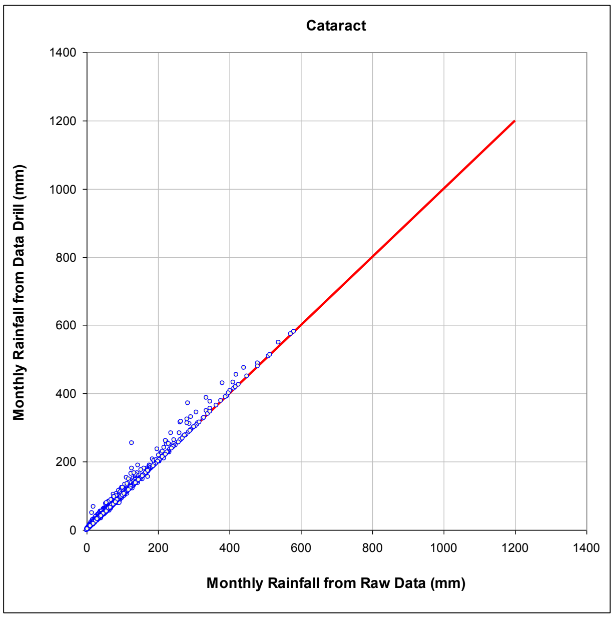
SILO DATA DRILL RAINFALL DATA

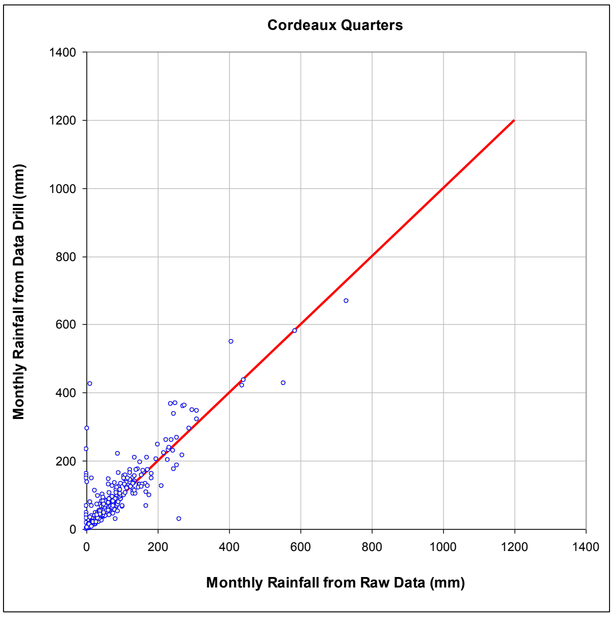

Letterbox Tower
Monthly Rainfall from Data Drill (mm)
0 200 400 600 800 1000 1200 1400
Monthly Rainfall from Raw Data (mm)


Mt Keira Scout Camp
Monthly Rainfall from Data Drill (mm)
0.0 200.0 400.0 600.0 800.0 1000.0 1200.0 1400.0
0 200 400 600 800 1000 1200 1400
Monthly Rainfall from Raw Data (mm)


Cataract Dam
Monthly Rainfall from Data Drill (mm)
0 200 400 600 800 1000 1200 1400
Monthly Rainfall from Raw Data (mm)


Beth Salem
Data Drill
0 200 400 600 800 1000 1200 1400
Raw Data


Cataract
Monthly Rainfall from Data Drill (mm)
0 200 400 600 800 1000 1200 1400
Monthly Rainfall from Raw Data (mm)


Cordeaux Quarters
Monthly Rainfall from Data Drill (mm)
0 200 400 600 800 1000 1200 1400
Monthly Rainfall from Raw Data (mm)

APPENDIX B

IMPACTS ON CATARACT CK STREAMFLOW

CALCULATED USING

OBSERVED BELLAMBI CREEK STREAMFLOW DATA

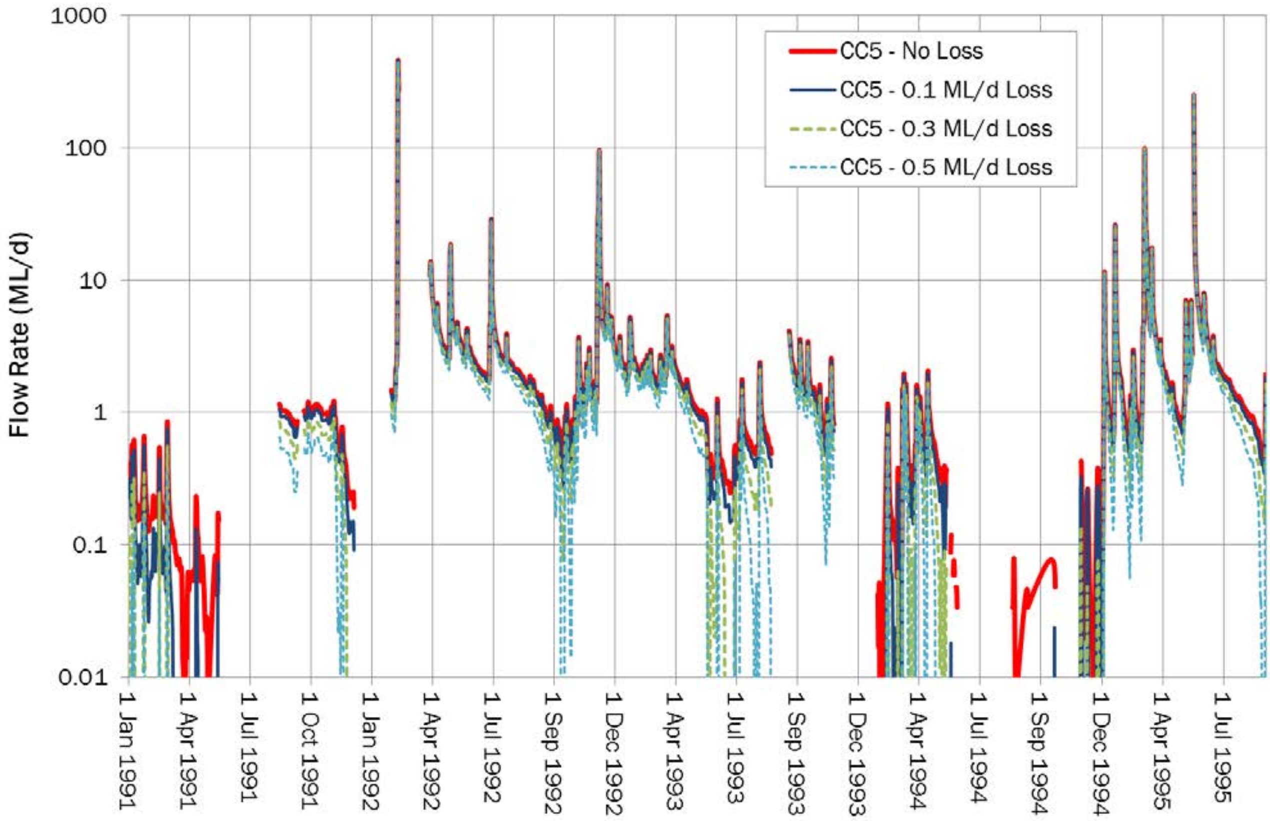


Figure 11.1 Example impact of flow loss on modelled hydrograph shape Cataract Ck at CC5 – Observed Data

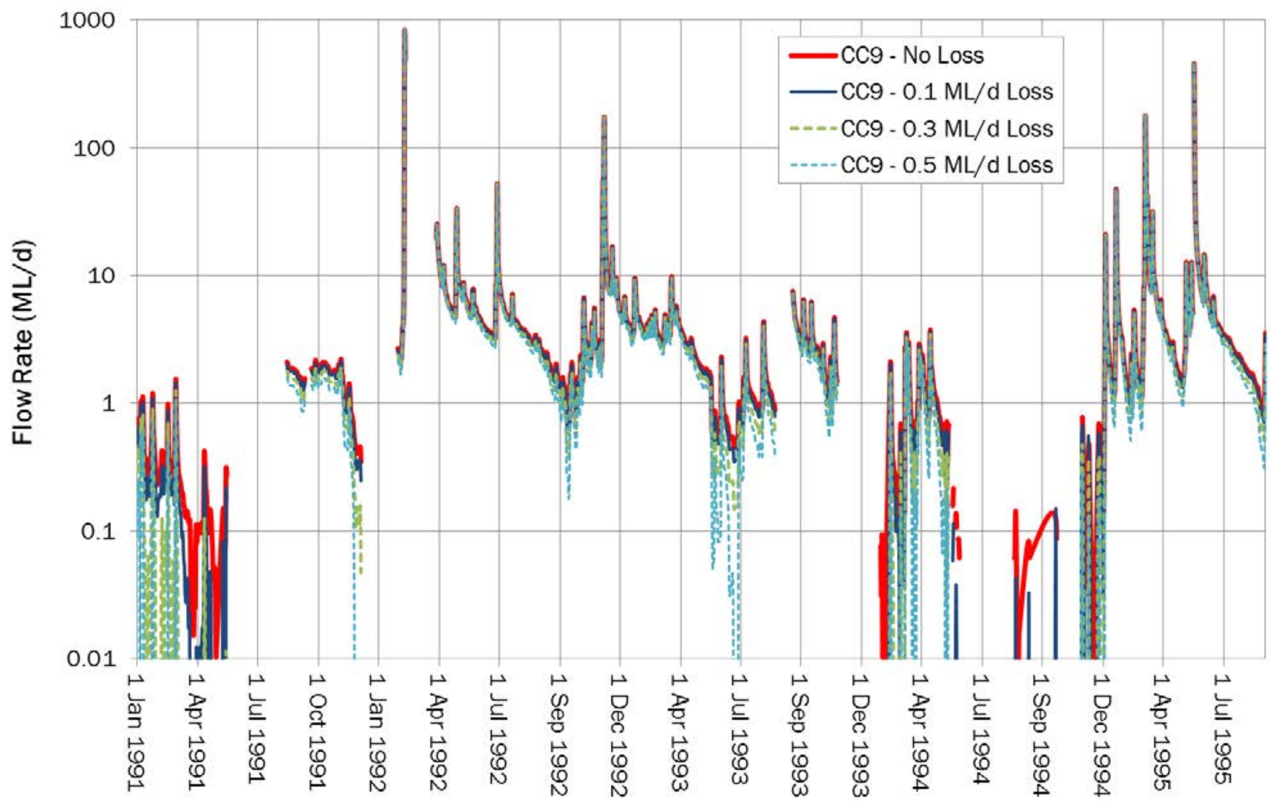


Figure 11.2 Example impact of flow loss on hydrograph shape Cataract Creek at CC9 – Observed Data

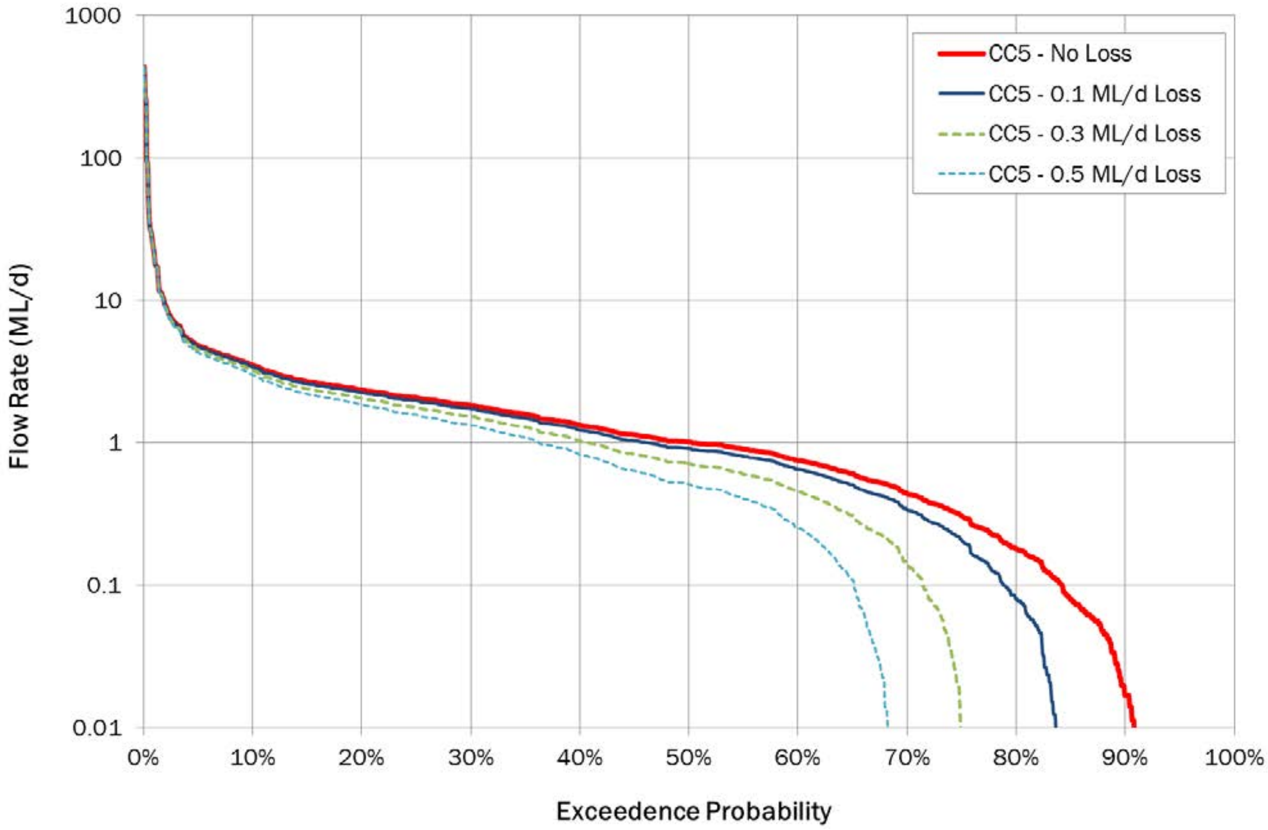


Figure 11.3 Impact of losses on Cataract Creek flow frequency curve at CC5 – Observed Data

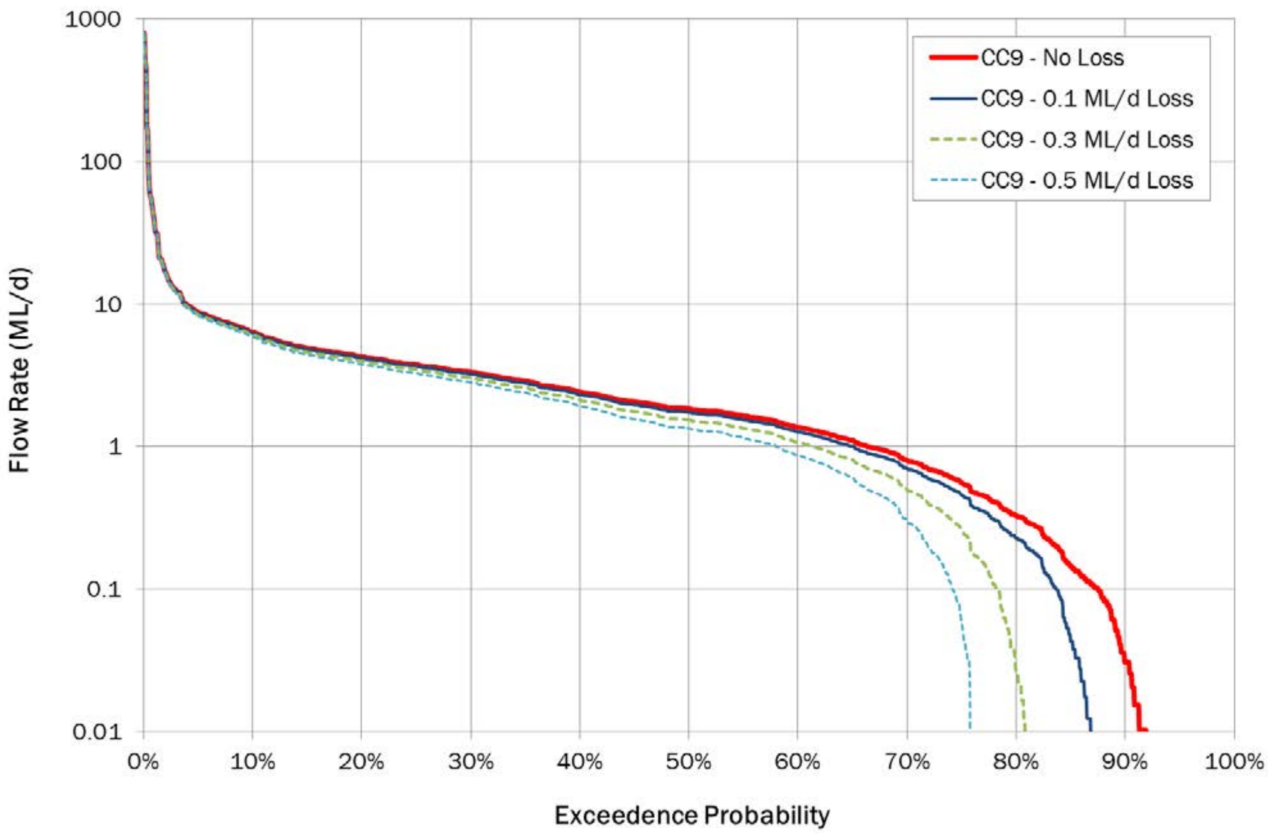


Figure 11.4 Impact of losses on Cataract Creek flow frequency curve at CC9 – Observed Data