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# Assessments of river condition under the current flow regime and proposed flow regimes in the lower Coxs River, New South Wales

A consultancy report to the Coxs River Review Joint Working Party, commissioned by the New South Wales Department of Land and Water Conservation

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## Context

During 1999 and 2000 the New South Wales Department of Land and Water Conservation (DLWC), Delta Electricity, and a community representative worked cooperatively to devise a regulated flow regime that would lead to improved environmental conditions in the Coxs River, while maintaining the social and economic benefits derived from the use of the river’s waters. Other changes in resource management that could lead to environmental benefits in the Coxs River and its catchment were also investigated.

A Steering Committee was established to recommend to DLWC – as the regulatory agency – an appropriate new flow regime for the Coxs River. The recommendations of the Steering Committee were to be based partly on the advice of a Joint Working Party – comprising DLWC and Delta Electricity – which was established to develop and assess a range of flow regime options for the Coxs River. The Joint Working Party, in turn, established a Scientific Reference Panel (SRP) comprising the authors of this report and led by the senior author. The SRP provided technical and scientific advice relating to the current condition of the Coxs River, prior environmental investigations of the river, and assessments of the environmental costs and benefits of the range of flow regime options.

## Disclaimer

The assessment of the current condition of the Coxs River in this report is based on pre-existing data and information, limited new analyses, and field observations. While the authors take responsibility for the correctness and appropriateness of new analyses, no responsibility is taken for the quality of the unpublished data and information that have been used. Where the conclusions drawn rely on such unpublished and unchecked data sources, it is recommended that the JWP or other readers of this report seek to determine the quality of the data used from those responsible for the data collection and subsequent data management. Alternatively independent means should be used to check these conclusions.

The assessments of flow options in this report are based partly on hydrological modelling done by DLWC. The SRP takes no responsibility for the correctness or accuracy of this modelling.

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Cover Photograph: sand deposition in the Coxs River upstream of the Ganbenang Creek junction, looking upstream. Photograph by Scott Tinsley, DLWC.

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# Introduction

This report has three parts. The first describes the current condition of the Coxs River, the second describes the method used for assessing proposed flow options, and the third details the flow option assessments. As the investigations conducted by the SRP were a part of a process to determine the licence conditions for the management of Lyell Dam, the focus of this report is on the section of the river from Lyell Dam to Lake Burragorang.

Because the investigations had a tight schedule, the assessment of the current condition of the Coxs River was not based on extensive new field studies. Instead, it was based on an interpretation of previous studies, some new analyses of pre-existing data sets, inspections of sections of the river, and the combined expert opinion of the SRP. In assessing proposed flow options, the SRP also relied on the hydrological modelling of options by DLWC, and on hydraulic data collected by DLWC and others.

# PART I – CURRENT CONDITION OF THE COXS RIVER

The current condition of the Coxs River was assessed with reference to river conditions both before the construction of Lyell Dam and before European settlement – to the extent that these conditions are known. Where possible, the assessment identifies the likely causes of changes in condition. It also describes how the biological condition of the river system is a function of the flow regime, physical habitat structure, and water and sediment quality. These attributes of the river are in turn determined by climate, land use and management, flow regulation and diversions, and direct river management, including vegetation management. By understanding these linkages, the range of ways to improve the river's condition can be identified. However, because of limited data and poor quantification of the biophysical relationships, it has only been possible to make qualitative assessments.

## *Catchment description*

The Coxs River drains a catchment of about 2630km$^2$ on the western side of the Blue Mountains (Figure 1). It is bounded to the west by the Great Dividing Range, to the north by the upper Colo River catchment, and to the south by the Wollondilly River catchment. A tributary of the Nepean River, the Coxs River now flows into Lake Burragorang (behind Warragamba Dam), the largest of Sydney's water-supply reservoirs. Over most of its length the Coxs River valley-floor trough is underlain by granite. The upper reaches of its eastern tributaries drain sandstone and shales; the western tributaries primarily drain granite. The granite-derived soils are typically thin and highly erodible.

Before European settlement Aborigines lived in the catchment for many thousands of years. While it is not known when Aborigines arrived, aboriginal artefacts from the catchment have been dated at 22,240 ± 1,000 years (Stockton and Holland, 1974). In journeys through the catchment in the early 19th century, both Gregory Blaxland and George Evans noted the fires lit by the Aborigines (Ryan *et al.*, undated). However, there is no evidence that aboriginal burning led to major changes in vegetation patterns in the Coxs River catchment. The journals of the early explorers provide a picture of the local vegetation, and many extracts from these journals are provided by Flannery (1998). The general picture is of heavily forested hillslopes, opening into more open woodland and some areas of grassland in the wider valleys such as the Megalong Valley and along the River Lett. In the upper tributaries, frost hollows in the valleys are likely to have prevented tree growth.

The current vegetation pattern (Figure 1) is one of extensive pasture in the upper and mid-catchment, while below Island Hill the land cover is nearly entirely native timber. Much of the latter area and most of the Kowmung River catchment are national parks. These major differences in land cover between the upper to mid-catchment and the lower catchment were not reported by early explorers, suggesting that large areas were cleared of timber during European settlement. Between 1820 and 1840 many land grants were allocated to settlers, primarily for grazing. While initially these areas would have provided ample grazing opportunity, it is likely that with forest regrowth, increasing rabbit populations, and the spread of weeds, there would have been an increase in ringbarking to promote pasture. Even without ringbarking to extend grazing areas, the early settlers felled many trees for building homesteads, fences and stockyards (Barrett, 1993). In 1905 a major bushfire swept through forests and pastures of the upper catchment leaving bare soil and blackened stumps (Barrett, 1993). Following this fire, rabbit populations increased rapidly, leading to widespread land degradation.

In addition to widespread grazing, forestry and coal mining now occur in the upper catchment, with the coal used in electricity generation at the Wallerawang and Mt Piper power stations. Together, these stations generate around one quarter of New South Wales's electricity, as a part of the national electricity grid. They obtain cooling water from the Coxs River Water Supply Scheme which includes three reservoirs: Lake Wallace (Wallerawang Reservoir), Lake Lyell, and Thompsons Creek Reservoir. The Coxs River catchment currently has around 21,000 inhabitants, with 12,000 living in the town of Lithgow.

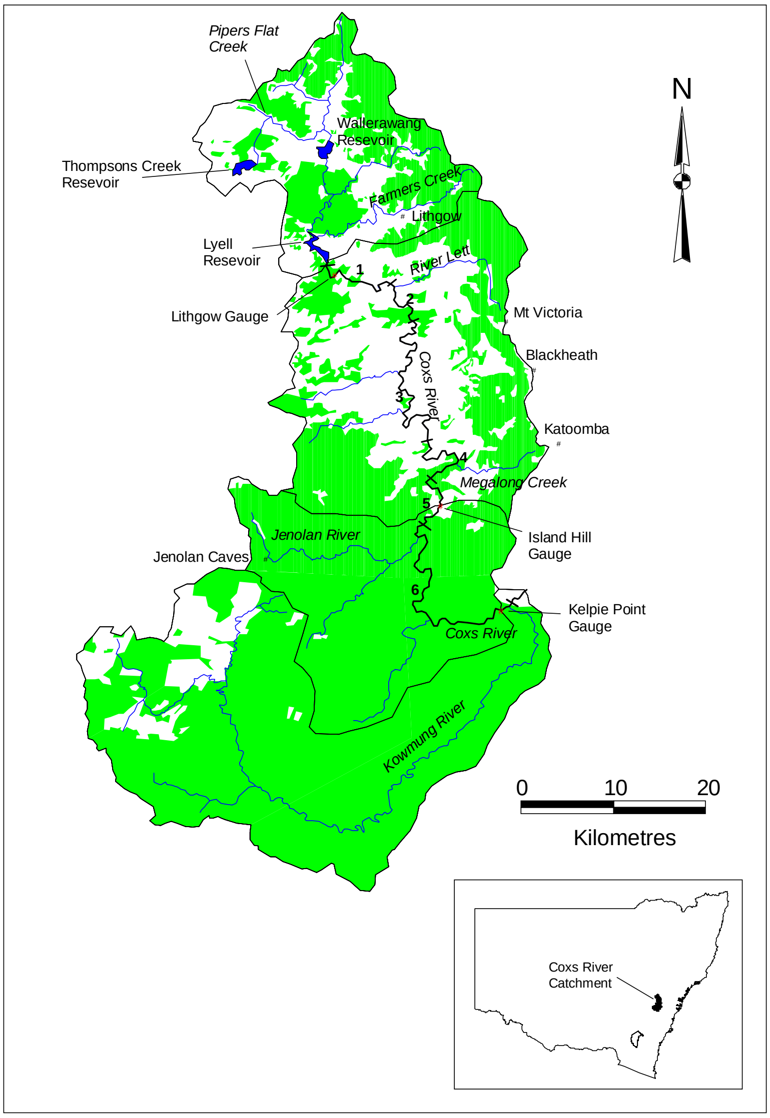


**Figure 1:** Current land cover of the Coxs River catchment showing the areas of native timber (shaded) and the areas of native and improved pasture (unshaded) (DLWC data). The six reaches of the Coxs River downstream of Lyell Dam used in this report are numbered, the locations of key gauging stations are shown, and the boundaries of contributing catchment areas for the three locations used in the hydrological modelling are indicated.

The climate is cool-temperate with wide variation in rainfall across the catchment (Figure 2). Spatially averaged mean annual rainfall values for the incremental catchment areas to the three locations used in the hydrological modelling are: Lyell Dam, 843mm, Island Hill, 915mm, and Kelpie Point, 954mm. The spatially averaged mean annual rainfall for the entire catchment (including the catchment of the Kowmung River) is 911mm.

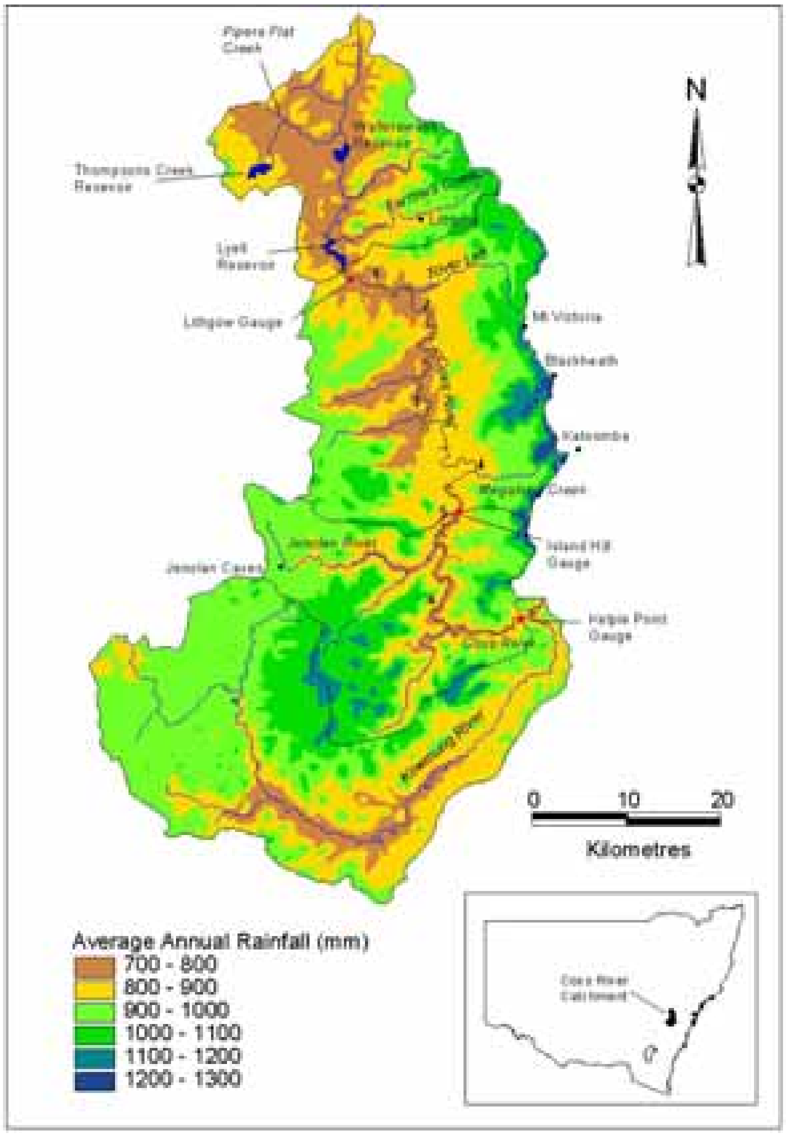


**Figure 2:** 100mm isopleths for the Coxs River catchment from ANUCLIM (MacMahon *et al.*, 1995). ANUCLIM is software package which uses all available climate and topography data and interpolation routines to allow prediction of spatial patterns in climate variables.

## Current river condition

The following sections summarise the current condition of the lower Coxs River, and where possible identify the major changes that have led to this condition. While ideally this would be presented as a fully integrated picture of the ecological 'health' of the river, there are two major impediments to such an approach. Firstly, there is no generally accepted method to combine the range of physical, chemical, and biological measures that describe river condition into an integrated measure or indicator of overall ecological health (Norris and Thoms, 1999). Secondly, the limited data on many aspects of river condition, the wide range of natural and human-influenced changes that have occurred in the river and its catchment, the complex interactions between the different physical and biological components of the system, and the spatial and temporal variability of all of these variables, make it extremely difficult to make defensible cause and effect statements. The following description of the current river condition is therefore divided into the following four sections: (i) hydrology, (ii) geomorphology, (iii) water and sediment quality, and (iv) riverine plants and animals.

### Hydrology

The three main factors that have affected the flow regime of the lower Coxs River in historical times are as follows: (i) land clearing in the upper and central parts of the catchment; (ii) regional climatic variations; and (iii) the construction and operation of Lyell Dam.

The change in land cover from native forests to pasture in parts of the catchment has probably altered runoff generation because evapo-transpiration is lower from grassland than from forest. Holmes and Sinclair (1986) analysed rainfall-runoff relationships for 19 large Victorian catchment with mean annual rainfall in the range 500-1500mm, and established empirical relationships between mean annual rainfall and mean annual evapo-transpiration for both grassland and eucalypt forest. The 'Holmes-Sinclair' relationship predicts than the mean annual runoff in an area with 900-1000mm mean annual rainfall is three-times higher from grassland than from native forest.

For the areas contributing to the three locations used in the hydrological modelling (immediately downstream of Lyell Dam, Island Hill and Kelpie Point) the respective values for the extent of grassland are 45%, 51%, and 2% (Figure 1). Using these values and the spatially averaged mean annual rainfall values in the Holmes-Sinclair relationship leads to estimates of the respective mean annual runoff depths for these three incremental areas (Table 1). Hydrological modelling of the flow regime without the Coxs River water supply scheme ('without-scheme') also allows estimates of the mean annual runoff depth for these areas (Table 1).

| Location | Annual Runoff (mm) | | |
|---|---|---|---|
| | Complete forest cover (HSR) | Current land cover (HSR) | Without-scheme flow regime (IQQM) |
| Below Lyell Dam | 62 | 141 | 133 |
| Island Hill gauge | 91 | 191 | 100 |
| Kelpie Point gauge | 108 | 112 | 187 |

**Table 1:** Comparison of the mean annual runoff depths for incremental areas of the Coxs River catchment estimated using the Holmes-Sinclair relationship (HSR) and the DLWC Integrated Quantity and Quality Model (IQQM).

While the catchment was probably not completely forested before European settlement, the HSR predicts major increases in runoff due to reductions in forest cover. Because rainfall and clearing are not uniform across the catchment, the HSR suggests that there will be substantial spatial differences in runoff. Results from IQQM also indicate differences in runoff between different parts of the catchment. However, the spatial pattern predicted by IQQM is different from that predicted by the HSR. IQQM, which uses historical rainfall and river flow data, suggests the highest runoff occurs between Island Hill and Kelpie Point and the lowest runoff occurs between Lithgow and Island Hill. This pattern cannot be explained by differences in land cover alone, and may reflect differences in soils types and topography which can strongly influence runoff generation processes. Because of natural spatial differences in runoff across the catchment, it is difficult to quantify the increases in runoff that have occurred because of changes in land cover after European settlement.

Substantial climatic variations have been identified in the hydrological records for the Hawkesbury-Nepean catchment (eg. Warner, 1994), and these will have influenced flows in the Coxs River. These climatic variations have been interpreted as flood- and drought-dominated regimes (eg. Warner, 1994, Erskine and Warner, 1998). For the Coxs River catchment these climatic variations are illustrated in Figure 3 which shows the rainfall residuals at Lithgow. On Figure 3, a negative slope indicates a drier-than-average period, and a positive slope indicates a wetter-than-average period. Hence for this record, 1894 to 1945 is considered to be a drought-dominated period, and 1946 to the present is considered to be a flood-dominated period. Flood frequencies and magnitudes are significantly higher in the flood–dominated period. For example, mean annual floods (2.33 year recurrence interval) during flood-dominated periods can be up to double the mean annual floods during drought-dominated periods.

Construction of Lyell Dam was completed in 1982 and the reservoir was operated transparently (no diversions) until 1991. The effects of the dam on the downstream flow regime were minor during this period. Total flow volumes would have been slightly reduced by evaporation from the reservoir, and the reservoir would have modified the shape of flood hydrographs. The storage volume of a reservoir increases the time taken for floods to pass downstream, thus transforming short, steep inflow hydrographs, into longer, flatter outflow hydrographs.

In 1992 water extraction from the reservoir increased, greatly modifying the flow regime immediately downstream. The simulated median and mean daily flows for the without-scheme and current flow conditions are shown for the three locations used in the hydrological modelling in Table 2, and the percentage flow recovery (current relative to without-scheme) plotted as a function of distance from the dam in Figure 4. The mean flow values indicate the reductions in total flow volumes, but are heavily influenced by the very high flows. The reductions in median flows better indicate the extent of the change in 'typical' flows. Both statistics indicate that while flows immediately below Lyell Dam are much reduced, the degree of impact declines with distance downstream in an approximately linear fashion.

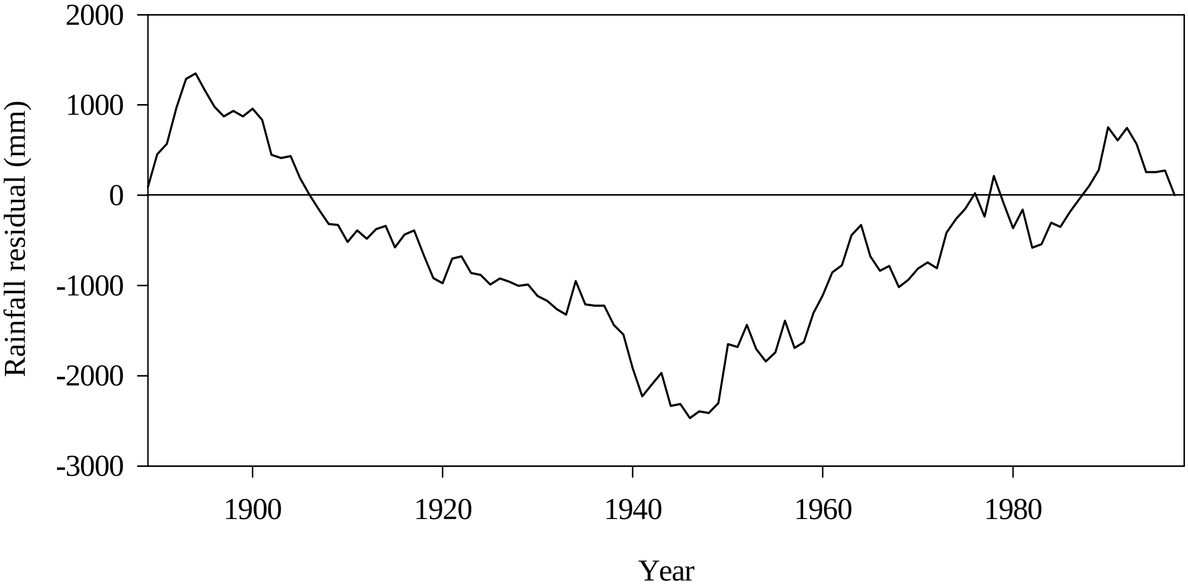


**Figure 3:** Rainfall residuals at Lithgow for the period 1889 to 1997.

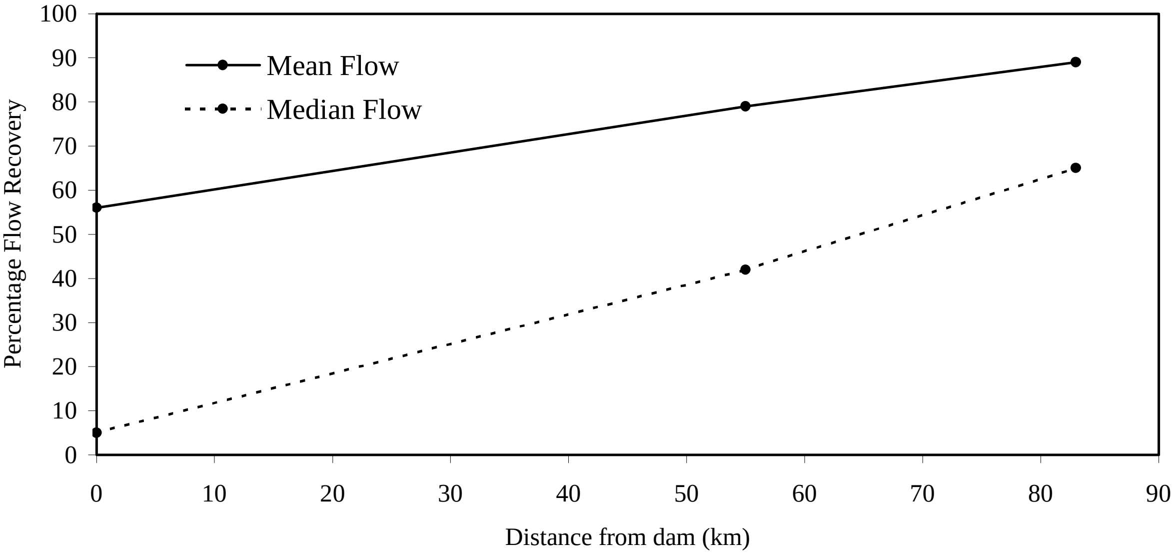


**Figure 4:** Percentage flow recovery (relative to without-scheme) as a function of distance from Lyell Dam.

| | Mean Flow | | | Median Flow | | |
|---|---|---|---|---|---|---|
| Location | Without-scheme | Current | % reduction | Without-scheme | Current | % reduction |
| Lyell Dam | 139 | 78 | 44 | 53 | 3 | 95 |
| Island Hill | 299 | 238 | 21 | 94 | 40 | 58 |
| Kelpie Point | 549 | 488 | 11 | 162 | 106 | 35 |

**Table 2:** Modelled mean and median daily flow values (ML/day) for the without-scheme and current flow regimes for the three locations used in the hydrological modelling.

The daily flow duration curves in Figure 5 compare the modelled without-scheme and current flow regimes at the three locations used in the hydrological modelling. Immediately downstream of the dam there has been a major reduction in flow variability (for nearly 80% of the time the flow is 2.6ML/day), with most flows greatly reduced in magnitude. At this location, even the highest flows are reduced, although this is difficult discern on the logarithmic scale. For example, the flow exceeded 0.25% of the time has been reduced by around 30%, and the maximum flow by around 35%. These very high flows are significant for sediment transport as discussed later in the report. The affect of the dam on the flow regime decreases progressively with distance downstream. Other hydrological comparisons are provided in the 'Option Assessments' section of this report.

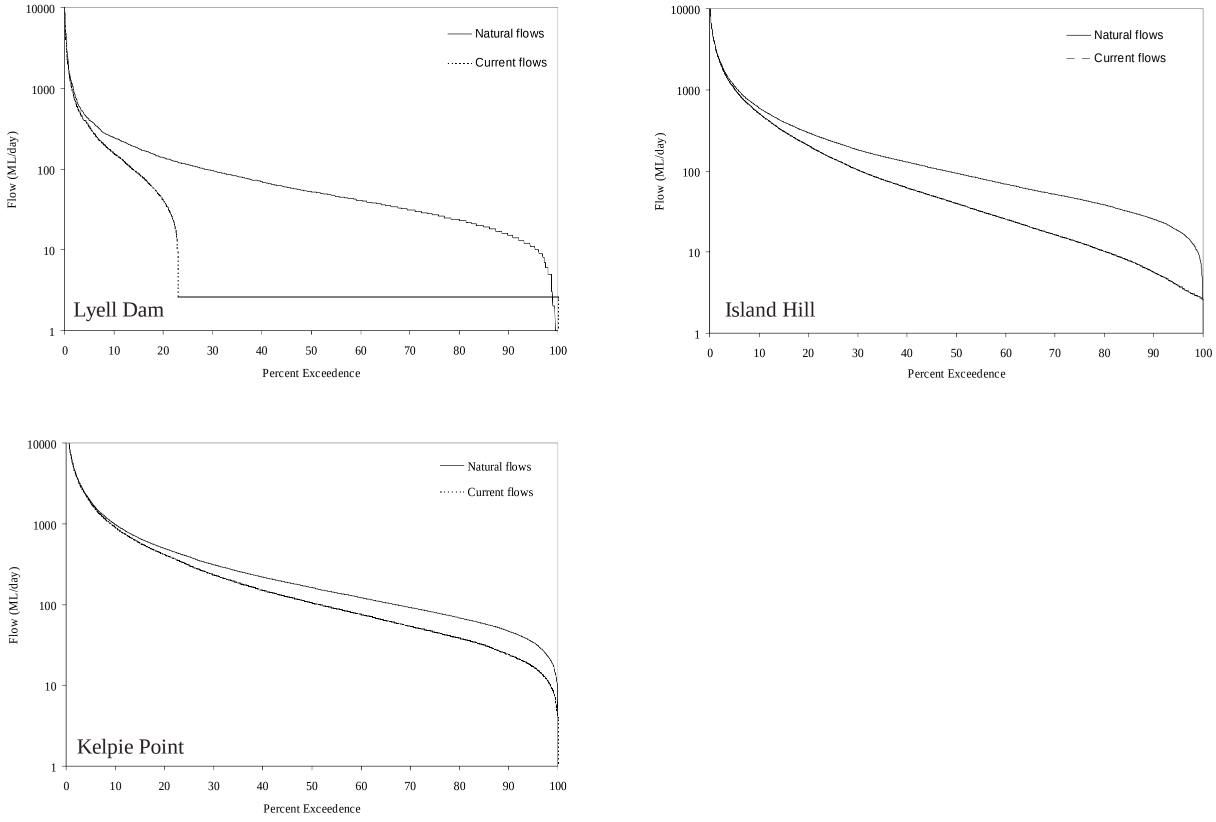
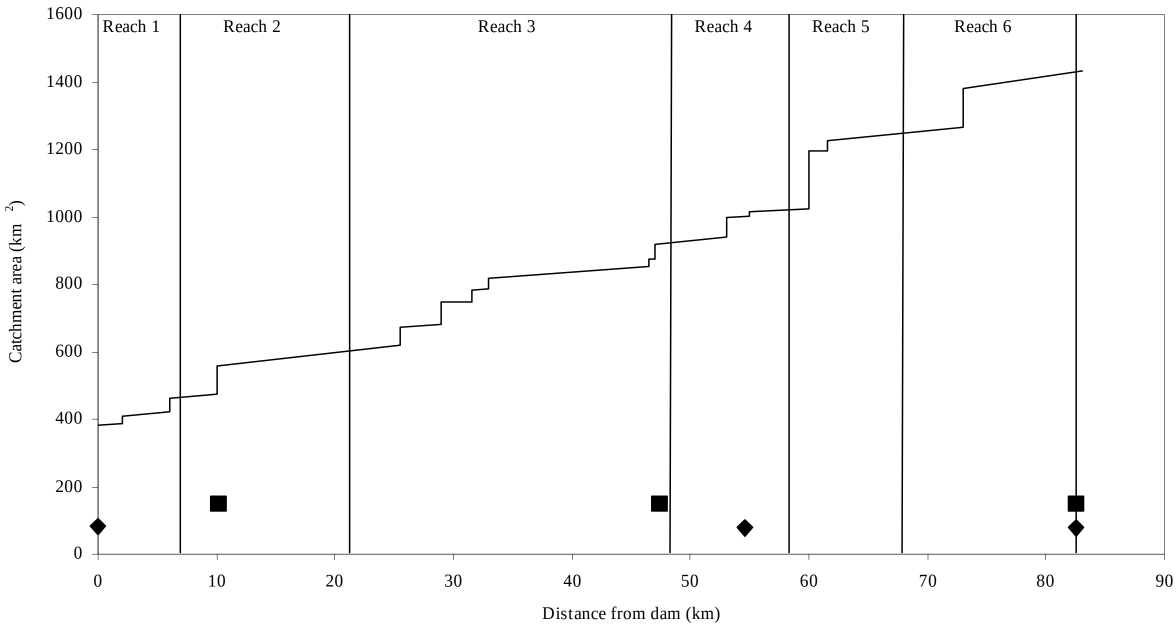


**Figure 5:** Daily flow duration curves based on hydrological modelling for without-scheme and current flow regimes for immediately downstream of Lyell Dam, Island Hill, and Kelpie Point.



F**igure 6:** Cumulative drainage area as a function of distance from Lyell Dam. Also indicated are reach boundaries (for definition see 'Geomorphology' section), the locations used in the hydrological modelling (diamonds), and the location of the flow assessment points (squares). For description of flow assessment points see 'Flow Option Assessment Method' section.

The downstream patterns of flow accumulation are indicated by the downstream increases in drainage area. These are shown in Figure 6, where at each vertical step a tributary enters the main channel. The definition of the river reaches is explained in the 'Geomorphology' section below. Figure 6 also indicates the three locations used in the hydrological modelling.

## Geomorphology

The channel form of the lower Coxs River varies considerably over the 83km from Lyell Dam to Kelpie Point as a function of the past and present river flow regimes (discussed above), the channel gradient, and the sediment supply to the river. Flow, and the sediment transported by the flow, control the river's planform (channel shape as seen from above), the size and shape of the channel cross section, the characteristics of the floodplain, river bedforms (bars, pools and riffles), and the nature of the sediments that form the channel bed. Channel slope strongly affects the sediment transport of the river, and so major changes in channel gradient are used to define river reaches below Lyell Dam. A description of these reaches is provided as the end of this section.

### *Gradient*

From Lyell Dam to Kelpie Point channel elevation drops by 590m (Figure 7). The channel gradient over this distance ranges from 0.0016 to 0.1 (Figure 8). The lowest gradient occurs between 38km and 44km downstream from Lyell Dam, between the junctions with Nortons and Chaplowe creeks. From a visual interpretation of the slope variations (Figure 8) six contiguous reaches were defined.

| Reach | Length (km) | Fall (m) | Gradient (m/m) | Drainage area range (km$^2$) | Indicative flow ratio |
|---|---|---|---|---|---|
| 1 | 7.7 | 40 | 0.005 | 381 to 460 | 0.31 |
| 2 | 14.2 | 120 | 0.008 | 460 to 600 | 0.39 |
| 3 | 26.8 | 110 | 0.004 | 600 to 920 | 0.56 |
| 4 | 10.3 | 200 | 0.019 | 920 to 1020 | 0.72 |
| 5 | 9.1 | 60 | 0.007 | 1020 to 1250 | 0.84 |
| 6 | 14.9 | 60 | 0.004 | 1250 to 1452 | 1.00 |

**Table 3:** Length, fall, gradient, drainage area, gauging station, and indicative flow ratio for each of the six reaches in the lower Coxs River. See text for an explanation of the flow ratios.

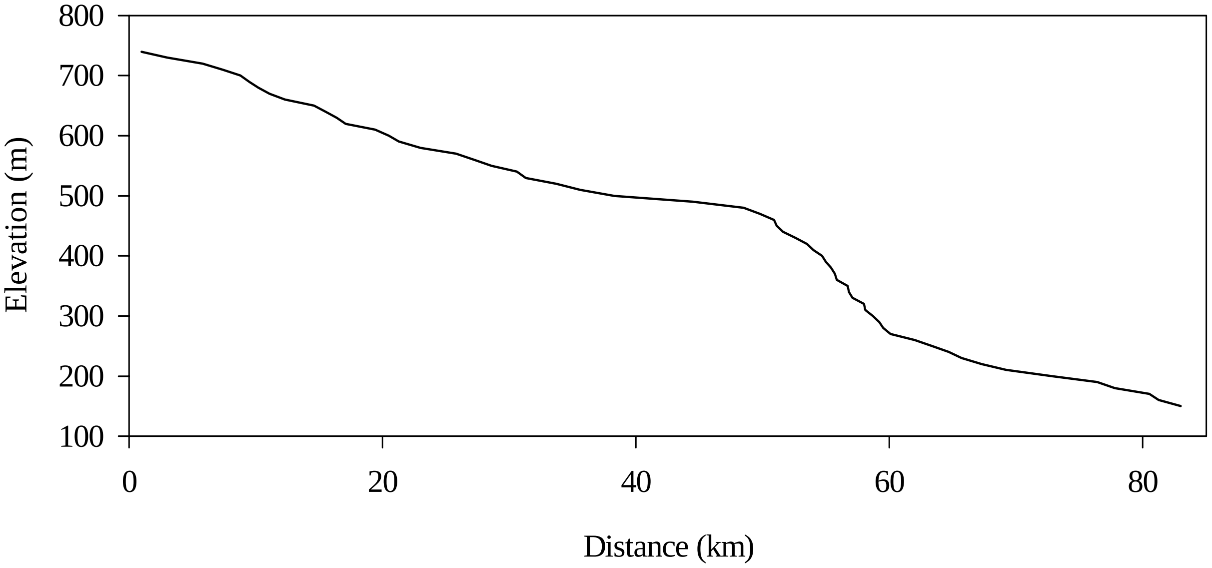


**Figure 7:** Coxs River long profile from Lyell Dam to Kelpie Point.

Attributes of the six reaches are given in Table 3. The indicative flow ratios indicate the approximate differences in the total (or mean) flow between the reaches relative to the flow in Reach 6, based on ratios of average drainage areas. For example, for Reach 1 the average drainage area is estimated as 420.5km$^2$ (mean of 381 at the upstream end and 460 at the downstream end), and for Reach 6 the average drainage area is 1351km$^2$ (mean of 1250 and 1452). The ratio of these values is 0.31.

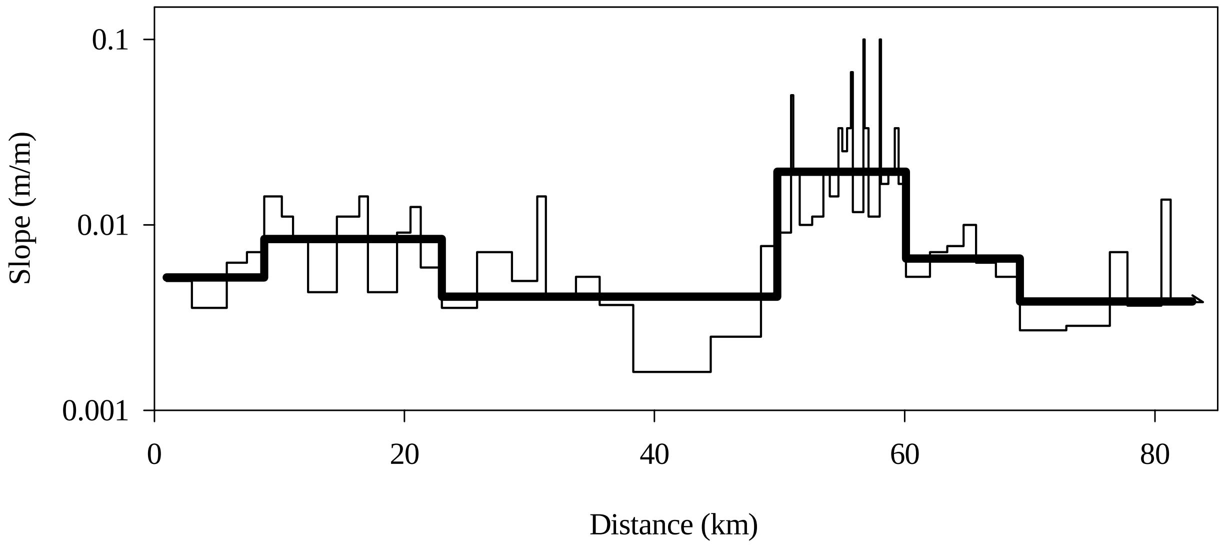


**Figure 8:** Coxs River slope (thin line) as a function of distance from Lyell Dam to Kelpie Point with average reach slopes indicated (heavy line).

### *Sediment Supply*

The three main factors that have influenced the sediment supply to the lower Coxs River in historical times are as follows: (i) land degradation in the catchment, (ii) erosion of the main river channel banks and floodplains, and (iii) the construction of Lyell Dam.

Land degradation has occurred extensively in the upper catchment (above Lyell Dam) and in the mid-catchment (above Island Hill). Changes in land cover (to increased areas of pasture), the effects of fire, increases in rabbit populations, and the impacts of stock, have all contributed to land degradation. In many areas of land degradation, particularly along the steeper mid-catchment tributaries, extensive gully networks have developed. Gully incision generally occurs as a result of a lowering of the shear stress required for erosion (Prosser and Winchester, 1996), which results from the combined effects of heavy grazing, trampling, and in some cases fire. There are 68km of gully and stream bank erosion in the upper catchment (31% of the catchment total), concentrated in Pipers Creek sub-catchment. In the mid-catchment to Island Hill there are 129km (59% of the catchment total), in the lower catchment to Kelpie Point there are 18km (8% of the catchment total), and in the catchment of the Kowmung a mere 3km (around 1% of the catchment total).

Lyell Dam traps all but the finest sediment eroded from the upper catchment, and so the current sediment supply to the river below the dam and downstream to Kelpie Point is delivered from the mid-catchment tributaries. Nonetheless, much of the sediment derived from the gully erosion in the upper catchment before dam closure is likely to have been transported at least as far the flatter reaches downstream from the dam. The gully networks in the mid-catchment tributaries have introduced large volumes of sand to the Coxs River channel. The densest gully networks in the mid-catchment occur in the tributaries that enter in Reach 3 between Grants Creek and Megalong Creek. The total length of upstream gully networks increases from around 31km to around 143km along this section. The cumulative tributary gully length through the mid-catchment of the Coxs River is shown in Figure 9.

Assuming a conservative gully cross section width of 1m, and a conservative depth of 1.5m, the volume of gully-derived sediment delivered to the river between the dam and the downstream end of Reach 3 is 214,500m$^3$. Head-cutting of these gullies has now largely ceased. This generally occurs either once gullies reach underlying bedrock, or once the gully reaches an equilibrium bed slope than prevents further gully bed erosion. Nonetheless, it is expected that these gullies are still delivering higher sediment loads to the main channel than occurred before their formation, because of sidewall erosion. These assumptions of gully evolution and their patterns of sediment yield are based on extensive work in other locations (eg. Wasson *et al.*, 1998).

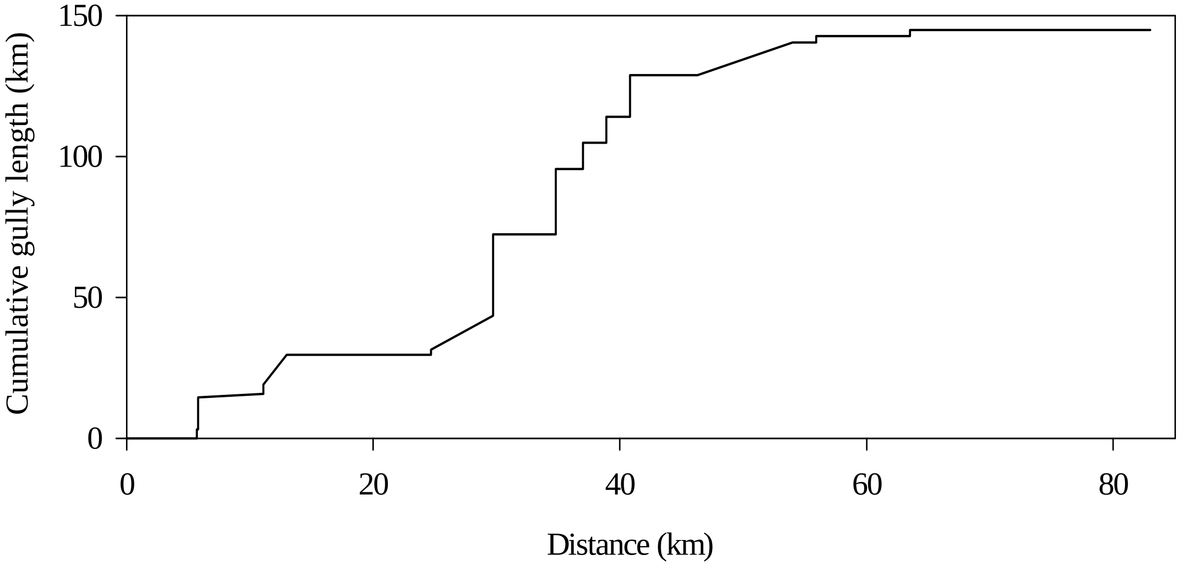


**Figure 9:** Cumulative total gully length (km) from Lyell Dam to Kelpie Point.

Surface erosion is also occurring in the Coxs River catchment. From Caesium-137 concentrations in the surface layers of sediment in Lake Burragorang, Fredericks (1994) estimated that as much as 25% of the contemporary sediment delivered to the Coxs River arm of the lake was derived from erosion of surface soils in the Coxs River catchment. The spatial patterns of surface erosion in the Coxs River catchment have not been assessed reliably. However, the potential for higher runoff and reduced cover in some pasture areas suggests that the upper catchment and the mid-catchment above Island Bend are likely to be the major source areas.

The flow regime shift in the mid-1940s – from a drought-dominated to a flood-dominated regime – led to the formation of flood chutes and extensive stripping of floodplain sediments along the Coxs River. These processes delivered large volumes of alluvial sand to the main channel, as well as widening the channel. However, because the channel margins are so resistant, the dominant source of remobilised sediment was alluvium stripped from the floodplain by high flows.

In summary, sediment supply to the Coxs River has increased since European settlement, in particular as a result of gully erosion following land degradation, and as a result of floodplain alluvium stripping following a flow regime shift. Lyell Dam is an efficient sediment trap for sediments eroded from the upper catchment. The first 5km downstream of the dam are starved of sediment (Figure 9), but from 25-45km downstream from the dam large volumes of gully-derived sediment have been delivered to the river.

### *Sediment Transport Capacity*

The sediment transport capacity of the river can be estimated as a function of the flow regime and the channel slope. From a review of many sediment transport studies, Prosser and Rustomji (2000) conclude that the sediment transport capacity is best predicted as a function of discharge to the power of 1.4 multiplied by slope to the power of 1.4. The sediment transport capacity of a river reach over a given time period is therefore proportional to the sum of the products of daily discharge (raised to the power 1.4) and channel slope (raised to the power of 1.4) as shown in Equation 1.

$$Q_s \propto \Sigma Q^{1.4} S^{1.4} \qquad \text{Equation 1}$$

Qs is sediment transport capacity, Q is discharge, and S is channel slope.

Using the flows simulated by IQQM the mean annual transport capacity at each of the locations used in the hydrological modelling can be calculated for the current and the without-scheme flow regimes. Linear interpolations between these values based on incremental drainage areas allows prediction of the downstream patterns in sediment transport capacity (Figure 10).

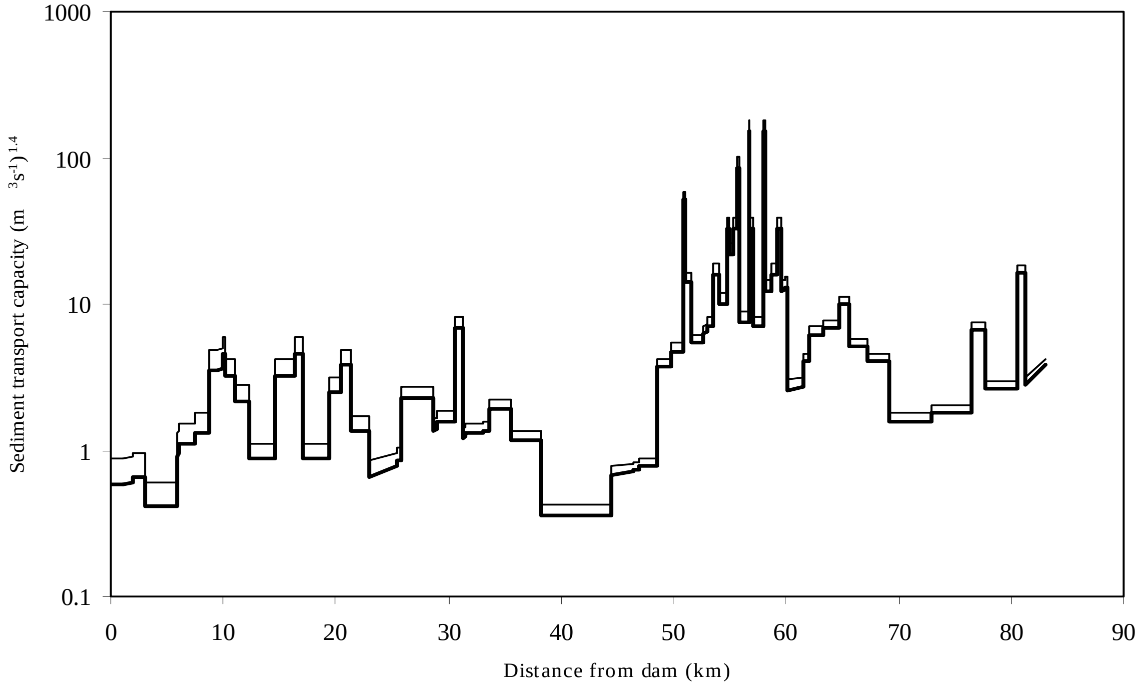


**Figure 10:** Sediment transport capacity as a function of distance from Lyell Dam for the current (heavy line) and the without-scheme (upper line) flow regimes.

Figure 10 shows that the sediment transport capacity of the Coxs River below Lyell Dam varies by nearly three orders of magnitude, mainly because of variations in channel slope rather than increases in discharge. The reductions in sediment transport capacity from the without-scheme flow regime to the current flow regime are also small relative to the downstream variations due to channel slope. The percentage reduction in sediment transport capacity is seen to decline with distance downstream as the percentage reduction in flow becomes less. Within any given reach however, the reductions in sediment transport capacity due to flow reductions are substantial. For example, in the first reaches below the dam the sediment transport capacity has been reduced by about 35% by flow abstraction and regulation.

Sediment deposition occurs when sediment supply is in excess of sediment transport capacity. Because of a lack of detailed hydraulic data it is not possible to compare the actual volumes of sediment supplied to the channel with actual volumes moved. However, a qualitative assessment is possible. In the steeper reaches, even the current flow regime (with its reduced transport capacity) is competent to transport the increased sediment load. In contrast, in the flatter reaches, even the without-scheme flows are not competent to transport the increased load. The reduced transport capacity in these reaches will mean a longer period will be required to flush out the sediment which has been deposited in these reaches, even though the current sediment supply is lower than during the period of most active gully erosion.

### *Channel Form*

After several decades, three distinct zones of channel adjustment typically emerge downstream of diversion dams in alluvial rivers (Petts, 1977). The first is a scour zone, where sediment-deficient flows remove finer materials from the channel bed and banks until they become armoured with coarser gravels preventing further channel erosion. The second is a zone of channel reduction, where although the relative reduction in flow is diminished by tributary inflows, channel adjustment occurs in response to smaller channel-forming discharges. Tributary sediment and material from the scour zone are reworked to produce benches that may become a new “inset” floodplain. With increasing distance from the dam, its downstream impacts on channel adjustments diminish. The third zone is one of no change, beginning where channel reduction is no longer apparent. Some of these typical adjustments can be observed in the lower Coxs River. However, the short period of adjustment since dam closure (17 years) and since diversion began (8 years), and the bedrock-boulder (rather than alluvial) nature of the channel immediately below the dam mean the downstream changes are less pronounced. Furthermore, as described above, the unusually high mid-catchment sediment inputs which were mostly delivered to the channel before dam closure, have had a greater impact on the geomorphic condition of the river channel than dam closure. The nature and condition of the six river reaches are described below.

**Reach 1** is a wide (80-100m) bedrock-boulder valley-floor trough with a channel of variable width and depth. It is characterised by long cobble-bedded shallow pools, with occasional sand patches, but very few riffles. Some cobble armouring of sand bars has occurred. Downstream hydraulic control on the pools are provided by bedrock and boulders. The marginal alluvial stores are dominated by parallel chutes and stripped alluvial stores. Sand is present in the channel immediately downstream of tributaries indicating supply source areas. The initial transparent operation of the dam meant that this reach received essentially a natural flow regime, but no sediment. In an alluvial channel this would have resulted in the formation of a significant scour zone immediately downstream of the dam. However, on the Coxs River this reach is a confined bedrock-boulder channel and the flow regime shift in the 1940s had already stripped most of its alluvial stores. Consequently, the dam has caused minimal geomorphic degradation of the channel in this reach. The lack of sediment supply means, however, that this reach is now geomorphologically inactive.

**Reach 2** is a multi-phase active anastomosing channel (multiple stable channels) in a valley-floor trough up to 200m wide. The channel is characterised by large numbers of short pools with extensive bedrock exposures. The bedrock is more prominent at the lower end of the reach, as are larger pools – some deeper than 2m. Pools account for an estimated 60-70% of the channel. Most fast-flowing areas are cascades over bedrock and large boulders. Channel banks have been stripped of alluvium to a greater extent than in Reach 1, with channel banks formed from large cobbles, boulders and sand. Channel narrowing as a result of the dam is not evident.

**Reach 3** is the second low gradient reach, with a slope similar to that of Reach 1. The lowest local gradient along the river – 0.0016 – is in this reach. Its tributaries are heavily gullied and much sand is in the channel. The channel is generally less confined than that upstream, being at its widest at Sandy Hook. This reach is severely impacted on by gully-derived sediment, masking any minor channel adjustments that may have occurred because of the presence and operation of Lyell Dam.

**Reach 4** is the steepest reach with a fall of 19m per km. It is predominantly a confined bedrock-boulder channel with little or no stored alluvium. The local gradients along this reach can exceed 0.1. Sediment transport, particularly of sand, is expected to be highly efficient in this reach.

**Reach 5** is the second of the steeper reaches. It is characterised by some rapids and sand stores adjacent to the channel near tributary junctions.

**Reach 6** is the third of the low gradient reaches – its lowest gradients being less than 0.004. Much sand is in the channel in spite of the heavily forested nature of the surroundings.

### Water quality

The physical and chemical characteristics of river water are a key determinant of ecological condition. Important variables include water temperature, pH, availability of dissolved oxygen, suspended sediment, carbon, nitrogen, phosphorus, and the major and minor cations and anions. These variables can be affected by changes in land use (including extent of urban areas and hence volumes of sewage effluent), land management (for example, stocking rates), and the presence of dams and reservoirs. Land use and management determine the loads of materials entering the river system, while reservoirs interrupt the transport and affect the transformations of the these materials. In the lower Coxs River catchment, changes in land use, increases in human and farm animal populations, and the presence of  Lyell Dam have changed the water quality in the river.

Data sourced from Jones (1992) for the period 1962-1990 and data collected by Australian Water Technologies for the period 1998-1999 allow an assessment of the general quality of water in the Coxs River and storages. These data were collected from two sites on Lake Wallace, one site on Farmers Creek (an inflow to Lake Lyell), five sites on the Coxs River below Lake Lyell, and six sites on tributaries that enter the Coxs River below Lake Lyell. Most measurements were reported without associated flow values, and in these cases the data have been interpreted without a knowledge of the associated flow conditions, and only concentrations, not loads, of dissolved and suspended materials are available. As the data were not available in an electronic form it was not practical to undertake new analyses; the interpretations below are based on inspection of the available graphical and statistical summaries of the data.

While there is no downstream trend in water quality. The best water quality occurs at Kelpie Point and in the river's headwaters. Nutrient concentrations and faecal coliform counts vary in the downstream direction, most probably as a function of the inputs from tributaries with differing levels of change to the natural land cover. Other water quality variables do not change appreciably along the length of the river.

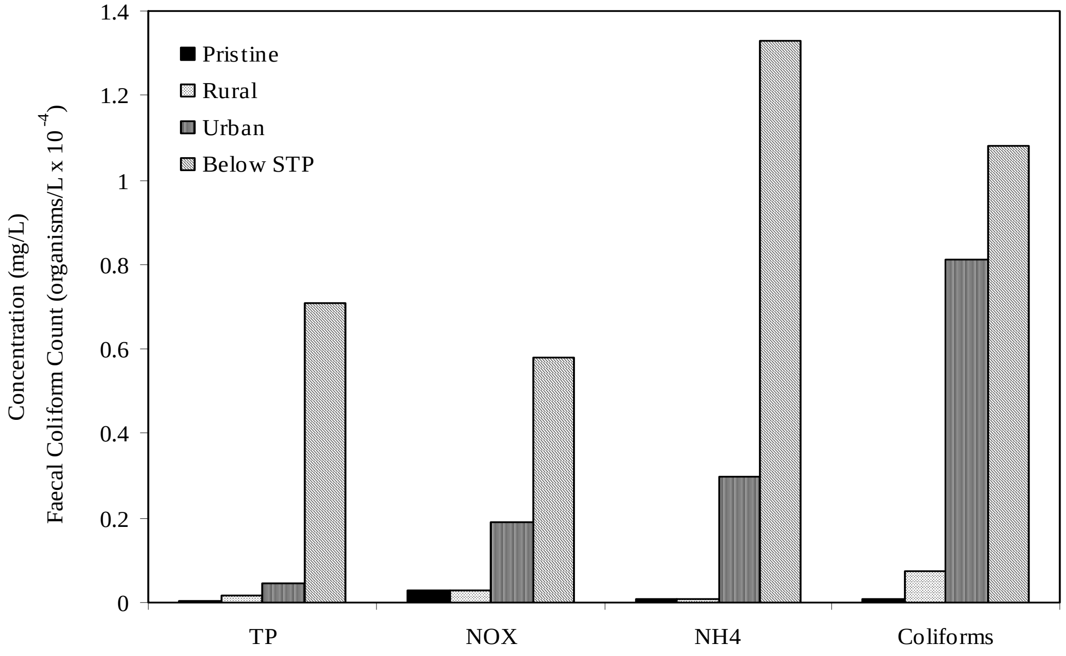


**Figure 11:** Typical water quality levels in Coxs River and tributaries (after Jones, 1992).

In general, nutrient concentrations and faecal coliform counts in the river are higher than those found in near-natural Blue Mountains streams (Jones, 1992; Growns *et al.*, 1995). Faecal coliform levels exceed the 150 organisms/100mL limit recommended for primary contact recreation (ANZECC, 1992). Most of the high nutrient concentrations were recorded during high flows. The main nutrient sources are assumed to be agricultural non-point sources and sewage treatment effluents (Figure 11). A large increase in phosphorus concentration occurs below Farmers Creek – presumably because of the inputs from the Lithgow sewage treatment plant. Total phosphorus concentrations at Kelpie Point are higher than those in near-natural Blue Mountains rivers, and high enough to cause the greater than natural levels of algal growth observed in the river. The high faecal coliform counts are primarily attributable to sewage effluent. Those occurring upstream of the sewage treatment plant are probably a result of sewage overflows and leaking sewers (Jones, 1992).

Turbidity, concentrations of suspended particulate matter, and conductivity, were highly variable through time and across sites, and generally indicative of a disturbed catchment. Higher values generally occurred at sites downstream of catchment disturbance including urbanisation, road construction, erosion resulting from land degradation, and grazing on river banks.

The pH at all sites was within the range (5-9) considered safe for aquatic life (ANZECC, 1992). The high pH values (>8.5) are likely to be a result of algal growth (which decreases the amount of carbon dioxide in the water), and the low pH values which were recorded in the upper catchment are likely to be a result of acid mine drainage. Two sites on the lower Coxs River had minima of 0.2mg/L of dissolved oxygen indicating oxygen depletion, probably as a result of a high organic material load. The recommended minimum oxygen concentration to protect aquatic life is 4mg/L (ANZECC, 1992).

| Variable | Pre-dam 1980-83 | Post-dam 1989-93 |
|---|---|---|
| Ammonia (mg/L) | 0.14 | 0.04 |
| Total phosphorus (mg/L) | 0.196 | 0.025 |
| Nitrate/nitrite (mg/L) | 1.46 | 0.2 |
| Non-filterable residue (mg/L) | 18.5 | 4.5 |
| Turbidity (NTU) | 5.0 | 1.9 |

**Table 4:** Comparisons of pre- and post-dam median values for some water quality variables 400m downstream of Lyell Dam. Data provided by Pacific Power International.

The influence of Lyell Dam on river water quality are indicated by data from a three year pre-dam period (1980-1983) and a four year post-dam period (1989-1993) at a site 400m downstream from the dam (Table 4). Median values of turbidity, and concentrations of suspended particulate matter (measured as non-filterable residue) and nutrients have all decreased markedly since dam construction, probably because of settling and assimilation processes, and dilution (mixing) of upstream point sources. Ratios of total nitrogen to total phosphorus indicate that primary production in the river at this site is nitrogen limited (cf. Chessman *et al*., 1992).

The data for other water quality variables from this site indicate that pH, conductivity and the concentrations of major cations and anions have not been affected by dam construction. Increases in conductivity occurred during 1981-83, but are probably a result of low flows rather than dam construction. Releases from Lyell Dam are of surface waters via an off-take tower, and dissolved oxygen data from AMBS (1999) indicate that releases from the dam are well aerated. The limited water temperature data suggest that the surface water releases mimic the natural seasonal pattern of water temperature in the river.

### Sediment quality

The chemical quality of the fine sediments in the river system affects instream habitats and so influences ecological condition. Various pollutants – particularly metals and hydrocarbons – can accumulate in fine river sediments and affect the health of the stream ecosystem. A comprehensive survey conducted by AWT (1994) indicated that most trace metal concentrations (arsenic, cadmium, chromium, copper, lead, nickel and tin) were below ANZECC/NHMRC (1992) guidelines for concentrations of metals in contaminated soils. Nine out of the 46 sites sampled had zinc concentrations exceeding the ANZECC criterion – mostly in the upper Coxs River catchment. The highest concentrations of reactive zinc were found in sediments from Marrangaroo Creek and Blackmans Creek. Most of the 46 sites had manganese concentrations exceeding the ANZECC criterion, again in the upper catchment of the Coxs River.

Organochlorines were detected in sediments – a result of insecticide use in the catchment. Petroleum hydrocarbons were also detected in most sediments, probably from atmospheric fall out, although at one site in Neubeck Creek the high concentrations were probably caused by inputs from adjacent coal-based industries. Phenol compounds were not detected in sediments. High concentrations of polycyclic aromatic hydrocarbon (PAHs) were found in Merisine Creek, Farmers Creek, Neubeck Creek and the River Lett; these probably originated from urban runoff, treated sewage, and drainage from a disused shale-oil refinery and from coal industries. PAHs may be being transported with sediments to Lake Burragorang.

### Riverine plants and animals

The riverine plants and animals of the lower Coxs River are described below based on field inspections of most of Reaches 1 and 2 and parts of Reach 3, as well as reference to existing data sets (AMBS, 1995; AMBS, 1997; AMBS, 1999; Booth *et al*., 1998; Gehrke and Harris 1996; Harris and Gehrke 1997; Gehrke *et al*., 1999).

The riparian zone of the lower Coxs River has a tree layer dominated by river oak (*Casuarina cunninghamiana*) near the water's edge and on bars and benches, and by *Eucalyptus* species on the adjacent hillslopes. In Reach 1, two age cohorts of river oak are evident, with large mature trees (50+ years), and occasional stands of younger plants (2-10 years old) on alluvial banks. In Reach 2, the older trees are possibly 70-80 years old, and several different cohorts are present in the regeneration areas – around 3, 5, and 10 years. In Reach 3, the riparian vegetation has been more extensively cleared. In Reaches 1 and 2, the roots of the older trees have been exposed by the stripping of surface alluvium. Occasional deposits of large woody debris – sometimes occurring as large debris dams – occur in the channel and on the floodplain.

Willows – mainly *Salix fragilis* – have invaded the channel and riparian zone, forming dense stands in some places. They contribute substantial leaf litter and large woody debris to the stream, sometimes forming small debris dams. Willows occur in isolated patches at the top end of Reach 1, and as dense clumps at the lower end – just upstream of McKanes Bridge. In Reach 2, extensive willow growth includes several very large trees. Some have been dislodged by high flows, and form dams with obvious effects on channel migration. In Reach 3, extensive willow stands are disrupting the water flow downstream of Duddawarra Bridge.

The original riparian shrub layer was probably dense, but has been reduced by cattle grazing and perhaps burning. In places an understorey of native genera such as *Acacia*, *Callistemon*, *Leptospermum*, *Lomatia* and *Bursaria* remains, but invasion by alien species such as blackberry (*Rubus fruticosus*) and broom (*Genista* sp.) is widespread. Broom is widespread downstream of Jock's Creek in Reach 1, and small patches occur in Reach 2. Blackberries are extensive throughout the first three reaches below the dam. The riparian ground layer consists of a complex mixture of native and alien forbs, herbs and grasses; in Reach 2 there are many herbaceous weeds.

In the channel and at its margins a wide range of emergent reeds, rushes and sedges occurs. Genera include *Carex*, *Cyperus*, *Juncus*, *Lomandra*, *Phragmites*, *Schoenoplectus* and *Typha*. In Reach 1 the edge vegetation – from the non-flooded portion of the channel to the bank – is dominated by emergent aquatic plants (*Lomandra*, *Juncus*, and *Carex*) with very few submerged or amphibious plants. In Reach 2 the edge has less tea-tree and other native shrubs than upstream, with extensive clearing of understorey. However, the steeper bedrock sections contain abundant shrub layers of *Leptospermum*, *Lomatia*, *Acacia dealbata* and *A. melanoxylon* and some *Callistemon*. *Lomandra* and *Carex* are present throughout the reach, and some emergent and amphibious aquatic plants such as *Cyperus*, *Typha*, *Phragmites*, *Juncus*, *Limosella australis*, *Ranunculus*, *Hydrocotyle,* and *Veronica* occur. Cattle are expected to be a significant influence on vegetation condition in this reach.

Floating and submerged species are low in abundance in the lower Coxs River, but include the native curly pondweed (*Potamogeton crispus*) and the alien Canadian pondweed (*Elodea canadensis*). Few aquatic plants were observed in Reach 1, while in Reach 2 one small patch ($10m^2$ )of *Elodea canadensis* was observed in 0.5m depth of water. In Reach 3 some *Myriophyllum* and other emergent and submerged aquatic plants were observed, although benthic edge vegetation was less.

Much of the river bed is coated with an algal-detrital matrix including extensive diatom growth and some cyanobacterial mats. Filamentous diatoms (eg. *Melosira),* and strand-forming filamentous green algae (*Cladophora* or *Rhizoclonium* species) may form massive growths in some areas, especially in conditions of high light, temperature, and nutrients, and reduced flow. Algal growth in the river has almost certainly been increased by nutrient enrichment from sewage and agricultural runoff, and probably makes a substantial contribution to the energy base of the river ecosystem. These attached algae were widespread in all reaches during field inspections, with rocks and *Casuarina* needles the most common substrata.

The macroinvertebrate fauna – worms, molluscs, mites, crustaceans, and insects – is diverse, but lacks some of the pollution-sensitive and flow-obligate species that would be expected to occur in the river under natural conditions. As a result of pollution and flow reduction, the invertebrate food web has probably been somewhat simplified. The fauna includes large numbers of rather generalised herbivorous-detritivorous species such as midge larvae.

The fish fauna is limited to seven species, and of the native species only one – the flat headed gudgeon (*Philypnodon grandiceps*) – is common. The large predatory fish in the river are native long-finned eels, *Anguilla reinhardti*, introduced brown trout and rainbow trout (*Salmo trutta* and *Oncorhynchus mykiss*). Relatively high summer temperatures probably limit the trout population, and trout in turn have probably suppressed the native mountain galaxias – *Galaxias olidus* – which is now rare. Introduced gambusia (*Gambusia holbrooki*) is the most abundant fish species. This species gives birth to live young, and rapidly produces large local populations over summer. Numbers often decline during winter when temperatures fall. Anecdotal accounts suggest that other fish species such as Australian bass, Macquarie perch and mullet may once have inhabited the lower reaches of the river. The presence of Warragamba Dam downstream now prevents upstream migration of Australian bass and mullet. Macquarie perch require clean gravel for spawning and have undergone a severe decline through most of their range, although local populations appear to be thriving elsewhere in the Hawkesbury-Nepean River system.

Waterfowl use the riparian corridor and some frog species have been recorded. Water dragons (*Physignathus lesueurii*), tortoises (*Chelodina longicollis*), native water rats (*Hydromys chrysogaster*) and platypus (*Ornithorhynchus anatinus*) also inhabit the river.

An important determinant of the ecological condition of the river is the degree of connectivity – both longitudinally through the river system, and laterally, between the river channel and its benches and narrow floodplains. Connectivity determines the patterns and amounts of sediment and nutrient transport both downstream, and to and from the riparian and floodplain areas. Longitudinal connectivity allows fish to move through the system, and allows the downstream transport of seeds, spores, and smaller biota such as algae, and invertebrates. Changes in connectivity occur because of the presence of dams and weirs, changes in flow levels, and changes in channel dimensions. In the lower Coxs River the longitudinal connectivity is disrupted at the bottom end by Lake Burragorang, and at the top end by Lyell Dam. Lateral connectivity is likely to have been reduced by the reduction in flood frequency.

### Summary of current river condition

| | |
|---|---|
| **Hydrology** | • Drought-dominated regime 1894-1946; flood-dominated regime 1946-present.<br>• Lyell Dam completed 1982, transparent operation until 1991.<br>• Current operation diverts 44% of Lyell Reservoir inflows.<br>• By Kelpie Point reduction in total flow is 11%.<br>• Current flow regime is less variable: constant base flow is maintained and the peak discharge values of all but the most infrequent floods are reduced. |
| **Geomorphology** | • Channel falls 590m from Lyell Dam to Kelpie Point; slope range is 0.1 to 0.0016.<br>• Gullying in mid-catchment tributaries has delivered large sand load to river.<br>• Largest sand input occurs in reach with lowest slope. Sand transport is low here and sand dominates the channel.<br>• Lyell Dam traps all coarse sediment from upper catchment, depriving first 5km of river below Lyell Dam of sediment.<br>• Many reaches below the dam are dominated by bedrock, creating long pools and stable riffles. |
| **Water Quality** | • pH in the river is within range considered safe for aquatic life.<br>• Nutrient enrichment has led to greater than natural riverine algal biomass.<br>• High faecal coliform counts downstream of Lithgow.<br>• High suspended sediment concentrations indicate catchment disturbance.<br>• Generally low trace metal concentrations in river sediments, but widespread contamination from insecticide residues, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons. |
| **Riverine plants and animals** | • Riparian tree layer dominated by river oak (*Casuarina cunninghamiana*), although willows have invaded many sections.<br>• Original riparian shrub layer has been cleared. Broom present and blackberry now common.<br>• Extensive benthic and filamentous algal growth occurs in the river, enhanced by nutrient enrichment and reduced flows.<br>• Macroinvertebrate fauna is diverse but lacks some pollution-sensitive and flow-obligate species.<br>• Only seven fish species, and only one native species is common. The introduced Gambusia is the most common fish. |

**Table 5:** Summary of current river condition for the lower Coxs River.

## *Improving river condition – opportunities and constraints*

The above summary of the current condition of the Coxs River highlights that many changes have occurred in the catchment that influence the present condition of the river. These include climate changes, land use and catchment activity changes, dam construction, and flow diversion. The legacy of some of these changes will affect the condition of the river for many decades to come, irrespective of improvements in how the river and its catchment are managed. For example, the large loads of sand in the river channel will not be removed in the short term. Other constraints to river improvement are the major dams, both upstream and downstream.

The main avenues, then, by which improvements in river condition can be achieved are rural and urban catchment management, flow management at Lyell Dam to provide a more natural flow regime, and direct control of introduced species, particularly introduced riverine vegetation – willows, broom, and blackberry. To achieve an overall improvement in river condition, all of these avenues should be explored. While the provision of environmental flows should certainly be a key part of a rehabilitation strategy for the Coxs River, environmental flows should be managed in conjunction with catchment and vegetation management activities, rather than in isolation.

A final caution is that because of the considerable variability in climate at the decadal scale, detecting the short to medium term (5-10 years) changes in river condition that result directly from any changes in flow regime or catchment management may be difficult.

# PART II – FLOW OPTION ASSESSMENT METHODS

The methods used to assess the expected environmental outcomes of the different proposed flow options were matched to data availability and constraints on time and resources. The main data made available were the simulated river flows at three locations in the Coxs River downstream from Lyell Dam under each proposed flow option for an 85 year historical rainfall sequence. These simulations were conducted by DLWC using IQQM (Podger *et al.*, 1994). The SRP cautions that the flow option assessments are heavily dependent on these data, and no formal assessment has been made by the SRP of the accuracy of this modelling, nor of the analyses of the modelling results undertaken by DLWC.

The three locations used in the hydrological modelling are not the best basis spatial for flow option assessment. For example, the point immediately downstream of the dam only represents conditions in the river for the first 1-2km, and the Island Hill gauge is in the steep gorge section well downstream of the most impaired reaches. As a basis for flow option assessment three locations were selected to represent the range of flow conditions along the length of the river. The three locations are described in Table 6 and their positions indicated on Figure 6.

The first assessment location is upstream of the River Lett confluence and includes the flow contributions from several small tributaries including Jocks Creek and Lowther Creek. This location is associated with the first two of the geomorphic reaches. The second assessment location is upstream of the Megalong Creek confluence and is in the flattest river reach where extensive sand deposition has occurred. This location is associated with the second two of the geomorphic reaches. The final assessment location is upstream of the Kowmung River. This is at the lower end of the gorge section through the national park; it is associated with the last two geomorphic reaches. The flow values for each option at the first two of these locations were obtained by interpolation between the Lyell Dam and Island Hill flows (from IQQM) according to the ratios of contributing catchment areas. Thus the first point has around 16% of the catchment inflows that occur between Lyell Dam and Island Hill added to the Lyell Dam flows, and the second point has about 84% of the catchment inflows that occur between Lyell Dam and Island Hill added to the Lyell Dam flows.

| Flow assessment location | River distance (km) | Drainage area (km$^2$) | Data source |
|---|---|---|---|
| Upstream of the River Lett | 10 | 476.5 | Interpolation between Lyell Dam and Island Hill flows |
| Upstream of Megalong Creek | 47 | 875.7 | Interpolation between Lyell Dam and Island Hill flows |
| Upstream of the Kowmung River | 83 | 1452.0 | Kelpie Point flows. |

**Table 6:** Flow assessment location descriptions.

Flow data for all options were analysed for each of the flow assessment locations. Analyses were also done for the case of fully transparent dam operation as a reference. Firstly, flow duration curves were prepared; these show the proportion of time a given flow is equalled or exceeded. Secondly, flow spell analyses were done for threshold flows of 10, 100 and 1,000ML/day; these define the periods of time spent above and below each threshold. The average lengths of the periods above and below the threshold, and the average number of periods – or spells – per year, are used to describe temporal flow variability. Thirdly, comparative flow statistics were calculated for each flow option. A statistic was developed to assess the overall hydrological deviation of an option from the transparent flow option. The statistic $M$ is the difference from 1 of the proportional flow deviation, averaged over $p$ daily flow percentile points as shown in Equation 2, where $o$ is the option flow value for percentile point $i$, and $t$ is the transparent flow value for percentile point $i$. To calculate $M$, approximately 3100 percentile points were used. The statistic $M$, gives equal weighting each percentile flow, from the lowest flow to the highest flow.

$$M = 1 - \frac{1}{p} \sum_{i=1}^{p} \left| \frac{o_i - t_i}{t_i} \right| \qquad \text{Equation 2}$$

To provide an indication of how the different flow options affect aquatic habitats in the river, relationships between flow and the wetted perimeter of the channel were developed. Such relationships have been used in defining minimum environmental flows in previous studies (eg. Gippel and Stewardson, 1998). These relationships were developed from data collected by AMBS (1999) and data collected by DLWC as a part of this investigation. Both data sets were less than ideal. The AMBS (1999) data are from a small number of individual cross sections (three sites in Reach 1 and one site in Reach 2) and so are unlikely to capture the variability of flow hydraulics over any significant length of channel. The data collected by DLWC were collected from five sites in Reach 1. At each site a number of hydraulic variables (including wetted perimeter) were sampled randomly across a grid laid over a 100m section of channel. This method has a greater potential to capture the hydraulic characteristics of the channel than measuring individual cross-sections. However, insufficient points data were sampled to adequately characterise channel hydraulics at any one flow, and because of time and resource constraints sampling was not conducted under enough different flow rates to establish a reliable relationship between wetted perimeter and flow. Furthermore, flow rates were not gauged at the sites, but rather were estimated with reference to the Lithgow gauge and rating curve. For this data set, only the flow values for the site near the Lithgow gauge are considered to be reliable.

To obtain the best possible relationship from the available data, the most reliable data from the two sources were combined. The data used were the DLWC data from the site downstream of Jocks Creek and the AMBS (1999) data from the site near McKanes Bridge, the site upstream of the River Lett confluence near Glenroy Bridge, and the site downstream of the River Lett confluence. In each case, the wetted perimeter values from each site were expressed as a proportion of the maximum measured wetted perimeter for the site. This normalisation was necessary as channel widths varied considerably between sites. The relationship for Reaches 1 and 2 (Figure 12) indicates how the relative wetted perimeter changes with flow. It shows that while channel width varied considerably between sites (increasing in size with flow additions), the channel shape was similar between sites.

Using the results from the various hydrological and hydraulic analyses, assessments for each option were made of low flow habitat conditions, moderate flow (freshes) habitat conditions, overall flow regime mimicking, sediment transport and channel form, and water quality in the lower Coxs River and the Coxs River arm of Lake Burragorang. In addition, each option was assessed in terms of how well it met the New South Wales Government River Flow Objectives (EPA, 1999), and how well it met the ‘ecological river management objectives’ agreed to for the Coxs River by the SRP, DLWC, Delta Electricity and local community representatives.

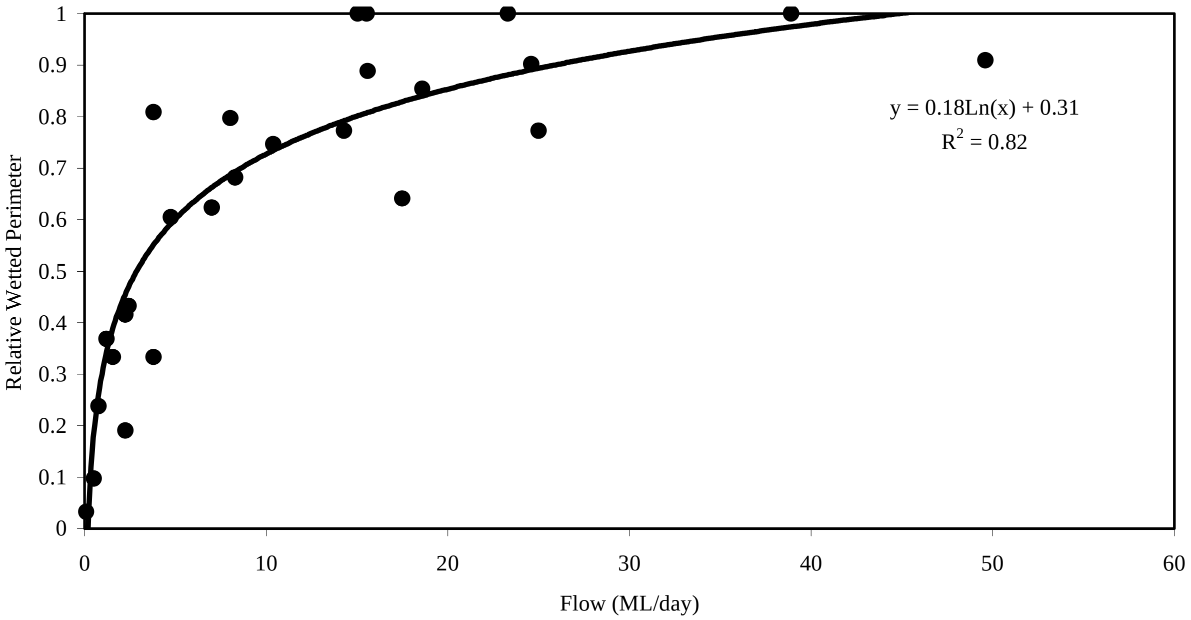


**Figure 12:** Relative wetted perimeter (normalised to site maxima) as a function of flow for Reaches 1 and 2.

The assessment of low flow habitat conditions included consideration of flow volumes, flow variability (flow spell analysis for 10ML/day), and relative wetted perimeter (for the first flow assessment location only). Wetted perimeter was assessed by transforming the flow duration curve using the relationship between relative wetted perimeter and flow to produce a ‘habitat duration curve’ which expresses the percentage of time a given relative wetted perimeter value is equalled or exceeded.

The assessment of moderate flow (freshes) habitat conditions included consideration of flow volumes and flow variability (flow spell analyses for 100 and 1,000ML/day). The assessment of flow regime mimicking was based on the mimicking statistic *M* described above. The assessments of sediment transport and channel form were based on the magnitude and frequency of extreme flows. The assessments of the quality of the inflows to Lake Burragorang were based on the flow volumes and the water quality of Lyell Dam outflows, lower catchment and Kowmung River inflows, and a consideration of the expected instream water quality transformations.

Qualitative overall assessments were made of the level of environmental benefits expected under each flow option at each assessment location, both for current river and catchment management and for 'best' river and catchment management. The assessments are relative ratings between an upper bound of "Most achievable" benefits and "No additional" benefits. The upper bound represents transparent dam flows with best river and catchment management at location 1, where with improved flow and river and catchment management the most benefits can be achieved. The lower bound ("No additional benefits") represents the current flow regime and current river and catchment management at all location; this is the "do nothing" option. The assessments were based on the SRP's subjective interpretation of available data and modelling results.

It was noted by the SRP that a major study was done in the lower Coxs River to assess the benefits to aquatic life of different flow regimes (AMBS, 1995, 1997, 1999). This study was in three stages. The first stage was between autumn 1995 and spring 1995 under a controlled baseline dam release of 0.9ML/day which had been in place since 1982. The weather conditions were considered average during this stage and hence the spill regime was representative of average conditions. The second stage was between autumn 1996 and spring 1996 under a new controlled baseline release of 2.6ML/day. The weather conditions were considered average during this stage and hence the spill regime was representative of average conditions. One 400ML flush was released between stages 1 and 2 and another was released near the end of stage 2. The third stage was between spring 1997 and autumn 1998. The weather conditions were considered considerably drier than average during this stage and hence the spill regime was reduced considerably from the average spill regime.

AMBS (1995, 1997, 1999) reported water quality, stream bed composition, macroinvertebrates, fish, amphibians, and riparian vegetation. Sampling sites were located in six separate reaches: three 'test' reaches between Lyell Dam and the River Lett, and three 'references' reaches – one upstream of Lyell Dam, one on the River Lett and one on the Coxs River downstream of the River Lett confluence. Sampling was conduced in late spring and early autumn in each stage, giving two sampling dates per stage. Sampling was done to test whether significant differences could be detected between the test and reference sites across all stages and between test and reference sites for each stage.

The results showed a general improvement in the condition of the Coxs River between 1995 and 1998. However, with only one exception the trends in condition were not significantly different between the test and reference reaches and so could not be attributed to factors operating differently in the two types of reaches. The exception was a decrease in the abundance of alien fish. This occurred in all reaches, but the rate of decrease was significantly greater in the test reaches than in the references reaches. This finding is difficult to interpret since the alien fish population is dominated by Gambusia which prefer calmer waters. Gambusia abundance would have been expected to increase in stage 3 because of the reduction in higher flows, but this increase did not occur.

Because of the lack of changes clearly attributable to altered flow management, the findings of AMBS (1995, 1997, 1999) could not be used by the SRP to assess the impacts on Coxs River biota of prior, current, of future flow regimes. In addition, the change in reservoir release regime monitored by AMBS was much smaller than the range of options considered by the SRP, and as acknowledged by AMBS (1999), the statistical requirement of independence between sites (reaches) for the analyses of variance and the analyses of similarity that were conducted was not met. There are longitudinal dependencies between the test and reference sites along the Coxs River, and probably spatial autocorrelation between the lower Coxs River sites and the site on the River Lett located only 100m upstream of the confluence. For example, fish, macroinvertebrates and plant propagules could easily move between the test and reference sites upstream and downstream of the River Lett confluence, and the River Lett itself. Moreover, two of the three "reference" sites have flow or sediment regimes affected by dams. The experimental design of the studies was therefore flawed, further reducing the value of the results. Nonetheless, the biological and physical data collected in these studies are likely to prove useful as baseline data against which to compare the results of future monitoring.

# PART III – FLOW OPTION ASSESSMENTS

Several flow options have been proposed for the lower Coxs River and modelled by DLWC using IQQM. The SRP was required to make environmental assessments of a subset of these (Table 7). The following subsequent sections report the assessments made in the manner described in Part II of this report. Flow duration curves, a habitat duration curve, flow spell analyses, and flow statistics are provided in the appendices to the report.

| **Option** | **Description** |
|---|---|
| 1 | A 2.6ML/day constant release and 400ML for freshes annually. This is the current flow regime. |
| 3s | Transparent releases up to 12ML/day from November to April and up to 22ML/day from May to October (annual average 13.6ML/day), translucent (25%) releases above the transparency limits, and an annual 800ML channel maintenance flow. Drought triggers when storage falls to 50,000ML and 40,000ML. After first trigger, transparent releases up to 9ML/day. After the second trigger, transparent releases up to 5ML/day. No translucent releases while drought triggers are active. |
| 4s | Transparent releases up to 12ML/day from November to April and up to 22ML/day from May to October (annual average 13.6ML/day), translucent (25%) releases above the transparency limits, and an annual 800ML channel maintenance flow. This regime was recommended by Booth *et al.* (1998). |
| 5s | Transparent releases up to 27ML/day from November to April and up to 40ML/day from May to October, translucent (25%) releases above the transparency limits, and an annual 800ML channel maintenance flow. |
| 6s | Transparent releases up to 27ML/day from November to April and up to 40ML/day from May to October, translucent (25%) releases above the transparency limits, and an annual 800ML channel maintenance flow. Drought trigger at 50,000ML storage. After trigger, transparent releases up to 5ML/day. No translucent releases while drought trigger is active. |
| 8 | Transparent releases up to 5ML/day, translucent (10%) releases above the transparency limit, and 400ML for freshes annually. Drought trigger at 50,000ML storage. After trigger, translucent releases cease, while transparent releases continue. |

**Table 7:** Descriptions of the flow options assessed by the SRP. An ‘s’ after an Option number denotes a seasonal component to the transparency definition.

The seasonal transparency in Options 3, 4, 5, and 6 (Table 7) was included because of the difference in flows through the year. For example, Option 3 has an average annual transparency limit of 13.6ML/day, a flow that is exceeded approximately 8% of the time under transparent dam conditions. However, the flow that is exceeded 8% of the time from November to April under transparent dam conditions is 12ML/day, and the flow that is exceeded 8% of the time from May to October is 22ML/day.

## *Low flow assessments*

| Option | Low Flow Assessment |
|---|---|
| 1 | Under this option releases are held constant at 2.6ML/day for long periods of time. The low flows downstream therefore lack variability and this is reflected in the spell analysis for 10ML/day which shows the spells below this threshold are nearly ten times longer than for a fully transparent dam, and the spells above this threshold are only about 20% of the length of those for a fully transparent dam. Low flow habitat extent and diversity are limited. A relative wetted perimeter of 0.8 is exceeded only about 30% of the time, compared to about 95% of the time for a fully transparent dam. |
| 3s | Under this option the low flows are much closer to the transparent dam case than Option 1 in terms of both volume and variability. Spell analysis for 10ML/day shows the mean spell below this threshold is 2.5 times longer than for a fully transparent dam, but the mean period above this threshold is nearly 70% of that under a fully transparent dam. Low flow habitat extent and diversity are greatly improved over Option 1 with a relative wetted perimeter of 0.8 being exceeded about 75% of the time. |
| 4s | Under this option the low flow regime is similar to the transparent dam case. The lengths of spells above and below the 10ML/day threshold are equivalent to those for a fully transparent dam. Low flow habitat extent and diversity are equivalent to under a fully transparent dam with a relative wetted perimeter of 0.8 being exceeded nearly 90% of the time. |
| 5s | Under this option the low flow regime is equivalent to the transparent dam case. The lengths of spells above and below the 10ML/day threshold are equivalent to those for a fully transparent dam. Low flow habitat extent and diversity are equivalent to under a fully transparent dam with a relative wetted perimeter of 0.8 being exceeded about 95% of the time. |

| | |
|---|---|
| 6s | Under this option the low flow regime is significantly different from the fully transparent dam case, and worse than under Options 3, 4, and 5. Spells above 10ML/day are about 70% of those for a fully transparent dam, but the spells below this threshold are nearly seven times as long as for a fully transparent dam. Low flow habitat extent and diversity are slightly poorer than Option 3 with a relative wetted perimeter of 0.8 being exceeded about 70% of the time. |
| 8 | The low flow regime under this option is an improvement over Option 1, because releases, although lower than under most options, are not held constant for long periods of time. As a result very low flows are more variable (higher spell frequency) under this option than under a fully transparent dam. The duration of spells below 10ML/day is about 40% higher than for a fully transparent dam, and the duration of spells above this threshold is about 15% of those for a fully transparent dam. However, although the low flow regime is variable, the flow volumes are depressed to the extent that low flow habitat extent and diversity are heavily impacted on. A relative wetted perimeter of 0.8 is exceeded only about 55% of the time. |

**Table 8:** Low flow assessments at flow assessment location 1

| Option | Low Flow Assessment |
|---|---|
| 1 | The flow contributions from tributaries below the dam mean that the low flow regime is less impacted on at flow assessment location 2 than at flow assessment location 1 for this and all options in terms of flow volumes and flow variability. The increase in flow volumes due to tributary inflows will improve the extent and diversity in instream habitat at this location compared to the upstream location. However, for Option 1 the low flow volumes are still greatly reduced from those for a fully transparent dam. The number of spells above/below 10ML/day is greater than for a fully transparent dam, the spells below are over six times as long, and the spells above are about 45% shorter. Instream habitat at low flow is expected to be greatly reduced in extent and diversity compared to the fully transparent dam case. |
| 3s | Low flow volumes under this option are moderately reduced from the fully transparent dam case. The number of spells above/below 10ML/day is greater than for a fully transparent dam, the spells below are over five times as long, and the spells above are about 35% shorter. Low flow habitat is expected to be greatly improved over Option 1, but substantially worse than for the fully transparent dam case. |
| 4s | Low flow volumes under this option are more similar to the fully transparent dam case. The number of spells above/below 10ML/day is greater than for a fully transparent dam, the spells below are over four times as long, and the spells above are about 35% shorter. Low flow habitat is expected to be somewhat improved over Option 3, but still worse than for the fully transparent dam case. |
| 5s | Low flow volumes under this option are equivalent to the fully transparent dam case. The number of spells above/below 10ML/day is similar to a fully transparent dam, and while the spells below are over four times as long, and the spells above are only about 15% shorter. Low flow habitat is expected to be similar to the fully transparent dam case. |
| 6s | Low flow volumes under this option are moderately reduced from the fully transparent dam case. The number of spells above/below 10ML/day is greater than for a fully transparent dam, the spells below are over three times as long, and the spells above are about 35% shorter. Low flow habitat is expected to be similar to that under Option 3 here. |
| 8 | Low flow volumes under this option are moderately reduced from the fully transparent dam case. Flow variability is only slightly impacted on. The number of spells above/below 10ML/day is similar to that for a fully transparent dam, the spells below are about three times as long, and the spells above are similar to the fully transparent dam case. Low flow habitat is expected to be greatly improved over Option 1, but substantially worse than for the fully transparent dam case. |

**Table 9:** Low flow assessments at flow assessment location 2

| Option | Low Flow Assessment |
|---|---|
| 1 | The additional flow contributions from tributaries between flow assessment locations 2 and 3 mean that the low flow regime is far less impacted on at flow assessment location 3 than at flow assessment location 2 for this and all options in terms of flow volumes and flow variability. The increase in flow volumes due to tributary inflows will improve the extent and diversity in instream habitat at this location compared to the upstream location. However, for Option 1 the low flow volumes are still moderately reduced from those for a fully transparent dam. At this location 10ML/day can be considered a very low flow, rather than just a low flow. The spell analysis for this threshold shows flow variability at this very low level is similar to that for a transparent dam for this and all options. Because of the reductions in flow volumes, instream habitat at low flow is expected to be moderately reduced in extent and diversity compared to the fully transparent dam case. |

| | |
|---|---|
| 3s | Low flow volumes under this option are somewhat reduced from the transparent dam case, leading to some reductions in low flow instream habitat extent and diversity. |
| 4s | Low flow volumes under this option are similar to the transparent dam case. Low flow instream habitat is expected to be similar in extent and diversity to that for the transparent dam case. |
| 5s | Low flow volumes under this option are equivalent to the transparent dam case. Low flow instream habitat is expected to be equivalent in extent and diversity to that for the transparent dam case. |
| 6s | Low flow volumes under this option are somewhat reduced from the transparent dam case, leading to some reductions in low flow instream habitat extent and diversity. |
| 8 | Low flow volumes under this option are somewhat reduced from the transparent dam case, leading to some reductions in low flow instream habitat extent and diversity. Under low flows, this option will be similar to Option 3 at this location. |

**Table 10:** Low flow assessments at flow assessment location 3

## *Assessment of freshes*

| Option | Assessment of Freshes |
|---|---|
| 1 | The flow spell analyses show that there are 40% fewer small freshes (100ML/day) per year under this option compared to the transparent dam case, and that these freshes are on average slightly shorter. Large freshes (1000ML/day) are 25% less frequent, although slightly longer than for the transparent dam case. The small freshes are useful for improving water quality under low flow conditions. These freshes will break the thermal stratification in pools that forms during low flow periods, and thus mix de-oxygenated bottom waters with surface layers. Under this option the ability to improve low flow water quality is significantly reduced from the transparent dam case. The large freshes are useful for flushing biofilm accumulations off the surfaces of bedrock and cobbles. Under this option the potential for biofilm flushing is somewhat reduced from the transparent dam case. |
| 3s | Under this option the potential for low flow water quality improvements is similar to Option 1, with freshes above 100ML/day about 40% less frequent than for the transparent dam case, and slightly shorter on average. The potential frequency for biofilm flushing (large freshes) is only about half that of the transparent dam case. |
| 4s | Under this option the potential for low flow water quality improvements is slightly better than Options 1 and 3, with freshes above 100ML/day about 35% less frequent that for the transparent dam case, and 25% shorter on average. The potential frequency for biofilm flushing (large freshes) is only about half that of the transparent dam case. |
| 5s | Under this option the potential for low flow water quality improvements is similar to Option 4, with freshes above 100ML/day about 35% less frequent that for the transparent dam case, and 20% shorter on average. The potential frequency for biofilm flushing (large freshes) is less than half that of the transparent dam case. |
| 6s | Under this option the potential for low flow water quality improvements is similar to Options 1 and 3, with freshes above 100ML/day about 45% less frequent that for the transparent dam case, and 10% shorter on average. The potential frequency for biofilm flushing (large freshes) is only about half that of the transparent dam case. |
| 8 | Under this option the potential for low flow water quality improvements is similar to Options 1 and 3, with freshes above 100ML/day about 40% less frequent that for the transparent dam case, and slightly shorter on average. The potential frequency for biofilm flushing (large freshes) is about 40% less than that of the transparent dam case. |

**Table 11:** Assessment of freshes at flow assessment location 1

| Option | Assessment of Freshes |
|---|---|
| 1 | By flow assessment location 2 the frequency and duration of freshes under all options are closer to the transparent dam case than at flow assessment location 1. Under Option 1 the frequency of small freshes is about 15% lower than the transparent dam case, and the average duration about 20% lower. The potential for low flow water quality flushing is therefore only slightly reduced. The frequency of large freshes is also about 20% lower than the transparent dam case, although the average duration of large freshes is about 40% longer. The potential for biofilm flushing is likely to be similar to the transparent dam case. |
| 3s | Under this option the frequency of small freshes is about 20% lower than the transparent dam case, while the average duration is about 20% longer. The potential for low flow water quality flushing is therefore probably similar to the transparent dam case. The frequency of large freshes is equivalent to the transparent dam case, and the average duration of large freshes is about 60% longer. The potential |

| | |
|---|---|
| | for biofilm flushing is likely to be greater than for the transparent dam case. |
| 4s | Under this option the frequency of small freshes is about 30% lower than the transparent dam case, while the average duration is about 50% longer. Low flow water quality flushing will occur less often but will be very effective when it occurs. The frequency of large freshes is about 30% higher than for the transparent dam case, and the average duration of large freshes is about 60% longer. The potential for biofilm flushing is likely to be greater than for the transparent dam case. |
| 5s | Under this option the frequency of small freshes is about 35% lower than the transparent dam case, while the average duration is about 80% longer. Low flow water quality flushing will occur less often but will be very effective when it occurs. The frequency of large freshes is about 55% higher than for the transparent dam case, and the average duration of large freshes is about 65% longer. The potential for biofilm flushing is likely to be greater than for the transparent dam case. |
| 6s | Under this option the frequency of small freshes is about 40% lower than the transparent dam case, while the average duration is over twice as long. Low flow water quality flushing will occur less often but will be very effective when it occurs. The frequency of large freshes is about 70% higher than for the transparent dam case, and the average duration of large freshes is about 70% longer. The potential for biofilm flushing is likely to be greater than for the transparent dam case. |
| 8 | Under this option the frequency of small freshes is about 45% lower than the transparent dam case, while the average duration is about 2.5 times as long. Low flow water quality flushing will occur less often but will be very effective when it occurs. The frequency of large freshes is close to twice that of the transparent dam case, and the average duration of large freshes is about 60% longer. The potential for biofilm flushing is likely to be greater than for the transparent dam case. |

**Table 12:** Assessment of freshes at flow assessment location 2

| Option | Assessment of Freshes |
|---|---|
| 1 | By flow assessment location 3 the frequency and duration of freshes under all options are closer to the transparent dam case than at flow assessment location 2. In many cases there is little difference from transparent dam case. For Option 1, the frequency and duration of small freshes are both slightly less than for the transparent dam case. This will slightly reduce the ability to mitigate poor low flow water quality. For this and all options, the frequency of large freshes is also slightly reduced although their average duration is equivalent to the transparent dam case. The potential for biofilm flushing will be similar to the transparent dam case. |
| 3s | For Option 3, the frequency of small freshes is similar to the transparent dam case, although the duration of these freshes is slightly less. The ability to mitigate poor low flow water quality will be similar to the transparent dam case. The frequency and duration of large freshes is equivalent to Option 1. The potential for biofilm flushing will be similar to the transparent dam case. |
| 4s | For Option 4, the frequency of small freshes is slightly higher than the transparent dam case, although the duration of these freshes is slightly less. The ability to mitigate poor low flow water quality will be similar to the transparent dam case. The frequency and duration of large freshes is equivalent to Options 1 and 3. The potential for biofilm flushing will be similar to the transparent dam case. |
| 5s | For Option 5, the frequency of small freshes is slightly higher than the transparent dam case, although the duration of these freshes is slightly less. The ability to mitigate poor low flow water quality will be similar to the transparent dam case. The frequency and duration of large freshes is equivalent to Options 1, 3, and 4. The potential for biofilm flushing will be similar to the transparent dam case. |
| 6s | For Option 6, the frequency of small freshes is slightly higher than the transparent dam case, although the duration of these freshes is slightly less. The ability to mitigate poor low flow water quality will be similar to the transparent dam case. The frequency and duration of large freshes is equivalent to Options 1-5. The potential for biofilm flushing will be similar to the transparent dam case. |
| 8 | For Option 8, the frequency and duration of small freshes are slightly less than the transparent dam case. The ability to mitigate poor low flow water quality will be slightly less than the transparent dam case. The frequency and duration of large freshes is equivalent to Options 1-6. The potential for biofilm flushing will be similar to the transparent dam case. |

**Table 13:** Assessment of freshes at flow assessment location 3

## *Flow regime assessment*

The overall degree to which each option mimics the fully transparent dam flow at each flow assessment location was assessed by the mimicking statistic *M*. The values of *M* are shown in Table 14.

| | 1 | 3s | 4s | 5s | 6s | 8 |
|---|---|---|---|---|---|---|
| Location 1 | 0.28 | 0.53 | 0.63 | 0.75 | 0.51 | 0.42 |
| Location 2 | 0.44 | 0.65 | 0.72 | 0.80 | 0.64 | 0.54 |
| Location 3 | 0.68 | 0.79 | 0.84 | 0.89 | 0.79 | 0.74 |

**Table 14:** Values of the flow mimicking statistic $M$ for each option and location. Higher values of $M$ represent greater similarity to the fully transparent flow regime.

The values in Table 14 show that Option 5 provides the best mimicking of the transparent flow regime, followed respectively by Options 4, 3, 6, 8, and 1. For every option, the extent to which transparent flows are mimicked improves with distance downstream, and the differences between the options reduce with distance downstream.

## *Sediment transport and channel form*

The sediment transport capacity of the different options can be assessed in the manner described earlier in this report. The comparison made earlier of the sediment transport capacities of the natural and current (Option 1) flow regimes indicated two important points: firstly, the downstream variations in sediment transport are dominated by the downstream variations in slope rather than flow, and secondly, the percentage reduction in sediment transport capacity from the natural to the current flow regime decreases with distance downstream because of the decreases in the percentage flow reduction (Figure 10).

Differences in relative sediment transport capacity between the different options are small (Table 15), though all differ from the fully transparent dam condition. Only immediately downstream of Lyell Dam is the sediment transport capacity of the current flow regime (Option 1) appreciably different from the other options. The average (across all options) reductions in sediment transport capacity from transparent conditions are 49% immediately downstream of Lyell Dam, 20% at Island Hill, and 11% at Kelpie Point.

| | Transparent | Option 1 | Option 3s | Option 4s | Option 5s | Option 6s | Option 8 |
|---|---|---|---|---|---|---|---|
| Location 1 | 1.00 | 0.73 | 0.63 | 0.56 | 0.55 | 0.62 | 0.68 |
| Location 2 | 1.00 | 0.84 | 0.79 | 0.75 | 0.75 | 0.78 | 0.82 |
| Location 3 | 1.00 | 0.92 | 0.90 | 0.87 | 0.87 | 0.89 | 0.91 |

**Table 15:** Relative (to transparent) sediment transport capacities of the different options at the three flow-prediction locations.

Flows that are competent to transport bed sediment will move sand and gravel through the existing channel form and modify in-channel sediment structures such as riffles and pools. While the 400ML freshes provided in Options 1 and 8 will have no significant effect on sediment transport, the 800ML freshes provided in Options 3, 4, 5, and 6, if delivered in 24 hours or less, will flush fine sediments (silts and clays) from the bed and will transport sand, particularly in constricted reaches. In this regard Options 3, 4, 5, and 6 provide a marginally better opportunity for bed disturbance and sediment transport than Options 1 and 8. Only the very highest flows (floods that occur once very 5 years or longer) modify the overall channel size and shape. As these very high flows have not been affected by flow impoundment and abstraction, no changes to the natural processes of channel shape and size evolution are expected under any of the flow options.

## *Water quality in the lower Coxs River and Coxs arm of Lake Burragorang*

The water quality of the lower Coxs River and of inflows to the Coxs River arm of Lake Burragorang can be considered in terms of both concentrations and total loads. From the perspective of the likely ecological conditions in the lower Coxs River and in the immediate receiving waters (the Coxs arm of Lake Burragorang) total loads and low flow concentrations are relevant. However, from the perspective of the likely impacts of water supplies drawn from Lake Burragorang only total loads are relevant because of the mixing which occurs within the lake.

For both loads and concentrations it is important to consider the relative contributions from the upper Coxs (Lyell Dam outflows), the lower Coxs and the Kowmung River to the total outflow. Under the natural flow regime the relative flow contributions from these three areas are: 14.4% (upper Coxs), 42.3% (lower Coxs), 43.3% (Kowmung). Under the current flow regime (Option 1) the relative flow contributions are 8.6% (upper Coxs), 45.3% (lower Coxs), 46.2% (Kowmung). In the other options, flows from Lyell Dam contribute between 8% and 14.4% of the total volume flowing into Lake Burragorang.

The quality of the water from these three contributing areas differs. The lowest values of a selection of water quality indicators (total phosphorus, turbidity, and faecal coliform levels) in data from Jones (1992) for the period 1962-1990, and data collected by Australian Water Technologies for the period 1998-1999 are for the Kowmung River. The values for Lyell Dam outflows are all 5-7 times higher than the Kowmung River values. The values for the lower Coxs range from almost as low as the values for the Kowmung River to higher than the values for the Lyell Dam outflows. Water quality in the lower Coxs River is a result of the quality of both the dam outflows (releases and spills) and tributary inflows from the lower catchment, as well as the strength and nature of the physical, chemical and biological processes that modify water quality along the length of the lower river. Biological processes, chemical transformations and physical processes of particulate trapping and settling are likely to be most important in determining low-flow concentrations when flow velocities are relatively low and travel times relatively long. Under these conditions such instream processes are able to operate over a sufficiently long time to cause significant water quality modification. These processes, however, are unlikely to affect total loads as much, since by far the majority of loads in rivers are usually carried by high flows when flow velocities are relatively high and travel times are relatively short.

Measurements by AWT (1999) of turbidity, nutrient concentrations and faecal coliform levels from the lower Coxs River at Kelpie Point indicate large differences between dry-weather and wet-weather flows. Median values of turbidity were over ten times higher under wet conditions (7 samples) than under dry conditions (11 samples). Median total phosphorus concentrations (2 wet samples, 11 dry samples) were over four times higher, and the geometric mean faecal coliform counts (6 wet samples, 11 dry samples) were over six times higher. These data reflect the increased erosion, inputs of farm animal faeces and possibly sewage overflows associated with rainfall events which lead to high concentrations in high flows.

Qualitatively it can be concluded that total sediment, nutrient and coliform loads reaching Lake Burragorang and the concentrations of these during high flows will be dominated by the flows derived from catchment of the lower Coxs which contributes over 40% of the flow volumes and generates moderate to high concentrations. The variability in volumes of water contributed by dam outflows under the various options will lead to insignificant differences in the total loads and high flow concentrations entering Lake Burragorang.

During low flows, the water quality in the lower Coxs is a result only of the quality of water released from the dam and the instream processes operating along the lower Coxs. It is difficult to predict the effects of the flow options on low-flow concentrations because of a lack of data describing instream processes in the lower Coxs River. Under low-flow conditions fine sediments will settle out, reducing turbidity, and nutrients will be assimilated by stream biota and deposited with sediments. However, under very dry conditions pools may thermally stratify, leading to a reduction in oxygen levels, especially in bottom waters, and these conditions influence the nutrient chemistry of the sediment-water interface, often allowing the release of chemically-bound phosphorus from bottom sediments into the water column. High nutrient concentrations, warm water, and low flow velocities in river pools are conducive to algal growth, and nuisance levels of algae may result. Very low and constant flows are the most likely to promote pool stratification and resultant water quality degradation. In this regard, Option 1 is the most likely to cause low flow water quality problems in the lower Coxs River and possibly in parts of the Coxs River arm of Lake Burragorang. To a lesser extent, Options 6 and 8 may also cause low-flow water quality problems.

## *New South Wales River Flow Objectives*

In the context of the flow options proposed for the Coxs River, River Flow Objective (RFO) 2 (protect very low flows), RFO 3 (protect moderately low flows and freshes), and RFO 6 (mimic natural flow variability) are the most relevant. With respect to RFO 2 (taken here to mean the lowest 3%) there is little difference between the options, with all options providing reasonable protection of the very low flows at all assessment locations. With respect to RFO 3 however, the option-by-option assessments above show that while by Kelpie Point the moderately low flows and freshes are well protected under all options, at the first two flow assessment locations, Option 5 gives excellent protection of moderately low flows, Option 4 gives good protection, Option 3 gives moderate protection, Options 6 and 8 give fair protection, and Option 1 gives poor protection. In all cases, the protection is much improved at flow assessment location 2 compared to flow assessment location 1. For freshes, Options 5, 6, 4, and 3 give moderate to good protection, while Options 8 and 1 give poor protection. Again, the protection at flow assessment location 2 is markedly better than at location 1, and by Kelpie Point, the impacts of any option on freshes is minor.

The flow spell analyses indicate that at flow assessment location 1, flow variability around the 10ML/day threshold is closest to the transparent dam case under Options 4 and 5. The other options fluctuate more frequently around this threshold than the transparent dam case, but the spells below are longer and the spells above are shorter than under the transparent dam case. At flow location 1, the flow variability around the 100 and 1,000ML/day thresholds is similar under all options, although for all options is less variable (lower frequency) than under the transparent dam case. At flow assessment location 2, the flow spell analyses indicate that flow variability (spell frequency) around the 10ML/day threshold is higher than under the transparent dam case for all options. For the 100ML/day threshold at flow assessment location 2, flow variability is lower than under the transparent dam case for all options. For the 1,000ML/day threshold at flow assessment location 2, flow variability is higher than under the transparent dam case for all options except for Option 1. By flow assessment location 3, flow variability around the 10ML/day threshold is similar to the transparent dam case for all options except for Option 3 for which variability is lower; flow variability around the 100ML/day threshold is higher than under the transparent dam case for all Options except Options 1 and 8; and flow variability around the 1,000ML/day threshold is lower than under the transparent dam case for all Options. The spell analyses do not present a simple picture of the changes in flow variability, although across all thresholds and locations Options 4 and 5 provide the best mimicking of the flow variability under the transparent dam case.

## *Assessment against objectives*

In June 1999 the SRP agreed on five ‘ecological river management objectives’ for the Coxs River, these being based on objectives agreed to at a community workshop, but modified to provide objectives that were expressed in scientific terms, and would enable comparative and qualitative assessments of the options. While the SRP supported other river management objectives agreed to at the community workshop, these were not relevant to the brief of the SRP. The five ecological river management objectives are:

1. The aquatic communities in the Coxs River be more similar to those that would have occurred in pre-European settlement conditions than present-day communities.
2. The diversity of riverine habitats in the Coxs River be suitable to support the diversity of species that make up aquatic communities.
3. The processes of nutrient and sediment transport in the Coxs River be suitable to maintain this diversity of habitats and species.
4. The abundance of introduced species (riparian, edge and aquatic) be reduced.
5. The incidence of blue-green algal blooms be reduced.

Qualitative assessments against these ecological objectives are provided below.

### Objective 1 – Aquatic Communities

Under the current condition (Option 1) aquatic communities in the Coxs River are not similar to those before European settlement. The macroinvertebrate fauna has probably lost some species that are particularly sensitive to adverse water quality or have a strong preference for cool, fast-flowing water. Other species have probably declined in abundance because of the loss of flowing-water habitat and the build-up of dense coatings and filamentous algal growths on stones in the river. The diversity of fish species has been lowered by a loss of native species, probably mainly as a result of the barrier effect of Warragamba Dam, and the competitive and predatory impact of alien species.

Option 1 has not been in place for a long period, and further changes in the aquatic communities may occur because of lagged adjustment to this new flow regime. Nevertheless, it seems unlikely that this option will enable restoration of faunal communities between Lyell Dam and flow assessment location 2, since it does not adequately restore the extent, diversity and temporal variability of low-flow habitat, or the small to medium flushes that provide habitat conditioning.

Options 8 is likely to provide only small improvements in aquatic communities over Option 1. Option 6 is likely to allow aquatic communities in the Coxs River to become closer to those existing before European settlement, with improved aquatic habitat between the dam and flow assessment location 2. Option 3 is likely to lead to further improvements, for example, by increasing the availability and diversity of prey for fish. Option 4 would be expected to yield further improvements in the aquatic communities, and Option 5, being the closest flow conditions to transparent dam operation, would allow the greatest recovery of aquatic communities in terms of fish and macroinvertebrate diversity, and would be expected to support the highest fish biomass.

Submerged vascular plants are not common in upland rivers such as the Coxs, and there are unlikely to be detectable differences in the submerged vascular plant communities in the river under any of the options. Emergent plants establish and grow along the river margins where flows provide suitable wetting, sediments allow root development, and scouring is not severe. In this regard, Options 4 and 5 are likely to provide better conditions for the establishment of emergent aquatic vegetation than Options 1, 3, 6, or 8, because of greater flow variability during low-flow periods.

None of the proposed flow Options with significantly alter the riparian vegetation in the Coxs River. Recruitment of the river oak *Casuarina* depends on germination after big floods particularly on strand lines and on the conditions for establishment and growth after that, and there are no significant differences between the flood regimes of the proposed Options.

### Objective 2 – Riverine Habitats

As a greater width of stream channel is wetted, the diversity of instream habitats will increase. Figure 16 in Appendix 2 indicates the relative wetted perimeter distributions for the river between the dam and flow assessment location 1. A similar pattern, although with smaller differences between options, is expected to occur at least as far downstream as flow assessment location 2. By Kelpie Point flows have sufficiently 'recovered' that the diversity of instream habitats is likely to similar to that under natural conditions.

Under the current flow regime (Option 1) the diversity of instream habitats is very low, and so the river is unable to support the natural diversity of species, and the total biomass the river can support has been reduced. Under Option 8, the diversity of riverine habitats would increase somewhat, and would probably support a higher diversity of species that the current flow regime. Option 6 would provide a low habitat diversity for 30% of the time, but greatly improved habitat diversity over Option 1 for the remainder of the time. However, it is unlikely that these increases in habitat diversity would translate equally into increased species diversity, as the very low habitat diversity for 30% of the time would limit ecological recovery.

Options 3, 4, and 5 would provide incremental increases in habitat diversity over Option 8, with Option 5 providing a habitat diversity equivalent to natural under low-flow conditions. Under these three Options the incremental increases in habitat diversity would support an incrementally more diverse aquatic community.

### Objective 3 – Sediment and Nutrient Transport

As shown in Table 15, the differences between the Options in terms of sediment transport are minor. Options 1 and 8 do provide minor increases in transport capacity over the other Options, but the sediment transport capacity of all Options is significantly less than natural for the first reaches downstream of the dam. In the lowest reaches, the sediment transport capacity under all options is about 10% less than natural.

While low-flow water quality in the river may differ between options, the total fluxes of nutrients, which are dominated by high flows, will not differ greatly between options. The high flows (those are exceeded less than 20 per cent of the time) are very similar between the options (Figures 15-17).

### Objective 4 – Introduced Species

Under Option 1, gambusia will probably continue as the dominant small fish species, while trout will persist as a predator. The increases in flow under Option 8 are unlikely to reduce the abundance of gambusia slightly. The added flow over Option 1 might provide small improvements in water quality, especially temperature, that could boost survival of trout. Whether trout survival and growth were enhanced or not, the resultant changes in fish numbers, diversity and community structure might be difficult to detect. In Option 6, increased velocity during freshes above the 60th percentile may temporarily displace gambusia from riffle zones, but pools and other still-water habitats would provide flow refuges from which these fish would rapidly recolonise riffles during low flows. A reduction in abundance of gambusia in pool habitats is unlikely. These assessments apply to the entire river downstream of the dam, since although flow volumes and flow variability increase with distance from the dam, under Option 1, 8, and 6 these increases are unlikely to provide a sufficient length of river with sufficient flow to reduce introduced fish populations, and allow significant recovery of native fish populations.

Under Options 3, 4, and 5, the incremental increases in velocity during low flows and freshes may reduce the amount of still water habitat for gambusia, leading to incrementally larger reductions in the abundance of this species. Reduced abundance of gambusia may have advantages for small native species. However, any possible increase in abundance of gudgeons or galaxiids as a result of reduced competition from gambusia, could be moderated or negated by increases in trout numbers, and a consequent increase in predation of small native fish.

None of the assessed flow options is likely to have any major impacts on the distribution of blackberry, broom, or willows in or along the Coxs River channel. While the better protection of moderately low flows and minor freshes in Options 4 and 5 may reduce the suitability of the mid-channel environment to young and adult willow trees, the same flows will increase the dispersal of vegetative propagules of this species, offsetting any potential benefits.

### Objective 5 – Blue-green Algae

Blue-green algal growth in the river downstream of Lyell Dam occurs primarily during very low or zero flow conditions. Those options that maintain higher base flows (Options 3, 4, 5, and 6) will decrease the frequency of algal blooms in the river reaches below the dam.

## *Overall assessment*

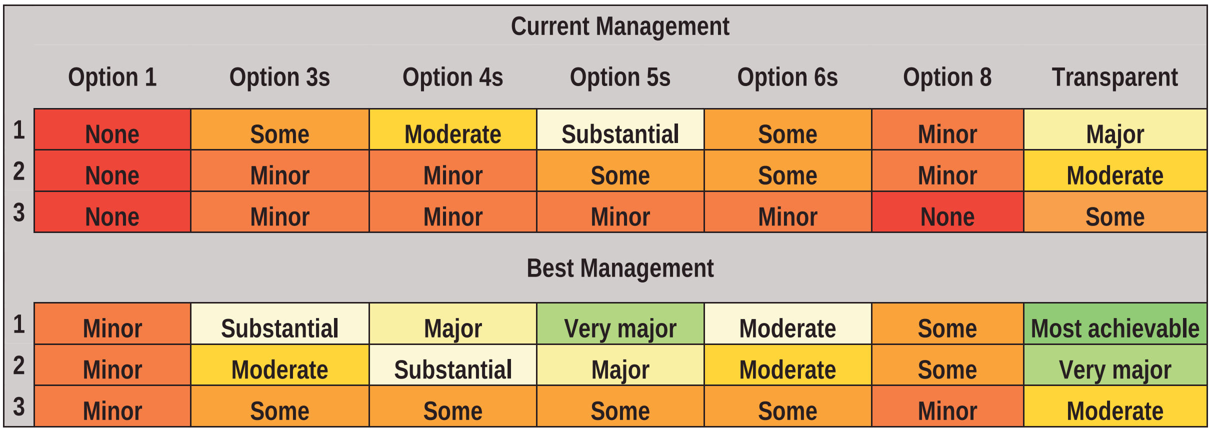
Brief summaries of the changes expected under each option are provided in Table 16. Scientific knowledge of responses to flow change is not yet adequate to allow the magnitude or exact timing of changes to be predicted. The flow differences between the options are likely to be less that the natural year-to-year differences in flow under any option, and so these inter-annual differences will affect the aquatic plants and animals to a greater extent. The overall recovery of the river will be limited by the rate at which the river geomorphology recovers, and this will be controlled by the frequency and magnitude of large floods which dominate the total sediment transport capacity. While the sediment transport capacity does not vary greatly between the options, it is significantly less than for the transparent dam operation.

| Option | Description |
|---|---|
| 1 | Slow reduction in in-channel sediment deposits, and hence a slow change towards a more bedrock-dominated channel, and possibly a continuing degradation of the aquatic communities in response to the reduced flows. No reductions in introduced fauna or flora, although adequate flushing of biofilms. Inadequate fast-water habitat extent and diversity for most of the time. |
| 3s | Very slow reduction in in-channel sediment deposits, and hence a very slow change towards a more bedrock-dominated channel. Improved protection of low flows (over Options 1, 6, and 8) and consequent improvements in instream habitat diversity and fauna. Some reductions in gambusia; no changes in flora, including introduced species. Adequate flushing of biofilms. |
| 4s | Very slow reduction in in-channel sediment deposits, and hence a very slow change towards a more bedrock-dominated channel. Improved protection of low flows (over Options 1, 3, 6, and 8) and improved protection of small freshes (over Options 1, 3, 6,and 8) leading to low-flow water quality improvements. Reasonable recovery of instream habitat and fauna, including some reductions in gambusia. Possible increases in emergent aquatic plant establishment, but no changes to riparian vegetation including introduced species. Adequate flushing of biofilms. |
| 5s | Very slow reduction in in-channel sediment deposits, and hence a very slow change towards a more bedrock-dominated channel. Improved protection of low flows (over Options 1, 3, 6, and 8) and improved protection of small freshes (over Options 1, 3, 6, and 8) leading low flow water quality improvements. Best option for recovery of instream fauna including reductions in introduced fish. Possible increases in emergent plant establishment, but no changes to riparian vegetation including introduced species. Adequate flushing of biofilms. |
| 6s | Very slow reduction in in-channel sediment deposits, and hence a very slow change towards a more bedrock-dominated channel. Poor protection of low flows although better than current flow regime. Moderate protection of small freshes leading to some low flow water quality improvement (over Options 1 and 8). Marginal improvements in river habitats and fauna over Option 1. No changes to native or introduced vegetation. Adequate flushing of biofilms. |
| 8s | Slow reduction in in-channel sediment deposits, and hence a slow change towards a more bedrock-dominated channel. Poor protection of low flows; marginally better than Option 1. Poor protection of small freshes (marginally better than Option 1) so minimal improvement in low-flow water quality. Few improvements in river fauna expected. No changes to native or introduced vegetation. Adequate flushing of biofilms. |

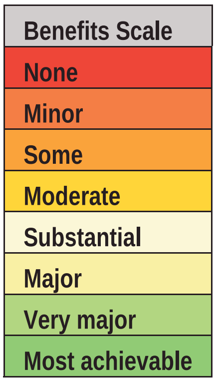
**Table 16:** Option assessment summaries.

Qualitative overall assessments have been made of the expected environmental benefits of each flow option at each assessment location, both for current river and catchment management and for 'best' river and catchment management (Table 17). The assessments are relative ratings between upper and lower bounds. The upper bound ("Most achievable" benefits") represents transparent dam flow with best river and catchment management at location 1, where with improved flow and river and catchment management the most benefits can be achieved. The lower bound ("No additional benefits") represents the current flow regime and current river and catchment management at all location; this is the “do nothing” option. The assessments are based on the SRP’s subjective interpretation of available data and modelling results.

These assessments highlight: (i) the differences in benefits expected from the six options relative to transparent dam flow; (ii) the differences in expected benefits between locations refecting current differences in river and catchment management; and (iii) the importance of river and catchment management relative to flow. For example, because conditions at location 3 are not highly degraded, only minor benefits are expected from increases in flow; the greatest relative benefits are expected at location 1.



| | Option 1 | Option 3s | Option 4s | Option 5s | Option 6s | Option 8 | Transparent |
|---|---|---|---|---|---|---|---|
| **Current Management** | | | | | | | |
| 1 | None | Some | Moderate | Substantial | Some | Minor | Major |
| 2 | None | Minor | Minor | Some | Some | Minor | Moderate |
| 3 | None | Minor | Minor | Minor | Minor | None | Some |
| **Best Management** | | | | | | | |
| 1 | Minor | Substantial | Major | Very major | Moderate | Some | Most achievable |
| 2 | Minor | Moderate | Substantial | Major | Moderate | Some | Very major |
| 3 | Minor | Some | Some | Some | Some | Minor | Moderate |



| Benefits Scale |
|---|
| None |
| Minor |
| Some |
| Moderate |
| Substantial |
| Major |
| Very major |
| Most achievable |

**Table 17:** Assessments of flow options (columns) by flow assessment location (rows) against a qualitative scale of environmental benefits from “none” (no additional benefits) to “most achievable”.

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# Appendix 1 – Flow Duration Curves

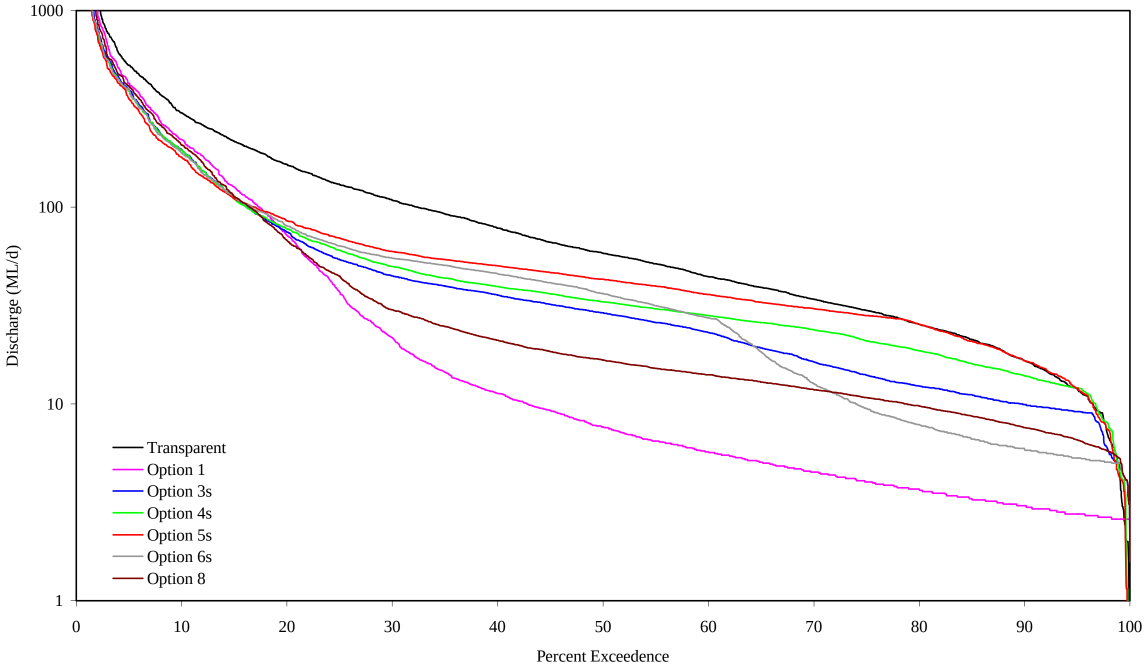

**Figure 13:** Daily flow duration curve for flow assessment location 1 (upstream of the River Lett confluence).

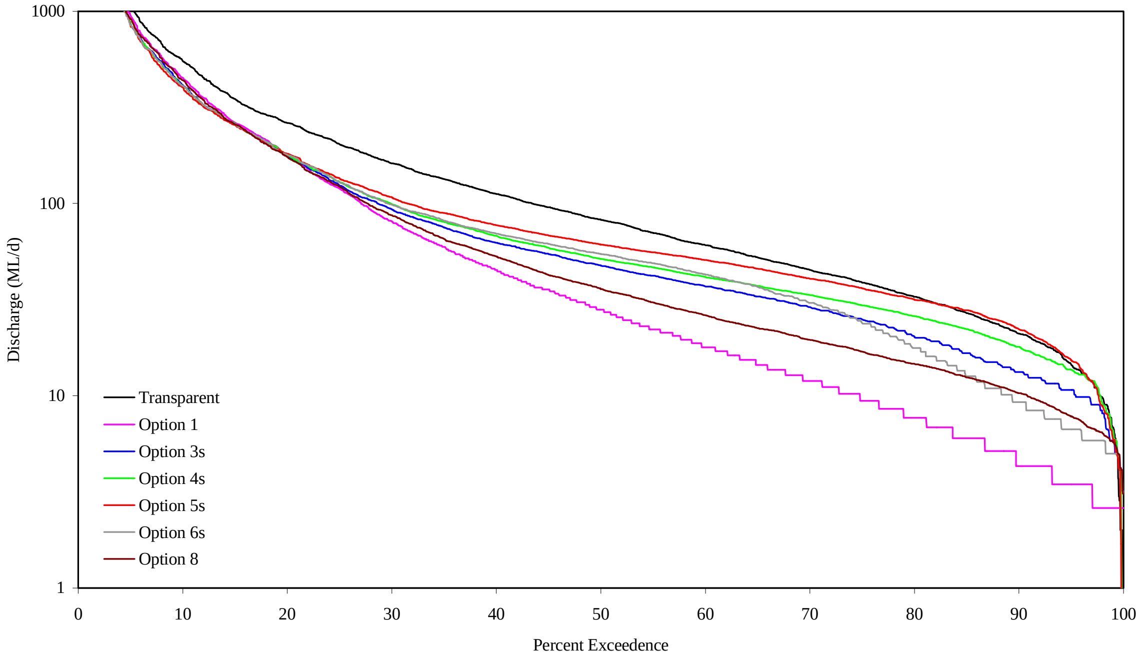

**Figure 14:** Daily flow duration curve for flow assessment location 2 (upstream of the Megalong Creek confluence).

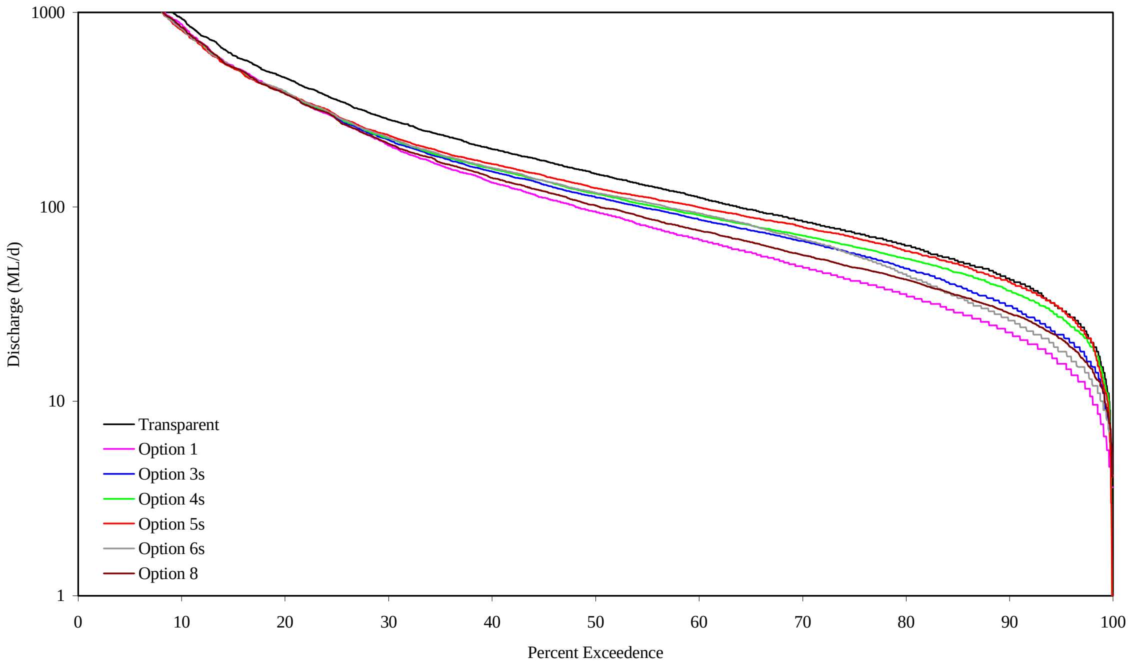

**Figure 15:** Daily flow duration curve for flow assessment location 3 (Kelpie Point).

## Appendix 2 – Habitat Duration Curve

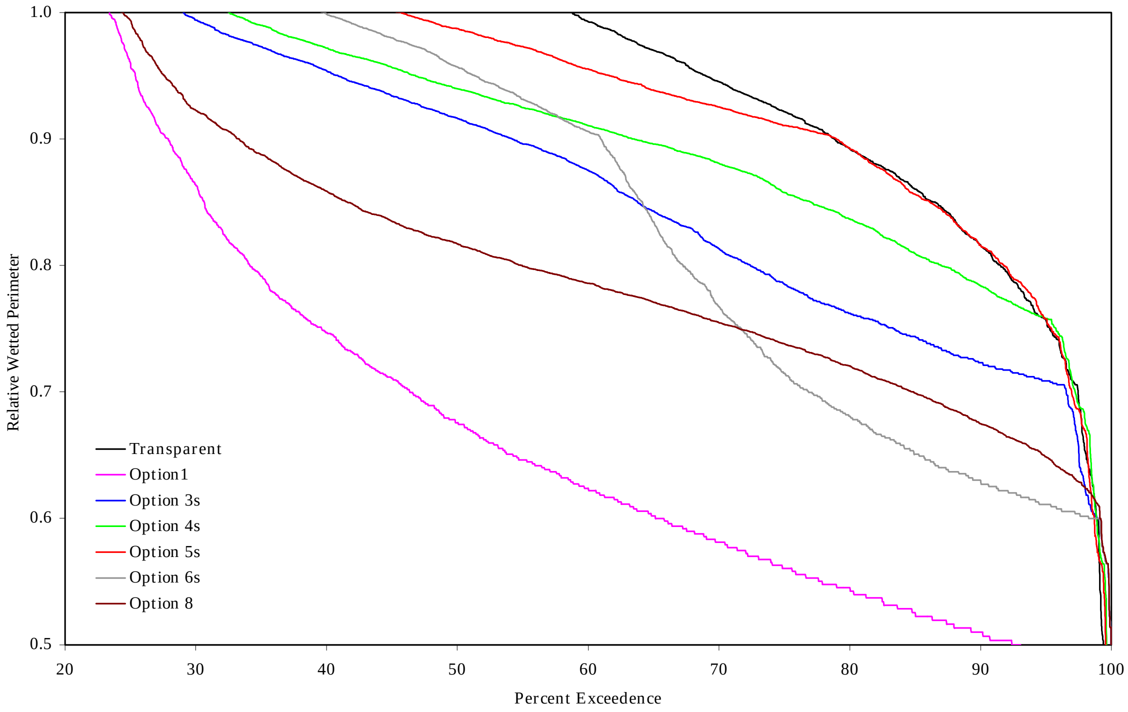

**Figure 16**: Percent exceedence of relative wetted perimeter in Reaches 1 and 2.

# Appendix 3 – Flow Spell Analyses

| Threshold | 10ML/day | | | 100ML/day | | | 1000ML/day | | |
|---|---|---|---|---|---|---|---|---|---|
| Statistic | Mean above | Mean below | Freq | Mean above | Mean below | Freq | Mean above | Mean below | Freq |
| Transparent dam | 64.7 | 2.5 | 5.4 | 9.5 | 19.7 | 12.5 | 2.3 | 109.0 | 3.3 |
| Option 1 | 13.8 | 19.2 | 11.1 | 8.1 | 39.9 | 7.6 | 2.7 | 144.1 | 2.5 |
| Option 3s | 43.7 | 6.4 | 7.3 | 7.9 | 41.3 | 7.4 | 2.9 | 192.9 | 1.9 |
| Option 4s | 62.0 | 2.3 | 5.7 | 7.4 | 38.1 | 8.0 | 2.9 | 204.0 | 1.8 |
| Option 5s | 61.3 | 2.6 | 5.7 | 7.7 | 38.2 | 7.9 | 3.1 | 237.6 | 1.5 |
| Option 6s | 45.1 | 16.5 | 5.9 | 8.4 | 43.4 | 7.0 | 3.1 | 212.4 | 1.7 |
| Option 8 | 10.4 | 3.4 | 26.4 | 8.2 | 42.3 | 7.2 | 2.8 | 158.7 | 2.2 |

**Table 19:** Flow spell analysis results for flow assessment location 1. Statistics reported are mean period (in days) spent above the threshold, mean period (in days) spent below the threshold, and the mean frequency (number per calendar year) of spells for the threshold.

| Threshold | 10ML/day | | | 100ML/day | | | 1000ML/day | | |
|---|---|---|---|---|---|---|---|---|---|
| Statistic | Mean above | Mean below | Freq | Mean above | Mean below | Freq | Mean above | Mean below | Freq |
| Transparent dam | 97.8 | 2.3 | 3.6 | 13.1 | 16.9 | 12.2 | 4.6 | 87.5 | 3.9 |
| Option 1 | 53.6 | 14.3 | 5.4 | 10.8 | 23.6 | 10.6 | 6.4 | 109.1 | 3.1 |
| Option 3s | 61.9 | 11.7 | 5.0 | 15.4 | 23.1 | 9.5 | 7.4 | 83.6 | 4.0 |
| Option 4s | 64.5 | 9.8 | 4.9 | 19.7 | 22.6 | 8.6 | 7.5 | 64.6 | 5.0 |
| Option 5s | 84.8 | 10.1 | 3.8 | 23.4 | 21.7 | 8.1 | 7.6 | 53.1 | 6.0 |
| Option 6s | 66.2 | 7.4 | 5.0 | 27.4 | 21.2 | 7.5 | 7.8 | 46.6 | 6.7 |
| Option 8 | 92.3 | 7.2 | 3.7 | 32.5 | 21.4 | 6.8 | 7.8 | 41.0 | 7.5 |

**Table 20:** Flow spell analysis results for flow assessment location 2. Statistics reported are mean period (in days) spent above the threshold, mean period (in days) spent below the threshold, and the mean frequency (number per calendar year) of spells for the threshold.

| Threshold | 10ML/day | | | 100ML/day | | | 1000ML/day | | |
|---|---|---|---|---|---|---|---|---|---|
| Statistic | Mean above | Mean below | Freq | Mean above | Mean below | Freq | Mean above | Mean below | Freq |
| Transparent dam | 598.6 | 62.0 | 0.6 | 24.9 | 14.0 | 9.4 | 4.4 | 43.7 | 7.6 |
| Option 1 | 448.2 | 8.3 | 0.8 | 20.7 | 21.8 | 8.6 | 4.4 | 47.9 | 6.9 |
| Option 3s | 1138.9 | 81.2 | 0.3 | 20.0 | 16.7 | 9.9 | 4.4 | 50.1 | 6.7 |
| Option 4s | 536.5 | 36.2 | 0.6 | 20.2 | 15.8 | 10.2 | 4.4 | 50.4 | 6.6 |
| Option 5s | 495.2 | 34.3 | 0.6 | 21.2 | 14.4 | 10.3 | 4.4 | 51.4 | 6.5 |
| Option 6s | 492.1 | 37.4 | 0.6 | 19.9 | 15.2 | 10.4 | 4.5 | 50.9 | 6.6 |
| Option 8 | 503.5 | 36.1 | 0.6 | 22.0 | 21.2 | 8.5 | 4.4 | 48.9 | 6.8 |

**Table 21:** Flow spell analysis results for flow assessment location 3. Statistics reported are mean period (in days) spent above the threshold, mean period (in days) spent below the threshold, and the mean frequency (number per calendar year) of spells for the threshold.

# Appendix 4 – Flow Statistics

| River Lett | Mean daily flow | Median daily flow | Coefficient of variation of daily flow | Percent of days dam spills |
|---|---|---|---|---|
| Transparent dam | 170 | 58 | 10 | n/a |
| Option 1 | 112 | 7 | 65 | 22.7 |
| Option 3s | 110 | 30 | 15 | 13.3 |
| Option 4s | 108 | 33 | 12 | 11.6 |
| Option 5s | 111 | 43 | 9 | 8.0 |
| Option 6s | 111 | 36 | 12 | 10.6 |
| Option 8 | 111 | 17 | 28 | 19.0 |

**Table 22:** Flow statistics for flow assessment location 1.

| Megalong Creek | Mean daily flow | Median daily flow | Coefficient of variation of daily flow |
|---|---|---|---|
| Transparent dam | 283 | 82 | 11 |
| Option 1 | 224 | 28 | 29 |
| Option 3s | 223 | 48 | 16 |
| Option 4s | 220 | 51 | 14 |
| Option 5s | 224 | 61 | 12 |
| Option 6s | 224 | 55 | 14 |
| Option 8 | 223 | 37 | 22 |

**Table 23:** Flow statistics for flow assessment location 2.

| Kelpie Point | Mean daily flow | Median daily flow | Coefficient of variation of daily flow |
|---|---|---|---|
| Transparent dam | 560 | 148 | 16 |
| Option 1 | 502 | 95 | 23 |
| Option 3s | 500 | 112 | 19 |
| Option 4s | 498 | 118 | 18 |
| Option 5s | 501 | 125 | 17 |
| Option 6s | 501 | 118 | 18 |
| Option 8 | 501 | 102 | 21 |

**Table 24:** Flow statistics for flow assessment location 3.