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Published
2001

Journal Title
Water Resources Research

DOI
10.1029/2001WR000341

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Relative changes in sediment supply and sediment transport capacity in a bedrock-controlled river

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Abstract. Rivers can be affected by multiple natural and human-induced changes to sediment supply and to sediment transport capacity. Assessment of the relative importance of these changes enables appropriate river management. Here assessments are made of the relative changes in sediment supply and sediment transport capacity of an 83 km section of the bedrock-controlled Coxs River, New South Wales, Australia. These relative changes are estimated, in turn, for land degradation, historical climate variations, and dam closure. Measurements of gully erosion extent from aerial photographs indicate that since European settlement the average annual sediment supply to the river has increased by a factor of ~20. Rainfall records and flow-gauging records show a climate shift in the mid-1940s. On the basis of hydrologic modeling the increased streamflow in the period since the mid-1940s is estimated to have increased sediment transport capacity by a factor of almost 3. Closure of Lyell Dam in 1982 stopped sediment supply from the upper catchment. On the basis of hydrologic modeling the flow regulation and abstraction at the dam is estimated to have reduced the long-term average sediment transport capacity downstream by 15%. The current sediment transport capacity after the climate shift and dam closure is 2.6 times higher than in the first half of this century. In spite of this net increase in sediment transport capacity the huge volume of sediment delivered to the channel from gully erosion has lead to widespread sand deposition along much of the river. Much of the river bed that was previously dominated by bedrock is now alluvial in character. Only the steepest reaches remain bedrock-dominated.

1. Introduction

River channel morphology is a result of past and present flow regimes and patterns of sediment supply and of the controls that catchment geology and regional tectonics place on long-profile development. The form of the channel adjusts in response to natural and human-induced changes to the flow regime and/or sediment supply. In many studies of changes in river form or process a single causal agent has been examined. Single causal agents may influence both the flow regime and the sediment supply. For example, forest clearing increases both catchment runoff and sediment supply [Calder and Maidment, 1992], and dam closure modifies the flow regime (by flow regulation and in some cases diversion) and cuts off upstream sediment supply [e.g., Williams and Wolman, 1984]. However, many rivers are responding to multiple changes at any point in time, and complete assessments of river adjustment need to take account of the relative importance of multiple influences on sediment supply and on the flow regime.

Changes to the flow regime and sediment supply may be gradual or sudden and may occur at a point or points in time or space or be continuous along a river length or through a period of time. The temporal and spatial variations in the balance between sediment supply and transport capacity determine the sediment regime of the channel and nature of benthic habitat. Where supply exceeds capacity, deposition occurs and the channel is alluvial. Where capacity exceeds supply, the channel erodes to bedrock or other resistant substrate. By expressing sediment supply as a function of drainage area and sediment transport capacity as a function of drainage area and channel slope, Montgomery et al. [1996] showed that bedrock and alluvial channels of Washington coastal rivers (United States) could be distinguished on an area-slope plot with bedrock reaches having higher slopes than alluvial channels with comparable drainage areas. In the formulation of Montgomery et al. [1996], bedrock and alluvial channels are separated by a threshold that can be expressed as a critical slope value for a given drainage area and for which sediment supply equals transport capacity.

Sediment transport capacity is a function of discharge and the local energy gradient which can be approximated by the channel slope. Simple representations of river form suggest a monotonic downstream decrease in slope and a uniform increase in discharge with drainage area [e.g., Church, 1996]. Such representations lead to rapid increases in sediment transport capacity with distance from the headwater to a midcatchment maximum, followed by a slower reduction in capacity with distance to the catchment exit [e.g., Lawler, 1992; Abernethy and Rutherford, 1998]. However, analyses of actual rivers
suggest this simple pattern seldom occurs [e.g., Knighton, 1999] because of geologic controls on long-profile development, the location of major tributary junctions, and the spatial variability in runoff generation. In many catchments, there are also strong spatial variations in erosion and hence sediment supply. In catchments where the downstream variations in sediment supply and discharge are poorly predicted by drainage area, drainage area and slope alone will be an insufficient basis on which to predict the occurrence of bedrock and alluvial channels.

The two most commonly reported human-induced causes of river adjustment are dam closure and land clearing. Dam closure is a discrete and very obvious event, to which the downstream responses have been widely studied. For example, Williams and Wolman [1984] report on the downstream changes caused by dam closure for 21 alluvial rivers in North America. While bed degradation immediately downstream of a dam is the most obvious initial response, this is only the first stage in channel adjustment to the imposed changes in flow and sediment regime. Pettis [1979] describes the potential for bed degradation, bed aggradation, and channel metamorphosis following dam closure. Over a longer period the entire downstream river adjusts its physical and ecological forms and processes [Pettis, 1980]. The time lags involved in the downstream channel adjustments, the sequencing of impacts, and the potential for feedback means that river adjustment to dam closure is a complex response. There have been several studies of the adjustment of coastal rivers in southeastern Australia to dam closure [e.g., Erskine, 1985; Bunn and Erskine, 1994; Erskine, 1996b; Erskine et al., 1999]. Adjustments have included bed aggradation, bed degradation, and channel contraction, depending on the effects on the flood regime of dam closure and operation and depending on the input of sediment from downstream tributaries.

The impacts of land use change on alluvial rivers have been widely reported, including the impacts of deforestation [e.g., Rai and Sharma, 1998], forest fires [e.g., White and Wells, 1979], and mining [e.g., Graf, 1979]. In southeastern Australia the removal of native forest and the disturbance of the catchment by introduced sheep, cattle, and rabbits led to the development of extensive gully networks and the entrenchment of previously discontinuous streams [Eyles, 1977]. These changes that resulted from European settlement around 150 years ago had a greater impact on gully incision than any other change in the last 10,000 years [Prosser and Winchester, 1996] and delivered large volumes of sediment to upland rivers. Significant volumes of sediment have been deposited in the lower reaches of many rivers affected by upstream gully erosion: both gravelly sands in the channel itself and finer sediments across the floodplain [Wasson et al., 1998]. As the postdisturbance sediment progresses downstream, new river reaches are affected by sediment deposition, altering substrate size and major bed forms such as pools and riffles and degrading instream habitat [Prosser et al., 2000].

Decadal and longer-term climate variations can cause flow regime changes that are substantial enough to cause detectable changes in sediment regimes and river morphology. In eastern New South Wales, Australia, a climate shift in the mid-1940s increased flood magnitudes leading to channel expansion at the expense of adjacent floodplains [e.g., Erskine and Bell, 1982; Erskine and Warner, 1988; Erskine, 1996a; Warner, 1992] and in many rivers the removal of the fine top-stratum sediment from floodplain surfaces (floodplain stripping) [Warner, 1997; Nanson and Erskine, 1988]. Here we examine the historical changes to sediment supply and sediment transport capacity in the Coxs River downstream of Lyell Dam. There has been increasing concern about the condition of the river, especially because of widespread sand deposition but also because of prolonged periods of low flow, excessive algal growth, and widespread invasion of the channel by woody weeds. The focus of recent investigations has been on flow regulation and diversions as the prime cause of river degradation; in this paper, however, we consider the relative importance of land degradation, historical climate variations, and dam closure to changes in the sediment supply and sediment transport capacity of the Coxs River.

2. Study Area

The Coxs River drains a catchment area of 2630 km² in eastern New South Wales, Australia, and flows into Lake Burrarorang, the major Sydney water supply reservoir created by Warragamba Dam on the Nepean River, which has inundated the lowest 20 km of the Coxs River valley (Figure 1). The upper catchment consists of broad, flat, mature valleys that have a general outlet to the Macquarie Basin to the west, while downstream the broad, flat valleys have been trenched by deep, juvenile gorges [Craft, 1928]. The eastern boundary of the catchment is an elevated sandstone block which rises in places to 1100 m above sea level. Between the Jenolan and Kowmung Rivers is the generally level Jenolan Plateau (average elevation ~1200 m above sea level) of soft Silurian rocks trenched by deep gorges [Craft, 1928]. The Coxs River itself is underlain by granites.

The Coxs catchment has a cool temperate climate with a mean annual rainfall at Lithgow of 876 mm. Rainfall varies strongly across the catchment largely because of the topography. Stations on the eastern catchment boundary have mean annual rainfalls in excess of 1400 mm, while the spatially averaged mean annual rainfall for the entire catchment is 911 mm based on the climate data and interpolation routines of the ANUCLIM software [Hutchinson, 1989].

The vegetation of the Coxs catchment is dominated by native forest, especially the southern half which is mostly national park. However, extensive areas of native and improved pastures occur in the middle and upper catchment (Figure 1). The native riparian vegetation has been cleared along much of the river, stock have access to many parts of the channel, and introduced willows (Salix spp), blackberry (Rubus fruticosus), and broom (Genista spp) are common in the channel and on the river banks.

The population of the catchment is ~21,000, with 12,000 living in Lithgow and the remainder mostly in the towns of Katoomba, Blackheath, and Mount Victoria. In the upper catchment the Coxs River Water Supply Scheme, which includes Thompsons Creek (27.5 × 10⁶ m³), Wallerawang (4.3 × 10⁶ m³), and Lyell (33.5 × 10⁶ m³) reservoirs, was commissioned in 1982 to supply cooling water to two coal-fired power stations (Figure 1), although substantial diversion did not commence until 1991. Most of the water diverted for cooling is lost to evaporation, although small flows are returned to the river between Wallerawang and Lyell Reservoirs. Pipelines and pumping stations allow both power stations to be supplied with water from any of the three reservoirs. There are no diversions, return flows, or regulation downstream of Lyell Dam, and so the net effect of the scheme on the flow regime of the lower river is determined by the flow releases from Lyell Dam. The
assessments of river response reported here are therefore for the 83 km of river channel between Lyell Dam and the Kelpie Point gauging station. Kelpie Point is a few kilometers upstream of Lake Burragorang and immediately upstream of the junction with the Kowmung River which drains mainly national park (Figure 1).

3. Hydrologic Regime

The hydrology of the Coxs River has been altered in historical times in at least three separate ways. First, substantial changes in mean annual rainfall have occurred; second, changes in forest cover have altered the patterns and amounts...
of catchment runoff; and third, river flows have been diverted and regulated by the Coxs River Water Supply Scheme. The magnitude of the first and last of these changes has been assessed using a daily rainfall-runoff and streamflow model. The model was developed by the New South Wales Department of Land and Water Conservation using the Integrated Quantity Quality Model [Simons et al., 1996]. Flow data from the Lithgow (1960–1984), Island Hill (1981–1984), and Kelpie Point (1962–1984) gauges were used to calibrate the model. Separate conceptual rainfall-runoff models were calibrated to predict the incremental catchment inflows to these gauges, using the Australian Water Balance Model [Boughton, 1988]. Daily rainfall data from the Lithgow climate station were used to predict Lithgow gauged flows, and daily rainfall data from the Little Hartley climate station were used to predict the incremental inflows between Lithgow and Island Hill and between Island Hill and Kelpie Point. While rainfall volumes vary strongly across the catchment, the temporal pattern is less variable. The use of only two rainfall stations proved adequate for capturing these temporal patterns; the spatial variations in rainfall volumes are adequately captured by the flow records. All three rainfall-runoff models used monthly evaporation data from the Bathurst Agricultural Research Station (latitude 33°26′, longitude 149°34′), the closest climate station to Lithgow that collects evaporation data. The monthly evaporation data were used by developing a relationship between the number of rain days in a month to the monthly evaporation at the Bathurst station and applying this relationship to the Lithgow and Little Hartley stations to estimate monthly evaporation values.

The parameters of the rainfall models were calibrated using the shuffled complex evolution algorithm of Duan et al. [1992]. The objective function used for the parameter optimization was the coefficient of efficiency of the log-transformed modeled and gauged daily flow duration curves (equation (1)):

\[
E = \frac{\sum_{i=1}^{n} (G_i - \bar{G})^2 - \sum_{i=1}^{n} (M_i - G_i)^2}{\sum_{i=1}^{n} (M_i - \bar{G})^2},
\]

where \(G_i\) are the sorted log-transformed gauged daily flows, \(\bar{G}\) is the mean of the log-transformed gauged daily flows, and \(M_i\) are the sorted log-transformed modeled daily flows. Muskingum flow routing [Miller and Cunge, 1975] was used between stations, and routing parameters were manually adjusted as they had only minor influence on the model calibration.

Model performance was assessed using the coefficient of efficiency of the sorted log-transformed daily flows (the objective function for calibration, (1)), the coefficient of efficiency of the sequential (unsorted) untransformed daily flows, and the modeled:gauged ratio of total flow volumes (Table 1). These measures of model performance indicate a good to very good matching of gauged and modeled daily flow duration curves and a reasonable matching of flow sequences. By optimizing to the flow duration curve, the best possible prediction of the frequency distribution of flows is obtained, with some loss of model performance in flow sequence matching. This calibration method is appropriate for this study where it is the frequency distribution of sediment transport capacities rather than their sequence that is important. The ratios of total flow volumes indicate that the model slightly overpredicts total flow volumes at Lithgow and Island Hill and slightly underpredicts total flow volumes at Kelpie Point. The generally poorer model performance at Island Hill is a result of the short gauging record. After calibration the model was run for an 85 year (1900–1984) historic climate sequence to simulate both the long-term flow regime under scheme operating rules followed between 1991 and 1999 (current scheme operation) and the long-term flow regime without the regulation and diversion influences of any of the scheme reservoirs (without scheme).

Analysis of the historic records of annual rainfall at Lithgow using cumulative deviations from the long-term annual mean show mean annual rainfall in the period since the mid-1940s has been substantially higher than for the period prior to the mid-1940s (Figure 2). This change is consistent with the changes in mean annual rainfall that occurred across much of eastern New South Wales [Pittock, 1975; Cornish, 1977]. The hydrologic modeling (without scheme) indicates that the increases in rainfall after the mid-1940s translate to increases in total flows of between 69% (below Lyell Dam site) and 105% (at Island Hill) (Table 2). Under the current regime of scheme operation the rainfall increases would have translated to increases in total flows of between 123% (at Kelpie Point) and 153% (below Lyell Dam site) (Table 2). Under scheme operation the total flow below the Lyell Dam is less, so the relative increase in flows volumes due to the rainfall increases would have been greater. The mid-1940s climate shift affected flows of all magnitudes (e.g., Figure 3a, below Lyell Dam site); however, it is the increases in the high flows that dominated the change in total flow and the changes in sediment transport capacity (discussed in section 4).

The construction and operation of the Coxs River Water Supply Scheme has greatly reduced flows downstream of Lyell Dam. Hydrologic modeling using the full climate sequence (1900–1984) indicates that current scheme operation reduces mean daily flows (and hence total volumes) by between 44% (below Lyell Dam) and 11% (at Kelpie Point) and reduces median daily flows by between 95% (below Lyell Dam) and 34% (at Kelpie Point) (Table 3). The operation of the scheme has affected all but the highest flows (e.g., Figure 3b, below Lyell Dam). For the 1900–1945 climate the simulated reduction in total flow due to current scheme operation is between

<table>
<thead>
<tr>
<th>Gauge Station</th>
<th>Coefficient of Efficiency of Sequential Daily Flows</th>
<th>Coefficient of Efficiency of Sorted, Log-Transformed Daily Flows</th>
<th>Modeled:Gauged Ratio of Total Flow Volumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithgow</td>
<td>0.77</td>
<td>0.91</td>
<td>1.015</td>
</tr>
<tr>
<td>Island Hill</td>
<td>0.64</td>
<td>0.84</td>
<td>1.023</td>
</tr>
<tr>
<td>Kelpie Point</td>
<td>0.63</td>
<td>0.95</td>
<td>0.937</td>
</tr>
</tbody>
</table>
57% (below Lyell Dam) and 16% (at Kelpie Point) (Table 4), and for the 1946–1984 climate the simulated reduction in total flow due to current scheme operation is between 35% (at Lyell Dam) and 8% (at Kelpie Point) (Table 4). The overall change in total flows since 1945 has been an increase of between 10% (below Lyell Dam) and 86% (at Kelpie Point) (Table 5), with the increase in moderate to high flows resulting from the mid-1940s climate shift partially offset by the decrease in low flows resulting from scheme operation (e.g., Figure 3c, below Lyell Dam).

Substantial reductions in forest cover have occurred in the catchment, and because evapotranspiration from forests is higher than from grasslands [Zhang et al., 1999], this will have increased runoff volumes. The changes in daily streamflow, flood magnitude, and sediment transport capacity resulting from changes to forest cover in the catchment have not been quantified because forest clearing was complete before flow-gauging records began, preventing accurate hydrologic simulation of these changes.

Assessments of the reductions in forest cover do allow the change in total annual flow to be estimated. The current extent of native forest is 55% above the Lithgow gauge station, 49% between the Lithgow and Island Hill gauge stations, and 98% between the Island Hill and Kelpie Point gauge stations (Figure 1). The journals of explorers in the early 1800s describe the presettlement vegetation as heavily forested hillslopes, opening into more open woodland and some areas of grassland in the wider valleys [Flannery, 1998], suggesting that, overall, the catchment was at least 90% forested. Between 1820 and 1840 many land grants were allocated for grazing, and in subsequent decades, forests were cleared to increase the available grazing land and to provide timber for homesteads, fences, and stockyards [Barrett, 1993]. Using a semiempirical relationship developed by Zhang et al. [1999], this degree of forest clearing is estimated to have increased annual streamflow by >50%. The relationship of Zhang et al. [1999] predicts annual evapotranspiration as a function of annual rainfall and the percentage of forest cover and was parameterized using least squares fits to data sets from >250 catchments across 29 countries.

This substantial increase in annual runoff does not imply an equivalent increase in flood magnitude. During extreme rainfall events the evapotranspiration term in the short-term water balance is small relative to the rainfall input and runoff output. Once the soil moisture store is full, nearly all rainfall is translated into streamflow, and land use effects are negligible. Hence, while minor increases in flood magnitude may have resulted from forest clearing, most of the streamflow increases are likely to have occurred as increases in moderate flows. Nonetheless, the affect of forest clearing on daily flows and on sediment transport capacity remains unquantified in this analysis.

**Table 2.** Ratios Comparing the 1946–1984 Period to the 1900–1945 Period for Total Flow and Sediment Transport Capacity

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Flow Ratio</th>
<th>Sediment Transport Capacity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Scheme</td>
<td>Current</td>
</tr>
<tr>
<td>Lyell Dam</td>
<td>1.69</td>
<td>2.53</td>
</tr>
<tr>
<td>Island Hill</td>
<td>2.05</td>
<td>2.50</td>
</tr>
<tr>
<td>Kelpie Point</td>
<td>2.03</td>
<td>2.23</td>
</tr>
</tbody>
</table>

*Average by reach for sediment transport capacity is 2.93 for without-scheme flow conditions.

*Average by reach for sediment transport capacity is 3.40 for current flow conditions.
4. Sediment Transport Capacity

Sediment transport capacity per unit channel width \( (q_s) \) can be modeled by the following function of discharge per unit channel width \( (q) \) and channel slope \( (S) \) (to approximate the hydraulic roughness) [Julien and Simons, 1985]:

\[
q_s = k q^{\beta} S^\gamma, \quad (2)
\]

where the \( k \) includes parameters describing hydraulic roughness and the bed sediments (e.g., size and density) and \( \beta \) and \( \gamma \) are empirically derived exponents. From a review of published sediment transport data from rivers, overland flow, and laboratory flumes, Prosset and Rustomji [2000] found median values of both \( \beta \) and \( \gamma \) to be 1.4. Total sediment transport capacity \( (Q_s) \) can therefore be expressed as the following function of channel slope, discharge \( (Q) \), and channel width \( (w) \):

\[
Q_s = k w^{-0.6} q^{1.4} S^{1.4}. \quad (3)
\]

Relative spatial or temporal changes can be investigated even when all of the terms cannot be evaluated, provided the terms that are not included can be reasonably shown to be spatially or temporally constant. The most difficult parameter to evaluate in (3) is the hydraulic roughness component of \( k \). Hydraulic roughness cannot be measured directly, and even indirect estimates are difficult to obtain. At transporting discharges, hydraulic roughness is likely to be dominated by channel shape and the extent of woody vegetation in the channel and on lateral benches. Sediment texture will be a minor component of hydraulic roughness at high flows. Detailed surveys have been made of 10 channel cross sections in the first 33 km downstream of Lyell Dam, and these show little downstream variation in channel cross-section shape. Substantial downstream changes in the extent of woody vegetation both in the channel and on lateral benches were observed in the field. Exotic willows (mainly, *Salix fragilis*) have invaded the much of the first 50 km of channel (and lateral benches) downstream from Lyell Dam, increasing hydraulic roughness. The lower 33 km of river is largely free of willow invasion, and aerial video of the river revealed only minor variations in channel form. Hydraulic roughness in this lower section is therefore treated as spatially and temporally variable. The hydraulic effect of the willows in the first 50 km of channel downstream from Lyell Dam is very difficult to quantify and so has been omitted from the analysis. This simplification will mean that for current conditions the sediment transport capacity in this section of river will be overestimated.

The surveyed cross sections show only a small variation (±20%) in total channel width (including flood channels and lateral benches) and no downstream trend in channel width. Cross sections have not been surveyed in the lower 50 km of channel, but approximate measurements from 1:25,000-scale topographic maps and from aerial video of the entire channel do not reveal any substantial downstream increase in total channel width over the 83 km river section and reveal only minor spatial variation in total channel width. In alluvial rivers, width typically covaries with slope, and the lack of substantial variation in width in the lower Coxs River is attributed to the extent of bedrock and the degree of valley confinement that generally limit channel widening. The small spatial variation in width and relatively weak dependence of sediment transport capacity on width (equation (3)) means treating width as spatially constant is a reasonable simplification to estimating relative changes in sediment transport capacity.

With width and \( k \) treated as constant, relative changes in sediment transport capacity will be determined by changes in discharge and slope. Reach-averaged channel slopes were measured from 1:25,000-scale maps. Between Lyell Dam and Kelpie Point the river drops by 590 m, and channel slopes range from 0.0016 to 0.1 (Figure 4). This sixty-fold variation in slope and the strong dependence of sediment transport capacity on slope mean the downstream patterns in sediment transport capacity are likely to be dominated by slope variations. Daily flows were modeled at Lyell Dam, Island Hill, and Kelpie Point. Incremental increases in drainage area between gauge stations were used to estimate the downstream pattern of daily discharge increase. Daily flows are of a sufficient resolution to distinguish individual rainfall events in this catchment and so are sufficient to capture the differences in both flow magnitude and variability between different climate or reservoir manage-

| Table 3. Modeled Mean and Median Daily Flows Under Without-scheme (WS) and Current (C) Flow Conditions for the Period 1900–1984* |
|--------------------|---------|---------|---------|---------|
|                    | WS      | C       | Ratio   |
| Lyell Dam          | 1.61    | 0.90    | 0.56    |
| Island Hill        | 3.46    | 2.75    | 0.79    |
| Kelpie Point       | 6.35    | 5.65    | 0.89    |
|                    | 0.61    | 0.03    | 0.05    |
|                    | 1.07    | 0.46    | 0.43    |
|                    | 1.87    | 1.23    | 0.66    |

| Table 4. Ratios Comparing the Current Regime to the Without-Scheme Regime for Total Flow and Sediment Transport Capacity |
|-----------------|---------|---------|---------|---------|---------|---------|
| Total Flow Ratio | Lyell Dam  | 0.43    | 0.65    | 0.50    | 0.69    |
|                  | Island Hill | 0.70    | 0.85    | 0.73    | 0.87    |
|                  | Kelpie Point | 0.84    | 0.92    | 0.87    | 0.93    |

*The effects of land use change have not been modeled. Flows are given in m³ s⁻¹.

bAverage by reach sediment transport capacity ratio (C/WS) is 0.85.
Table 5. Ratios Comparing the Current Regime Under 1946-1984 Climate to the Without-Scheme Regime Under 1900-1945 Climate for Total Flow and Sediment Transport Capacity

<table>
<thead>
<tr>
<th></th>
<th>Total Flow Ratio</th>
<th>Sediment Transport Capacity Ratio*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyell Dam</td>
<td>1.10</td>
<td>1.41</td>
</tr>
<tr>
<td>Island Hill</td>
<td>1.74</td>
<td>2.62</td>
</tr>
<tr>
<td>Kelpie Point</td>
<td>1.86</td>
<td>2.51</td>
</tr>
</tbody>
</table>

*Average reach sediment transport capacity is 2.56.

Using (3) and the simplifications described above, the relative downstream changes and relative temporal changes (current flow regime to without-scheme regime) in sediment transport capacity in the Coxs River were investigated (Figure 5). The sediment transport capacity ratios are expressed relative to the mean sediment transport capacity of all reaches under long-term (1900-1984) without-scheme flow conditions. Figure 5 shows that sediment transport capacity in the lower Coxs River does not simply decrease with distance downstream as is the case in simple models of river form. Sediment transport capacity varies spatially by a factor of nearly 500, largely as a result of slope variations. The average total annual discharge only varies by a factor of 2 over the 83 km, and so the discharge increase with distance and the spacing of tributary streams do not greatly influence the downstream patterns in transport capacity. The reaches with the lowest sediment transport capacity are, first, the 6 km immediately downstream of Lyell Dam; second, two short reaches (2.3 km) before the 20 km mark and one longer reach (4.5 km) after the 20 km mark; and, finally, the 12 km reach from 38 km to 50 km (Figure 5).

Although the slope between 70 km and 76 km is again very low, there are significant additions of flow by this point, so that the sediment transport capacity here is higher. The highest capacity reaches are those between 50 km and 60 km downstream from Lyell Dam.

The mid-1940s climate shift increased the average sediment transport capacity of the without-scheme flow regime by a factor of 2.9 (Table 2 and Figure 5a). Under current scheme operation the climate change would have increased the average sediment transport capacity by a factor of 3.4 (Table 2). Dam closure caused an average reduction in sediment transport capacity of only 15% relative to long-term (1900-1984) without-scheme conditions (Table 3 and Figure 5b). The reduction in sediment transport capacity due to dam closure reduces with distance downstream as the relative reduction in flow becomes less, even though discharge variations do not dominate the downstream changes in sediment transport capacity (Table 3 and Figure 5b). At Lyell Dam the reduction in sediment transport capacity due to dam closure is 38%, but at Kelpie Point the reduction is only 9% (Table 3). The combined effect of the mid-1940s climate shift and dam closure has been to increase the average sediment transport capacity by a factor of 2.6 (Table 5 and Figure 5c).

5. Sediment Supply

In the last 150 years the sediment supply to the lower Coxs River is likely to have been modified by widespread gully erosion in the catchment, by the mid-1940s climate shift that remobilized floodplain deposits, and by closure of Lyell Dam that cut off sediment supply from the upper catchment.

The extent and severity of gully networks across the catchment has been mapped by the New South Wales Department of Land and Water Conservation using aerial photographs from the early 1980s and limited field surveys. The gullies are mostly less than 1 km in length, have small cross sections, and have drainage areas <3 km². The networks are densest in the catchments of midcatchment tributaries, such as the 51 km².
Figure 5. Modeled relative sediment transport capacity in the lower Coxs River as a function of distance downstream from Lyell Dam showing (a) the effect of the climate shift, (b) the effect of the scheme operation, and (c) the combined effects of the climate shift and the dam operation. Transport capacities are relative to the modeled long-term (1900–1984) average transport capacity for the without-scheme flow regime.
Ganbenang Creek subcatchment where the density of the gully network is 0.56 km km\(^{-2}\). Because extensive forested areas remain, the average density of gully erosion in the Coxs River catchment is low (Table 6). From the gully mapping, gully lengths were determined for each tributary catchment and intertributary area and totaled to show the accumulation of gully length with distance down the Coxs River (Figure 6). There are 215 km of gullies in the catchment above Kelpie Point, 197 km of which are upstream of Island Hill (Table 6). The strong spatial patterns in land degradation mean that postdisturbance sediment supply in the Coxs River cannot be predicted as a simple function of increasing drainage area.

To assess the relative change in sediment supply, gully erosion rates were compared to background surface erosion rates in the catchment. This required converting gully lengths to sediment volumes using average gully dimensions. The gully mapping indicates the depth class (0.5–1.5 m, 1.5–3 m, 3–6 m, or >6 m) of individual gullies, and distance weighting by the average depth value for each class (and using 7.5 m for the top depth class) provided an estimate of 2.0 m for the average gully depth in the Coxs catchment. This figure is comparable to the average depth of ~2.5 m (range 0.5–4 m) for 44 gullies at Bredbo in southern New South Wales, where gully depth was found to be unrelated to drainage area but, rather, reflected the depth of alluvium or colluvium [Prosper and Winchester, 1996]. Gully widths in the Coxs River catchment have not been surveyed; however, field observations suggest they are of similar dimensions to the gullies surveyed by Prosper and Winchester [1996] in the Bredo catchment. The gully mapping in the Coxs catchment indicates gully drainage areas of <3 km\(^2\), and measurements by Prosper and Winchester [1996] show the average width of gullies in the Bredo catchment with drainage areas of <3 km\(^2\) is 2.0 m (range 0.5–5.5 m). Using the estimated gully depth of 2.0 m and an assumed average width of 2.0 m, it was estimated that a total of 860,000 m\(^3\) of sediment has been eroded from gullies in the catchment upstream from Kelpie Point.

To determine average annual sediment yields, the sediment volumes were averaged over an estimated 140 years of delivery. This delivery period was assumed from the knowledge that gully initiation usually begins soon after forest clearing has become widespread [Eyles, 1977], that forest clearing in the Coxs River catchment began in the middle of the nineteenth century, and that long-term flood records for farther downstream in the Hawkesbury-Nepean River system indicate that between 1860 and 1900 more floods were experienced than in the 60 years before or after [Hall, 1927; Riley, 1980]. As forest clearing in Coxs catchment was already widespread by 1860, it is likely that it was during the period 1860 to 1900 that the gully network began to develop. The period 1860–2000 was therefore selected for averaging sediment delivery. The gullies are all well connected to the stream network, and so complete delivery of eroded material was assumed.

The average annual yield for the catchment above Kelpie Point is 6143 m\(^3\) yr\(^{-1}\), and the average specific yield is 4.2 m\(^3\) km\(^{-2}\) yr\(^{-1}\). The specific yield for Ganbenang Creek, the most gullied subcatchment, is 16.1 m\(^3\) km\(^{-2}\) yr\(^{-1}\). Because of small gully cross sections this is not a high long-term yield from gully erosion. A specific annual gully erosion yield of 72 m\(^3\) km\(^{-2}\) yr\(^{-1}\) was calculated for a 102 year period in the 45 km\(^2\) Waggarah Creek catchment in southeast New South Wales by Prosper et al. [1994], and a specific annual gully erosion yield of 118 m\(^3\) km\(^{-2}\) yr\(^{-1}\) was calculated for a 115 year period in the 80 km\(^2\) Fernances Creek catchment in eastern New South Wales by Melville and Erskine [1986]. In these cases, although the gully network densities were comparable to those in the Coxs River catchment, the gully cross sections were consider-
Figure 7. Spatially and temporally averaged relative sediment supply in the lower Coxs River as a function of distance downstream from Lyell Dam. Sediment supply is relative to the average predisturbance surface erosion rate. The top curve shows the ratio of the sum of gully and surface erosion loads to the surface erosion load; it indicates the relative increase due to land degradation ignoring sediment trapping by Lyell Dam. The middle curve shows the relative sediment supply assuming surface erosion only is trapped by Lyell Dam, that is, assuming all gully-derived sediment from upstream of the dam passed the dam site before closure. The bottom curve shows the relative sediment supply assuming all upstream surface and gully erosion sediment has been trapped by Lyell Dam since closure.

ably larger: ~15 m² and 20 m² in Wangarah Creek and Fernances Creek, respectively. For comparison with background surface erosion rates the volumetric yields were converted to mass yields using a bulk soil density of 1.5 t m⁻³.

The predisturbance and ongoing surface erosion rates in the Coxs River catchment (Figure 6) were estimated using a regression relationship between yield (t yr⁻¹) and catchment area (km²) derived by Wasson [1994]. This relationship (yield = 1.6(drainage area^0.78), r² = 0.85) is based on presettlement average annual sediment yields estimated by stratigraphic methods in 11 catchments (all <500 km²) on the southern tablelands of New South Wales. The average specific surface erosion yield for the Coxs catchment upstream of Kelpie Point was estimated as 0.35 t km⁻² yr⁻¹.

Comparing the sum of the gully and surface erosion yields (average sediment supply after catchment disturbance) to the surface erosion yield (average sediment supply before catchment disturbance) provides an indication of the relative increase in sediment supply due to land degradation alone (top curve in Figure 7), that is, without any reduction due to Lyell Reservoir. The value at 0 km on Figure 7 is the relative increase in sediment supply for the upper 381 km² of the catchment (above Lyell Dam). The relative increase varies between ~16 and 27; the highest relative increase occurs between 38 and 47 km downstream from Lyell Dam and is coincident with the lowest sediment transport capacities. On average, land degradation has increased the erosion rate by a factor of 19.5. In comparison, Neil and Fogarty [1991] used data from 12 gullied catchments and four undisturbed catchments (all <5 km²) to estimate that discontinuous gully networks increased sediment yield 11-fold, and continuous gully networks increased sediment yield 64-fold.

Channel expansion and stripping of floodplain alluvium in many eastern New South Wales catchments, including rivers in the Hawkesbury-Nepean Basin, have been linked to the mid-1940s climate shift by comparisons of historical channel cross-section surveys [e.g., Erskine, 1986; Warner, 1991], photogrammetry of historical aerial photographs [e.g., Department of Public Works, 1987], and field observations [e.g., Warner, 1995]. Historical channel surveys are not available for the Coxs River downstream of Lyell Dam, but comparisons between aerial photographs from the 1930s to 1950s and field observations and aerial video of the current channel reveal the development of parallel and meander chutes especially upstream of Island Hill. Field observations also indicate that most of the fine alluvium has been removed from floodplains, stripping floodplain surfaces down to cobble and boulder bases. Small areas of finer sediment remain, held in place by the roots of native river oaks (Casuarina cunninghamiana). While there is sufficient evidence from the historical aerial photographs to reasonably attribute these changes to the mid-1940s climate shift, there is insufficient quantitative information to accurately determine volumes of sediment mobilized. Field observations indicate that chutes are ~3–4 m wide and 1 m deep, and there are estimated to be many kilometers of chutes between Lyell Dam and Island Hill. The stripping of 1–4 m depth of fine alluvium has been reported for floodplain surfaces in other coastal New South Wales locations [Warner, 1997], and crude calculations based on these values suggest that the volume of sediment derived from chute formation and floodplain surface stripping in the Coxs River may be a similar order of magnitude to the volume of sediment derived from gully erosion. However, because of the high uncertainty in the estimates of alluvium mobilized since the mid-1940s climate shift, these volumes have not been included in this analysis of relative changes in sediment supply.
The closure of Lyell Dam in 1982 stopped all transport of coarse sediment from the upper catchment to the lower river. The sediment supply to the lower river is now from the mid-catchment tributaries and from the reworking of main channel alluvium. The proportion of the sediment derived from gully erosion in the upper catchment that was transported past the dam site before dam closure is unknown; hence the exact impact of the dam on sediment supply is unknown. The smallest effect the dam can have had on sediment supply is to have cut off delivery of all coarse sediment derived from surface erosion in the upper catchment (middle curve in Figure 7). This assumes that all of the coarse sediment derived from gully erosion in the upper catchment was transported past the dam site before closure. This scenario represents a 5% reduction in sediment supply below the dam, reducing to <2% by Kelpie Point. The greatest effect the dam can have had on sediment supply is to have cut off the delivery of the coarse sediment derived both from surface erosion and from gully erosion in the upper catchment (bottom curve in Figure 7). This assumes that in the period between the initiation of gully erosion and the construction of the dam, no sediment from upper catchment gullies was transported past the dam site. This represents a 100% reduction in sediment supply below the dam, reducing to 31% by Kelpie Point. Even under this scenario of complete sediment trapping by the dam, the current sediment supply to the river by Kelpie Point is still over 13 times higher than before catchment disturbance. The actual effect of the dam on sediment supply is expected to be closer to the smaller reduction in sediment supply; that is, a substantial fraction of the gully-derived sediment from above the dam site is expected to have been transported past the dam site. Over 15% of the gully erosion above the dam site has occurred in Farmers Creek which now flows into Lyell Reservoir. At least this fraction of the gully-derived sediment from above the dam site can reasonably be expected to have been transported past the dam site.

6. Discussion

In the last 150 years the sediment regime of the Coxs River has changed as a result of forest clearing and consequent gully erosion, historical climate variations, and dam closure. By far the largest relative change in the sediment regime of the Coxs River has been the nearly 20-fold increase in sediment supply due to gully erosion. Spatial patterns in gully erosion across the catchment mean that sediment supply cannot be predicted as a simple function of drainage area. The mid-1940s climate shift is estimated to have increased the sediment transport capacity by a factor of 2.9, while dam closure has only reduced transport capacity by 15% and sediment supply by between 10% and 25%. Future climate variability is therefore expected to have a greater influence on the sediment regime of the river than any changes to the amounts and patterns of water diversion from the dam. Overall, channel responses will have been dominated by the increase in sediment supply due to gully erosion, rather than the increase in transport capacity due to the mid-1940s climate shift or the relatively minor changes in supply and capacity due to the flow regulation and dam closure.

The actual impact of the changes in sediment supply and transport capacity depends on the relative balance between capacity and supply. The Coxs River is bedrock-dominated but has an alluvial bed in the flatter reaches. The susceptibility of the bedrock reaches to increased supply and/or decreased capacity depends how close they are to the alluvial-bedrock threshold. To compare capacity to supply requires full dimensional evaluation of (3), and as k cannot be measured directly, it must be evaluated by measurements of transport rates. Without transport measurements for the Coxs River an indication of susceptibility was obtained using a value for k derived by Yang [1972] from existing data sets using his unit stream power approach. For (3) in SI units (kilograms, meters, and seconds), the value of k used was $2.5 \times 10^4$ and indicated that for the long-term average natural transport capacity the increases in sediment supply from gully erosion could have caused as much as half the length of the lower Coxs River to cross the threshold from bedrock to alluvial. Field observations by the authors and aerial video have revealed that sand deposition is widespread along much of the lower Coxs River, including many reaches in the national park and downstream of the Kowmung junction. Many reaches that were previously bedrock are now alluvial. The volume of sand that appears to still be stored in channel deposits suggests that many decades will be required for the channel to fully adjust to the pulse of sediment delivered from gully erosion.

The analyses of supply and capacity changes in the Coxs River demonstrate a simple approach for assessing the likely impacts of land degradation, climate variability, and flow regulation on river channel character. Such analyses can be used to identify the major causes of channel change and to guide remedial actions. In the Coxs River, for example, it is clear that environmental flows are not an effective means of rehabilitating the riverbed. Rather, control of sediment sources and the removal of in-channel deposits and/or stabilization with native vegetation are preferred approaches to rehabilitation. Analyses of this type could be extended by detailed surveying of the river channel to determine the volumes and locations of stored sediment. Comparing the volumes of sediment stored to the volumes supplied to the river would enable construction of a sediment budget, allowing dimensional quantification of average transport rates. This would provide more certainty to rehabilitation efforts, as it would allow an estimate of the period required to flush stored sediment from the channel. Quantification of a sediment budget would also provide improved estimates of k in (3) for reconnaissance studies of other rivers.

This study of the Coxs River illustrates the need to assess the relative importance of multiple influences on sediment supply and sediment transport capacity and to assess resulting spatial and temporal patterns in a river's sediment. The requirement to assess multiple influences on sediment supply and transport capacity occurs in many rivers, and the better known Snowy River in southeastern Australia is another obvious example. Interbasin transfers divert 99% of the flow from the upper Snowy River [Snowy Mountain Hydro-Electric Authority, 1993] such that the only flows that pass Jindabyne Dam to the lower Snowy River are controlled low-flow releases. Immediately below the dam, the capacity to transport coarse sediment has been reduced to zero, and the overall sediment trap efficiency of the dam has been estimated as 99.5% [Erskine et al., 1999]. Severe land degradation on the Monaro Tablelands downstream of the dam has delivered large volumes of sand to the channel [Caiotechion et al., 1991], and the patterns of sand deposition along the channel are well documented [Brizga and Finlayson, 1992, 1994]. Although a detailed analysis of the downstream patterns of relative change in sediment supply and sediment transport capacity has not been made, it has been acknowledged [Erskine et al., 1999; Brizga and Finlayson, 1994].
that the current sediment regime and bed condition of the lower Snowy River are a result of both land degradation and dam closure.

The changes influencing the sediment regime of the Coxs River occur in many rivers. Gully erosion of similar or greater intensity to that of the Coxs River catchment has occurred in many southeastern Australian catchments [Prosser and Winchester, 1996] and in other parts of the world [e.g., Cooke and Reeves, 1976; Nachtergaele and Poesen, 1999]. The mid 1940s climate shift that occurred in the Coxs River catchment has been noted for most of eastern New South Wales [Pittock, 1975; Cornish, 1977], and other historical climate variations of hydrological significance have been described by Knox [1993] and Balling and Wells [1990]. The impacts of dams on sediment regimes have been widely studied [e.g., Petts, 1979; Williams and Wolman, 1984] and depend on the flood mitigation ability of the dam. Dams that have a large storage volume relative to the inflow volume and dams that are operated to provide flood storage, reduce flood peaks to a greater extent and hence have a greater impact on the downstream sediment transport capacity. Lyell Dam has a capacity of less than 70% of the mean annual inflow volume, and the minor flood mitigation effect it provides is reflected in the small reduction in downstream sediment transport capacity. Many dams have much larger relative storage capacity and hence a far greater impact on sediment transport capacity. While many rivers will have been influenced by land degradation, climate variations, and dam closure, the relative importance of these changes will vary between catchments.

7. Conclusions

Bedrock-controlled rivers seldom have simple concave long profiles, and large variations in channel slope result in large variations in sediment transport capacity with distance downstream. Land degradation, climate variation, and dam closure can influence river sediment regimes, and where land degradation is heterogeneous across a catchment, spatial patterns in sediment supply result. In the Coxs River, Australia, gully erosion in the upper and midcatchment from the middle to late nineteenth century increased sediment supply by varying degrees along the river, on average, by a factor of 20. A climate shift in the mid 1940s led to an almost threefold increase in sediment transport capacity. Subsequent closure of Lyell Dam in the early 1980s caused a 15% reduction in sediment transport capacity and reduced sediment supply to the lower river by as much as 25%. Dam closure, the most recent and most publicly obvious change, has had only minor relatively impacts on the sediment regime of the river. Many reaches of the Coxs River that were previously bedrock-dominated are now alluvial, primarily as a result of the large increase in sediment supply from catchment gully erosion. Future climate variations and reductions in gully-derived sediment loads are more likely to affect the sediment regime of the Coxs River than changes to the levels of abstraction from Lyell Dam. This study of the Coxs River highlights the need to assess the relative importance of a range of natural and anthropogenic influences on river sediment regimes as a guide to effective rehabilitation.

Acknowledgments. The New South Wales Department of Land and Water Conservation funded aspects of this work and kindly provided access to data. Carole Williams and Andrew Davidson from New South Wales Department of Land and Water Conservation undertook the hydrologic modeling, and Andy Marr from Snowy Mountains Engineering Corporation assisted with interpretation of the modeling results. Anthony Scott and Andrew Hughes assisted with data analysis, aerial photograph interpretation, and figure preparation. Heinz Buettikofer also assisted with figure preparation. Constructive comments by Peter Hairline and Ian Rutherford and reviews by John Buffington and Robert Ryan improved the manuscript.

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(Received September 30, 2000; revised June 19, 2001; accepted June 19, 2001.)