

OPINION

Post-European changes to the fluvial geomorphology of Bega catchment, Australia: implications for river ecology

GARY J. BRIERLEY, TIM COHEN, KIRSTIE FRYIRS AND ANDREW BROOKS

School of Earth Sciences, Macquarie University, North Ryde, New South Wales 2109, Australia

SUMMARY

1. Within a few decades of European disturbance in the mid-nineteenth century, river character and behaviour were transformed in Bega catchment on the south coast of New South Wales, Australia. Ecological impacts of geomorphic changes to river structure and function throughout the catchment are assessed.
2. At the time of European settlement, many water courses in Bega catchment were discontinuous, with extensive swamps along middle and upper courses. Following a series of direct and indirect human impacts, channels became continuous in the middle and upper parts of the catchment, as extensive valley fills at the base of the escarpment were incised. Along the lowland plain, the channel widened by over 300%, fundamentally altering the relationship between the channel and its adjacent floodplain.
3. Geomorphic changes to river structure have modified habitat availability throughout Bega catchment. The impacts have been least pronounced in headwater streams, but have been dramatic along virtually all river courses beyond the base of the escarpment.
4. Changes in river structure have been directly related to altered riparian vegetation cover, and *vice versa*. As a consequence of changes to river structure, bed substrate calibre (and supply volume/rate) has been modified along most streams.
5. A series of indirect, secondary impacts have modified habitat viability along river courses. Lateral, longitudinal and vertical linkages within the river system have been altered, affecting the transfer of water, sediment, organic matter, nutrients and other biotic interactions.
6. These direct and indirect consequences of geomorphic changes in river structure suggest that ecologists need to adopt a longer-term, catchment-framed view of human disturbance to river ecosystems.
7. Effective, sustainable ecological rehabilitation of river courses is dependent on an understanding of geomorphic processes and determination of appropriate river structure at differing positions in catchments.

Introduction

Conservation of biodiversity in aquatic ecosystems is contingent on maintenance of habitat availability along river courses. In turn, habitat availability is

conditioned by river structure, which is innately determined by the geomorphic character and behaviour of rivers (e.g. Brussock *et al.*, 1985; Gregory *et al.*, 1991; Fisher, 1997; Richards *et al.*, 1997). Anthropogenic disturbance to riparian zones and adjacent slopes, and associated adjustments to flow and bed-load quantity or calibre, can transform the physical character and stability of a river. This can directly modify the character and pattern of riparian vegetation, input of woody debris, and habitat formation.

*Correspondence and present address: Gary J. Brierley, School of Earth Sciences, Macquarie University, North Ryde, New South Wales 2109, Australia.
E-mail: gbrierli@laurel.ocs.mq.edu.au

These changes may induce a range of secondary impacts on ecosystem functioning through changes to water temperature (e.g. Hawkins *et al.*, 1997), availability of light (energy), and the production, processing and retention of nutrients and organic materials in river systems. In many instances, human impacts on river structure have been so pronounced that these undermine the biodiversity of aquatic ecosystems, imposing critical constraints on practical efforts at river rehabilitation (e.g. Brookes & Shields, 1996).

Human impacts on biophysical processes in rivers are dramatically exemplified in Australia, where impacts of human disturbance can be related to a defined pre-disturbance condition. In the last 200 years, the physical structure and function of rivers have been transformed across large tracts of the continent (CSIRO, 1992; Wasson, 1994). In Bega catchment, on the south coast of New South Wales (NSW), landscape changes since European settlement have fundamentally altered river structure throughout virtually the entire catchment (Brierley & Fryirs, 1998; Fryirs & Brierley, 1998a,b; Brooks & Brierley, 1997, in press). Geomorphic changes to the river have effectively destroyed the range of habitat which existed prior to European disturbance. Longitudinal, lateral and vertical transfer of water, sediment, nutrients and organic matter within the river system have been transformed. This paper assesses the implications of changes to the character and linkage of geomorphic processes throughout Bega catchment for the structure and function of aquatic ecosystems. Finally, these insights are used to comment on the potential for river rehabilitation in this catchment.

Geomorphic template of rivers

In thorough reviews of the ecology of Australian running waters, Lake (1994, 1995) highlighted a complex web of interactions which affect freshwater species diversity, influenced by factors such as habitat structure and heterogeneity, disturbance (manifest through changes to the flow and sediment regimes), availability of resources and the strength of biotic interactions. Abiotic control on habitat availability along river courses is essentially determined by the interplay between river geomorphology, riparian vegetation and river hydrology. However, to date, the principles of fluvial geomorphology and the profound changes to river structure which have

taken place since European settlement of the continent have received limited attention in interpretations of 'controls' on riverine ecology and assessment of river health in Australia. Changes to river geomorphology in other parts of the world which have been subjected to anthropogenic disturbance (i.e. virtually everywhere) are unlikely to be significantly less dramatic than evidenced in Australia.

Geomorphic processes determine the structure, or physical template, of a river system, providing the framework upon which a wide range of biophysical processes interact. Channel morphology, sediment character and riparian vegetation (and associated coarse woody debris) are dynamically adjusted, such that change in one variable can modify other parts of the river system (e.g. Cummins *et al.*, 1995; Malanson, 1993). These structural attributes of a river system result in a mosaic of ecological patches along river corridors (e.g. Brussock *et al.*, 1985; Pringle *et al.*, 1988; Salo *et al.*, 1988; Townsend, 1989; Gregory *et al.*, 1991). The diversity, size, density and distribution of different patches, among other attributes, determine the availability of habitat and resources within differing river reaches, affecting nutrient cycling and retention within the system (e.g. Pringle *et al.*, 1988; Townsend, 1989). Instream structural diversity of aquatic species is closely related to active morphodynamics of the river bed (see Statzner *et al.*, 1988; Newbury & Gaboury, 1993). The nature of hydraulic interaction is influenced primarily by bed roughness and flow stage. In turn, these conditions are determined by the grain size distribution and the assemblage of geomorphic features, the pattern of riparian vegetation, and the distribution of coarse woody debris which line the channel bed and margins. The pattern of geomorphic units along river courses is determined by material availability and the capacity of the river to rework sediments in differing reaches (e.g. Brierley, 1996; Montgomery & Buffington, 1997). The greater the structural diversity (or heterogeneity) of a river reach, the greater the availability of niche habitats (Shields & Smith, 1992).

Other than in headwater locations, it is virtually impossible to gauge in detail the pre-disturbance ecological character of rivers since only disconnected remnants remain. Anthropogenic disturbance to riparian zones and adjacent slopes, especially associated with vegetation clearance, the removal of coarse woody debris, and altered patterns of drainage,

have resulted in profound changes to river structure and function. Changes to river morphology, along with altered patterns of water and sediment transfer through river systems, have impacted directly on the formation of habitat and the production of nutritional resources for aquatic ecosystems (Vannote *et al.*, 1980; Brussock *et al.*, 1985; Minshall *et al.*, 1985; Gregory *et al.*, 1991; Kershner & Snider, 1992; Shields & Smith, 1992; Hawkins *et al.*, 1993; Malanson, 1993).

Geomorphic disruptions can profoundly alter the pattern of longitudinal, lateral and vertical linkages of biophysical processes in river systems (cf. Ward, 1989), with a range of direct and indirect implications for the structure and functioning of aquatic ecosystems. Alterations to either the flow or sediment budget may alter the assemblage of geomorphic units, modifying channel geometry and associated instream habitat relations, along with functional relationships between the channel and floodplain. Localized areas of differing geomorphometry may respond differently to the same disturbance regime (Pringle *et al.*, 1988).

The underlying premise of the present manuscript is as follows: if river morphology is a dependent variable to stream biota, then by definition, changes to river form will influence habitat associations along the river course. Changes to river morphology will directly impact on the character and distribution of riparian vegetation and woody debris (and *vice versa*), indirectly impacting on a range of biophysical controls on ecosystem functioning, such as temperature, light (energy), and the processing and retention of nutrients and organic materials. This is perhaps best exemplified by a simple example. If the geomorphic structure of a river system is altered such that pools are infilled with sediment, flow is conveyed downstream more efficiently and water is retained for shorter periods. This directly impacts on species dependent on pools and the long-term viability of pools as refugia.

To date, research on geomorphological controls on habitat availability along river courses has focused almost exclusively on pool-riffle sequences (e.g. Scullion *et al.*, 1982; Brussock *et al.*, 1985; Davies, 1989; Gregory *et al.*, 1991; Jowett, 1993; Harris, 1995). A range of pool-riffle characteristics has been shown to influence habitat availability and viability, such as spacing, width, length, depth, size of substrate, turbidity, temperature and retention of organic

particles (e.g. Davies, 1989; Jowett, 1993). In general, pools and riffles highlight the adaptations of stream biota to slow and fast water habitats. For example, pools are often the preferred habitats for juvenile fish, adult platypus and filter feeders (Grant, 1992; Harris, 1994). However, in most instances, simple pool-riffle associations are irrelevant to Australian rivers since these structural attributes of alluvial, meandering rivers are the exception rather than the norm in the Australian landscape (Brierley *et al.*, 1996). Far more prevalent, in south-eastern Australia at least, are bedrock controlled and/or confined rivers, or water-courses which were discontinuous at the time of European settlement. In the present manuscript, geomorphic disturbance to formerly discontinuous river systems, and associated ecological implications, are demonstrated in Bega catchment, where a series of studies have demonstrated systematic, but inadvertent, changes to river character throughout the river system.

Anthropogenic impacts on river structure in Bega catchment from 1850 to the present

Based on analysis of portion plans from the 1850s and 1860s, along with field examination of river geomorphology and associated sediment sequences, river courses through the middle to upper parts of Bega catchment were discontinuous at the time of European settlement (Brierley & Fryirs, 1998; Fryirs & Brierley, 1998a,b). There were extensive swamps along the middle and upper courses, and a continuous, low-capacity channel along the lowland plain (Fig. 1) (Brooks & Brierley, 1997, in press). The metamorphosis of the lower Bega River occurred within a few decades of European disturbance, triggered by clearance of riparian and floodplain vegetation, and drainage of wetlands and backswamps. A comparison of portion plans from the 1850s and 1860s with archival photographs from the 1890s and early twentieth century indicate that the channel immediately upstream from Bega township widened from around 40 to 140 m (Fig. 2a). This has been confirmed by field analysis of remnant river oaks, *Casuarina cunninghamiana*, which lined the former channel (Brooks & Brierley, 1997). As a response to anthropogenic disturbance, pools were infilled and up to 2 m of sand accumulated on floodplains which were previously dominated by

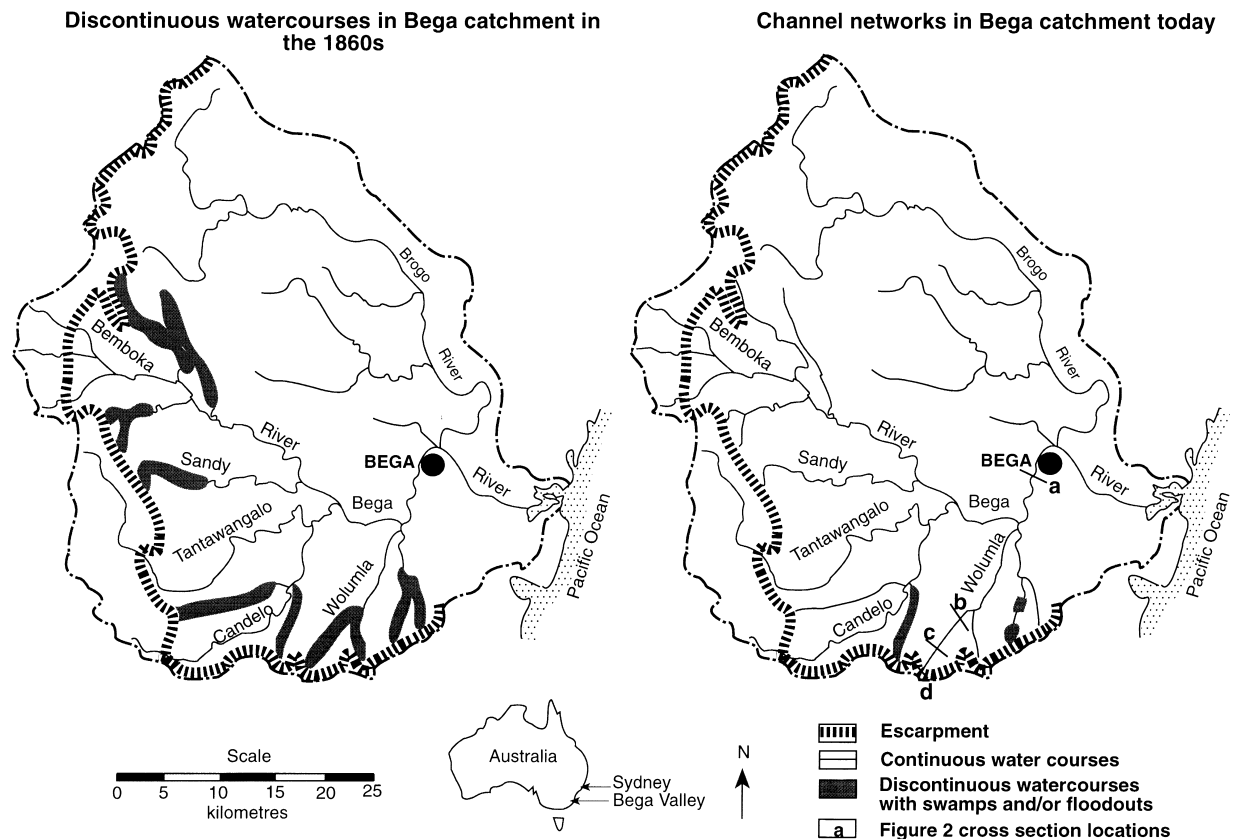


Fig. 1 Distribution of discontinuous, swampy watercourses in Bega catchment mapped from portion plans from the 1860s and evident in the field today.

silt. Detailed field investigations have indicated that relatively little change to river structure occurred between 1900 and 1960 (Brooks & Brierley, in press). However, since the 1960s, the lowland channel has become choked by willows and other exotic vegetation. A complex pattern of bars and islands has developed within a braided channel planform (Brooks, 1994). These structural changes to river morphology have fundamentally altered physical process interactions with riparian vegetation and coarse woody debris, impacting on the structural and ecological controls that these elements have on aquatic ecosystems.

River metamorphosis in Bega catchment has not been restricted to the lowland plain. At the time of European settlement, upland sections of various

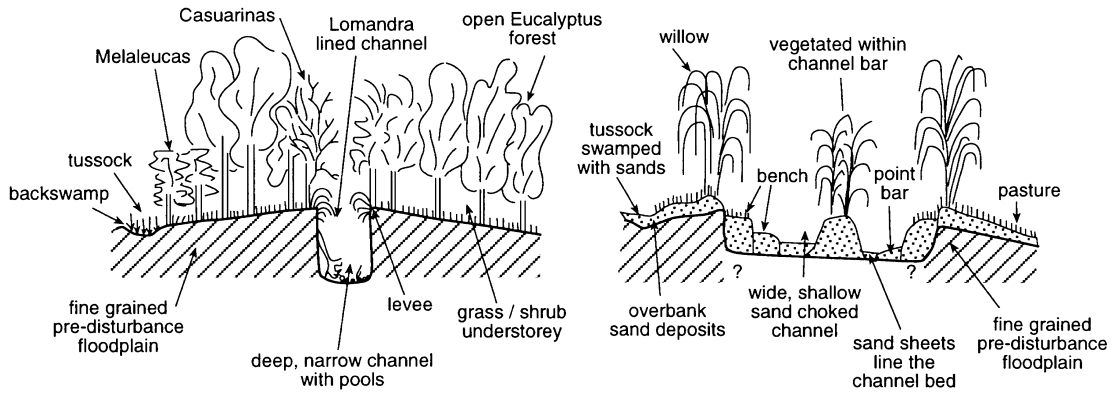
subcatchments comprised continuous valley fills (Fig. 1) (Fryirs, 1995; Fryirs & Brierley, 1998a,b). Within a few decades of settlement, drainage of upland swamps and a range of indirect responses to early agricultural pursuits triggered headcut incision into these large sediment sources (Brierley & Fryirs, 1998, in press; Fryirs & Brierley, 1998a,b, in press). Incision was quickly followed by extensive channel expansion, supplying massive volumes of sediment to the lower catchment. Incised channels are locally more than 10 m deep and 100 m wide. Channel floors are functionally detached from their perched valley fills (Fig. 2c). Many of the ecological values of these former swamps have been lost and the few tributary swamps which remain in the catchment have been cleared of their native vegetation cover.

Fig. 2 Channel adjustments in Bega catchment from pre-disturbance times (left hand side) to the present (right hand side). The analysis has been completed from portion plans, air photographs, field mapping and sedimentological evidence. The four sites are located on Figure. 1. A discussion of the channel changes is presented in the text.

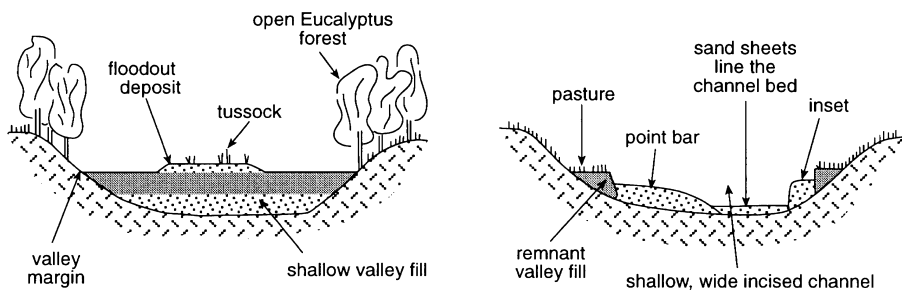
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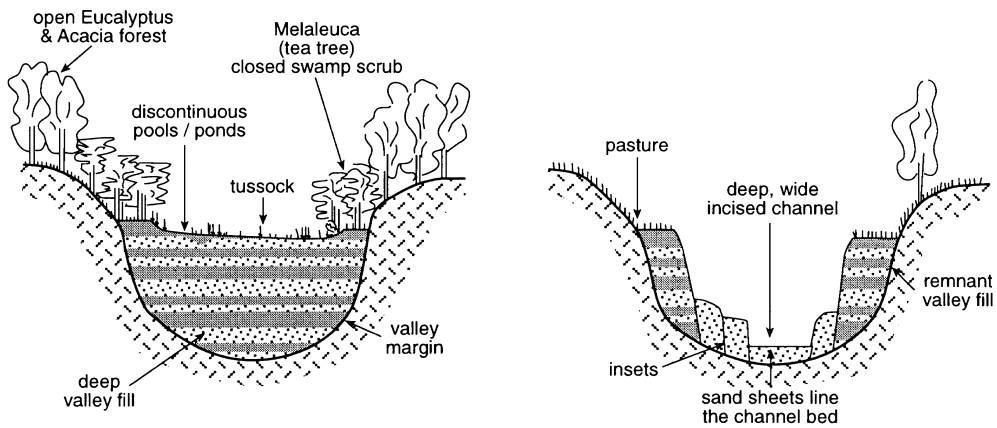
a) Lower Bega River



b) Mid catchment - Wolumla Creek



c) Base of escarpment - Wolumla Creek



d) Headwaters - Wolumla Creek

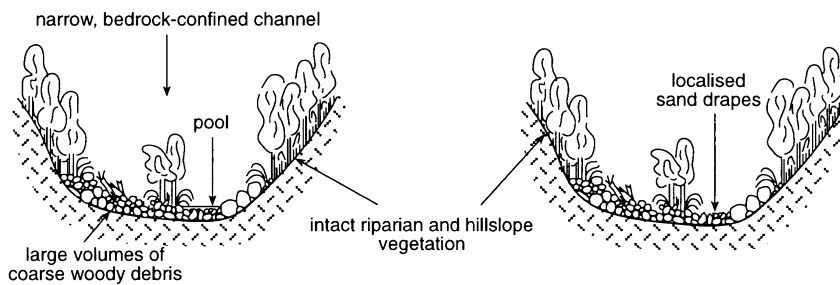


Fig. 2.

River reaches that connect the base of the escarpment to the lowland plain are largely bedrock-confined. These parts of the catchment have acted as sediment transfer or throughput zones (Brierley & Murn, 1997; Fryirs & Brierley, 1998b). Channel bed elevation has risen and fallen at different stages in the passage of sediment slugs (*sensu* Nicholas *et al.*, 1996; see Fryirs & Brierley, 1998b; Fig. 2b). Only patches of riparian vegetation remain in mid-catchment. Native seed sources are significantly depleted, limiting the potential for regeneration of native vegetation, whereas exotic vegetation, notably willows, have expanded dramatically. Today these reaches are severely degraded in ecological terms.

Headwater streams have been the least affected reaches of Bega catchment in the period following European settlement. These reaches lie within the escarpment zone or are located in dissected plateau country atop the escarpment. Forestry practices have been active since the turn of the century, but there has been only partial forest clearance (and subsequent regrowth) and riparian vegetation has largely been left intact (Fig. 2d). River structure is much more intact in these lower order streams than elsewhere in Bega catchment.

Indirect changes to biophysical processes in river systems in Bega catchment

While changes in river morphology have directly affected habitat availability along river courses in Bega catchment, a series of secondary, indirect impacts on aquatic ecosystem functioning have been triggered by changes to the longitudinal, lateral and vertical connectivity of biophysical processes.

Longitudinal connections

In most instances, human disturbance to river systems has been noted in terms of impacts of flow regulation, which has longitudinally disconnected fluvial landscapes and their associated aquatic ecosystems (e.g. Sedell *et al.*, 1990; Walker *et al.*, 1992; Xu Jionxin & Shi Changxing, 1997). In many ways, human impacts on aquatic ecosystems in the non-regulated Bega catchment differ substantively from changes to river character documented elsewhere since the longitudinal connectivity of biophysical processes has increased throughout the catchment in the post-

settlement period. This reflects the transformation of discontinuous watercourses to continuous ephemeral channels, greatly reducing the heterogeneity of river structure along river courses. Although the direction of change in Bega catchment is different to that demonstrated elsewhere, the ecological consequences are no less devastating.

Incision of former swamps in the middle and upper courses of tributary trunk streams, and subsequent gullyng of lower order drainage lines has resulted in a much more continuous channel network throughout Bega catchment (Brierley & Fryirs, 1997). The transition from discontinuous channels to continuous watercourses has increased the capacity of the system to transfer flow, sediment, and organic matter and other nutrients. For example, base flow contributions from the middle and upper catchment have been reduced. Given the extensive deposition of sand sheets, a large percentage of flow is now subsurface. The mixed load river of the pre-disturbance era, in which fine grained materials were retained in upland and mid-catchment swamps and on the distal floodplain of the lowland plain, has been transformed into a bedload dominated system, which efficiently flushes sand through middle and upper courses, but accumulates sand both instream and on the floodplain along the lowland plain.

Contemporary channel character throughout Bega catchment is more homogenous than prior to disturbance. This has reduced the structural complexity of rivers throughout the catchment, limiting the range of niche habitats along river courses. For example, many of the biotic attributes of swampy, discontinuous watercourses have been lost. Incision of swamp deposits, and the passage of sand slugs have resulted in uniform, sand-sized materials along the bed and banks. Instream flow resistance and the hydraulic ecology of rivers have been fundamentally transformed. These various factors have compromised the ecological diversity of rivers in Bega catchment.

Lateral connections

Changes to channel form throughout Bega catchment have altered the lateral transfer of water, sediment, organic matter and nutrients from the channel to the floodplain. This effect has varied at differing positions within the catchment. While headwater reaches have experienced few changes, valley fills at the base of the

escarpment are no longer inundated because of deeply incised channels (Fig. 2c). In contrast, flood inundation has increased on the lowland plain, where extensive volumes of sand have aggraded (Fig. 2a). Deposition of coarse sands atop the formerly fine-grained floodplain has partially infilled backswamps. This has changed the linkage of biophysical processes between the channel, floodplain and adjacent wetlands, impacting on the capacity of the lowland plain to act as a nutrient sink, habitat provider and food source.

Vertical connections

The development of a continuous channel network, associated changes to channel-floodplain relationships, and the highly degraded riparian vegetation cover, have altered the depth of the water table along river courses throughout Bega catchment. While the water table has been lowered in the cut-and-fill landscapes at the base of the escarpment, where valley fill deposits have been deeply incised (see Fig. 2c), the water table has effectively been raised in lowland areas of the catchment, where extensive bed aggradation has occurred (see Fig. 2a). These changes, along with the contemporary homogeneity of bed material size (contrasting with the swamps, bedrock pools and discontinuous sand bars of the predisturbance channel), and changes to the sedimentology of surface and subsurface fractions, have modified the function of hyporheic zone processes along rivers in Bega catchment. Any former differences between swamps and continuous channels are now considerably less evident in Bega catchment than these were prior to European settlement. The potential for hydraulic diversity at differing flow stages has been compromised in the relatively smooth, sand-lined contemporary channel.

Implications for river rehabilitation in Bega catchment

Although change is an integral and a natural part of aquatic ecosystems, human disturbance has introduced a source of change that is foreign to the geomorphic and biotic conditions of rivers and floodplains (Whiting, 1993, personal communication). Most Australian rivers are part of highly modified landscapes in which human activities are dominant

(CSIRO, 1992; Wasson, 1994). Dramatic changes to channel and floodplain morphology have been recorded for many river systems in the period following European settlement of the continent. This metamorphosis has taken several forms, ranging from catchment to catchment, and at differing positions within individual catchments. Channel morphology has been altered, in terms of both dimensions and shape, and channel planform has been modified, in terms of channel alignment and/or sinuosity. Riparian vegetation cover has been transformed, as has the connection between channels and their adjacent floodplains. Rates of landscape change, such as floodplain aggradation, have occurred at levels unprecedented the last 5000 years (Brooks & Brierley, 1997). In many instances, these geomorphic changes have altered the downstream and lateral linkages of biophysical processes within river systems.

Changes to river structure have important implications for habitat availability, viability and aquatic ecosystem functioning. A series of direct and indirect ecological consequences of geomorphic changes to river character and behaviour have been reported throughout Bega catchment. The geomorphic impacts of European disturbance were most pronounced within a few decades of settlement (Brooks & Brierley, 1997; Fryirs & Brierley, 1998). Essentially, the critical changes to the landscape had occurred by 1900. Other than responses of the lowland channel to invasion by exotic species since the 1960s, river morphology has changed little since the early decades of this century. Channel adjustments since the first air photographs, taken in the early 1940s have been trivial. This implies that notional 'recovery' of channels has been underway for at least 50 years (*sensu* Simon, 1989, 1992; Brookes & Shields, 1996). The effectiveness of channel recovery has been constrained by several factors, such as the lack of riparian vegetation cover and the modified sediment budget of the catchment (Fryirs & Brierley, 1998b). While upstream reaches are effectively starved of sediment, such that it will take thousands of years for the valley fill trench at the base of the escarpment to re-fill (Fryirs & Brierley, 1998a,b), the lower Bega River has been over-supplied with sand, a large proportion of which is now trapped by willows and other forms of exotic vegetation (Brooks & Brierley, in press).

From the above, it is inferred that the potential for rivers in Bega catchment to adopt structures which

equate to the pre-disturbance condition is virtually zero over 'management' timeframes. Effectively, many changes to river structure must be considered to be irreversible (CSIRO, 1992) and the linkage of geomorphic processes within the catchment has been transformed. The capacity for the aquatic ecology of this system to recover is equally constrained. Most of the riparian zone downstream of the escarpment in Bega catchment has limited habitat availability. River courses are characterized by homogenous sand sheets, with highly degraded riparian vegetation cover. Other than in headwater reaches, the nature of ecosystem functioning has been irreconcilably altered. Remnant aquatic ecosystems in these upland areas beyond the escarpment are functionally disconnected from the remainder of the catchment. The diverse habitat structure of former river courses have been replaced by a limited range of habitats, making the contemporary river system depauperate *in relative terms*.

The structural attributes of the contemporary river throughout Bega catchment, such as channel geometry, planform, substrate and the diversity of geomorphic units (e.g. pools, levees and backswamps), are so fundamentally different to the pre-disturbance condition that former habitat values cannot realistically be established as target conditions for river rehabilitation. While it would be nice to think that the changes to river morphology reported in the present study document an unusual response to European disturbance of catchments, there are a number of river systems in south-eastern Australia where equivalent stories could be unravelled (e.g. Brierley & Murn, 1997; numerous examples in Rutherford & Walker, 1996). The systematic, but inadvertent, destruction of habitat along these river courses makes existing remnants all the more precious in terms of their conservation and heritage values.

Finally, geomorphic changes to river structure and function provide potential insights into the altered ecological potential of aquatic ecosystems. Once direct linkages between geomorphic attributes of rivers and habitat availability are determined, long-term changes to river geomorphology can be used to infer changes to the biodiversity of river systems. This makes research into remaining remnants of near-intact river courses especially relevant, particularly when considering the impacts of human disturbance on the freshwater biology of river courses (cf. Triska, 1984). There are no self-evident reasons why many of the

impacts of European disturbance on rivers in the Bega catchment of south-eastern Australia should be more pronounced than human impacts on rivers elsewhere in the world.

Acknowledgments

This work commenced on an ARC Small Grant and has been followed up by support from LWRRDC Project MQU1. Two Honours theses (by A.B. and K.F.) documented the post-settlement history of river changes in Bega catchment. Fiona Nagel assisted with the literature review for this document. Insightful referee comments by David Montgomery helped to tighten the argument and improve the presentation of the manuscript.

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(Manuscript accepted 5 October 1998)