Progress in Physical Geography 29, 1 (2005) pp. 27–49

Did humid-temperate rivers in the Old and New Worlds respond differently to clearance of riparian vegetation and removal of woody debris?

Gary J. Brierley[1,*], Andrew P. Brooks[2], Kirstie Fryirs[1] and Mark P. Taylor[1]

[1] Department of Physical Geography, Macquarie University,
North Ryde NSW 2109, Australia
[2] Centre for Riverine Landscapes, Griffith University,
Nathan Qld 4111, Australia

Abstract: Clearance of riparian vegetation and removal of woody debris are perhaps the most pervasive of all forms of human disturbance to river courses. Geomorphic consequences of these impacts have varied markedly from river system to river system, a result of variations in catchment setting, climate, geology, sediment supply and evolutionary history. In this paper, geomorphic responses of rivers to rapid, systematic clearance of riparian vegetation in New World (colonial) societies are contrasted with changes associated with gradual, piecemeal, yet progressive clearance of riparian forests in northern Europe (the Old World). It is postulated that the dramatic nature of river metamorphosis experienced in landscapes such as southeastern Australia records the breaching of fundamental geomorphic thresholds in a different manner to that experienced in Old World landscapes.

Key words: channel changes, human disturbance, riparian vegetation, threshold, woody debris.

I Introduction

> With the disappearance of the forest, all is changed … The soil is bared of its covering of leaves, broken and loosened by the plough, deprived of the fibrous rootlets which held it together, dried and pulverized by sun and wind, and at last exhausted by new combinations. The face of the earth is no longer a sponge, but a dust heap, and the floods which the waters of the sky pour over it hurry swiftly along its slopes, carrying in suspension vast quantities of earthy particles which increase the abrading power and mechanical force of the current, and, augmented by the sand and gravel of falling banks, fill the beds of the streams, divert them into new channels and obstruct their outlets … From these causes, there is constant

---

*Author for correspondence: School of Geography and Environmental Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand. E-mail: g.brierley@auckland.ac.nz

10.1191/0309133305pp433ra

> degradation of the uplands, and a consequent elevation of the beds of watercourses and of lakes by the deposition of the mineral and vegetable matter carried down by the waters. The channels of great rivers become unnavigable, their estuaries are choked up, and harbours which once sheltered large navies are shoaled by dangerous sandbars. (Marsh, 1864: 186–87)

The quote above, taken from George Perkins Marsh's (1864) classical treatise entitled *Man and nature*, is indicative of the recognition in the mid–late nineteenth century of the interrelated set of impacts that vegetation clearance induced on river courses. Building on a series of case studies in northern Africa, the French Alps and northern Italy, Marsh (1864) demonstrated the critical nature of ground cover as a control on geomorphic processes, the linkages between hillslope and river processes, and off-site impacts of disturbance set within a catchment context. He goes on to discuss how the nature, pattern and rate of changes to these processes are likely to vary in New World situations, where the impacts can be more readily observed, emphasizing that the best place to measure the effects of land use impacts is in continents such as Australia, where European settlement occurred much later than elsewhere (Marsh, 1864: 49). In this article, a synthesis is provided of the lessons learnt from contemporary research into the impacts of clearance of riparian vegetation cover and removal of woody debris along river courses in parts of the New World, framing these observations in context of prevailing debates on long-term human-induced changes to rivers in the Old World.

Most rivers throughout the world have been subjected to some form of human disturbance (Heede, 1972, 1981; Kellerhals and Miles, 1996). Perhaps the most pervasive form of disturbance is that associated with the direct and indirect consequences of changes to riparian vegetation cover and removal of woody debris. Putting aside variations in scale, climate, geology and topography, and the variable geomorphic role of riparian vegetation and woody debris in differing environmental settings (e.g., Hupp and Osterkamp, 1996; Gurnell *et al.*, 2002), the question posed in this paper is: were geomorphic responses of rivers to the clearance of riparian vegetation and removal of woody debris in the Old World consistent with patterns and rates of river metamorphosis following human disturbance in the New World, where clearance was much more rapid and systematic over large areas? Prior to assessing the differential geomorphic responses of rivers to changes to riparian vegetation cover and removal of woody debris in the Old and New Worlds, their variable geomorphic roles in different environmental settings are summarized. This is followed by a brief review of the ways in which riparian vegetation and woody debris influence river morphology and an appraisal of the longer-term evolutionary context that underpins the geomorphological consequences of human-induced changes to riparian vegetation cover.

II Geographic variability in the geomorphic role of riparian vegetation and woody debris

The evolution of forests and the associated input of woody debris into rivers extends back over the last 400 million years (Schumm, 1968). Indeed, the first appearance of meandering stream deposits in the geologic record coincides with the evolution of land plants, marking a transition from braided depositional environments characterized by rapidly shifting channels over largely unimpeded valley floors (Schumm, 1968; Cotter, 1978). Late Cenozoic changes in global vegetation patterns imparted substantial variability to the role of riparian forests and associated woody debris in rivers in differing parts of the world. For example, whereas parts of eastern Australia have been continuously forested for over 100 million years, only a few European rivers maintained forest refugia during glacial maxima (Montgomery and Piégay, 2003). Modern forests cover around one-third of the Earth's land surface. In some settings, significant human-induced changes to forests have occurred over at least the last 6000 years. Forests in southern Europe were already confined to mountainous areas by classical times (Marsh, 1864; Darby, 1956). In historic times, humans have reduced global forest cover to about half its maximum Holocene extent, and eliminated all but a fraction of the world's aboriginal forests (Montgomery and Piégay, 2003).

The geomorphic role of riparian vegetation and woody debris is quite different in humid-temperate or tropical settings, given the nature and abundance of riparian forests relative to, say, arid and semi-arid climates, whether hot or cold (arctic) desert conditions. Notable differences in geomorphic process activity are observed in river systems characterized by no vegetation or systems with grass, shrub or tree cover (whether in the form of a corridor or a fully developed riparian forest) or in systems with swampy vegetation. Hence, disturbances to riparian vegetation cover may bring about profound changes to the pattern and rate of geomorphic activity, impacting on the nature and extent of geomorphic adjustments and the capacity of river systems to recover (e.g., Wolman and Gerson, 1978). Further complications are presented by differences in tree/forest structure and related issues of vegetation size, root structure and whether, as a function of its density, the wood floats once it falls into a river (e.g., Abernethy and Rutherfurd, 1998). For example, widely spreading or multiple-stemmed hardwoods are more prone to forming snags than accumulating as racked members of large log jams because they extend laterally as well as beyond their bole diameter (Montgomery and Piégay, 2003). In contrast, coniferous wood debris tends to produce cylindrical pieces that are more readily transported through river systems, resulting in local concentrations of log jams. While the decay rate of wood in tropical rivers is rapid, temperate streams may retain the same pieces of wood for several thousand years (Nanson *et al.*, 1995).

This paper does not focus on the geomorphic role of riparian vegetation and woody debris in different environmental settings. To minimize this acknowledged variability, emphasis in our analysis focuses on river responses to variable rates of clearance of riparian vegetation and removal of woody debris in systems that previously were characterized by near-continuous riparian forests in humid-temperate settings of the Old and New World, focusing on Europe and North America/Australia, respectively. As noted in the following section, until recently the geomorphic role of riparian vegetation cover as a determinant of river forms and processes in these settings has been barely appreciated or examined.

III The geomorphic role of riparian vegetation and woody debris

Although geomorphic responses to vegetation clearance have been noted for some time (e.g., Marsh, 1864), our understanding of the direct process-based roles played by riparian vegetation and woody debris as controls on river forms and processes has emerged only in the past two decades. Prior to the 1980s, only a few studies had highlighted linkages between riparian vegetation and river morphology (e.g., Mackin, 1956; Zimmerman *et al.*, 1967; Nanson and Beach, 1977; Graf, 1978; Charlton *et al.*, 1978). Indeed, Hickin (1984) suggested that the science of fluvial geomorphology was flawed because of its failure to incorporate the vegetation component into fluid hydraulics and geomorphic theory. In a similar vein, Montgomery and Piégay (2003: 1) highlight the neglected significance of the geomorphic role of woody debris in river systems in their recent editorial, in which they comment:

> No doubt about it, wood complicates fluvial geomorphology. It messes up nice tidy streams, complicates quantitative analyses, invalidates convenient assumptions, and opens new questions about how different contemporary channels are from their pristine state. It is no coincidence that modern fluvial geomorphology developed through the study of channels

> lacking a substantial load of wood debris (Leopold *et al.*, 1964) and there is little mystery as to why geomorphologists sought to study rivers or river reaches where wood does not exert a significant influence on channel morphology and processes. As a consequence, many of the empirical relationships used to describe various components of river system behaviour must be viewed as characterising modified channel morphology.

In recent years, however, an increasing body of theoretical and empirical work has demonstrated the significance of riparian vegetation and woody debris as controls on river morphology and behaviour.

Through controls on increased bank shear strength, and reduced boundary layer shear stress, riparian vegetation exerts a significant control on channel size and shape (Zimmerman *et al.*, 1967; Smith, 1976; Thorne, 1990; Millar and Quick, 1993; Abernethy and Rutherfurd, 1998; Millar, 2000). Empirical studies have shown that channels with dense bank vegetation (i.e., trees and shrubs) are on average between 0.5 and 0.7 times the width of an equivalent channel vegetated only by grass (Charlton *et al.*, 1978; Hey and Thorne, 1983, 1986; Andrews, 1984). Theoretical modelling has confirmed these empirical relationships (e.g., Ikeda and Izumi, 1990; Millar and Quick, 1993, 1998; Huang and Nanson, 1997, 1998). Other research has demonstrated the role of vegetation in enhancing bar and bank stability (Smith, 1976; Hughes *et al.*, 1997; Brooks and Brierley, 2000), while aquatic plants (including mosses and macrophytes), algae and even freshwater sponges may promote the biological stabilization of channel beds (Brown and Quine, 1999). Li and Shen (1973) demonstrated from flume studies that flow resistance associated with in-channel vegetation can reduce bedload transport rates by more than 90%. Alternatively, vegetation incursions into channels may increase flow roughness, reduce flow velocities, induce wash-load deposition and stabilize in-channel sediment deposits (e.g., Petts, 1984; Thorne, 1990; Abt *et al.*, 1994). A nonlinear relationship has been demonstrated between hydraulic resistance due to vegetation and flow stage (Li and Shen, 1973; Petryk and Bosmajian, 1975; Kouwen and Li, 1980), reflecting flexural rigidity and foliage distribution of the vegetation, among many factors.

Numerous authors have reported channel narrowing and planform adjustments following the colonization of the riparian zone of formerly unvegetated rivers by exotic vegetation (e.g., Hadley, 1961; Nevins, 1969; Schumm, 1969; Burkham, 1972, 1976; Graf, 1977, 1978; Friedman *et al.*, 1996; Brooks and Brierley, 2000). Indeed, vegetative controls on bank strength may influence channel planform and the associated geomorphic structure of rivers (e.g. Mackin, 1956; Brice, 1964; Ferguson, 1987; Marston *et al.*, 1995; Millar, 2000). Hickin (1984) noted that lateral migration rates of channels with vegetated banks were half those of channels with cleared or cultivated riparian zones. Beeson and Doyle (1995) supported these findings, observing that nonvegetated banks were nearly five times more likely to undergo notable erosion compared with vegetated banks. Variations in the height, density and flexibility of aquatic vegetation can also influence reach-scale flow resistance. As such, changes to riparian vegetation may alter floodplain roughness and the surface area exposed to the flow and sedimentation, potentially modifying patterns and rates of depositional processes and the capacity for floodplain reworking (e.g., Brown and Brookes, 1997).

As a general rule, the proportion of vegetation occupying a channel cross-section decreases downstream as the channel becomes larger (Abernethy and Rutherfurd, 1998). Zimmerman *et al.* (1967) suggested that in very small catchments, up to approximately 2 km^2, grass- and sedge-dominated channels are smaller than channels having similar catchment area (or discharge) that are dominated by trees. However, moving downstream, channels dominated by trees are comparatively smaller than channels with equivalent catchment area but only grass and sedge on the banks and floodplain. Similar patterns have been reported elsewhere (e.g., Keller and Tally, 1979; Gregory and Gurnell, 1988; Thorne, 1990; Fetherston *et al.*, 1995; Abernethy and Rutherfurd, 1996, 1998), while Millar and Quick (1993, 1998) acknowledge this phenomenon from a theoretical perspective.

An equivalent set of downstream relationships has been described for the geomorphic role of woody debris. The stability of woody debris and its influence on channel forms and processes reflects the relative size of key wood elements compared with channel size (Montgomery and Piégay, 2003). In low-order channels, woody debris may induce channel blockage ratios as high as 80% (Keller and Tally, 1979; Bilby and Ward, 1989; Thorne, 1990; Nakamura and Swanson, 1993; Keller *et al.*, 1995; Abernethy and Rutherfurd, 1996, 1998). Moving downstream, woody debris tends to be rotated subparallel to the flow (Kochel *et al.*, 1987; Fetherston *et al.*, 1995; Abbe and Montgomery, 1996, 2003), minimizing the blockage ratio but maximizing its role in bar accretion and bank toe protection (Nanson, 1980; Hickin, 1984; Abbe and Montgomery, 1996). Indeed, various studies have demonstrated the influence of woody debris as a control on channel width (e.g., Beschta, 1979; Keller and Tally, 1979; Lisle, 1986, 1995; Nakamura and Swanson, 1993; Keller *et al.*, 1995; Montgomery *et al.*, 1995, 1996; Woodsmith and Buffington, 1996; Hogan *et al.*, 1998; Curran and Wohl, 2003). In wider channels, woody debris may be transported beyond the fall point, and become incorporated into log jams, potentially causing local bank erosion, triggering channel avulsion or cut-off development (e.g., Swanson *et al.*, 1976; Keller and Swanson, 1979; Heede, 1981; Marston, 1982; Hickin, 1984; Gregory and Gurnell, 1988; Piégay, 1993; Nakamura and Swanson, 1993; Fetherston *et al.*, 1995; Montgomery *et al.*, 1995, 1996; Abbe and Montgomery, 1996, 2003; Piégay and Gurnell, 1997; Piégay and Marston, 1998; Cohen and Brierley, 2000; Daniels and Rhoads, 2003). Indeed, the influence of woody debris may even shape the formation of floodplains and valley-bottom landforms, as exemplified by island development (Harwood and Brown, 1993; Abbe and Montgomery, 1996, 2003; Piégay and Gurnell, 1997; Gurnell *et al.*, 2001; Brooks *et al.*, 2003; Jeffries *et al.*, 2003; O'Connor *et al.*, 2003). In addition, woody debris may enhance geomorphic recovery following a major disturbance by increasing roughness and helping to stabilize in-channel sediment (e.g., Cohen and Brierley, 2000).

Many of the geomorphic effects of wood in rivers arise from its influence as an obstruction to local flow hydraulics, as the capacity to create significant hydraulic roughness influences flow velocity, shear stress, bedload transport rates, and reach-average surface grain sizes (Keller and Tally, 1979; Mosley, 1981; Macdonald and Keller, 1987; Shields and Smith, 1992; Smith *et al.*, 1993a, b; Lisle, 1995; Assani and Petit, 1995; Shields and Gippel, 1995; Keller *et al.*, 1995; Buffington and Montgomery, 1999; Manga and Kirchner, 2000; Montgomery and Piégay, 2003). Numerous studies have demonstrated how woody debris, whether as individual pieces, log jams or through its influence as a determinant of the size, type and evolution of in-channel features such as pools, bars and steps, can impart significant hydraulic resistance (Beven *et al.*, 1979; Gregory *et al.*, 1985; Gippel *et al.*, 1994, 1996; Gippel, 1995; Shields and Gippel, 1995; Abernethy and Rutherfurd, 1996; Brooks and Brierley, 2002).

These recent developments in our understanding of vegetative controls on river character and behaviour present an intriguing context with which to reappraise our interpretations of river responses to environmental change, enabling us to more accurately decipher the long-term evolution of river systems and their responses to human disturbance. There is now sufficient, unequivocal evidence to assert that riparian vegetation and woody debris represent fundamental controls on geomorphic river forms and processes. However, depending on an array of factors such as the type of river under investigation, its within-catchment position, its sensitivity to change, and the nature of the vegetation and woody debris, the geomorphological influence exerted by riparian vegetation and responses to its removal, can be remarkably variable. Prior to assessing geomorphic river responses to differing patterns and rates of riparian vegetation clearance in humid-temperate settings of the Old and New Worlds, changes to river morphology induced by altered riparian vegetation cover are placed in their longer-term evolutionary context.

IV Placing geomorphic river responses to vegetation change in a broader context

A series of inherent limitations will always be encountered in making generalized arguments about, or comparisons of, landscape behaviour, as a multitude of factors drive system change over differing spatial and temporal scales. Ultimately, system responses to disturbance are catchment-specific, reflecting the spatial configuration of any particular system, the history, patterns and rates of response to disturbance events, system sensitivity to change and the persistence of factors from the past that continue to exert an influence on contemporary system forms and processes, among many other considerations. In framing the argument presented in this paper, two broad-based aspects of longer-term evolutionary history must be considered in appraisal of system responses to riparian vegetation disturbance in Old World northern Europe relative to the New World in parts of North America and Australia. First, the impacts of glacial history are starkly different in the northern and southern hemispheres, impacting profoundly on the volume and calibre of sediment made available for rivers to transport through the Holocene. Secondly, sediment availability is not solely determined by differences in glacial history. Longer-term geological history and associated topography, as influenced by tectonic setting, present stark differences in landscape setting when comparing system responses to disturbance in Australia relative to Europe or North America. These boundary conditions, along with influences exerted by climate variability and differences in substrate (and other variables), frame the context in which appraisals of system response to clearance of riparian vegetation and removal of woody debris must be made. Throughout the discussion that follows, it should be remembered that reference is being made to differences in the sensitivity of response to disturbance in riparian forests in humid-temperate settings.

Changes to channel dimensions and morphology are brought about by any factor that unsettles the pre-existing balance in impelling and resisting forces along a reach. Adjustments that modify the water-sediment regime or riparian vegetation cover bring about changes to either the *driving forces* that promote change, or the *resisting forces* that inhibit change. Ultimately, changes to river morphology reflect river responses to differing forms of disturbance events, however induced. Natural disturbances may be external (e.g., climate change or tectonic activity) or internal (e.g., slope adjustments along longitudinal profiles). Human-induced disturbances may be direct (i.e., generally purposeful in-channel disturbances) or indirect (i.e., accidental or unintended disturbances, often associated with changes in ground cover at the catchment scale).

Recognizing that a multitude of factors may promote river change, unravelling causality requires that adjustments are placed in their longer-term, late Quaternary, context. In general terms, large shifts in climate over the timescale of glacial cycles bring about profound river changes. However, the sensitivity of alluvial channels, especially reaches that are close to a threshold condition, may ensure that relatively modest climatic changes can trigger major episodes of fluvial adjustment (see Knox, 1993, 1995;

Elliot *et al.*, 1999). At particular stages in their evolution, concatenations of natural processes, such as major bushfires followed by extreme flood events, may conspire to bring about river metamorphosis. It is in this context that human-induced changes to river forms and processes must be viewed.

Knox (1995) identified three primary phases of fluvial activity over the past 20 000 years:

1. *20–14 ka BP*. Major continental ice sheets dominated temperate latitudes, reaching their maximum extent by around 18 ka BP. Large volumes of glacial meltwater and sediment were contributed to proglacial areas, where extensive braided river systems developed.
2. *14–9 ka BP*. Major climatic change saw the transition from glacial to post-glacial conditions. Initially rates of sediment supply were very high during deglaciation, but they progressively subsided as vegetation cover increased. Meltwater sources and increasing precipitation maintained high river discharges. Over time, the reduced sediment load coupled with relatively high discharges brought about a transition from an aggrading to an erosional regime, and an associated shift from braided to meandering in many temperate valleys.
3. *9–0 ka BP*. Sea level has risen by around 130 m since the last glacial maximum. The Holocene marine transgression, which was largely accomplished by around 6 ka BP with relatively minor oscillations in sea level thereafter, brought about different sets of river adjustment in upland and lowland zones of catchments. The global warming that characterized the commencement of the Holocene around 10 ka BP marked the start of a more climatically stable period. During the Climatic Optimum, from 9–4 ka BP, temperatures were higher than those of today across much of the northern temperate zone. This was followed by an episode of climatic deterioration, which became most marked around 3–2.5 ka BP. Two subsequent climatic fluctuations are of note in this period: the Little Optimum centred on approximately 1200 AD and the Little Ice Age around 1550–1700 AD, which was characterized by marked increases in flood activity in some areas.

The extent and impacts of glacial activity were very different in the northern and southern hemispheres. A large proportion of the northern hemisphere was glaciated at glacial maxima. In contrast, across the Australian continent the effects of Quaternary glaciation were marked by changes to sea level and rainfall and temperature regimes, but they were not accompanied by glacial erosion and reworking of materials on a scale comparable with landscape settings in the northern hemisphere. The legacy imposed by sediment stores generated in response to glacial activity continues to be a major factor influencing contemporary landscape forms and processes across much of the northern hemisphere (Church and Slaymaker, 1989). Geomorphic responses of landscapes are particularly pronounced in the 'paraglacial interval', when climate variability is pronounced and vegetation cover is yet to be fully established (Church and Ryder, 1972). The pattern and rate of system adjustment to these enhanced sediment loadings draws into question whether these river systems had established an 'equilibrium' configuration prior to the impacts of human disturbance, as highlighted in the following section.

Nanson *et al.* (2003) present a picture of cyclical but generally declining episodes of fluvial activity for rivers across southeastern Australia during the past full glacial cycle, in direct response to climate and flow regime changes. By the early Holocene, conditions were such that highly sinuous, slowly migrating, suspended load rivers had replaced the much larger, actively migrating mixed- or bedload-dominated channels that had characterized the Murrumbidgee River over the previous 100 000 years (Page and Nanson, 1996).

In this catchment, relatively little change to river morphology is inferred throughout the Holocene. Roughly parallel longer-term climate-induced phases of river adjustment are evident along the lower Wollondilly-Nepean River (Nanson *et al.*, 2003). However, alluvial fills of smaller, relatively confined coastal valleys have preserved a slightly different record of river changes during the Holocene. In part this reflects the impacts of base level adjustments associated with sea level changes. In these systems, the late Pleistocene and early to mid-Holocene (12 000–3000 years ago) was marked by much lower flows than those experienced earlier in the Pleistocene, and was characterized, in broad terms, by lateral reworking and terrace formation (Nanson *et al.*, 2003). Other than a few remnants, the early to mid-Holocene alluvium was reworked, aided by the confining effect of the Pleistocene terraces. A shift in climate in the mid–late Holocene, which ranged from around 4000 to 2500 years ago in different valleys, led to an increase in sediment preservation with the development of relatively stable vertically accreting floodplains alongside well-vegetated channels (Nanson *et al.*, 2003). It was these low-energy, laterally stable rivers that European land clearance so dramatically destabilized (Nanson and Doyle, 1999). However, Brooks and Brierley (2002) and Brooks *et al.* (2003) note that the Thurra and Cann Rivers, adjacent systems in Eastern Gippsland, Victoria have been actively migrating and occasionally avulsing over at least the last 20 000 years. The Thurra River remains remarkably intact today (Brooks and Brierley, 2002), while riparian vegetation removal and a desnagging programme along the Cann River brought about dramatic metamorphosis within a few decades of disturbance (Brooks *et al.*, 2003).

The tectonic stability and generally low relief of the Australian land mass, along with the lack of a glacial history of notable extent and the fact that climate changes along the eastern highlands and coast were not sufficiently extreme as to have caused the transformation of forests, clearly goes a long way to explaining some key differences between channel response in Australia and their glaciated counterparts of the northern hemisphere–whether in Old World countries of northern Europe or New World countries such as the USA. It is in the context of this longer-term perspective that the rate and magnitude of human-induced disturbance must be gauged. This presents a template upon which the nature, rate and consequences of geomorphic river adjustments to different patterns and rates of riparian vegetation clearance in the Old and New World can be contrasted. To address this issue, available literature on river responses to land use changes in Europe is contrasted with river responses to human disturbance in New World (colonial) settings in North America and Australia.

V The imprint of land use changes on Holocene river evolution in Europe

Rivers across Europe changed profoundly at the end of the last glaciation and continued to change, although less dramatically, during the mid–late Holocene, as climate changes affected the hydrology, sedimentology and vegetation cover of floodplains (Starkel, 1991; Brown, 1997). Inherent differences in system configuration, sediment availability and the history of forcing events, among many factors, induced spatial and temporal variability in the transition from braided to meandering or anastamosing channel planforms, but the picture that has emerged indicates that many European rivers had achieved a condition of relative geomorphic stability by the mid-Holocene (e.g., Kozarski and Rotnicki, 1977). It is interesting to note that vegetation-induced variation in bank strength may have strongly influenced the transition in channel planform (Millar, 2000).

Brown (1997) indicates that various river systems in Britain have considerable thickness of Lateglacial and post-Boreal sediments (12 000–10 000 years ago), but relatively few sediments from the early to mid-Holocene

(Boreal and Early Atlantic; 9500–6500 years ago). Inevitably, the distribution of geomorphic processes and the resulting history of sediment accumulation recorded in Holocene alluvial sequences vary in different parts of the landscape. In upland and piedmont zones, where stream powers are higher, incision dominated the post-glacial landscape. In contrast, lowland zones were affected by rising sea levels coupled with low floodplain gradients and low stream power conditions, which resulted in the accumulation of vertically accreted alluvium. Changes to the pattern and rate of overbank sedimentation can be linked directly to vegetation development on floodplains (Brown, 1997). Although alder arrived in Britain before 9000 years ago, it was around 2000 years later that it became a major forest component with most lowland floodplains covered by alder-dominated woodland or alder–hazel woodland by around 6000 years ago (Brown, 1997). Over time, changes to the flow and sediment regime of these rivers transformed bedload-dominated systems into more stable, suspended load systems, commonly with anastamosed channel networks (Brown, 2002). Vegetation and woody debris likely played a critical role in this stabilization phase (e.g., Brown and Keough, 1992; Brown and Quine, 1999).

Since the Neolithic period (around 5500 years ago), human activity has had a significant impact on floodplain forest systems. The stepped, diachronous nature of alder decline in pollen diagrams in the mid-Holocene has been attributed to changes in population density, settlement history and land use control (Brown, 1997). Although progressive changes to forest cover are implied, and some 'smoothing' of sedimentary records has undoubtedly occurred through reworking and bioturbation, riparian vegetation clearance probably occurred in a piecemeal manner. It is inferred that intensive human land use was initially localized and transient. Relatively low rates of population growth in the mid-Holocene were mirrored by gradual land use changes, building out from fragmented areas of forest clearance. Impacts extended over millennia, rather than a few centuries. Major episodes of woodland regeneration are also likely to have occurred (Brown, 1997).

Similar patterns of riparian vegetation changes have been inferred from southern Poland, where the transition from fragmented clearances set within a matrix of alder woodland to large interconnected cleared areas with woodlands isolated in the landscape occurred around 6000 years ago (Godlowska *et al.*, 1987). Starkel (1995) inferred that deforestation associated with the development of arable cultivation and the formation of meadows and willow scrub accelerated the rate of lateral channel migration and induced aggradation. Such assertions imply that channel capacity was not markedly increased; otherwise floodplain inundation rates and concomitant aggradation would have been diminished. Reported changes to these rivers note adjustments to channel morphology and migration rate, and increases in sediment flux, rather than 'catastrophic' metamorphosis. Profound adjustments to river morphology seem to have occurred much later than this initial phase of vegetation disturbance, associated primarily with direct human modification to river courses through channelization programmes thousands of years later.

While there is good evidence from several valleys for an increase in flooding and alluviation during the Roman occupation of Britain (around 2000–1600 years ago), along with mid- to late-medieval alluviation in lowland and piedmont valleys (around 800–500 years ago), remarkably little change to channel capacity, planform shape and lateral stability was experienced along most lowland river systems in Britain (Brown, 1997). The impacts of channel instability associated with simultaneous down-cutting of channels in upper–middle catchments, following the emplacement of channel embankments and human-induced channel narrowing and straightening (e.g., Gregory, 1977; Klimek, 1987; Lewin, 1987), were seemingly damped down through catchments, and did not impose significant responses in lowland reaches.

Starkel (1995) noted that forest clearance on floodplains and an increase in soil erosion in southern Poland during the late Roman and Medieval times caused a tendency towards aggradation, and, in some reaches, the formation of braided channels. Pronounced increases in the yield of fine-grained sediments are inferred for the late pre-historic to medieval period around 500 years ago (e.g., Bork, 1989), with local variability considered to record differing phases of agricultural expansion and agricultural intensity (Brown, 1997). However, these geomorphic adjustments occurred thousands of years after the initiation of human impacts on riparian vegetation cover. Subsistence practices of previous millennia in Old World settings were replaced by feudal land tenure practices that did not promote extensive, synchronous clearance of catchments and river corridors, which would have led to broad-scale landscape transformation.

By the end of the medieval period, deforestation of floodplains for pasture and arable cultivation was almost complete across most of Britain and northwest Europe, the few large exceptions generally being forests preserved for hunting (Brown, 1997). Montgomery and Piégay (2003) refer to manipulation of riparian vegetation cover along European streams during this period as 'riparian gardening', characterized by successive clearing campaigns, tree selection favouring root network growth and efforts to prevent bank erosion.

Although initial endeavours at river clearing and engineering date back to the Roman era (e.g., Herget, 2000), systematic river channelization only began in earnest in the 1600s. Since then, lowland rivers across Europe have been extensively modified by programmes that set out to 'control' natural variability, primarily in the interests of navigation and flood control (Petts, 1989; Brown, 1997). Virtually all lowland reaches were 'homogenized' for human purposes. Seemingly, it was in this interval of direct human intervention to river courses, rather than the indirect responses associated with riparian forest clearance over preceding millennia, that profound river metamorphosis occurred. Societal changes accompanied this phase of landscape adjustment. For example, the industrial revolution and associated drift of the rural poor into cities brought about changes to the intensity of land use, impacting on sediment yield. Examples of the impacts of such changes in land use intensity have been demonstrated through appraisals of the impacts of collectivization on soil erosion across many parts of eastern Europe (e.g., Hanušin, 2000). Rivers have continued to adjust to ongoing changes in their boundary conditions, whether intentional or otherwise.

It is interesting to note that impacts on European riparian forests from the mid-Holocene onwards were manifest primarily through localized removal of riparian vegetation, subsequently leading to wholesale clearance of floodplains, without necessarily impacting directly on the loading of woody debris until the commencement of channelization programmes. Modelling work reported by Brooks (1999a, b) indicates that it is changes to the wood loading in some rivers that triggers profound adjustments in morphology, rather than alterations to floodplain forest cover or bank vegetation *per se*. This may, in part, explain why adjustments to European rivers were relatively small prior to the implementation of channelization and desnagging programmes. It was not until loadings of woody debris were extensively reduced for navigation purposes, and to clear channels to enhance flow conveyance associated with perceived flood inundation problems, that river metamorphosis occurred.

As noted by Montgomery and Piégay (2003), it is difficult to discern the role of wood in temperate fluvial systems of Europe because so little wood has been retained and there are no historical documents that demonstrate the presence or abundance of wood in pristine European rivers. Today, the

British Isles has no river systems with primary (natural) cover on floodplains, very few without channels that have been channelized and highly engineered, and none without some management of flow regimes through reservoirs, weirs or land drainage. As a consequence, most 'lowland British floodplains generally exhibit a greatly reduced set of floodplain processes and relatively low rates of channel erosion and floodplain change, having in effect entombed themselves' (Brown and Quine, 1999: 12). However, as outlined below, analysis of the remaining reaches of river with intact riparian vegetation and associated loads of woody debris in humid-temperate settings of the New World may not provide ideal analogues with which to appraise the history of geomorphic river responses to human disturbance.

In summary, many river courses in northern Europe have been subjected to multiple forms of disturbance over millennia, such that their contemporary character and behaviour reflect the cumulative nature of responses to these impacts. Despite the profound nature of human-induced disturbances to vegetation cover, and associated increases in the fine-grained sediment yield, the record of systematic river metamorphosis over the past 5000 years is quite equivocal, other than those changes associated with channelization over the past 400 years or so. This picture contrasts starkly with landscapes in parts of the New World in which human-induced disturbances to riparian vegetation cover brought about fundamental changes to river character and behaviour within a matter of decades of European settlement.

VI River responses to land use changes in the New World

The history of land use practices in the New World differs markedly from that experienced in the Old World. This reflects, in part, differences in social 'development' associated with the process of colonization of the New World. The very underpinnings of agricultural expansion in the New World were totally different to the aim and intent of practices that had been experienced in the Old World. Large-scale, agricultural 'development', applied with virtual total disregard for pre-existing cultural practices, was driven by state-run (or sponsored) capitalist exploitation for the benefit of the mother lands in the Old World. Despoilation of other parts of the New World, while sparing the homeland, was encouraged by colonial powers, as it brought benefits of new products and resources without the need to consider human or environmental costs.

In addition to fundamental differences in social and political context, clearance of riparian vegetation and removal of woody debris in New World societies was facilitated by far more efficient tools than were available at the time of Old World woodland clearance and land use changes (see Crosby, 1986; Lines, 1991; Flannery, 1994; Diamond, 1997). This is not to say that changes to riparian vegetation cover were brought about by sophisticated and well-orchestrated plans, using well-considered and clearly-targeted practices. Rather, as graphically illustrated in Figure 1, vast tracts of land were cleared in seemingly haphazard acts of bastardry in the nineteenth and twentieth centuries using axes, bullocks, fire and ring-barking practices, with no consideration given to the consequences of these actions.

Riparian zone clearance was an early priority of pioneer settlers, as these were the most fertile and well-watered lands. Initial desnagging efforts minimized the loading of woody debris in rivers to improve navigation; later programmes were applied for flood mitigation purposes or even to remove perceived barriers to fish migration (Triska, 1984; Gregory *et al.*, 1993; Maser and Sedell, 1994; Gippel *et al.*, 1994). New World agricultural systems were more extensive, widespread and synchronous than initial endeavours in the Old World, employing technologically advanced practices. These combined activities brought about rapid landscape changes.

Figure 1 The social underpinnings of expansionist agricultural exploits in the New World differed from the relatively fragmented and piecemeal practices that developed over previous millennia in the Old World. This picture, taken a few years after European settlement of the northeastern Cape of North Island, New Zealand, graphically demonstrates the rape and pillage of landscapes that accompanied pioneer settlements. Haphazard felling of trees was accompanied instantaneously by stocking by non-native animals, impacting dramatically on erosion rates on hillslopes and along river corridors. This photograph, entitled 'Sheep crossing Mata River at Puketoro Station, East Coast, NZ', taken by Frederick Hargreaves (Reference Number 304. 6–20), is used by permission of the Tairawhiti Museum, Gisborne

In contrast to the clearance of European forests over millennia, the vast forests of North America vanished over centuries or even decades, with forest stands near rivers usually the first to be logged (Montgomery and Piégay, 2003). By the late nineteenth century, efforts to clear wood from rivers had extended to the west coast of the USA (Sedell and Frogatt, 1984; Collins *et al.*, 2002). While large rivers were being cleared of snags and jams, smaller tributary streams were cleared through practices such as splash damming, salvage of in-stream wood or stream cleaning (Triska, 1984; Harmon *et al.*, 1986; Maser and Sedell, 1994).

The recent history of newly colonized areas, combined with some documentary records, provides compelling evidence of the changes to river forms and processes. In many instances profound landscape changes were observed within individual lifetimes. Historical evidence derived from analysis of old documents such as explorers notes, maps, surveyors plans, paintings and photographs provides an intriguing, but fragmentary, set of insights into the nature and rate of these geomorphic changes (e.g., Johns *et al.*, 1998; Davis and Finlayson, 1999). In many instances, catastrophic landscape disturbance in the New World brought about river metamorphosis within the first generation after colonization. For example, Knox (1972, 1977, 1987, 1989) identified significant incision, channel straightening and channel widening in the period following deforestation, mining and cultivation practices associated with the sudden replacement of woodlands by arable and pastoral agriculture, following European settlement of Wisconsin, North America. Various studies in the Pacific Northwest of the USA and British Columbia, Canada have shown how rivers in old growth forest settings that retain their full loading of woody debris and riparian vegetation tend to be characterized by single thread meandering channels or anastomosing channels (Abbe and Montgomery, 1996, 2003; Kellerhals and Miles, 1996; Millar, 1998, 2000; Collins *et al.*, 2002). Upon removal of riparian vegetation and woody debris, these channels are rapidly transformed into broad, shallow braided rivers (Kellerhals and Miles, 1996; Millar, 2000).

Despite marked differences in terms of landscape setting, whether viewed in terms of relief, tectonic setting, glacial history or sediment delivery relationships, a remarkably similar set of geomorphic adjustments has been reported following clearance of humid-temperate riparian forests in southeastern Australia. Typically, alluvial or semi-alluvial rivers along the east coast, the eastern tablelands and in the upper reaches of westerly draining rivers have become deeper, wider, straighter and more homogenous in the period since European settlement (e.g., Pickup, 1976; Eyles, 1977a, b; Henry, 1977; Erskine and Bell, 1982; Erskine, 1986; Prosser, 1991; Prosser *et al.*, 1994; Rutherfurd, 1996, 2000; Warner, 1997; Brierley and Murn, 1997; Brooks and Brierley, 1997, 2000; Fryirs and Brierley, 1998, 2001; Page and Carden, 1998; Wasson *et al.*, 1998; Brooks *et al.*, 2003).

In many instances changes to river geomorphology in southeastern Australia were initiated along the lowland course of the river – the reach first subjected to European disturbance (Brooks and Brierley, 1997, 2000). For example, contributors to the Hunter Royal Commission in 1870 (Moriarty, 1869) described the channel capacity of the Hunter River, north of Sydney, as doubling in size during their lifetime. In a similar vein, in 1803 Governor King called for vegetation removal along the lower course of the Hawkesbury-Nepean River, near Sydney, to be discontinued (Lloyd, 1988). This implies that within 15 years of European settlement of Australia, conversion of the original riparian forest community to one dominated by pasture grass had significantly reduced bank shear strength, as well as altered in-channel resistance characteristics, bringing about dramatic transformations in river morphology. The fundamental changes to channel boundary conditions caused by the initial riparian vegetation disturbance set in place a sequence of events still being experienced today. Irreversible geomorphological changes have ensued, at least over timescales of centuries (e.g., Fryirs and Brierley, 2001; Brooks *et al.*, 2003; Brooks and Brierley, 2004). For example, within a few decades of direct human disturbance to the riparian vegetation cover along the Cann River in East Gippsland, Victoria, coupled with a desnagging programme, channel capacity increased by 700%, channel depth increased by 360%, there was a 240% increase in channel slope, and there was a 150-fold increase in the rate of lateral channel migration (Brooks *et al.*, 2003). Numerous thresholds have been crossed as a result of historical channel changes, particularly the relationship between average length of woody debris pieces and channel width and exceedance of critical bank height once incision was initiated. Profound changes to patterns and rates of sediment flux have ensued, with marked differences in downstream coupling and associated residence times for sediment storage from catchment to catchment.

The critical issue for the argument presented here is that parallel forms of geomorphic river response to disturbance of riparian vegetation cover have been observed in New World settings of North America and Australia, despite self-evident differences in their geomorphological settings. In this manuscript we contend that human disturbance to riparian vegetation has been a more forceful agent of change over the last few centuries, effectively over-riding other environmental controls. However, the long-term consequences of these changes may vary markedly along river courses in North America relative to Australian rivers, as the potential for geomorphic recovery in these different settings is starkly different, reflecting critical differences in sediment storage along river courses and the rate of sediment generation and transfer.

VII Why did rivers in the Old and New World respond differently to the clearance of riparian vegetation and removal of woody debris?

Our capacity to interpret the geomorphic responses of river systems to the clearance of riparian vegetation is constrained, in large part, by the lack of undisturbed reference sites and the incomplete preservation of alluvial sequences. Even across much of the New World, few river systems retain an intact riparian forest and associated loading of woody debris. Given this shortcoming, our insights into the nature, patterns and rate of geomorphic adjustment to human disturbance are often inferential, and the link between cause and effect must be implied rather than directly proven. Theoretical models that incorporate both bank vegetation and woody debris as components of bank strength and hydraulic roughness (e.g., Millar and Quick, 1993, 1998; Shields and Gippel, 1995; Huang and Nanson, 1998) show good agreement with empirical observations of river change when the bank vegetation is removed or modified and when woody debris is removed, and as such provide a rational means of corroborating the field evidence, such as it is.

We contend that prior to human disturbance, geomorphic adjustments in systems with an intact riparian forest were localized and were mediated by resisting components induced by the vegetation cover and loading of woody debris, such that river systems were able to re-equilibrate whenever they were subjected to 'natural' disturbance events (Brooks and Brierley, 2002). The inherent roughness of these riparian landscapes was such that thresholds for geomorphic change were virtually unattainable and floods were unable to bring about river metamorphosis. Pronounced geomorphic change could only occur if the landscape was 'sensitized' through changes to these resisting elements. This required a very unlikely set of circumstances, such as concatenations in which a series of large floods immediately followed a major fire. Detailed analyses of floodplain deposits along alluvial reaches of the Cann and Thurra Rivers in East Gippsland, Victoria, indicate that such scenarios have not occurred in this part of southeastern Australia over at least the last 20 000 years (Brooks and Brierley, 2002; Brooks *et al.*, 2003). Even if such unlikely circumstances should eventuate, these systems had sufficient potential for geomorphic recovery, given within-system roughness, the availability of seed sources and the fact that disturbance was not system-wide (in contrast with subsequent systematic catchment-wide clearance of hillslope and riparian vegetation). In other words, we postulate that the inherent resilience of these valley floors ensured that they were subjected to progressive aggradation, but such behaviour was no longer sustainable once core resisting components of river structure were removed (Montgomery *et al.*, 1996; Brooks and Brierley, 2002; Brooks *et al.*, 2003). Post-disturbance, these systems are now characterized by progressive degradation (cf. Erskine, 1999).

Undoubtedly there are some examples of rivers in steep, sandy settings where thresholds of stability are exceeded in the absence of direct channel or riparian zone disturbance (e.g., Cohen and Brierley, 2000). However, examples such as this are rare, and represent one extreme of the population of river styles and responses to natural disturbances.

The near-instantaneous reduction to the buffering capacity of riverscapes in New World settings following the removal of vegetative roughness elements effectively lowered fundamental threshold conditions that determine bed level stability and critical bank height (e.g., Thorne and Furbish, 1995; Brooks *et al.*, 2003), such that rivers became highly sensitive to change. As a consequence, flood events that brought about minor perturbations under intact vegetation conditions were much more geomorphologically effective under altered boundary conditions. Exceedance of threshold conditions brought about fundamental shifts in river character and behaviour. Along many river courses the primary initial response was channel incision, followed by lateral expansion (Schumm *et al.*, 1984). In this scenario, the progressively enlarging channel is increasingly able to concentrate flow energy at flood stage, further enhancing erosional activity, and the channel becames decoupled from its floodplain (cf. Elliot *et al.*, 1999).

The short lag time between disturbance and metamorphosis, typically measured in terms of a few decades, ensured that once critical trigger events were experienced it was exceedingly difficult for systems to recover. The systematic nature of riparian vegetation clearance, along with the fact that vegetation regrowth was seldom possible (whether associated with stocking rates or subsequent land management practice), almost entirely negated the opportunity for future recruitment of woody debris and associated geomorphic recovery mechanisms. In some instances recovery was further inhibited by sediment exhaustion. In these situations, geomorphic changes experienced over a remarkably short interval induced river responses that are effectively irreversible over timeframes of centuries or even millennia (Fryirs and Brierley, 2001; Brooks and Brierley, 2004). Once threshold conditions were breached, a completely different set of river-forming processes was established under altered channel and catchment boundary conditions.

The implication presented here postulates that piecemeal disturbance of riparian vegetation cover along rivers in the Old World enabled progressive adjustments and/or recovery to occur over millennia, and fundamental threshold conditions that prompt river metamorphosis were not breached prior to the implementation of channelization programmes. Inevitably, evidence for such responses may have been swamped or ameliorated by climate-induced signals.

Ultimately, environmental changes and anthropogenic activities act concurrently in determining the nature, timing and pattern of river changes. The relative influence of these factors is likely to vary in each catchment, given their unique configuration, pattern of linkages and history of landscape-forming events. Unfortunately, unravelling these histories of geomorphic river adjustment to human disturbance will always remain conjectural, with generalities masked by system-to-system variability and nonexistent or incomplete historical records. In addition, much of the evidence for geomorphic changes has been subsequently completely eroded, buried or built upon.

Despite these limitations, the geomorphic evidence presented in this paper does not indicate that river systems in the Old World 'fell apart' following disturbance to riparian vegetation cover in a way that has been evidenced in various parts of the New World. If profound river metamorphosis did occur following clearance of riparian vegetation, substantive evidence would surely have been found to support such dramatic river changes, even if it is fragmentary. Viewed in this manner, we contend that progressive geomorphic readjustments were experienced, in which fundamental internal threshold conditions were not breached. Although threshold conditions for river metamorphosis were lowered following piecemeal and fragmentary removal of riparian vegetation and woody debris in the Old World, river systems retained sufficient resistance such that geomorphic changes were moderated, and rivers were able to re-equilibrate following disturbance events. As the impacts of human disturbance were not catchment-wide *at the same time*, the geomorphic effectiveness of flood events was moderated relative to the situation faced in New World landscapes. Inevitably, local river adjustments occurred, especially in upper catchment reaches, and overbank sedimentation rates may have increased along middle–lower reaches. However, wholesale and systematic changes to river character and behaviour were not experienced in the same way that occurred in New World settings.

VIII Conculsion and implications

It has long been recognized that vegetation cover is the key control on river character and behaviour that can be modified by human activity. One of the key factors in interpreting river responses to human disturbance lies in understanding the interplay between riparian vegetation, its close associate woody debris, and all other variables within the fluvial system, such as sediment calibre and supply rate, flow dynamics, bank material composition and valley morphology. This involves assessing the control exerted by riparian vegetation and woody debris on various feedback linkages that influence channel capacity, hydraulic roughness, channel slope, sinuosity, sediment transport rates, bank strength and floodplain evolution. Variations in vegetation character associated with vegetation structure, root networks, etc., can affect the relationships between these variables. Human-induced changes to riparian vegetation cover and the associated loading of woody debris tend to sensitize rivers, enhancing the capacity for forms and processes to shift outside their 'natural' range of variability. In some landscape settings the role of human-disturbance has brought about geomorphic changes that have not been manifest in these systems for many thousands of years (e.g., Brooks and Brierley, 1997; Brooks *et al.*, 2003).

Regardless of environmental setting, contemporary river morphodynamics across most of the globe have adjusted to conditions in which riparian vegetation and woody debris are either absent or highly altered. We contend that the differing rate and extent of riparian vegetation clearance and removal of woody debris in the Old World compared with the New World settings induced profound differences in the nature and extent of disturbance response. Near continuous land use changes over thousands of years in Old World settings induced progressive adjustments in river morphology, culminating in a phase of pronounced human-induced metamorphosis following channelization over the last 500 years or so. In contrast, river metamorphosis in New World settings occurred within a few decades of European settlement, reflecting the breaching of fundamental geomorphic thresholds following wholesale destruction of catchment-wide riparian vegetation cover in near instantaneous geological time.

Catchments comprise complex, interactive landscapes. Their unique configuration and history fashion catchment-specific patterns and rates of biophysical fluxes and associated responses to disturbance. Whether induced by environmental (climatic) changes, bushfire activity or as a consequence of human activity, changes to riparian vegetation cover may induce catchment-wide changes to river structure and function, with profound implications for the nature and rate of biogeochemical fluxes (e.g., Brierley *et al.*, 1999).

Given the complexity of biophysical linkages and the cumulative nature of disturbance impacts, along with profound variability in the inherent sensitivity of individual river systems to adjustment, it is often difficult to isolate cause–effect relationships that can directly link changes in river morphology to discrete underlying factors. Within any given catchment, not all landforms have responded to the last external influence in the same way, resulting in considerable complexity in patterns and/or rates of landscape responses to disturbance events. As impacts following disturbance are conveyed through a system, consequences may be manifest for some time, possibly up to thousands of years. Patterns, rates and consequences of geomorphic river responses to disturbance are catchment-specific.

Some landscapes are more resistant to change than others (Brunsden and Thornes, 1979). Different rivers respond to changes in discharge, sediment load or vegetation cover in different ways over different timeframes. For example, river sensitivity to change following disturbance to riparian vegetation is likely to vary markedly dependent on substrate texture. In sand-bed rivers with noncohesive banks, riparian vegetation has a proportionally higher effect on total bank strength than the same vegetation would have if bank materials comprise cohesive sediments. Hence, channel response to vegetation removal will be more rapid and proportionally greater in the channel with noncohesive bank sediments relative to the channel with cohesive banks. A similar situation applies for removal of woody debris; indeed, system sensitivity to change associated with bed-level instability may be even more pronounced.

In systems with large buffering capacity and/or with large thresholds to overcome, there may be considerable time lags between perturbation and morphological response. The nature and level of perturbation may be such that some landscapes are capable of withstanding external disturbance, while others rapidly undergo metamorphosis. Profound variability in the manner and rate of river responses to disturbance in differing landscape settings, and associated potential for geomorphic recovery, reflect, in part, sediment availability. The resistance of a river system to disturbing forces, and the associated proximity to thresholds, dictate the ability of a system to recover after disturbance (Downs and Gregory, 1993). In relative terms, the capacity of river systems to recover following disturbance may be enhanced in transport-limited landscapes, where sediments are readily available to be reworked, compared with supply-limited landscapes, where the timeframe for recovery may be prolonged once sediments are evacuated from a reach. The latter scenario may be evidenced along many river courses in Australia (e.g., Fryirs and Brierley, 2001; Brooks and Brierley, 2004). Antecedent controls on sediment availability can have a distinct spatial element, shaping landscape responses to subsequent disturbance events. Variability in sediment availability, supply rates and associated reworking are key determinants of differences in river response to human disturbance evident in Australian rivers relative to their New World counterparts in North America or Old World rivers in northern Europe. The availability of seed sources preserved in remnant pockets of native vegetation, or alternatively the expansion of exotic vegetation along river courses, are further considerations that determine the potential for geomorphic recovery.

Acknowledgements

This study marks the culmination of many years of work in analysis of river responses to human disturbance in southeastern Australia, supported by Ph.D. scholarships awarded to Andrew Brooks and Kirstie Fryirs by Land and Water Australia and Macquarie University, respectively, and associated research grants provided by these organizations over the past 10 years. The dating evidence upon which many of the interpretations reported here have been based was supported by various AINSE grants. We gratefully acknowledge these differing forms of support. In addition, we thank several colleagues for sharing their insights into river character and behaviour in many fruitful discussions, especially Tim Cohen and John Jansen. Comments on an earlier version of this manuscript by Tony Brown helped clarify various points.

References

Abbe, T.B. and **Montgomery, D.R.** 1996: Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers Research and Management* 12, 201–21.

— 2003: Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* 51, 81–107.

Abernethy, B. and **Rutherfurd, I.D.** 1996: Vegetation and bank stability in relation to changing channel scale. In Rutherfurd, I.D. and Walker, M., editors, *First national conference on stream management in Australia*. Melbourne: Merrijig, Co-operative Research Centre for Catchment Hydrology, 213–19.

— 1998: Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* 23, 55–75.

Abt, S.R., **Clary, W.P.** and **Thornton, C.I.** 1994: Sediment deposition and entrapment in vegetated streambeds. *Journal of Irrigation and Drainage Engineering* 120, 1098–111.

Andrews, E.D. 1984: Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Geological Society of America Bulletin* 95, 371–78.

Assani, A.A. and **Petit, F.** 1995: Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. *Catena* 25, 117–26.

Beeson, C.E. and **Doyle, P.F.** 1995: Comparison of bank erosion at vegetated and non-vegetated channel bends. *Water Resources Bulletin* 31, 983–90.

Beschta, R.L. 1979: Debris removal and its effects on sedimentation in an Oregon coast range stream. *Northwest Science* 53, 71–77.

Beven, K., **Gilman, K.** and **Newson, M.** 1979: Flow and flow routing in upland channel networks. *Hydrological Sciences Bulletin* 24, 303–25.

Bilby, R.E. and **Ward, J.W.** 1989: Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118, 368–78.

Bork, H.-R. 1989: Soil erosion during the past millennium in central Europe and its significance within the geomorphodynamics of the Holocene. *Catena* 15, 121–31.

Brice, J.C. 1964: Channel patterns and terraces of the Loup rivers in Nebraska. *United States Geological Survey Professional Paper* 422-D, 1–41.

Brierley, G.J. and **Murn, C.P.** 1997: European impacts on downstream sediment transfer and bank erosion in Cobargo catchment, New South Wales, Australia. *Catena* 31, 119–36.

Brierley, G.J., **Cohen, T.**, **Fryirs, K.** and **Brooks, A.** 1999: Post-European changes to the fluvial geomorphology of Bega Catchment, Australia: Implications for river ecology. *Freshwater Biology* 41, 1–10.

Brooks, A.P. 1999a: Pre- and post-European disturbance river morphodynamics in East Gippsland, Australia. Unpublished Ph.D. Thesis, School of Earth Sciences, Macquarie University, 356 pp.

— 1999b: Large woody debris and the geomorphology of a perennial river in southeast Australia. In Rutherfurd, I. and Bartley, R., editors, *Proceedings of the second Australian stream management conference*. Adelaide: Co-operative Research Centre for Catchment Hydrology, 129–36.

Brooks, A.P. and **Brierley, G.J.** 1997: Geomorphic response of lower Bega River to catchment disturbance, 1851–1926. *Geomorphology* 18, 291–304.

— 2000: The role of European disturbance in the metamorphosis of lower Bega River. In Finlayson, B.L. and Brizga, S.A., editors, *River management: the Australasian experience*. Chichester: Wiley, 221–46.

— 2002: Mediated equilibrium: the influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river. *Earth Surface Processes and Landforms* 27, 343–67.

— 2004: Framing realistic river rehabilitation programs in light of altered sediment transfer relationships: lessons from East Gippsland, Australia. *Geomorphology* 58, 107–23.

Brooks, A.P., **Brierley, G.J.** and **Millar, R.G.** 2003: The long term control of vegetation and woody debris on channel and floodplain evolution: insights from a paired catchment study between a pristine and a disturbed lowland alluvial river in southeastern Australia. *Geomorphology* 51, 7–29.

Brown, A.G. 1997: *Alluvial geoarchaeology*. Cambridge: Cambridge University Press.

— 2002: Learning from the past: palaeohydrology and palaeoecology. *Freshwater Biology* 47, 817–29.

Brown, A.G. and **Brookes, A.** 1997: Floodplain vegetation and overbank erosion and sedimentation. In Large, A., editor, *Floodplain rivers: hydrological processes and ecological significance*. British Hydrological Society Occasional Papers No. 8. London: British Hydrological Society, UK.

Brown, A.G. and **Keough, M.** 1992: Holocene floodplain metamorphosis in the Midlands, United Kingdom. *Geomorphology* 4, 433–45.

Brown, A.G. and **Quine, T.A.** 1999: Fluvial processes and environmental change: an overview. In Brown, A.G. and Quine, T.A., editors, *Fluvial processes and environmental change*. Chichester: Wiley, 1–27.

Brunsden, D. and **Thornes, J.B.** 1979: Landscape sensitivity and change. *Transactions of the Institute of British Geographers* 4, 463–84.

Buffington, J.M. and **Montgomery, D.R.** 1999: Effects of hydraulic roughness on surface textures in gravel-bed rivers. *Water Resources Research* 35, 3507–22.

Burkham, D. 1972: Channel changes of the Gila River in Safford Valley, Arizona, 1846–1970. *United States Geological Survey Professional Paper* 655-G, 24 pp.

— 1976: Hydraulic effects of changes to bottomland vegetation on three major floods, Gila River in southeastern Arizona. *United States Geological Survey Professional Paper* 655-J, 14 pp.

Charlton, F.G., **Brown, P.M.** and **Benson, R.W.** 1978: *The hydraulic geometry of some gravel rivers in Britain*. Wallingford: Hydraulic Research Station.

Church, M. and **Ryder, J.M.** 1972: Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin* 83, 3059–72.

Church, M. and **Slaymaker, O.** 1989: Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* 337, 452–54.

Cohen, T. and **Brierley, G.J.** 2000: Channel instability in a forested catchment, East Gippsland, Australia. *Geomorphology* 32, 109–28.

Collins, B.D., **Montgomery, D.R.** and **Haas, A.** 2002: Historic changes in the distribution and functions of large woody debris in Puget lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59, 66–76.

Cotter, E. 1978: The evolution of fluvial style, with special reference to the central Appalachian Paleozoic. In Miall, A.D., editor, *Fluvial sedimentology*. Canadian Society of Petroleum Geologists Memoir. Calgary: Canadian Society of Petroleum Geologists, Volume 5, 361–83.

Crosby, A.W. 1986: *Ecological imperialism. The biological expansion of Europe, 900–1900*. Cambridge: Cambridge University Press.

Curran, J.H. and **Wohl, E.E.** 2003: Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 51, 141–57.

Daniels, M.D. and **Rhoads, B.L.** 2003: Influence of a large woody debris obstruction on three-dimensional flow structure in a meander bend. *Geomorphology* 51, 159–73.

Darby, H.C. 1956: The clearing of the woodland of Europe. In Thomas, W.L., Jr, Sauer, C.O., Bates, M. and Mumford, L., editors, *Man's role in changing the face of the Earth*. Chicago IL: University of Chicago Press, 183–216.

Davis, J. and **Finlayson, B.** 1999: The role of historical research in stream rehabilitation: a case study from central Victoria. In Rutherfurd I. and Bartley, R., editors, *Proceedings of the second Australian stream management conference*. Adelaide: Co-operative Research Centre for Catchment Hydrology, 199–204.

Diamond, J. 1997: *Guns, germs and steel. A short history of everybody for the last 13,000 years*. London: Jonathon Cape.

Downs, P.W. and **Gregory, K.J.** 1993: The sensitivity of river channels in the landscape system. In Thomas, D.S.G. and Allison, R.J., editors, *Landscape sensitivity*. Chichester: Wiley, 299–310.

Elliot, J.G., **Gellis, A.C.** and **Aby, S.B.** 1999: Evolution of arroyos: incised channels of the southwestern United States. In Darby, S.E. and Simon, A., editors, *Incised river channels: processes, forms, engineering and management*. Chichester: Wiley, 153–86.

Erskine, W.D. 1986: River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949. *Australian Geographical Studies* 24, 88–107.

— 1999: Oscillatory response versus progressive degradation of incised channels in southeastern Australia. In Darby, S.E. and Simon, A., editors, *Incised river channels: processes, forms, engineering and management*. Chichester: Wiley, 67–96.

Erskine, W.D. and **Bell, F.C.** 1982: Rainfall floods and river channel changes in the upper Hunter. *Australian Geographical Studies* 20, 183–96.

Eyles, R.J. 1977a: Birchams Creek: the transition from a chain of ponds to a gully. *Australian Geographic Studies* 15, 146–57.

— 1977b: Changes in drainage networks since 1820, Southern Tablelands, N.S.W. *Australian Geographer* 13, 377–86.

Ferguson, R.I. 1987: Hydraulic and sedimentary controls of channel pattern. In Richards, K., editor, *River channels: environment and processes*. Oxford: Blackwell, 129–58.

Fetherston, K.L., **Naiman, R.J.** and **Bilby, R.E.** 1995: Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13, 133–44.

Flannery, T. 1994: *The future eaters.* Port Melbourne: Reed, 423 pp.

Friedman, J.M., **Osterkamp, W.R.** and **Lewis, W.M., Jr.** 1996: Channel narrowing and vegetation development following a great plains flood. *Ecology* 77, 2167–81.

Fryirs, K. and **Brierley, G.J.** 1998: The character and age structure of valley fills in upper Wolumla Creek, South Coast, New South Wales, Australia. *Earth Surface Processes and Landforms* 23, 271–87.

— 2001: Variability in sediment delivery and storage in Bega catchment, NSW, Australia: implications for geomorphic river recovery. *Geomorphology* 38, 237–65.

Gippel, C.J. 1995: Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* 121, 388–95.

Gippel, C.J., Finlayson, B.L. and **O'Neill, I.C.** 1994: Distribution and hydraulic significance of large woody debris in a lowland Australian river. *Hydrobiologia* 318, 179–94.

Gippel, C.J., O'Neill, I.C., Finlayson, B.L. and **Schnatz, I.** 1996: Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research and Management* 12, 223–36.

Godlowska, M., Kozlowski, J., Starkel, L. and **Wasylikowa, K.** 1987: Neolithic settlement at Pleszow and changes in the natural environment in the Vistula valley. *Przeglad Archeologiczny* 34, 133–59.

Graf, W.L. 1977: Geomorphic impact of changes in riparian vegetation in the canyons of the Colorado Plateau. In *Geomorphology: human induced changes: 1977 annual meeting of the Association of American Geographers*. Salt Lake City UT, 24–27 April, 1–18.

— 1978: Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geological Society of America Bulletin* 89, 1491–501.

Gregory, K.J. 1977: *River channel changes*. Chichester: Wiley, 450 pp.

Gregory, K.J. and **Gurnell, A.** 1988: Vegetation and river channel form and process. In Viles, H.A., editor, *Biogeomorphology*. Oxford: Blackwell, 11–42.

Gregory, K.J., Gurnell, A.M. and **Hill, C.T.** 1985: The permanence of debris dams related to river channel processes. *Hydrological Sciences Journal* 30, 371–81.

Gregory, K.J., Davis, R.J. and **Tooth, S.** 1993: Spatial distribution of coarse woody debris dams in the Lymington Basin, Hampshire, UK. *Geomorphology* 6, 207–24.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollman, J., Ward, J.V. and **Tockner, K.** 2001: Riparian vegetation and island formation along the gravel-bed Riume Tagliamento, Italy. *Earth Surface Processes and Landforms* 26, 31–62.

Gurnell, A.M., Piégay, H., Gregory, S.V. and **Swanson, F.J.** 2002: Large wood and fluvial processes. *Freshwater Biology* 47, 601–19.

Hadley, R.F. 1961: Influence of riparian vegetation on channel shape, northeastern Arizona. *United States Geological Survey Professional Paper* 424-C, 30–31.

Hanušin, J. 2000: Hydrological–geomorphological aspects of differing farming practices. In Suri, M., editor, *International symposium on geomorphic response to land use changes*. Smolenice, Slovak Republic: Slovak Academy of Sciences, 25.

Harmon, M.F., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cine, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr and **Cummins, K.W.** 1986: Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15, 133–302.

Harwood, K. and **Brown, A.G.** 1993: Changing in-channel and overbank flood velocity distributions and the morphology of forested multiple channel (anastomosing) systems. *Earth Surface Processes and Landforms* 18, 741–48.

Heede, B.H. 1972: Influences of a forest on the hydraulic geometry of two mountain streams. *Water Resources Bulletin* 8, 523–30.

— 1981: Dynamics of selected mountain streams in the western United States of America. *Zeitschrift für Geomorphologie* 25, 17–32.

Henry, H.M. 1977: Catastrophic channel changes in the MacDonald Valley, New South Wales 1949–1955. *Journal and Proceedings, Royal Society of New South Wales* 110, 1–16.

Herget, J. 2000: Holocene development of the River Lippe valley, Germany: a case study of anthropogenic influence. *Earth Surface Processes and Landforms* 25, 293–305.

Hey, R.D. and **Thorne, C.R.** 1983: Hydraulic geometry of gravel-bed rivers. In *Proceedings of the second international symposium on river sedimentation, Nanjing, China*. Water Resource and Electric Power Press.

— 1986: Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering* 112, 671–89.

Hickin, E.J. 1984: Vegetation and river channel dynamics. *Canadian Geographer* 28, 111–26.

Hogan, D.L., Bird, S.A. and **Hassan, M.A.** 1998: Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. In Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B., editors, *Gravel-bed rivers in the environment*. Englewood Cliffs, NJ: Water Resources Publications, 365–92.

Huang, H.Q. and **Nanson, G.C.** 1997: Vegetation and channel variation; a case study of four small streams in southeastern Australia. *Geomorphology* 18, 237–49.

— 1998: The influence of bank strength on channel geometry: an integrated analysis of some observations. *Earth Surface Processes and Landforms* 23, 865–76.

Hughes, F.M.R., Harris, T., Richards, K., El Hames, A., Barsoum, N., Girel, R., Peiry, J.-L. and **Foussadier, R.** 1997: Woody riparian species response to different soil moisture conditions: laboratory experiments on *Alnus incana*. *Global Ecology and Biogeography Letters* 6, 247–56.

Hupp, C.R. and **Osterkamp, W.R.** 1996: Riparian vegetation and fluvial geomorphic processes. *Geomorphology* 14, 277–95.

Ikeda, S. and **Izumi, N.** 1990: Width and depth of self-formed straight gravel rivers with bank vegetation. *Water Resources Research* 26, 2353–64.

Jeffries, R., Darby, S.E. and **Sear, D.A.** 2003: The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. *Geomorphology* 51, 61–80.

Johns, E., **Sayers, A.**, **Kornhauser, E.M.** and **Ellis, A.** 1998: *New worlds from old; 19th century Australian and American landscapes*. Canberra: National Gallery of Australia, 271 pp.

Keller, E.A. and **Swanson, F.J.** 1979: Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* 4, 361–80.

Keller, E.A. and **Tally, T.** 1979: Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In Rhodes, D.D. and Williams, G.P., editors, *Adjustments of the fluvial system*. Dubuque, IA: Kendall Hunt, 169–98.

Keller, E.A., **Macdonald, A.**, **Tally, T.** and **Merrit, N.J.** 1995: Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek, Northwestern California. *United States Geological Survey Professional Paper* 1454-P, 29 pp.

Kellerhals, R. and **Miles, M.** 1996: Fluvial geomorphology and fish habitat: implications for river restoration. In *Proceedings of the second IAHR symposium on habitat hydraulics, ecohydraulics 2000*. Quebec City: International Association for Hydraulic Research, A261–279.

Klimek, K. 1987: Man's impact on fluvial processes in the Polish Western Carpathians. *Geografiska Annaler* 69A, 221–26.

Knox, J.C. 1972: Valley alluviation in southwestern Wisconsin. *Annals of the Association of American Geographers* 62, 401–10.

— 1977: Human impacts on Wisconsin stream channels. *Annals of the Association of Americam Geographers* 67, 323–42.

— 1987: Historical valley floor sedimentation in the Upper Mississippi Valley. *Annals of the Association of American Geographers* 77, 224–44.

— 1989: Long- and short-term episodic storage and removal of sediment in watersheds of southwestern Wisconsin and northwestern Illinois. In Hadley, R.F. and Ongley, E.D., editors, *Sediment and the environment*. Proceedings of the Baltimore Symposium, May 1989. International Association of Hydrological Sciences Publication no. 184, 157–64.

— 1993: Large increases in flood magnitude in response to modest changes in climate. *Nature* 361, 430–32.

— 1995: Fluvial systems since 20,000 years BP. In Gregory, K.J., Starkel, L. and Baker, V.R., editors, *Global continetal palaeohydrology*. Chichester: Wiley, 87–108.

Kochel, R.C., **Ritter, D.F.** and **Miller, J.** 1987: Role of tree dams in the construction of pseudo-terraces and variable geomorphic response to floods in Little River valley, Virginia. *Geology* 15, 718–21.

Kouwen, N. and **Li, R.M.** 1980: Biomechanics of vegetative channel linings. *Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers)* 106, 1085–103.

Kozarski, S. and **Rotnicki, K.** 1977: Valley floors and changes of river channel patterns in the north Polish Plain during the late Wurm and Holocene. *Quaestiones Geographicae* 4, 51–93.

Leopold, L.B., **Wolman, M.G.** and **Miller, J.P.** 1964: *Fluvial processes in geomorphology*. San Francisco CA: W.H. Freeman and Co.

Lewin, J. 1987: Historical river channel changes. In Gregory, K.J., Lewin, J. and Thornes, J.B., editors, *Palaeohydrology in practice, a river basin analysis*. Chichester: Wiley, 161–75.

Li, R.M. and **Shen, H.W.** 1973: Effects of tall vegetation on flow and sediment. *Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers)* 99, 793–814.

Lines, W.J. 1991: *Taming the Great South Land. A history of the conquest of nature in Australia*. North Sydney: Allen and Unwin, 337 pp.

Lisle, T.E. 1986: Stabilisation of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. *Water Resources Research* 97, 999–1011.

— 1995: Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* 31, 1797–808.

Lloyd, C.J. 1988: *Either drought or plenty. Water development and management in New South Wales*. Parramatta: Department of Water Resources.

Macdonald, A. and **Keller, E.A.** 1987: Stream channel response to the removal of large woody debris, Larry Damm Creek, northwestern California. In Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G. and Swanson, F.J., editors, *Proceedings of the symposium on erosion and sedimentation in the Pacific Rim*. International Association of Hydrological Sciences Publication 165, 405–406.

Mackin, J.H. 1956: Cause of braiding by a graded river. *Geological Society of America Bulletin* 67, 1717–18.

Manga, M. and **Kirchner, J.W.** 2000: Stress partitioning in streams by large woody debris. *Water Resources Research* 36, 2373–79.

Marsh, G.P. 1864: *Man and nature*. Cambridge MA: The Belknap Press of Harvard University Press. 472 pp.

Marston, R.A. 1982: The geomorphic significance of log steps in forest streams. *Annals of the Association of American Geographers* 72, 99–108.

Marston, R.A., **Girel, J.**, **Pautou, G.**, **Piégay, H.**, **Bravard, J.P.** and **Arneson, C.** 1995: Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. *Geomorphology* 13, 121–31.

Maser, C. and **Sedell, J.R.** 1994: *From the forest to the sea*. Delray Beach, Boca Raton, FL: St. Lucie Press, 200 pp.

Millar, R.G. 1998: Meandering–braiding transition. In Jayawardena, A.W., Lee, J.H.W. and Wang, Z.Y., editors, *7th international conference on river sedimentation*. Hong Kong: International Symposium on River Sedimentation, 239–45.

— 2000: Influence of bank vegetation on alluvial channel patterns. *Water Resources Research* 36, 1109–18.

Millar, R.G. and **Quick, M.C.** 1993: Effect of bank stability on geometry of gravel rivers. *Journal of Hydraulic Engineering* 119, 1343–63.

— 1998: Stable width and depth of gravel-bed rivers with cohesive banks. *Journal of Hydraulic Engineering* 124, 1005–13.

Montgomery, D.R. and **Piégay, H.** 2003: Wood in rivers: interactions with channel morphology and processes. *Geomorphology* 51, 1–5.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M. and **Pess, G.R.** 1995: Pool frequency in forested channels. *Water Resources Research* 31, 1097–105.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M. and **Stock, J.D.** 1996: Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* 381, 587–89.

Moriarty, E.O. 1869: *Report on the prevention of floods in the Hunter*. Sydney: Legislative Assembly of New South Wales.

Mosley, M.P. 1981: The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. *Earth Surface Processes and Landforms* 6, 571–79.

Nakamura, F. and **Swanson, F.J.** 1993: Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in Western Oregon. *Earth Surface Processes and Landforms* 18, 43–61.

Nanson, G.C. 1980: Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada. *Sedimentology* 27, 3–29.

Nanson, G.C. and **Beach, H.F.** 1977: Forest succession and sedimentation on a meandering-river floodplain, northeast British Colombia, Canada. *Journal of Biogeography* 4, 229–51.

Nanson, G.C. and **Doyle, C.J.** 1999: Landscape stability, Quaternary climate change and European degradation of coastal rivers in southeastern Australia. In Rutherfurd, I. and Bartley, R., editors, *Proceedings of the second Australian stream management conference*. Adelaide: Co-operative Research Centre for Catchment Hydrology, 473–80.

Nanson, G.C., Barbetti, M. and **Taylor, G.** 1995: River stabilisation due to changing climate and vegetation during the later Quaternary in western Tasmania, Australia. *Geomorphology* 13, 145–58.

Nanson, G.C., Cohen, T.C., Doyle, C.J. and **Price, D.M.** 2003: Alluvial evidence of major late-Quaternary climate and flow-regime changes on the coastal rivers of New South Wales, Australia. In Gregory, K. and Benito, G., editors, *Palaeohydrology: understanding global change*. Chichester: Wiley, 233–58.

Nevins, T.H.F. 1969: River-training: the single-thread channel. *New Zealand Engineering* 15, 367–73.

O'Connor, J.E., Jones, M.A. and **Haluska, T.L.** 2003: Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology* 51, 31–59.

Page, K.J. and **Carden, Y.R.** 1998: Channel adjustments following the crossing of a threshold: Tarcutta Creek, Southeastern Australia. *Australian Geographical Studies* 36, 289–311.

Page, K.J. and **Nanson, G.C.** 1996: Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. *Sedimentology* 43, 927–45.

Petryk, S. and **Bosmajian, G.** 1975: Analysis of flow through vegetation. *Journal of the Hydraulics Division, American Society of Civil Engineers* 101, 871–83.

Petts, G.E. 1984: *Impounded rivers: perspectives for ecological management*. Chichester: Wiley.

— 1989: Historical analysis of fluvial hydrosystems. In Petts, G.E., Moller, H. and Roux, A.L., editors, *Historical change of large alluvial rivers: Western Europe*. Chichester: Wiley, 1–18.

Pickup, G. 1976: Geomorphic effects of changes in river runoff, Cumberland Basin, N.S.W. *Australian Geographer* 13, 188–93.

Piégay, H. 1993: Nature, mass and preferential sites of coarse woody debris in the lower Ain Valley (Mollon Reach), France. *Regulated Rivers: Research and Management* 8, 359–72.

Piégay, H. and **Gurnell, A.M.** 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology* 19, 99–116.

Piégay, H. and **Marston, R.A.** 1998: Distribution of coarse woody debris along the concave bank of a meandering river (the Ain River, France). *Physical Geography* 19, 318–40.

Prosser, I.P. 1991: A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales. *Australian Geographical Studies* 29, 139–54.

Prosser, I.P., Chappell, J. and **Gillespie, R.** 1994: Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia. *Earth Surface Processes and Landforms* 19, 465–80.

Rutherfurd, I.D. 1996: Sand-slugs in south east Australian streams: origins, distribution and management. In Rutherfurd, I.D. and Walker, M., editors, *First national conference on stream management in Australia*. Merrijig: Co-operative Research Centre for Catchment Hydrology.

Rutherfurd, I. 2000: Some human impacts on Australian stream channel morphology. In Brizga, S. and

Finlayson, B., editors, *River management: the Australasian experience*. Chichester: Wiley, 11–49.

Schumm, S.A. 1968: Speculations concerning paleohydrologic controls of terrestrial sedimentation. *Geological Society of America Bulletin* 79, 1573–88.

— 1969: River metamorphosis. *Journal of the Hydraulics Division (Proceedings of the American Society of Civil Engineers)* 95, 255–73.

Schumm, S.A., Harvey, M.D. and **Watson, C.C.** 1984: *Incised channels: morphology, dynamics and control*. Highlands Ranch, CO: Water Resources Publications.

Sedell, J.R. and **Frogatt, J.L.** 1984: Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. *Verhandlungen – Internationale Vereinigung für Theoretifche und Angewandte Limnologie* 22, 1828–34.

Shields, F.D., Jr and **Gippel, C.J.** 1995: Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering* 121, 341–54.

Shields, F.D., Jr and **Smith, R.D.** 1992: Effects of large woody debris removal on the physical characteristics of a sand-bed river. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2, 145–63.

Smith, D.G. 1976: Effect of vegetation on lateral migration of anastomosed channels of a glacial meltwater river. *Geological Society of America Bulletin* 87, 857–60.

Smith, R.D., Sidle, R.C. and **Porter, P.E.** 1993a: Effects on bedload transport of experimental removal of woody debris from a forest gravel-bed stream. *Earth Surface Processes and Landforms* 18, 455–68.

Smith, R.D., Sidle, R.C., Porter, P.E. and **Noel, J.R.** 1993b: Effects of experimental removal of woody debris on channel morphology of a forest, gravel-bed stream. *Journal of Hydrology* 152, 153–78.

Starkel, L. 1991: Long-distance correlation of fluvial events in the temperate zone. In Starkel, L., Gregory, K.J. and Thornes, J.B., editors, *Temperate palaeohydrology*. Chichester: Wiley, 473–93.

— 1995: Changes of river channels in Europe during the Holocene. In Gurnell, A.M. and Petts, G.E., editors, *Changing river channels*. Chichester: Wiley, 27–42.

Swanson, F.J., Lienkaemper, G.W. and **Sedell, J.R.** 1976: *History, physical effects, and management implications of large organic debris in Western Oregon streams*. Portland, OR: Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, General Technical Report GTR-PNW-56, 15 pp.

Thorne, C.R. 1990: Effects of vegetation on riverbank erosion and stability. In Thornes, J.B., editor, *Vegetation and erosion*. Chichester: John Wiley, 125–44.

Thorne, S.D. and **Furbish, D.J.** 1995: Influence of coarse bank roughness on flow within a sharply curved river bend. *Geomorphology* 12, 241–57.

Triska, F.J. 1984: Role of wood debris in modifying channel morphology and riparian areas of a large lowland river under pristine conditions: a historical case study. *Verhandlungen – Internationale Vereinigung für Theoretifche und Angewandte Limnologie* 22, 1876–92.

Warner, R.F. 1997: Floodplain stripping: another form of adjustment to secular hydrologic regime change in southeast Australia. *Catena* 30, 263–82.

Wasson, R.J., Mazari, R.K., Starr, B. and **Clifton, G.** 1998: The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australian: sediment flux dominated by channel incision. *Geomorphology* 24, 291–308.

Wolman, M.G. and **Gerson, R.** 1978: Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth Surface Processes* 3, 189–208.

Woodsmith, R.D. and **Buffington, J.M.** 1996: Multivariate geomorphic analysis of forest streams: implications for assessment of land use impact on channel condition. *Earth Surface Processes and Landforms* 21, 377–93.

Zimmerman, R.C., Goodlett, J.C. and **Comer, G.H.** 1967: The influence of vegetation on channel form of small streams. *Proceedings of the Symposium on River Morphology*. 25 September–7 October 1967. Gentbrugge: Interscience Association of Scientific Hydrology, Publication No. 75, 255–75.