Braided river management: from assessment of river behaviour to improved sustainable development

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ABSTRACT

Braided rivers change their geometry so rapidly, thereby modifying their boundaries and floodplains, that key management questions are difficult to resolve. This paper discusses aspects of braided channel evolution, considers management issues and problems posed by this evolution, and develops these ideas using several contrasting case studies drawn from around the world. In some cases, management is designed to reduce braiding activity because of economic considerations, a desire to reduce hazards, and an absence of ecological constraints. In other parts of the world, the ecological benefits of braided rivers are prompting scientists and managers to develop strategies to preserve and, in some cases, to restore them.

Management strategies that have been proposed for controlling braided rivers include protecting the developed floodplain by engineered structures, mining gravel from braided channels, regulating sediment from contributing tributaries, and afforesting the catchment. Conversely, braiding and its attendant benefits can be promoted by removing channel vegetation, increasing coarse sediment supply, promoting bank erosion, mitigating ecological disruption, and improving planning and development. These different examples show that there is no unique solution to managing braided rivers, but that management depends on the stage of geomorphological evolution of the river, ecological dynamics and concerns, and human needs and safety. For scientists wishing to propose 'sustainable' solutions, they must consider the cost-benefit aspects of their options, and the needs and desires of society. This requires an interdisciplinary approach linking earth scientists and social scientists concerned with environmental economics, planning, and societal and political strategies, in order to fully evaluate the economic and social validity of different options for different time-scales.

Keywords Human impacts, river restoration, flooding risk management, channel adjustment, ecological conservation, geomorphological sensitivity, braided rivers.

INTRODUCTION

Braided rivers are strongly influenced by high sediment delivery from nearby sources (e.g. glacial outwash, torrential tributaries) coupled with lower sediment throughput due to hydraulic conditions (primarily gentle slopes). They are sensitive to changes in their flood regime or sediment influx, and can completely modify their geometry over a few decades (Ferguson, 1993). Common braided river adjustments to changing environmental conditions typically include both narrowing (Kondolf, 1997; Nakamura & Shin, 2001; Liébault & Piégay, 2002; Surian & Rinaldi, 2003), and widening (Lyons & Beschta, 1983; Page *et al.*, 2000). Moreover, rivers can shift from other planforms to a braided pattern when human activities accelerate sediment delivery processes. At the same time, climatic conditions and human influences that reduce sediment production can have the opposite effect, with braiding slowly diminishing through time. Thus the dynamic nature of braided rivers makes it difficult for societies to both predict the direction of their evolution and maintain nearby and associated infrastructure.

Braided channels are rarely in a steady state and are indicative of a valley bottom still actively undergoing construction. In undeveloped floodplain areas, braided rivers are considered part of the natural environment and are typically preserved because of their associated ecological richness. However, when permanent infrastructure is built in such active floodplains many problems can occur. This problem is particularly acute in central Japan, where rivers drain steep mountains with unstable geology, large-scale landsliding and intense rainfall, which is coupled with densely populated and sensitive alluvial plains (Nishiyama & Miyazaka, 2001; Maita and Shizuoka River Work Office, 2001).

In response to these problems, scientists and engineers have sought to reduce braiding activity, particularly where braiding results from human impacts or degrades resources, ecological diversity and human safety. Examples of this approach can be found in the northern island of New Zealand or Japan (Marutani *et al.*, 2001). Conversely, in other parts of the world, the high ecological value of braided rivers has led to technical approaches and management strategies to preserve and, in some cases, restore braided conditions (Bornette & Amoros, 1991; Gilvear, 1993; Ward *et al.*, 1999). Some braided rivers are extremely productive biologically, such as the Fraser River in British Columbia or the Waitaki River on the southern island of New Zealand, where Chinook salmon fisheries are of national significance (James, 1992). This paradox of opposing management strategies for braided rivers can be seen with reference to Pine Creek in Idaho, USA and the Drôme River in France (Kondolf *et al.*, 2002) (Fig. 1).

The aim of this paper is to propose a conceptual model for the temporal evolution of braided rivers, consider the implications of this behaviour from social and ecological perspectives, and provide several contrasting case studies from around the world that illustrate the way managers and scientists approach the issues of braided river management in different landscape, societal and ecological contexts.

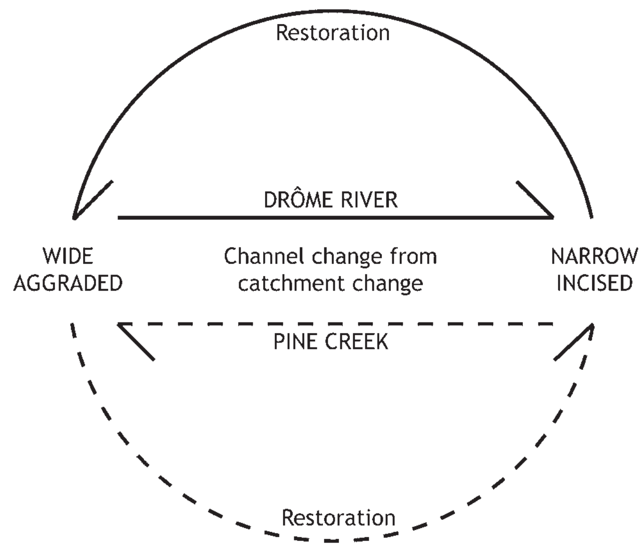


Fig. 1 Contrasting directions of channel planform evolution due to changes in catchment sediment yield, and consequent directions of intended restoration in Pine Creek, Wyoming, USA and the Drôme River, southern France (From Kondolf *et al.*, 2002; with permission from Elsevier).

The conceptual model of braided river temporal trajectory

Braided rivers can be distinguished according to their stage of evolution and the human and ecological benefits they provide. These attributes, in turn, result directly from the relation between sediment supply and braiding intensity (Fig. 2). A braided river typically aggrades and widens when sediment supply is high, thereby progressively occupying more and more of the valley bottom; this is referred to as the *expansion phase*. The active channel shifts laterally, either by bank erosion or avulsion. Considerable economic costs can be incurred if the valley bottom is developed during this phase. On the other hand, under conditions when sediment supply or peak flows are reduced, referred to here as the *contraction phase*, braided rivers typically narrow and incise their beds. This degradation, in turn, can destabilize bridges, dams, erosion control works and other infrastructure. It is proposed, therefore, that the social and economic costs and benefits associated with braiding therefore follow a bell-shaped curve, with the greatest human benefits occurring in the middle

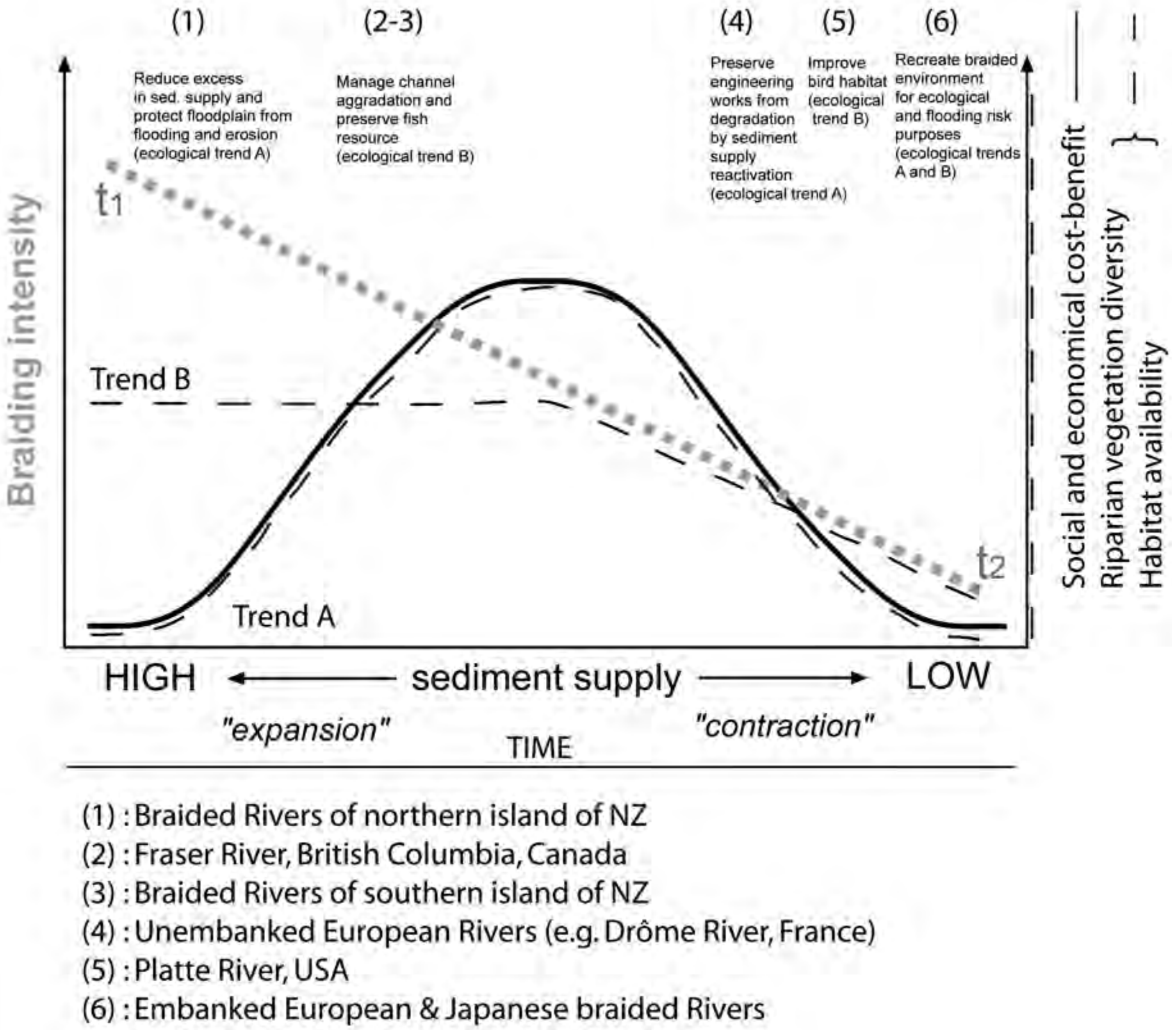


Fig. 2 Conceptual framework for understanding the relationship between braiding intensity as a function of sediment supply and the ecological and human benefits derived from braided rivers. Braiding intensity (dotted grey line) decreases with decreasing sediment supply: t1 and t2 represent time-points along a trajectory of evolution from high sediment loads, high braiding intensity (‘*expansion phase*’) to low sediment supply, low braiding intensity (‘*contraction phase*’). Social and economic benefits of braided rivers (solid black line) describe a bell-shaped curve, with intermediate levels of braiding providing the most benefits. Ecological benefits (dashed black lines) of braided rivers differ from one system to another according to other parameters (low flow conditions, turbidity, α versus β diversity). Following trend A, ecological diversity has a peak in intermediate levels of braiding, mostly in riparian environments. Some rivers can also follow trend B (e.g. Fraser River, Platte River) providing ecological value not only at the intermediate levels of braiding, but all along the braiding stage; their ecological interest diminishes once the gravel surface area decreases, and the associated optimal habitat conditions are no longer present.

section of the trajectory (Fig. 2). Ecological benefits associated with the trend from high to low braiding intensity are more complex (Fig. 2). In some of the examples discussed below, extremely low or high braiding intensity is associated with poor riparian and aquatic habitat conditions, while in other examples the full spectrum of braiding conditions promotes ecological diversity.

The above conceptual model suggests that it is important to understand both the stage and trajectory of river evolution before managing a braided river to solve immediate problems such as loss of property due to bank erosion, flooding, or to improve ecological conditions. Such an approach allows managers to evaluate the potential efficacy of proposed actions and likely future problems. This conceptual model therefore helps managers to anticipate changes and consider management options across longer time-scales.

To amplify these points, examples drawn from around the world, of braided rivers in both their expansion and contraction phases, are presented. Drawing on the conceptual model, it is emphasized how the geomorphological dynamics of these systems in different phases affect both ecological functions and social costs and benefits.

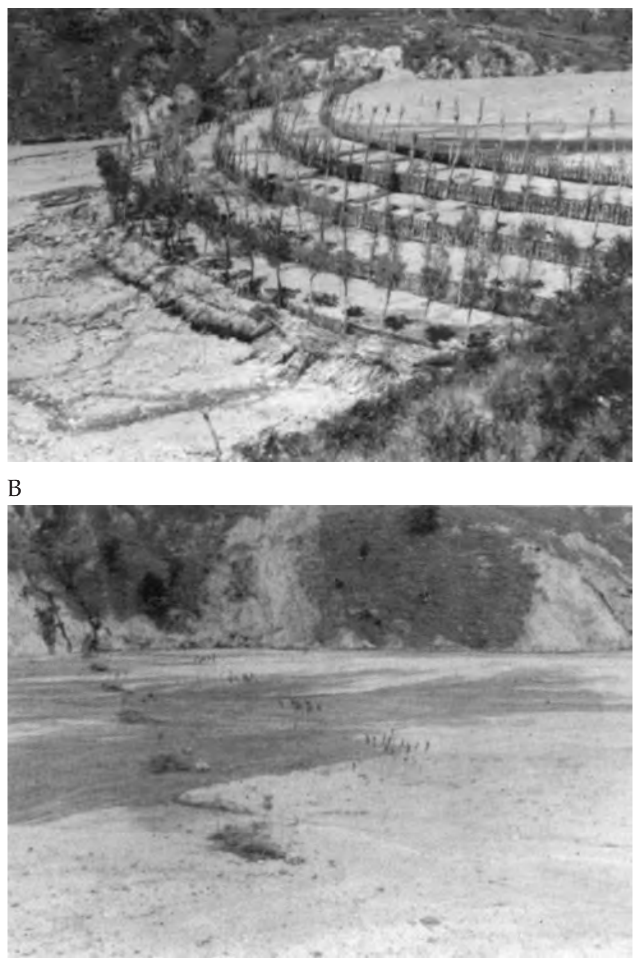
Examples of expanding braided systems: the Waiapu and Waiapoa Rivers in New Zealand

The Waiapu and Waiapoa Rivers (ca. 1800 and 2000 km^2 respectively) are located on the East Coast of the North Island of New Zealand and represent good examples of braided rivers in their expansion phases with associated negative consequences. In this setting, the intrinsically high rates of geomorphological activity and associated erosion and sedimentation have been accelerated by the extensive deforestation associated with European settlers as they began pastoral farming between 1880 and 1920 (Hicks *et al.*, 2000). In particular, the clearing of native forest initiated gullying in the headwaters of the Mangatu and Waipaoa Rivers, resulting in a cumulative eroded area of 290 ha in 1939 and 1250 ha in 1960 (DeRose *et al.*, 1998).

The rivers have undergone substantial changes over this period. As reported in the Tairawhiti—Conservation Quorum (1998, issue 14, pp. 5–6), Stanley Tait, who was born in Whatatutu in 1897, described the Waipaoa early in the last century as '*hard and full of huge boulders. The water was clear and sweet and it ran fast. Children swam in the clear pools and there were eels, native trout and freshwater mussels*'. Brush had been burned between 1890 and 1910 for sheep grazing but the roots still held the soils for several years. In the early 1930s, earthflow and gully development increased suspended and bedload sediment input to channels, inducing channel aggradation and widening. A reach 60 m wide in 1896 attained 400 m in width by 1939. Aggradation buried fertile river terraces, tracks and buildings, and greatly reduced the navigability of rivers. Photographs show how rapid sediment delivery buried a large debris trap built in the Te Weraroa stream in the Waipaoa river basin (Peacock, 1998) (Fig. 3). Active aggradation has also been reported at the Rip bridge crossing the Raparapaririki stream (Hudson, 1998). In March 1988, after Cyclone Bola, the bed of the river buried the lower third of the piers. By 1994, the deck of the bridge was barely above water. In 1995, the deck of the bridge was removed and by 1998 no trace remained of the bridge. A new bridge was constructed downstream.

The lower reaches of the Waiapu River and its main tributaries are still aggrading and widening today, affecting infrastructure, private property and ecological diversity. With the Waipaoa River aggrading

A



B

Fig. 3 (A) Large debris trap built during the 1950s in the Te Weraroa Stream, New Zealand. (B) The same structure overwhelmed by high sediment loads derived from an active gully immediately upstream.

2 to 5 cm yr^{-1}, flood control schemes and reservoirs are steadily losing capacity, increasing the risk of flooding in townships such as Te Karaka. High suspended sediment concentrations, low discharges, and shallow flows disrupt and limit fish habitat. Few species and low abundance of fish are observed in these rivers. Due to aggradation and widening, the active channel occupies most of the valley bottom, eroding the foot of the valley sides. Where the valley bottom still exists, channel aggradation is so rapid that riparian vegetation cannot easily become established on channel bars and floodplains.

These two rivers clearly display negative effects associated with the rapid increase in braiding intensity due to high introduced sediment loads. Although the floodplains in this region are relatively undeveloped by global standards, impacts on human infrastructure and ecosystems are still severe.

Examples of contracting braided systems: the French Alpine rivers

Both expansion and contraction phases have been observed in French braided rivers that aggraded during the modern period (17th to 19th centuries), and then degraded after 1880 (Bravard, 1989; Kondolf *et al.*, 2002; Liébault, 2003). The initial expansion phase was driven by human land-use changes due to increased population density in rural areas of the French Alps, which reached a maximum during the mid-19th century (Taillefumier & Piégay, 2002). By the end of that century, hillslope farming and overgrazing had increased both sediment delivery to the rivers and the frequency of peak flows. Photographs taken at the end of the 19th century reveal extensive braided rivers that generally occupied all of the valley bottoms without riparian forests, and with channels directly in contact with active alluvial fans (Fig. 4). This trend occurred during a period when economic development and increasing technical and financial capacity promoted the construction of important infrastructure, such as bridges and dykes, to improve transportation and prevent floods.

Since the end of the 19th century, the cumulative effect of human activities has been to reverse this trend. Many braided reaches have been destroyed by embankment protection measures, as discussed by Bravard *et al.* (1986) for the upper Rhône.

A

B

Fig. 4 Landscape of the valley bottom of the Ubaye River immediately downstream from Barcelonnette, France, in (A) 1894 and (B) 1996. The Rioux Bourdoux is the prominent tributary to the Ubaye; this tributary was called 'the Monster' 100 yr ago. (The photograph of 1894 has been provided by Restouration des terrains de montagne (RTM), Digne.)

Moreover, changing land-use activities, in-channel mining, upland afforestation and dam construction in headwater areas have resulted in a large sediment deficit in braided rivers, inducing a progressive metamorphosis and incision (Bravard *et al.*, 1999). For example, the Fier and the Arve Rivers in the northern French Alps incised up to a maximum of 12 to 14 m (Peiry *et al.*, 1994). Of the few braided rivers still active in the French Mediterranean piedmont area, many have undergone significant narrowing. Some of those located in the northern piedmont area, such as the Ain River, changed from a braided to a sinuous single-thread and locally meandering channel (Marston *et al.*, 1995).

The consequences of these changes are that specific channel environments, such as braid bars and islands, are being lost (Bravard & Peiry, 1993) and that preserving the last braided corridors will require deliberate action and management. Underscoring the need for such action is the recognition that braided rivers support valuable ecosystems (Michelot, 1994) and represent our natural heritage. Another problem concerns the stability of infrastructure, for example, dyke complexes built a century ago are being undermined by channel degradation of 2 m or more. This is a fairly common situation along many reaches, and can lead to dyke failure during floods. On the Drôme River, 7.5 km of dykes are now destabilized (12% of the total length). Bridges are also destroyed during floods by pile undermining, requiring protection by weirs. In the case of the Drôme catchment, 64 bridges (one of which was destroyed in 1995 and another destabilized in November 2003) are protected by weirs that require regular maintenance. Where channel degradation is ongoing, some weirs have been restored or protected by a second weir located immediately downstream. This is the case in the Arve River where a weir was built in 1984 to stop incision, then restored in 1996 and protected by a new one downstream in 2001.

Ecology and temporal evolution of braided rivers: theory and examples

Although the bell-shaped cost-benefit model appears reasonable for issues surrounding human impacts associated with braided rivers (e.g. bank erosion, flooding, and risk to property in valley bottoms), the form of the trend is more complex when considering ecological impacts and benefits.

It is recognized that intermediate braiding activity can provide high ecological values for riparian ecosystems. Braided channels shift course within the floodplain, destroying old riparian units, and creating new ones with a variety of physical conditions, thereby favouring higher plant diversity (Hirakawa & Ono, 1974; Pautou & Wuillot, 1989). Theoretically, diversity of riparian tree species will be maximized where braiding intensity is somewhere between the extreme expansion phase, where seedling establishment is inhibited and plant mortality high, and the contraction phase, where flood disturbance is insufficiently frequent to reset and renew riparian surfaces (Fig. 2—trend A). This intermediate disturbance condition may provide both exposed mineral soil conditions for pioneer species to become established, and relatively stable 'safe sites' where mid- and late-successional species can survive. This model corresponds to the Intermediate Disturbance Hypothesis developed by Connell (1978).

Braided rivers can, however, provide ecological value throughout their temporal trajectory. In particular, during their expansion phase, braided rivers provide unique animal habitats, such as gravel bars for avian resting, or in-channel rearing and spawning areas for fish species (Fig. 2—trend B). Ecological potential, therefore, does not follow a simple bell-shaped curve but may be high for rivers with significant braiding and then diminish once the gravel surface area decreases, and optimal habitat conditions are no longer present.

An example from the Platte River in central Nebraska, USA, illustrates such an ecological trend. The Platte River has historically been a major resting and breeding site for many species of migratory birds. It currently provides critical habitat for the migration of endangered whooping cranes (*Grus americana*) and 90% of the world's population of lesser sandhill cranes (*Grus canadensis*), along with millions of ducks and geese, over 200 other species of migratory birds, and a range of other endangered or threatened plant, clam and fish species (Johnsgard, 1991; Farrar, 1992). Over the past 100 yr, dams and diversions have reduced peak flows and sediment supply to the braided reaches of the Platte, while irrigation returns have increased base flows (Williams, 1978; Nadler & Schumm, 1981). Reduced peak flows do not scour sandbars, thereby preventing woody vegetation establishment. Instead, the channel has narrowed and incised, and woody vegetation, primarily cottonwood (*Populus deltoides*) and willow (*Salix exigua*), has colonized the once active braid bars and meadows, further restricting lateral migration of the river. The river went from being 450 m wide in the early 1900s to a single thread channel just 100 m wide by 1970 (Fig. 5). Reduced instream flows have also affected adjacent wet meadows and mesic prairie ecosystems by lowering groundwater tables and surface flow (Sidle *et al.*, 1989). These planform and groundwater changes have so altered the structure of riparian habitats that the

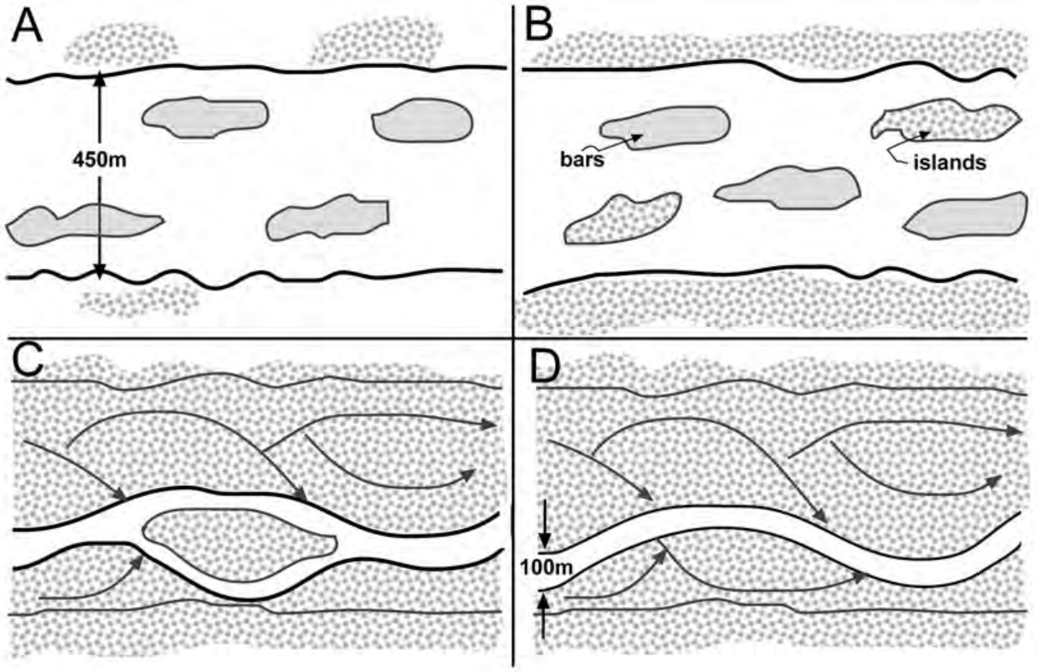


Fig. 5 Transformation of the South Platte River from a multi-thread braided river to a single thread meandering river. (A) Early 1800s: flows are intermittent and transient bars dominate channel. (B) Late 1800s, discharge is perennial due to irrigation returns, vegetation is stabilizing bars and encroaching on floodplain. (C) Early 1900s, low flow during droughts allows vegetation to establish below mean annual high water level, bars become stable, vegetated islands and a single-thread channel forms. (D) The modern single-thread channel and densely wooded floodplain. Braided patterns on floodplain are vestiges of historical channels. (Modified from Nadler & Schumm, 1981.)

sustainability of migratory and resident birds and other biota is in question.

Along with birds, other studies have demonstrated the ecological importance of braided river patterns for fish and invertebrate communities because of the diversity of in-channel habitats (Church *et al.*, 2000; Rempel *et al.*, 2000). Church (2001) described how the braided Fraser River in British Columbia, Canada is one of the most productive rivers in the world, providing complex channel habitat for spawning and rearing fish. Around 30 fish species such as the chum (*Oncorhynchus keta*), pink salmon (*O. gorbuscha*), coho (*O. kisutch*), chinook (*O. tshawytscha*) or sockeye salmon (*O. nerka*) were identified as utilizing braided reaches of the Fraser. Similarly, valuable habitat for fish with associated high sport fishing value is found in the braided rivers of southern New Zealand (Mosley, 1982). For example, sockeye salmon, brown trout and rainbow trout utilize the braided Ohau river. Graynoth *et al.* (2003) stated that because of its width and large number of braids the lower Waitaki River might support more trout per kilometre than most New Zealand rivers (Table 1). Key habitat features include large riffles, runs and braids suitable for spawning by Chinook salmon, while brown trout spawn in the smaller main channel braids as well as the tributaries. The Waitaki River also provides suitable habitat for several species of native fish, such as upland bullies in most braids, and long finned eels in braids where vegetation and debris provide cover. Jellyman *et al.* (2003) indicated that the value of this river is mainly in its middle reach, and depends on a wide range of habitats and water types accessible for a variety of fish species to use. As braiding intensity decreases due to changing discharge and bedload delivery, the braided river structure may retain enough internal heterogeneity to maintain a given level of biodiversity until the braided structure disappears entirely (Mosley, 1982).

The ecological value of braided rivers requires consideration in any plan for sustainable management. As discussed in the next section, the challenge

Table 1 Subjective assessment of the relative importance (%) of the tributaries and different sections of the lower Waitaki River for fish spawning, rearing and fishing (From Graynoth *et al.*, 2003, p. 34)

Species	Function	Tributaries	Section 1	Section 2	Section 3
Brown trout	Spawning	50	5	45	0
	Juvenile rearing	40	5	50	5
	Adult rearing	30	10	50	10
	Fishing	20	10	50	20
Salmon	Spawning	12	6	82	0
	Juvenile rearing	5	3	82	10
	Fishing	0	0	40	60
Rainbow trout	Spawning	90	10*	0	0
	Juvenile rearing	35	20	40	5
	Adult rearing	9	40	50	1
	Fishing	9	40	50	1

*Assumes some juveniles originate from Lake Waitaki.

in such schemes is to find a reasonable equilibrium between satisfying immediate human needs and environmental preservation, which in the long run will guarantee sustained human needs. Such an equilibrium is not easily reached when braiding is both a social problem and has high ecological values. The two objectives are easier to reconcile during the contraction phase of evolution.

SUSTAINABLE MANAGEMENT OPTIONS FOR BRAIDED RIVERS

Balancing sustainable development of braided river valleys without compromising natural river ecosystem functions is a complex task. In this section strategies for achieving this, drawing on global examples, are established.

Expansion phase

Protecting development against flooding at the reach scale

One popular approach to reducing the flooding and bank erosion risks of an actively braided river is to remove excess gravel; this may also prevent rapid avulsions. Kondolf (1994) reported the case of the Waimakariri River near Christchurch in New Zealand, which transports 150,000 m^3 yr^{-1} of sediment from the Alps and aggraded an average of almost 3 m over the downstream-most 15 km between 1929 and 1973. During this period, a reach-averaged depth of almost 6 m of gravel and sand was extracted, saving the town of Christchurch from channel avulsion (Basher *et al.*, 1988).

Where there is high regional demand for gravel, most braided rivers have been heavily mined because of the high gravel quality, ease of mining, and proximity between sites of production and consumption. Gravel extraction is an effective solution where both flood risk and demand for gravel is high, but excess gravel extraction may cause other problems, as discussed below. In France, where gravel extraction has been prohibited since 1994, along with other Mediterranean countries, excess gravel mining has resulted in dramatic channel degradation (Kondolf, 1994; Rinaldi *et al.*, 2005).

Using gravel extraction as a solution to heightened flood risk is more problematic in regions where there is no demand for gravel as a resource, and the cost of gravel mining and storage must therefore be directly borne by local inhabitants. In such situations, gravel extraction is expensive and difficult to maintain, and involves complex trade-offs among different stakeholders and users. Ultimately, the issue becomes how to best satisfy the legitimate needs of flood protection, without

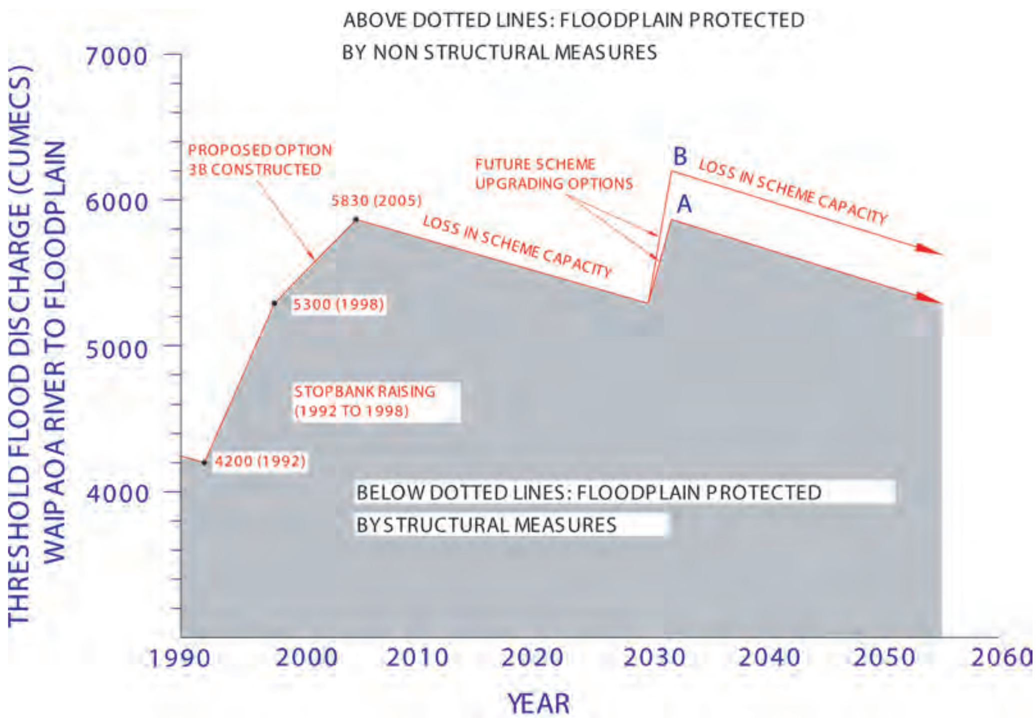


Fig. 6 Potential models of change in the level of protection to the Poverty Bay floodplain, Waipaoa mouth, East Coast region, North Island, New Zealand. (From Peacock, 1998.)

wasting a gravel resource of high quality and degrading the river's conditions to the extent that other users and resources are compromised.

The immediate risk of flooding can often be prevented by developing engineering structures. This approach may be necessary if existing conditions or time lags prevent the use of other countermeasures. For example, as described by Peacock (1998), by 1995 about 30% of the upper Waipaoa in New Zealand was afforested, resulting in a 5% reduction in gravel entering the river. However, afforestation is only an effective strategy on a long-term (multidecade) basis, and a large quantity of gravel had already been delivered to the channel. This material is temporarily stored in the upper reaches of the river and will progressively move downstream for years. The best solution in the short to medium term (years to decades) is therefore to upgrade the dykes in order to protect settlements, coupled with the construction of diversion cuts (Fig. 6). In the long term, because of the negative environmental consequences and recurring costs of such works, new approaches must be developed.

The case of New Zealand's Waiho River is a good example of an alternative approach (Rouse *et al.*, 2001). To combat continuing river aggradation, which increased bed elevation by 5 m in the past 20 yr, with the associated risks of avulsion and damage to local infrastructure, one option was to raise the levees or stop banks. Studies showed that the aggradation was not natural but associated with the reduction of the apex sector angle of the river fan by the river-control stop-banks (Davies & McSaveney, 2001). Some argued that raising the levees would increase the chance of seepage or piping-driven collapse of banks, with increased risk of flooding, and would also increase the costs of maintaining development in the protected area. An alternative option was the continued protection of the right bank but removal of the left one and relocation of its inhabitants.

Reducing sediment delivery to decrease braiding intensity

Excess sediment produced by unstable montane hillslopes in the European Alps sparked development of major mountain restoration programmes in France, Italy, Germany and Austria. These followed the pioneer works of Demontzey (1882) in the Ubaye catchment, where a torrent called the 'monster'—the Rioux Bourdoux—received most of the attention (Fig. 4). In the Drôme catchment in southern France, 16% of the basin (ca. 13,000 ha) was afforested by the Mountain Restoration Services mainly between 1887 and 1917. Between 1863 and 1887, foresters prepared the area by building engineered structures designed to reduce the river's slope and decrease gravel output (i.e. check-dams of various heights constructed with wood or piers). Valley walls were also stabilized by wooden structures. Between 1887 and 1917, the previously stabilized slopes were afforested (Liébault, 2003). These pioneering approaches led to the construction of 'sabo dams' to trap sediment from debris flows, and broad flats at the base of the slopes to dissipate flow energy and promote sediment retention. Such structures have been built all over the world, most notably in Japan, where the first structures were established on the Ishikari River in Hokkaido (Marutani *et al.*, 2001).

Afforestation policies to reduce sediment input from landsliding are actively pursued in the Gisborne–East Coast region of New Zealand. About 16% of the region is planted in exotic forest with an average annual planting rate of ca. 6500 ha. In 1955, the government approved a plan to buy the worst eroding land from the farmers in order to plant closed-canopy forest. Erosion control planting began in 1960. Research demonstrates that the landslide rate under forest is about ten times less than under pasture (Hicks, 1991; Marden & Rowan, 1994). Following replacement of grazed areas by forest, sediment production from 11 gullies in a 4 km^2 area in the Waipaoa headwater area decreased from 2480 t ha^{-1} yr^{-1} during the 1939–1958 period to 1550 t ha^{-1} yr^{-1} between 1958 and 1992. Among the 315 gullies observed at Mangatu forest in the Waipaoa catchment in 1960, only 102 gullies remain today. Reforestation has both contributed to stabilization of many small gullies and prevented formation of new ones.

In pursuing an afforestation approach to reducing sediment delivery to streams, knowledge of land type and storm magnitude–frequency zones enables better targeting of landslide susceptible areas and therefore more effective restoration strategies. For example, a reduction of 50% in landslide-derived sediment can be achieved when only 12% of the catchment area is forested if priority is given to areas sensitive to landsliding (Fig. 7). On the other hand, the same reduction would require treating 30% of the catchment area if reforestation was distributed randomly. Sediment reduction through reforestation of landslide areas is a long-term solution, however, and may require additional measures for short- to medium-term protection. For example, sediment production from the two major landslides of the Waipaoa catchment, the Mangatu (27 ha) and the Tarndale (20 ha), generated 73% of the total basin output between 1939 and 1958. From 1958 onward, reforestation decreased their surface area by only 5% and 30%, respectively, and although sediment production was decreased the two landslides were still producing 95% of the sediment between 1958 and 1992. Reducing the negative consequences of high sediment transport and braiding in downstream rivers therefore requires additional countermeasures.

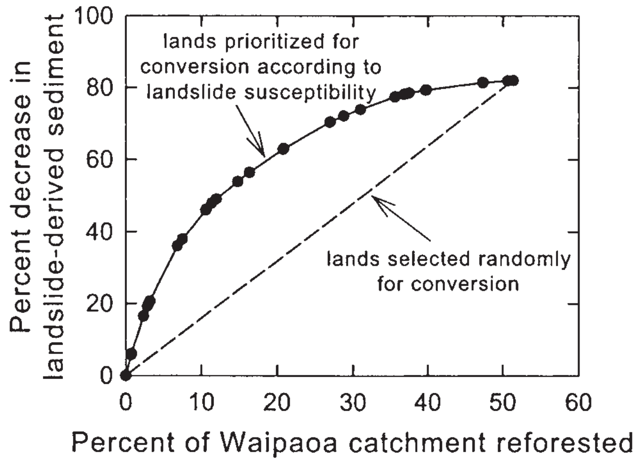


Fig. 7 Percentage of difference in landslide-derived sediment for targeted versus random reforestation strategies. (From Reid & Page, 2002, with permission from Elsevier.)

Balancing human needs in active braided systems

Geomorphological analysis coupled with careful management and engineered interventions can achieve multiple objectives in braided rivers. The Fraser River in central British Columbia, Canada, for example, poses significant flood hazards to those communities and urban areas that border it, although population densities in these areas are not high by global standards. Flood risks are growing for several reasons. A 100-yr period of dyking and channel training works directed at reducing the lateral instability and migration of the channel has restricted access of the river to its floodplain and wetlands, thereby increasing in-channel flows. Simultaneously, the natural trend of bed aggradation across the river's alluvial fan at the gradient and valley width transition between the mountains and the lowlands has been exacerbated by dykes and levees that concentrate coarse sediment deposition in the main channel (Church & McLean, 1994; Church *et al.*, 2001).

The complexity of river management in the Fraser Valley is further heightened by the river's ecological value. The distinctive behaviour and planform morphology of this gravel braided river create unique aquatic and terrestrial habitats, including those associated with bars, islands and secondary channels, that are threatened if braiding is suppressed by levees or flow diversion. The quality of the habitat is such that the 10 species of salmonid fishes found in the Fraser represent the greatest abundance of salmon for any river in the world (Northcote & Larkin, 1989). The lateral and vertical instability characteristic of braided channels is required to renew and maintain the unique habitats that support these fish communities.

River managers and policy makers therefore face complex trade-offs among measures to reduce flood risk, limit lateral instability, whilst at the same time maintaining aquatic habitat. They have adopted an approach that calls for selective and carefully monitored gravel extraction as a means of reducing flood risk in aggrading reaches without sacrificing river morphology. To accomplish this, they commissioned a detailed geomorphological study and sediment budget for the most actively aggrading reach (Church *et al.*, 2001).

As a result of this analysis, long-term gravel recruitment rates were used to establish recommendations for gravel extraction rates and locales (Church *et al.*, 2001). Specific recommendations called for extraction to occur in ways and over timescales that maintained the overall flux of sediment through the reach and the stability of the bar system. Moreover, extraction was designed to mimic sedimentary features that create irregular bar edges in order to maintain physical microhabitat features (Fig. 8). Finally a focused programme of monitoring was called for to assess the effects of extraction as they occurred and modify the plan as necessary.

The Fraser River therefore represents an example of how studies designed to understand the geomorphological template and processes creating that template can be used to direct management activities in such a way that multiple objectives for both risk reduction and ecosystem maintenance can be achieved.

Contraction phase

Widespread loss of braided features, as has occurred throughout southern Europe over the past 100 yr, heightens the ecological value of braided rivers and has led to efforts to actively restore some degree of braiding by various means while still managing flood risks. However, although there are ecological reasons to reduce incision, the primary motivation is typically to protect infrastructure from undermining (Fig. 9).

Increasing sediment delivery to stop channel degradation

Efforts to increase sediment delivery to channels stand in stark contrast to the many efforts worldwide to reduce erosion, and therefore require deliberate planning. For example, in 1997 the regional master plan SDAGE (*Schéma Directeur d'Aménagement et de Gestion des Eaux*) recognized that bedload is a key functional element of river ecosystems of the Rhône basin, France, and that such resources have to be managed in a sustainable way. A variety of measures were taken in order to prevent and limit channel degradation. Traditional civil engineering techniques, such as weir construction to slow down channel degradation, were considered as well as supplementing sediment supply and helping to restore natural erosional processes. Managers also defined new rules for sediment management, banning mining and regulating gravel removal that was being utilized to reduce flood risk.

These measures led to the development of the streamway concept: the idea of defining a band within the valley bottom in which bank erosion is accepted. Guidelines published in 1998 (Malavoi *et al.*, 1998) explain the technical background

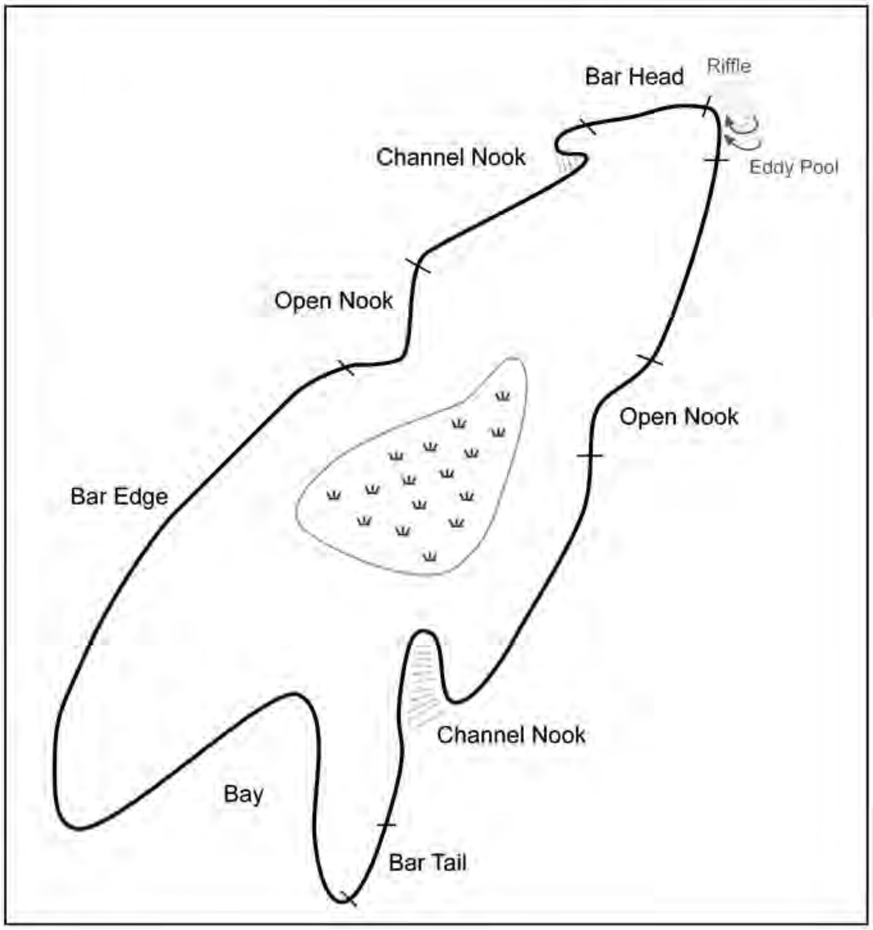


Fig. 8 Microhabitats associated with braid bars identified for the Fraser River by Church *et al.* (2001). These habitats were, in turn, associated with specific fish assemblages.

and help decision-makers implement the concept. Some aspects of the concept seem counter-intuitive. For example, continued bank erosion in reaches that are undergoing degradation is actively encouraged and anticipated to promote aggradation of the active channel. Following SDAGE, the French Government introduced several new regulations, including that as of January 2001 mining is no longer allowed in the streamway, which must be mapped on any channel length greater than 5 km where mining is presently occurring. In addition, landowners must recognize that some degree of river planform change must be accepted in the stream-way to preserve or restore fundamental hydro-logical and geomorphological processes. The law allows owners to be exempt of any liability in relation to these charges.

In the Drôme catchment, an integrated management study released in 1997 promoted measures to help the river aggrade by sediment augmentation. The Forest Service, which is the agency in charge of torrent regulation and forest management in the basin, and therefore responsible for controlling channel degradation, has implemented new practices. Several different methods are used to return gravel to the river in places where it was previously removed by gravel mining. Sediment trapped upstream from grade control weirs is now moved past the weirs and allowed to continue to move downstream. Trenches are constructed in the axis of the channel in aggrading braided reaches in order to concentrate the flow in a single channel, and increase the capacity of the reach to transport gravel that has been mechanically deposited at the channel margin.

Measures are also being introduced to increase the sediment delivery capacity of the basin. After identifying target incised reaches, the bedload

Fig. 9 Photographs showing destabilization of infrastructures within the Drôme catchment (France) because of channel degradation. (A) Bridge at Die destabilized during the November 2003 flood. (© F.Liébault.) (B) Undermined weir at Luc-en-Diois requiring restoration.

transport of potential conveyor tributaries upstream is surveyed for 6 yr. This helps determine potential sources of sediment for supplying downstream, degraded reaches, taking into account the annual transport distance for bedload and protecting supply over a 10-yr time-scale. The geology (lithology) of the watershed is also used to identify possible sediment sources in the basin and evaluate the connectivity of these erosion sites to the stream network.

The next phase (2003–2006) of this programme will be to test this approach under the auspices of the European LIFE programme 'Forests for Water'. Hydraulic modelling will be done to assess the capacity of the conveyor channels to transport more sediment downstream and to identify some intermediate segments where the bedload could be stored. Some pilot sites will then be selected, and engineering and forestry measures will be implemented to reduce channel roughness and resistance and promote gravel movement.

Improving the ecosystem quality of highly disturbed braided rivers

When it is not possible to modify the sediment supply regime and thereby slow down channel evolution, mitigation measures can be implemented at the reach scale to improve the quality of remnant ecosystems associated with braided rivers. For example, restoration activities in the Platte River have been underway since the late 1970s. Analyses have revealed that availability of open channel and wet meadow roosting and foraging habitats are most critical for preserving crane populations, and restoration activities have focused on increasing these habitat types.

Restoration of open river channels to create crane roosting habitat began in 1982 and is accomplished through removing woody vegetation on

Fig. 10 Oblique aerial photograph of the Platte River, Nebraska, Cottonwood Ranch study reach, taken 26 March 2003 (top of the photograph is west/upstream). The channel has been engineered to recreate secondary channels and wetlands. Sandy areas towards the top and middle of the photograph along the right-hand side of the middle braid have been stripped of trees. (Photograph courtesy of Lawrence R. Davis, Davis Aviation.)

banks and sandbars (Fig. 10). The effectiveness, cost and environmental impact of several potential mechanical and chemical treatment combinations for clearing operations were evaluated, and shredding followed by disking was determined to be the most effective and environmentally safe treatment (Currier, 1991). Over 35 km of river channel have been reclaimed using these methods. Follow-up studies to evaluate crane use of roosting sites have revealed that most crane roosts were in river sections that had been mechanically cleared and maintained (Platte River Trust, 2001). Restoration of wet meadow habitat has proven more difficult, primarily because river incision has lowered groundwater tables. Heavy equipment is now used to contour the land surface to recreate a semblance of the historical ridge and slough topography typical of the Platte River, or to maximize the amount of wetland in a given area before planting with native species. The effectiveness of these techniques is now being evaluated (Currier, 1998).

Similar efforts are underway towards recovery of the kaki (black stilt) along rivers such as the Waitaki River in the south island of New Zealand. The restoration programme was intended to mitigate adverse human impacts. Here, the aim was to maintain a large active channel for habitat, retaining flood-carrying capacity, and control exotic weeds in the surrounding wetland to maintain and restore feeding and nesting habitats.

Perhaps the most critical question for such programmes is whether long-term restoration goals can be met without changing the flow regime of the river itself. Particularly in semi-arid areas with extensive agricultural development, such as the Platte River, USA, the issue of how much water can be allocated to river restoration is highly contentious, with many legal and social ramifications. In the case of the Platte, discussions among river users, environmentalists and scientists are now underway to determine what the flow requirements might be to maintain braid bars and open areas for birds.

Balancing risk management and ecological improvement in former braided rivers

Another approach to restoring a former natural braided pattern involves removing bank revetments and dykes. This type of approach is intended to both prevent flood risks while improving the ecology of the river, by providing more space for the river corridor, and recreating remnant alluvial dynamics.

Jaeggi & Oplatka (2001) described the case of the Thur River, a tributary of the Rhine with a drainage area of 1756 km^2, which was dyked, deepened and straightened a century ago to protect cultivated floodplains from flooding. Despite these measures, this area has had problems because the reach is still vulnerable during large floods due to extensive human developments behind the dykes. At the same time, the ecological integrity of the river has decreased due to the control works.

Two types of measures have been promoted to mitigate the effects of the engineered flood works: (i) allowing the channel to widen by bank erosion, which permits new gravel bars to develop, increases bedload transport, improves fish spawning conditions and establishes pioneer riparian vegetation; and (ii) locally enlarging the dykes to re-establish hydraulic connections between the perifluvial wetlands and the main channel. With this second option, the managers expect to locally restore a free meandering or, optimally, a braided reach (Jaeggi & Oplatka, 2001).

The third correction of the Rhône, which is in preparation in Switzerland under the aegis of the *Grand Conseil du Canton du Valais* (see www.vs.ch/Home2/fr/rapport/resume.html), also illustrates this approach. By Swiss law any regulation work must now respect or restore the natural pattern of the river as much as possible.

Restoration measures conducted on the French border of the Rhine River are similarly based on increasing connectivity between the embanked channel and the disconnected floodplain. The floodplain forest located on the reach of Erstein (south of Strasbourg) is now periodically inundated by the Rhine for renaturalization and flood management purposes. It was flooded during January 2004 for the first time since 1968, and ecological monitoring is in progress to evaluate the benefits of such measures. Such approaches have also been utilized on strongly regulated rivers in Austria and Switzerland. The Drau River located in southeastern Austria, near Lienz, is undergoing an ecosystem restoration project that allows the river to move in a wider natural corridor.

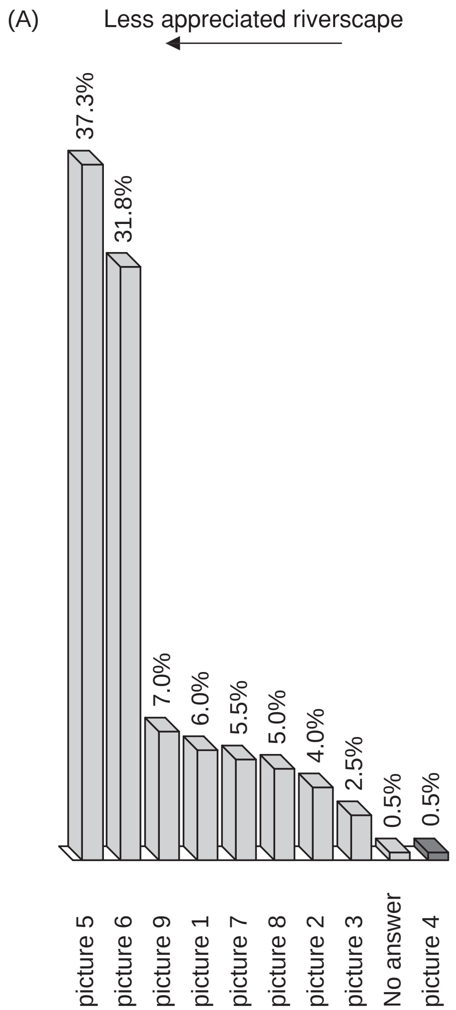
CONCLUSIONS

These different examples show that there is not a unique solution to managing braided rivers. Approaches vary depending on: (i) where the river is in its temporal non-linear trajectory of geomorphological evolution; (ii) existing or potential ecological values and benefits; and (iii) human requirements for safety and protection of economic interests. Each solution therefore depends on a complex cost-benefit analysis appropriate to the specific geomorphological, ecological and human context. This framework suggests that developing information to guide management decisions for presently or formerly braided rivers can be organized around a few key concepts. First, it is valuable to know what the risk associated with the river is in terms of flooding and loss of property. Second, its ecological condition needs to assessed, which may include considerations such as the abundance and diversity of current and historical species and populations, and other factors controlling eco-system structure, including flow regime, turbidity, the stream temperature and water quality, and the extent of active and inaccessible floodplain area.

From historical analyses, including historical accounts, maps, photographs and channel measurements, it should be possible to establish where the river is located on its evolutionary trajectory (Fig. 3). From this historical analysis coupled with information about the current river and basin condition (extent of erosion control works, dam regulation of flows, overall basin-wide sediment production), it should be possible to predict the river's likely future trajectory and therefore expected consequences in term of socio-economic and ecological benefits. In order to identify the best management options, it is necessary to couple this analysis with broader considerations of the regional role and setting of a river system, both in ecological and socio-economic terms.

A key issue here is how the river is perceived and valued by its human inhabitants. This perception is critical to any management decision, and it is not uncommon for experts and local inhabitants to disagree about what needs to be done. In some cases, braided rivers may be viewed as more problematic than more stable single-thread channels. A survey done in the Roubion Valley of France with local inhabitants ($n = 201$) using characteristic photographs of river scenes (three pictures showing straight reaches with a few bars, and six pictures showing braided valley floors) showed that the braided sections were not seen positively (Fig. 11). A quarter of those surveyed preferred riverscapes with abundant flowing waters, well-developed green vegetation providing shade, small areas with sand, and an overall feeling of tranquility. The presence of boulders and bedrock outcrops was also appreciated by the respondents. Boulders were cited as key elements explaining the preference of 65% of the persons surveyed for picture 7, one of the two most appreciated landscapes of the survey. Among the nine scenes, two of the least appreciated landscapes were large braided sections. The reasons given by the respondents for their lack of preference included the following: lack of water, high surface area occupied by gravel, the impression of an inhospitable and barren desert, an area not attractive for human use, and not pleasing. The impression of a uniform, monotonous landscape partly explains why braided rivers are not so popular with many. Moving forward with some of the schemes and approaches discussed here may require public education to help rehabilitate the image and value of braided rivers in the collective mind.

Major efforts by scientists over the past decades have promoted interdisciplinary research to develop sustainable solutions for river systems. The last *Gravel Bed River Conference* in September 2000 in New Zealand as well as *The Braided River Conference* in Birmingham in April 2003 are good examples of the increasing level of interaction among engineers, geomorphologists and ecologists. Nevertheless, if scientists wish to contribute to 'sustainable' solutions for managers, they should consider the socio-economic and cost-benefit aspects of their options together with general societal desires. This suggests that developing options for braided rivers in the future will require interdisciplinary teams of earth scientists and biologists coupled with social scientists concerned with environmental economics, planning, and social and political strategies. New approaches will need to be tested both against geomorphological and ecological criteria, as well as economic and social viability. The real challenge may be to reconcile the spatial and temporal scales and methods of the various disciplinary



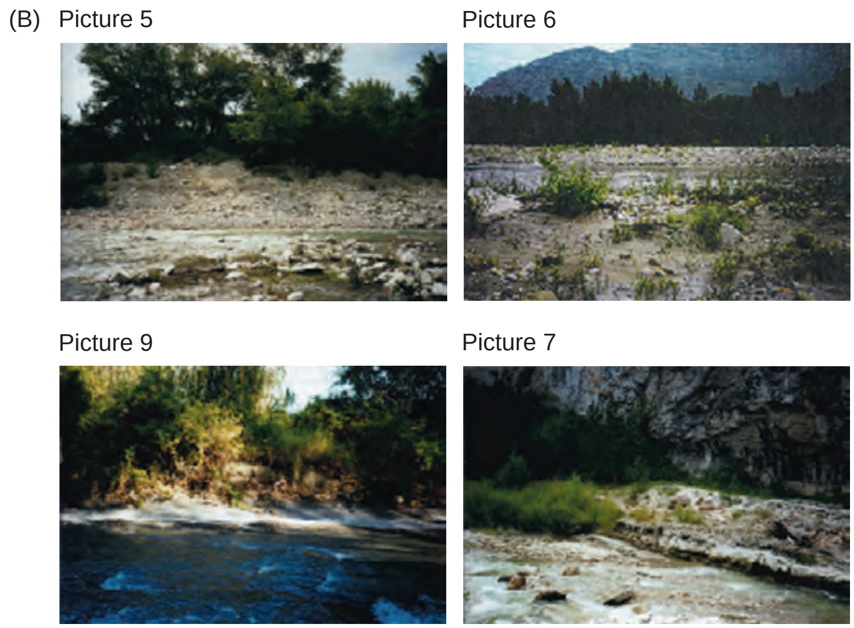


Fig. 11 (A) Order of preference of nine photographs according to a gradient of desirable and undesirable riverscape aesthetics as scored by inhabitants of a braided river valley. (B) Examples of photographs used in the analysis, the Roubion, southeast France. (From M. Cossin, unpublished data.)

and institutional players and local inhabitants involved with braided rivers.

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REFERENCES

Basher, L.R., Hicks, D.M., McSaveney, M.J. and Whitehouse, I.E. (1988) *The Lower Waimakariri River Floodplain: a Geomorphic Perspective*. North Canterbury Catchment board, Department of Scientific and Industrial Research, Division of Land and Soil Sciences, Christchuch, New Zealand.

Bornette, G. and Amoros, C. (1991) Aquatic vegetation and hydrology of a braided river floodplain. *J. Veg. Sci.*, **2**, 497–512.

Bravard, J.P. (1989) La métamorphose des rivières des Alpes françaises à la fin du moyen-âge et à l'époque moderne. *Bull. Soc. Géog. Liège*, **25**, 145–157.

Bravard, J.P. and Peiry, J.L. (1993) La disparition du tressage fluvial dans les Alpes françaises sous l'effet de l'aménagement de cours d'eau (19–20ème siècle). *Z. Geomorphol.*, **88**, 67–79.

Bravard, J.P., Amoros, C. and Pautou, G. (1986) Impact of civil engineering works on the successions of communities in a fluvial system. A methodological and predictive approach applied to a section of the Upper Rhone River, France. *Oikos*, **47**, 92–111.

Bravard, J.P., Kondolf, G.M. and Piégay, H. (1999) Environmental and societal effects of river incision and remedial strategies. In: *Incised River Channels* (Eds A. Simon and S. Darby), pp. 303–341. Wiley, Chichester.

Church, M. (2001) River science and Fraser River, who controls the river? In: *Gravel Bed Rivers V* (Ed. M.P. Mosley), pp. 607–632. New Zealand Hydrological Society, Wellington.

Church, M. and McLean, D. (1994) Sedimentation in lower Fraser River, British Columbia; implications for management. In: *The Variability of Large Alluvial Rivers* (Eds S. Schumm and B. Winkley), pp. 221–241. American Society of Civil Engineers, New York.

Church, M., Rempel, L.L. and Rice, S. (2000) *Morphological and Habitat Classification of the Lower Fraser River Gravel-bed Reach*. Report prepared for the Fraser Basin Council, Geography Department, University of British Columbia, Vancouver, 77 pp.

Church, M., Ham, D. and Weatherly, H. (2001) *Gravel Management in Lower Fraser River*. Report prepared for the City of Chilliwack, Chilliwack, B.C., 119 pp.

Connell, J.H. (1978) Diversity in tropical rain forests and coral reefs. *Science*, **199**, 1302–1310.

Currier, P.J. (1991) Reclamation of crane roosting habitat on the Platte River and restoration of riverine wetlands. In: *Proceedings of the International Crane Workshop*, 1–10 May 1987, Qiqihar, Peoples Republic of China. pp. 403–407,

Currier, P.J. (1998) Wetland restoration on the Platte River floodplain in Nebraska. In: *Ecology of Wetlands and Associated Systems* (Eds S.K. Majumdar, E.W. Miller and F.J. Brenner), pp. 611–627. Pennsylvania Academy of Sciences, Easton, PA.

Davies, T.R.H. and McSaveney, M.J. (2001) Anthropogenic fan head aggradation, Waiho River, Westland, New Zealand. In: *Gravel Bed Rivers V* (Ed. M.P. Mosley), pp. 531–554. New Zealand Hydrological Society, Wellington.

Demontzey, P. (1882) *Traité pratique du reboisement et du gazonnement des montagnes*, 2nd edn. Rotschild, Paris, 520 pp.

DeRose, R.C., Gomez, B., Marden, M. and Trustrum, N.A. (1998) Gully erosion in Mangatu Forest, New Zealand, estimated from Digital Elevation Models. *Earth Surf. Process. Landf.*, **23**, 1045–1053.

Farrar, J. (1992) Platte River Instream Flow—Who Needs It? Nebraskaland. Nebraska Game and Parks Commission, Lincoln, NE.

Ferguson, R.I. (1993) Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 73–87. Special Publication 75, Geological Society Publishing House, Bath.

Gilvear, D.J. (1993) River management and conservation issues on formerly braided river systems; the case of the river Tay, Scotland. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 231–240. Special Publication 75, Geological Society Publishing House, Bath.

Graynoth, E., James, G., Hayes, J. and Bonnett, M. (2003) *Project Aqua: Environmental Study—Aquatic Ecosystems: Salmon and Trout*. Meridian Energy Ltd and Niwa. Christchurch, New Zealand, 93 pp.

Hicks, D.M. (1991) Erosion under pasture, pine plantations, scrub and indigenous forest. *N. Z. Forest.*, **26**, 21–22.

Hicks, D.M., Gomez, B. and Trustrum, N.A. (2000) Erosion thresholds and suspended sediment yields, Waipaoa river basin, New Zealand. *Water Resour. Res.*, **36**, 1129–1142.

Hirakawa, K. and Ono, Y. (1974) The landform evolution of the Tokachi Plain. *Geogr. Rev. Jpn*, **47**(10), 607–632 (In Japanese with English abstract.)

Hudson, K. (1998) The burying of bridges. *Tairawhiti—Conservation Quorum* (Gisborne), **14**, 8–9.

Jaeggi, M. and Oplatka, M. (2001) L'aménagement récent de la Thur: un exemple d'une politique multidisciplinaire de protection contre les crues et de revitalisation de rivière. In: *Scientifiques et Décideurs, Agir Ensemble pour une Gestion Durable des Systèmes Fluviaux*. Colloque International, Agence de l'Eau RMC, Lyon, CD-ROM.

James, G.D. (1992) Chinook salmon angler catch and effort for the lower Waitaki River, 1985–1987. *N. Z. Freshw. Fish. Rep.*, **132**, 16 pp.

Jellyman, D., Bonnett, M., Boubée, J. and Taylor, M.J. (2003) *Project Aqua: Environmental Study—Aquatic Ecosystems: Native Fish*. Meridian Energy Ltd and Niwa. Christchurch, New Zealand, 102 pp.

Johnsgard, P.A. (1991) *Crane Music*. Smithsonian Institution Press. Washington and London, 136 pp.

Kondolf, G.M. (1994) Geomorphic and environmental effects of instream gravel mining. *Landsc. Urb. Plan.*, **28**, 225–243.

Kondolf, G.M. (1997) Hungry water: effects of dams and gravel mining on river channel. *Environ. Manag.*, **21**, 533–551.

Kondolf, M.G., Piégay, H. and Landon, N. (2002) Channel response to increased and decreased bedload supply from land-use change since 1900: contrasts between catchments in the Rocky Mountains of Idaho and the Pre-Alps of France. *Geomorphology*, **45**, 35–51.

Liébault, F. (2003) *Les rivières torrentielles des montagnes drômoises: évolution contemporaine et fonctionnement géomorphologique actuel (massifs du Diois et des Baronnies)*. Unpublished PhD thesis, University of Lyon 2 and UMR 5600—CNRS, France, 357 pp.

Liébault, F. and Piégay, H. (2002) Causes of 20th century channel narrowing in mountain and piedmont rivers and streams of Southeastern France. *Earth Surf. Process. Landf.*, **27**, 425–444.

Lyons, J. and Beschta, R. (1983) Land use, floods, and channel changes; upper Middle Fork Willamette River, Oregon (1936–1980). *Water Resour. Res.*, **19**, 463–471.

Maita, H. and Shizuoka River Work Office (2001) Oi River. In: *Source-to-sink Sedimentary Cascades in the Pacific Rim Geo-systems* (Eds T. Marutani, G.J. Brierley, N.A. Trustrum, and M. Page), pp. 36–43. Ministry of Land, Insfrastructure and Transport, Matsumoto Sabo Work Office, Japan.

Malavoi, J.R., Bravard, J.P., Piégay, H., Hérouin, E. and Ramez, P. (1998) *Détermination de l'Espace de Liberté des Cours d'Eau*. Guide Technique no 2, SDAGE RMC, Comité de bassin RMC and DIREN de bassin RMC, Lyon, 39 pp.

Marden, M. and Rowan, D. (1994) Protective value of vegetation on Tertiary terrain before and during cyclone Bola, East Coast, North Island, New Zealand. *N. Z. J. For. Sci.*, **23**, 255–263.

Marston, R.A., Girel, J., Pautou, G., Piegay, H., Bravard, J.P. and Arneson, C. (1995) Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. *Geomorphology*, **13**, 121–131.

Marutani, T., Brierley, G.J., Trustrum, N.A. and Page, M. (Eds) (2001) *Source-to-sink Sedimentary Cascades in the Pacific Rim Geo-systems*. Ministry of Land, Insfrastructure and Transport, Matsumoto Sabo Work Office, Japan, 183 pp.

Michelot, J.L. (1994) *Gestion et Suivi des Milieux Fluviaux, l'Expérience des Réserves Naturelles*. Réserves Naturelles de France, Quétigny, 440 pp.

Mosley, M.P. (1982) Analysis of the effect of changing discharge on channel morphology and instream uses in a braided river, Ohau River, New Zealand. *Water Resour. Res.*, **18**, 800–812.

Nadler, C.T. and Schumm, S.A. (1981) Metamorphosis of South Platte and Arkansas Rivers, eastern Colorado. *Physical Geography*, **2**, 95–115.

Nakamura, F. and Shin, N. (2001) The downstream effects of dams on the regeneration of riparian tree species in northern Japan. In: *Geomorphic Processes and Riverine Habitat* (Eds J.M. Dorava, D.R. Montgomery, B.B. Palcsak and F.A. Fitzpatrick). *Am. Geophys. Union Wat. Sci. Appl.*, **4**, 173–181.

Nishiyama, K. and Miyazaka, T. (2001) Hime River. In: *Source-to-sink Sedimentary Cascades in the Pacific Rim Geo-systems* (Eds T. Marutani, G.J. Brierley, N.A. Trustrum, and M. Page), pp. 14–19. Ministry of Land, Insfrastructure and Transport, Matsumoto Sabo Work Office, Japan.

Northcote, T.G. and Larkin, P.A. (1989) The Fraser River: a major salmonine production system. In: *Proceedings of the International Large River Symposium* (Ed. J.P. Dodge). *Can. Spec. Publ. Fish. Aquat. Sci.*, **106**, 172–204.

Page, N.J., Trustrum, N.A. and Gomez, B. (2000) Implications of a century of anthropogenic erosion for future land use in the Gisborne-East Coast Region of New Zealand. *N. Z. Geogr.*, **56**, 13–24.

Pautou, G. and Wuillot, J. (1989) La diversité spatiale des forêts alluviales dans les îles du Haut-Rhône français. *Bull. Ecol.*, **20**, 211–230.

Peacock, D. (1998) Integrated management of an aggrading floodplain, Powerty Bay, East Coast, North Island, New Zealand: a case study. In: *Project Risk Management, Proceedings*. Cathay Pacific Risk Management Co. Ltd, Beijing, China.

Peiry, J.L., Salvador, P.G. and Nouguier, F. (1994) L'incision des rivières des Alpes du Nord: état de la question. *Rev. Géogr. Lyon*, **69**, 47–56.

Platte River Trust (2001) *Crane and Waterfowl Migration Report—Spring 2001*. Platte River Trust, Wood River, Nebraska, 8 pp.

Reid, L.M. and Page, M.J. (2002) Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology*, **49**, 71–88.

Rempel, L.L., Healey, M. and Richardson, J.R. (2000) Macroinvertebrate community structure along gradients of hydraulic and sedimentary conditions in a large gravel-bed river. *Freshwat. Biol.*, **45**, 57–73.

Rinaldi, M., Surian, N. and Wyzga, B. (2005) Effects of sediment mining on channel morphology and environment in alluvial rivers. *River Res. Appl.*, **21**(7), 805–828.

Rouse, H.L., Day, T.J. and Davies, T.R.H. (2001) The transit New Zealand Waiho workshop. In: *Gravel Bed Rivers V* (Ed. M.P. Mosley), pp. 633–642. New Zealand Hydrological Society, Wellington.

Sidle, J.G., Miller, E.D. and Currier, P.J. (1989) Changing habitats in the Platte River valley of Nebraska. *Prair. Natural.*, **21**, 91–104.

Surian, N. and Rinaldi, M. (2003) Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, **50**, 307–326.

Taillefumier, F. and Piégay, H. (2002) Contemporary land use change in prealpine Mediterranean mountains: a multivariate GIS-based approach. *Catena*, **724**, 1–30.

Ward, J.V. and Stanford, J.A. (1995) The serial discontinuity concept : extending the model to floodplain rivers. *Reg. River. Res. Manag*., **10**, 159–168.

Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Bretschko, G., Gurnell, A.M., Petts, G.E. and Rossaro, B. (1999) A reference river system for the Alps: the 'Fiume Tagliamento'. *Regul. River. Res. Manag.*, **15**, 63–75.

Williams, G.P. (1978) The case of the shrinking channels —the North Platte and Platte Rivers in Nebraska. *U.S. Geol. Surv. Circ*., **781**, 48 pp.