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River Styles, a Geomorphic Approach to Catchment Characterization: Implications for River Rehabilitation in Bega Catchment, New South Wales, Australia

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ABSTRACT / Geomorphologically derived river styles provide an integrative framework for examining the interactions of biophysical processes in rivers throughout a drainage basin. Nine styles of river character and behavior are identified in Bega catchment, on the south coast of New South Wales, Australia. Headwater streams above the escarpment drain into gorges in the escarpment zone. In different subcatchments at the base of the escarpment, there are three different river styles, namely cut-and-fill, vertically accreted floodplains, and fans. Downstream of these river styles, in the rounded foothills of the catchment, throughput and transfer river styles convey sediments to the lowland plain. In one mid-catchment setting, a floodout traps sediment. Finally, along the lowland plain of Bega River, there is a floodplain accumulation river style. Downstream patterns of river styles in differing subcatchments of the Bega River basin are differentiated into three types, reflecting river adjustments to valley width, slope, and responses to human disturbance.

Analysis of the character and condition of each river style in Bega catchment, and their downstream patterns, are used to provide a biophysical basis to prioritize river management strategies. These reach-scale strategies are prioritorized within an integrative catchment framework. Conserving near-intact sections of the catchment is the first priority. Second, those parts of the catchment that have natural recovery potential are targeted. Finally, rehabilitation priorities are considered for highly degraded reaches. At these sites, erosion and sedimentation problems may reflect irreversible changes to river structure.

Among the many challenges facing resource managers is how to prioritize expenditure on river management practices, whether within an individual catchment or between river systems. In New South Wales (NSW), Australia, most on-the-ground strategies for river rehabilitation are implemented by local community groups (either Rivercare or Landcare groups). Such efforts are typically coordinated by a catchment management committee (CMC), with technical support from the state government agency (NSW Department of Land and Water Conservation). Since 1997 a major federal government initiative, the Natural Heritage Trust (NHT) program, has provided extensive financial support for on-the-ground river management works in Australia. In the initial 5-year plan, implemented in 1998, over $90 million was allocated for Rivercare projects. These projects strive to improve river health, rehabilitate landscapes, and develop sustainable land and water use practices. Although significant political controversy has surrounded the prioritorization and allocation of money for NHT projects, many questions remain unanswered in the scientific and technical community regarding the most efficient and effective means by which river management priorities should be determined. It is argued in this paper that such decisions cannot be made in a systematic, rigorous manner without catchment-framed baseline surveys of the character and distribution of biophysical processes, examining the connections between differing parts of landscapes. A geomorphic framework is considered the ideal basal template upon which such biophysical processes should be recorded (cf., Newson 1992, Hey 1994, Sear 1994, 1996, Brookes 1995, Downs 1995, Sear and others 1995, Brookes and Sear 1996, Brookes and Shields 1996, Downs and Thorne 1996, Thorne 1997, 1998, Thorne and others 1996, 1997).

Geomorphic processes determine the structure, or physical template, of a river system, providing the framework upon which a wide range of biophysical processes interact. River morphology, sediment character, the flow regime, and riparian vegetation are dynamically adjusted, such that change in one variable can modify other parts of the river system, impacting directly on habitat availability, viability, and aquatic ecosys-

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tem functioning (e.g., Barinaga 1996, Osborne and others 1993, Shields 1996, Richards and others 1997, Brierley and others 1999). In terms of river rehabilitation, river geometry and vegetation associations must be appropriately reconstructed before sympathetic rehabilitation of riverine ecology will occur (Newbury and Gaboury 1993). Hence, if the physical structure of the river is appropriate to the local landscape setting, ecological benefits will be maximized. A geomorphic template, as such, provides the ideal platform for examining human impacts on the geoecology of rivers.

Ecologically sustainable river management strategies are likely to be most efficient and effective if they work with the natural behavior of river systems. In this study, a modified version of the Rosgen approach to river classification (Rosgen 1994, 1996) is applied within the catchment-based hierarchical framework documented by Frissell and others (1986), to demonstrate the range and downstream patterns of river character and behaviour in Bega catchment, on the south coast of NSW. This baseline survey of river character and behavior is used to develop a prioritorization framework for river rehabilitation strategies in the catchment.

A Nested Hierarchical Approach to River Characterization

Historically, differentiation of river types has been based on channel planform, defined as the configuration of a river in plan view. However, this perspective underplays the significance of both channel morphology and channel–floodplain relationships. A wide range of studies have demonstrated that there is a continuum of river character and behavior, spread across the spectrum of stream power and grain-size trends (e.g., Bridge 1984, Brierley 1996).

The Rosgen (1994, 1996) approach to river classification evaluates river behavior from its appearance, assessing the relative stability of differing river types. Sediment and hydraulic relationships are identified for each river type, providing a basis to assess ecological interactions. Unfortunately, the Rosgen (1994, 1996) approach does not explain river behavior or place river behavior within either a spatial (e.g., catchment) or temporal (i.e., evolutionary) context (c.f., Miller and Ritter 1996). The approach focuses on channel conditions, with relative disregard for their associated floodplains.

The suite of river types proposed by Rosgen (1994, 1996) bears little relation to rivers that are evidenced across vast tracts of the Australian continent. In the deeply etched, bedrock-dominated landscapes of Australia, few river systems are truly alluvial (see Brierley and others 1996). Rather, the contemporary behavior of most Australian rivers reflects inherited or antecedent landscape controls, namely the dominance of bedrock and ancient alluvial materials over which rivers flow, relief variability that ranges from escarpment-dominated systems to exceedingly low-slope systems of the continental interior, and limited material availability. Superimposed on these controls are extreme discharge variability and differing system-to-system responses to human impacts. There is considerable danger in taking geomorphological notions developed elsewhere, for quite different river systems, and developing management strategies for Australian rivers based on these notions (cf., DEST 1996, CRCCH 1998).

In the approach to river classification adopted in this study, river character and behavior in Bega catchment are analyzed at four interlinked scales: catchments, landscape units, river styles, and geomorphic units (Figure 1, Table 1). In general terms, broad-scale parameters in the nested hierarchy determine the boundary conditions and range of behavior of physical processes at smaller scale units. The approach effectively dissects a catchment, characterizing river styles for differing landscape units. Landscape units comprise characteristic patterns of landforms and are differentiated on the basis of physiographic setting (landscape position) and morphology (elevation and slope). Examples include tablelands, the escarpment zone, rounded foothills, and the lowland plain. Variability in river styles in differing subcatchments reflects either the downstream pattern of landscape units or differences in river behavior within individual landscape units.

In this study, river styles are defined as river reaches that have a characteristic river structure (cf., Kellerhals and others 1976, Thorne 1998), analyzed in terms of channel geometry (size and shape), channel planform, and the assemblage of geomorphic units in a river reach. Geomorphic units are the building blocks of river systems (Brierley 1996). These landforms represent specific associations between landscape morphology and the set of processes that produce that form. Examples include differing types of bar, sand sheets, pools, riffles, benches, levees, backswamps, valley fill, terraces, etc. In general terms, packages of genetically associated geomorphic units can be determined for differing river styles (Table 2).

Methods

The procedure used to identify and characterize river styles in Bega catchment has been developed by

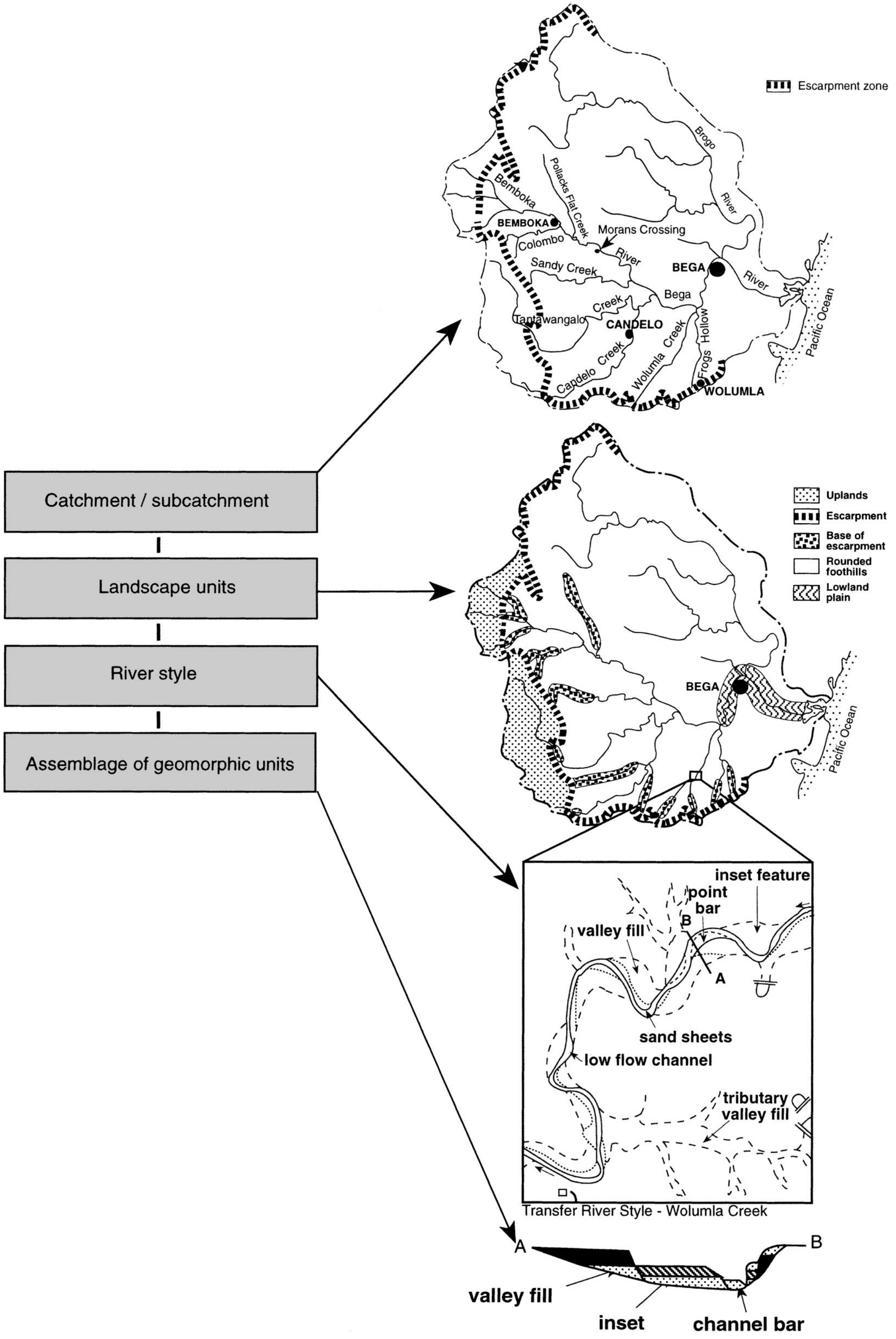

Figure 1. The nested hierarchical framework of the catchment characterisation procedure employed in this study (based on Frissell and others 1986). The catchment comprises a range of landscape units. These topographic features can be differentiated into various river styles, providing a summary of river character and behaviour in each reach. Each river style comprises a characteristic array of geomorphic units.

Table 1. Scalar approach to catchment characterization

Scalar unit	Definition	Primary role in catchment characterization	Primary data source
Catchment	Land surface area defined by topographic boundary (watershed divide) which contributes water and sediment to the specified stream network	Determines boundary conditions within which river operates	Small-scale maps, government department records, remote sensing imagery
Landscape unit	Physiographically defined unit, based on relief, morphology, and landscape position	Determines boundary conditions within which river operates	Small-scale maps
River style	Length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of geomorphic units results	Described by river planform, channel geometry and the assemblage of geomorphic units	Large scale maps and air photographs along with field assessment
Geomorphic unit	Fluvial landforms of channel and floodplain zones	Landforms represent distinct form-process associations; analysis of these building blocks of the river system are used to interpret river character and behavior	Detailed field analysis of channel and floodplain zones

the authors in LWRRDC Project MQU1 at Macquarie University (Brierley and Fryirs 1997, Brierley and others 1996, Fryirs and Brierley 1998b). Catchment-scale attributes, including landscape units, were mapped at 1:100,000 scale using GIS. River styles were identified along primary river courses for each major subcatchment. This was undertaken at a scale of 1:12,500, using the most recent air photograph set (from 1994). River style boundaries were ratified in the field, and the distribution and character of geomorphic units was mapped for each river style. Representative valley-scale cross sections were surveyed for each river style, quantifying the dimensions of the channel and each geomorphic unit. Vegetation associations and the sedimentology of geomorphic units were analyzed in each river style.

The Rational Method from Australian Rainfall and Runoff (Pilgrim 1987) was used to derive discharge estimates for differing flood recurrence intervals at each representative cross section, enabling the determination of bankfull flood recurrence (referred to here as the formative flow). Valley slopes were measured for each river style from the 1:25,000 topographic maps. These data were combined with field estimates of Mannings n to determine estimates of unit stream power for each river style.

Finally, this study draws on previous research that has documented the post-disturbance history of river adjustments in Bega catchment, based on portion plans from last century, historical air photographs (dating from 1944), and extensive field analysis (Brierley and Fryirs 1998, Brierley and others 1999, Brooks and Brierley 1997, 1999, Fryirs and Brierley 1998a,b).

Regional Setting

Location and Geology

Upstream of Bega township, the Bega/Bemboka river system drains a catchment area of 1040 km^2. The catchment has an amphitheatre shape, with five primary subcatchments, namely Wolumla, Candelo, Tantawangalo, Sandy, and Bemboka. The landscape of Bega catchment is dominated by the escarpment, which rises gradually to the north of the catchment, where it attains an elevation of 1070 m (Figure 1).

The geology of Bega catchment is dominated by Devonian granites and granodiorites of the Bega Batholith. Among the exceptions are the headwaters of Bemboka River and Pollacks Flat, which drain from Ordovician metasedimentary rocks and Upper Devonian conglomerates, sandstones, quartzites, and shales. Tertiary basalts occur in upper Candelo, Tantawangalo, and Bemboka subcatchments.

Landscape Units

Five landscape units have been identified in Bega catchment, namely uplands, escarpment, base of escarpment, rounded foothills, and lowland plain (Figure 1). The upland landscape unit is characterized by steep

Table 2. Attributes of river styles in Bega catchment

	Definitive characteristics				Other attributes	
River style	Channel planform	Channel morphology	Channel geometry	Definitive geomorphic units	Bed character	Vegetation character and cover / woody debris loading
Headwater	Single thread, highly stable	Irregular	25 m wide and 1.5 m deep	Discontinuous floodplain, pools, riffles, glides, runs, vegetated islands	Bedrock or boulder / gravel dominated, with steps and / or pools and riffles; B-max 200 mm	Continuous native open forest; high woody debris loading
Gorge	Single thread, straight, highly stable	Symmetrical with bedrock irregularity	10–35 m wide and 1–2 m deep	No floodplain, bedrock steps, pools and riffles	Bedrock or boulder / gravel dominated, with steps and / or pools and riffles; B-max 400–3000 mm	Continuous native open forest; high woody debris loading
Incised cut-and-fill	Single, straight channel, unstable	Stepped, compound channel	10–160 m wide and 2–10 m deep; wide and deep incised channel	Discontinuous or continuous valley fill, terraces, inset features, sand sheets	Sand sheets with occasional gravel (B-max 30 mm) and bedrock	Scattered, native and exotic vegetation; no woody debris
Intact cut-and-fill	No channel	n / a	n / a	Continuous, intact swamp	Intact swamp, dominated by muds deposited from suspension	Tussock grasses and Melaleucas; no woody debris
Vertically accreted floodplain	Single, straight channel, moderately stable	Symmetrical	10–25 m wide and 1–4 m deep; narrow and deep	Discontinuous or continuous, narrow floodplain, mid-channel bars, pools and riffles, bedrock outcrops	Bedrock controlled channel with pools, riffles and mid-channel bars; B-max 300 mm	Thin riparian open forest association; low woody debris
Fan	Distributary network, moderately stable	Symmetrical	25 m wide and 1.5 m deep; narrow and deep	No floodplain; fans extend to valley margins	Bedrock controlled channel with pools and lateral bars; B-max 2000 mm	Continuous native open forest; low woody debris loading
Throughput	Single, straight, channel, highly stable	Symmetrical with bedrock irregularity	15–125 m wide and 1–6 m deep; highly variable	Discontinuous or absent floodplain, extensive bedrock outcrops, sand sheets, pools	Either a bedrock controlled channel with pools, sand sheets and lateral bars or sand sheets with occasional bedrock outcrops; B-max 350 mm	Scattered or continuous open forest associations comprised or exotics and natives; low woody debris loadings
Floodout	No channel	n / a	n / a	Continuous intact swamp with floodout	Intact swamp with floodout	Tussock grasses and Melaleucas; no woody debris
Transfer	Single thread channel; sinuous valley alignment	Asymmetrical	30–140 m wide and 2–8 m wide	Discontinuous floodplain, point bars, point benches and sand sheets	Sand sheets with occasional bedrock, or sequences of point bars with a well defined thalweg; B-max 200 mm	Scattered or absent riparian vegetation cover; no woody debris
Floodplain accumulation	Single channel consisting of an anabranching within channel network; potentially avulsive and unstable	Symmetrical, compound channel	60–175 m wide and 2–6 m deep; wide and shallow	Continuous floodplain with backswamps, levees; benches, mid-channel ridges	Continuous sand sheet with ridges, mid channel bars and channel marginal benches; B-max 10–15 mm	Scattered exotic vegetation associations dominated by willows; no woody debris

B-max = the diameter of the intermediate axis, i.e., the perpendicular of the longest axis, of a clast.

slopes, reflecting dissection of the plateau. It is only prominent in Bemboka, Tantawangalo, and Candelo subcatchments, as the headwaters of other subcatchments lie in the escarpment zone. This differing configuration of landscape units at the upstream end of the subcatchments plays a significant role in determining river morphology in downstream landscape units, especially at the base of the escarpment.

Although the base of the escarpment landscape unit is found in all subcatchments, there is pronounced variability in river style (and response to human disturbance) in this part of the catchment. The differing length of the tongues that extend from the escarpment and the extent of sediment accumulation in this landscape unit account for many of the differences in river character in differing subcatchments.

In areal terms, the rounded foothills are the most significant landscape unit in Bega catchment. This landscape unit comprises hillslopes of 8–15° and is dissected by a multitude of lower-order channels. The rounded foothills and the lowland plain have been almost entirely cleared of vegetation. The lowland plain extends to the Pacific Ocean, although lower Bega River flows through a bedrock-confined reach (Bottleneck Reach) prior to its estuary.

Rainfall

Annual rainfall in Bega catchment ranges from more than 1050 mm/yr above the escarpment to 850–1000 mm/yr at the base of the escarpment and 750–800 mm/yr in central parts of the catchment. The largest flood on record, in February 1971, had an estimated discharge at Morans Crossing (located on Figure 1) in excess of 1800 m^3/sec (Water Resources Commission of NSW 1971).

Historical Land Use and Vegetation Cover

The Bega district was first explored in 1829 and settled by Europeans in the 1830s and 1840s. On the 1851 portion plan, Bega township is well established (Brooks and Brierley 1997). Dairying began in the Bega region soon after settlement, and by the 1870s it was the principal form of land use. Dairying is still the primary land use in the catchment. Within a few decades of settlement, virtually the entire forest cover had been cleared from the lowland zone. Photographs taken at the turn of the century show the character of the landscape to be very similar to today (Bega Family Museum). Intact vegetation coverage in Bega catchment is around 30%, most of which is in the escarpment zone and upland areas.

River Styles in Bega Catchment

Nine river styles have been identified in Bega catchment (Table 2, Figure 2). The distribution of river styles is presented in Figure 3.

Headwater river styles, which are found in the uplands landscape unit, have a wide range of geomorphic units. They have confined, laterally stable channels set within a dissected plateau atop the escarpment. Gorge river styles are found within the escarpment zone, set within a deeply incised V-shaped valley. This river style is dominated by a bedrock channel that occupies the entire valley floor (i.e., there is no floodplain) and comprises an alternating series of pools and vertical drops. Given significant bed and bank heterogeneity, and the intact condition of riparian vegetation, habitat availability in headwater and gorge river styles is high.

Three river styles have been identified in the base of the escarpment landscape unit. Cut-and-fill river styles reflect channel incision into valley fill deposits and infilling of these channels (Fryirs and Brierley 1998a). Two substyles of cut-and-fill river behavior have been identified. During intact filling phases, swamps characterize the valley floor. In some instances, swamps contain chains of ponds (Eyles 1977). These river styles store large volumes of material. During incised cutting phases, deep and wide continuous channels release large volumes of material downstream.

Vertically accreted floodplain river styles have laterally stable, moderately deep, narrow channels, with discontinuous floodplains at valley margins. The channel has mid-channel bars with pools and occasional riffles. The third river style that is found in the base of the escarpment landscape unit is a fan river style. Fans have a convex-upward profile, and comprise coarse boulders. Narrow, moderately shallow channels have shifted position over the fan surface.

Three river styles have also been identified in the rounded foothills landscape unit. Throughput river styles are bedrock-confined, with the channel often occupying the entire valley floor. The channel is stable and acts as a conveyor of sediment. The extent of bed aggradation and degradation indicates the volume of material moving through the system and the efficiency of flushing. Transfer river styles, which have an imposed sinuous channel within a meandering valley alignment, are characterized by point bar and point bench deposition on the inside of bends and by erosion of near-vertical concave banks. In contrast to these two styles of river behavior, floodout river styles accumulate materials in mid-catchment locations. Floodouts have an intact

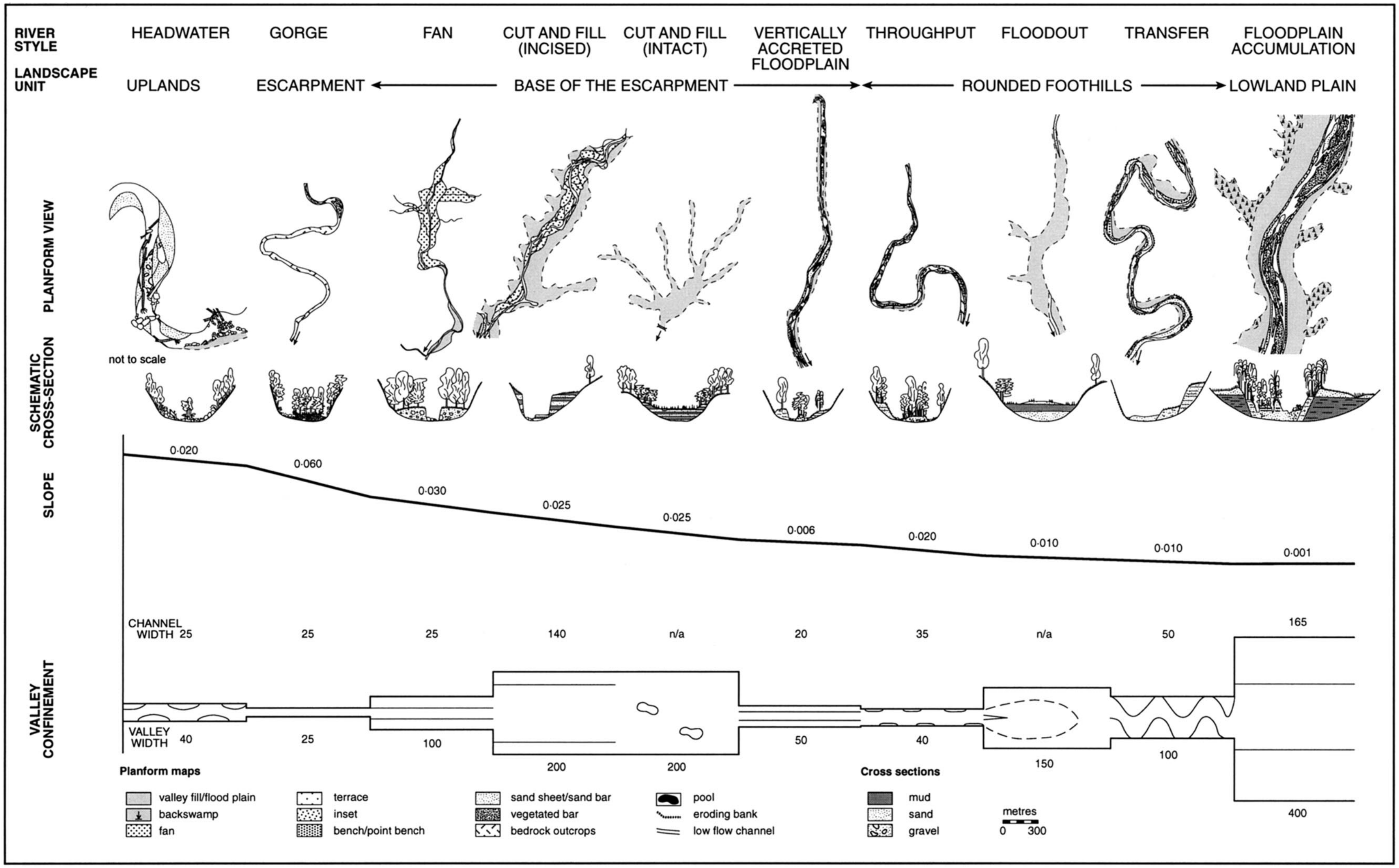

Figure 2. River styles in Bega catchment. River styles are defined in terms of channel geometry, channel planform, and the assemblage of geomorphic units (see Table 3). Differing river styles are identified for each landscape unit. River character and behavior are distinctive for each river style. Note the critical role played by slope and valley width as controls on the distribution of river styles.

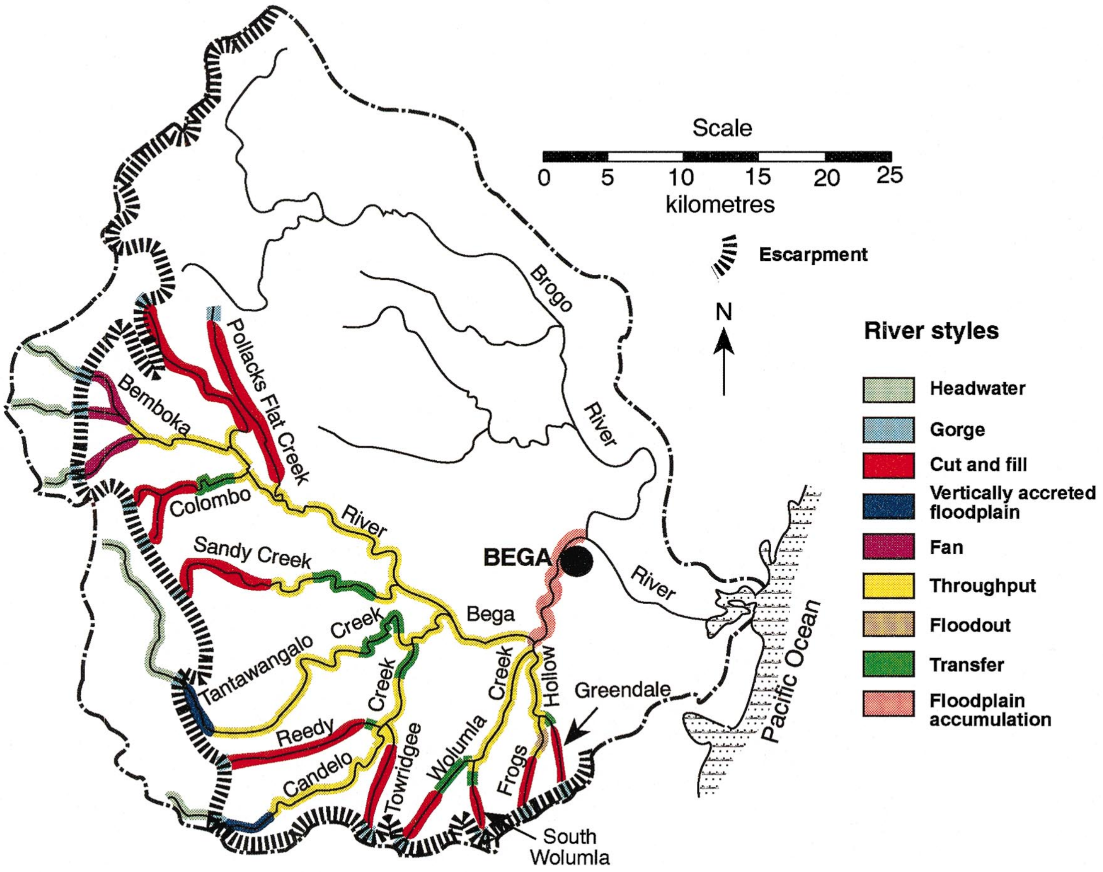

Figure 3. The distribution of river styles in Bega catchment. Three distinctive downstream patterns of river styles can be discerned for differing subcatchments (Figure 4), conditioned primarily by the river style found at the base of the escarpment (i.e., cut-and-fill, versus vertically accreted floodplain versus fan).

valley fill surface (i.e., a swamp) upon which sand sheets are deposited. Sediment supply to this river style results from discontinuous gullying of upland valley fill deposits. In many ways, this river style is an analog for numerous former river courses in the Bega Valley (Brierley and others 1999). These settings are stable unless nickpoints develop in the fill.

Finally, the floodplain accumulation river style is set within the wide valley of the lowland plain and has an extensive, continuous floodplain. The channel is wide, relatively shallow, and choked with sand in the form of large vegetated ridges, mid-channel and bank-attached bars, sand sheets, and densely vegetated channel-marginal benches. This has formed an anabranching network within the channel zone. The floodplain, which is characterized by proximal levees and distal backswamps, has been inundated by sand sheets.

Controls on river styles in Bega catchment are summarized in Table 3. These controls on river character and behavior are discussed in relation to downstream patterns of river styles in the following section.

Downstream Patterns of River Styles in Bega Catchment

Each river style is found at a particular position within the catchment, reflecting a distinct response to imposed boundary conditions (Figure 3; Table 3). As a consequence of differing patterns of these controls in differing subcatchments, the downstream sequence of river styles varies from subcatchment to subcatchment. This results in significant within-catchment variability in the connectivity of biophysical processes in rivers, with associated implications for the downstream transfer of water and sediment.

Three distinct downstream patterns of river styles have been identified in subcatchments of Bega catchment (Figure 4). These patterns are ultimately controlled by longer term landscape evolution associated with escarpment retreat and antecedent controls on valley morphology and sediment storage and supply. The position of the escarpment within each subcatchment, along with the valley morphology (especially

Table 3. Controls on river character and behaviour in Bega catchment

River style	Valley slope	Valley width (m)	Catchment area (km^2)	Unit stream power (W/m^2)					Formative (bankfull) recurrence interval (years)
				1 in 2	1 in 5	1 in 10	1 in 50	1 in 100	
Headwater	0.02	40	>20	—	—	—	—	—	—
Gorge	0.04–0.08	10–40	0–135	—	—	—	—	—	—
Incised cut-and-fill	0.005–0.03	<300	<20	100	125	440	1020	1140	>100
Intact cut-and-fill	0.020–0.028	200	<20	3	4	25	70	100	n/a
Vertically accreted floodplain	0.006–0.02	<50	>30	230	310	650	810	870	2–10
Fan	0.03	100	>80	—	—	—	—	—	—
Throughput (trunk)	0.004–0.006	60–240	100–1000	100	130	390	640	730	>100
Throughput (tributaries)	0.005–0.029	20–80	20–325	165	210	680	1270	1520	2–50
Floodout	0.010	150	<30	3	4	25	70	100	n/a
Transfer	0.005–0.012	40–210	<200	95	120	410	820	1030	10–50
Floodplain accumulation	0.002–0.0008	100–650	500–1840	30	35	95	220	280	5–10

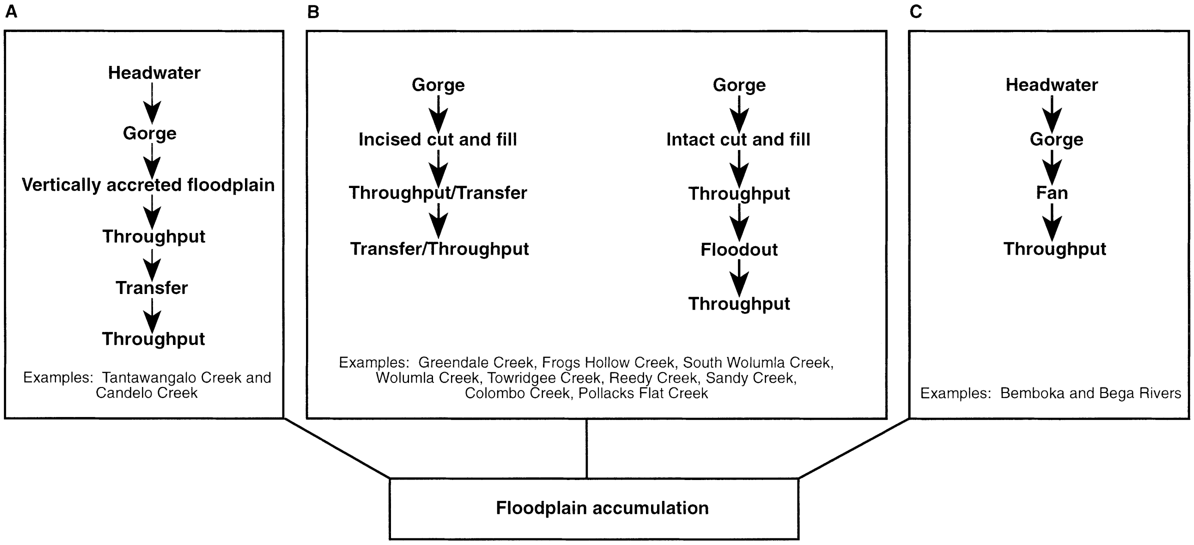

Figure 4. The downstream patterns of river styles observed in differing subcatchments of Bega catchment. The differing combinations of river styles in the middle and upper catchment converge prior to the floodplain accumulation river style observed along the lowland plain.

width) and the break in slope at the base of the escarpment, are primary controls on river character and behavior. Based on differing combinations of valley morphology, slope, and upstream catchment areas, three differing river styles are found at the base of the escarpment, namely, cut-and-fill, vertically accreted floodplain, and fan river styles.

There are two subcatchments in which vertically accreted floodplains are found at the base of the escarpment (Tantawangalo and Candelo; see Figures 3 and 4A). The vertically accreted floodplain river style is found in narrow valleys where significant catchment areas (>30 km^2) drain the uplands landscape unit. They are formed on low valley slopes (0.006–0.020). Immediately downstream, in the rounded foothills, an alternating series of throughput and transfer river styles extend to the trunk stream. Throughput river styles are found in the narrow (20–80 m) and steeper (up to 0.030) sections of these tributaries, while transfer river styles are formed in wider (40–210 m), sinuous valleys that have gentler slopes (<0.012). A schematic representation of downstream changes in channel and valley

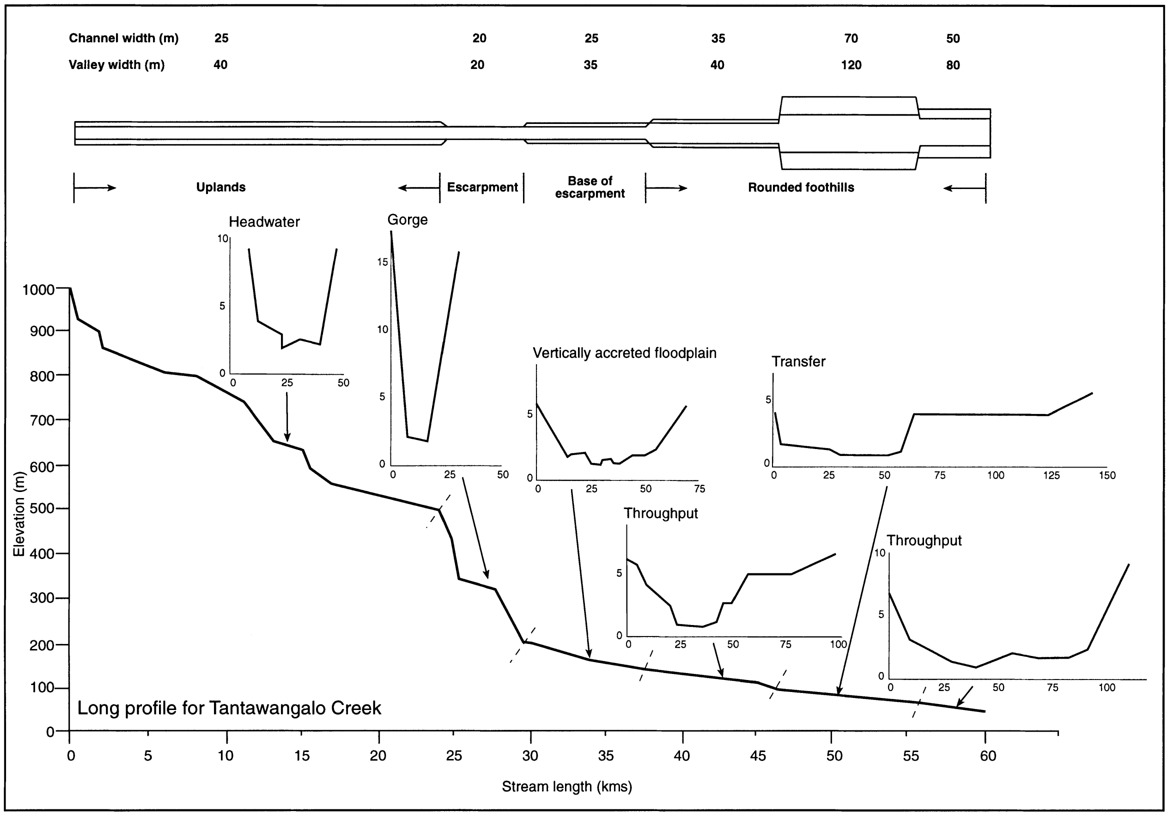

Figure 5. The downstream pattern of river styles in Tantawangalo subcatchment (cf., Figure 4A). Note the elongate valley alignment, the stepped nature of the longitudinal profile, and the area of catchment extending into the uplands landscape unit. Channel dimensions increase downstream in a roughly systematic manner.

width along the longitudinal profile of Tantawangalo Creek is shown in Figure 5. In this downstream pattern of river styles, valley width changes little downstream, only widening in the lower part of the rounded foothills setting. There is an equivalent pattern of minimal downstream change in channel width. Unit stream power throughout this pattern of river styles is consistently high, exceeding 900 wm^2 for all events >1-in-2-year flood. This seemingly explains the limited sediment storage along these tributary river courses. Formative (bankfull) flows are highly variable ranging from 2–10 years at the base of the escarpment to 2–50 years in transfer and throughput river styles.

Most subcatchments in Bega catchment drain directly from the escarpment. In these tributaries, where the uplands landscape unit is absent, cut-and-fill river styles are formed at the base of the escarpment (Figure 4B). Hence, the catchment areas in which cut-and-fill river styles are formed are small (<20 km^2). Cut-and-fill river styles are only found in wide valleys (>200 m wide), and on moderately high slopes (0.011–0.030). In the rounded foothills, throughput and transfer river styles extend to the trunk stream. Only two subcatchments retain an intact cut-and-fill river style at the base of the escarpment (Frogs Hollow Creek and Towridgee Creek). In the former instance, a floodout river style characterizes part of the rounded foothills landscape unit. The floodout is found in similar settings to transfer river styles, in wide valleys (around 150 m) on gentle slopes (around 0.010). Should the floodout and intact cut-and-fill sections of these river courses become incised, the downstream sequences indicated in Figure 4B would become directly equivalent.

Downstream patterns of river styles in which cut-and-fill river styles are found at the base of the escarpment, are characterized by funnel-shaped valley morphologies (Figure 6) In this pattern, the rivers have smooth concave-upward longitudinal profiles, with a distinct break in slope at the base of the escarpment. Channel geometries along this pattern of river styles are highly variable, with deep, wide incised channels at the base of the escarpment and shallow, wide channels in middle and lower sections of the catchment. Estimates of unit stream power exceed 95 wm^2 for all events beyond the 1-in-2-year flood for each river style. This indicates the significant potential for flow to rework sediments stored

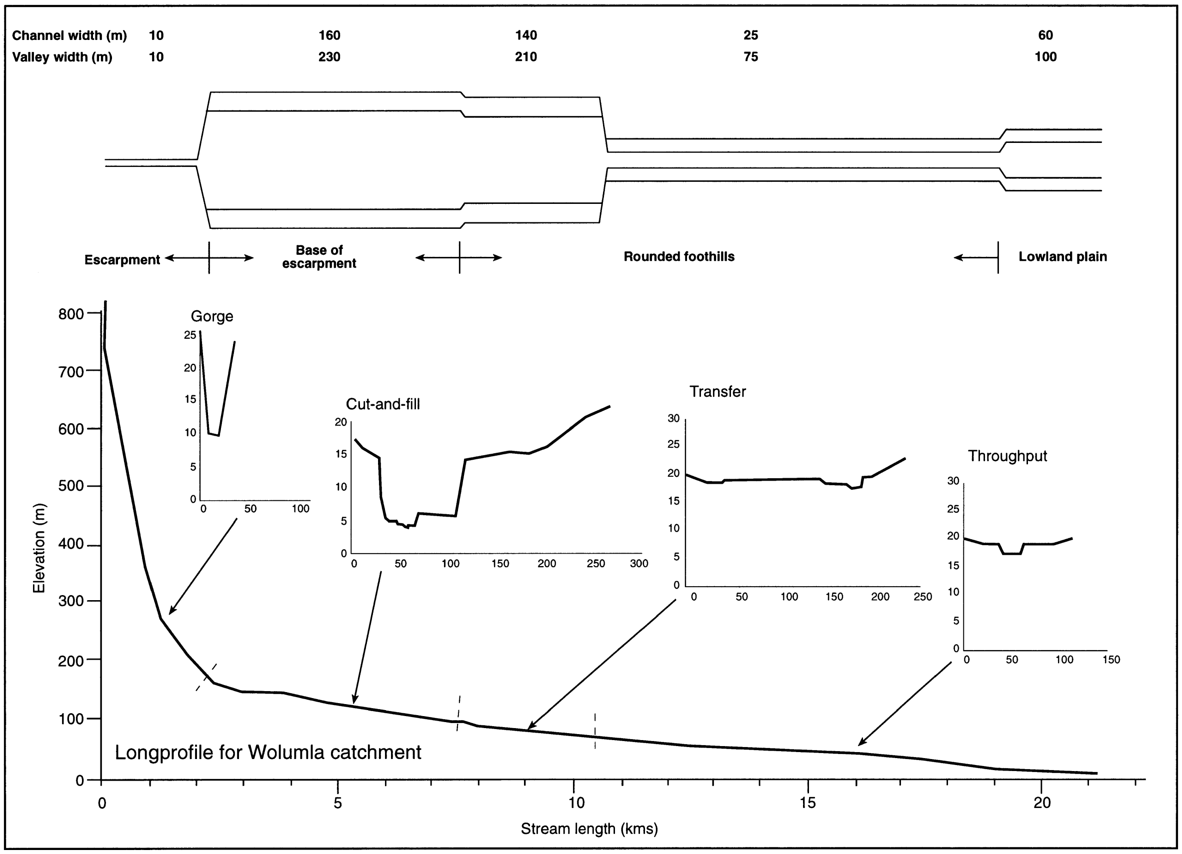

Figure 6. The downstream pattern of river styles in Wolumla subcatchment (cf., Figure 4B). Note the funnel-shaped valley alignment, and the smooth concave-up longitudinal profile. No catchment area exists above the escarpment. Channel dimensions do not increase downstream in a systematic manner, with greatly enlarged channel capacity evident in the cut-and-fill river style.

along these river courses, especially in the incised cut-and-fill settings (where all flows up to and beyond the 1-in-100-year flood are contained within the channel). In the two subcatchments where valley floor surfaces remain intact, unit stream power estimates do not exceed 95 wm^2 for any analyzed flood event other than the 1-in-100-year flood. This reflects dissipation of flow over the valley floor and along discontinuous river courses.

The simplest of the three downstream patterns of river styles observed in Bega catchment is found along Bemboka/Bega trunk stream where a fan is found at the base of the escarpment (Figures 4c and 7). The longitudinal profile has a relatively smooth, concave-upwards form, although this is locally oversteepened in the escarpment zone (the gorge river style). Associated with this downstream change in slope, there is progressive downstream widening of both the channel and the valley.

The fan is found in a wide valley (>100 m), which drains a catchment area >80 km^2. The slope is steep (0.030). In the rounded foothills, a throughput river style is found. No transfer river style occurs along the trunk stream. A floodplain accumulation river style occurs along the lowland plain, where the valley extends up to 650 m wide, and the slope is gentle (<0.002). Other than the floodplain accumulation river style, estimates of unit stream power exceed 95 wm^2 for 1-in-2-year floods throughout these river courses. Along the lowland plain, unit stream power does not exceed 95 wm^2 until the 1-in-50-year flood. In this river style, formative flows range from 5 to 10 years. However, in the widened sections of channel in throughput zones along the trunk stream, formative flows are highly irregular (estimates exceed the 1-in-100-year flood events).

River Changes in Bega Catchment Following European Settlement

Variability in the extent and character of river changes in differing subcatchments of Bega catchment has been

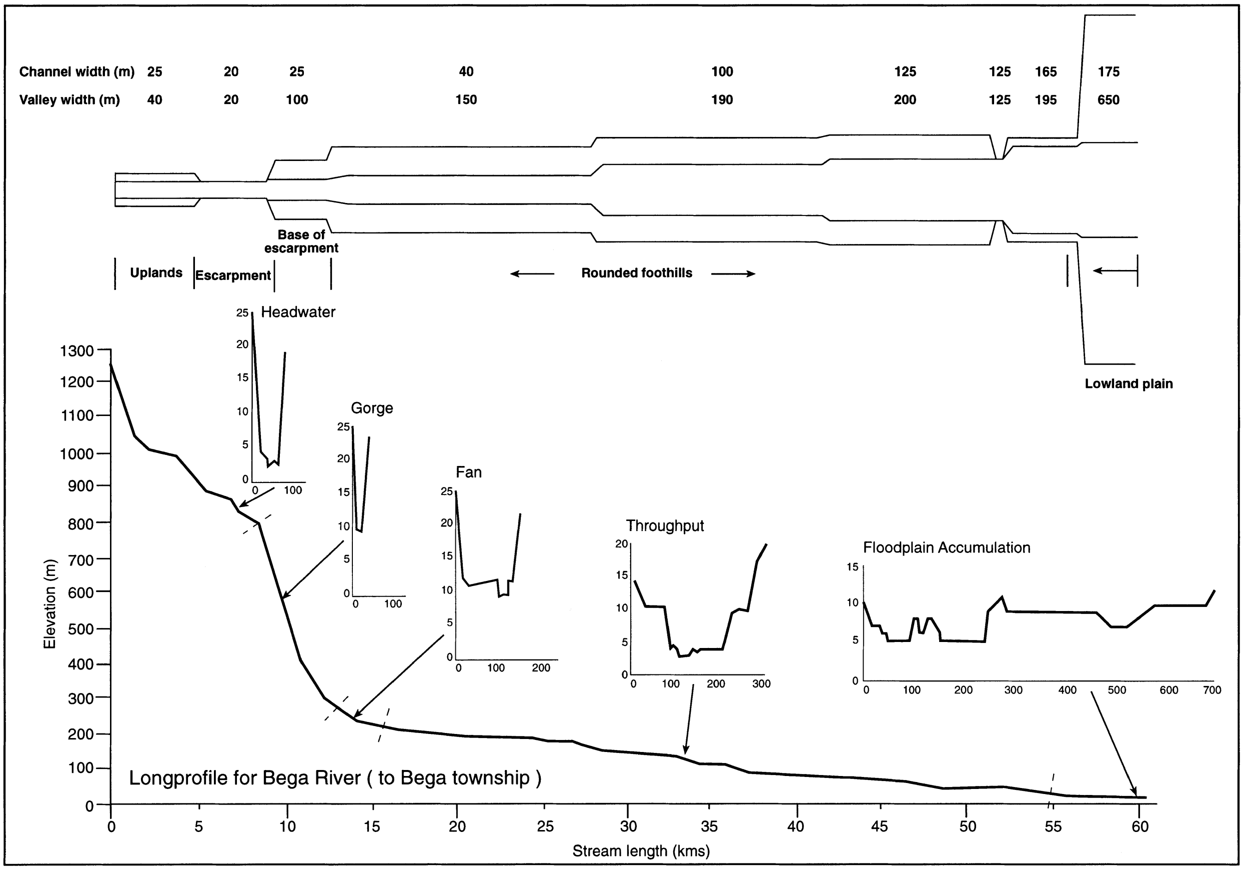

Figure 7. The downstream pattern of river styles in Bemboka/Bega subcatchment (cf., Figure 4C). Note the systematic downstream widening of the channel and valley, and the area of catchment extending into the uplands landscape unit.

conditioned by the river style found in the base of the escarpment landscape unit. Cut-and-fill river styles in upper Wolumla, South Wolumla, Reedy, Sandy, Colombo, and Pollacks Flat subcatchments have been particularly sensitive to disturbance. Former discontinuous watercourses have incised, releasing significant volumes of material. Sediments released from cut-and-fill river styles and floodouts were efficiently conveyed in sediment slugs to the lowland plain via throughput river styles (Fryirs and Brierley 1999, Brierley and Fryirs 1998, 1999). However, in Towridgee and Frogs Hollow subcatchments, several million cubic meters of material remain stored in intact valley fills along river courses.

In contrast, the fan and vertically accreted floodplain river styles at the base of the escarpment in Bemboka, Candelo, and Tantawangalo subcatchments have experienced negligible adjustments in morphology. Downstream transfer and throughput river styles have acted as conduits for the relatively small volumes of material supplied from upstream.

The cumulative sediment contributions from all subcatchments have aided the metamorphosis of river character along the lowland plain of Bega catchment, where the channel widened from 40 to 140 m within a few decades of European settlement (Brooks and Brierley 1997, 1999). The river was transformed from a narrow, deep, mixed-load river to a shallow, wide, sandbed system. Extensive sand sheets have accumulated on the floodplain, modifying the connection between the channel and valley-marginal backswamps.

Catchment clearance and direct changes to riparian vegetation cover seemingly triggered the profound changes to river character in Bega catchment (Brierley and Fryirs 1998, 1999, Brooks and Brierley 1997, 1999, Fryirs and Brierley 1998a, 1999). Essentially, the critical impacts on the landscape had occurred by 1900. Throughout the twentieth century, rivers have adjusted their morphology to the altered sediment budget (Fryirs and Brierley 1998b). Other than responses of the lowland channel to invasion by exotic species since the 1960s, river morphology has changed little this century. Channel adjustments since the first air photographs, taken in the early 1940s, have been trivial. This implies that notional recovery of channels has been underway for at least 50 years (sensu Brookes and Shields 1996, Simon 1992). The effectiveness of channel recovery has been constrained by several factors, such as the lack of riparian vegetation cover and the modified sediment budget of the catchment. While upstream reaches are effectively starved of sediment, such that it will take thousands of years for the valley fill trench at the base of the escarpment to refill (Fryirs and Brierley 1998b), the lower Bega River has been oversupplied with sand, a large proportion of which is now trapped by willows and other forms of exotic vegetation (Brooks and Brierley 1999).

From this, it is inferred that the observed changes to river structure in large parts of Bega catchment are irreversible (cf., Fryirs and Brierley (submitted) CSIRO 1992). Human impacts on river structure have been so pronounced that they have undermined the biodiversity and sustainability of aquatic ecosystems (Brierley and others 1999), and the system is now operating under an altered set of boundary conditions. Efforts at river rehabilitation cannot realistically aim to reconstruct landscapes of the past.

A River Rehabilitation Strategy for Bega Catchment

Scientific perspectives on river management may bear little relation to community perspectives on management directives. This is particularly significant in Australia, where most on-the-ground river works are implemented by local community groups. Unfortunately, many of these river rehabilitation projects have been applied in a piecemeal manner, treating short reaches of stream in isolation from their catchment context. Such reactive strategies are not the most efficient and cost-effective way to prioritize efforts at river management. An alternative approach to prioritorization of rehabilitation efforts, based on river styles and geomorphic assessment of recovery potential of rivers [e.g., Fryirs and Brierley (submitted), Simon 1992, Brookes and Shields 1996], is outlined in Table 4 and Figure 8.

The philosophical perspective which underpins the prioritorization strategy for catchment-based efforts at river rehabilitation in this study is as follows:

1. **Conservation precedes rehabilitation.** Strategies for sustainable catchment management must balance efforts at conservation and rehabilitation of river courses. Since habitat conservation is the key to maintaining the biodiversity of aquatic ecosystems, preservation of remaining near-intact fragments of river courses is considered to be the first priority in the proposed framework. Identification of those parts of catchments that are relatively undisturbed or that represent sensitive sites for future disturbance (termed strategic sites) are key areas for landscape preservation. In this proactive strategy, problems are tackled before they get out of hand. For example, repairing a river course once a head cut has passed is inordinately more expensive than preemptive emplacement of a bed control structure at the nick point (e.g., Newson 1992).
2. The next strategy is to **work in those sections of the catchment with high natural recovery potential,** thereby maximizing the likelihood of management success. In many instances, these reaches are attached to conservation priorities. A do-nothing option may be quite feasible for these sites. Elsewhere, ‘‘soft’’ engineering approaches to river rehabilitation based on riparian vegetation management may be employed to facilitate accelerated recovery. These are minimally invasive rehabilitation strategies.
3. **Contemplate more difficult tasks.** In unstable reaches where the river may be undergoing a sustained period of readjustment, inordinate expense may not yield substantive outcomes, impacting on community confidence in terms of river management efforts. These longer-term rehabilitation programs require invasive rehabilitation techniques. Although conventional river engineering practices can be employed, the most effective strategy may simply be to wait for these reaches to regain some sort of physical balance before adoption of intervention strategies.

The character and behavior of individual river styles, and their downstream pattern in each subcatchment, provide an appropriate biophysical framework with which to develop river rehabilitation schemes that work with the natural behavior of rivers. Target conditions for each river style must be designed within an integrative, catchment perspective, if they are to be sustainable over the long term (Kondolf and Downs 1996). Due regard must be given to potential off-site impacts, ensuring that balanced perspectives on sediment transfer are determined (cf., Sear 1996). For example, it may be pointless to expend significant effort and resource on fixing a downstream reach if a large sediment slug sits immediately upstream, as the future geomorphological behavior of the downstream reach will reflect river responses to the transfer and/or accumulation of those materials.

Post-European settlement changes to the sediment flux in Bega catchment underpin management efforts to rehabilitate river structure and function (Fryirs and Brierley 1998b). Most efforts at river rehabilitation in Bega catchment have to deal with a transformed river

Table 4. Catchment-based prioritization of sites for river rehabilitation

Priority	Nature of sites
1. Conservation reaches	These are the least disturbed parts of the catchment. River structure and vegetation associations are relatively intact. Management strategies aim to maintain, or improve, the current river style, ensuring the preservation of all threatened reaches that contain endangered organisms, or act as corridors between important habitats. These remnant or refuge reaches provide a good base to work out from, into more degraded sections of the catchment. They provide a good seed source for native vegetation.
2. Strategic sites	In general, strategic sites are reaches of river that may be sensitive to disturbance, triggering impacts that may have off-site secondary responses. Proactive (or preemptive) management strategies are the most effective means of river conservation. Particular emphasis should be placed on reaches or point impacts where disturbances may threaten the integrity of remnant or refuge reaches (Priority One sites). Once adjustments are set in motion following disturbance, a phase of accelerated change may commence. This stage may be almost uncontrollable without inordinate, impractical expense (e.g. Newson 1992). Perhaps the key example is the management of nick points or bed-level instability. Unless bed level issues are addressed, significant secondary forms of instability may develop (e.g. Schumm and others 1987).
3. Connected reaches with high recovery potential	If a reach shows signs of natural recovery (i.e., the river is showing signs of self-adjustment, in a manner that fits the contemporary boundary conditions and the landscape setting or river style), there is a high likelihood that management efforts that work with the behavior of the river can achieve quick, visible success. While the ‘‘do-nothing’’ option may be viable at these sites, minimally invasive approaches will facilitate accelerated recovery. In some reaches it may be possible to promote river rehabilitation simply by excluding stock from the river course. Reaches attached to conservation sites are tackled first, building outwards to other reaches of the catchment. This principle follows that employed in bush regeneration work (n.b., upstream reaches also have good seed sources). Alternatively, where a reach in poor condition lies between higher priority reaches, there is significant likelihood of management success in rehabilitating the linking reach. Maintenance and improvement of river structure and vegetation associations at these sites will aid protection of adjoining conservation sites, ensuring the prevention of destablising elements (such as accelerated flows, or high sediment input) from extending upstream or downstream.
4. Isolated reaches with high recovery potential	These reaches have high inherent recovery potential, as noted for Priority Three sites, but are relatively isolated within the catchment. Minimally invasive rehabilitation strategies based on management of riparian vegetation cover should suffice in these reaches, aiming to assist the capacity of the river to self-adjust. These reaches can form nodes for future broader-based efforts at rehabilitation.
5. Potential rehabilitation reaches	These moderately degraded reaches have reasonable potential to recover and can be rehabilitated at reasonable cost. They are isolated sites in the catchment. River structure and vegetation associations require improvement. Invasive strategies are often required to change the character or behavior of the reach. This aids natural recovery, providing a basis upon which improvement can occur. Direct planting and seeding is often required. These sites should be tackled once adjacent river styles which are less degraded have been improved. In some instances, moderately degraded reaches may be in a very poor condition with their natural recovery limited by some external factor. These have been termed impeded recovery reaches (CRCCH 1998). For example, a reach may have a good natural source of seeds, but grazing limits regeneration of riparian vegetation. Simply fencing the site off would produce dramatic results.
6. Highly degraded rehabilitation reaches	These highly degraded reaches of the catchment have little natural recovery potential (i.e., the river shows signs of continued degradation, such as accelerated sedimentation or erosion, or demonstrates a river style that does not fit the landscape setting). These reaches are generally large sediment sources or sediment accumulation zones. Invasive, physical intervention is required for these reaches to recover. This is often expensive, with uncertain outcomes. Once destabilized, the most effective strategy may be to wait for the system to regain some sort of balance before adoption of physical intervention strategies. In most instances, rehabilitation should only continue once upstream sites have been rehabilitated and catchment wide sediment and vegetation management plans are implemented. Any strategy that attempts to rehabilitate these sites in isolation is destined to fail. In some instances, management efforts in these reaches strive to adopt a differing style of river character and behavior.

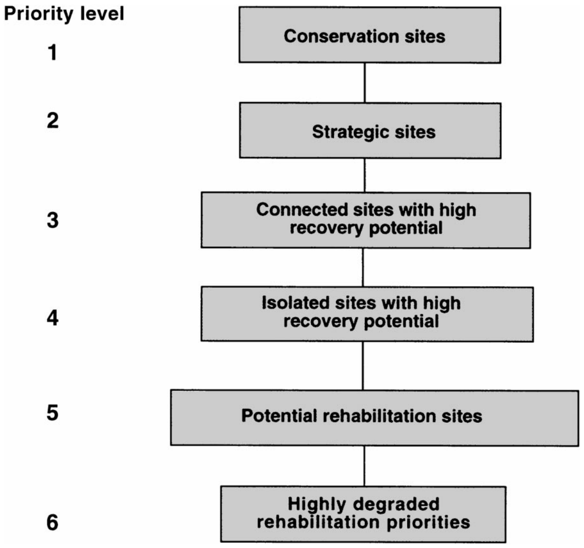

Figure 8. The catchment-framed procedure for prioritorization of river rehabilitation strategies adopted in this study.

system in which the sediment regime has been dramatically altered. Ultimately, for effective rehabilitation, sediments will have to be locked up within the catchment.

Catchment-based application of the prioritorization procedure for river rehabilitation efforts in Bega catchment is shown in Figure 9. Few fragments of this river system retain attributes of their predisturbance condition. These near-intact reaches are primarily restricted to headwater areas. However, there are some sections of the middle to upper catchment where intact valley fills and floodouts are still evident (i.e., Towridgee and Frogs Hollow subcatchments). These reaches are considered to be the key conservation sites in the catchment. These sites store large volumes of material and are threatened by head cuts. While flow management strategies based on vegetation management programs would aid rehabilitation of these sites, engineering structures are required at strategic sites such as the head cut downstream of Frogs Hollow swamp in upper Frogs Hollow subcatchment.

Whenever possible, the ideal reaches to commence rehabilitation programs are connected to those parts of the catchment in which river character and behavior are relatively stable, such that longer-term strategies can build on greater lengths of river that have appropriate river structures for their setting. This strategy replicates that pursued in bush regeneration techniques. In determining target conditions for rehabilitation efforts in river reaches with moderate to high recovery potential, less impacted sections of a river style can be used to assess appropriate target conditions for more degraded river reaches of the same river style (cf., Rosgen 1994, 1996). Rehabilitation strategies have a greater likelihood of success in those reaches that join conservation priorities, as flow and sediment transfer are likely to be in-balance. Many of these upstream reaches also have a near-continuous cover of native riparian vegetation, from which seed sources can aid recovery of downstream reaches. Most of the high recovery potential and degraded reaches in Bega catchment lie in the rounded foothills landscape unit. While throughput river styles generally have high recovery potential, transfer river styles are moderately to degraded (priorities 5 and 6 in Table 4 and Figure 9).

As an example of the procedure to apply river rehabilitation strategies based on recovery potential, a downstream sequence of reach-based strategies would be employed in Tantawangalo subcatchment (see Figures 5 and 9). In this instance, the vertically accreted floodplain river style at the base of the escarpment has a reasonable river structure, but vegetation management is required in the riparian zone. As this reach lies immediately downstream of an extensive near-intact reach of gorge and headwater river styles, which are identified as conservation priorities, the potential for natural recovery of riparian vegetation cover is considered high, as upstream native vegetation seed sources are substantive. Stock exclusion would promote native vegetation regeneration in the vertically accreted floodplain river style. Downstream of this reach, Tantawangalo Creek is characterized by a throughput river style. Once more, the river structure is relatively good in this reach, but effective rehabilitation of the riparian zone is constrained by the condition of the upstream reach. The same principle also applies to the downstream reach of transfer river style, immediately upstream of the confluence with Candelo Creek. However, in the reach characterized by a transfer river style, the river structure also requires some work, as the channel has become enlarged through channel expansion at bends. Minimally invasive, vegetation-based rehabilitation strategies, aimed at developing benches or inset forms, would likely suffice in striving to encourage the river to adopt a more appropriate structure. For these reasons, the transfer river style along lower Tantawangalo Creek has been identified as a potential rehabilitation site.

While vegetation-based river rehabilitation programs seemingly provide the best option for numerous reaches of Bega catchment, there are many instances in which the situation is not quite so hopeful. In many subcatchments, especially those characterized by cut-and-fill river styles and along the lowland plain, changes to river character since European settlement have brought about irreversible changes to river structure. Significant

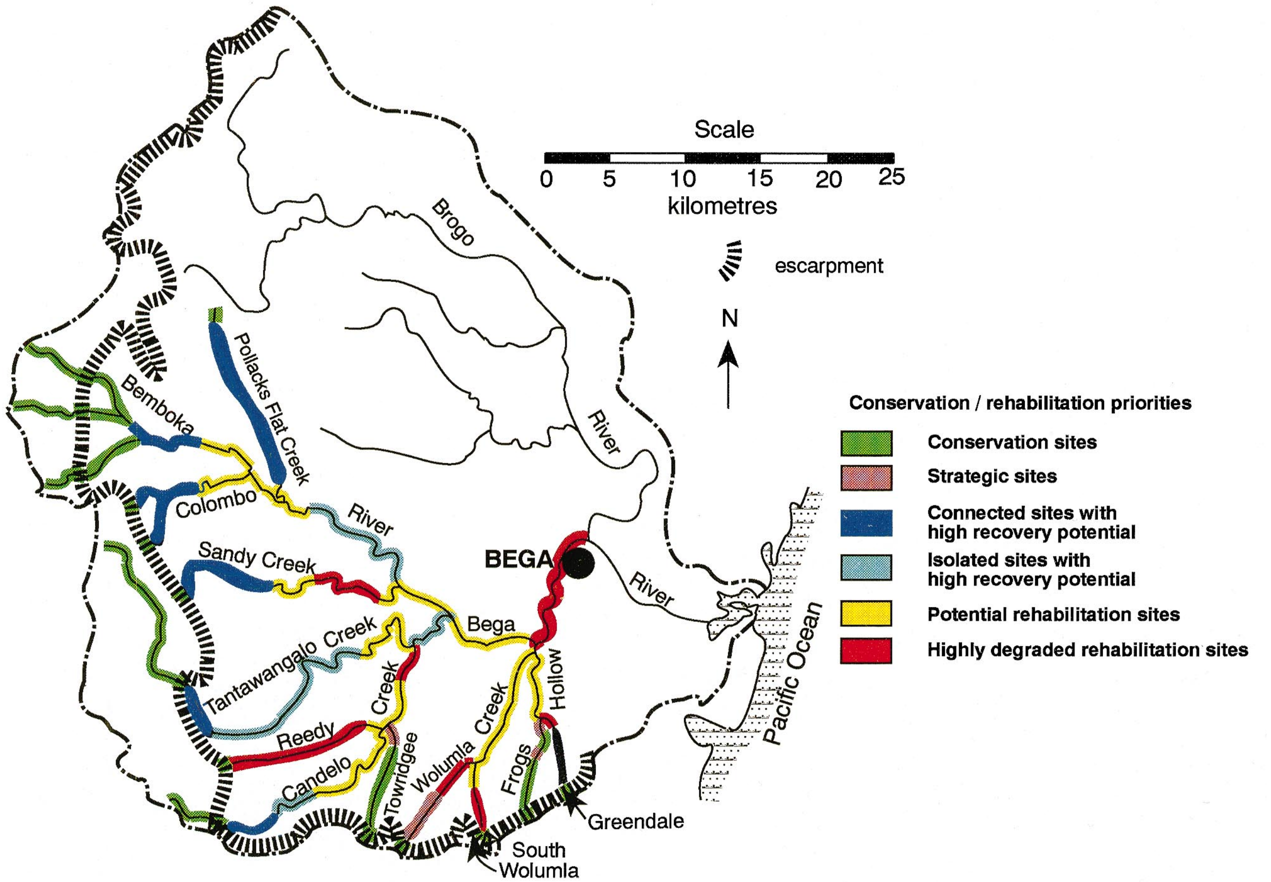

Figure 9. Prioritorization of river rehabilitation reaches in Bega catchment, using the framework shown in Table 4 and Figure 8. This strategy builds out from the near intact sections of the catchment to the most degraded reaches, while targeting strategic sites in the catchment.

intervention is required to bring about rehabilitation of these degraded reaches, as these sites have either limited or no natural recovery potential in the short to medium term. Physical, engineering-based intervention is required for these reaches to recover. This is often expensive, requiring detailed research to design an appropriate rehabilitation plan. Implementation may be difficult and expensive, with uncertain outcomes and potential off-site risks. For example, in striving to manipulate the willow-infested, highly modified river structure of lower Bega River, significant volumes of sand may be released, impacting on downstream river reaches and the estuary. In these reaches, it may be advisable to wait for the system to regain some sort of balance before adoption of physical intervention strategies. Effective rehabilitation should only continue once upstream sites have been rehabilitated and catchment-wide sediment and vegetation management plans are implemented. Degraded sections of Bega catchment are still adjusting to an altered sediment regime, as these reaches respond to lagged impacts to the sediment budget initiated at the end of last century (Fryirs and Brierley 1998b).

Implications

As rivers demonstrate remarkably different character, behavior, and evolutionary traits, both between and within catchments, individual catchments need to be managed in a flexible manner, recognizing what forms and processes occur where, why, how often, and how these processes have changed over time. River styles present a catchment-framed reconnaissance survey of river character and behavior, indicating the condition that a river reach may demonstrate under prevailing boundary conditions. The explanatory and predictive basis of the approach provide a rigorous physical basis for management decision-making (Table 5). However, it is recognized implicitly that the procedure is scientifically based, while decision-making on management efforts is a consultative processes, driven by a wide range of agendas from multiple stakeholders. The river styles

Table 5. Applications of catchment characterization procedure

In geomorphic terms, the proposed procedure:

- Evaluates river behavior from its appearance, characterising river styles for differing landscape settings
- Provides a baseline survey of river character and behaviour throughout a catchment
- Explains the within-catchment distribution of river forms and processes in context of system evolution
- Assesses linkages between differing river styles, demonstrating how changes in one part of a catchment have impacted elsewhere, over what time frame
- Assesses the relative stability of differing river styles, providing insight into likely future patterns of adjustment
- Is open-ended and generic

In terms of geomorphic links with river ecology, the proposed procedure:

- Determines the physical template of a river at differing positions throughout a catchment, providing a framework to assess habitat availability along river courses
- Assesses changes in river structure over time, thereby showing how habitat availability has changed
- Provides a basis to determine suitable river structures to support viable habitats along river courses

In terms of river management, the proposed procedure:

- Helps to develop proactive, rather than reactive, management strategies, more effectively prioritorising resource allocation to management issues
- Provides appropriate understanding of the controls on erosion and sedimentation problems, enabling realistic target conditions to be determined for river rehabilitation, based on geomorphological understanding of river processes
- Ensures that site-specific river rehabilitation strategies are linked within a reach and catchment-based vision
- Can be used to guide selection of representative sites in programs to monitor river condition and to audit the effectiveness of river management strategies

approach provides no sense of landscape aesthetics or political and/or community expediency in determination of what the river character should look like, but it does provide a biophysical basis for prioritorization of efforts in terms of river conservation and/or rehabilitation.

The applications and potential implications of this procedure must be communicated effectively to all stakeholders who participate in on-the-ground river management. Working through technical facilitators within state government agencies, geomorphologists need to provide appropriate insights into the character and linkages of biophysical processes within catchments, ensuring that appropriate technical advice is provided to local community groups with which to implement land (and river) management strategies.

It is recognized implicitly that river management must continue regardless of limitations of knowledge. However, as a general rule, the precautionary principle should be observed in the absence of background scientific understanding, and advice to community groups should not be prescriptive. Given the community focus of river rehabilitation projects in Australia, and the underlying emphasis on the return for dollars spent, working at sites with a high likelihood of success provides a sound management strategy in biophysical, socioeconomic, and environmental terms.

The river styles procedure is generic and open-ended. Although styles of river character and behavior in Bega catchment may differ from those evident elsewhere, and the relative sensitivity of this granitic catchment to disturbance in the period following European settlement may not be representative of the continent as a whole, there are no obvious reasons why the procedure cannot be applied elsewhere. As such, the river styles framework has the potential to underpin management efforts that implement water reforms in Australia, as impacts of differing flow regimes will vary for differing river styles. This biophysical approach also provides an ideal baseline assessment for determining systematic sampling strategies for environmental monitoring programs that evaluate river condition. An appropriate geomorphic template of rivers in differing landscape settings throughout a catchment provides the platform for sustainable efforts at river rehabilitation.

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