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The human role in changing river channels

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Abstract

Direct consequences of *the human role*, where human activity affects river channels through engineering works including channelization, dam construction, diversion and culverting, have been long recognised [Marsh, G.P., 1864. Man and Nature or Physical Geography as Modified by Human Action. Charles Scribner, New York; Thomas Jr., W.L., (ed.) 1956. Man's Role in Changing the Face of the Earth. Chicago, University of Chicago Press, Chicago.]. The less obvious indirect effects of point and reach changes occurring downstream and throughout the basin, however, are much more recently appreciated, dating from key contributions by Strahler [Strahler, A.N., 1956. The nature of induced erosion and aggradation. In W. L. Thomas (Ed.), Man's Role in Changing the Face of the Earth. University of Chicago Press, Chicago, 621–638.], Wolman [Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A, 385–95.], Schumm [Schumm, S.A., 1969. River metamorphosis. Proceedings American Society of Civil Engineers, Journal Hydraulics Division 95, 255–73.], and Graf [Graf, W.L., 1977. The rate law in fluvial geomorphology. American Journal of Science, 277, 178–191.]. These are complemented by effects of alterations of land use, such as deforestation, intensive agriculture and incidence of fire, with the most extreme effects produced by building activity and urbanisation.

Changing river channels are most evident in the channel cross-section where changes of size, shape and composition are now well-established, with up to tenfold increases or decreases illustrated by results from more than 200 world studies. In addition the overall channel planform, the network and the ecology have changed. Specific terms have become associated with changing river channels including enlargement, shrinkage and metamorphosis. Although the scope of adjustment has been established, it has not always been possible to predict what will happen in a particular location, because of complex response and contingency. The ways in which changes in cross-section relate to reach and network changes are less clear, despite investigations showing the distribution of changes along segmented channels.

When considering the *human role in relation to changing river channels*, at least five challenges persist. First, because prediction of the nature and amount of likely change at a particular location is not certain, and because the contrasting responses of humid and arid systems needs to be considered, modelling is required to reduce uncertainty, as was first emphasised by Burkham [Burkham, D.E., 1981. Uncertainties resulting from changes in river form. American Society Civil Engineers Proceedings, Journal Hydraulics Division 107, 593–610.]. Second, feedback effects incorporated within the relationship between changes at channel, reach and network scales can have considerable implications, especially because changes now evident may have occurred, or have been initiated, under different environmental conditions. Third, consideration of global climate change is imperative when considering channel sensitivity and responses to threshold conditions. Fourth, channel design involving geomorphology should now be an integral part of restoration procedures. This requires, fifthly, greater awareness of different cultures as a basis for understanding constraints imposed by legislative frameworks. Better understanding of the ways in which the perception of the human role in changing river channels varies with culture as well as varying over time should enhance application of design for river channel landscapes.

Keywords: River channel changes; River channel management; Human impact

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1. Introduction

A paper published 50 years ago (Strahler, 1956) was one of several key foundations for understanding of the human role in changing river channels, so that 2006 is an appropriate year to reflect upon the way in which our understanding has grown and the significance of that understanding has become appreciated. Six chronological phases of river use (Downs and Gregory, 2004, Table 1.2, p.9) catalogue the major ways in which human influence has affected river channels over the last 5000 years through dam construction, river diversions and engineering since the first phase of the early hydraulic civilisations affected river channels. The culmination of that phase, and the five subsequent ones, produced river channels that are extensively modified by human activity, although the spatial pattern of modification varies across the world. Such modifications, which include direct purposeful changes (Brown, 1970) and indirect, less obvious changes (Table 1), are now complemented by ways in which the human role, in a third phase, is beginning to redress earlier effects of human action; for example by dam removal (Heinz Center, 2002; Graf, 2003) or by stream and river restoration (Downs and Gregory, 2004; Sear and Darby, in press).

Against this background, reticence to investigate the human role in changing river channels is surprising because studies did not really begin until 1955 (Lane, 1955; Strahler, 1956). Most emphasis was given to effects on the hydrological regime rather than upon the channels despite some important individual contributions such as changes in downstream sediment transport because of placer mining (Gilbert, 1917), modification of the 'physiographical balance' by interference with natural conditions (Sonderegger, 1935) illustrated by effects on the Rio Grande downstream of Elephant Butte dam, and the importance of fluvial morphology in hydraulic engineering (Lane, 1955), subsequently developed further by Schumm (1977). Downstream of dams the effects of scour were considered in engineering design (e.g. Komura and Simons, 1967) but apart from occasional studies (e.g. Sonderegger, 1935) little attention was given to the channel further downstream. As the broader implications of channel change became appreciated, at least four fundamental influences emerged (Fig. 1). The spatial relationship between gullying and induced aggradation (Strahler, 1956) identified the network consequences of channel change (Fig. 1A); the way in which changing land use over time culminating in building activity and then urbanisation (Wolman, 1967) was related to channel condition (Fig. 1B) was formulated; the notion of river metamorphosis and of thresholds (Schumm, 1969); and the application of a rate law (Graf, 1977) involving reaction–and relaxation–times as parts of the response time pertinent to changing from one equilibrium condition to another, are embraced in the diagram (Fig. 1C) showing types of equilibrium (Gregory and Downs, in press). These four contributions, complemented by important individual papers (e.g. Leopold, 1973), provided important foundations for understanding the human role in changing river channels. By the time *River Channel Changes* (Gregory, 1977a) was published, a clear understanding existed of the need to focus upon channel cross-section, channel planform and network changes induced by human activity.

Since 1977, the impacts of human activities in changing river channels have been further elaborated so that the magnitude of potential change is now known much more completely. Research benefiting from the established foundations (Fig. 1), together with awareness of the magnitude of various categories of human influence (Table 2), provided the basis for nearly thirty years of research, during which progress made was founded upon important key contributions (Table 1). Following sections show how conclusions reached about

Table 1
Some key contributions in interpreting human impact on river channels

Contribution	Implementation	Source
Types of channel change	$Q_sD \approx Q_wS$ involving bed material load (Q_s), particle diameter (D), water discharge (Q_w) and stream slope (S) used to indicate implications of six types of change	Lane (1955)
Induced aggradation	Gullying or channel extension upstream complemented by aggradation downstream (see Fig. 1A)	Strahler (1956)
Cycle of erosion in urban channels	Changing channel morphology depicted during land use change from forest through agricultural land to urbanisation (see Fig. 1B)	Wolman (1967)
River metamorphosis, thresholds and complex response	Effects of changing discharge and sediment load on channel morphology indicated by equalities such as: Q_s^+, $Q_w^{++} \approx S^-$, $d50^+$, D^+, W^+, using equality to relate sediment (Q_s) and water discharge (Q_w) to slope (S), median diameter of bed material (d50), flow depth (D) and flow width (W)	Schumm (1969)
Rate law	Change from one equilibrium to another through a response time and a reaction time (see Fig. 1C)	Graf (1977)

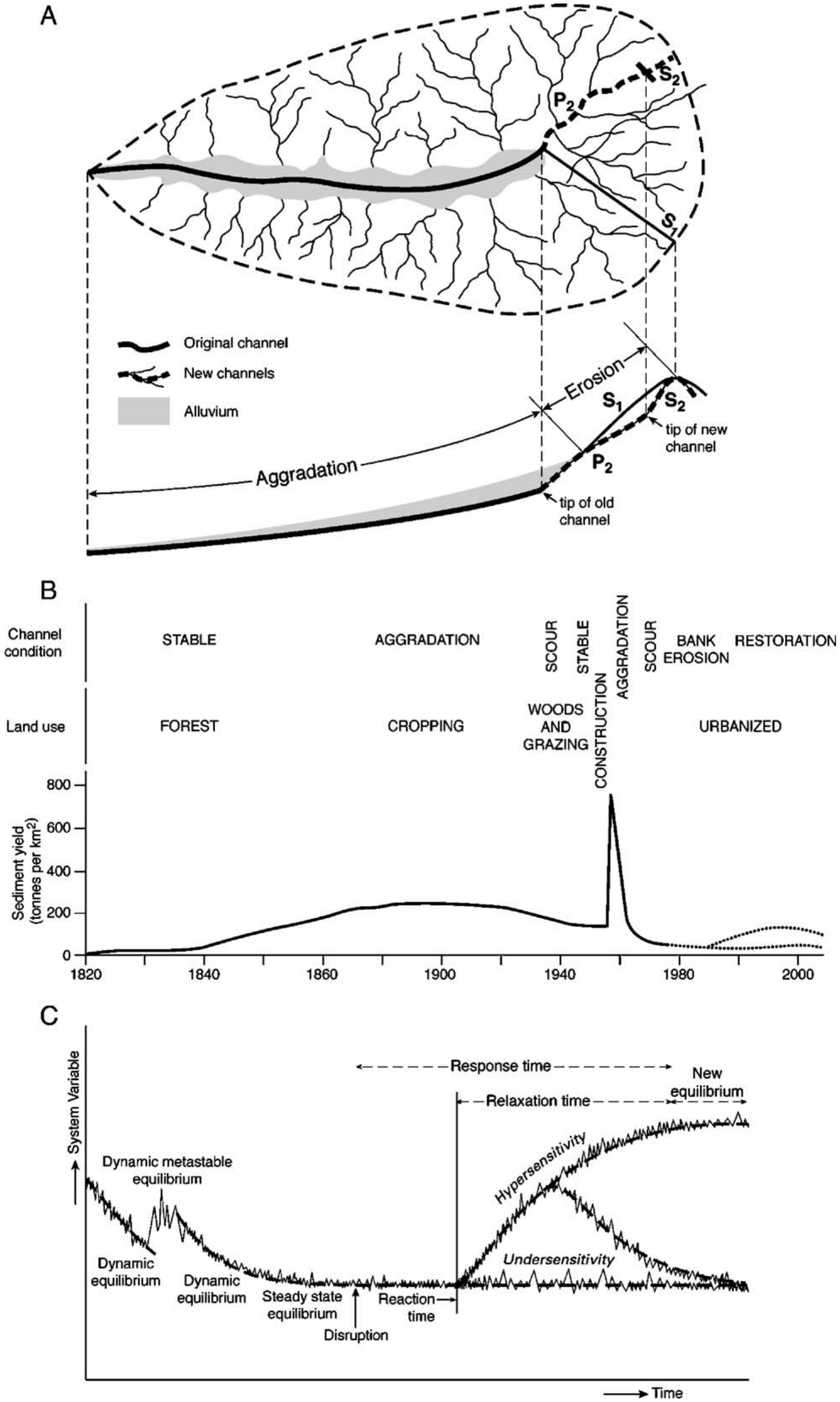

Fig. 1. Foundations for studies of the human impact upon river channels. A is redrawn from Strahler (1956); B is adapted from Wolman (1967); and C incorporates ideas from Graf (1977) and Schumm (1979). For explanation see Table 1 and text pp. 00–00.

Table 2
Examples of human impacts pertinent to change in river channels

Type of impact	Examples	Source
Dams	At least 45,000 large dams (>15 m high or 5–15 m high if reservoir volume>3 million m^3)	World Commission on Dams (2000)
	More than 400,000 km^2 inundated behind the world's large dams	McCully (1996)
	Fragmentation of nearly all rivers in North America due to presence of dams, with 80,000 dams>6 ft (1.83 m) and including all structures may be 2.5 million in the USA	Dynesius and Nilsson, 1994; Heinz Center, 2002
	More than 1500 large- and medium-sized dams in India and 100 barrages on all major river systems	Gopal (2000)
	Australia has 447 large dams and several million farm dams which modify river flows	Schofield et al. (2000)
Channelization	In the USA 26,550 km of major works gives a channelized density of 0.003 km/km^2	Leopold (1977)
	In England and Wales 8504 km of major or capital works gives a density of 0.06 km/km^2, and there is also a further 35,500 km of river which is maintained	Brookes, Gregory and Dawson (1983)
Channel modification	Average of <10% of length of Alpine rivers is in a semi-natural condition ranging from 2.5% in Germany, 4.9% in Switzerland, 9% in Italy and 18% in France	Ward et al. (1999)
River diversions	By the end of the 13th Century the 1780 km Beijing–Hangzhou Grand canal built to link 5 river basins and transfer water from Yangtze to North China Plain	Li, Liu and Mou (2000)
Water extraction	Approximately 11% of freshwater runoff in USA and Canada withdrawn for human use	Karr et al. (2000)
	Water abstraction of about one fifth of total water resources with 87% for irrigation agriculture in China	Li, Liu and Mou (2000)

changing river channels can now be consolidated (Section 2), providing a basis for identifying the challenges which remain (Section 3), leading to recommendations which can be considered (Section 4).

2. Changing river channels

2.1. Basic questions

During investigations of river channel changes, a series of questions were formulated, not always explicitly, to guide research in a wide variety of areas. Identifying the questions which were asked is necessary to consolidate knowledge of changes of river channels (Gregory, 1987a). Such questions, listed on the left hand side of Fig. 2, are affected by emphases in research, and relate to who will be affected and will meet the costs. Emphases in research (middle column, Fig. 2) include contributions by engineers (e.g. Yearke, 1971; Parker and Andres, 1976; Tsujimoto et al., 1980; Surian and Rinaldi, 2003), geomorphologists (e.g. Williams, 1978; Petts, 1980; Graf, 1980), ecologists, (e.g. Stanford and Ward, 1979; Obrdlik et al., 1989) and geologists (e.g. Booth, 1991) as well as by practising river managers (e.g. Qiwei et al., 1982). The great range of types of human action identified meant that separate studies were undertaken including the influence of dams and reservoirs, of channel impacts, and of land use change leading to urbanisation; research was affected by current debates which included emphasis upon the impact of channelization in the US (e.g. Heuvelmans, 1974) and debate about dams, including criticism of the work of the Corps of Engineers (Morgan, 1970) leading to the suggestion of a reverence for rivers (Leopold, 1977) anticipating the progression from hard to soft engineering (see Downs and Gregory, 2004). The types of channel effect produced were most frequently considered in terms of impact on the channel cross-section, although some studies identified changes of channel planform or, less frequently of the drainage network (Gregory, 1977b). Investigations tended to focus upon small or medium scale rivers whereas large rivers present particular problems (Thorne, 2002). A focus on relatively short time scales also occurred because the potential contribution of palaeohydrological research had yet to be demonstrated (Gregory, 1995). Additionally, styles of adjustment due to human impact have to be related to enhance understanding of the styles of natural change, and be reflected in classifications of channel typologies (Hooke, 1997).

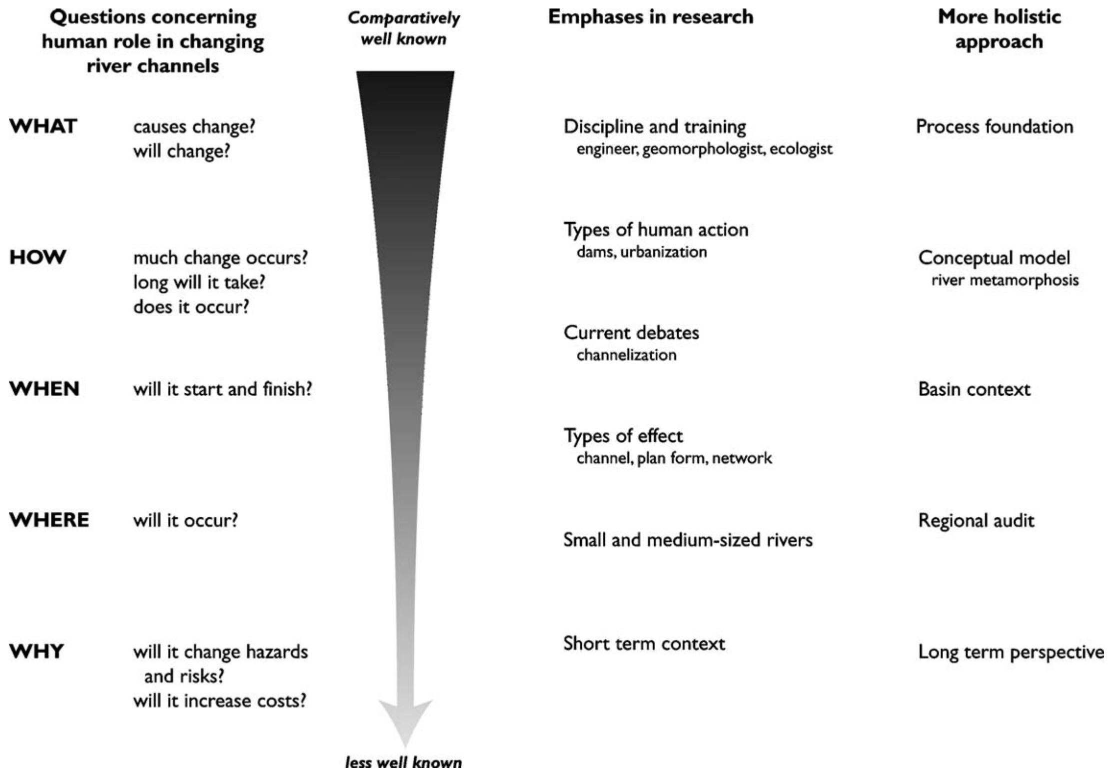

Fig. 2. Questions posed in relation to human impact upon river channels together with emphases in research and methods of moving towards a more holistic approach. Developed from a diagram in Gregory (1987a).

Despite these factors a large number of investigations has given answers to the questions listed in Fig. 2. The question of what causes change has been answered by development of an increasingly long list of human impacts that can have effects upon channels. Table 3 illustrates the major types of influence, direct and indirect, and gives examples of the magnitude of those influences. This range of causes of channel change is paralleled by a diversity of effects in terms of what will change (Table 4), although the majority of changes reported are either changes of channel capacity or of channel width (Gregory, 1987a). How much change occurs can be demonstrated from a range of studies (Gregory, 1995); by defining channel change as the ratio of channel capacity, width or depth after change to that before, it is possible to show the range of changes which have been reported (Table 4) although spatial interpolation techniques have to be employed carefully (Ebisemiju, 1991). For certain types of change there have been comprehensive summaries produced, including the morphological and ecological effects downstream of dams and reservoirs (Petts, 1984). The downstream effects of 21 dams on alluvial rivers in the USA, mostly in the semiarid western States, demonstrated considerable variability in responses (Williams and Wolman, 1984). Channelization has also been the basis for a comprehensive approach demonstrating the range of ecological and morphological consequences (Brookes, 1988) and implications (Brookes and Shields, 1996). Although many answers to these initial questions have been provided, it has been less easy to decide how long change will take or how it occurs. Downstream of dams most degradation occurred during the first decade or two after dam closure but bed degradation varied from negligible to about 7.5 m in the cross-sections studied (Williams and Wolman, 1984). It is not easy to determine when change will start and finish, because this may be triggered by the incidence of hydrological events of a certain size; or where it will occur, because the incidence of change depends upon the characteristics of the channel (Phillips, 2003); or why it will change hazards and risks and may increase costs.

2.2. Approaches to the investigation of channel change

During the course of numerous individual investigations of river channel change, it was appreciated that a more comprehensive view was required to succeed the

Table 3
What causes change and what may change (see Fig. 2)

What causes change	What may change		
	Processes: hydrology H, sediment S	River channel	
Channel		Adjustment locally evident	Adjustment spatially extensive
Channel cross-section/point			
Dam construction	H− S− then S+	Scour below dam	Downstream may have reduced channel capacity but variations possible due to sediment trapped
Weirs	H− S− then S+	Scour below weir	
Diversion of flow, including mill leats, HEP	H−	Aggradation after flow diverted, scour possible close to where drainage returned to channel	Not applicable
Abstraction of flow	H−		Not applicable
Return flow, drains, outfalls	H+		Not applicable
Bridge Crossings	H+	Scour around bridge piers	Not applicable
Culverts under roads and crossings	H+	Scour at downstream end	Not applicable
Channel reach			
Desnagging and clearing	S+	Sediment transport increase and may have accelerated erosion	Not applicable
Grazing	S+	Localised bank and channel erosion may occur	Not applicable
Embankments and levee construction	H+		May have apparent effects downstream
Channelization	H+ S+		Effects downstream may arise from increased flow velocities. Knickpoint recession may occur upstream from channelization
: Bank protection and stabilization	H+ S−		
: Resectioning, dredging	H+–S−		
: Channel straightening, cutoffs	H+		
Clearance of riparian vegetation/ tree clearance	S+	Localised bank and channel erosion may occur	Not applicable
Beaver removal	H+, S+	Localised channel adjustment possible	Not applicable
Sediment removal, mining gravel extraction	S+	Localised channel adjustment	Sediment transfer downstream or scour may affect channel morphology
Sediment addition, mining spoil	S+	Localised aggradation possible	May affect aggradation downstream and upstream as well
Boat waves, bank erosion	S+	Can induce localised bank erosion	Not applicable
Invasion by exotic vegetation species	S−	Stabilise sections of channel and banks	May reduce sediment transfer downstream
Afforestation	S− but may increase from tracks	Progressive decrease of channel capacity possible but depends upon forest drainage system	
Conservation measures	H− S−	Progressive decrease of channel capacity possible but depends upon management of drainage network	
Restoration and allied techniques	H− S−	Designed channel characteristics	Reduced erosion, and deposition, downstream
Drainage basin			
Network			
Drainage schemes	H+	Channel adjustment possible where flow extracted	Not applicable
Agricultural drains	H+	Localised effects possible where drainage reaches channel	Not applicable
Irrigation networks	H−	Channel adjustment possible where flow extracted	If many locations of flow extraction can have noticeable effects
Ditches	H−	Channel adjustment possible as result of flow extracted	Not applicable
Stormwater drains	H+	Scour around outfalls	If numerous outfalls can then increased peak

(continued on next page)

Table 3 (*continued*)

What causes change	What may change		
	Processes: hydrology H, sediment S	River channel	
l		Adjustment locally evident	Adjustment spatially extensive
			flows induce erosion downstream
Spatial			
Deforestation	H+ S+		Gully development may occur with knickpoint recession upstream. Downstream may have channel change and often increased capacities but depending upon sediment availability
Grazing	S+	Local effects by degradation of channel banks	
Fire, burning	H+ S+	Channel change after fire events	
Agriculture, ploughing	H+ S+	Localised effects often where tributaries join main streams	
Land use, conservation measures	H− S−	Progressive decrease of channel capacity possible but depends upon management of drainage network	
Afforestation	S− but may increase from tracks	Progressive decrease of channel capacity possible but depends upon forest drainage system	
Building construction	S+	Channel affected by large sediment load locally	Temporary drainage complements drainage network
Urbanisation	H+ S−	Scour may occur at stormwater outfalls	Stormwater drains augment drainage network

Discharge is shown as H with increased flows designated as H+, and decreased flow as H−. Similarly, sediment transport increased is shown as S+ and decreased sediment transport as S−.

emphasis placed on one type of change, for example those downstream of dams. Such a comprehensive or holistic view was obtained in at least five ways (Fig. 2, right hand column). Some studies arose as a consequence of investigation of hydrological process changes and in such cases it was inevitable that different types of channel adjustment were included. Thus, in the Platte watershed of southwestern Wisconsin, three- to five-fold increases in flood magnitude arose from land use change to agricultural uses (Knox, 1977) with channel metamorphosis including headwater and tributary channels that are relatively wide and shallow when compared to pre-settlement forms, whereas main channel forms are narrow and deep compared to pre-settlement forms (Knox, 2003). Channel changes must be considered bearing in mind that river metamorphosis can occur in certain areas without major environmental changes (Brizga and Finlayson, 1990), especially when significant changes occur in storm events.

A conceptual model was also a means of achieving a more holistic approach: river metamorphosis, a complete change of morphology could be instigated if changes in discharge and sediment load were of sufficient magnitude (Schumm, 1969, 1973). Schumm (1973, 1977) employed empirical equations as a framework for discussing natural and man-induced changes of river morphology, an approach not dissimilar from the approach of Lane (1955) with six categories of river channel change (Table 1). This method provided an indication of the major ways in which channel morphology might change (see Table 1) but could not be proscriptive because of uncertainty associated with a particular environment. Most long term models of channel adjustment, however, have been one-dimensional and neglected some aspects of adjustment, such as channel widening and downstream aggradation (Doyle and Harbor, 2003).

A third way of providing a more comprehensive understanding was to consider the drainage basin context by focusing on the interrelationship of all channel changes within a single basin. Consideration of channel metamorphosis throughout the basin of Dumaresq Creek, NSW Australia could be related to land use change since the early nineteenth century, to dam construction at the end of the nineteenth century, and to urbanisation in the second half of the twentieth century, including a significant effect instigated when rainwater tanks were succeeded by piped water supply (Gregory, 1977b).

Table 4
How much change occurs of river channels?

Cause of change	Range of channel change ratios	Number of studies used	Results	Major reasons for variations
River regulation by reservoir and dam construction, weirs, navigation	0.09–3.0	77	73% of studies show reduction	Response varies with place and river characteristics, depending on factors including geomorphological context, type of regulation, sediment transport post-impoundment, sediment availability, and specific stream power. Bench development may occur where channels contract, planform may change and sinuosity decrease. Reservoirs affect tributary channels through higher base levels
Urban development	0.15–>10.0	46	72% of studies show increase	Channel capacities and widths may increase with associated changes of pool riffle spacing. Bed lowering may occur, entrenchment and gullying may be related to boundary disturbance and road crossings; and instability affected by erodibility, riparian conditions
Channelization and reach changes including river training, mineral extraction, dam removal, removal of woody debris	0.23–>12.0	65	52% of studies show increase	Braided patterns often now less common due to changed flood discharges and sediment supply; after channelization increases in width may be followed by aggradation; stability at bridges, roads and culverts depends upon erodibility, riparian and hydraulic conditions; mining effects may persist due to sediment released as slugs; unstable reaches may be associated with tributary confluences; Large Woody Debris (LWD) can occupy 2% of stream bed but account for 50% of flow resistance; more data required on effects of dam removal
Catchment land use changes	0.05–15.0	66	61% of studies show increase	Changes may include channel pattern, and multiple often changed to single thread channels; changes affected by proximity to thresholds, nature of coupling through different parts of the catchment, because sediment moved may be stored and not coupled to rest of basin, and some catchments more resistant to change than others; streams may become entrenched; some basins show disproportionate geomorphological change for small hydrological change due to hypersensitivity; incidence of floods may trigger changes
Water transfers	0.95–> 9.0	11	82% of studies show increase	Increases where water transferred in; if water extracted response may be similar to dams

Channel change ratio equal to the capacity, width or depth after change divided by that before. Developed from Brookes and Gregory (1988), Gregory (1995, 1987b), Downs and Gregory (2004) with additional data.

More extensive than a single basin approach are regional audits of causes and consequences of channel change, as have been particularly successful in Australia. Because human impacts on river systems constitute a major area of study in modern fluvial geomorphology, catchment alterations, including deforestation, grazing, cropping, urbanisation, and changes in conservation practices, can cause changes in the delivery of water and sediment to the channel and hence channel morphological adjustments occur (Warner, 1984). Subsequently human impacts on channels in New South Wales were seen (Warner and Bird, 1988) as direct (channel regulation, channelization, vegetation management, urban drainage improvements) or non-deliberate inadvertent (aggregate extraction and mining disturbance, flood mitigation, additions of water discharge, loss of discharge), and the impacts were analysed spatially by Rutherfurd (2000).

Although such comprehensive studies consider channel adjustments over longer periods of time, a long term perspective has the advantage that human-induced channel adjustment can be placed in the context of long term natural/secular change over periods as long as 4000 years (Gregory, 1995). In lowland temperate environments relatively stable multiple channel systems (anastomosing) were more common in the late Holocene (10,000–2000 years B. P.) than today (Brown, 1995). The natural state of lowland rivers in much of northwest Europe was multi—rather than single thread, braided anastomosing or anabranching (Brown, 2002). A further benefit of a long term perspective is use of a geomorphological hazards approach to provide a basis for understanding adjustments of the river channel; types and degrees of channel adjustments can be analysed according to the degree of risk or geomorphological hazard, characterised by Schumm (1988) as either abrupt change that produces a catastrophic event, progressive change that leads to abrupt change, or progressive change that has slow but progressive results. Thus, the adjustment process can be placed in the long term context of the complex of risks and hazards that exists in the fluvial system, reflecting relative stability of the river channel (Downs and Gregory, 2004). For example, by characterising channel segments in a system according to the associated stream channel hazards it is possible to indicate the most significant hazards that require management and thence to suggest management options, as demonstrated for semiarid systems in Fountain Hills, Arizona (Chin and Gregory, 2005).

2.3. Prediction for channel management

The outcome of numerous studies of river channel adjustment has been that the magnitude of river channel change, described by terms including enlargement, shrinkage and metamorphosis, has become broadly known, but it has not always been possible to predict what will happen in a particular location (e.g. Table 4), because of complex response and contingency. Complex response (Schumm, 1979) is the variety of changes which may occur after crossing a geomorphic threshold, whereas historical contingency means that the state of systems or environment is at least partially dependent on one or more previous states or events in the past (Phillips, 2001). The state of a given feature, being uniquely dependent upon local history or a specific past event, signifies inheritance and conditionality; therefore reasons for uncertainty include scale, location, convergence, divergence, singularity, sensitivity and complexity (Schumm, 1985). Cases of hypersensitivity (Brown and Quine, 1999), where a large amount of change results from a small hydrological change, and of undersensitivity (see Fig. 1C) relate to the proximity at particular locations to threshold conditions. This lack of consistent channel response and the incidence of multiple modes of channel adjustment are demonstrated where channel scour occurs for about 60 km downstream of Livingston dam in Texas (Phillips et al., 2005).

A more holistic view of changing channels can be developed by focusing upon the relationship between channel cross-section, planform and channel extent; one way of achieving this has been by examining the spatial pattern of channel adjustments. In the Monk's Brook, Hampshire, UK, the distribution of channel change downstream of urbanisation was mapped by using sections of channel of similar character (Gregory et al., 1992). Once the complete drainage network was delimited, it was subdivided into segments with similar characteristics by general procedures for stream reconnaissance (Gregory and Chin, 2002). This involves either auditing the characteristics of the channels (Kellerhals et al., 1976; Thorne, 1998), so that at a subsequent second stage the audited information can be used to determine categories, or by delimiting the extent of a particular channel type (e.g.

Table 5
Examples of classification of stream channels useful in relation to the adjustment of river channels (developed from Gregory and Chin, 2002)

Basis of classification	Example of specific studies which are based on:	Source
Comprehensive, descriptive	Channel characteristics:	Rosgen, 1994; Thorne, 1998
	Specific characteristics: often based on downstream sequence	Frissell et al., 1986; Bisson and Montgomery, 1996
	Quantitative reconnaissance:	Gordon et al. (1992)
Adjustment	Stability:	Simon, 1989; Johnson et al., 1999; Bledsoe and Watson, 2001
	Comparison of stability indicators: including distinguishing between stable and degrading sites	Doyle et al. (2000)
	Thresholds:	Olsen et al. (1998)
Potential	River recovery potential:	Fryirs and Brierley (2000)
	Restabilizing potential: developed for stream channels in urban watersheds	Henshaw and Booth (2000)
Disturbance	Susceptibility to disturbance: designed for UK streams	NRA (1990)
Combined	Stability and stream classification:	Myers and Swanson (1996)

Gregory et al., 1992). Segments of stream channels may then be classified in at least 5 ways (Table 5): comprehensive methods that describe the characteristics of segments; those that focus upon adjustment, often expressed in terms of stable or unstable segments or proximity to thresholds; approaches based upon potential for recovery (Fryirs and Brierley, 2000) or rehabilitation (Henshaw and Booth, 2000); those that consider degrees of disturbance giving geomorphological sensitivity (e.g. NRA, 1990); and those that combine some of these attributes. Such methods (Table 5) can be combined with stream classification (Myers and Swanson, 1996), often requiring subsequent survey and research to follow up rapid methods of assessment (Gregory, 2002b) to decide which management strategies might be used most effectively. Rapid methods that have been suggested include qualitative reconnaissance surveys (Gordon et al., 1992), network characterisation for channel segments related to catchment-based plans for stormwater management (Gregory, 2002b), and a geomorphic approach to the identification of river recovery potential (Fryirs and Brierley, 2000).

Once segments have been identified, they can be described in terms of hazards affecting the stream channels. Hazards have usually been associated with natural events (Alexander, 1992) and geomorphic hazards, generally regarded as landscape changes that affect human systems (Gares et al., 1994), have been identified in relation to the fluvial system (Schumm, 1988, 1994). Although not specifically applied to urban fluvial systems it is the hazards associated with urban stream channels that have necessitated a range of management responses in the context of proposals for the restoration of stream channels. Hazard, in the sense used by Schumm (1994), is a potential danger or risk and is comparable to geomorphic hazards (Schumm, 1988) where landform changes, natural or otherwise, may adversely affect the geomorphic stability of a place. The assessment of flood hazard for land use planning has been described in Arizona (Rhoads, 1986) but hazards have not previously been associated with adjusting channel segments in an urban area as exemplified in Fountain Hills, Arizona (Chin and Gregory, 2005).

More complete answers to the questions posed in Fig. 2 can be provided for 'what' and 'how' questions, but less readily for the 'when,' 'where' and 'why' questions. Answers to questions about the human role in changing river channels in specific places are still required to understand why change occurred and also to assist in the management of river channels. As river channel management has progressed from hard to soft engineering methods and from a design with nature to a management with nature approach (Downs and Gregory, 2004, especially Table 11.1) what has been described as a "paradigm lock" can occur because scientists do not grasp what managers require, and managers and stakeholders do not appreciate the scientific alternatives available (Bonell and Askew, 2000; Endreny, 2001; Gregory, 2004a). Knowledge of changing river channels can assist in relaxing the paradigm lock existing between the managers/stakeholders and the researchers analysing change in river channels. Challenges, therefore, remain for further assessments of changes in river channels to be related to the management of river channels.

3. Challenges for understanding river channel change and applying the results

3.1. Prediction of channel change

Applying knowledge of change in river channels to management requires a greater appreciation of the answers to the questions of when, where and why (Fig. 2); in securing that appreciation at least five challenges have to be addressed. The first challenge is the prediction of the nature and amount of change likely at a particular location. This is not easily ascertained as can be shown by a number of examples. Along the Kansas River some reaches, inactive during the late 1800s and early 1900s, became active after 1960, but for other reaches the reverse was true, and overall only 53% of the river had been actively eroding in the past 125 years (Burke, 1984). Degrees of instability along a channel were demonstrated by Graf (1984), who subsequently showed that locational probability could indicate the most probable previous location and configuration of the channel for the Salt River Arizona (Graf, 2000). Arid and humid systems exhibit contrasting responses, albeit perhaps at the end of a spectrum of change. This may be because the effects of sediment storage and infrequent large events lead to episodic reaction in semiarid environments as shown for channels in New South Wales (Nanson and Erskine, 1988). Rivers in drylands are characterised by extreme variability of flow with long periods of little or no flow interspersed with occasional and sometimes extreme floods (Tooth and Nanson, 2000) and, thus, exhibit both equilibrium and nonequilibrium conditions. This is highlighted in Fountain Hills, Arizona where the relationship between channel capacity and drainage area for semiarid channels contrasts with such relationships for humid areas (Chin and Gregory, 2001, 2005). In some semiarid areas the occasional large event can erode channels, so that channel capacities are greatly increased, whereas the equivalent large events in humid areas simply exceed the channel capacity and induce flow over the flood plain. Given the wide range of responses in different environments it is, therefore, necessary to reduce uncertainty, as first emphasised by Burkham (1981) in the context of the location of channel change. One way of achieving this is by an adaptive modelling process (Wilcock et al., 2002).

3.2. Feedback effects

A second challenge is that feedback effects, incorporated within the relationship between changes at channel, reach and network scales, can have considerable implications, especially because channel changes now evident may have occurred, or have been initiated, under different environmental conditions. For example, the incidence of large channel forming events (e.g. Erskine, 1999; Rutherfurd, 2000) and geomorphically effective floods (Newson and Macklin, 1990) in relation to vertical instability in river channels can trigger a feedback mechanism that requires an understanding on how the Quaternary climatic history and lithology establish particular thresholds. The incidence of channel changes may not depend solely upon the magnitude of hydrological events, because coupling throughout the system operates at time scales ranging from the individual event with a return period of decades to centuries for downstream coupling (Harvey, 2002). More specifically, the identification of the connectivity

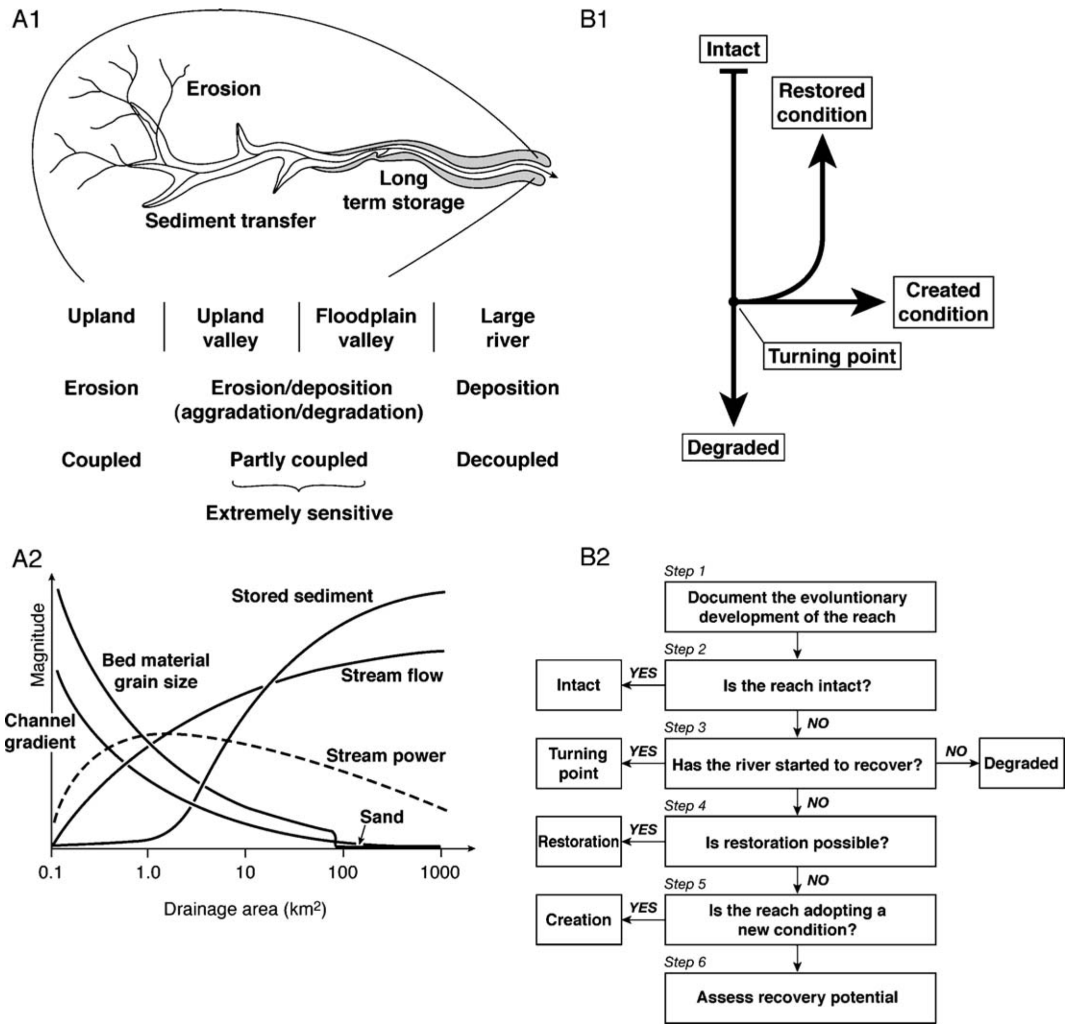

Fig. 3. Contemporary perspectives relevant to human impact on river channels. A1 shows a view of the drainage basin developed from Schumm (1977) and related to sediment transfer (Church, 2002) that displays patterns of variation on A2. B1 demonstrates a conceptual view of changing channels (Fryirs and Brierley, 2000) where the vertical line represents change from an intact to a degraded condition, whereas two alternative pathways are shown to a restored condition or to a created one. Steps in measuring river condition for B1 are shown in B2 (after Fryirs and Brierley, 2000).

of coarse sediments in down river channel systems is important for understanding the mechanisms and propagation of channel change (Hooke, 2003). More extensively, buffers, barriers and blankets may account for delays in the adjustment process and have to be seen as creating critical threshold conditions (Fryirs et al., in press). One further feedback effect is the ability of a changed channel to accommodate discharges. Downstream of an urban area a channel may increase in capacity but this increased capacity in turn can accommodate larger flows and so may reduce the incidence of flooding, a consequence of enlarged channels that results from incision in west central Wisconsin (Faulkner, 1998). Furthermore, if increased delivery of sediment is involved, consequent aggradation and reduced capacities may lower the ability of a channel to accommodate flood discharges, as suggested for the Kungai Selang in Malaysia (Brookes and Gregory, 1988).

3.3. Global change

Third, consideration of global climate change is imperative when considering the sensitivity and response of channels to threshold conditions. Although comparatively few studies have explored the ways in which channel change may be affected by future global climate change, studies of past periods have shown how alterations of the incidence of hydrological events have disrupted the pattern of coupling in the fluvial system (Gregory et al., 2006a,b,c). Relatively little of the international global change science initiative has made appropriate use of experience gained from past environmental changes (Baker, 1995; Alverson et al., 2003; Oldfield, 2003) although sustainability in either weaker or stronger variants (Williams and Millington, 2004) can be informed by a longer term understanding of environmental change. Despite progress made in palaeohydrology (Gregory, 1983) and other palaeoenvironmental research, investigations of climate change and associated global change have not fully explored specific impacts on the hydrological and channel systems, although these effectively demonstrate the major impacts of global change. An important consequence of change in hydrological and channel systems is that the pattern of thresholds may alter so that the catchment picture with its various manifestations (Fig. 3A) may vary quite significantly (Church, 2002). As basin changes affect land cover in a river basin, then, a key question is how such changes either amplify or reduce the climate signal recorded in fluvial sediments (Macklin et al., 2006). The paradigm lock (Endreny, 2001) disparity described above requires links to be forged between the reductionist research of subdisciplines and practice. For example, in the context of research on dam removal, it has been argued (Graf, 2003) that adaptive science needs to identify significant questions, seek to answer them, and then, in consultation with managers, redefine the questions. Such adaptive science could benefit understanding of other aspects of river channel change.

3.4. Incorporating geomorphological design

Fourth, to achieve an effective link between research and practice, channel design should be an integral part of restoration procedures. The concept of designing with nature has roots traceable in Europe to the mid 19th Century (Petts et al., 2000); it was originally adopted by landscape architects (e.g. McHarg, 1969, 1992) and utilised by ecologists as a method whereby ecology could inform the planning process. It progressed to the appreciation that, although a general ecological foundation was influential, more input from hydrology, geomorphology, and other branches of physical geography and environmental sciences was needed (McHarg, 1996). As river landscapes rather than the channel alone are increasingly visualised as the basis for restoration and softer management techniques, this effectively requires concern with design aspects of the entire river landscape. Geomorphologists, physical geographers or environmental scientists, involved in such design procedures, do not require an eclectic super-scientist approach, but rather participation in a multidisciplinary team as one member who has the advantage of knowledge of the evolution of river channel systems and river landscapes (Gregory, 2004b). Such members can facilitate the improved application of hydrology, geomorphology and biology to effective management of rivers (Calow and Petts, 1992), possibly including the concept of patchworks (Bravard and Gilvear, 1996) or the use of channel types (Table 5). Such knowledge of the evolution of systems is necessary for implementing the idea of working with nature which was advocated for river regulation (Winkley, 1972). This could remedy the absence of geomorphology in design considerations, as highlighted by McHarg (1996). It has been argued that the growth of geomorphology, as a practical profession, requires geomorphologists to devote effort to developing and refining a design science to support the profession (Rhoads and Thorn, 1996 p.135). Impressive examples now exist of ways in which geomorphologists have contributed to the design of restoration projects (e.g. Brookes et al., 2004). Involvement of geomorphological approaches is even more vital as awareness of the need for an alternative to hard engineering produced a general movement towards a softer management approach which included restoring the landscape to a more 'natural' character. A design science could provide the basis for a professionalization of geomorphology that codifies a body of information, tools and skills for licensing or certification of programs (Rhoads and Thorn, 1996), and defines alternative strategies for management at the reach and watershed scales (Brookes, 1995).

A suite of methods for incorporating geomorphological information into existing practices of river management embodies the basic notion that geomorphology has contributions to make across the broad sector of river management (Sear and Newson, 2003; Sear and Arnell, 2006) and some specific design areas have already been identified (Newson, 1995). Geomorphological techniques could be developed to complement the way in which a method for re-establishing biological components of a river corridor landscape as proposed for the Salt River, Arizona, based on ecosystem modelling (Cook, 1991). The impact and legacy of freshwater mills on English

Table 6
Elements of design for river channel landscapes (developed from Gregory, 2004a and tables in Gregory, 2003; Downs and Gregory, 2004)

Major design stage	Requirement involved
Preliminary stage	The basis for an approach • *Importance of place* — construct strategy with awareness of the spatial environmental context • *Implications of scale* — Use catchment-scale integrated basin planning with a holistic approach to channel and flood management • *Situation in time* — refer to the temporal position in the sequence of channel development, with any detectable phases in the palaeohydrology or sediment budget record (Table 1, Fig. 1) • *Cultural context* — cultural differences between countries and regions may require differential responses to river channel management challenges • *Political framework* — including requirements for legal implementation ensuring that institutional organization and structures are sufficiently flexible Environmental assessment • *Collect historical data* on floods, flood hazard and flood mitigation measures, channel behaviour and channel adjustments • *Consider the period of records* used as the basis for earlier channel management decisions • *Review* causes of possible change (Table 3) and potential effects (Table 4) • *Take into account high spatial and temporal variability* of floods and flood impacts, and their feedback effects • *Select appropriate time scale*, augmenting the continuous record as necessary Outline planning • *Use integrated, basin wide planning*, and a holistic approach for channel management • Use *any detectable phases in the palaeohydrology or sediment budget record* to set the management into a temporal pattern
Implementation	Reviewing alternatives • *Utilise a basin framework* to identify homogeneous reaches requiring similar management activity, reaches of channel that are unstable/sensitive, as a result of mitigation or management measures or impact of human activity, including those that may become sensitive in the future (Table 5) • *Set the pattern of sensitive reaches in a dynamic basin context* by taking account of changes in sediment history including phases of storage and exhaustion and past river channel adjustments • *Use environmental condition of reaches to select approaches and to identify assessment techniques* — based on principles of preservation and natural recovery, restoring flow and sediment transport, prompted recovery, morphological reconstruction, and instability management • *Identify hazards* created by erosion and sedimentation together with those of flood discharges, with structures designed for high sediment loads • *Adopt non-structural and do nothing approaches wherever possible*, using sustainable procedures that have least damaging environmental impacts • *Work with nature and not against it*, emulating nature in river designs using knowledge of past and present to determine what is 'natural'; restore environmental (habitat) heterogeneity but let the river do the work • *When restoring channels give careful consideration* to: Is restoration feasible for the particular channel? Is restoration to be to a more natural state or to some specific prior condition and if the latter what is the basis for the decision? Does the restored state present the most stable channel which will avoid impacts downstream or upstream? Consider 'natural' in any area as a social construct which must be negotiated with the local community giving opportunity for education of that community in relation to palaeohydrology
Implementation	Reviewing alternatives

Table 6 (*continued*)

Major design stage	Requirement involved
	• *Ensure that the scheme implemented is as sustainable as possible* and capable of adaptive modification • *Rationalize risk to support decision-making* and assess the risks involved • *Management with Stakeholders*— including formulation of shared visions, and stakeholder education • *Set priorities in relation to competing claims, statutory obligations* • *Employ a detailed appraisal process*, consult widely, considering all the environmental issues at the range of appropriate scales alongside the engineering and economic objectives
Effecting the design	*Catchment scale approach to design with nature* (see Gregory, 2004b; Downs and Gregory, 2004) including: 1. catchment and corridor policies 2. methods for improving network connectivity 3. in-stream measures 4. channel reconstruction 5. methods for reinforcing the channel perimeter
Post project consideration stage	Keep areas under review by Adaptive ecosystem management including • *Post-project appraisal* so that knowledge about impacts of river management and significance of river channel change continues to grow • *Incorporating Future Conditions* — including managing natural recovery and created environments and developing improved predicted models • *Coping with Uncertainties* — requiring adaptive management and education of river managers • *Ensure continuing proactive involvement of the range of management bodies*

rivers needs to be considered in restoration (Downward and Skinner, 2005) exemplifying how knowledge of channel change can be usefully employed. This study shows that where mill structures have been maintained, geomorphological stability can be sustained, but where maintenance has not occurred, then failure of mill structures can lead to extensive channel instability. More extensively, the removal of dams (Graf, 2003; Heinz Center, 2002) introduces new aspects of channel design and restoration. Furthermore, the method of Channel Migration Zoning used in the US to guide planners and river managers (Rapp and Abbe, 2003), is similar to locational probability maps (Graf, 2000). Other examples using a geomorphological approach are exemplified by river recovery potential (Fryirs and Brierley, 2000), visualised in the context of the assessment of geomorphic river condition (Fig. 3B). This enables the geomorphologically interpreted pattern of recovery to be applied to a specific catchment as the basis for proposing the most expedient restoration course for particular reaches. This has also been developed in the light of barriers, buffers, and blankets which are discontinuity phenomena acting as constraints upon river recovery potential after disturbance events of different magnitude and frequency demonstrate (dis)connectivity in a catchment (Fryirs et al., in press).

A more geomorphological contribution to the design of river landscapes, incorporating knowledge of the adjustments of river channels, could follow 'principles' of river channel management (Gregory, 2003). By collapsing the comparatively few explicit statements of principles available to guide river managers, it is possible to suggest how these principles (Downs and Gregory, 2004) might be modified in the light of research on river channel change to yield basic principles (Table 6) that can be considered in river channel design (Gregory, 2004b).

3.5. The cultural dimension

Fifth, greater awareness is needed of the impact of different cultures as a basis for understanding constraints imposed by legislative frameworks as well as by public attitudes. Culture is not automatically considered by geomorphologists although a more cultural physical geography has been reviewed (Gregory, 2000). Just as a more society-oriented climatology or cultural climatology can be envisioned (Thornes and McGregor, 2003) so we can now contemplate a cultural geomorphology. This was implicitly embodied in impressive contributions by Yi Fu Tuan, including views of physical environment in *Topophilia* (Tuan, 1974) and personal experience of *Space and Place* (Tuan, 1977). Is it now timely for a 'cultural turn' that affected human sciences (Jackson, 2003) including human geography (Johnston, 1997) to be embraced by geomorphology? Implications of different conceptions of nature for progress towards a more integrated geography (Urban and Rhoads, 2003) raise the possibility of links with human geography and social scientists which, from a human geography viewpoint, have appeared as *entanglements of nature and culture* (Harrison et al., 2004). A trend in this direction

Table 7
Cultural issues for consideration prior to implementing river channel management, for example employing the context suggested in Table 6

Cultural strand	Illustrative implications/questions
Knowledge of river channels and their perception	Assumptions about rivers and their mechanics Attitude to rivers: water, sediment, biota, channel, floodplain, riverscape Are rivers revered? Associated with religion, mythology, customs, beliefs? Language of rivers How are rivers portrayed in literature, visual arts, the media? Presentation in terms of threats, risks?
Valuation of rivers	Past and present valuation of rivers, commercially and aesthetically Economic value, expenditure on maintenance and management Pollution control Risk tolerant and allowing for continuing change
Attitude to the management of river channels	Non interference or structural solutions or non-structural options Upstream and downstream effects and spatial context considered? Understanding that rivers have a history Individual decision makers or public involvement and shared vision? Embrace post-project appraisal and adaptive management
Expression of river aesthetics in relation to environment	Leave undisturbed Interpretation of 'design with nature' Restore to 'garden' character or to perceived natural condition
Involvement of ethical considerations as unwritten codes to guide action	Human ecology viewpoint? Shallow or deep ecology perspective? Conservation and sustainability pre-eminent?
Legislation for rivers	Codes of practice and laws; institutions with responsibility for rivers Local, regional, national or international controls upon decision-making or some amalgam of these? How political systems react to, and reflect the above issues

does not detract from the existing prospectus of investigations of form, process and change in geomorphology, but rather follows from them. For example, it has been contended that 'where cities once exploited, abused and then ignored rivers in their midst, they are now coming to recognise, restore and appreciate them' (Bolling, 1994, p. 207).Thus, with knowledge of processes and changes of river channels it seems expedient to consider cultural reactions and perceptions.

A general definition of culture as a particular form or stage of civilisation includes the pattern of human knowledge, belief, and behaviour embracing language, ideas, beliefs, customs, codes, institutions, tools, techniques and works of art, and so should be reflected in legislation and in ethical values. Thus, what is called nature in one culture at one time may be viewed very differently in a culture affected by different political, historical, and social factors (Palmer, 2003, p. 33). Variations from one culture to another may arise in part as a result of different environments, including rivers, so it is to be expected that, at a particular time and place, culture will have an effect upon the way in which river management is perceived. One must understand public attitudes to rivers in the past and present to fully appreciate the nature of river management in different cultures. Moreover, it is also increasingly important to acknowledge cultural differences in relation to future plans. It is therefore not realistic to prescribe a universal approach to managing rivers but only one which reflects the influence of the particular cultural overlay.

Therefore, geomorphologists can now raise awareness of such cultural distinctions and consider them when constructing recommendations. Just as it is necessary to understand the character of past cultures that, for example, have led to the five periods of engineering impacts on the Rhine River channels and flood plain (Herget et al., 2005), so it is important to include such awareness in relation to present and future management. Provisionally some of the different strands that need to be considered are suggested in Table 7, and provide a filter to be applied when contemplating the aspects of channel design outlined in Table 6. Holism has been thought of as requiring a more basin-based and temporal view (e.g. Gregory and Downs, in press) and it also requires awareness of legislative frameworks, ethical approaches and public attitudes that are integral to culture.

Although benefits should arise from greater understanding of how the perception of the human role in changing river channels varies with space as well as over time, this is an area where relatively little research and explicit review has occurred. The cultural associations of river landscapes (Table 7) have been explored

(Penning-Rowsell and Burgess, 1997) leading to the conclusion that the river landscape will increase in importance as the emphasis in river and catchment management moves away from reliance on a land use planning or an engineering approach towards enhancing what the general public finds important and valuable in their local river scene. As public opinion is increasingly considered in river management (e.g. House and Fordham, 1997), public perception of rivers can be influential. Some specific examples are known of differences between geomorphological knowledge and local perception that may condition decision-making (e.g. Brizga and Finlayson, 1994; Finlayson and Brizga, 1995). How well the dynamics of the catchment hydrosystem are understood and explained the perception by individuals may affect all forms of local decision-making (Downs and Gregory, 2004). Along the Missouri River in Montana, for example, landowners believe that the operation of the Fort Peck dam has initiated bank erosion, whereas geomorphological evaluation indicates that bed degradation and bank erosion have declined since construction of the dam (Darby and Thorne, 2000). On the Herbert River, Queensland, the widespread perception of an aggrading river since European settlement is not supported by historical accounts, by gauging station data since 1940, nor by cross-sections compared since 1968 (Ladson and Tilleard, 1999).

Anecdotal observation suggests that in some countries river channels are treated very sensitively, in some they are landscaped and almost cosmetically managed, and in some they are ignored and serve as dumps for refuse. Arguably, hard and soft engineering are aspects of the cultural perception of what is acceptable and desirable, and differences also occur in reactions to adjustment and to management in different cultures. Such cultural effects are superimposed upon the differences in river channel change that exist between major world areas. Thus it has been questioned whether humid temperate rivers in old and new worlds responded differently to the clearance of riparian vegetation and woody debris: dramatic river metamorphosis in southeastern Australia arose because geomorphic thresholds were breached in a way that differed from that experienced in Old World landscapes (Brierley et al., 2005). In Fountain Hills Arizona a preliminary questionnaire of local perceptions revealed that the majority favoured maintaining channels with an appearance perceived to be near-natural, although views were quite divergent. Such views should be considered when deciding how the channels should be maintained, managed, and restored (Chin and Gregory, 2005). Cultural tradition should be included when linking human actions, the changing river health, and plans for stream rehabilitation (Booth et al., 2004). Attitudes to wood in rivers can vary considerably (Gregory and Davis, 1993; Gregory, 2002a) and the cultural setting (Piegay et al., 2005) can influence how management of wood relates to changes of the river channel.

4. Conclusion

The human role in changing river channels has been exercised for more than 4000 years. Only since 1956 has this topic been addressed in widespread explicit scientific investigations. In that half century, answers have been obtained for a number of questions, including what changes occur in rivers in response to human impacts and how these changes occur, but other questions, especially concerning when, where, and why the changes occur have proved more difficult to answer. The extrinsic and intrinsic human roles affecting channels have been thought of as the human role in changing river channels but they have now been complemented by a more deliberate human role. This more direct impact embraces sustainable design of channels, which is conceived to acknowledge local cultural attitudes (Table 7) to channels, to channel change, and to channel management. To guide progress, and also to encapsulate the achievements of the past fifty years, it is now possible to provisionally suggest how knowledge of the human role in changing river channels might positively constrain the management of river channels (Table 6). It is only by refinement of such statements (Table 6) that we can progress the applications of research, seeking to reduce the paradigm lock between research and practice because the human role in changing river channels is pertinent to both.

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