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Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol

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Abstract

Significant developments have been achieved in applicable and applied fluvial geomorphology as shown in publications of the last three decades, analyzed as the basis for using results of studies of environmental change as a basis for management. The range of types of publications and of activities are more pertinent to river channel management as a result of concern with sustainability, global climate change, environmental ethics, ecosystem health concepts and public participation. Possible applications, with particular reference to river channel changes, include those concerned with form and process, assessment of channel change, urbanization, channelization, extractive industries, impact of engineering works, historical changes in land use, and restoration with specific examples illustrated in Table 1. In order to achieve general significance for fluvial geomorphology, more theory and extension by modelling methods is needed, and examples related to morphology and process characteristics, integrated approaches, and changes of the fluvial system are collected in Table 2. The ways in which potential applications are communicated to decision-makers range from applicable outputs including publications ranging from review papers, book chapters, and books, to applied outputs which include interdisciplinary problem solving, educational outreach, and direct involvement, with examples summarized in Table 3. On the basis of results gained from investigations covering periods longer than continuous records, a protocol embracing palaeohydrological inputs for application to river channel management is illustrated and developed as a synopsis version (Table 4), demonstrating how conclusions from geomorphological research can be expressed in a format which can be considered by managers.

Keywords: Fluvial geomorphology; Applicable and applied research; River channel change; Palaeohydrology; Protocol

1. Introduction

How applied should we become was the question posed (Gregory, 1979) when geomorphology was only just beginning to realize the potential of research applications, with an applied stance being relatively rare at that time. Whereas the 1960's had been associated with processes and systems, and the 1970's had focused upon temporal change (Gregory, 1985, 2000), it was logical for the 1980s to be concerned with applications as well. Prior to 1979 existing applications involved engineers (e.g. Blench, 1957, 1969) rather than geomorphologists, and were largely theory-based.

Although there has been a suggestion that there had been relatively little development of geomorphology

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since Davis (Sherman, 1996), a different structure of geomorphology in physical geography is now evident (Gregory et al., 2002) and progress in fluvial geomorphology has led to important potential applications. These have been evident in books concerned with geomorphology as applied to environmental management (e.g. Cooke and Doornkamp, 1974, 1990); with river channel management (Downs and Gregory, 2004); with a particular approach such as river styles (Brierley and Fryirs, 2004); with the benefits of field investigation (Wohl, 2001); with a particular aspect such as river impoundment (Petts, 1984) or channelization (Brookes, 1988); or with particular spatial areas such as the Colorado (Graf, 1985). Collections in edited volumes focusing upon general applications (Hooke, 1988; Thorne et al., 1997a; Anthony et al., 2001) or upon specific aspects such as channelization (e.g. Brookes and Shields, 1996), have been complemented by special issues of journals (e.g. Thorne and Thompson, 1995; Giardino and Marston, 1999), including recognition of the importance of a sound understanding of geomorphological processes (e.g. Thorne and Thompson, 1995, p.583–584). In addition, other publications introduced applications for particular types of area such as urban environments (Douglas, 1981; Cooke et al., 1982), by specialists such as engineers (Fookes and Vaughan, 1986; Fookes et al., 2005) or for particular spatial areas such as Australasia (Brizga and Finlayson, 2000). Such examples, exemplifying applications of fluvial geomorphology, have been complemented by geomorphologists' coordination of interdisciplinary and collaborative committees. Thus W.L. Graf chaired the National Research Council Committee on Watershed Management leading to publication of *New Strategies for America*'*s Watersheds*; and he subsequently chaired the Panel on Economic, Environmental and Social Outcomes of Dam Removal which led to the publication of *Dam removal: science and decision making* (Heinz Center, 2002). Collaboration in the UK led to the production of a *Guidebook of Applied Fluvial Geomorphology* (Sear et al., 2003), and in November 2003 an ad hoc committee on applied fluvial geomorphology was formed during a meeting of interested members of the Geological Society of America's Quaternary Geology and Geomorphology Division, leading to a position statement posted for discussion at http://www.cla.sc.edu/geog/gsgdocs/FluvComm/1.Survey.html. (20/10/2006).

These developments, illustrating the effort directed towards applications of fluvial geomorphology, have been catalysed by a number of changes. Research into fluvial processes and morphology has been driven to a large extent by management requirements, as shown in New Zealand for example (Mosley and Jowett, 1999). More interdisciplinary journals have been created (e.g. *Applied Geography*,1981; *Environmental Management*, 1976; *Regulated Rivers*,1984; *Hydrological Processes* 1987); as well as the refocusing of others (e.g. *Journal American Water Resources Association*). A larger spectrum of appropriate techniques has become available (e.g. Kondolf and Piegay, 2003) especially associated with remote sensing and GIS, as well as greater emphasis upon geomorphological hazards (Schumm, 1988; Alexander, 1993). Significant shifts in environmental focii external to geomorphology have occurred in disciplines such as ecology, with important developments for restoration (e.g. Gore, 1985; Naiman and Decamps, 1990; Naiman, 1992; Naiman and Bilby, 1998), or for stream classification (Rosgen, 1996). Importantly engineering has embraced the needs of land surface evaluation for engineering practice (Griffiths, 2001), the progression from river engineering to river management (Williams, 2001) and hard engineering has been complemented, if not succeeded, by soft engineering (Downs and Gregory, 2004). In general, river management has evolved from a product-oriented, engineering approach to a dynamic multi-objective management approach which aspirationally incorporates adaptive management (Hunt, 2000). Examples of significant multidisciplinary developments involving geomorphologists have been concerned with *River Conservation and Management* (Boon et al., 1992), with *Rehabilitation of Rivers: principles and implementation* (De Waal et al., 1998), or with *Global Perspectives on River Conservation*: *science*, *policy and practice* (Boon et al., 2000). A development in ecological energetics (Mitsch and Jorgensen, 2004) has much in common with the approach of geomorphic engineering (Coates, 1976, 1990); biotechnical engineering (Brookes, 1988) includes the use of living plants to control bank stability; and soil bioengineering combines engineering and ecological concepts for erosion and sediment control (Gore et al., 1995). These changes have been accompanied by different approaches to river channel erosion and flood hazards. There is a need to emphasize watershed-based regional planning and integrated development in which at-a-point solutions based on multiobjective design, combining engineering design with biotic, aesthetic and land use values, succeed single-purpose intensive solutions, such as monolithic riprap or concrete lined channels and drop structures (Haltiner, 1995).

A more holistic approach to river and basin management is therefore acknowledged wherever possible. This makes a geomorphological contribution more feasible but requires awareness of other external developments. *Sustainability*, requiring use of the environment in ways that do not detract from its ecological integrity or value to future generations (Everard, 1998), provides challenges for scientists, economists, regulators, land owners, and the general public. Addressing sustainability is particularly important with widespread acceptance that *global climate change* is occurring so that fluvial geomorphology can consider potential impacts. Great attention is now accorded to ethical considerations (Leopold, 2004) associated with particular courses of action, requiring awareness of developments in *environmental ethics* (e.g. Light and Rolston, 2003). An overall ethic of care, respect and responsibility was proposed (Reed and Slaymaker, 1993) because otherwise the contribution to the sustainability debate will remain muted, as ethical considerations must underpin policies applied to both environmental management and human development (Richards, 2003). Implementation of management procedures has changed with greater *public participation* prior to decision making, illustrated by Local Environmental Agency Plans (LEAPS) in the UK (Calder, 1999), during preparation for channelization schemes in the USA (e.g. Rhoads et al., 1999), and prior to implementation of stormwater management plans in Australia (e.g. Hunter Water Corporation, 1999; Gregory, 2002). In European countries the EU Water Framework Directive (2000/60/EC), including the requirement for river basin management plans, is likely to have a great impact on river channel management.

Such external changes, coinciding with a shift from nature-dominated to human-dominated environmental changes (Messerli et al., 2000), mean that understanding global change requires new perspectives and synergisms; management approaches necessitate a sustainable knowledge base of process interaction with human interaction (Anderson et al., 1996); relevance has become an issue of major importance demanding much closer ties to the study of social processes (Wolman, 1995); and a deterioration of common cores of knowledge in geomorphology prompt the need for conceptual thinking to catch up with measurement and analysis technology, and to explicitly incorporate human decision-making, fully integrating nomothetic and idiographic approaches (Phillips, 2004). The challenge of fluvial geomorphology is at a cross roads (Smith, 1993), and the vision of geomorphological work as relatively obscure, unlike that of doctors, dentists, or lawyers (Vitek and Giardino, 1993, p.x.), may now be less appropriate because of developments in applied fluvial geomorphology. However, this has not filtered down to a volume on applied geography (Pacione, 1999) which has no section on geomorphology and an index which does not include channelization, integrated basin planning, river channel management, watershed management or drainage basin management.

Applications of fluvial geomorphology research can arise where results or new facts may be applicable to environmental problems (applicable research) or where results are related to environmental problems in a specific area (applied research). In addition planning research, management research and sustainability research can be identified (Gregory, 1998, 2000). This paper considers what applications are feasible (Section 2), what accompanying advances have been and are still necessary in theory and modelling (Section 3), and how we communicate applications (Section 4), especially of results from palaeohydrology.

2. Possible applications

It is possible to classify applications emerging during the last 2 or 3 decades according to purpose, as the very comprehensive review of fluvial geomorphology (Dollar, 2004) drew attention to 4 themes: river landscape and classification; ecological water requirements; the European Union Water Framework Directive; and river restoration and remediation. Alternatively, we can look at examples of the subjects investigated and highlight those producing specific management recommendations (italics in Table 1). Such studies can be grouped under three headings.

2.1. Form and process

Those derived from investigations of form and process, either separately or in combination, include a significant number which lead to potential applications. Of those concerned primarily with form, studies of channel classification, often including channel ecology (e.g. Thorne et al., 1996; Newson and Newson, 2000) have been particularly relevant to applied fluvial geomorphology. Some of these have been explicitly applied, as in the case of a conceptual framework for diagnostic monitoring (Montgomery and Macdonald, 2002) to assess reach-level channel conditions in relation to response potential. This and other examples of channel assessment (Simon and Downs, 1995; Hooke, 2001) have focused on the channel's capacity to adjust, and progress has also been made in regard to the categorization of channels according to the way in which they are perceived (Gregory and Davis, 1993; Piegay et al., 2006). Documentation has occurred of links between form and

Table 1
Some recent examples of applications in fluvial geomorphology (in bold italic where recommendations for management are explicitly given)

Subject of attention	Application in fluvial geomorphology	Reference source
Form/process relations in river channels		
Increased sediment delivery	Aggradation and reduced capacities may lower the channel's ability to accommodate flood discharges	Brookes and Gregory (1988)
Channel dimensions	Used to estimate flood discharge	Wharton et al. (1989) See also Robson and Reed (1999)
Channel coarse woody debris	***Channel management determinants***	***Gregory and Davis (1992)***
Riverscape aesthetics	Perception in relation to management	Gregory and Davis (1993)
Basin sediment system	***Sustainable integrated development guidance from fluvial geomorphology***	***Newson (1994)***
Pool-riffle sequence	Relation to design of changing channels	Gregory et al. (1994).
Alluvial channels	***Methodology for potential instability***	***Simon and Downs (1995)***
Coarse woody debris in channels	***Management options for CWD***	***Gurnell et al. (1995)***
River channel reconnaissance	River analysis, engineering and management	Thorne et al. (1996)
Bank vegetation	Trees related to spatial zones of bank erosion processes	Abernethy and Rutherfurd (1998)
Channel incision	***Incised channels contain floods***	***Faulkner (1998)***
River channel habitats	Geomorphological channel classification	Newson and Newson (2000)
Stream channel assessments and monitoring	***Diagnostic approach***	***Montgomery and Macdonald (2002)***
BF hydraulic geometry relationships	***Necessary for channel design purposes***	***Sweet and Geratz (2003)***
Coarse sediment connectivity	Important for understanding the mechanisms and propagation of channel change	Hooke (2003)
Assessment of change of river channels		
Stream stability	***Thresholds from flow competence***	***Olsen et al. (1998)***
Indicators of geomorphic stability	***Effects of urbanisation***	***Doyle et al. (2000)***
Urbanizing stream	***Locational probability of channel change 1935–97 could indicate the most probable location and configuration of the channel***	***Graf (2000)***
Consequences of impoundment of river channels		
Bed degradation	Most occurred during first two decades or after dam closure varying from negligible to about 7.5 m	Williams and Wolman (1984)
Australia's fluvial systems	Underdesign of dam spillways in NSW	Tooth and Nanson (1995)
Effects of impoundment	Channels 35–53% of former widths	Warner (2000)
Downstream effects	Location of change depends upon the characteristics of the channel	Phillips (2003)
Freshwater mills	Geomorphological stability sustained where structures maintained but no maintenance can give failure of mill structures and extensive channel instability	Downward and Skinner (2005)
Impact of flood events	Flood effects provide foundation for aquatic and riparian diversity	Tiegs and Pohl (2005)
Effects of flow diversion on river channels		
Water diversions	Flood events reduced, channel narrowed, vegetation established	Gaeuman et al. (2005)

Urbanization and river channel management		
Urban channel adjustments	***Channel classification for management***	***Gregory (2002)***
Urban channels	Erodibility	Allen et al. (2002)
Urban channels	***Spatial management in relation to hazards***	***Chin and Gregory (2005)***
Plunge pools	Act as energy dissipators to increase flow resistance and enhance channel stability	Allan and Estes (2005)
Channelization		
Engineered river channels	Restoration and enhancement	Brookes (1990)
Impacts of engineering	***Alternative designs***	***Brookes (1995)***
Extractive industries and river channel management		
Mining sediments, hydraulic gold mining	Channel responses related to flood risk assessments, stability of engineering structures	***James (1999)***
Extractive industries	***Geomorphic effects including channel pattern changes***	***Erskine and Green (2000)***
Gravel mining	Channel incision related to gravel mining of channels	Uribelarrea et al. (2003)
Impact of engineering works and river channel management		
Community succession	Impact of civil engineering works	Bravard et al. (1985)
River training works	Effects of works on channel stability	Erskine (1992)
Civil engineering works	***Protecting engineering works threatened by incision etc should be priorities in determining sustainable development policies.***	***Bravard et al. (1999)***
Undersized engineering works	Insufficient to cope with changes in sediment transfers	Anthony and Julian (1999)
Sediment-related river maintenance	***Role of fluvial geomorphology***	***Sear et al. (1995)***
Historical change including land use changes		
Multiple channel floodplains	Occurred prior to deforestation and channelization	Brown (1998)
Fluvial activity	Valley floor and floodplain processes enhanced 1250–1550 and 1750–1900	Rumsby (2001)
Channel narrowing	Recovery from flood effects and afforestation	Liebault and Piegay (2002)
Land use changes	Change rates of bedload supply with channel effects	Kondolf et al. (2002)
Restoration in river channel management		
Channel restoration	Channel design algorithm	Morris (1995)
Restoration of impounded rivers	Geomorphological inputs to what is natural	Graf (1996)
Rehabilitation of a river	Reconciling flood defence with habitat diversity and geomorphological sustainability	Downs and Thorne (2000)
River condition	***Recovery in relation to river condition***	***Fryirs and Brierley (2000)***
River styles	***Implications for river rehabilitation***	***Brierley and Fryirs (2004)***
River styles framework	***Assessing recovery potential***	***Brierley et al. (2002)***
River recovery potential	***River condition and pathways of adjustment for river styles***	***Fryirs and Brierley (2000)***
River rehabilitation targets	***Set in relation to changed sediment supply and transport relationships***	***Brooks and Brierley (2004)***
Flood embankment abandonment	Channel returned to original condition in c. 50 years	Parsons and Gilvear (2002)

process; the potential of hydraulic geometry relationships for design (Sweet and Geratz, 2003); the estimation of flood discharges at ungauged sites from channel dimensions (Wharton et al., 1989; Wharton, 1992); and the extent to which changes in the spacing of the pool riffle sequence may adjust during channel change (Gregory et al., 1994). Coarse woody debris (CWD) in channels was the subject for an international conference (Gregory et al., 2003), and has prompted a range of management options, from complete removal to reintroduction of wood (Gregory and Davis, 1992; Gurnell et al., 1995). Other investigations relating form and process have focused on bank erosion, its measurement (Lawler, 1993), its relationship to bank vegetation (Abernethy and Rutherfurd, 1998), the role of riparian trees along river corridors as ecosystem engineers pertinent to managing channel change (Gurnell and Petts, 2006), the debate over what vegetation is most appropriate for management of banks (Montgomery, 1997), and changes in sediment loads (e.g. Walling and Fang, 2003). Changes in land use have been investigated in relation to alterations of channel process, including effects of reafforestation on channel incision (Lach and Wyzga, 2002) and the way in which channel change can have implications for flood frequency (Faulkner, 1998) because higher peak flows that occasion larger channels may be better accommodated by those enlarged channels. The consequences of altered channel processes also need to be considered in relation to management in the case of increased sediment delivery from which consequent aggradation and reduced capacities may lower the channel's ability to accommodate flood discharges (Brookes and Gregory, 1988). The passage of sediment slugs (Nicholas et al., 1995) and connectivity of the sediment system are of importance for understanding the mechanisms and propagation of channel change (Hooke, 2003), so that cumulatively in the sediment system it is possible to provide sustainable integrated development guidance from fluvial geomorphology (Newson, 1994).

2.2. Factors affecting changes of form and process

Assessment of channel change is increasingly recognized as a consideration necessary during channel management, so that specific methods of mapping change (Gregory et al., 1992; Gregory, 2002) and of relating changes to erosion risk (Piégay et al., 1997) have been devised (Table 1). Indicators of geomorphic stability have been developed for urban areas (Doyle et al., 2000), and other methods have been related to thresholds (Olsen et al., 1998). Analysis of channel pattern change to demonstrate locational probability of channel change of the Salt River 1935–97 is a way of indicating the most probable location and configuration of the channel (Graf, 2000).

Specific reasons for channel change have been long investigated but research is now producing conclusions very pertinent to the management of river channels. Thus, downstream from impoundments by reservoirs bed degradation varied from negligible to about 7.5 m with most occurring during the first two decades after dam closure (Williams and Wolman, 1984); channels can be 35–53% of their former widths (Warner, 2000); the exact location of change depends upon the characteristics of the channel (Phillips, 2003); and multiple modes of channel adjustment are possible (Phillips et al., 2005). Other causes of impoundment and their consequences have been investigated including lock construction (Rutherfurd, 2000) and freshwater mills (Downward and Skinner, 2005) showing that geomorphological stability is sustained where structures are maintained but lack of maintenance can give failure of mill structures and extensive channel instability. Following impoundment, implications have been demonstrated to include the basis for riparian vegetation development (Tiegs and Pohl, 2005), the implications for ecology (NRC, 2005), exemplified by the threatened and endangered species of the Platte river, and the under-design of dam spillways in NSW, Australia (Tooth and Nanson, 1995). Flow diversion has similar consequences with flood events reduced, the channel narrowed, and vegetation established (Gaeuman et al., 2005).

Investigations of channels in, and downstream from, urban areas have demonstrated the range of adjustments that can occur (Gregory, 2006), with additional attention given to the way in which variations change downstream (Gregory et al., 1992); the extent to which responses in humid and arid areas are similar (Chin and Gregory, 2001); the ways in which channel classification relates to erodibility (Allen et al., 2002), and to channel management in urban areas (Gregory and Chin, 2002); as well as to specific features such as the role of plunge pools as energy dissipators to increase flow resistance and enhance channel stability (Allan and Estes, 2005). More generally, it has been possible to relate channel hazards to sections of the channel system (Chin and Gregory, 2005). Channelization was often associated with urban areas and documenting its spatial extent (Brookes et al., 1983) can be an important reference for management. In addition to human influences on channel change (Brookes, 1992), recovery and restoration (Brookes, 1992), restoration and enhancement (Brookes, 1990) it is now possible to suggest alternative designs that can be employed (Brookes, 1995). Channel change is also affected by extractive industries and as a

Table 2
Some requirements in applications of fluvial geomorphology that can be facilitated by theory development and modelling i.e. particularly to facilitate extrapolation to other locations

Subject	Requirement	Example or citation
Morphological		
River channel capacity	Standard method of determination	Downs and Gregory (2004)
Channel classification	Stream channel types related to risks	Montgomery and Macdonald (2002)
Degrees of freedom	Relate to possible adjustments of alluvial channels	Hey (1997)
Drainage network	Dynamics related to extraction from large scale maps or remote sensing	Wharton (1994)
Process		
Flow estimation	Estimates (e.g. Qbf) from channel dimensions	(Wharton et al., 1989; Wharton, 1992)
Complement flow records	Add palaeflood discharges to continuous records to reconstruct flood history	Baker (2003a)
Sediment transport modelling	Model sediment transport for ungauged sites	Downs and Priestnall (2003)
Channel pattern changes	Cutoffs inherent in meander behaviour	Hooke (2004)
Disequilibrium flood plain development	Floodplains evolve in response to a sequence of episodic cycles	Nanson (1986)
Hazards	Identify hazards associated with channel reaches	Gregory and Chin (2002)
Environmental hydraulics	Geomorphological methods to calibrate and validate hydraulic models	(Bates et al., 2005a,b)
Hydraulic surface friction (roughness)	Re-evaluation of roughness topography	Lane (2005)
Integrated aspects		
Sensitivity	Extent to which channel reaches are sensitive to change	Downs and Gregory (1995)
Thresholds	Limiting conditions beyond which aspect(s) of the fluvial system may change	Church (2002)
Stream power	Combines fluid density, slope, gravitational acceleration and discharge and used as a unifying theme in urban geomorphology	Rhoads (1995)
Stability analysis	To distinguish between stable and degrading or aggrading sites	Doyle et al. (2000)
Geomorphic work	Quantitative relationship between flow energy parameters (e.g. stream power) and landform development	Benito (1997)
Changes		
Metamorphosis	Specification of how parameters may change with adjusting channels	Hooke (1997)
Channel incision	Magnitude of incision likely after sediment extraction or channel straightening	Simon and Downs (1995)
Channel response to dam removal	Predict rates, magnitudes and mechanisms by which sediment removed from a reservoir following dam removal and predict where sediment will be deposited downstream	Doyle et al. (2002)
River styles framework	Identify pathways of adjustment to distinguish categories of river condition	Brierley and Fryirs (2004)
Catchment sediment budget related to reach hydraulics	Modelling sediment restorage in sustainable river rehabilitation	Brooks and Brierley (2004)
Catchment response related to environmental change	How changes in climate and basin land use affect sediment transfer and alluviation	Coulthard et al. (2005)
Restoration objectives	Definition of types of condition available as objectives for restoration	(Gregory and Chin, 2002; Downs and Gregory, 2004)
Recovery potential	Estimation based on connectivity of reaches and limiting factors to recovery	Brooks and Brierley (2004)

consequence of hydraulic gold mining, channel responses related to flood risk assessments, together with the stability of engineering structures have been documented (James, 1999); although, as with effects downstream of reservoirs and urban areas, there can be differential channel responses (Bird, 2000). Gravel mining of channels may trigger important fluvial impacts that include bedload reduction giving hungry water (Kondolf, 1997) and severe channel incision and width changes (Uribelarrea et al., 2003). Such geomorphic effects including channel pattern changes can provide useful information for management recommendations (Erskine and Green, 2000).

Specific studies have been made of the impact of engineering works on ecology and community succession (Bravard et al., 1985), and on channel stability (Erskine, 1992, 1998) leading to investigations which have shown how protection of engineering works threatened by incision should be a priority in determining sustainable development policies (Bravard et al., 1999). It can be demonstrated how undersized works can be insufficient to cope with changes in sediment transfers (Anthony and Julian, 1999), and how there is a clear role for the geomorphologist to contribute in relation to sediment-related river maintenance (Sear et al., 1995).

Many of these applications involve changes over short periods of time but the value of research investigations of historical change, including land-use changes over longer periods, is being increasingly recognized (e.g. Orr and Carling, 2006). Palaeohydrological investigations can furnish information on processes and change prior to continuous records (e.g. Gregory, 2003). Significant research has demonstrated how discharges estimated from palaeofloods and historical floods can exceed those from the instrumental record, so that traditional methods of return period analysis for risk planning should be modified (Benito and Thorndycraft, 2004). In many areas the largest known floods are greater than those recorded during periods of continuous hydrological records, so that flood frequency analyses can be radically different when palaeoflood data are included (Baker, 2003a). Palaeoflood hydrology data have been corroborated by results from other dating methods and beneficially incorporated into modelling procedures for risk assessments (Baker, 2003b). Although this event-based stratigraphy may produce accurate records for individual floods (Benito et al., 2003), robust dating controls employing improved optically stimulated luminescence (OSL) techniques are needed to date alluvial sequences (Duller, 2004). Therefore identification of flood-prone areas should also be based upon more extensive multidisciplinary evidence (Thorndycraft et al., 2003). Historical studies in particular areas have reconstructed the sequence of environmental degradation (Warner, 1991), demonstrated in Great Britain how valley floor and floodplain processes were enhanced during specific time periods such as 1250–1550 and 1750–1900 (Rumsby, 2001), shown how European impacts in the New World affected sediment transfer and bank erosion (Brierley and Murn, 1997), and revealed how, prior to extensive deforestation, multiple channel systems may have preceded present single thread systems in many parts of Europe (Brown, 1998). Research is now demonstrating ways in which river ecology is affected by post-European changes in Australia (Brierley et al., 1999), how recovery from flood effects and afforestation can be responsible for channel narrowing (Liebault and Piegay, 2002), and how changing rates of bedload supply can be associated with channel changes following land-use effects (Kondolf et al., 2002). We have now reached the stage at which not only has the relevance of historical change been shown to be a valuable background for management but also geomorphological research investigations can reconstruct processes and stages of development and indicate what can happen next (e.g. Dadson and Church, 2005) thus being vital for consideration prior to making management decisions.

2.3. River channel management

Such contributions necessarily provide background and sometimes explicit recommendations for consideration when constructing river channel management plans. A major emphasis in channel management has been on restoration in general but this has ranged over a spectrum of objectives including rehabilitation, re-establishment, recovery, enhancement, creation, naturalization and preservation (Gregory, 2000; Downs and Gregory, 2004). Although the prime decision to be made is whether restoration is towards some more natural condition, one that is appropriate for the specific area or one that is pertinent to the time period, in Europe it can be affected by whether a channel is in 'good ecological status' or can achieve 'maximum ecological potential' in the terms of the Water Framework Directive. It has been demonstrated that geomorphological inputs can be made to assist in determining what is natural (Graf, 1996) and a geomorphic algorithm for channel design has been proposed (Morris, 1995). In eastern Australia particularly important contributions have plotted pathways of channel disturbance and recovery since Europeans arrived (Fryirs and Brierley, 2000) as the basis for catchment restoration and management. The river styles framework (Fryirs and Brierley, 2001; Brierley and Fryirs, 2004) provides a basis for the spatial characterization of channels in a catchment, giving insights for temporal management issues in restoration by providing a basis for assessing geomorphic river condition and recovery potential in relation to different evolutionary pathways of river styles since the European settlement of Australia (Brierley et al., 2002). This acknowledges how the legacy of past human activity can still be very influential over many parts of the catchment. The change of connectivity and patterns of sediment movement within any catchment system has been interpreted as being controlled by buffers, barriers and blankets in the upper Hunter catchment, NSW, Australia (Fryirs et al., 2007), where buffers are landforms that prevent sediment movement into channels, barriers are landforms that prevent or disrupt sediment movement along channels, and blankets are sediments that smother other landforms thus temporarily removing some stores

Table 3
Some examples of methods of communication between geomorphologists and managers

Methodology	Purpose	Example reference
Applicable research output		
Review papers summarizing potential for application	Framework for incorporating geomorphological tools within river management	Newson and Sear (1994)
	6 Policy recommendations for management in Mediterranean environments	Poesen and Hooke (1997)
	Integrating geomorphological tools in ecological and management studies.	Kondolf et al. (2003)
Book chapters in volume intended to circulate beyond the discipline	Engineering geomorphology: application of geomorphological knowledge to civil engineering by the education of both engineers and geomorphologists.	Fookes and Vaughan (1986)
	Geomorphology for Engineers: Handbook of geomorphology for engineers including	Fookes et al. (2005)
	Fluvial geomorphology applications	(Lee, 2005; Gregory, 2005)
	River Channel Restoration: Guiding principles for sustainable projects	Brookes and Shields Jr. (1996)
Book of edited contributions intended to include readership beyond the discipline	The Rivers Handbook	Calow and Petts (1992)
	Applied Fluvial Geomorphology for River Engineering and Management.	Thorne et al. (1997b)
Collected case studies of applications	Use 12 examples to demonstrate geomorphological input and growing respect between geomorphologists and engineers	Newson et al. (1997)
Review papers/chapters dealing with specific applications	Evaluation of engineering approach in a case study of channelization producing management recommendations	Wyzga (2001)
Applied research papers submitted to non-geomorphology journals	Solving an urban river erosion problem on the Tilmore Brook, Hampshire (UK).	Brookes et al. (2004)
Research papers with potential for application	Equations for flood estimates at ungauged sites	(Wharton et al., 1989; Wharton, 1992; Robson and Reed, 1999)
	Suggestions for structural approach to management of CWD in association with forestry	Gurnell et al. (1995)
	Determinants for management strategy for wood in channels	Gregory and Davis (1992)
	Proposal of scheme for urban catchment management plan	Gregory (2002)
	Extension of discharge records to enhance flood frequency curve with palaeofloods	Baker (2003b)
Book on specific subject intended to include readership beyond the discipline	Provide ingredients for individuals to develop their own philosophy for river channel management employing summary tables including Rudiments of river channel management with nature	Downs and Gregory (2004).
	Stream classification appropriate for Applied River Morphology.	Rosgen (1996)
Contracted report outlining state-of-the-art in application	Guidebook of Applied Fluvial Geomorphology : R and D Technical Report FD1914	Sear et al. (2003).
	River Geomorphology: a Practical Guide.	Thorne et al. (1998).
Applied research output		
Geomorphology research output targeted at interdisciplinary problem solving	Adaptive modelling: Objectives, mechanisms and tolerances of model adjusted in ongoing dialogue	Wilcock et al. (2002)
	Post project appraisal: ability to adjust programmes and policies in the light of experience gained during adaptive management programme	Downs and Kondolf (2002)
	Uncertainty in engineering wildlife habitats	Brookes et al. (1998)
	Guidelines for flood alleviation schemes	Hey and Heritage (1993)
	Restoration design guidelines	Soar and Thorne (2001)

(continued on next page)

Table 3 (*continued*)

Methodology	Purpose	Example reference
Incorporating geomorphology tools in interdisciplinary problem solving	Online toolkits for restoration design	NCED (National Center for Earth Dynamics)
Geomorphology contributions to interdisciplinary problem solving	Federal interagency handbook on stream corridor restoration	Federal Interagency Stream Restoration Working Group (FISRWG) (1998)
	Dam removal and its consequences	The Heinz Center (2002)
	Endangered and threatened species of the Platte River	NRC (2005)
Presentation of applied results for communication	Guidelines for plutonium transport downstream on the Rio Grande	Graf (1994)
	Diagrammatic representation of river channel restoration with a focus on geomorphological concerns	Kondolf and Downs (1996)
	Checklist for identifying waterway management needs in relation to urban areas	Riley (1998)
	Protocol relating to the use of past hydrological events for understanding global change	(Gregory, 2003; Gregory et al., 2006a,b)
Educational outreach		
Geomorphologists participation in non-geomorphology conferences	Attending and contributing to multidisciplinary and other discipline conferences	e.g. ASCE, restoration-based conferences
Geomorphology-centred workshop to inform state-of-the-art beyond the discipline	ESF LESC Exploratory Workshop on "Large wood in European Rivers: dynamics, human perception, challenge for restoration and application to other areas" Lyon, France, 16–20 October 2005 giving recommendations for future river management	Piegay and Gregory (2005)
	Stillwater/Berkeley/SF State flume workshops	
Geomorphology shortcourses/training	e.g. Principles and practice of stream restoration and geomorphology and sediment transport in channel design channel classification course	Utah State University Department of Aquatic, Watershed, and EarthResources courses Rosgen (1996)
Geomorphology contributions to public education	Fluvial Geomorphology of Great Britain, Signboards and other information for the public	Gregory (1997) Joint Nature Conservation Committee
	Teaching of geomorphology beyond the classroom	Davis (2002)
	Flood education and flood perception	Benito and Thorndycraft (2004)
Direct involvement		
Chartered status	Chartered geographer (C.Geog Geomorph.)	www.rgs.org/CGeogApplication
Problem resolution	Geomorphologists asked to give expert testimony pertaining to legal disputes	e.g. Schumm (1994)
Non-government employment	Geomorphologists in NGOs bringing pressure for geomorphological integration into environmental problem solving	Brookes (1995)
	Geomorphologists in consultancies involved with professional application of geomorphology knowledge, working in conjunction with other disciplinary scientists e.g. ecologists and biologists, civil, ecological and environmental engineers, landscape planners and architects	e.g. Stillwater Sciences provides geomorphic services to support a variety of biological, water quality and engineering objectives in river management; UK geomorphologists as RRC advisors or consultants; Brunsden (1999)
Policy development (implementation, guidance, direction)	Geomorphologists involved in directing implementation of government environmental policy	
	Geomorphologists involved in guiding development of protocols for application	Lead Scientist to Calfed Environmental Water Program
	Geomorphologists contributing to or member of expert panels	e.g. W.L.Graf Chair of Panels producing (NRC, 1999; Heinz Center, 2002; NRC, 2005)
	Geomorphologists directly involved with policy making and management research agendas	Employment and secondments to Regional, national government agencies

from the sedimentary cascade. These buffers, barriers and blankets can hold the operational keys to switching connectivity on or off in particular basins (Gregory and Downs, in press). Other investigations of restoration have included recovery time, for example after a flood embankment was abandoned (Parsons and Gilvear, 2002), the way in which flood defence can be reconciled with habitat diversity and sustainability (Downs and Thorne, 2000), the implications of public participation and of community-based interaction between scientists and non-scientists (Rhoads et al., 1999), and implications for restoration of dam removal on a large scale (Graf, 2003).

Much fluvial geomorphology research has therefore evolved towards potential applications. Although there is acceptance that a multidisciplinary approach is required (Bravard and Gilvear, 1996), for example combining ecology with hydrology in ecohydrology (Rodriguez-Iturbe, 2000) or with archaeology in alluvial archaeology (Macklin and Needham, 1992), the geomorphological inputs perhaps not replicated by other disciplines include a holistic approach (Phillips, 1999), involving the spatial and temporal contexts which allow an approach of environmentally sensitive river engineering (Hey, 1994) or one employing a fluvial hydrosystem framework (Gilvear, 1999). The challenges and objectives for geomorphology have therefore been recognized, for example in UK river management (Brookes, 1995), but further progress requires the development of theory and associated modelling approaches.

3. Advances in theory and modelling

Many of the examples (Table 1) derived from specific local investigations and, in order to achieve general significance, more general theory and extension by modelling methods is needed. Whereas Hooke (1999) identified a second phase of engineering geomorphology as one answering geomorphological questions, providing geomorphological information, and implementing management, involving case study work at specific locations, she then anticipated a third phase involving modelling, and predicting responses in ways which deal adequately with complexity, positive feedback, non-linearity and holism. This requires not merely spatial extension, to other locations, but also application of knowledge from different timescales in order to reduce uncertainty (Gregory and Downs, in press). Indeed it has been argued that river engineers need to understand fluvial systems as they change through time (James, 1999) requiring advances in the theoretical basis underpinning our understanding of process and morphology of the fluvial system and of future change.

Ways in which theory might be developed to further applications of fluvial geomorphology are of three major kinds: those associated with morphological and process characteristics, with integrated aspects of the fluvial system to assist extrapolation, and those concerned with changes of the fluvial system (Table 2).

3.1. Morphology and process

Although some possible examples are listed in Table 2 the need remains for standard procedures for characterizing morphological aspects, because landform developments lagged behind the understanding of process in the quantitative study of earth's surface (Lane et al., 1998). River channel capacity is a fundamental fluvial landform and so requires improved interpretation to progress beyond the way in which it is often characterized in engineering terms (Wharton, 1995; Downs and Gregory, 2004). Assessment of stream channel types is needed and has been approached in a diagnostic way (Montgomery and Macdonald, 2002) and also for the purpose of comparison from one area to another for river channel management. Thus a channel classification framework can be envisaged (Downs and Gregory, 2004, p. 58) as 7 hierarchical levels extending from the river environment at a point through within-channel, channel unit, stream reaches, valley segments, zones, to the drainage basin. Short term channel change, visualized in terms of degrees of freedom, originally suggested by Lane (1955), expressed as four by Knighton (1998, p. 156) and developed to nine degrees of freedom by Hey (1997), is basic to the approach of environmentally sensitive river engineering (Hey, 1994). Just as river channel cross sections have been over-simplified in the past, so drainage networks have been extracted from maps and remote sensing without sufficient consideration of how they relate to the dynamics of the network in the basin. Both cases require methods of data extraction which meaningfully represent ways in which the channel and the network function (Wharton, 1994) and interact with other processes.

Aspects of process characteristics are traditionally associated with modelling methods, particularly with estimation of discharge by catchment and routing models and with modelling of sediment transport. However, geomorphological inputs can give flow estimation, especially of peak or flood flows, based upon channel dimensions (Wharton, 1992); can enhance regional flow estimation by derivation of palaeoflood values prior to continuously monitored records (Baker, 2003a,b); and can be employed in sediment transport modelling to estimate budgets for ungauged sites (Downs and Priestnall, 2003). Processes associated with channel planform, such as the generation of cutoffs (Hooke, 2004), require generalization from empirical studies to models for widespread application. Similarly, understanding the generation of floodplain environments needs to incorporate the role of episodic cycles in disequilbrium floodplain development (Nanson, 1986). In such ways it is possible to present and refine models, conceptual and mathematical, of how the fluvial environment functions. Management is then concerned to allow for the effects of stream channel hazards so that, if a general model can be developed of the way in which such hazards relate to sections of stream channel throughout the basin, this can provide a useful foundation (Chin and Gregory, 2005). Environmental hydraulics have been rapidly developed taking advantage of the progress in computer technology which allows computational fluid dynamics (CFD) modelling at fine resolution levels to model hydraulic processes occurring within river channels and floodplains (Anderson et al., 1996) using two- and three-dimensional computations of free surface flows. The CFD model results require geomorphological methods to calibrate and validate their performance (Lane et al., 2005). The detailed topography of river channels and floodplains is probably the most critical factor affecting the model result due to its influence both on model predictions of hydraulic processes (Horritt, 2005) and on the resultant areal extent of the simulated flood (Horritt and Bates, 2001; Casas et al., 2006). The high complexity of two- and three-dimensional hydraulic models requires high resolution topography to attain a high level of process representation (Bates et al., 2005a,b), and new methods for determining flow resistance based on the topographic variability (Lane, 2005; Casas et al., 2005).

3.2. Integrated approaches to the fluvial system

Several ways have been explored of providing integrated approaches appropriate for analysis in relation to applied problems (Table 2). One of these is based on sensitivity (Downs and Gregory, 1995) which can be employed to gauge the risk associated with channel-related hazards, including erosion and deposition, as well as the susceptibility of channel-related assets which include features of great habitat or other environmental value (Downs and Gregory, 2004). Because sensitivity describes the ratio between the magnitude of channel adjustment and the amount of change in the stimulus causing adjustment, it can reflect proximity to thresholds in channel behaviour. Understanding of geomorphic thresholds in rivers is important because of their influence upon morphology and habitat and because human activity and/or climate change can precipitate threshold crossings (Church, 2002). Stream power potentially provides an ideal integrated index for analysis of the fluvial system because it incorporates critical elements directly related to the physical capability for performing geomorphic work (Benito, 1997) and so should be a basis for characterizing different types of fluvial systems including adjusting situations. Although it has proved complex to utilize, it has been advocated as a unifying theme for urban fluvial geomorphology (Rhoads, 1995) and could be the basis for relating channel types or types of channel adjustment to absolute power values or to changes in power. A technique of stability analysis, proposed to distinguish between stable and degrading or aggrading sites (Doyle et al., 2000), can provide an integrated approach to channel adjustments.

3.3. Change of the fluvial system

Other studies have been concerned with modelling changes of the fluvial system. Developed from the ideas of Lane (Lane, 1955), degrees of freedom (Hey, 1997) and river metamorphosis approaches have provided a basis for considering styles of channel change (Hooke, 1997). Methods have been applied in specific situations, such as magnitude of incision likely after sediment extraction or channel straightening (Simon and Downs, 1995), or channel response to dam removal to predict rates, magnitudes and mechanisms of sediment movement from the former reservoir and also to predict where sediment will be deposited downstream (Doyle et al., 2002). More generally for the Australian environment, pathways of adjustment have been associated with different river styles and thence categories of river condition have been distinguished (Brierley and Fryirs, 2004). Utilizing a catchment approach, geomorphological inputs can be valuable for modeling sediment restorage in sustainable river rehabilitation (Brooks and Brierley, 2004), as well as for demonstrating catchment response to land-use and climate change by modelling how changes in climate and basin land-use affect sediment transfer and alluviation (Coulthard et al., 2005). Such developments are appropriate for the several objectives of restoration.

4. How are applications communicated?

Despite numerous empirical investigations together with improved theory and models there is an outstanding question of how potential applications are actually

Table 4
Synopsis of a protocol on the use of past hydrological events for understanding global change

A. Relation to global change

Global change, usually connected with climate fluctuations of different magnitude, is a term used in a variety of ways. It is principally climatic but includes natural or anthropogenic environmental changes induced by causes which are world wide but which have different effects in particular regions, and is interrelated with major continental land use changes and other effects of human activity. Continuous records may be too short in duration to give sufficient information on past hydrological events, whereas long term geomorphological records provide data to reconstruct their magnitude and frequency as well as their impacts on natural systems (channel change, avulsion, incision, aggradation).

B. Hydrological events

Hydrological events are defined as having a magnitude higher (flood events) or lower (drought events) than a critical threshold, including extreme events, and may be clustered in time and will give hydrological responses associated with changes in sediment budgets. Augment the continuous record as necessary with as much data as appropriate. Record of individual hydrological events (namely floods) can be obtained from detailed fluvial interdisciplinary studies. For particular areas, information on ^{14}C dated samples can be obtained to analyse dates marking geomorphologically significant changes in Holocene river activity. The assembled databank can identify periods of heightened or changing alluvial activity, likely to reflect phases of increased flood frequency and magnitude.

C. Past hydrological events related to global change

Attempt to place records within the longer term context, because a short term trend from a limited temporal record may be a limb of a longer term cyclical fluctuation. Establish links between event sequences and global change. Past hydrological event descriptors include discharge regime and sediment regime indicators which can be obtained from sedimentological and geomorphological records. Standardized methods on field and laboratory data collection need to be established; methods for reconstructing past hydrological events (discharge, sediment flux, erosion, fluvial dynamics) are available in a number of methodological guidelines and technical reports. Main phases or clusters of past hydrological events can be obtained from reach, catchment, regional and continental analysis, which can be linked to other climate and environmental proxies (e.g., pollen and tree-ring analysis), establishing a cause–effect relationship. Comparative analysis of records at different spatial–temporal scales allow evaluation of the relative and varying roles of climate and land-use on fluvial dynamics, which can be used as a predictive tool to assess river response to future environmental changes (e.g. Macklin et al., 2006; Starkel et al., 2006; Thorndycraft and Benito, 2006).

D. Applications

How information on past hydrological events and their impacts may be of use in management including ecosystem protection and restoration, flood risk management, and water resources management.

- Consider the range of techniques available for extending the data sequence beyond the length of continuous records including production of a data base.
- Determine a timescale and a design period appropriate for the particular location, setting incidence of phases of higher frequency of channel aggradation and accelerated erosion and deposition into a probability-based record of Holocene riverine alluvial activity.
- Employ modelling, not only to extend data sequences but also to identify the relationships between climate and catchment output for particular areas.
- Evaluate hazards created by erosion and sedimentation together with those of flood discharges, making reference to structures designed for high sediment loads and to the period of record used for making earlier management decisions. Palaeoflood hydrological approaches can discover the nature of flood causation and identify zones that are hazardous to human development.
- Identify channel reaches that are unstable/sensitive within a basin, as a result of mitigation or management measures or impacts of human activity, highlighting those reaches that may be sensitive in the future, because these reaches can guide development away from areas at risk of channel erosion. Ascertain the implications of changing flows in relation to specific segments of fluvial landscapes such as the channel migration zones (CMZ) which can be used in relation to property and infrastructure risks, and may be appropriate in relation to design levels for flood risk mapping and planning controls.
- In the light of past hydrological events, work with nature and not against it, considering what is natural; ensure that any scheme is as sustainable as possible and also amenable to adaptive modification, adopting non-structural and 'do nothing' approaches wherever possible, and using procedures that have the least damaging environmental impacts.
- As new flood management strategies are required and are devised, ensure that contributions to designated flow levels utilise studies of past hydrological events.
- Better understanding of the impact of global warming on extreme event frequency and magnitude patterns.
- Development of statistical tools dealing with non-stationarity of hydrological events due to climatic and land-use changes.

E. Future needs include

- Standardised methods and terminology used by different scientific groups
- Information exchange from different spatio/temporal study scales
- Re-analysis and comparison of existing data
- Review of methods and their use in e.g. flood risk mapping, determining hydromorphological status in support of ecological status (major applied research need), locations and scales of impact of different kinds of flood events, how channels might change in response to climate can land use change, contribution or role in management priority problems e.g. diffuse pollution, flood inundation

communicated to decision-makers. Managers cannot be familiar with the detail of all the necessary books and papers so that communication between scientists and managers has been described as a paradigm lock, cited (Endreny, 2001) as one of four obstacles to implementation of sustainable water management through the HELP United Nations Project. The paradigm lock occurs because scientists (e.g. geomorphologists specifically concerned with river channel research) do not grasp what managers require, and managers and stakeholders (exemplified by river channel managers) do not appreciate the scientific alternatives available. In applying this paradigm lock to river landscapes and to physical geography (Gregory, 2004a) it was suggested that blue skies and strategic research are integral parts of geomorphology research, whereas accepted practice derives from applied research and is affected by perceptions of the results of scientific research. A review of hydrology, geomorphology and public policy as employed in the management of river resources in the US (Graf, 1992) also showed how endeavours are poorly connected to each other. The ultimate challenge is the need to raise awareness of the function of geomorphological processes in landscape and environmental management in the minds of policy makers and of the general public (Higgitt and Lee, 2001). This may be achieved with more interdisciplinarity and effected by demonstrating the relevance and wider benefits of geomorphology.

A growing bond is reported between geomorphologists and engineers bringing talents from each side; from geomorphology the talents are listed as field experience, sediment supply/transport, longer timescales, generalist breadth, erosion/deposition processes, complex/sinuous channel dynamics, basin scale, personal insights, and chest waders (Newson et al., 1997, p. 312, Table 12.1). Further dialogue is needed and, if geomorphologists do not meet the need, then other disciplines will as demonstrated by *Restoring Streams in Cities* (Riley, 1998). Communication of results has been addressed in several ways (Table 3). Applicable research output ranges from review papers to contracted reports and specific examples are illustrated in Table 3. Transitional between applicable and applied outputs are specific subject books, for example a book dealing with river channel management (Downs and Gregory, 2004) started from the viewpoint of geomorphology but reflected a background that is increasingly multidisciplinary in scope and subject to international influences and trends. Stream channel classification (Rosgen, 1996) has been employed as the basis for river management, a guidebook or a summary of applications has been provided in *River Geomorphology: a Practical Guide* (Thorne et al., 1998), and contracted reports exemplified by the *Guidebook of Applied Fluvial Geomorphology* (Sear et al., 2003) produced for DEFRA in the UK.

Progress made in applications to management problems has now led geomorphologists to contribute to applied research in interdisciplinary problem solving in a number of ways (Table 3) and there is also a range of ways in which applied results can be communicated including guidelines, diagrammatic representation, checklists and a protocol (Table 3) although in practice it is primarily through decision support tools or management plans. Four key contributions of fluvial geomorphology to river and floodplain management (Gilvear, 1999) were identified as promoting recognition of lateral, vertical and downstream connectivity; the importance of fluvial history and chronology; the sensitivity of systems to disturbance, especially near thresholds; and the importance of land-forming processes in controlling fluvial biotopes. Communication needs to reach different national and regional levels: in the USA disjointed policies at federal and state levels as well as local efforts for integrated planning remain relatively ineffective in most states, so that there is a need to develop a new paradigm together with use of the Web to gather and share data and to educate (Brown et al., 2002).

A protocol can be utilized as a basic set of rules for presentation to managers; it should be precisely articulated to incorporate knowledge gained by geomorphological investigations and presented in a way that can be considered by managers. It is generally agreed that continuous hydrological records are not of sufficient length or are monitored at enough locations to provide sufficient data to analyze past hydrological systems in relation to possible future changes. Collaborative research enabled six international research groups to combine results for periods prior to those of continuous instrumental records, with each group focusing on hydrological events at their specific time and spatial scales (Gregory et al., 2006a). In order to recognize experience gained from a range of investigations covering more than the period of continuous records, a method is needed to summarize available information in such a way that it could be utilized as a checklist in relation to management problems in a particular area (Gregory, 2004b), building upon the earlier guidelines for river channel management (Gregory, 2003). A protocol embracing palaeohydrological inputs for application to river channel management was suggested (Gregory, 2003), was discussed at several international meetings (including IGU, 2004; IAG 2005) and developed after collaboration by several international groups to provide recommendations about the use of past hydrological events related to understanding global change. It was constructed to involve four components: global change, approaches to hydrological events, relationship of such events to global change, and preliminary applications (Gregory et al., 2006a). As a result of conclusions of papers contributed to an international research meeting and of the ensuing discussion, the protocol was modified to a synopsis version (Gregory et al., 2006b,c), illustrating how experience and practice from geomorphological research can be expressed in a format which can be considered by managers (Table 4). This content is capable of further development and future needs are indicated in Table 4 to include more standardised methods employed by different scientific groups, improved information exchange relating to different spatio/temporal study scales, and benefits from re-analysis and comparison of existing data. This protocol is just one illustration but a similar approach could be employed for other purposes in fluvial geomorphology, for example to provide guidance for specific methods (C in Table 4).

Communication also takes place through educational outreach including participation in non-Geomorphology conferences, workshops, training courses and contributions to public education as exemplified by a fluvial geomorphology volume for the Geological Conservation Review Series (Gregory, 1997) or the volume on *New Strategies for America's Watersheds* (National Research Council, 1999). Thus an ESF LESC Exploratory Workshop on "Large wood in European Rivers: dynamics, human perception, challenge for restoration and application to other areas" was convened by H. Piegay and K.J. Gregory in Lyon, France, 16–20 October 2005 collating research contributions from 9 countries, one aim being to report the analysis of results from individual countries and to develop collective conclusions together with recommendations for future river management, leading to the design of innovative research topics. To be directly involved it is helpful to have recognized chartered status now available within Chartered Geographer (www.rgs.org/pdf/CGeogApplication). An increasing range of opportunities continue to arise from contributions to problem resolution and in the course of non-government employment or policy development (Table 3).

5. Conclusion

Numerous applications of fluvial geomorphology are now appearing (e.g. Table 1) and will be further catalyzed by enhanced generalization and modelling (Table 2). Such developments support the suggestion that 'Geomorphology as a natural science is returning to its roots of a close association with environmental resource management and public policy…..there is a new emphasis on application of established theory to address issues of social concern' (Graf, 1996, p. 443). However such developments require an increasing dependence upon multidisciplinary and interdisciplinary contributions which in turn reinforce the need for awareness of a sound theoretical foundation, a long term framework, sustainability and design with nature, together with ethical issues. The protocol illustrated (Table 4) provides an expeditious way of presenting results of fluvial geomorphological research in a format appropriate for consideration by managers and decision-makers. As the importance of geomorphology to both science and daily life can only increase (Leopold, 2004), there is no doubt that the potential of fluvial geomorphology is becoming recognized but if its potential is not realized by geomorphologists, it could be adopted by others who are discovering geomorphology.

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