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Geomorphological concepts and tools for sustainable river ecosystem management

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ABSTRACT

1. Under definitions of 'strong' sustainability, ecosystem protection and the valuation of natural goods and services figure prominently. These priorities also lie at the heart of the EC Water Framework Directive (WFD).
2. This paper explores the ability of fluvial geomorphology to describe, monitor and predict river channel conditions and behaviour at the basin and smaller scales. It also examines how geomorphology can help to create management 'tools' and work in interdisciplinary frameworks with freshwater ecology to assess instream physical habitat.
3. Systematic views of river basins and predictive techniques based on system drivers have been popular in fluvial geomorphology for 50 years. System states are seen as resulting from the balance between all relevant processes. However, channel dimensions and forms at a site are much harder to predict and their dynamic adjustment can occur rapidly, exhibiting 'threshold' behaviour.
4. Direct human impacts have been a focus of research but long-term monitoring of channel states and adjustments has been neglected; River Habitat Survey offers major opportunities in this respect, even though it was not designed specifically for geomorphological interpretation.
5. In the UK, local or 'reach'-scale channel adjustment is widespread, justifying a major empirical survey effort in support of management decisions. Channels are supply-limited in sediment terms, polycyclic in profile, confined within glacial and periglacial sediments and extensively manipulated by engineering modifications. Whilst system properties are vital to the choice of management options over long timescales, conditions on a hierarchy of smaller scales can confound the systematic attempts of geomorphologists to classify and predict channel states.
6. Freshwater ecologists have long appreciated the need for a scaled approach to river systems. This paper argues for extensions to shared data collection and analysis programmes before immutable policy becomes established around unfinished management tools. Adaptive management creates a more realistic medium for the use of uncertain geomorphological and ecological predictions.

KEY WORDS: sustainability; geomorphology; river channels; systems; adjustment; surveys; ecology; eco-hydrology

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SUSTAINABILITY AND ITS DEMANDS UPON RIVER SCIENCE

Background

The meaning of 'sustainable' is hotly contested by academics and politicians. A helpful contribution to the definition debate has come from the notion of the varying 'strength' of sustainability (e.g. Pearce, 1993). In this approach 'strength' is determined by the degree to which strategies and operations are directed predominantly by human demands ('weak' sustainability) or ecosystem demands ('strong' sustainability). The EC Water Framework Directive (WFD) advances a 'strong' sustainability platform for river ecosystem management by adopting the principles of freshwater ecosystem protection and restoration. However, in so doing, it seeks to replace a traditional management system based almost entirely on human demands, such as flood protection, on engineering priorities and judgements, and on site-specific activity. It therefore places new demands upon river science, not least in respect of the need for 'usable knowledge' and practical 'tools' that permit decision-making at a variety of scales in space and time.

In assessing the 'hydromorphological status' of fresh waters the WFD requires robust protocols for the description and monitoring of river channel features relevant to ecosystem protection (European Commission, 2000). As an inevitable consequence, it also demands an interdisciplinary predictive platform for the strategic location and design of rehabilitation. The Directive has rekindled debates over disputed terms such as 'natural' in the search for reference conditions by which to assess quality and 'stability' in the context of ecological mitigation works.

Fluvial geomorphology is emerging from a purely academic background in the UK to help provide practical guidance for river managers (Brookes, 1995; Thorne *et al*., 1997; Environment Agency, 1998; Newson *et al*., 2001). Inevitably, it does so in a slightly schizophrenic way by advocating both predictive design tools and a high degree of precaution in their use. Its research outputs demonstrate widespread consensus at the scale of system drivers and gross impacts; this facilitates the development of (albeit inexact and uncertain) management tools. However, there is much stronger technical debate and hence a delay in delivery of 'tools' about channel problems presented at smaller scales. There is more willingness amongst applied fluvial geomorphologists to consider their contribution as one from environmental science, rather than simply as an aid to routine engineering; and the professional dilemma surrounding uncertainty is not unusual in modern environmental science. A widely accepted practical compromise occurs through application of the Precautionary Principle in the incorporation of scientific guidance. Adaptive management systems are the appropriate framework for incorporating precautionary scientific outputs (Clark, 2002).

'Nice adjustment' and ecosystem protection

Fluvial geomorphologists have been fascinated with both qualitative and quantitative statements of river system states for at least two centuries. Playfair described 'a system of valleys, communicating with one another, and having such a nice adjustment of their declivities, that none of them join the principal valley, either on too high or too low a level' (Playfair, 1802). Playfair advanced 'nice adjustment' as a system property, a fundamental change from the religious view that order was evidence of a deity acting protectively to humankind, between punishing us with calamities such as floods. Modern river management has been too often cast in a similar role to that deity!

Geomorphology and hydrology as systematic sciences are very different from, and much younger than, Playfair's descriptive geology; nevertheless, the quantitative systems-science view of rivers has also tended to advance 'nice adjustment' as a 'natural' property and one which might be naively set as the broad objective for — and offering the tools to attain — sustainably managed 'stable' rivers (Table 1).

Freshwater ecology, another relatively new discipline, has found usable concepts within the quantifiable conclusions from systematic fluvial geomorphology. However, the contemporary role for both sciences in

Table 1. Systems-science views of 'nice adjustment' in the river basin

Author/date	Concepts
Horton, 1945	Laws of stream order
Inglis, 1949	Regime theory of channel dimensions
Leopold and Maddock, 1953	Hydraulic geometry of channels, predictable downstream and at a station
Melton, 1958	Correlation structure of basin morphometry
Leopold and Wolman, 1957	Planform patterns of channels predicted by bankfull discharge, slope
Schumm, 1963	Channel shape predictable from bank materials
NERC, 1975	Parameters of flood frequency and hydrograph predictable from basin morphometry and climate

environmental management seems far from the routine application of research-derived predictions and prescriptions to benefit human society. Rather, it comes from the awakening of the international political system to the need for environmental protection. In this model, fluvial geomorphology is seen as contributing guidance on such issues as the resilience and sensitivity of river channels to development impacts. There is widespread international agreement about the appropriateness of the river basin unit for land, water and development policies (Newson, 1997). Geomorphological features figure prominently in the 'spontaneous regulation' of the basin system over long timescales (Marchand and Toornstra, 1986). Where these regulators, such as floodplains and wetlands, are extensively destroyed during the process of development the system is unlikely to recover in the way that rivers recover from a pollution episode. Society incurs the costs of replacing their function, for example by water purification, structural flood protection, or increasingly by schemes for restoring them.

Aldo Leopold wrote of the essential 'integrity, stability and beauty' of ecosystems, including river basins, untainted by human impacts (Leopold, 1949). Society now faces a profound dilemma in its choice of scientific (and aphoristic) guidance on, and coping strategies for, the direction and rates of change that are widely predicted as the result of climate trends and the impacts of more direct development processes. Given the new role of geomorphological knowledge and the policy demands upon it within river management systems, it is vital to re-examine the validity of geomorphological concepts, particularly at a variety of space and time scales and their relevance to freshwater ecosystems. Physical habitat has grown in importance in river management terms, following largely successful campaigns in developed countries to address the problems of poor water quality. It is hoped that this conceptual and practical re-examination will help to facilitate both interdisciplinary understanding between geomorphologists and ecologists and between scientists and managers.

RIVER CHANNEL DIMENSIONS AND FORMS: THEORY AND REALITY

Acreman (2000) has suggested that, in a systems model for managing river basins, the following core elements exist:

- Driving forces;
- Pressures;
- States;
- Impacts;
- Responses.

It has proved easier to provide both theoretical and empirical tools in the first two and final two categories in this list. System and site states have attracted much less interest because monitoring is seldom a scientific or political priority.

In fluvial geomorphology the concept of 'nice adjustment' prevailed during the early decades of quantification and there was little questioning of linear predictive models of channel state (Table 1). However, virtually no country in the world has had a monitoring system for river channel state, creating fortuitous conditions for theoreticians, especially given the traditional academic preoccupations of geomorphology. In this respect River Habitat Survey (RHS) has been of major benefit to geomorphologists in the UK, even though the aim is to record and monitor the major structural elements of physical habitat rather than the more arcane elements of fluvial geomorphology (Raven *et al*., 1998a, b). More than 5000 river sites were surveyed between 1994 and 1996 on a geographically stratified random sampling pattern of 500 m river lengths across the UK. Fortunately, RHS partly anticipated the requirements of the Water Framework Directive. The still-growing database, including a recently developed geomorphological component, will be the foundation for monitoring hydromorphological features of rivers in the UK as required by the WFD. Whilst the adequacy of the sampling programme has been the subject of many checks and trials, and the training of surveyors thorough, no geomorphological evaluation is attempted in the field. The geomorphological interpretation of RHS data is therefore heavily restricted by its content, spatial scale and spatial referencing protocols (Newson *et al*., 1998a).

Prior to the arrival of comprehensive and widespread empirical data concerning river channel state and partly as a result of the apparent power of fluvial systems predictors, applications of fluvial geomorphology occurred in an engineering framework, i.e. with the optimism that channel morphology at any location could be predicted from, for example, hydraulic geometry, an empirical form of regime theory. Deviation from theoretical states revealed by actual channel states became identified as 'instability', and causative factors (mainly human) were sought for this condition. However, by the late 1970s a school of 'channel change' studies was established (Gregory, 1977). This began to demonstrate the importance of conditioning factors for channel states at scales much smaller than the river basin. Empirical studies of channel change revealed a natural dynamism involving adjustments, often complex, as a response to both extrinsic and intrinsic, present and past factors (Schumm, 1977).

None of these studies was targeted at modified rivers and indeed the lowland channel in the UK has, with a few notable exceptions (e.g. Downs, 1992), been gravely neglected by academic geomorphological researchers — a further reason for making the maximum use of the full RHS database for both semi-natural and modified channels.

This change of conceptual viewpoint towards the 'naturalness' of channel adjustment, but the complexity of its prediction, is important in view of the demands of the WFD to describe reference (totally or nearly undisturbed) conditions for hydromorphological status. It is also highly relevant to ecosystem protection and restoration. Those seeking to protect ecosystems often exaggerate their vulnerability. River channel change studies demonstrated that river systems have resilience as well as sensitivity, especially over the longer timescales associated with sustainability concepts. Werritty (1997) has described 'robust landforms' and 'responsive landforms'. Where response occurs it is important to know the timescales involved, especially if it includes threshold phenomena that result in costly surprises to management systems (Newson, 1992). Nevertheless, 'robust' landforms also adjust. It is perhaps within this robust-responsive concept, as further developed by Brunsden (2001) and Thomas (2001), that the apparent ambivalence of academic geomorphological advice on river management lies. For example, an applied geomorphologist may easily respond effectively to a challenge to design a rehabilitation scheme for a high-profile river reach, whereas the academic viewpoint might stress the potential role of adjustment, within a system viewpoint, to deliver 'assisted natural recovery' as the most sustainable form of rehabilitation (Brookes and Sear, 1996; Newson *et al*., 2002).

TOWARDS MANAGEMENT 'TOOLS' FROM FLUVIAL GEOMORPHOLOGY

Fluvial geomorphology advocates both the systems view of river basins and the importance of smaller-scale, local contexts of sediment transport and deposition that can create chaotic, unpredictable dynamics. The discipline is experiencing a testing time in response to the modern scientific needs of sustainable river management. Research in fluvial geomorphology in the UK has been mainly limited to investigating processes and forms at small, unmodified, headwater sites; for at least three decades the investigation of process has dominated that of form. However, during the last decade, the scientific basis for the participation of geomorphologists in both river management strategies and operations has been formalized as a series of investigative procedures (Newson *et al*., 2001). Over the same period RHS surveys have established the first national inventory of field observations of river dimensions and features, although not necessarily those which can be readily input to analyses of geomorphological processes or system states (see Newson *et al*., 1998a).

These recent developments have helped towards developing appropriate geomorphological 'tools' for sustainable river management, but they are of a different character to the theoretical and quasi-empirical predictions and prescriptions offered when fluvial geomorphologists worked more in the engineering tradition of river management. The theme is now very clearly environmental and the 'tools' befit the kind of adaptive management described elsewhere in this volume by Clark (2002).

General statements of process and form

To secure the transition from research to development and implementation it is essential to establish for users the simple basic scientific principles involved. The fundamental drivers for river channel development

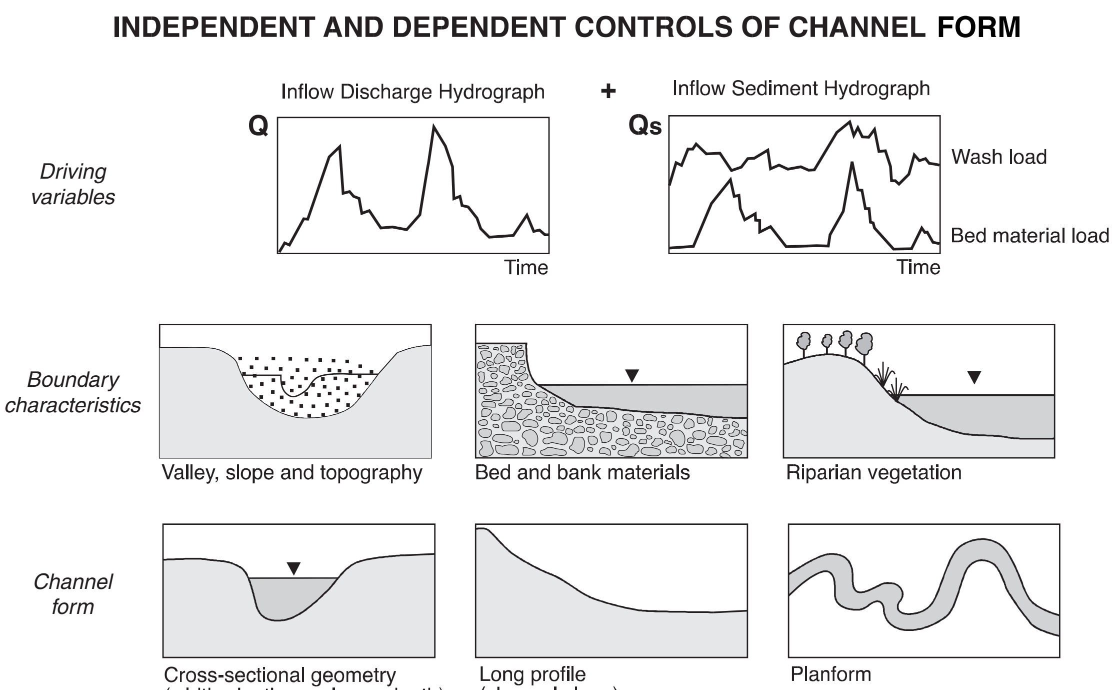

Figure 1. Drivers and boundary conditions for fluvial geomorphology, illustrating the discrepancy between the systematic interplay of flow/sediment fluxes and morphological outcomes at a site (ignoring the dimension of time). After Thorne (1997).

are derived from basic physics. A river channel exists to carry, and is adjusted to, the fluxes of water and sediments from source to sea (Thorne, 1997). However, there are immediate complications when one considers the boundary conditions that constrain these processes (Figure 1). In varied topographies and climates, these inevitably lead to widespread local deviations from Playfair's notion of 'nice adjustment'. A major boundary condition is that of local channel form and local sediment flux, neither of which exists in the continuum supposed by earlier models. For example, in terms of coarse sediment transport and deposition, Ferguson (1981) describes the fluvial sediment system as 'a jerky conveyor belt', creating adjustments at sites of temporary deprivation or supply of materials in the general flux, leading to patterns of complex response (Schumm, 1977).

Whilst the basic planform patterns for rivers, such as braided, meandering and straight channels, are relatively well understood, they only develop fully where rivers are working their own alluvium rather than deposits from ice-sheets, glaciers or even those left by rare floods. Channel dimensions can also be predicted from systems reasoning, improved by empirical survey (Hey, 1997). However, predictions can only be applied to lengths of river where the fairly simple rules implied by hydraulic geometry or regime theory are met. Not surprisingly, there is wide variability in channel dimensions in relation to formative flow values (Dangerfield, 1999), implying channel adjustment at the majority of semi-natural UK sites that possess sufficient stream power (Brookes, 1990) or where sediment budgets have significantly changed, such as downstream from dams.

As a direct result of this dynamic and often local behaviour the 'tools' most widely used by river managers, largely for flood defence and river restoration purposes, have been the empirical field survey techniques labelled Catchment Baseline Survey and Fluvial Audit (Environment Agency, 1998). 'Geomorphological Audit', developed as an extension to RHS, has also been applied at a number of sites in support of river management objectives (Figure 2). The major element of fluvial geomorphology that has reached the status of a management tool, by being incorporated in a decision-making algorithm, is in the field assessment of bank erosion problems and selection of remedies (Environment Agency, 1999). It is highly characteristic of the geomorphological approach that, amongst the remedial options for bank erosion, 'do nothing, but monitor' figures highly for environmentally sensitive sites.

Whilst the Environment Agency's publication entitled *River Geomorphology: A Practical Guide* (Environment Agency, 1998) offers managers techniques involving geomorphological theory and design these have been much less widely applied, except in the field of river restoration (Newson and Sear, 2001). Nevertheless, geomorphological advice has become a vital adjunct to engineering design and works in a wide variety of projects in the UK (Newson *et al*., 1997). Handbooks describing how geomorphology and engineering can work beneficially together are being published (e.g., Hoey *et al*., 1998).

Representing dynamic channel states

To geomorphologists investigating apparent departures from systematic behaviour of the flow-sediment-channel form system, the concept of transient behaviour has become prominent (Richards, 1987). This suggests that, at any scale of study, a river channel may be adjusting to drivers that are not locally or currently active, a situation further complicated by the reflexive relationship between process and form. As Richards (1987) puts it (p. 3):

> systems which are reacting to circumstances in which the initial conditions change faster than the processes of system adjustment, leading to transient behaviour in which feedback occurs between system state (form) variables and process variables. 'slow relaxation results in a preponderance of transient forms....prediction of behaviour based on a combination of universal (equilibrium) covering laws and sets of initial conditions will be impossible.

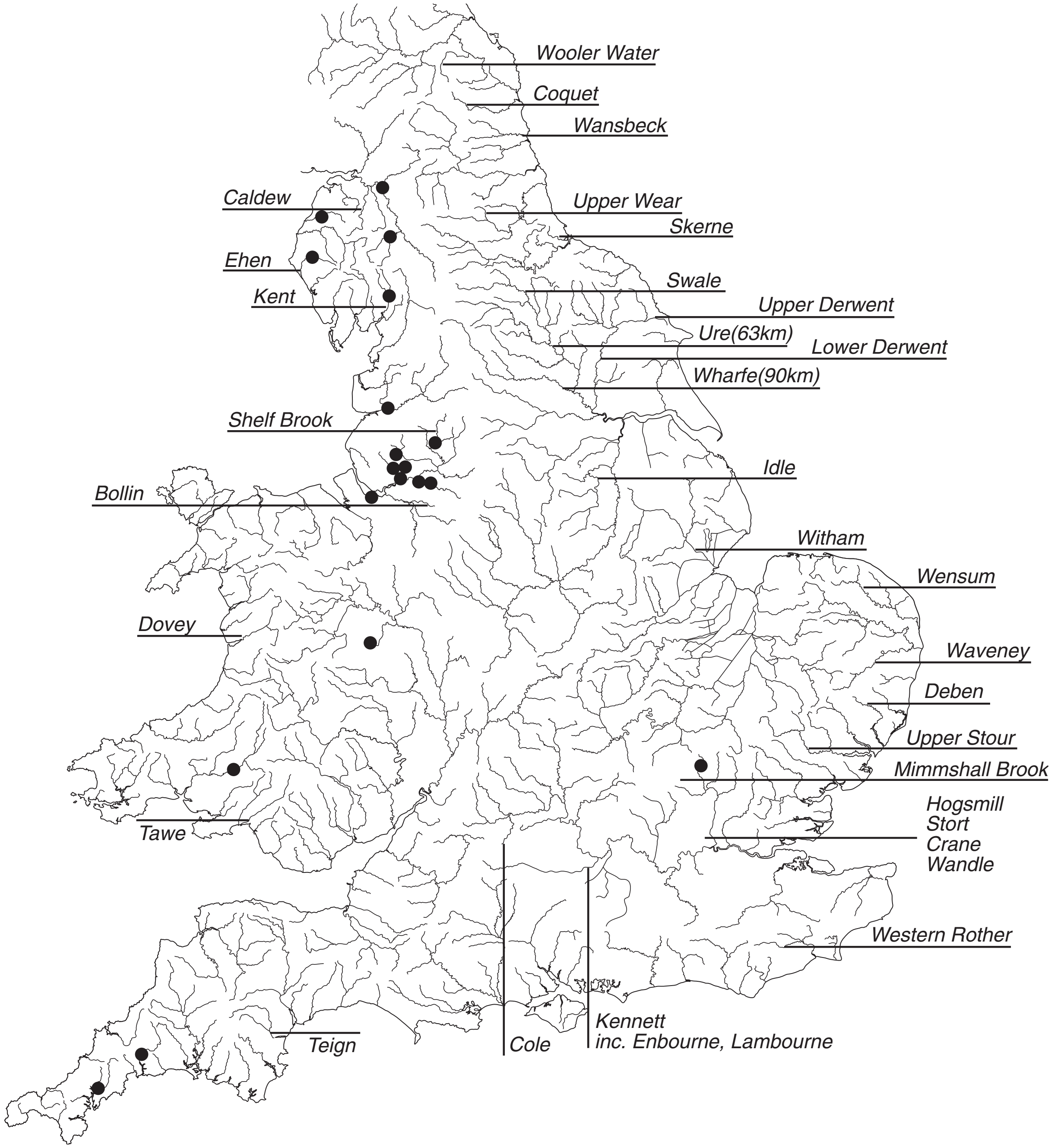

Figure 2. Rivers where empirical surveys investigating morphological system state have been undertaken in England and Wales, using Geomorphological Audit and Fluvial Audit procedures (Environment Agency, 1998). • Catchments in which environment agency has carried out 'geomorphological audits', based upon River Habitat Survey methodology

This is particularly true for channels in the UK where local boundary conditions are sufficiently important to constitute 'drivers' of channel state in their own right. For example:

- The generally low rates of catchment sediment supply to channels make local sources and tributary inputs vitally important to the transport system and, therefore, resulting channel form;
- Complex channel long-profiles have been created by glaciation and eustatic/isostatic adjustments of base level;
- Most valley floors are occupied by sediments that are not alluvial, but are glacial or periglacial, leading to river confinement or high rates of local sediment supply;
- Widespread and intensive channel modifications or flow modifications have been made in support of flood conveyance or water resource management.

The precipitation regimes that cause river floods in the UK also tend to favour a disjointed natural response by trunk streams, tributaries and slopes; Harvey's unique record of slope and channel adjustment in the Howgill Fells confirms the poorly coupled response of these systems (Harvey, 2001). Geomorphologically significant river lengths or 'reaches', those lengths characterized by sediment sources, sinks and morphology, tend to be determined mainly by tributary inputs, thus confirming the 'jerky conveyor belt' concept (Rumsby and Macklin, 1994). Rice *et al.* (2001) have described the 'link discontinuity concept' between tributaries in Canada and prove it to have significance for the distribution and abundance of benthic organisms. They refer to the need for 'zonal' approaches to river habitats, rather than 'clinal', a vocabulary that mirrors the current interest by geomorphologists in 'sites' rather than 'systems' — though clearly there is an appropriate scale for each application within river management.

The lack of success in classifying UK channels on the basis of RHS data may therefore be explained by the within-system variability of process and response and the transient nature of some channel adjustments (Newson *et al.*, 1998a). Not surprisingly it is easier to group similar 500 m survey sites in the hyperspace of multivariate analysis than in the geographical space of the same river basin (Jeffers, 1998). Clearly, however, whilst hyperspace linkages may have utility for choosing channel analogues for restoration programmes, geographical space is the more relevant to understanding the longer term adjustment process at any given site. More effort is clearly needed, using RHS and other data, to investigate the systematic variation of channel form in UK catchments. Such work may reveal classifiable forms of channel adjustment within different climatic or geology and relief regions of the UK (Dangerfield, 1999).

It has proved somewhat easier to establish typologies for river adjustment than for channel form in the UK. Brookes (1987) suggested five styles of adjustment to engineered river straightening, whilst Hooke (1997) describes styles of meander migration. At a larger scale, there have been attempts to classify adjustment in the Thames catchment (Downs, 1995; Simon and Downs, 1995). It must be emphasized that adjustment is often achieved by erosional or depositional features that may not be prominent or recordable by simple observational survey. Examples include small features such as 'inset' deposits of fines at the base of banks and subtle underwater changes in bed elevation caused by aggradation or degradation.

In both the USA and Australia, classifications of river channel type have reached the stage of application to river management. In the USA that of Rosgen (1996) has benefits for channel design by incorporating features and dimensions capable of becoming input data for predictive equations. By contrast, in Australia, the technique of describing 'River Styles' relies more heavily on empirical geomorphological survey of the basin's sediment dynamics. This is followed by a scaled, hierarchical approach to the derivation of the properties of each 'Style' (Brierley and Fryirs, 2000). Interestingly, there is a focus on channel adjustment and in this system 'natural' is defined as a channel which is 'dynamically adjusted', working within a range of 'variability set by the river style' and the 'catchment context'.

HYDRO-ECOLOGY: HYDROMORPHOLOGY AND RIVER ECOSYSTEMS

Much of the foregoing discussion of the conceptual and practical elements of fluvial geomorphology has focused on form, rather than on process. The longer timescales appropriate to a consideration of system state make this appropriate. However, the interdisciplinary relationship between fluvial geomorphology and freshwater ecology has a more dynamic focus. The dynamics of physical habitat are those of the fluctuating 'usable area' of the river bed and banks, the hydraulics of flow types, both in the flow column and in the boundary layer and the transport of substrate sediments during flood events.

A major challenge of the Water Framework Directive lies in the integration of the principles of fluvial geomorphology and freshwater ecology within the definition of 'hydromorphological status'. Some major points of contact between fluvial geomorphology and freshwater ecology have already been made but there remains a lack of joint research. Dunbar and Acreman (2001) outline the necessary and sufficient conditions for 'hydro-ecology' to flourish but conclude that 'Functional connections between disciplines (are) not yet achieved except in rare cases'.

Nevertheless, there are emerging themes in geomorphology and freshwater ecology that could provide, jointly, the basis for more effective river management 'tools'. These require the dynamic state of the physical river environment and the vital importance of scale hierarchies as a basis for understanding and predicting dynamic change. Harper and Everard (1998) express, from an ecological viewpoint, many of the characteristics of the current situation in fluvial geomorphology described above:

> rivers are dynamic ecotones, controlled by processes that operate over a range of timescales and geographic extent, and they comprise a matrix of interdependent, transient habitats. Nevertheless, management issues need to reconcile the dynamic reality of rivers.... with a structural framework for management decisions. (p. 407).

Thus, in the formulation of management tools there needs to be a compromise between an understanding of natural transience and the need for structure and 'working' scales in management, even in adaptive management situations.

Freshwater ecologists have utilized a number of the quantitative geomorphological outputs from the earlier studies of channel and network form (Table 1). For example, the River Continuum Concept was based upon Stream Order (Vannote *et al.*, 1980) and more recent habitat concepts such as patch dynamics have referred to hydraulic geometry (e.g. Stazner and Borchardt, 1994). Fluvial geomorphology has also strongly advocated the wider river habitat picture inherent in the 'fluvial hydro system' (Petts and Amoros, 1996) in four dimensions (including time) and in locations on the valley floor well beyond the channel itself. Ward *et al.* (2001) suggest that there remains almost total neglect of two spatial dimensions of river systems; (i) lateral, connecting channels to corridors and floodplains and (ii), vertical, linking to aquifers. This neglect is important for strategic river management policy because it is the high resilience of laterally connected river systems which makes them a practicable and politically defensible focus for conserving and restoring river systems. Ward *et al.* (2001) further emphasize the role of geomorphological processes (which they term 'landscape-scale ecological processes') by describing channel migration as a self-perpetuating mechanism of river restoration.

Ecologists have made progress in addressing scale dependency, but without carrying out empirical tests or employing models available from landscape ecology and spatial statistics. For example, Hildrew and Giller (1994) refine the early statements of Frissell *et al.* (1986) to incorporate the time-dependency of ecosystem process and pattern; Fisher (1994) is more cautious about 'scale-switching' in process terms but advocates pattern as a worthy surrogate for process. Habersack (2000) has suggested an analytical framework based on the 'River Scaling Concept', advocating a range of traditional and new technology methodologies for ecosystem description, prediction and monitoring. A fundamental contribution to understanding the flexibility of driving variables at various scales was provided for geomorphology by Schumm and Lichty (1965). As an interdisciplinary focus for ecology and geomorphology, the scale of process-form relationships, in both space and time, appears to be unrivalled.

Geomorphologists have begun to make a contribution at a working, meso-scale, but their 'hydromorphological' treatment of biotopes lacks the direct involvement of ecologists (Newson and Newson, 2000). Collaboration between geomorphologists and ecologists, however, often occurs 'after the event' in terms of data collection (Newson *et al.*, 1998b). Although there have been promising uses of the meso-scale habitat descriptors within the RHS database to predict the distribution of certain species (Naura and Robinson, 1998) the mantra 'morphological diversity = biodiversity' currently remains an act of faith.

CONCLUSIONS: APPLIED FLUVIAL GEOMORPHOLOGY — RESPONDING TO NEW QUESTIONS AND CONTEXTS

Twenty years ago it was extremely rare to discover channel management activity in the UK that considered the fluvial sediment system in any way whatsoever (Hydraulics Research, 1987). The system remains ignored in important current research ventures such as the Environmental Change Network (Sear and Newson, in press). Providing small amounts of illumination in complete darkness has been relatively easy for geomorphologists, but the agenda is now much more challenging. The manner in which a 'pure' science becomes adopted by practical, applied needs, changing some of the rules of scientific appraisal and shedding purely academic information in the search for 'tools' is barely understood by the sociologists of science (Ziman, 2000). Yet this process is vital to the complex and open decision-making procedures which characterize sustainable environmental management (Clark, 2002).

The author's view is that, unless the nature of the 'tools' offered by fluvial geomorphologists is understood by managers unfamiliar with the discipline, the dangers of disappointment are extremely high. Fluvial geomorphology has proved itself capable of two forms of application — as an engineering science and as an environmental science — but the two practical scenarios are completely different. The newer form of contribution, including the links to freshwater ecology, is empirical, evaluative and environmental. It is both more confident (under sustainable development protocols) about user needs and economic strictures and less certain about its predictions and prescriptions. It believes that river channel states dictate the specific applied science approach taken to each problem. When the drive for data is paramount, it is willing

Table 2. Geomorphological 'tools' for river management. Taken largely from Newson *et al.* (1997)

Issues with a geomorphological contribution	'Tools' utilized from R&D
River engineering projects	
Channel design	Cross-sectional analysis (regime), analysis of flood discharges, sediment transport.
Channel structures/crossings	Bank stability and scour analysis, meander migration.
Erosion assessment/protection	Bank stability, submerged vanes design
Maintenance of channel conveyance	Impact of engineering on adjustment, sediment transport, local sediment inputs.
Environmental management	
Impact of impoundments	Sediment transport and deposition, 'flushing flows'.
Impact of land use on sediments	Cultivation/drainage/vehicular pressure and sediment yields; analysis of historical floods.
Habitat restoration/enhancement	Fluvial Audit, assessment of 'stability', riffle-pool design, meander design.
Conservation management	Design of in-channel features and tests of flood conveyance.

to accept that intelligent clients are capable of carrying out their own surveys, despite professional worries about observations by non-experts expressed by Downs and Thorne (1996) and by McEwen *et al.* (1997).

There is no doubt that the predictive capabilities of quantitative fluvial geomorphology have reached a critical point in terms of applications for both form and process elements of the science. Table 2 lists some of these. Geomorphologists are acutely aware that their early applied experience warrants maximum attention to post-project appraisal and monitoring activity. In many applications this essential element is unfunded or neglected despite available technical guidance (Downs and Brookes, 1994; Downs, 2001). At present, the statistical confidence limits of geomorphological prediction are often represented by a precautionary approach to the spatial adjustment needs of a dynamic system. Current land management policies in the riparian zone and supporting agri-environment schemes such as Countryside Stewardship tend to favour concepts such as 'erosion belts' or riparian tree-planting, but this flexibility may be only temporary and the refinement of geomorphological predictions is a scientific obligation. Monitoring *in vivo* experiments, such as geomorphologically designed schemes of channel rehabilitation, and the ecological response, is vital to these refinements in future.

Perhaps the most misunderstood element of applied fluvial geomorphology, one that also characterizes interdisciplinary effort with freshwater ecologists, is the obsession with timescales, whilst simultaneously stressing the spatial dimension of each problem. The sediment system has memory, in other words the current observable format of the system may have been constructed by past processes. Whilst glacial and periglacial processes occurred 10–12 000 years ago, in terms of many elements of landscape they continue to define a significant group of influences on river management problems in the UK. The need for historical investigations constitutes a blind spot in the 'menu' of applied fluvial geomorphology. For example, the influence of morphologically effective floods that may have occurred decades ago is still rated low in river management circles (Wolman and Gerson, 1978; Newson, 1980). Survey and evaluation of the historical context of each basin and each site is a vital contribution from applied fluvial geomorphology, particularly in view of the climate trends for which scenarios are available.

It is strange for a science on the verge of extensive application to be stressing the need for empirical study. So extensive has been the neglect of measurements concerning the sediment system in UK rivers (Hydraulics Research, 1987) and of the resulting channel that there exists a basic need at a reconnaissance level for surveys of the fluvial sediment system, with perhaps more emphasis on stores than on fluxes. Downs and Thorne (1996) have argued that a rapid deployment of river channel reconnaissance surveys in support of river management is 'the only viable source of relevant geomorphological data' and support this by illustrating both the qualitative and quantitative results of a case study (Thorne *et al.*, 1996). The qualitative element of geomorphological 'tools' is essential as it 'rests on the interpretation of process from form using careful observation across the whole system, together with the application of well-established geomorphological principles' (Thorne *et al.*, 1996, p. 469). Public policy in the UK is more comfortable with empirical data as a basis for management 'tools' and might claim to have benefited for decades from engineering experience in the design of flood channels and erosion protection works (Hemphill and Bramley, 1989). As such, availability of recent survey data from both Fluvial Audits and from RHS surveys is a very positive and direct 'tool' for applications if the information is couched in the framework of decision-making management.

It is not the role of this paper to catalogue the past and present applications of fluvial geomorphology in river management; such work is currently under way as part of government-sponsored Research and Development in the form of a guidebook of applied geomorphology. Nevertheless, the simplest and shortest contribution may be that of definition. Table 3 offers a tentative framework to support important definitions of river channel scale and state of relevance to the practical outcomes of the EC Water Framework Directive.

The emphasis on ecosystem protection and, *inter alia*, strong sustainability in the Directive means that evaluation of river physical habitat will require the kind of expansion of field data collection typified by

Table 3. Definitions as 'tools' — suggestions for geomorphological interpretation of 'hydromorphological status in the Water Framework Directive relevant to the UK

Terminology	Suggested geomorphological description for UK rivers
Reach	Length of river in which channel dimensions and features relate characteristically to identifiable sediment sources and sinks. Reaches may be demarcated by tributary inputs under certain conditions of climate, river regulation and land use.
Stable (i.e. channel planform/elevation)	Essential to differentiate between engineering concepts of stability, legal/popular interpretation and natural resilience or 'robust' behaviour. Geomorphological stability incorporates adjustments, short of threshold behaviour, that can be predicted from assessment of channel 'styles'.
Reference conditions (or 'natural')	Rivers with planform/sectional geometry and features which represent the full interplay of water and sediment fluxes with local boundary conditions. 'Natural' rivers are free to adjust their form and features (by aggradation/degradation and lateral migration across floodplain/valley floor) to both system-scale drivers and local conditions. 'Natural' rivers, therefore, provide a diverse physical habitat in both space and time.
Heavily modified rivers	Rivers which, through human modification or repeated actions, are constrained in their direction/rate of adjustment and diversity of features, frequently to the extent that they create a geomorphological hiatus in the flow/sediment system, causing upstream or downstream impacts or both. Depending on system location and conditions they may recover if human action is ceased or modified.

current proposals for building on the core RHS method so as to include system 'state' at a variety of scales. This would involve both quantitative information on extrinsic 'drivers' such as: (i) sediment flux, not measured routinely by hydrometric networks in the UK and impossible to include in RHS, and (ii) the role of boundary conditions, including intrinsic drivers at successively smaller spatial scales. Such a programme could usefully incorporate both the broader ecological definition of river system as the fluvial hydro-system and elements of ecological survey at the 'physical biotope' scale.

Realistically, we have only a moderate proportion of the intellectual and financial resources needed to satisfy the clients for applied fluvial geomorphology within the short timescales available for providing ideal predictive, prescriptive and precautionary options for sustainable management of rivers. Therefore existing protocols and platforms such as RHS, although not originally designed to expand the predictive capacity of fluvial geomorphology and freshwater ecology, must be modified where possible to yield the best available knowledge. There are huge opportunities to incorporate technological innovation in the form of remote sensing data including remote satellite and aircraft platforms and ground survey techniques. Our ability to measure form has virtually overtaken our ability to measure process; the cost-effectiveness of surveying and monitoring is growing and there are resulting opportunities to embark on new empirical science agendas linking ecosystem with human needs for a fresh approach to rivers. There are currently encouraging signs that such research developments are under way.

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REFERENCES

Acreman MC (ed.). 2000. The changing hydrology of the United Kingdom. In *The Hydrology of the UK: A Study of Change*. Routledge: London; xxvii–xxxi.

Brierley GJ, Fryirs K. 2000. River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management* **25**: 661–679.

Brookes A. 1987. The distribution and management of channelized streams in Denmark. *Regulated Rivers, Research and Management* **1**: 3–16.
Brookes A. 1990. Restoration and enhancement of engineered river channels: some European experiences. *Regulated Rivers: Research and Management* **5**: 45–56.
Brookes A. 1995. Challenges and objectives for geomorphology in UK river management. *Earth Surface Processes and Landforms* **20**: 593–610.
Brookes A, Sear DA. 1996. Geomorphological principles for restoring channels. In *River Channel Restoration: Guiding Principles for Sustainable Projects*, Brookes A, Shields FD (eds). John Wiley: Chichester; 75–101.
Brunsden D. 2001. A critical assessment of the sensitivity concept in geomorphology. *Catena* **42**: 99–123.
Clark MJ 2002. Dealing with uncertainty: adaptive approaches to sustainable river management. *Aquatic Conservation: Marine and Freshwater Ecosystems* **12**: 347–363.
Dangerfield HR. 1999. A study of channel geometry-discharge relationships in semi-natural rivers as a basis for river restoration and management. Unpublished PhD thesis, Queen Mary and Westfield College, University of London.
Downs P. 1992. Spatial variations in river channel adjustments: implications for channel management in South-East England. Unpublished PhD thesis, University of Southampton.
Downs P. 1995. Estimating the probability of river channel adjustment. *Earth Surface Processes and Landforms* **20**: 687–705.
Downs P. 2001. Geomorphological evaluation of river restoration schemes: principles, method, monitoring, assessment, evaluation. Progress? In *River Restoration in Europe — Practical Approaches,* Nijland HJ, Cals MJR (eds). Institute for Inland Water Management and Waste Water Treatment/RIZA. Lelystad, The Netherlands; 243–249.
Downs P, Brookes A. 1994. Developing a standard geomorphological approach for the appraisal of river projects. In *Integrated River Basin Development*, Kirby C, White WR (eds). John Wiley: Chichester; 299–310.
Downs P, Thorne CR. 1996. A geomorphological justification of channel reconnaissance surveys. *Transactions of the Institute of British Geographers* **NS21**: 455–468.
Dunbar M, Acreman MC. 2001. Applied hydro-ecological science for the 21st century. In *Hydro-ecology: Linking Hydrology and Aquatic Ecology*, Acreman MC (ed.). IAHS Publication 266: Wallingford; 1–17.
Environment Agency. 1998. River geomorphology: a practical guide. Guidance Note 18, National Centre for Risk Analysis and Options Appraisal: London.
Environment Agency. 1999. Waterway bank protection: a guide to erosion assessment and management. R&D Project W5–635, Bristol.
European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23rd October 2000: establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* **L327**: 1–72.
Ferguson RI. 1981. Channel form and channel changes. In *British Rivers*, Lewin J (ed.). Allen and Unwin: London; 90–125.
Fisher SG. 1994. Pattern, process and scale in freshwater systems: some unifying thoughts. In *Aquatic Ecology: Scale, Pattern and Process*, Giller PS, Hildrew AG, Rafaelli DG (eds). Blackwell: Oxford; 575–591.
Frissell CA, Liss WJ, Warren CJ, Hurlet MD. 1986. A hierarchical framework for stream habitat classification. Viewing streams in a watershed context. *Environmental Management* **10**: 199–214.
Gregory KJ (ed.). 1977. *River Channel Changes*. John Wiley: Chichester.
Habersack HM. 2000. The river-scaling concept (RSC): a basis for ecological assessments. *Hydrobiologia* **422/423**: 49–60.
Harper D, Everard M. 1998. Why should the habitat-level approach underpin holistic river survey and management? *Aquatic Conservation: Marine and Freshwater Systems* **8**: 395–413.
Harvey AM. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena* **42**: 225–250.
Hemphill RW, Bramley ME. 1989. *Protection of River and Canal Banks*. Butterworths: London.
Hey RD. 1997. Stable river morphology. In *Applied Fluvial Geomorphology for River Engineering and Management*, Thorne CR, Hey RD, Newson MD (eds). John Wiley: Chichester; 223–236.
Hildrew AG, Giller PS. 1994. Patchiness, species interaction and disturbance in the stream benthos. In *Aquatic Ecology: Scale, Pattern and Process*, Giller PS, Hildrew AG, Rafaelli DG (eds). Blackwell: Oxford; 21–62.
Hoey TB, Smart DWJ, Pender G, Metcalfe N. 1998. Engineering methods for Scottish gravel-bed rivers. Scottish Natural Heritage Review 47, Edinburgh.
Hooke JM. 1997. Styles of channel change. In *Applied Fluvial Geomorphology for River Engineering and Management*, Thorne CR, Hey RD, Newson MD (eds). John Wiley, Chichester; 237–268.

Horton RE. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* **56**: 275–370.

Hydraulics Research. 1987. Morphological effect of river works. A review of current practice. Report SR116, Wallingford.

Inglis CC. 1949. The behaviour and control of rivers. Research Publication 13, Irrigation Board, Poona, India.

Jeffers JNR. 1998. Characterization of river habitats and prediction of habitat features using ordination techniques. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**: 529–540.

Leopold A. 1949. *A Sand County Almanac*. Oxford University Press: Oxford.

Leopold LB, Maddock T. 1953. The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey Professional Paper 252, Washington, DC.

Leopold LB, Wolman MG. 1957. River channel patterns: braided, meandering and straight. United States Geological Survey Professional Paper 282B, 39–85, Washington, DC.

Marchand M, Toornstra FH. 1986. Ecological guidelines for River Basin development. Centrum voor Mileukunde, Rept. 28, Rijksuniversiteit, Leiden.

McEwen LJ, Brazier V, Gordon JE. 1997. Evaluating the geomorphology of fresh waters: an assessment of approaches. In *Freshwater Quality: Defining the Indefinable?* Boon PJ, Howell DL (eds). Stationery Office: Edinburgh; 258–281.

Melton MA. 1958. Correlation structure of morphometric properties of drainage systems and their controlling agents. *Journal of Geology* **66**: 442–460.

Naura M, Robinson M. 1998. Principles of using River Habitat Survey to predict the distribution of aquatic species: an example applied to the native white-clawed crayfish *Austropotamobius pallipes*. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**: 515–527.

NERC. 1975. *Flood Studies Report*. Natural Environment Research Council: London.

Newson MD. 1980. The geomorphological effectiveness of floods. *Earth Surface Processes* **5**: 1–16.

Newson MD. 1992. Geomorphic thresholds in gravel-bed rivers. In *Dynamics of Gravel-bed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). John Wiley: Chichester; 3–20.

Newson MD. 1997. *Land, Water and Development: River Basins and their Sustainable Development*, 2nd edn. Routledge: London.

Newson MD, Hey RD, Bathurst JC, Brookes A, Carling PA, Petts GE, Sear DA. 1997. Case studies in the application of geomorphology to river management. In *Applied Fluvial Geomorphology for River Engineering and Management*, Thorne CR, Hey RD, Newson MD (eds). John Wiley: Chichester; 311–363.

Newson MD, Clark MJ, Sear DA, Brookes A. 1998a. The geomorphological basis for classifying rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**: 415–430.

Newson MD, Harper DH, Padmore CL, Kemp JL, Vogel B. 1998b. A cost-effective approach to linking habitats, flow types and species requirements. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**: 431–446.

Newson MD, Newson CL. 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography* **24**: 195–217.

Newson MD, Sear DA. 2001. Geomorphological procedures and river restoration: science, survey and sustainability. In *River Restoration in Europe — Practical Approaches*, Nijland HJ, Cals MJR (eds). Institute for Inland Water Management and Waste Water Treatment/RIZA: Lelystad, The Netherlands; 251–253.

Newson MD, Thorne CR, Brookes A. 2001. The management of gravel-bed rivers in England and Wales: from geomorphological research to strategy and operations. In *Gravel-Bed Rivers V*, Mosley MP (ed.). New Zealand Hydrological Society: Wellington; 581–606.

Newson MD, Pitlick J, Sear DA. 2002. Running water: fluvial geomorphology and river restoration. In *Handbook of Ecological Restoration,* Perrow M (ed.). Cambridge University Press: Cambridge.

Pearce D (ed.). 1993. *Blueprint 3: Measuring Sustainable Development*. Earthscan: London.

Petts GE, Amoros C. 1996. *Fluvial Hydrosystems*. Chapman & Hall: London.

Playfair J. 1802. *Illustrations of the Huttonian Theory of the Earth*. William Creech: Edinburgh.

Raven PJ, Holmes NTH, Dawson FH, Fox PJA, Everard M, Fozzard IR, Rouen KJ. 1998a. River Habitat Quality: the physical character of rivers and streams in the UK and Isle of Man. River Habitat Survey Report No. 2, Environment Agency, Bristol.

Raven PJ, Holmes NTH, Dawson FH, Everard M. 1998b. Quality assessment using River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems* **8**: 477–499.

Rice SP, Greenwood MT, Joyce CB. 2001. Tributaries, sediment sources and the longitudinal organisation of macroinvertebrate fauna along river systems. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 824–840.

Richards KS. 1987. Rivers: environment, process and form. In *River Channels: Environment and Process*, Richards KS (ed.). Blackwell: Oxford; 1–13.

Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology: Pagova Springs, CO.

Rumsby BT, Macklin MG. 1994. Channel and floodplain response to recent abrupt climate change: the Tyne basin, northern England. *Earth Surface Processes and Landforms* **19**: 499–515.

Schumm SA. 1963. Sinuosity of alluvial rivers on the Great Plains. *Geological Society of America Bulletin* **74**: 1089–1110.

Schumm SA. 1977. *The Fluvial System*. John Wiley: New York.

Schumm SA, Lichty RW. 1965. Time, space and causality in geomorphology *American Journal of Science* **263**: 110–119.

Sear DA, Newson MD. (in press). River channel change: a neglected element of environmental change monitoring. *Science of the Total Environment*.

Simon A, Downs P. 1995. An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology* **12**: 215–232.

Statzner B, Borchardt D. 1994. Longitudinal patterns and processes along streams: modelling ecological responses to physical gradients. In *Aquatic Ecology: Scale, Pattern and Process*, Giller PS, Hildrew AG, Raffaelli DG (eds). Blackwell: Oxford; 113–140.

Thomas MF. 2001. Landscape sensitivity in time and space — an introduction. *Catena* **42**: 83–98.

Thorne CR, Hey RD, Newson MD (eds). 1997. *Applied Fluvial Geomorphology for River Engineering and Management*. John Wiley: Chichester.

Thorne CR. 1997. Channel types and morphological classification. In *Applied Fluvial Geomorphology for River Engineering and Management*, Thorne CR, Hey RD, Newson MD (eds). John Wiley: Chichester; 175–222.

Thorne CR, Allen RG, Simon A. 1996. Geomorphological river channel reconnaissance for river analysis, engineering and management. *Transactions of the Institute of British Geographers* **NS21**: 469–483.

Vannote RL, Minshall GW, Cummins KW, Sedell JW, Cushing CE. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 130–137.

Ward JV, Tockner K, Uehlinger U, Malard F. 2001. Understanding natural patterns and processes in river corridors as the basis for effective river restoration. *Regulated Rivers: Research and Management* **17**: 311–323.

Werritty A. 1997. Short-term changes in channel stability. In *Applied Fluvial Geomorphology for River Engineering and Management*, Thorne CR, Hey RD, Newson MD (eds). John Wiley: Chichester; 47–65.

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

Ziman J. 2000. *Real Science. What it is and What it Means*. Cambridge University Press: Cambridge.

