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Integrating Geomorphological Tools in Ecological and Management Studies

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21.1 INTRODUCTION

Fluvial geomorphology can be useful to other disciplines, such as ecology (e.g., to provide a framework within which to analyze habitats) and engineers, as well as practitioners, such as planners and river managers (e.g., to understand risks and effects of flooding, or to regulate instream gravel extraction), and those who implement ecological restoration programs (e.g., through insights into the functioning of former ecosystems and constraints posed by human alterations). Geomorphological questions posed by other scientists and practitioners are often complex and merit being subdivided into a set of more specific questions. The physical, chemical, and biological interactions in river systems operate at multiple temporal and spatial scales implying that to understand relations or to solve problems typically requires application of multiple tools. Some of these tools are proper to geomorphology, while others were developed in allied fields (such as biology or engineering sciences) and are applied to geomorphological problems. These tools range widely in the temporal and spatial scales of application, from a few minutes or hours (the duration of the bedload movement during a flood event) to several centuries (the time needed for a fluvial system to adjust its geometry to a climate change), and from centimeters (benthic invertebrate habitat) to thousands of square kilometers (large river catchments).

Through the range of tools presented in this book, we have sought to provide a reference not only for the practicing geomorphologist and graduate student, but also to provide the manager and scientist working with geomorphologists with an idea of the range of approaches potentially available to address fluvial geomorphic problems. The purpose of this chapter is to provide a framework within which the tools can be used, and to present examples of application of geomorphic tools to problems in river management and restoration.

21.2 MOTIVATIONS FOR APPLYING FLUVIAL GEOMORPHOLOGY TO MANAGEMENT

"It should be possible to persuade decision-makers that incorporating historical or empirical geomorphic information into river management strategies is at least as valuable as basing decisions on precise, yet fallible mechanistic models" (Rhoads 1994). This statement captures the sense of potential for applied fluvial geomorphology that rose in concert with growth in environmental awareness and political will to recognize and account for the environment in land and water management. Since the late 1980s, applied fluvial geomorphology has risen up the operational and policy agendas of river management authorities, most recently propelled by the demands for "morphological" assessment in support of river restoration (Sear *et al.* 1995, Brookes and Shields 1996).

With increasing emphasis on environmental river management and interest in sustainable approaches to use of water (and other natural) resources, managers must base their decisions on insights from a variety of disciplines. Because fluvial geomorphology provides the overall framework within which habitats develop, ecological processes operate, floods propagate, and waters may (or may not) undergo purification en route to the river and downstream, geomorphological analyses are central to understanding many issues in river management, including maintenance and restoration of aquatic and riparian habitat, flood risk, and water quality. Specifically, fluvial geomorphologists are increasingly called upon to answer questions at different temporal and spatial scales than other disciplines have typically employed. Graf (1996) describes this recent resurgence of geomorphological application as the "return to its roots of a close association with environmental resource management and public policy", arguing that geomorphology is now mature enough after a period characterized by a focus on basic research, to begin applying this collective wisdom to issues of social concern.

The upsurge in the application of geomorphology has also been driven by the recognition of the costs, financial as well as environmental, of ignoring natural system processes and structure in river channel management (Gilvear 1999). Legislative and economic drivers aimed at reversing a trend of ecological degradation have begun to transform the way many agencies approach intervention in river systems. But as Newson (1988) has made clear, translation of science into policy frequently has long lead times, and uptake of policy at the operational level is probably much longer again. Furthermore, the trigger for any particular phase of uptake may be an externally imposed policy shift, which invites a subsequent scientific input, rather than a science advance that demands policy modification. The recent policy emphasis on sustainable river channel management (Raven *et al.* 2002) exemplifies a shift of stance driven by political pressure rather than scientific logic. Nevertheless, statutory requirements to take regard for "physiographic features" or "hydromorphology" (note the emphasis on the static descriptive nature of "geomorphology" in legislation, which lags 30–40 years behind the shift away from this position in the discipline) and the ecological integrity of river systems have focused attention on their natural form and function. Most recently, the rise of physical habitat restoration has provoked new research initiatives among engineers focusing on the hydraulic functions of river channel features, whilst ecologists are increasingly recognizing the value of geomorphology in describing and accounting for the habitat structure of aquatic systems (Jeffers 1998, Newson *et al.* 1998a, Newson and Newson 2000).

21.3 CHALLENGES FOR GEOMORPHOLOGISTS IN EMBRACING APPLIED QUESTIONS

The potential contribution of geomorphology to river channel management has yet to be fully realized, for four main reasons:

1. The awareness of the subject among the public and other environmental and engineering sciences is low. Whilst most people have heard of geologists and engineers, few (at least in Europe) have heard of geomorphologists! Public perception is misinformed, since geomorphology is often seen as an academic and descriptive discipline rather than a management-oriented predictive science. Graf (1996) argues that the acceptance of geomorphological research by society assists adoption among management authorities.
2. It has been difficult for geomorphology to establish its position within existing management structures. Where should it fit as an operational discipline? This is a management issue as much as a technical problem. In the UK, a management context could be suggested for fluvial geomorphology in association with either engineering or conservation—arguments for both are strong. The challenge is one of chronology rather than function, and does not imply that geomorphology is more or less ambiguous than other operational components. New elements imposed on existing management structures always struggle for assimilation.
3. The cost–benefit models (or other economically based option appraisal devices) used for project justification tend to undervalue or ignore the longer-term benefits provided by geomorphological contributions.
4. There is a relative lack of specialists prepared to apply the science in some countries. This is partly a reflection of inappropriate training curricula in the disciplines concerned, and partly an indication that a lack of perceived professional need militates against recruitment in the area concerned. Geomorphological programs in most universities are relatively small components of geological or geographical departments, and the number of students produced has historically not been large. Moreover, until quite recently, most academic fluvial

geomorphologists have focused on theoretical or historical questions rather than applied problems, and have historically made little effort to make their work accessible to other fields or applicable to practical problems.

21.4 MEETING THE DEMAND: GEOMORPHOLOGICAL TRAINING AND APPLICATION

As river managers and other scientific disciplines recognized a need for geomorphological input over the past two decades, the established field of geomorphology was not prepared to meet the demand. Instead, much of this demand was met by non-geomorphologists with little academic training (at least in geomorphology), and frequently using what might be termed "shortcuts". For example, non-geomorphologists have based channel reconstructions on relations between channel width and meander wavelength, and on predictions of "stable" channel configuration derived from a classification scheme, instead of undertaking a historical–geomorphological study of the river under consideration. Although these applications are often termed "geomorphically based", they lack an understanding of basin-scale influences or even channel-level process interactions that actually determine the success of the intervention (Sear 1994). Moreover, they typically involve applications of only the (limited) tools with which the non-geomorphologist has been exposed.

A "cookbook" approach to restoration, involving application of the channel classification system of Rosgen (1994), has proved enormously popular among managers and other non-geomorphologists in the US. In part, this has been because of the availability of one-week training courses where managers and staff learned the system, becoming overnight experts and apparently obviating the need for detailed geomorphic studies, and apparently satisfying the demand for integration of geomorphology into river management (Kondolf 1995). Most river restoration projects designed in this way have never been objectively evaluated, but of those that have undergone post-project appraisal, the track record has included a high proportion of failures (Smith 1997, Kondolf *et al.* 2001, also see Chapter 7, this volume).

More recently, academically trained geomorphologists have responded to the demand from managers by evolving classification and design methods using the basic research within the discipline (Fryirs and Brierley 1998, Newson *et al.* 1998a,b), and by conducting post-project appraisals of restoration as a basis for improving future designs (Downs and Kondolf 2002). The challenge remains, however, to educate a broad section of society as to the existence of the field and its real potential contributions to the management of rivers (Brookes 1995, Kondolf and Larson 1995), and to communicate to practitioners alternative approaches to the cookbook methods so popular now. Wilcock (1997) observed that while the scientific community has criticized restoration projects whose failures could be attributed to lack of substantial geomorphic study:

> Practitioners may be inclined to dismiss criticism from those who do not leave their handiwork on the landscape ... This view, however, misses the point that the job of science is not to address particular cases, but to find the general principles that apply to all cases. Also, it is likely that much of the criticism is basically correct (given the advantage of hindsight). The problem is not faulty criticism, nor that scientists do not have the right to criticize. The problem is that the critique is ineffective, if effectiveness is measured in terms of injecting better ideas and reliability into practice ... To be heard, the scientific community must come up with a message that is not only correct, but also simple, direct, and coherent. (Wilcock 1997: 454)

When we assess the performance of restoration projects designed and implemented by professionals without a solid background in fluvial geomorphology, we see that commonly the designers have not recognized basic but important controls on channel form, such as legacy effects of mining or flood control efforts, changed sediment supply from the catchment, or even the implications of the position of the reach within the larger drainage network (e.g., depositional reaches at the transition from piedmont uplands to coastal plain along the Atlantic Seaboard of the US). Reading the written justifications for such projects, it is clear that one of the shortcomings of the lack of substantive training is that one neither tends to ask the right questions, nor to use the full range of tools available. With limited training, one is likely to approach every problem in essentially the same way, and one is unlikely to step back from the manager's immediate concern (be it with bank erosion or degradation of fish habitat) to redefine the problem in terms of longer-term and catchment-scale processes that may be the underlying cause of the perceived reach-level problem. The advantages of taking a larger-scale geomorphic approach are illustrated in case studies presented in this chapter.

21.5 INTERACTIONS BETWEEN GEOMORPHOLOGISTS, STAKEHOLDERS AND RIVER MANAGERS

Interactions between geomorphologists (and for that matter, scientists in general) and managers can be tricky, because the goals and methods of operation of the two groups are frequently at odds. To get past the traditional behavioral and institutional barriers may require that each makes efforts to understand the perspective of the other. Managers and geomorphologists often approach problems in very different ways, as reflected in their different attitudes to issues such as uncertainty, the timescale of problem definition (managers typically being concerned with shorter timescales than the geomorphologists), the timescale within which an answer is desired, the spatial scale of problem definition (managers typically taking a site-specific view as opposed to the catchment-scale view needed to understand many geomorphic processes), and willingness to invest in substantive studies by qualified technical personnel.

Interactions between scientists and managers have been further complicated by the emergence in recent years of participation in decision-making by stakeholders and the public in general. Overall, this has probably been a good thing, as decision-makers are less likely to make unilateral decisions that run counter to local interests, but it poses an interesting challenge to geomorphologists, who must now communicate not only with elected officials and appointed administrators, but also with members of the public, whose scientific backgrounds and ability to understand sometimes complex interactions may vary widely. For the geomorphologists, this puts a premium on effective communication (public education). It has also created situations in which members of the public and interest groups have *voted* on what are essentially scientific questions. This perhaps is not very different from juries deciding questions of fact in legal cases that involve expert witness testimony, but it has resulted in some strange (at least to a trained scientist) conclusions being drawn.

As described by Wilcock *et al.* (2003), increasing use of models as a basis for decisions in natural resource management has led to more frequent interactions between managers and modelers in fluvial geomorphology, and these interactions have highlighted differences in objectives between managers and modelers. "The policy or legal context [may demand] a precision in model predictions that the available knowledge cannot support", such as the requirement of water law in states of the western US that in-stream water users claim only the minimum flow needed for a purpose, such as maintenance of channel form. Conflict may also arise between managers and modelers because management questions may require predictions that are more temporally and spatially explicit than possible or practical (Wilcock *et al.* 2003). However, models can serve useful functions besides prediction: "to educate managers about the ecosystem, to identify gaps in the current knowledge, to allocate scarce research dollars for future work, and to define plausible management scenarios that merit further evaluation" (Wilcock *et al.* 2003). For example, in framing the range of possible dam operation alternatives along the Colorado River below Glen Canyon Dam and their potential effect on a multitude of resources (ranging from extent of sand beaches to hydropower generation to native fish), models cannot produce specific predictions, but can increase understanding of how parts of the system work together (Schmidt *et al.* 1998, Wilcock *et al.* 2003).

Most rivers have been affected by human intervention to one degree or another, so their current conditions result from the interplay of the river and social systems (Figure 21.1). Within the river system, flow regime (Q) and sediment load (Q_s) from the basin are the independent variables that largely determine alluvial channel form, as reflected in the adjustment of dependent variables of width, depth, grain size, and pattern. This simple system can be made more complex by adding the biological and chemical elements and their relationships with the geomorphic elements. Human activities (a function of the social system) can affect both the independent variables (e.g., through urbanization and flashier runoff) and the channel form directly (e.g., by channelization, or in-channel sand and gravel mining), with resulting effects on water chemistry and aquatic and riverine ecology. Because rivers are dynamic systems, such actions typically beget reactions, such as channel incision, which in turn can affect human infrastructure or other uses (e.g., through undermining bridges and pipeline crossings) (Bravard *et al.* 1999). In response to such negative feedback from the river system, the social system tends to respond with countermeasures such as structures to control erosion of bed and banks, which in turn may produce further erosion elsewhere in the channel.

Although we speak here of the social system as a single entity, in reality, the human actors or "stakeholders" range widely in interests, motivation, and

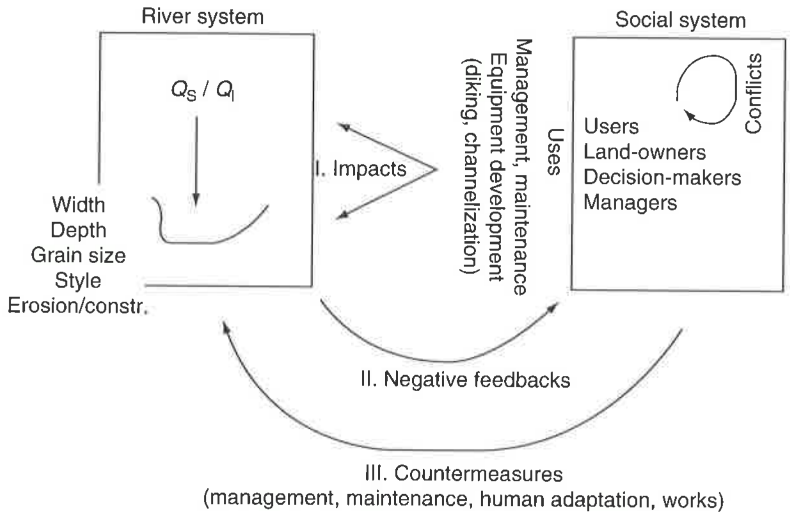

Figure 21.1 Interactions between the geomorphological river system and the social system: impacts, negative feedbacks, and countermeasures

power. Landowners, recreational users, resource managers, and elected decision-makers can act and react at different spatial and temporal scales, sometimes in complete contradiction to one another. Some conflicts occur on many rivers, such as those between canoeists and fishers, between hydroelectric companies and fish and wildlife agencies, between managers of upstream reaches and managers of downstream reaches, and between regional and local planners. Each has specific objectives and stakes, which may conflict with others.

In this environment, fluvial geomorphologists must pursue the science and encourage participatory planning and management to diagnose problems and propose solutions so they can be understood by the broadest community of actors. Applied fluvial geomorphic questions can generally be classed as relating to (I) impacts of human development on the river system, (II) the response of the river system to these human influences, or (III) the countermeasures taken by human actors to deal with the river response to development. The success of the solutions proposed will depend in large measure on how the geomorphologist interacts with the social system. At level II, it is essential for them to interact with other disciplines such as ecology, economy, and history to show the cascading consequences of geomorphological adjustments or functioning in terms of biodiversity or financial fluxes as well as job provided or lost. At level III, scenarios must be generated to project not only the river's geomorphologic response, but also resulting natural hazards, resource availability, user satisfaction, and sustainable development at the basin scale. Otherwise, the solutions proposed may be effective only at a short timescale.

Applied fluvial geomorphology is now called on to evaluate the river system's function, sensitivity to change, and its ecological potential. These concerns have arisen because the river is increasingly viewed as dynamic and supporting a variety of resources, and has to be managed sustainably to continue providing those resources. A sampling of such questions and concerns is presented in Table 21.1, and the case studies in this chapter. One class of questions asks: "How does the river work?" This question is typically posed by users who want to know if a projected action may trigger unwanted responses. Another class of questions asks: "Where is the river going?" This is typically posed to understand the consequences of ongoing river adjustments to past interventions. A final class of questions, "How can we improve the state of the river?", encompasses questions related to sustainable river management and restoration.

21.6 COMPONENTS OF GEOMORPHOLOGICAL STUDIES IN RIVER MANAGEMENT

An assessment of current geomorphological practice suggests that fluvial geomorphology provides management information in four key areas:

Table 21.1 Examples of geomorphological questions posed to help end-users such as aquatic ecologists or natural resources managers to answer their questions

Geomorphological questions	Reasons why geomorphological questions posed	End-users	Examples
How does the river work? Assessment of on-going processes and forms			
What is (or what will be if . . . ?) the sediment transport in a given reach?	Rate of reservoir filling	Water resource managers	Polish Carpathians (Lajczak 1996)
	Flooding frequency increase	Risk managers	Waiho fan, New Zealand (Davies and McSaveney 2001)
	Gravel resource availability	Gravel miners, regulators	Rhône River, France (Petit *et al.* 1996)
What is the sensitivity of the river system to any modifications of runoff and sediment load?	Assess possible consequences of development	Natural resource managers, developers	Streams in Washington state (Moscrip and Montgomery 1997)
How do former river channels (e.g., oxbow lakes) vary in terms of sedimentation rate and geometry in a given reach?	Vegetation diversity and successional rates, lifespan of given states	Landscape ecologists, environmentalists	Ain River corridor, France (Piégay *et al.* 2000)
Where the river is going? Assessment of human impacts at various spatial and temporal scales			
What is the impact of a dam on the sediment transport and channel form downstream?	Changes in fish habitat	Aquatic ecologists, fisheries agencies	North Tyne: hydropower regulation impacts on spawning riffles and channel geometry (Sear 1995)
	Changes in channel geometry (narrowing, incision, aggradation)	Manager of natural hazard (flooding)	Hanjiang River, China (Xu 1997)
	Changes in vegetation mosaic in the riparian zone	Landscape/aquatic ecologists and environmentalists	Large dammed rivers in USA (Collier *et al.* 1996)
Have past human actions (e.g., engineering works/mining) induced channel changes downstream?	Increase in channel instability	Land managers	Action of river maintenance activities in the UK rivers (Sear *et al.* 1995)
	Geometry adjustment	River managers	Californian rivers (Kondolf 1997); rivers of England and Wales (Brookes 1987)
	Effects on biological communities	Ecologists, environmental planners	Redwood Creek Basin, Northwestern California (Ricks 1995); Pennsylvania streams (Wohl and Carline 1996)

What is the magnitude of current and potential channel incision following channel straightening or mining?	Sensitivity of bridges to undermining	Civil engineers	Streams in southern US (Simon and Downs 1995)
	Drop in groundwater	Aquatic ecologists, agriculture and water resource managers	Coal Creek, Colorado (Scott *et al.* 1999)
What is the effect of an in-channel mining site on the bedload transport?	Beach degradation downstream	Land managers, engineers	Fiume Seccu and Figarella in Corsica (Gaillot and Piégay 1999)
	Fish habitat degradation	Aquatic ecologists	Wooler water—massive channel incision (Sear and Archer 1998)
What are the effects of catchment afforestation/deforestation?	Channel geometry and associated flooding risks and bank erosion	Managers of natural hazards (flooding)	Conifer afforestation in upland humid temperate climates (Newson and Leeks 1987)
How can we improve the state of the river? Sustainable management and restoration			
What are the effects of restoration practices?	Monitoring	Planners and managers	Lowland UK rivers (Sear *et al.* 1998)
What are the channel types at the regional/national scale?	Monitoring	Planners	UK/France channel classifications (Newson *et al.* 1998a,b, Raven *et al.* 2002; Chapter 7, this volume)
What are the best maintenance practices to balance flood hazard and natural quality?	Mitigate regulation/maintenance practices	Managers, environmentalists	Sustainable river maintenance procedure for the UK rivers (Sear *et al.* 1995); French guidelines for riparian forest maintenance (Boyer *et al.* 1998). Danish streams (Iversen *et al.* 1993)
What are the geomorphological designs to promote on a given site?	Improve the landscape and ecological integrity	Managers, environmental planners	Mimmshall brook (Sear *et al.* 1994); Mississippi streams (Shields *et al.* 1995)
What is the lifespan of a given restored habitat (gravel bar)?	Aquatic habitat monitoring	Managers, environmental planners	Kissimmee River (Toth *et al.* 1995)

- *Assessment* — Establishing cause and effect in river management problems
- *Decision support* — Strategic decisions on when, and when not to intervene
  Operational guidance as to where and what intervention to adopt
- *Design* — Mainly used on enhancement and restoration projects
  Advice on type and dimensions of channel morphology, appropriate flushing flow regimes, sedimentology, and nature of adjustments
- *Post-project appraisal* — For a range of river management practices

In the UK, a decade of investment in geomorphological research and development has culminated in a suite of "standard" methods for incorporating geomorphological information into existing river management practice that provides a useful template for deploying the range of tools discussed within this volume (Environment Agency 1998). At their core lies the basic notion that geomorphology has contributions to make across the broad sector of river management, including strategic and operational management, the latter involves actions that modify watercourses.

An axiom of this approach is that it is essential to understand the cause of the management problem. The methods are designed to nest in a quasi-hierarchical fashion, collapsing from the catchment (strategic) over-view of physical habitat resource, down to the project level design and assessment. This framework involves deployment of a range of geomorphological tools to provide increasing levels of certainty in the interpretation of system functioning, in support of specific management goals. The approach is based on the view of the river network as a continuum, whereby reaches are classified according to the information recovered from the catchment under study. This prevents the imposition of rigid classifications, and recognizes the inherent value in the uniqueness of a river, whilst seeking to encourage standard approaches to the analysis of channel processes and the resulting forms and habitats. While these generic methodologies may be applied to a range of river management projects, there will of course be more specific studies required by individual projects. In this case, the tools described in this book should be considered within the context of the specific project brief. For example, the setting of flushing flows for watercourses may require measurement of sediment transport in relation to specific discharges.

Table 21.2 provides examples of the scale and nature of the information produced by these different methods of data collection and assessment. Within each scale of survey, different tools are required for the collection of the relevant data. For example, with the evolution of remote sensing technology and data post-processing, much of the catchment and network scale topography and morphology may be generated without full ground survey; although calibration and ground-truthing will still be necessary.

The following section takes each scale of geomorphological analysis in Table 21.2, and elaborates through case studies, the application of different tools to solve specific management problems.

21.7 GEOMORPHOLOGICAL ASSESSMENT AT THE CATCHMENT SCALE

Catchment Baseline Survey

At the largest scale, catchment baseline surveys aim to provide catchment inventories of the geomorphological sensitivity of the river network, and conservation status of each reach. The information from catchment surveys is used strategically to target investment in rehabilitation or conservation designations based on physical habitat diversity. Figure 21.2 illustrates an output from a catchment scale survey of the river Britt, a low gradient groundwater dominated stream in southern England. An important component in both catchment surveys and fluvial audits (discussed below) is visualization of the data sets. Application of GIS to spatial geomorphological data is a powerful tool in itself both for analysis and presentation, the latter an important consideration when communicating results to non-specialist audiences. The use of a GIS also permits integration of other data sets that may be relevant to a particular study, for example, the presence and structure of macrophyte, invertebrate, and fish communities.

The method of field data collection and desk-top study may be standardized in terms of the type of information collected through the use of data entry forms which can be mounted on digital hand-held platforms for direct data entry. The advantage of standardized approaches is that they can be β-tested and are replicable (and therefore accountable) with clearly defined outputs (Table 21.2). Their main dis-

Table 21.2 A framework for incorporating geomorphological tools within river management (after Newson and Sear 1993)

Stage	Planning/project		Project	Project	Project
	Geomorphological assessment		*Geomorphological dynamic assessment*	*Geomorphological channel design*	*Geomorphological post-project appraisal*
	Catchment baseline study	Fluvial audit			
Aims	Overview of the river channel morphology and classification of geomorphological conservation value	Overview of the river basin sediment system typically aimed at addressing specific sediment related management problems and identifying sediment source, transfer and storage reaches within in the river network	To provide quantitative guidance on stream power, sediment transport, and bank stability processes through a specific reach with the aim of understanding the relationships between reach dynamics and channel morphology	To design channels within the context of the basin sediment system and local processes	To assess the degree of compliance between design expectations and outcomes in terms of geomorphological processes, dimensions and morphology
Scale	Catchment (size <1–3000+ km^2)	Catchment (size <1–3000+ km^2) to channel segment	Project and adjacent reach	Project reach	Project reach
Methods	Data collation, including reconnaissance fieldwork at key points throughout catchment. Integration of data within GIS	Detailed studies of sediment sources, sinks, transport processes, floods, and land use impacts on sediment system. Historical and contemporary data sets derived from desk-based study. Integration of data within GIS	Field survey of channel form and flows; hydrological and hydraulic data, bank materials, bed sediments (GA/FA if not available)	Quantitative description of channel dimensions and location of features, substrates, revetments, etc. (GDA/FA/GA if not available)	Review of project aims/expectations. Compliance audit of channel against design. Re-survey of project data sets. Field survey approach
Core information	*Characterization* of river lengths on basis of morphology and sensitivity to management intervention	Identifies *range of options* and "potentially destabilizing phenomena" (PDP) for sediment-related river management problems	Sediment transport *rates* and morphological *stability/trends*. "Regime" approach where appropriate	The "appropriate" *features* and their *dimensions* within a functionally designed channel	*Extent of changes or conformity* to original project design and recommendations for mitigation options

(*Continues*)

Table 21.2 (*Continued*)

Stage	Planning/project		Project	Project	Project
Procedure	*Geomorphological assessment*		*Geomorphological dynamic assessment*	*Geomorphological channel design*	*Geomorphological post project appraisal*
	Catchment baseline study	Fluvial audit			
Outputs	15–30 page report; GIS including photographs detailing conservation value and sensitivity of reaches to management actions	GIS; time chart of potentially destabilizing phenomena; report including recommendations for further geomorphological input where necessary	Quantitative guidance as to intervention (or not) and predicted impacts on reach and beyond. Identification of causes of specific problems where possible	Plans, drawings, tables and report suitable as input to quantity surveying and engineering costings. Justification for design. Explicit consideration of channel dynamics and sediment transport	Plans, tables, report. Assessment of project performance in terms of geomorphological processes and morphology/physical habitat. Recommendations for input into adaptive management.
Destination	Feasibility studies for rehab/restoration.	Investment/management staff, river managers or policy forums, Project steering groups	River managers and project steering groups	River managers and project steering groups	River managers and project steering groups

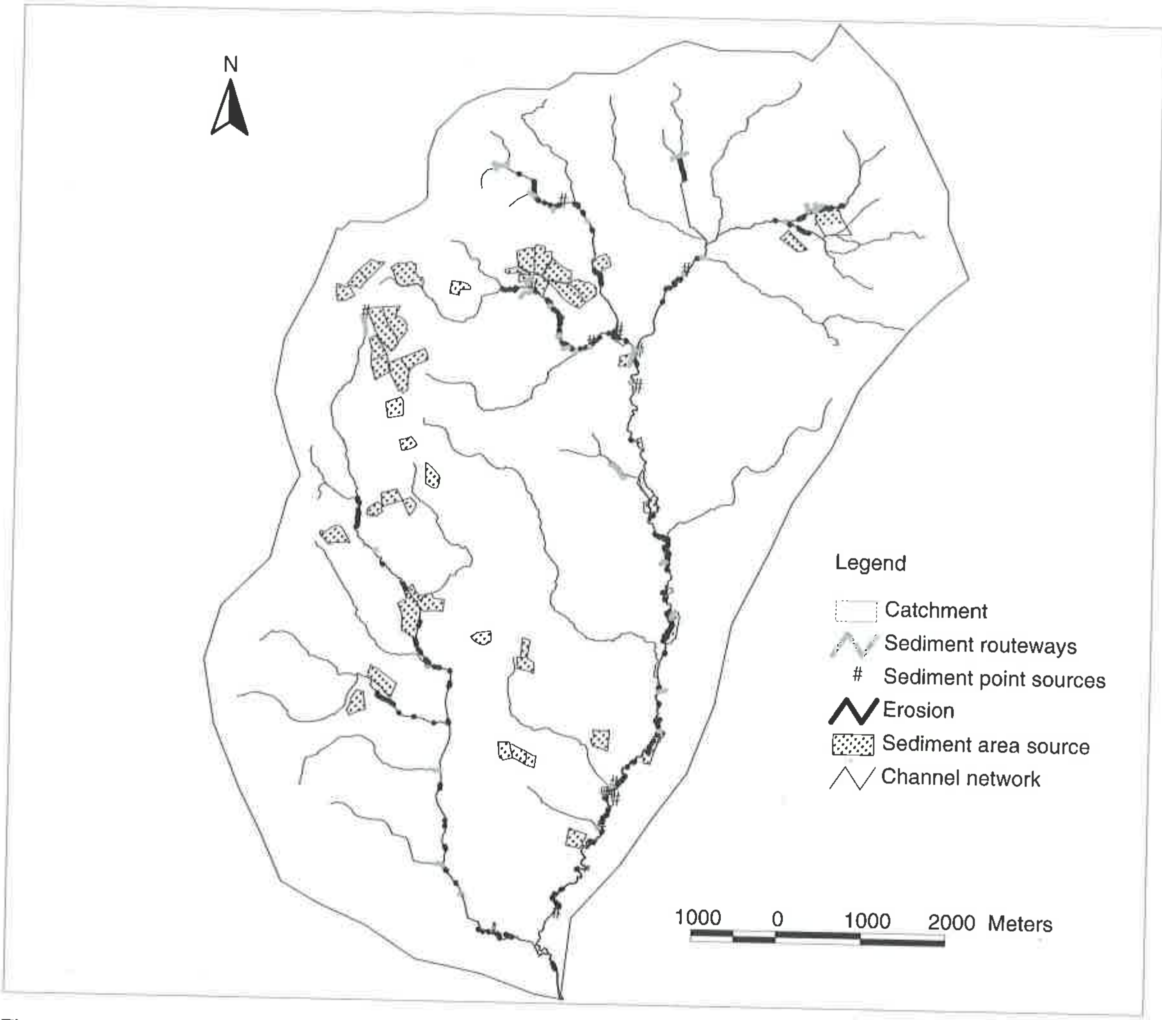

Figure 21.2 Example of a GIS output from a catchment-scale geomorphological assessment; the river Britt, a groundwater dominated river in southern UK

advantages are their inflexibility in the face of unique conditions.

The Fluvial Audit

An audit represents the second level of geomorphological analysis of a river catchment and is aimed at providing an interpretation of the functioning of the river system in terms of a sediment budget, and establishing a link between this functioning and the morphology and physical habitats of the system. Like the catchment survey, the fluvial audit is a field-based, reconnaissance survey, undertaken in a structured framework to provide consistency and ease of data entry and analysis within the GIS environment. The field survey is continuous, and includes inventories of features, coupled with assessments of materials and processes operating within the river corridor (Sear *et al.* 1995). Estimates of sediment supply and storage are calculated from measures of sediment deposits within the channel and floodplain (see Chapters 2, 9–11, 13, and 16), whilst supply from bank erosion is informed from measures of bank morphology and historical rates of erosion determined from historical surveys, maps, and remotely sensed data (see Chapters 4 and 6). In this way, historical information is integrated with contemporary survey to establish a process-based classification based on channel activity (both vertical and lateral). Classification of the data within the GIS (see Chapters 7 and 8) facilitates identification of zones of sediment storage, supply, and transfer. In addition, information on the types of erosion and deposition processes are displayed that may be used to guide erosion control measures (Sear *et al.* 1995). This catchment scale information should ultimately seek to provide a calibrated sediment budget (though often without fluxes in European rivers) that can inform river managers of the sources of sediments that may be causing sedimentation problems or the most probable impact on the sediment system (see Chapter 5) of undertaking a given channel modification. Ideally, another layer in the information includes field-determination of physical habitats and associated biological communities (Newson and Newson 2000). This information not only provides guidance on the relationships between the geomorphology of the river and the floodplain and channel ecology, but also establishes a framework for integrating different disciplines.

Case Study: Strategic Assessment of a Proposed Plan for Rehabilitating Salmonid Spawning Habitat Using Catchment Survey Methods

Deer Creek drains 540 km^2 (average discharge 9 m^3 s^{-1}), originating on the western slopes of Mount Lassen, the southernmost volcano of the Cascades range, and flows southwestward through rugged bedrock canyons to the Sacramento Valley floor, where it traverses its alluvial fan for about 17 km before joining the Sacramento River at Vina, California. Historically, flood flows would overflow the current channel of Deer Creek and flow across the floodplain, on which land use is primarily livestock grazing and orchards. The multiple distributaries appearing on the topographic map hint at the history of channel aggradation and avulsion by which such alluvial fans are built (Figure 21.3).

Adult spring-run chinook salmon traverse the lower, alluvial reach en route to remote canyons cut into volcanic rocks that offer them suitable spawning and rearing habitat. Fall-run chinook use the alluvial reach for spawning, and spring-run, winter-run, and other salmonids, mostly from other drainages, use the alluvial reach for rearing.

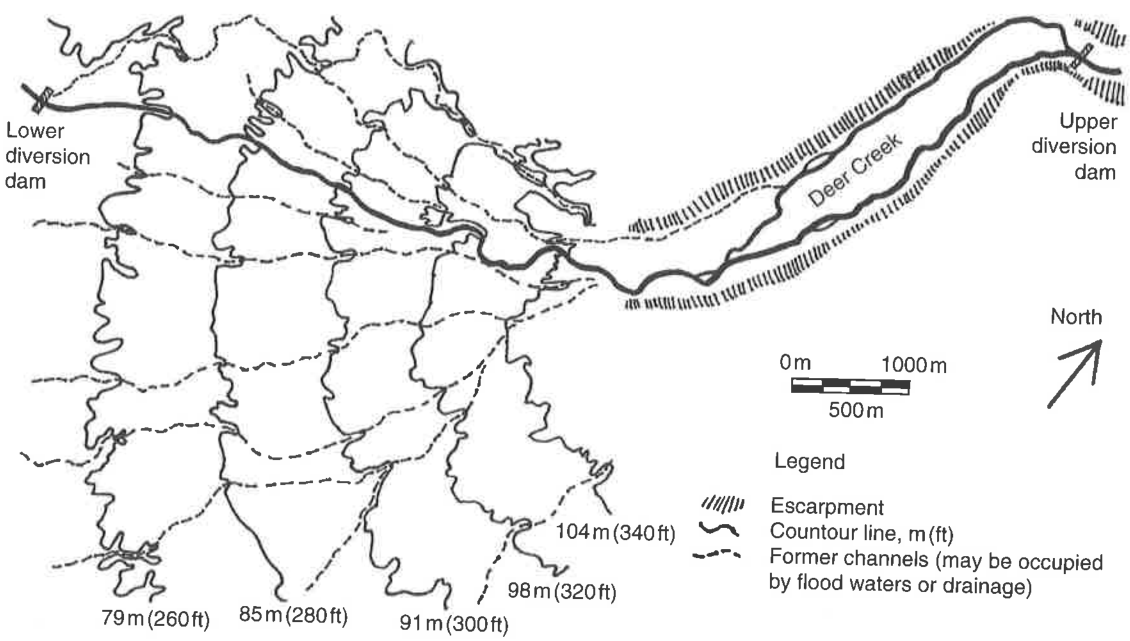

Figure 21.3 Distributaries of Deer Creek (based on 1:24 000 US Geological Survey topographic maps)

Habitat conditions in the alluvial reach of Deer Creek are not ideal. There is relatively little shade because vegetation is lacking along most banks, the channel form is very simple, and the gravel sizes (D_{50} decreases from 190 mm near the foot of the mountains to 55 mm about 3 km upstream of the Sacramento River confluence) are larger than ideal for chinook salmon spawning (Kondolf and Wolman 1993). The channel lacks complex features that provide good habitat, such as tight bends and secondary circulations, undercut banks, scour pools, woody debris jams, and a well-developed pool-riffle sequence. To partially address these problems, planning documents for salmon restoration programs in the early 1990s proposed planting riparian vegetation along the low-flow channel banks and constructing spawning riffles by regrading the bed and adding smaller-sized gravels to the creek.

In 1949 the US Army Corps of Engineers straightened and cleared the channel, and constructed levees along much of the lower 11 km of Deer Creek. The manager of the Stanford-Vina ranch, immediately downstream of the proposed levees, protested against the project, accurately predicting that the proposed flood control project would deliver to his ranch "... more water and at greater velocity than under existing conditions" (Robson 1948). Given its then entirely agricultural land use, the need for federally funded flood control along Deer Creek is not obvious. Despite the apparent lack of benefit, and despite the protest of the downstream landowner, the project was completed and responsibility for maintaining the levees was given to the county, with responsibility for the channel bed to the state. In the early 1980s, the California Department of Water Resources cleared the channel of accumulated gravel and vegetation to maintain channel capacity. During a large flood in January 1997, Deer Creek broke through its left bank levee about 8 km upstream of the Sacramento River confluence and flowed across the floodplain, some water flowing directly into the Sacramento, some flowing back into Deer Creek (Figure 21.4). The channel had broken through its levee in the same place in the early 1980s. After the recent flooding, and the history of levee failure, there was strong interest among local residents and land owners to find a more sustainable solution to flooding along Deer Creek.

A geomorphic study conducted as part of the Deer Creek Watershed Management Plan (DCWC 1998) reviewed historical maps and aerial photographs, measured bed material size along the channel, and evaluated current conditions in a longer-term and larger-scale context. Examination of aerial photographs from 1939, prior to the flood control project, showed highly complex channel forms, with frequent pool-riffle alternations, meander bends, and gravel bars, with trees overhanging the channel, undercut banks, and log jams (Figure 21.5). Aerial photographs taken after the flood control project showed a marked simplification of the channel and thus loss of habitat (Figure 21.5). The geomorphic study concluded that habitat in Deer Creek was limited mostly by the effects of the flood control project, not only because of the direct impacts of clearing and subsequent maintenance, but also because the levees constrain high flows within the low-flow channel, so that a given flow is deeper (and thus exerts greater shear stress on the channel bed) than was the case when floods overflowed onto the floodplain. As a result, very high shear stresses in the channel wash out spawning gravels, complex channel forms, and riparian vegetation. The report also concluded that the proposed riparian plantings and spawning riffle construction along and in the channel would probably wash out in the high shear stresses of the constrained levee system.

In this example, a geomorphic analysis suggested that the habitat problems previously identified along Deer Creek—lack of shading, simplified channel form, and reported lack of suitable spawning gravels—were all symptoms of an underlying cause: the effects of a flood control project built five decades before. Rather than spending restoration funds on treating the symptoms (planting trees and adding gravel to the channel) the report recommended addressing the problem and redesigning the flood infrastructure to allow Deer Creek to flood its (still mostly agricultural) floodplain in a controlled way, protecting vulnerable structures by ring levees. This approach would have the advantages of providing better flood protection to the structures on the floodplain, while reducing shear stresses in the low-flow channel, allowing bars to build and riparian vegetation to establish within the currently "maintained" (cleared) floodway, thereby improving habitat in the channel of Deer Creek. A feasibility study for the Deer Creek floodplain project has recently been identified for funding by the California Bay Delta Ecosystem Restoration program, and a three-dimensional modeling study is currently underway as part of a Ph.D. thesis. Fortunately, the Deer Creek floodplain remains mostly agricultural so there is a better opportunity here to reconnect the floodplain and channel than along most streams in California.

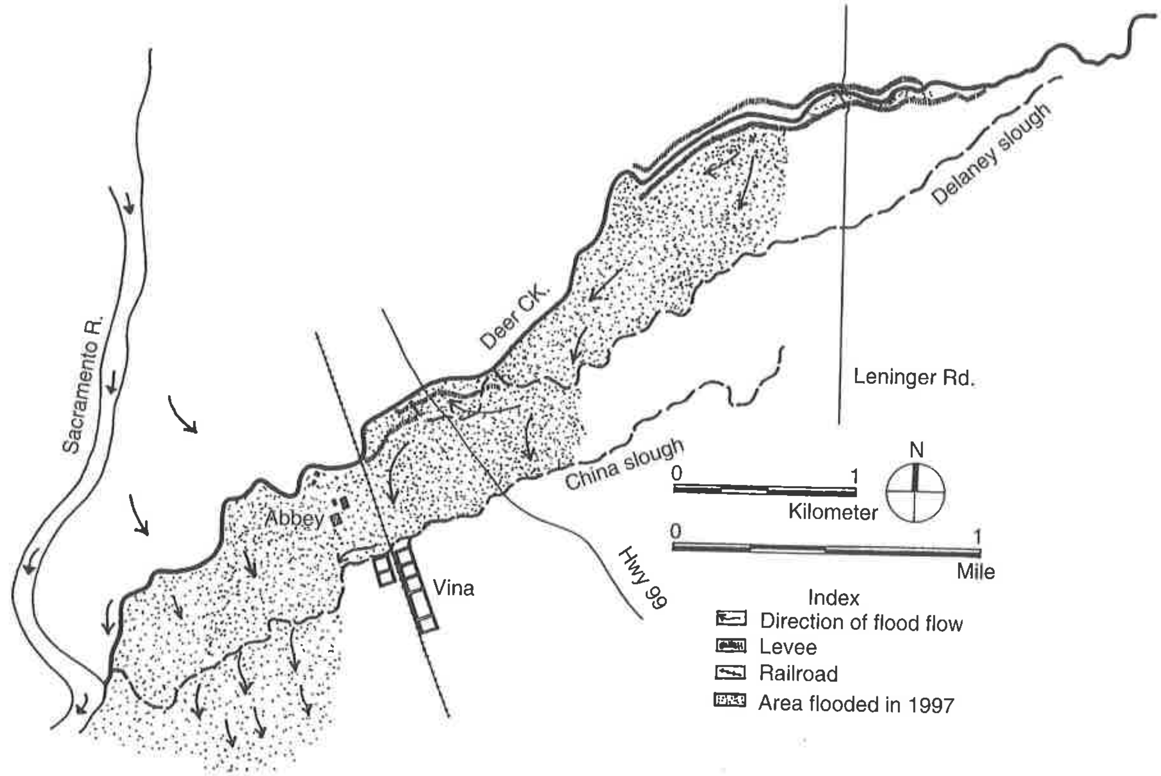

Figure 21.4 Extent of flooding in 1997 along Deer Creek and its floodplain. Some of the overflow returned to the main channel at Hwy 99, the rest followed China slough to flow directly into the Sacramento River. Based on contemporary observations, high water marks documented shortly after the flood, and post-flood interviews with residents

21.8 GEOMORPHOLOGICAL DYNAMIC ASSESSMENT AT THE REACH SCALE

The remaining levels of geomorphological assessment relate to reach-scale, problem-focused management, often associated with specific schemes (e.g., design of river restoration projects, bank erosion control measures, etc.). The nature of the questions posed is more specific, and entail deployment of tools necessary for quantifying system functionality (See Chapters 6, 11–20). Thus, a Geomorphological Dynamics Assessment may quantify bank stability and sediment transfer within a design or "problem" reach, while establishing it within the broader catchment context by applying a fluvial audit catchment survey. Numerous examples exist in the geomorphological literature of what could be termed "Geomorphological Dynamics Assessment". Specific examples include Sear *et al.* (1994), Kondolf and Wilcock (1996), and Thorne *et al.* (1996). The range of tools deployed within differing studies is dependent on project budget and availability. In large-scale restoration programs, where sediment load and hydrodynamics are crucial factors to quantify, then the sums of money may justify expensive pre-project monitoring programs and model calibration. In many cases, however, the budgets are more modest, and the tools used must be carefully selected in order to provide the most robust answers. For example, the sedimentation of a small rural land drainage channel is unlikely to attract the level of investment in geomorphology that is required in order to understand the sediment dynamics of a major hydropower or restoration program. A crucial point to consider here is the validity of the information obtained,

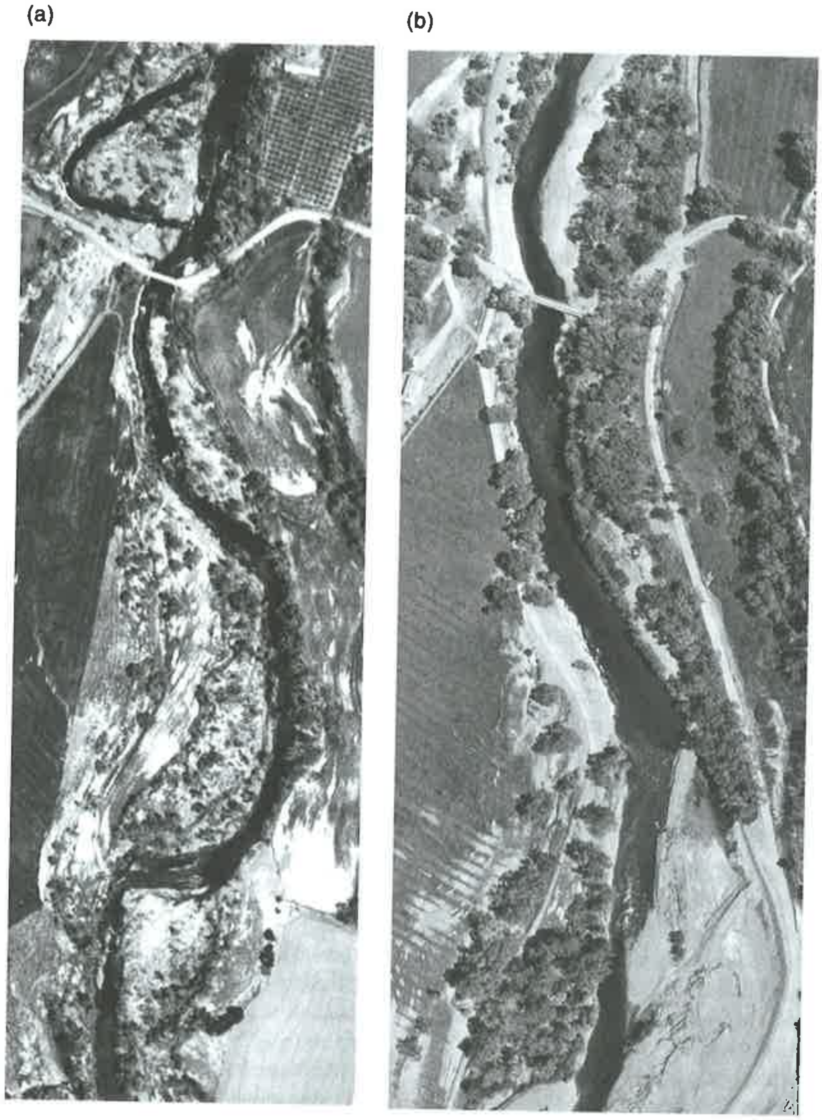

Figure 21.5 Details from aerial photographs of Deer Creek near Leininger bridge in 1939 and 1997. Flow is from top to bottom, length of river shown is about 1100 m. (a) The 1939 channel was more complex, sinuous, and with more frequent bed variations, gravel bars, and undercut banks with adjacent riparian vegetation. (b) The 1997 channel is less sinuous, wider, and less complex, reflecting the effects of the 1949 flood control project, and subsequent maintenance. Also visible in the 1997 photo detail is the levee breach along the left (south) bank

particularly when legal challenge is possible. However, geomorphologists must avoid "advocacy science" (Graf, pers. comm. 2002), and if more investment is necessary to answer a problem, then the science case must be made to the stakeholders.

21.9 GEOMORPHOLOGICAL CHANNEL DESIGN

Aims

This approach uses geomorphological principles to develop an appropriate channel design. In practice, the tools deployed will depend on the nature of the design problem and the type of river system under study. For example, the restoration of a channel for physical habitat enhancement in an urban setting may be constrained in terms of what is possible in comparison to a similar scheme undertaken in relatively undeveloped landscapes. Similarly, low-energy cohesive channels may require more detailed design consideration compared with higher energy alluvial streams that are in effect able to design themselves (Sear *et al.* 1998). Approaches to geomorphological design may be based on the derivation of local hydraulic geometry relationships or from analogue reaches within the same or adjacent basins. In many situations, however, development of the catchment and modification of the hydrology and channel form may be so extensive that such approaches are not possible. In these situations, modeling of the channel form may be attempted provided that effective calibration is made (See Chapters 17–19). Recent consideration of the process of geomorphological channel design has highlighted the role of both field survey and modeling in quantifying and reducing levels of uncertainty, and communicating these to the other disciplines associated with the process.

Case Study: Setting Riparian Channel Widths. An example of Geomorphological Channel Design

An interdisciplinary problem. Riparian zones have been recognized as critical environments for biodiversity in river systems (Odum 1978, Naiman *et al.* 1993). Riparian zones influence aquatic ecosystems because living tree roots and branches, as well as dead wood, create channel (and thus habitat) complexity, because leaves and invertebrates falling into the channel from the canopy provide food, and because shading by trees influences water temperature (Meehan *et al.* 1977, Vannote *et al.* 1980, Gregory *et al.* 1991). Riparian vegetation diversity in turn depends on channel migration and rejuvenation of floodplain habitats (Pautou and Wuillot 1989, Marston *et al.* 1995, Bornette *et al.* 1998). In addition, well-vegetated riparian zones can also serve to filter sediments, nutrients, and contaminants from runoff, thereby improving water quality in rivers. Accordingly, riparian buffer strips or streamside management zones are commonly prescribed, often for multiple objectives, and riparian zones have been the object of conservation and restoration efforts (Nilsson 1992, Petersen *et al.* 1992, Goodwin *et al.* 1997, Landers 1997, Hunter *et al.* 1999).

In addition to the inherent ecological values of a vegetated riparian zone, setting human structures back from the active channel can minimize conflicts between dynamic river behavior and human development. Engineering measures to protect human structures, such as dikes, bank protection, and channel straightening or deepening, affect channel geometry and bedload transport, often with negative consequences for habitat (Brookes 1988, Petts 1989). The "streamway" concept is to leave a wide belt within which the river channel can freely move and flood; for a meandering river this zone can correspond to the meander belt (Palmer 1976, Piégay *et al.* 1994, 1996, Brookes 1996). The regional agency in charge of water management in the Rhône Basin, France (SDAGE RMC 1997) defined the streamway as a floodplain band within which channel migration is useful for the ecosystems and bedload supply.

One of the questions posed by managers and decision-makers to scientists in order to maintain an optimal river corridor which can support, over a long period of time, many uses and high biodiversity is: "What is the riparian width to be preserved or to be restored?". It is an interdisciplinary question, which can be shared in many sub-disciplinary questions (Budd *et al.* 1987). What is the width of the riparian zone within which most of the riparian vegetation species (Spackman and Hughes 1995) or most of the avian communities (Keller *et al.* 1993) are observed? What is the wooded corridor width to be preserved to mitigate the effects of logging on stream habitat, invertebrate community composition and fish abundance (Davies and Nelson 1994)? What is the width of the riparian zone required for plants to take up most of the nutrients (e.g., nitrates) coming from neighboring agricultural areas (Pinay and Décamps 1988, Petersen *et al.* 1992)? What width of wooded corridor is needed to trap sediments and woody debris from floodwaters to protect floodplain farmland against damage from sediment and woody debris? This is an important question in the lower Rhône Valley, where tributaries traverse alluvial plains with vineyards, which are sensitive to scouring and burial under sediments during floods, but not to inundation (Piégay and Bravard 1997).

What streamway width should be preserved for ecological or long-term socio-economical purposes (Malavoi *et al.* 1998, Piégay and Saulnier 2000)? The last question needs not only geomorphological and ecological analysis, but also economic and policy analysis to evaluate relative costs of bank erosion versus bank protection construction and maintenance, the price of the land, and the annual value of its agricultural production (Combe 1991, Piégay *et al.* 1997).

Applying geomorphic tools to assess channel migration. The magnitude and frequency of the channel shifting may be of interest at a local scale to a land owner, at a larger scale to decision-makers and managers designing a streamway for ecological conservation or to minimize future conflicts between human settlement and bank erosion processes. From a geomorphological point of view, bank erosion is a natural process, which contributes to the overall physical functioning of the river. If we counteract this process, it may involve cascading changes in channel geometry, and may affect other human uses. In actively shifting channels (wandering, meandering, and braided channels), the geomorphological approach is first applied at the scale of a homogeneous reach (from 10^0 to 10^2 km) where bank erosion occurs. For example, if the river is characterized by a meander train, it is first important to work at the scale of the whole train rather than at the single curve scale.

Two main approaches include historical studies of channel mobility, increasingly using GIS technology (Downward *et al.* 1994, Marston *et al.* 1995). Historical maps and air photos are scanned, georeferenced, and rectified. Using several temporal series, it is possible to overlay the different channel courses, documenting temporal and spatial variation of the channel migration rate, channel cut-off frequency and character, and the areas of newly eroded and constructed floodplain, and assessing the sensitivity to erosion of individual reaches (Figure 21.6).

Analysis of a series of air photos of the Ain River showed that from 1945 to 2000, the surface area of the unvegetated, active channel reduced from 630 to 450 ha, and riparian forest established in the formerly open channel (Piégay and Saulnier 2000). Erosion of the floodplain surface averaged 7 ha $year^{-1}$ over a 40-km reach between 1980 and 1996; 8.3 ha $year^{-1}$ between 1996 and 2000. Fortunately, only 6% of the eroded areas were occupied by agriculture, most of the remaining areas consisted of the riparian forest established on the former active channel. In this context of in-channel forest establishment and low human pressure on the riparian zone, the streamway concept (preventing development within the river corridor) has potential to succeed. The streamway zone width is based on historical analysis of channel change, with different patches distinguished according to their probability of being eroded in the next three decades. Such mapping has been done on few tens of rivers in France. The Ain River is one of the most advanced example (Figure 21.6). Channel shifting has been mapped over a 40-km reach over the last five decades, as a basis for determining the streamway. River managers have identified land ownership within the streaming band and are now determining guidelines for managing actions such as forest harvest, bridge construction, or extension of existing mining sites.

Because this approach is based on expert information, historical channel mobility as a basis to predict future mobility and future advances on numerical modeling to simulate channel evolution should improve the process. At this stage of the research process, such tools are available but not robust enough to be used in an applied sense. Numerical modeling has progressed such that it is now possible to simulate channel meandering or braiding (see Chapter 19, this volume). Models of meander migration are based on a general relationship relating lateral bank erosion rate to the near-bank velocity, channel depth, and bank erodability. Previously limited to neck cut-offs, recent models incorporate not only chute cut-offs from probability function but also spatial variability of bank erodability (exposure of resistant floodplain or terrace sediments, bedrock outcrops). Moreover, Howard (1996) also simulated the meander belt width which can be defined as the maximum floodplain width occupied by the meandering stream during the simulation time. He proposed different sceneries including chute cut-offs and also resistant valley walls or oxbow plugs (Figure 21.7). These models can help set streamway width, as well as other objectives, such as assessing the residence time of contaminants in the floodplain sediments.

Recent work combining planform models and bank erosion models (Rinaldi and Casagli 1999) may improve model predictions further. Tools to assess bank erosion at a short timescale, such as traditional erosion pins, terrestrial photogrammetry, and Photo-Electronic Erosion Pin (PEEP) system, can be easily applied to a wide range of environments at low cost, and provide accurate results even for bank retreat of few millimeters (Lawler 1993). However, they yield information at the site scale, and must be somehow scaled up to provide meaningful insights at a larger scale (Figure 21.8).

Applying geomorphic tools to assess potential incision. Use of buffer strips to improve water quality is increasingly popular among managers, but the efficiency of such measures depends strongly on the potential of the reach to affect biogeochemistry of shallow groundwater, which is partly controlled by channel geometry. For example, nitrates in shallow groundwater can be transformed by soil (denitrification

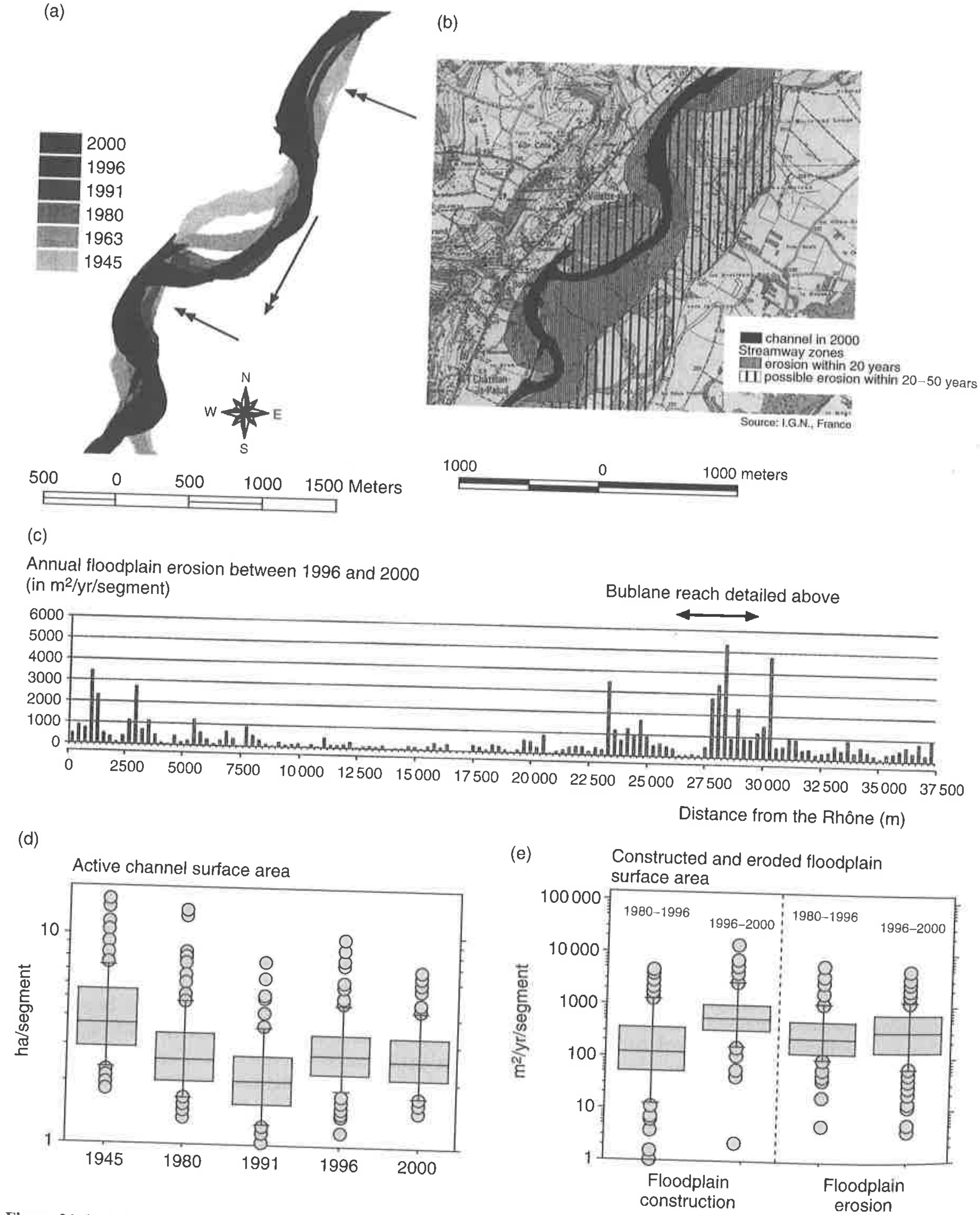

Figure 21.6 Retrospective analysis of the Ain channel mobility. View of the different channels (a), streamway differentiated according to sensitivity of zones to erosion (b), diagnosis graph showing longitudinal trends in terms of recent eroded floodplain surfaces (c), as well as temporal trends in terms of channel surface area (d), and eroded floodplain surfaces versus created floodplain surfaces (e)

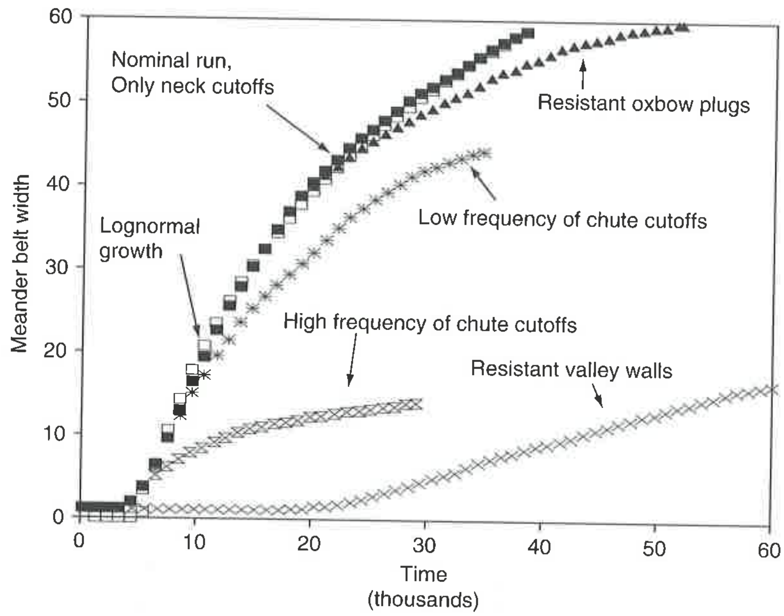

Figure 21.7 Cumulative meander belt width versus simulation time (arbitrary units). Filled boxes for simulated meandering with uniform bank erodability and no lateral constraints. Open boxes are a logarithmic growth curve fit to simulate results. Other curves show effects on growth rate of chute cut-offs, resistant clay plugs, and resistant valley walls (from Howard 1996) (reproduced by permission of John Wiley and Sons, Ltd.)

process based on bacteria activity) and root systems (nitrates are absorbed by plants). However, if the channel incises, and the alluvial water table drops, the denitrification process is reduced or inactive. Accordingly, when planning riparian restoration projects with such water quality objectives, it is essential to assess the sensitivity of the channel to incision and its current status.

The current status, future trends, and potential for incision are important attributes to assess in establishing riparian buffer zones and for other purposes. First, we can examine evidence for recent and ongoing incision, such as historical cross-sections, bridge drawings, and field evidence (Simon 1992, Piégay and Peiry 1997, Landon 1999). Historical documents demonstrated incision over the downstream 160 km of the Arno River, with a maximum of 10 m in the lower Valadarno during the contemporary period (Figure 21.9a) (Rinaldi *et al.* 1997). Cross-sections for 1890–1920 showed incision from basin afforestation and reduced sediment delivery from the catchment, while cross-sections from 1945 to 2000 showed incision caused by channel regulation and mining (Figure 21.9b).

We can also evaluate whether incision is continuing. As described in Chapter 11 for channels in loess, if at least two topographical surveys are available, it is possible to predict (by extrapolation) the elevation of the channel bed at time t_n from an exponential function. The more detailed the temporal series and the more extensive the survey, the better this approach can predict the duration of adjustment and the stages attained in different reaches. A channel survey upstream and downstream from the study reach can indicate the existence or absence of headcuts or destabilized banks from regressive and progressive erosion. A detailed historical analysis of human factors that could produce incision can provide information on probable future trends.

The inherent sensitivity of the channel to incision can be evaluated from the stratigraphy of the valley sediments and the elevation of the bedrock. In several rivers in the French Alps, a few meters of alluvial gravel overlie fine-grained lacustrine silts, sand, and peat. Once the channel incises through the gravel, the underlying fine sediments erode rapidly (Peiry *et al.* 1994). By contrast, incision through the gravel bed on the Roubion River from gravel mining and reduced sediment supply from the catchment has exhumed boulders deposited by large floods during the last glacial period, effectively armoring the bed. Similarly, exhumed moraines or bedrock outcrops can limit incision. For the bed material now exposed, grain size

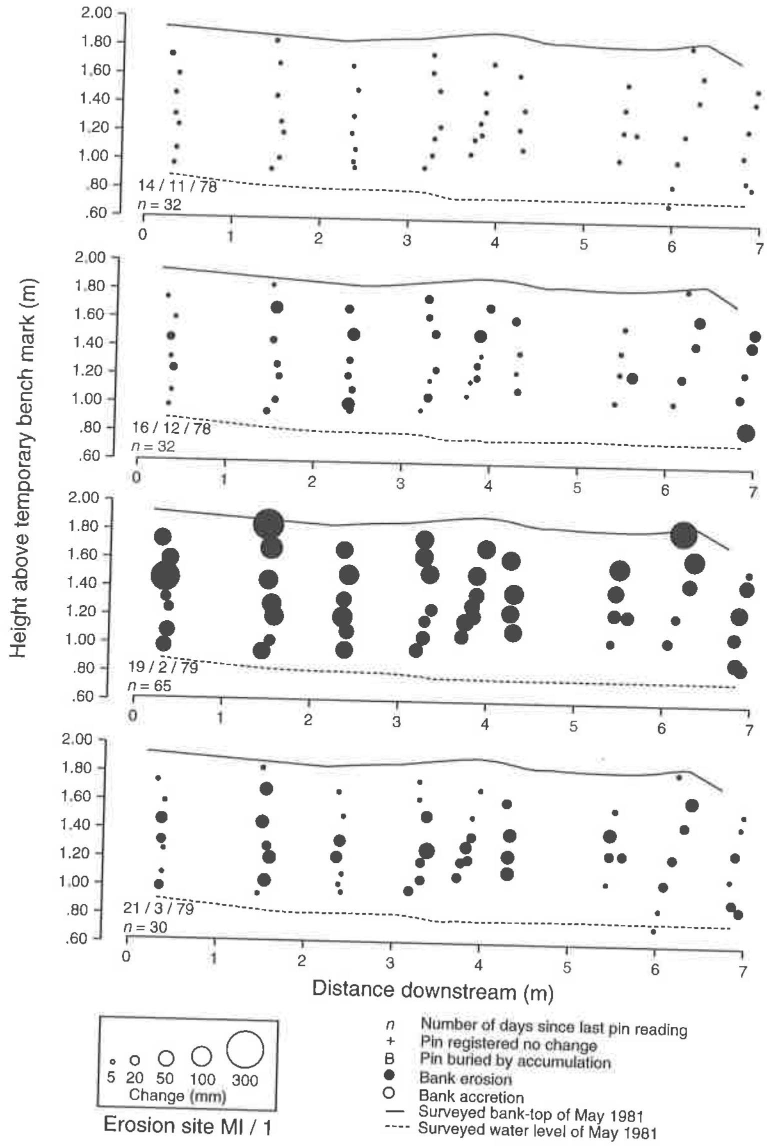

Figure 21.8 Example of information derived from erosion pins: variation on the vertical face of a bank of erosion rates for the river Ilston (South Wales). Erosion value is given for each pin and mapped as a proportional circle. The bank is viewed as a vertical face (from Lawler 1993) (reproduced by permission of John Wiley and Sons, Ltd.)

can be measured, the critical shear stress required to move it estimated, and compared with the expected range of discharges, thereby assessing the sensitivity of reaches to winnowing and armoring. These approaches can be useful on reaches with reduced sediment supply, such as downstream of dams (Komura and Simons 1967).

21.10 GEOMORPHOLOGICAL POST-PROJECT APPRAISAL: EXAMPLE OF THE RIVER WYLYE RESTORATION PROJECT

This final phase in the approach again deploys a range of tools to determine the success or otherwise of a river management program, and aims to feedback

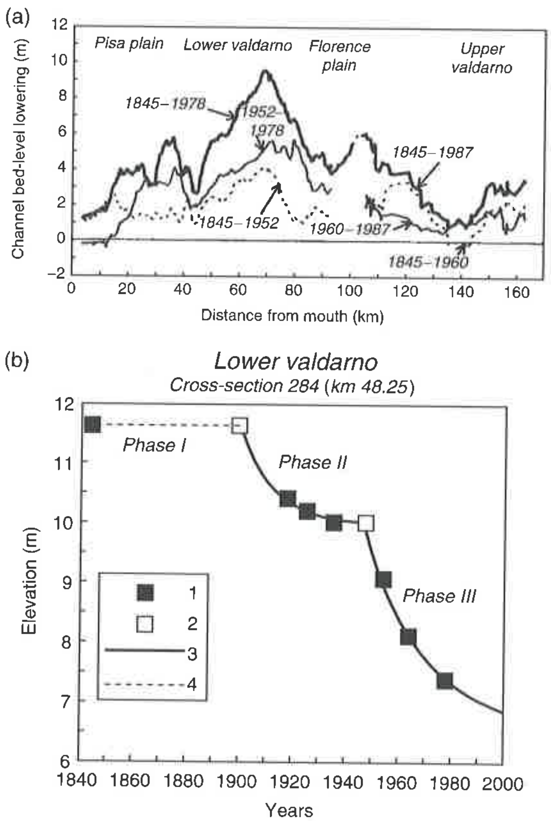

Figure 21.9 Retrospective analysis of channel degradation: the Arno River between 1845 and 1987: (a) summary of lowering over the downstream 160 km course of the river; (b) summery of lowering through time at cross-section 284 (km 48.25) (from Rinaldi *et al.* 1997) (reproduced by permission of University of Mississippi)

into the adaptive management process (Downs and Kondolf 2002). Geomorphological post-project appraisal is, however, often overlooked and underfunded by river managers who see it as an expensive "luxury" rather than as a valuable tool in itself. Those published studies demonstrate that at worse, the information may lead to a need to intervene in a scheme, but even in these cases, the information derived has value in terms of lessons learned that can be input into other projects.

Restoration of groundwater dominated rivers in the UK is largely undertaken in order to provide enhanced physical habitat diversity for different lifestages of salmonids, or as part of a wider program of rehabilitation of past channelization. Typical rehabilitation options include narrowing of the channel to encourage flushing of silt from the gravels, and the re-introduction of riffles. Typically, these schemes are undertaken without any reference to geomorphological processes, but are intuitively designed by people with some knowledge of fisheries. As part of a wider study of the sediment dynamics and physical habitat of the river Wylye (see Figure 21.2), a geomorphological post-project appraisal was undertaken in order to establish the geomorphological impact and performance of a range of rehabilitation schemes.

Setting the performance criteria for such schemes depends on establishing their original aims. In the case of the restoration schemes on the Wylye, the main aims were to flush silt, create riffles for salmonids, and to restore a physically diverse habitat. Assessing such criteria can prove problematic since few schemes have quantified targets (e.g., establish silt levels at <10% by weight of bulk sampled gravels), as was the case in this instance. Instead, an alternative approach was adopted that sought to establish the performance of the restored channels as measured by three criteria:

(a) channel geomorphology and erosion/deposition processes,
(b) substrate heterogeneity, and
(c) hydraulic habitat.

The performance of each rehabilitated reach was measured against an adjacent control reach that had not been rehabilitated. In addition, a reference condition site was measured in order to provide a suitable analog for assessing overall success of each scheme (Figure 21.10).

Channel geomorphology and processes were recorded through geomorphological mapping of each site, locating the features (pools, riffles, etc.) and processes (sediment storage and erosion). Channel form, channel geometry, and water surface elevation were recorded at cross-sections spaced at every bankfull channel width using standard Total Station surveying. Water surface slope was determined through the reach for the time of survey. Physical habitat was quantified for 20 randomly selected sections through each reach. At each section, five measures were made at points located in the channel center, edges, and mid-way between these points. These measures included; average velocity (0.6 depth), flow depth, and substrate. Flow velocity was measured using an electromagnetic current meter that is not mechanically affected by submerged aquatic macrophytes. Substrate was estimated

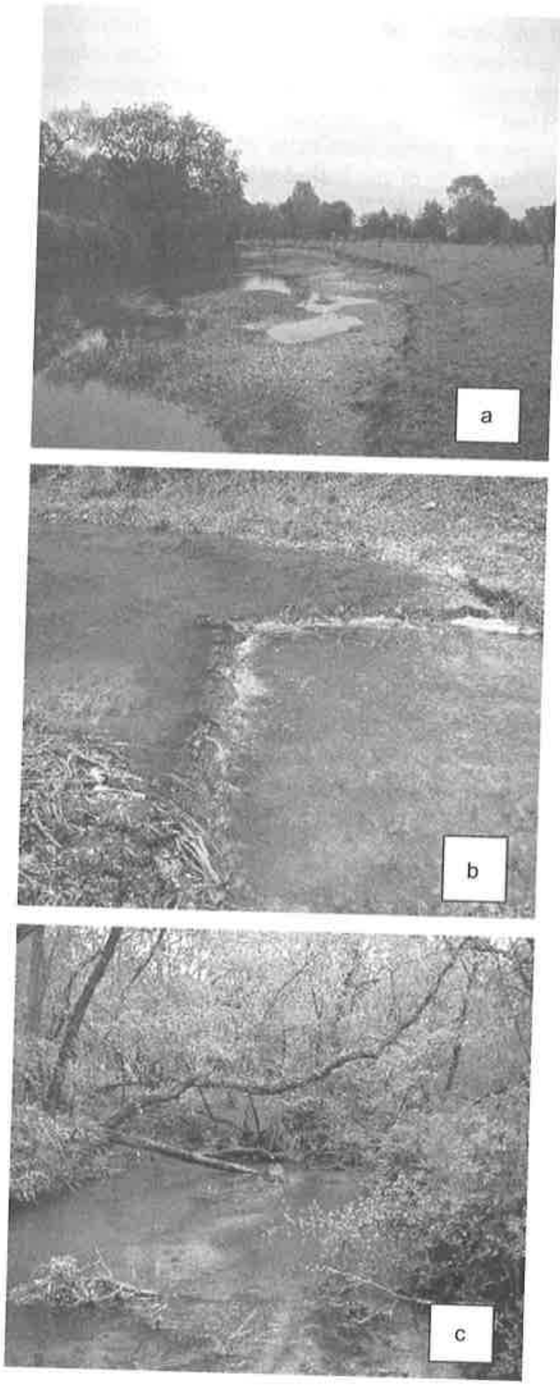

Figure 21.10 River Wylye geomorphological post-project appraisal. (a) A reach subjected to dredging in the 1950s for land drainage. (b) A rehabilitated reach, using soft engineering to manipulate channel form. (c) The semi-natural reference condition site

visually as flow depths precluded manual sampling. A total of 100 spot readings were therefore made for each reach.

The geomorphological maps were used to generate indices of geomorphological and physical biotope (flow type), diversity, and patchiness (sensu, Newson and Newson 2000). Diversity scores are estimated as the product of the number of different features and the total number of features within a reach. The values are normalized by reach length and multiplied up to a standard 100 m length to give scores in terms of 100 m channel sections. Patchiness is simply the number of different features recorded; again normalized by reach length and multiplied up to 100 m lengths. The hydraulic and substrate data were used to generate summary statistics and distributions for comparison.

The process level analysis was based on an assessment of the sediment transport and stream power characteristics of each reach. Three criteria were used:

1. ability to mobilize median surface bed material which was seen as a test of the overall stability of the river bed;
2. sediment continuity through the reach, which was used as a test of the sustainability of the reach in terms of sediment transfer (reaches in equilibrium should convey as much sediment on entry as exit) and a way of assessing the impacts of rehabilitation;
3. presence of significant fluvial or geotechnical bank erosion in the reach.

Estimates of stream power, critical entrainment threshold for the median (D_{50}) particle motion and sediment transport rates ($kg\,m^{-1}\,s^{-1}$) were all established for each cross-section, in each reach for bankfull conditions using standard one–dimensional hydraulic and sediment transport modeling (See Chapter 18).

From the information collected at each site, the following specific conclusions can be drawn regarding the geomorphological process regimes. First, at all of the sites except one semi-natural reach, bed substrates are immobile at bankfull and lower discharges. This supports the findings of the wider "fluvial audit" that had highlighted the absence of bed morphology derived from scour and deposition of coarse sediments relative to other stream types. Secondly, the impact of rehabilitation has been to increase sediment transport capacity and maximum mobile particle size, but not sufficiently to generate a self-sustaining coarse sediment morphology (bars, pools, riffles). Rather, sediment conveyance is limited at most sites to at most fine gravels (<4 mm) and sands (<2 mm). Rehabilitation, has maintained sediment continuity with as much transport capacity into as out of the reach. Thirdly, at bankfull discharges, all the channels are competent to mobilize fine sediments (<2 mm). The observed accumulation of fines within each reach is therefore related to local zones of lower transport capacity such as channel margins and backwaters, or where flows are locally over-deep; for example, the pools between the rehabilitated riffles at one site. The relative roughness of vegetated channel margins and areas of flow recirculation downstream of meander bends are susceptible sites for fine sediment accumulation. This is corroborated by field observations of vegetated and unvegetated fine sediment berms at most sites.

In terms of channel geometry, the impacts of rehabilitation are again site specific, but in general they reduce bankfull depth (one of the design aims) and result in higher and more varied width:depth ratios. In this respect, they are probably moving towards the typical cross-section of natural chalk streams (Sear *et al.* 1999).

The physical features that contribute to channel form and habitat are an important measure of rehabilitation effectiveness, especially when they are the result of physical processes. Most rehabilitation schemes are based on the assumption that high physical habitat diversity or a specific suite of physical habitats will create improvements in biodiversity or specific target species. In practice, few studies have explicitly made this link. The analysis of physical habitat diversity undertaken for the river Wylye, revealed the following points; first the presence of coarse woody debris and riparian trees significantly increases the total number and type of geomorphological features present in a given length of channel. Thus, while rehabilitation of sites on the Wylye has increased both the frequency and type of geomorphological features found in a reach, they have not optimized these when considered in relation to a semi-natural analog stream (Figure 21.11). Secondly, the control reaches on the Wylye, which may be considered as typical of reaches that have been subjected to dredging, are shown to have an impoverished geomorphology relative to semi-natural reaches in the same river (Figure 21.11). However, rehabilitation has not achieved the same balance of features as those found in semi-natural chalk streams. Overall, there are too few pools and berms, and too many runs. Woody debris, though present, is currently

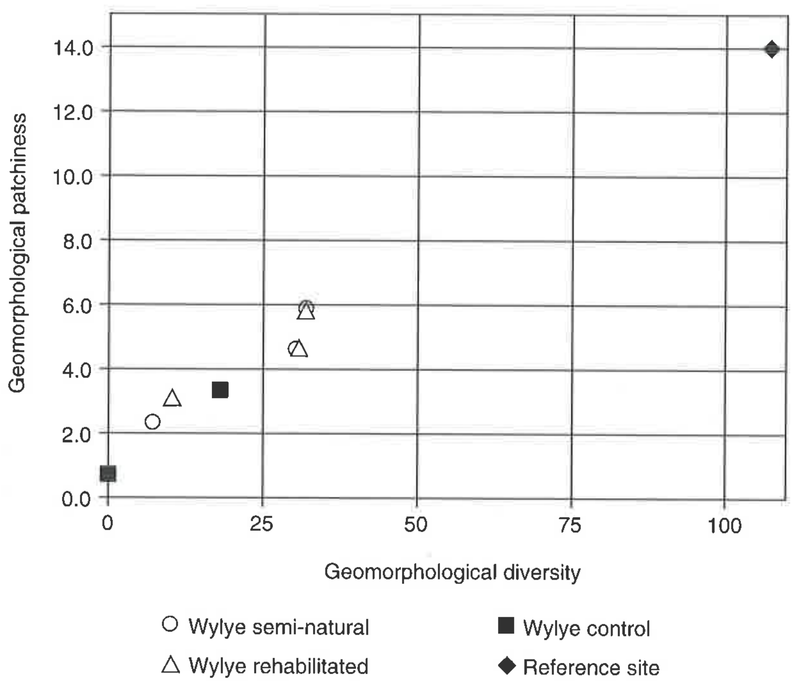

Figure 21.11 Geomorphological diversity and patchiness for control, rehabilitated, and reference sites illustrating the effect of coarse woody debris on physical habitat diversity

limited to bankside features or "island" type features that are not common in semi-natural chalk streams.

Overall, the rehabilitation has not significantly increased bed mobility or bank erosion. It has increased fine sediment transport capacity, but at the same time can increase the opportunities for accumulation due to the creation of a more varied hydraulic habitat. In terms of channel geometry cross-section form remains simple and relatively uniform. Only where riffle creation has been undertaken does the long profile show significant changes over control conditions. It is here where hydraulic conditions vary most and where fine sediment loads have increased over control conditions. Rehabilitation has decreased hydraulic variability whilst increasing depth variability at two sites, but it is very clear that each site has reacted differently. At no sites did physical habitat diversity approach that found in a semi-natural stream. Future rehabilitation programs should seek to create more varied physical habitat through the use of large woody debris. However, without treatment of the catchment-scale problems of fine sediment delivery, such rehabilitation projects will be subject to sedimentation. A more strategic approach that includes the catchment-scale issues is to be advocated.

21.11 CONCLUSIONS

The framework presented within this chapter is only one of many evolving within different regions around the world (Rosgen 1994, Brierley *et al.* 2002, Raven *et al.* 2002). Some, such as the river styles approach developed by Brierley *et al.* (2002), share a similar hierarchical structure in an attempt to integrate catchment-scale and reach-scale levels of investigation. Others, however, are tailored to provide specific outputs for a specific purpose (See Chapter 7). What is common to all is that the application of geomorphological tools must be undertaken within a clear conceptual framework designed to identify the geomorphic principles relevant to the management requirements. Furthermore, it is also vital in most applications, to interface with other relevant disciplines. GIS and the transfer of technology between disciplines are useful vehicles towards achieving these goals.

Social demands are complex, with multiple stakeholders and conflicts amongst them. With river management agencies increasingly considering longer-term perspective and larger spatial scales, the opportunity for geomorphologists to participate in the assessment of specific issues and to propose solutions is increasing (Piégay *et al.* 2002).

Land-owners, flood managers, ecosystem/nature conservancy managers, land managers and planners, civil engineers, as well as ecologists and other scientists can benefit from understanding geomorphological controls upon habitat dynamics and complexity, environmental chemistry, the complexity of fluvial forms and processes operating in the river system, basin-scale water and sediment transfer, and biogeochemical cycles.

Geomorphology programs in universities are now training more students who can operate at a practical level, and who typically work for management agencies or private companies conducting geomorphological studies and engineering designs. Moreover, interdisciplinary teams of scientists are increasingly common, and the traditional boundaries between disciplines are eroding as new fields such as ecogeomorphology, hydrogeomorphology, and ecohydrology develop.

There is a clear need to better explain to end-users the geomorphic basis of management-oriented classifications, and the tools geomorphologists use for different applications.

Fluvial geomorphic tools can support design planning, river bank protection, sediment supply, evaluation of impacts of proposed actions, sensitivity of systems, channel maintenance, ecological restoration and conservation.

At this stage of the evolution of the discipline and its increasing application to solving problems, there are strong needs to articulate the benefits of the geomorphological approach, to identify indicators and metrics to monitor and assess the efficiency of measures, to learn from experience in river interventions, to develop more collaborations within the geomorphological communities in order to make profit of the different experiences, and to use more of the (complementary) tools available. The development of models is a key challenge, as there is a need to simplify them, then to adapt them to the local cases, and to test their performance and calibrate them by using retrospective information. For each river of application, the development of conceptual models should be encouraged providing a schedule within which some hypothesized links can be tested. Finally, even if the geomorphological analyses and predictions are correct, that does not guarantee a successful project. Other factors such as cost efficiency, water resources demands, and social consequences must be considered. Interdisciplinary teams and scenario elaboration (prospective approaches) can help improve the chances of success of future projects.

Whilst the increasing use of geomorphology is encouraging, a further problem lies in ensuring that the information is translated into policy and improved practices.

Information derived using tools such as those described in this book is only valuable if the people commissioning the work understand its value and utility. Perhaps after all, among the most powerful tools available to the geomorphologist is the ability to educate non-specialists!

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