Journal of Applied Ecology 2005
42, 201–207

SPECIAL PROFILE

River restoration: seeking ecological standards. Editor's introduction

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Summary

1. In the face of continuing anthropogenic stressors to freshwater systems world-wide, the natural resilience and resistance of the freshwater ecosystems that enables them to cope with or recover rapidly from certain levels of perturbation is under significant threat. In many systems, the changes brought about through human activities have significantly altered the physical habitat and ecological functioning of the natural systems.
2. Given the importance of freshwater systems in the provision of ecological services and diverse habitats for a huge range of species, there is a clear need for restoration that can maintain sustainable ecological services whilst reinstating ecosystem function and habitat range.
3. While restoration has been attracting huge financial investment in recent times, to date there has been little or no consensus as to what constitutes successful ecological restoration. The studies highlighted in this Special Profile attempt to meet this challenge. The Forum paper establishes a set of criteria or standards against which restoration projects can be evaluated, and these criteria are discussed by both practitioners and researchers in two Comment papers.
4. The five criteria proposed in the Forum paper include the establishment of a dynamic ecological endpoint to the restoration, providing for a 'guiding image' of a healthier river, and an improvement in the river's ecological condition, that ideally leads to a more self-sustaining and resilient system. No lasting harm should be inflicted on the system during the restoration, and pre- and post-assessment and monitoring must be incorporated into the overall restoration project. An additional sixth criterion is proposed in one of the Comment papers whereby a description or prediction of the ecological mechanisms should be determined through which the intended restoration strategy will achieve its goals
5. The kinds of mechanisms that might be involved are explored in three research articles in the Special Profile, centred on river systems that have been subject to regulation or channelization. The mitigation of the effects of river regulation measures and the successful restoration of floodplain ecosystems has a focus on re-establishing river flow dynamics (temporal heterogeneity) and connectivity of the river with the floodplain. Restoration of channelized systems is centred on increasing the structural (spatial) heterogeneity of the system.
6. *Synthesis and applications*. River restoration is a world-wide phenomenon of growing importance as we attempt to redress the problems that have arisen from our use and misuse of freshwater habitats and resources. The adoption of standards for ecologically successful river restoration promoted by Palmer *et al*. (2005), along with the clarifications raised in the Comment papers, will go a long way towards meeting this objective. There is a clear responsibility for funding agencies to undertake meaningful monitoring of restoration projects, not only to provide information on the effectiveness of the restoration in ecological terms, but also to provide much needed data to help establish further the science of restoration. The objective of this significant initiative is eventually to achieve approval of the standards by the sponsoring/funding agencies of restoration, by the practitioner community that carries out the restoration, and by the scientific research community. This will require much greater interaction between ecologists, the

larger academic community and the practitioners, with the common goal of implementing more ecologically effective restoration projects, a goal that must also be embraced by the restoration project sponsors and regulators.

Key-words: ecological services, ecological standards, freshwater resources, river regulation, river restoration

Journal of Applied Ecology (2005) **42**, 201–207
doi: 10.1111/j.1365-2664.2005.01020.x

Introduction

Functionally intact and biologically complex freshwater ecosystems play important and unique roles for society through provisioning (e.g. of products and food), supporting (e.g. waste processing and sustained supply of clean water) and enriching or cultural (e.g. aesthetic and recreational) services (Postel & Carpenter 1997; Covich *et al*. 2004). However, the number and magnitude of anthropogenic stressors that threaten these services is growing rapidly (Giller *et al*. 2004). These arise from the myriad of human activities that include engineering, pollution and forced climate change and overexploitation of natural resources (see reviews by Postel & Carpenter 1997; Malmqvist & Rundle 2002). These stressors are both internal, such as direct pollution and geomorphic engineering of the river channel, and external, for example through land-use change in the catchment.

All major rivers and lakes world-wide have large human conurbations on them. The growth of the human population, and the mismatch between such growth and provision and accessibility of potable water resources, is a huge cause for concern (Cohen 1995, 1997). Even now, it is estimated that 1·8 billion people live under a high degree of water stress (Vörösmarty *et al*. 2000). Much ongoing water management is based around manipulating the hydrological cycle at local to catchment scales, such a flood alleviation and channelization, water regulation and irrigation. Engineers have built thousands of kilometres of diversion canals, channels and levees to divert water for human use; drained wetlands for urban development; channelized systems to aid navigation; and dammed rivers for water abstraction and the generation of hydroelectric power. More than 70% of the large rivers of Europe, North America and the former Soviet Union are strongly regulated, and there are more than 800 000 dams world-wide that obstruct approximately two-thirds of the fresh water flowing to the oceans (Dynesius & Nilsson 1994; Rosenberg, McCully & Pringle 2000). In Sweden alone, more than 70% of the rivers are regulated and more than 33 000 km channelized (Jansson *et al*. 2000; Törnlund & Östlund 2002). While some of this activity provides important services for the human population, it also significantly and negatively degrades many others. The example of the demise of the Aral Sea is a clear case in point (Micklin 1992). Freshwater habitats and organisms are threatened throughout the world (Palmer *et al*. 1997), and in fact species loss is greater in freshwaters than any other system (Jenkins 2003).

Lakes are susceptible to various stressors because of the slow turnover of water, potential for accumulation of toxins, etc. in their sediments, and dependence on the quality and quantity of water inputs from inflow streams. The susceptibility of rivers, on the other hand, is exacerbated by their linear and unidirectional nature, such that almost any activity within a river catchment has the potential to cause environmental change, and any significant pollutant entering a river is likely to exert some effect for large distances downstream (Malmqvist & Rundle 2002). The wide range of stressors and impacts that can affect freshwater systems can be conveniently classified into four major types: ecosystem destruction, physical habitat alteration, water chemistry alteration and direct species additions and removals (Malmqvist & Rundle 2002). Figure 1 highlights the general interactions between six major services provided by freshwater systems and 14 major threats.

There is a strong regional influence on the nature of threats to freshwater ecosystems, dependent largely on the economic activity and state of development of the country. Pressure on potable water quality is high in much of north and east Africa, Australia and parts of North America. Even in the more temperate countries, major concentrations of human population are often located in areas of lowest rainfall, creating local water deficits that require large-scale engineering projects and water regulation activities to overcome them. These pressures on water resources are predicted to become even more pronounced in Africa and South America by 2025 (Vörösmarty *et al*. 2000). Eutrophication and lowering of water tables as a result of groundwater abstraction threaten lakes in the developed world, while in the developing world overexploitation of fish and invasion from exotic plants (e.g. the water hyacinth *Eichhornia crassipes* or Himalayan balsam *Impatiens glandulifera*; Wadsworth *et al*. 2000) are more problematic. Destruction of running water habitats is extensive in much of the developed world as a consequence of

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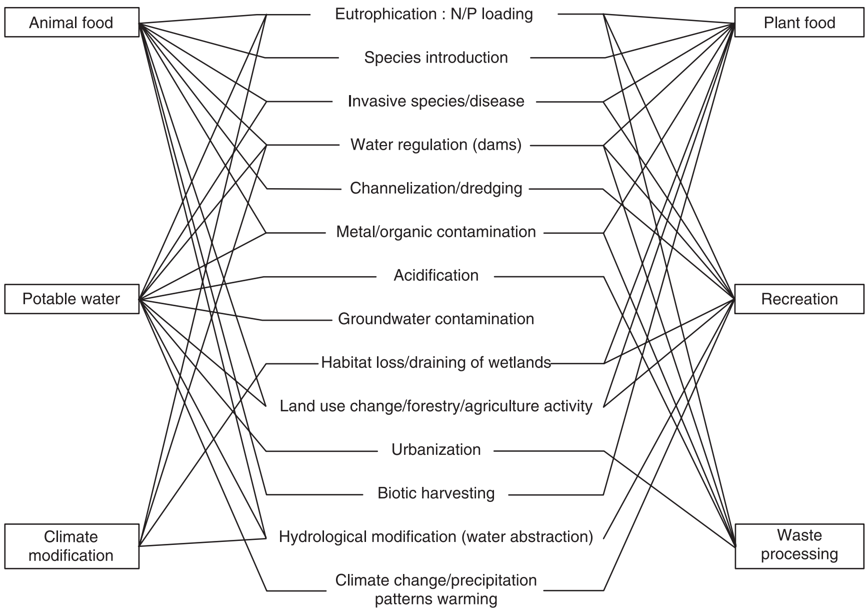

Fig. 1. The interaction between six major ecosystem services, provided by freshwater systems, and 14 potential threats and stressors in the freshwater domain. Adapted with permission from *Sustaining Biodiversity and Ecosystem Services in Soils and Sediments*, © 2004 Island Press (Giller *et al*. 2004).

flood control, drainage schemes and navigation, and in the developing world largely from dam construction and mining (Covich *et al*. 2004). Waste disposal (domestic and industrial, treated and untreated) threatens many systems, and leads to significant levels of eutrophication. This occurs in rivers in developed states, such as the Rhine and its tributaries (Giller *et al*. 2004), and in developing countries, such as the Aweta river in Ethiopia. These freshwater systems are also susceptible to metal and other chemical contamination. Changing land use in the catchment, such as deforestation, overgrazing and intensification of agriculture, can lead to diffuse (non-point source) pollution, sedimentation and eutrophication. The loss of riparian zones that often accompanies such intensification (e.g. as in the Netherlands) also leads to dramatic changes in ecosystem functioning. More than 95% of lowland river channels in south-east England and Denmark have been modified to enhance land drainage, for flood prevention and for navigation, resulting in simplified and uniform channels, unnaturally steep banks and significantly reduced connectivity with the floodplains (Harrison *et al*. 2004). Even atmospheric pollution can impact on aquatic systems, as evidenced by the acidification problems that have occurred across northern Europe, north-eastern USA and Canada (Stoddard *et al*. 1999).

River regulation for hydroelectric power generation and/or irrigation is a provisional service of growing importance yet it has negative consequences on other ecosystem services (*sensu* ecosystem disservices; Giller *et al*. 2004). Natural rivers and streams are temporally heterogeneous systems and the whole raison d'être of river regulation is to reduce or regulate the naturally variable flow patterns. The homogenization is also often increased through habitat loss, and fragmentation can occur. In heavily regulated systems a general change from lotic to lentic, or even to dewatered, conditions along certain stretches of river is possible. Regulation-related flow alterations and other river engineering activities thus have the potential to cause fundamental changes to entire biotas (Malmqvist & Englund 1996; Postal & Carpenter 1997; Rosenberg, McCully & Pringle 2000; Giller *et al*. 2004; Harrison *et al*. 2004). The impacts on the functioning of these systems is also significant (Lepori, Palm & Malmqvist 2005). Similarly, channelization is a major cause of habitat degradation in running waters (Allan & Flecker 1993), leading to loss of structural diversity, simplified flow patterns and poor retention of organic matter.

Given all the various threats to ecosystem functioning in freshwater ecosystems, one could ask why the problem is not worse than it is. The answer lies partly with the level of technology and infrastructure we are able to bring to bear to ameliorate the effects, and partly with the natural resilience and resistance of the freshwater ecosystems that enables them to cope with or recover rapidly from certain levels of perturbation. But what happens when this innate capacity is overcome, when vital ecological services are compromised or when managers are legally obliged to meet certain environmental standards, international conventions and directives, such as the European Union (EU) Water Framework Directive? This leads us to the topic of this Special Profile, river restoration.

Restoration is growing in importance as we attempt to redress the problems that have arisen from our use and misuse of freshwater habitats and resources. River and stream restoration is a booming and world-wide phenomenon (Henry, Amoros & Roset 2002; Ormerod 2003; Palmer *et al*. 2005). But what are the goals of such restoration? Reinstatement of the entire pre-disturbed system, or of its functions, or both? Recovery of damaged species populations or return of species lost during the environmental changes that have taken place? Or perhaps recovery of the connections between the system being restored and other ecosystems such as floodplains, riparian zones, groundwaters and down-stream habitats? In this Special Profile these issues are explored from a number of viewpoints through a major Forum paper (Palmer *et al*. 2005), two commentaries on the Forum paper (Gillilan *et al.* 2005; Jansson *et al*. 2005) and three research-based papers (Lepori, Palm & Malmqvist 2005; van Geest *et al*. 2005; Leyer 2005).

Restoration approaches

River restoration projects aim to increase ecosystem goods and services, and ideally convert damaged freshwater systems into sustainable ones whilst protecting downstream and coastal ecosystems (Palmer *et al*. 2005). River rehabilitation can be passive, where we simply allow natural hydraulic forces to reshape rivers slowly and reinstate the natural heterogeneity (Gillilan *et al.* 2005). Alternatively, we can apply specific and active measures more rapidly to modify channel form and structure or to reintroduce variations in stream flow, recognizing that river systems are naturally dynamic. In the UK, for example, most recent restoration schemes have developed from those initiated in the USA since the 1920s (Harrison *et al*. 2004). A number of recent examples of such schemes and their impacts have been published in the *Journal of Applied Ecology* (Muotka & Laasonen 2002; Pretty *et al*. 2003; Harrison *et al*. 2004). In the USA, variable stream flow techniques have been introduced to management strategies to balance water delivery for irrigation and power generation with instream ecological needs (Baron *et al*. 2002). This approach also helps to reconnect the river system to the riparian and groundwater systems, which is essential for fully functional riverine ecosystems. Variable stream flow is proposed as a possible management tool to solve problems caused by flow regulation in major European rivers such as the Elbe (Leyer 2005).

Other restoration approaches target pollution, both point source and diffuse, to enhance water quality. The Rhine and Meuse comprise one of the most dramatic examples. Since the early 1900s, increased nutrients, salts and heavy metals, in addition to increasing levels of organic micropollutants (such as PCBs, insecticides and herbicides), have arisen from inputs from several countries, and have accumulated in and contaminated sediments, particularly in the lower sections of the rivers (for a summary see Giller *et al*. 2004). The dramatic changes to water chemistry have enhanced the invasion of exotic species and led to significant increases in primary production of riverine plankton. Over the past few decades, the Rhine Action Plan, established by the Dutch government, has implemented various measures to restore water quality through sewage treatment, control of point source pollution, reduction of pollution loads in the entire drainage basin, restoration of wetland vegetation and re-establishing connections between the main channel and floodplain lakes (van den Brink 1994). Jungwirth, Muhar & Schmutz (2002) provide a number of other examples of similar river and floodplain restoration projects, and van Geest *et al*. (2005) have undertaken a large-scale assessment of the effects of river regulation on vegetation of floodplain lakes in the lower Rhine system.

A further approach to restoring water quality in freshwater systems involves the overall management of entire catchments or river basins, including land-use and management practices associated with forestry and agriculture. The management of the Catskill Mountains watershed to provide New York city's water supply is the major success story in this respect (Ashendorff *et al*. 1997; Foran *et al*. 2000). National directives and guidelines have been produced all over the world in an attempt to set goals for water quality and targets for other ecosystem services, such as the European Water Framework Directive and the US EPA guidelines for acceptable nutrient runoff for different regions (based on the total maximum daily load of a pollutant that a water body can receive; Baron *et al*. 2002).

Measuring/assessing success of restoration

As Palmer *et al*. (2005) point out in this Special Profile, there is growing interest in applying river restoration techniques to solve the multitude of environmental problems arising from human misuse of freshwater systems, yet there is very little agreement on exactly what constitutes a successful restoration project. Despite the huge interest and activity in river restoration, and the fact that ecologically effective restoration has been actively pursued for more than three decades, practical criteria for judging ecological success do not exist. Stringent evaluations of the ecological consequences of restoration schemes are scarce (Bash & Ryan 2002) and projects cited as restoration successes may in fact not be ecologically successful. This is clearly a problem, because the ecological assessment of restoration work is necessary for management reasons and to improve our understanding of how ecosystems work (Bradshaw 1993). Also, under national and international conventions and directives, it is clear that achieving successful ecological restoration is critical.

In their Forum paper 'Standards for ecologically successful restoration', Palmer *et al*. (2005) propose a set of five criteria for measuring success. This is built around specifying a dynamic ecological endpoint to the restoration, providing a 'guiding image' of a healthier river that could exist at the site. The restoration must improve the river's ecological condition, and lead to a more self-sustaining and resilient system. No lasting harm should be inflicted on the system during the restoration construction phase, and pre- and post-assessment and monitoring must be incorporated into the overall restoration project. Palmer *et al*. (2005) also suggest standards of evaluation for each of these criteria and examples of suitable indicators. The goal of this significant initiative is eventually to achieve approval of the standards by the sponsoring/funding agencies of restoration, by the practitioner community that carries out the restoration, and by the scientific research community. Thereafter, it will be necessary to identify the appropriate sets of indicators to evaluate ecologically successful restoration, which could range from re-establishment of single species or multi-species communities, to more complex food webs and more efficient or enhanced ecosystem functions.

Palmer *et al*.'s (2005) Forum calls for broad input, comments and critique from the research and practitioner communities in order to achieve their goal, and this call has been responded to in the two Comment papers in this issue (Gillilan *et al.* 2005; Jansson *et al*. 2005). As practitioners, Gillilan *et al.* (2005) strongly support the need for ecologically based standards in restoration. They identify a continuum of restoration types that range from targets with strong ecological goals to hard engineering erosion control and containment efforts. The early establishment of a guiding image with a dynamical ecological end state is seen as the most critical aspect of a restoration project. By objectively placing their projects along this continuum as part of the guiding image process, practitioners and sponsors of restoration can identify the relative ecological benefits of their project and act accordingly. As Ormerod (2003) has proposed, where conservation has failed and critical ecological services have diminished, ecologically sound restoration should be the option. However, historical data on structure and functioning of the freshwater ecosystem prior to degradation is often absent, leading to major problems for practitioners (and sponsors of projects) in defining the appropriate guiding image. This problem can be overcome to an extent through the identification of appropriate reference systems as the guide. This approach offers the possibility of further assessment of success of the restoration project through comparisons of rates of change in various ecological variables between restored and reference channels. Jansson *et al*. (2005) propose further development of the guiding image principle. They propose a sixth criterion to measure ecological success of restoration whereby the image should be supplemented by a description or prediction of the ecological mechanisms through which the intended restoration strategy will achieve its goals. They argue that, by adopting this additional criterion, we will not only gain an improved understanding of why certain restoration projects succeed but also provide a more powerful deductive framework for recommending future successful strategies across river systems. The practical application of this criterion poses significant challenges to the practitioner community (as point out by Jansson *et al*. 2005) but would cement the need for strong scientific involvement at all stages in all restoration projects.

Both Gillilan *et al.* (2005) and Jansson *et al*. (2005) stress the need for funding agencies to undertake meaningful monitoring of restoration projects, not only to provide information on the effectiveness of the restoration in ecological terms, but also to provide much needed data to help further establish the science of restoration. Again as Jansson *et al*. (2005) point out, much of the uncertainty about the success of restoration projects in the past stems from poorly designed studies. We must learn from these mistakes and ensure that future projects include well-planned, adequately replicated studies with carefully chosen reference reaches and appropriate measurements of relevant dependant variables for assessment of ecological success (as exemplified by the studies of Pretty *et al*. 2003; Harrison *et al*. 2004). In this context it is essential that the outcomes of restoration, even the failures, are widely disseminated.

Developing guidelines for restoration: case studies from river regulation and channelization

To provide appropriate guidelines on how to rehabilitate impacted systems, we need to know how regulation of river discharge affects the biodiversity and ecosystem functioning of large rivers. Two research papers in this Special Profile (Leyer 2005; van Geest *et al*. 2005) explore the consequences of river regulation on floodplain and riparian vegetation. They illustrate some of the functions involved and give pointers towards future management approaches and restoration targets, and provide a glimpse of possible mechanisms through which restoration may act. The third paper in the Special Profile (Lepori, Palm & Malmqvist 2005) examines the effectiveness of restoration at the ecological level and illustrates the application of some of the standards proposed by Palmer *et al*. (2005).

Nearly all the large rivers in central Europe and the USA are affected by dykes and other channel containments. As discussed earlier, this reduces seasonal variation in water levels and peak flows and hence disrupts the connectivity between river and floodplain. This leads to the considerable loss and degradation of floodplains and also disruption to various ecological processes in the river itself. The River Elbe in Germany is a case in point. By examining a gradient from highly fluctuating (unregulated natural floodplains) to stable (highly regulated) water tables, Leyer (2005) has investigated the response of floodplain grassland species. Dams and dykes cause drought stress at high elevations where water level fluctuations are significantly damped, but the reverse is seen at low elevations such as floodplain depressions, because of permanent inundation conditions. The data allow clear predictions of the shifts in the floodplain vegetation in the face of regulation of the river system. The study concludes that restoration of floodplain meadows will fail unless river–floodplain connectivity is improved. The intensity of floodplain fragmentation by dykes and dams, defined as the ratio of recent to entire floodplain area, could be considered as a possible indicator of ecological status and successful ecological restoration in riverine systems. As Leyer (2005) points out, the EU Water Framework Directive needs to pay much more attention to the ecological status of floodplain systems.

A study of the artificially created water regimes of the lower Rhine in the Netherlands by van Geest *et al*. (2005) describes how the reduction in seasonal variation in water levels and in peak flows negatively influences the diversity and sustainability of floodplain inundation lakes. The problems arise from the effective stabilization of river water levels during low discharge, which negatively affect species composition and successional processes. Flooding, through surface connections with the main river channel, river seepage and infiltration, influences water levels and other characteristics of the floodplain lakes. van Geest *et al*. (2005) found a decreasing amplitude of water level fluctuation with lake age that impacts negatively on macrophyte succession. They also demonstrated that the strongly stabilized water levels in the main channel and adjacent floodplain lakes leads to a decline in overall plant species richness and loss of characteristic riverine species. Changes in water levels during low river discharge periods are of particular importance to the natural functioning of these systems. Thus the natural water level regime should be restored to conserve the full successional range of floodplain water bodies. Management, including the temporary recovery of river water level, may enhance the ecological status of regulated rivers. Understanding these kinds of relationships and understanding the mechanisms controlling the ecological communities and processes illustrated by these two papers (Leyer 2005; van Geest *et al*. 2005) will assist the development of informative guidelines for future successful rehabilitation of riverine systems.

The mitigation of the effects of river regulation measures and the successful restoration of floodplain ecosystems has a focus on re-establishing river flow dynamics and connectivity of the river with the floodplain. This is effectively re-establishing temporal heterogeneity in conditions. Instream restoration from channelization is based around spatial/structural heterogeneity, and Lepori, Palm & Malmqvist (2005) provide an excellent example of recovery of ecosystem functioning through restoration. Most river restoration in Sweden is targeted at enhancement of this structural heterogeneity through the replacement of boulders and removal of instream constructions (Muotka *et al*. 2002). The restoration of channelized streams examined by Lepori, Palm & Malmqvist (2005) would be classed as enhancement under Gillilan *et al.*'s (2005) restoration project type continuum, as it involves placement of boulders. As a way of assessing the ecological restoration of these streams, two key ecosystem functions (retentiveness and litter breakdown) were examined. Retentiveness of organic matter increased significantly in restored sites but litter breakdown rates were not affected and the detritivore communities were similar in channelized and restored systems. However, the low retentiveness and rapid mechanical breakdown of litter during high flows in channelized streams led to rapid depletion of benthic coarse particulate organic matter, weakening the vital heterotrophic energy pathways and probably much of the biological production in these systems. The restoration successfully reversed these impacts of channelization and reinstated much of the ecological functioning.

These kinds of studies begin to identify the kind of mechanisms sought by Jansson *et al*. (2005) and identify some of the potential indicators through which we can begin to assess the ecological success of restoration projects as proposed by Palmer *et al*. (2005). As Gillilan *et al.* (2005) point out, there is a need to elevate the practice of river restoration to a science of restoration. The adoption of standards for ecologically successful river restoration promoted by Palmer *et al*. (2005), and supported by practitioners and researchers alike, will go a long way towards meeting this objective. We will, however, need much greater interaction between ecologists, the larger academic community and the practitioners, with the common goal of implementing more ecologically effective restoration projects. This goal must also be embraced by the project sponsors and regulators, and therein lies a major yet critical challenge.

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Received 26 January 2005; final copy received 1 February 2005