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THE ROYAL SOCIETY

Ecological response to and management of increased flooding caused by climate change

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River channels and their flood plains are among the most naturally dynamic ecosystems on earth, in large part due to periodic flooding. The components of a river's natural flood regime (magnitude, frequency, duration and timing of peak flows) interact to maintain great habitat heterogeneity and to promote high species diversity and ecosystem productivity. Flood regimes vary within and among rivers, depending on catchment size, geology and regional hydroclimatology. Geographic variation in contemporary flood regimes results in river-to-river variation in ecosystem structure, and therefore in potential river ecosystem response to increased future flooding. The greater the deviation in flood regime from contemporary or recent historical conditions, the greater the expected ecological alteration. Ecological response will also depend on how extensively humans have altered natural river dynamics through land-use practices. Examples of human-caused changes in flood regime (e.g. urbanization, agricultural practices) provide analogues to explore the ecological implications of region-specific climate change. In many settings where humans have severely modified rivers (e.g. through leveeing), more frequent larger floods will work to re-establish connections with severed flood-plain and riparian wetlands in human-dominated river valleys. Developing and implementing non-structural flood-management policies based on ecological principles can benefit river ecosystems, as well as human society.

Keywords: floods; rivers; ecosystem; non-structural flood control; climate change

I do not know much about gods; but I think the river
Is a strong brown god—sullen, untamed and intractable,
Patient to some degree, at first recognized as a frontier;
Useful, untrustworthy, as a conveyer of commerce;
Then only a problem confronting the builder of bridges.
The problem once solved, the brown god is almost forgotten
By the dwellers in cities—ever, however, implacable,
Keeping his seasons and rages, destroyer, reminder
Of what men choose to forget. Unhonoured, unpropitiated
By worshippers of the machine, but waiting, watching and
Waiting.

T. S. Eliot, *The dry salvages*

One contribution of 18 to a Discussion Meeting 'Flood risk in a changing climate'.

1. Introduction

From a purely physical-science perspective, rivers are simply conduits of water and sediment (along with associated chemical constituents) moving downhill. During floods, great volumes of water and sediment flow through the river valley, pausing temporarily on flood plains on their route to the sea. From an engineering and social perspective, rivers often represent untamed nature in need of harnessing for human progress. Floods destroy structures and often cause severe dislocation of human populations and commerce. From an ecological perspective, floods are the life blood of rivers. Flood waters do extensive work on the river channel and boundaries, eroding and depositing sediment within the channel and on the flood plain, and they inundate riparian wetlands, enriching them with suspended nutrients. The rhythm of flooding defines the river ecosystem. Science now recognizes these extreme events as beneficial natural disturbances, essential to maintaining a mosaic of dynamic, heterogeneous habitat types that support many species having different environmental requirements, and thereby sustaining the high biological productivity and ecological integrity of rivers (e.g. Resh *et al.* 1988; Junk *et al.* 1989; Poff *et al.* 1997).

Indeed, due to the mechanical disturbance created by flooding, rivers and their flood plains are among the most biologically diverse and productive ecosystem types on the planet (Bayley 1995; Naiman & Décamps 1997). They support unique species that specialize in exploiting the spatially and temporally heterogeneous transition zones between aquatic and terrestrial (upland) ecosystems. In short, from an ecological perspective, floods are not *disasters* in the sense that human society typically views them. Through destruction, floods rejuvenate river ecosystems by maintaining dynamic ecological structure and function. Therefore, when flood regimes are altered, natural river functioning may become impaired.

Humans have greatly modified rivers in order to exploit the natural resources they provide. The cornerstone of the 'taming' of rivers has been flood management, which has allowed humans to live in ever closer contact with them. Humans have endeavoured to engineer rivers to convey flood waters rapidly downstream by decreasing natural storage through such activities as wetland drainage, channelization and leveeing of flood plains. Another primary type of alteration has been the construction of dams to capture flood waters to promote settlement of downstream flood plains. While these actions have allowed greater exploitation of river valleys, their unintended consequences have been to impair many of the natural functions of rivers precisely by diminishing the ecological rejuvenation provided by flooding. Growing social concerns over the alteration of natural biophysical processes, the persistence of rare and endangered species, and the sustainability of fisheries in regulated rivers, has stimulated much discussion about the science of river restoration (e.g. NRC 1992; Naiman *et al.* 1995; Poff *et al.* 1997).

Anthropogenic climate change that alters dominant patterns of precipitation and run-off presents a real threat to the structure and function of aquatic ecosystems, including rivers, lakes, wetlands and coastal systems (Meyer *et al.* 1999; Poff *et al.* 2001; Poff *et al.* 2002). An increase in flood frequency is likely to substantially alter many river ecosystems, but the degree to which that happens will likely depend on deviation from background conditions and on how humans respond to the increased flooding. A review of current understanding of the important role of flooding in structuring river ecosystems and an examination of how rivers are likely to respond both

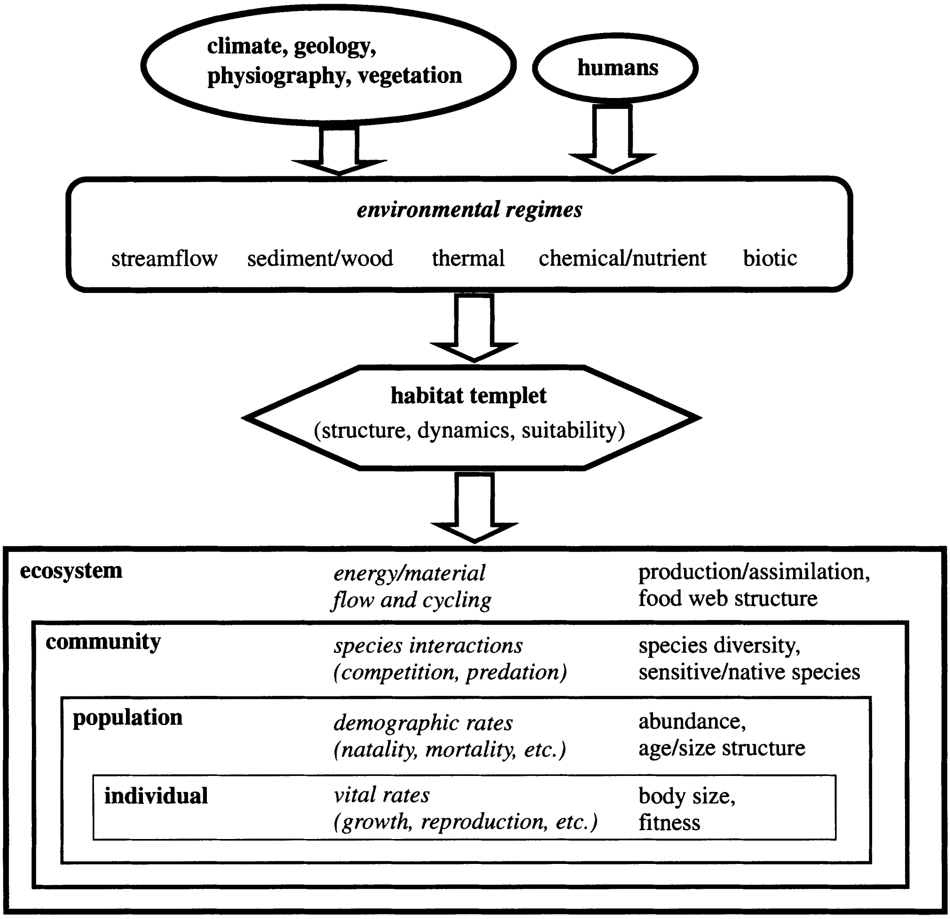

Figure 1. Conceptual illustration of the habitat templet model of ecological organization in riverine ecosystems, showing controls on dominant environmental regimes at the catchment scale and how these regimes define habitat characteristics and thereby mediate the outcomes of multi-scaled ecological processes to influence ecological structure and function in an ecological hierarchy.

physically and biologically can provide a framework for evaluating river responses to climate change.

2. Ecological responses to flood regime

Environmental variability (including flooding) plays a critical role in structuring aquatic and riparian ecosystems through mediating the directions and outcomes of ecological processes at multiple scales of hierarchical ecological organization (figure 1). The structure we observe in these ecosystems results from the complex interactions of these many processes with the temporal variation in environmental 'drivers', which when integrated over space create a dynamic physical templet that defines habitat quantity, quality and suitability (Poff & Ward 1990; Townsend & Hildrew 1994). A change in environmental drivers modifies the templet, which in turn modifies the relative outcomes of ecological processes, resulting in a change in ecological structure and function. This is the basic conceptual model for ecological response to environmental alteration, such as rapid climate change, where the regimes of one or more environmental drivers may be expected to change on a regional scale and thereby modify river ecosystems.

Many examples in the literature show how individual species populations, whole communities and ecosystem processes are directly influenced by streamflow regimes, a dominant environmental driver. Several good reviews of this topic are available (Poff *et al.* 1997; Gasith & Resh 1999; Bunn & Arthington 2002). Flooding is an important aspect of the streamflow regime, and here I provide some selective examples that illustrate how flood disturbance per se regulates ecological processes and pattern.

Floods are important ecological agents for at least two reasons. First, they directly kill many organisms via such physical processes as scouring, burial or displacement into unsuitable habitats. Many species have evolved specific traits to avoid flood-related mortality. Second, they create new habitat and alter resource distributions via transport and/or deposition of sediment, woody debris and nutrients. Many species have adaptations to exploit these newly created (and often transient) conditions.

Species differ greatly in their resistance to flood damage. For example, species inhabiting arid-land streams subject to unpredictable flash flooding have behavioural adaptations. Native fish (unlike introduced species in the same streams) will seek slack water refuge upon the slightest increase in water velocity (Meffe 1984) and some aquatic insects will crawl onto land perpendicular to the stream in response to intense rainfall on the stream surface (Lytle 1999).

Mortality can be a function of life stage. Small fish can be washed downstream (Harvey 1987) and juvenile aquatic invertebrates can be crushed (Fisher *et al.* 1982). Natural selection has favoured adaptations that minimize mortality risk for vulnerable life stages. Furthermore, species often differ regionally in the timing of reproduction in response to the timing of floods. For example, stream species inhabiting regions with a predictable annual snow-melt peak may time their reproduction so that eggs hatch after expected peak flows. The rainbow trout (*Oncorhynchus mykiss*) typically spawns in spring and the fry emerge by early summer, a strategy that apparently fits the winter to early spring flooding regimes of their original range in the western US. This species has failed to become successfully transplanted to many regions of the world, including much of Europe, where the timing of flood flows coincides with the vulnerable young juvenile stage (Fausch *et al.* 2001). Similarly, introductions of non-native trout species that have their eggs in the gravel over the winter months have had limited success in streams in the Pacific Coast states of the US, where heavy winter flows scour the fish nests (e.g. Erman *et al.* 1988).

Some species actually rely on floods to complete their life cycles. Perhaps the best example is provided by various species of cottonwood trees (*Populus*) in arid western North America. The seeds of these trees are released during the predictable period of spring snow melt, and they are rafted up onto freshly scoured or deposited flood-plain soils where they germinate (Scott *et al.* 1996). The absence of flooding of adequate magnitude, duration and timing can cause dramatic declines in flood-dependent species, such as cottonwoods, and promote the establishment of non-native or competitively inferior species that are intolerant of flooding, with a subsequent loss of riparian species diversity (e.g. Merritt & Cooper 2000).

The productivity of rivers and flood plains can also be influenced by flooding. Frequent scouring can reduce invertebrate biomass and production (Fisher *et al.* 1982), and the absence of flooding via regulation can modify aquatic food webs (Wootton *et al.* 1996). On flood plains, flooding saturates accumulated organic matter and promotes nutrient cycling and ecosystem production in both arid (Molles *et al.* 1998) and humid (Nilsson *et al.* 1999) regions. One of the dominant paradigms in large-river ecology, the flood-pulse concept (Junk *et al.* 1989), explicitly incorporates the importance of flooding for ecosystem productivity. On large rivers globally, annual floods spill over onto well-developed flood plains creating habitat for fish and waterfowl. The stimulation of nutrient cycling promotes production of macrophytes, phytoplankton and zooplankton, which support juvenile fish. Fishery production has been shown to be enhanced in river–flood plain systems that experience the flood pulse, in both tropical and temperate rivers, including Europe (Bayley 1995). Where the flood pulse is truncated by levees, dams, etc., flood-plain production and species diversity decline (Sparks 1994).

The central importance of flooding to river ecology is now recognized. Indeed, one of the emerging principles of management of regulated rivers, at least in the US, is restoration or maintenance of the magnitude and natural timing of flooding to maintain flood-dependent species and diminish the negative impacts of non-native species, both aquatic and riparian (e.g. Poff *et al.* 1997). Further modification of natural flood regimes has the clear potential to significantly modify ecological processes and change ecosystem structure and function, depending on species characteristics and on the specific type of flood alteration.

3. Geographic variation in flood regimes

Not all rivers exhibit the same flood regime. Regional variation exists, due to both intrinsic (river size, geologic setting) and extrinsic (climate) controls on flooding. Within a basin, flood regime typically varies with respect to river size, or position within the basin. Headwater and smaller streams have relatively greater topographic relief and thus steeper gradients, more confined channels, and little flood-plain development. Because smaller streams have smaller catchments, they respond rapidly to localized precipitation. Floods mobilize and transport bed sediments, thereby causing extensive in-channel mortality and exporting stored organic carbon and nutrients. The physical severity of floods selectively favours 'weedy' species that are adapted to high rates of mortality and thus able to recolonize quickly. As one moves downstream, channels broaden and valleys generally widen into alluvial flood plains. Floods are typically generated by larger-scale climatic events, often seasonally (e.g. frontal systems, hurricanes, snow melt), and these systems are correspondingly less flashy. Of course, smaller rivers can also have flood plains (even mountain valleys) and these alluvial valleys are biologically diverse and productive (e.g. Stanford & Ward 1993).

Given the ecological responses to flooding described previously, characterization of regional differences in flood regimes is an important step in evaluating the sensitivity of particular rivers to future changes in flooding. Geographic variation in streamflow patterns has been long appreciated and quantified with the availability of long-term run-off records. Several classifications of flow regimes have been produced, at different scales and for different regions of the world. For example, Haines *et al.* (1989) classified flow regimes at a global scale using data from different continents. At a continental scale, Grimm (1968) identified nine major groups of flow types for Europe (based on frequency and timing of peak flows and low flows). Lins (1997) generated

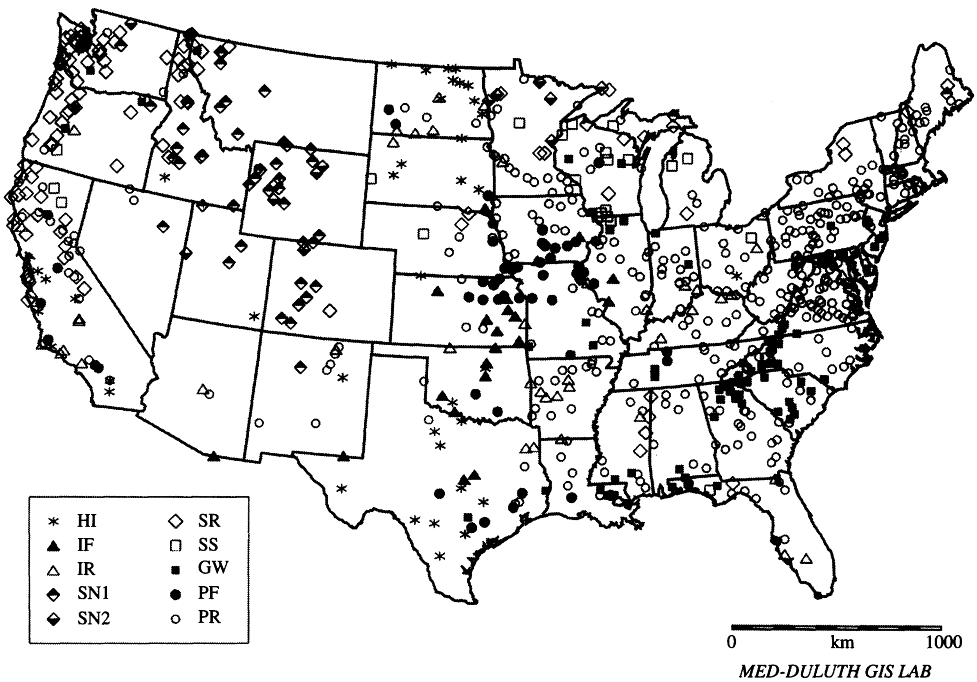

Figure 2. Hydrogeography of 806 undammed streams and rivers in the US based on 10 hydrological descriptors: HI, harsh intermittent; IF, intermittent flashy; IR, intermittent run-off; SR, snow plus rain; SN, snow melt; SS, super-stable groundwater; GW, stable groundwater; PF, perennial flashy; PR, perennial run-off. (Reproduced from Poff (1996, fig. 3) with permission of Blackwell Science.)

a hydroclimatological classification of 11 regions for the US based on seasonal and inter-annual flow variation.

Such regionalizations are valuable for providing a baseline hydrologic context against which climate-change effects on flow regimes may be assessed; however, the particular flow variables used in the aforementioned classifications are not specifically tailored to address questions of ecological sensitivity. In the last decade, as ecologists have begun to recognize the critical linkages between flow variation and ecosystem characteristics (e.g. Junk *et al.* 1989; Poff *et al.* 1997), regional flow-regime classifications have been constructed based on hydrological variables that are explicitly relevant to ecological processes in streams and rivers. These hydroecological classifications emphasize the patterning of flow variability at multiple time-scales, described in terms of frequency, magnitude, duration, timing and rate of change of flow events with ecological relevance (Poff *et al.* 1997). Computer software tools are now available and widely used to assist in codifying this approach (Richter *et al.* 1996). Several hydroecological classifications have been developed around the world, including in the US (Poff & Ward 1989; Poff 1996), in Australia (Hughes & James 1989) and in New Zealand (Clausen & Biggs 2000). As an example of such a classification, Poff's (1996) analysis is presented in figure 2, which shows the distribution of nine types of small-to-medium-sized undammed rivers in the continental US based on more than 20 years of daily streamflow data provided by the US Geological Survey. The interaction of prevailing climate and catchment factors such as geologic setting influence the geographic clustering of the streams, causing geographically proximate streams to sometimes fall into different ecological flow types. This ecological approach to classifying streams and rivers has been tested in both the US (e.g. Poff & Allan 1995; Richards *et al.* 1997) and New Zealand (Clausen & Biggs 1997) and appears to provide a reasonable basis for assessing how flow alteration (including increased flooding by climate change) may modify ecosystem attributes in rivers.

4. River responses to increased flooding

An increase in flood magnitude or frequency will amplify the role of flooding in structuring river ecosystems. However, not all rivers will respond similarly, because responses should be condition specific, i.e. set by the context of the extent of deviation relative to current or historical conditions. Again, flood regime alone will not dictate ecological response, because other critical aspects of the flow regime (e.g. drought) and environmental change (e.g. increased sediment input) may alter ecological resilience as well.

Many responses cannot be predicted with precision, due to uncertainties in predicting future climate at a regional scale (Senior *et al.* 2002). However, we can evaluate some possible changes based on current understanding of how the physical system responds to a change in the balance between water and sediment flux that will occur with increased flooding. Examples can be taken both from current analogues of increased flooding (e.g. urbanization, agricultural practices) and from historical analyses of previous periods of climate change.

(*a*) *Physical channel changes*

The response of stream and river channels to climate change is an important ecological consideration, because alteration in channel dimensions translates directly into modification in aquatic and riparian habitat. Shifts in channel dimensions occur when the balance between sediment and water flux is shifted, requiring channels to convey more or less water or sediment. The rate of channel response varies with the rate at which water and sediment regimes are modified.

Urbanization provides a possible analogue for evaluating channel response to increased flooding. By covering parts of a catchment with impervious surfaces, sediment supply is reduced and rapid run-off is enhanced. Typically, urbanized channels enlarge and straighten through channel downcutting and/or widening through bank erosion, depending on the relative erodibility of bed and banks, riparian condition and other factors (Wolman 1967; Bledsoe & Watson 2001). Sediment moves downstream through the network and may accumulate on flood plains as deposits during high flows. These changes can be rapid, especially for erodible channels near geomorphic thresholds (see Bledsoe & Watson 2001). Channels that are probably most sensitive to enhanced stream power and reduced sediment supply have beds or banks composed of non-cohesive sand, coupled with little vegetation and/or ability to dissipate energy of high flows on flood plains (Montgomery & Buffington 1998).

On a slightly longer time-scale, natural climate variability has been identified as causing rapid shifts in channel geometry over the last 200 years. Expansions and contractions of channel widths up to an order of magnitude have been documented in rivers of arid lands in response to changes in precipitation and vegetative cover (see Schumm & Lichty (1963) and references cited therein). In the US, Knox (2000) asserts that the unusually high frequencies of large floods observed in many regions since the early 1950s are attributable not only to conspicuous land-use change, but also to the 'rapid climate forcing' due to increased atmospheric greenhouse gases.

Relatively rapid changes in river channels preserved in the geologic record have also been attributed to climate change. Several palaeohydrological studies suggest that climatic shifts can alter run-off–erosion relationships that govern channel form (slope, width, depth). Shifts from wetter to drier climates can reduce catchment vegetative cover and thus increase flooding and channel erosion (e.g. widening) for the same unit of precipitation (e.g. Schumm 1968). In a historical reconstruction of flood histories for upper Mississippi River tributaries over the last 7000 years, Knox (1993) found that small shifts in temperature (1–2 °C) and precipitation (10–20%) caused sudden changes in flood magnitude and frequency. Knox (2000) also concluded that flood chronologies from several regions suggest that more frequent occurrences of large and extreme floods tend to be associated with periods of rapid climate change.

(*b*) *Hydrologic responses*

In addition to these expected changes in river morphology, the specific deviation in flood regime from present conditions will modify ecological systems. For example, increased frequency of large floods will disrupt ecological processes such as riparian plant succession or availability of low-energy, backwater habitat for aquatic species. Theory in river ecology suggests that frequent disturbances can reduce diversity by selectively eliminating all but very tolerant and highly mobile species (e.g. Resh *et al*. 1988; Townsend & Hildrew 1994). Thus, streams and rivers that now experience relatively uncommon flood disturbances would appear to be most susceptible to a large increase in flood frequency.

In many regions, an increase in flood magnitude or frequency per se may not be the most important alteration to the flood regime. In high-latitude or high-elevation catchments, seasonal snow melt is the dominant source of peak flows, and it is very predictable (e.g. Poff & Ward 1989). Increases in temperature over the 20th century have already shifted the timing of floods from spring snow-melt peaks to winter rainfall peaks in parts of the Northern Hemisphere (see Frederick & Gleick (1999) and references cited therein). Future warming may have severe consequences. For example, Loukas & Quick (1999) modelled future changes in flood timing for two catchments in British Columbia, one on the coast (maritime) and the other inland (continental). Floods in the maritime catchment are projected to increase in magnitude by 14%, in volume by 94%, in frequency by 11%, and in duration by 44%, with the timing of floods remaining unchanged. By contrast, in the interior mountain catchment floods are projected to decrease in magnitude by 7%, in volume by 38%, and in frequency by 23%, with little change in duration. Significantly, the timing of floods shifted to almost a month earlier. For fishes that have their eggs buried in the gravel during winter when they are subject to flood scour, or for riparian trees that rely on spring snow melt for seed dispersal and establishment, a shift of one month in an historically predictable flood flow is highly significant ecologically. This example emphasizes the relevance of ecologically based streamflow classification schemes (e.g. Poff & Ward 1989; Poff 1996; see also figure 2) that allow specific predictions of the biological relevance of specific flow alterations.

5. Human contribution to increased flooding

As already mentioned, humans have greatly modified landscapes to disrupt the balance of water and sediment flux in river channels. Increased water input to channels occurs in response to land-use change (urbanization, agriculture). Some argue that increased flooding now reflects these extensive land-use conversions (e.g. Knox 2000).

Humans have greatly modified the storage capacity of rivers to absorb flood waters through the destruction of wetlands and the severing of flood plains from main channels. In the US, for example, more than half of the wetlands in the lower 48 states have been converted to other uses since the mid 1700s (NRC 1995), and globally over half of all wetlands have been lost (IUCN 2000). The agricultural conversion of wetlands and forested landscapes in the last few hundred years has contributed to increased flooding in the US (Knox 2001) and almost certainly elsewhere.

In an effort to minimize flooding in heavily modified catchments, levees and flood walls have been constructed; however, there is now mounting evidence that these structures are, ironically, increasing flood magnitude and frequency. For example, in the last half of the 20th century in the Mississippi River basin in the US, floods have increased as a direct result of the increased disconnection of the flood plain from the river by extensive leveeing (USGS 1999). Larger river systems in this basin that have not experienced extensive flood-plain disconnection have not flooded so severely during this same time period (Criss & Shock 2001). Of course, flood-plain disconnection is extensive in most of the developed world. In Europe for example, most rivers no longer connect with their flood plains over significant lengths of river (Petts *et al.* 1989).

6. Ecological benefits and management of increased flooding?

If humans are increasing flood risk through engineering approaches to managing floods in rivers, then it stands to follow that increased flood magnitudes in the future will only amplify current levels of flood damage. An alternative approach to flood management is the use of so-called non-structural approaches. Non-structural flood-damage control relies on techniques that involve 'little or no channel manipulation, mechanical habitat alteration, or building of structures' and they have been called for on regulated rivers as a way to meet societal and ecological goals (Galat *et al.* 1998). This approach essentially emphasizes basic hydrological and ecological principles to reduce run-off to, and increase natural storage in, rivers to minimize flood damage to humans.

Some notable successes have been documented. For example, in the Boston, MA, area, the Charles River drains a rural but rapidly urbanizing catchment prone to flooding. More than two decades ago, the US Army Corps of Engineers implemented non-structural flood controls by purchasing the development rights to flood-plain wetlands in the upper portion of the Charles River catchment. The *ca.* 3500 ha purchased allowed for a storage capacity of more than 60×10^6 m^3 of water, at a cost of less than 10% of the projected cost of the originally proposed dam and levee project. The state compensated local communities for lost tax revenues due to land set-asides and many of these 'natural valley storage' areas are managed for recreation and for wildlife habitat. When near-record flooding occurred in 1979 and 1982, 'the wetlands performed effectively each time, absorbing flood surges and then gradually passing them downstream' (Faber 1996).

The prospect of restoring the natural absorptive capacity of wetlands and flood plains as mitigation against future flooding has also received some explicit attention. Retention of flood-generating run-off in small catchments can occur with better land-use practices, such as increasing wetlands and forest cover. Widespread implementation of such approaches could have tremendous benefit. For example, Reynard *et al.* (2001) concluded that a 50% increase in forest cover could counteract the impact of increased flooding during climate change in large British catchments.

The benefits of such an approach are numerous, being both social and ecological. For example, water quality increases in catchments with more wetland or forest cover (Roth *et al.* 1996) and the costs of water treatment decline as well. Human health may directly benefit. In an interesting study, Curriero *et al.* (2001) reported that the incidence of waterborne-disease outbreaks in the US has been strongly correlated with precipitation intensity in the last half of the 20th century. They showed that, of the 548 reported outbreaks from 1948 through 1994, 68% of outbreaks were associated with the 80th percentile ($P = 0.001$) of precipitation intensity. The causal linkages are not known, but because the outbreaks were associated with surface run-off, they were plausibly caused by run-off from agricultural lands, leaking septic tanks or storm-water overflows. This study strongly implies that increased precipitation intensity in the future carries a health risk, and that non-structural flood management can reduce this risk by detaining degraded run-off in natural storage areas with high biological activity (e.g. wetlands).

Non-structural flood management clearly has ecological benefits by directly restoring wetland and flood-plain habitat. Aquatic habitat would generally improve, and the diversity and productivity of river–flood plain ecosystems could be greatly increased by reconnecting flood plains for flood storage. Already in the wake of the disastrous 1993 flood in the upper Mississippi River basin, the US federal government has begun to purchase private land to remove levees and reconnect flood plains to the river for both flood storage and wildlife habitat (USGS 1999). Even in the highly urbanized countries of Europe, such approaches might produce tangible ecological benefits. For example, in the River Oder, Bischoff & Wolter (2001) documented habitat diversity to increase in response to a very large flood, and they suggested that more large floods could enhance fish recovery in this highly regulated system. Similarly, Raat (2001) indicated that reconnection of isolated flood-plain lakes with the Rhine River would likely enhance the fishery. Similar ecological benefits to fisheries have recently been documented in the highly agricultural areas of central California as well (see Sommer *et al.* 2001).

7. Improving ecological modelling for climate-change management

Ecology is often viewed as a science that lacks predictive capacity. Ecological systems represent a complex integration of physical, biological and human-influenced processes over space and time, and this complexity complicates mechanistic (reductionistic) understanding and quantitative prediction of processes at fine scales where management actions are often needed. Importantly, ecology does not claim sole ownership of this problem. In the context of climate change, the atmospheric sciences are unable to reliably predict any details about how regional precipitation patterns will change (NAST 2000; Senior *et al.* 2002), and the hydrological sciences cannot predict how stream channels at particular locations will change given a new water or sediment budget (Benda *et al.* 1998). Without physical predictions at these scales, quantitative habitat-scale ecological predictions cannot be expected either.

Despite the uncertainties about environmental and social responses to climate change, our present level of ecological understanding *is* adequate to inform management policies in a *qualitative* sense. For example, volumes of research and practical experience lead to the inexorable conclusion that expanding the aquatic–terrestrial interface through re-establishing wetlands or reconnecting flood plains with river channels is bound to have strong, positive ecological benefits (e.g. NRC 1992), just as we know that improved water quality promotes persistence of sensitive species. In the absence of reliable, quantitative predictions about site-specific or catchment-specific hydrogeomorphic responses to climate change, general principles of ecological understanding can serve as general qualitative policy guides.

Ecologists understand the linkages between many ecological processes and the dynamics of sediment and water flux in rivers, as illustrated by the examples given earlier. What ecologists need now are predictive tools from physical scientists and engineers that can route water and sediment through channel networks to predict frequency–magnitude–duration characteristics at relatively fine spatial scales (e.g. individual stream reaches or flood-plain wetlands) for catchments with known hydrologic and sediment regimes. Supported by this level of hydrogeomorphic habitat modelling, predictive ecology will progress rapidly. Important questions such as 'how much wetland habitat is needed to provide some specified degree of ecological integrity, and where exactly is this habitat needed?' could then be more quantitatively addressed. Concurrently with tool development, 'experiments' are needed to test and refine our ecological knowledge at larger scales, such as whole catchments (Stanford *et al.* 1996). In the specific context of management of flood risk, planned experiments (including simulation modelling) are needed that manipulate quantity and location of wetland restoration and test *a priori* models of hydrogeomorphic and ecological response. Such experiments are costly and potentially socially controversial and, therefore, require strong support by government, through research prioritization and funding. Developing predictive tools and iteratively improving upon them through interdisciplinary experimentation is a critical research need, particularly if society wishes to develop the scientific basis for sustaining ecological integrity and minimizing increased flood risk in the not-so-distant future.

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References

Bayley, P. B. 1995 Understanding large river floodplain ecosystems. *Bioscience* **45**, 153–158.

Benda, L. E., Miller, D. J., Dunne, T., Reeves, G. H. & Agee, J. K. 1998 Dynamic landscape systems. In *River ecology and management: lessons from the Pacific coastal ecoregion* (ed. R. J. Naiman & R. E. Bilby), pp. 261–288. Springer.

Bischoff, A. & Wolter, C. 2001 The flood the century on the River Oder: effects of the 0+ fish community and implications for floodplain restoration. *Reg. Rivers Res. Mngmt* **17**, 171–190.

Bledsoe, B. P. & Watson, C. C. 2001 Effects of urbanization on channel instability. *J. Am. Water Resources Assoc.* **37**, 255–270.

Bunn, S. E. & Arthington, A. H. 2002 Consequences of altered hydrological regimes for aquatic biodiversity. *Environ. Mngmt.* (In the press.)

Clausen, B. & Biggs, B. J. F. 1997 Relationships between benthic biota and hydrological incides in New Zealand streams. *Freshw. Biol.* **38**, 327–342.

Clausen, B. & Biggs, B. J. F. 2000 Flow indices for ecological studies in temperate streams: groupings based on covariance. *J. Hydrol.* **237**, 174–197.

Criss, R. E. & Shock, E. L. 2001 Flood enhancement through flood control. *Geology* **29**, 875–878.

Curriero, F. C., Patz, J. A., Rose, J. B. & Lele, S. 2001 The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *Am. J. Public Health* **91**, 1194–1199.

Erman, D. C., Andrews, E. D. & Yoder-Williams, M. 1988 Effects of winter floods on fishes in the Sierra Nevada. *Can. J. Fish. Aquat. Sci.* **45**, 2195–2200.

Faber, S. 1996 *On borrowed land: public policies for floodplains.* Cambridge, MA: Lincoln Institute of Land Policy.

Fausch, K. D., Taniguch, Y., Nakano, S., Grossman, G. D. & Townsend, C. R. 2001 Flood disturbance regimes influence rainbow trout invasion success among five Holarctic regions. *Ecol. Appl.* **11**, 1438–1455.

Fisher, S. G., Gray, L. J., Grimm, N. B. & Busch, D. E. 1982 Temporal succession in a desert stream ecosystem following flash flooding. *Ecol. Monogr.* **52**, 93–110.

Frederick, K. D. & Gleick, P. H. 1999 *Water and global climate change: potential impacts on US water resources.* Arlington, VA: Pew Center on Global Climate Change.

Galat, D. L. (and 16 others) 1998 Flooding to restore connectivity of regulated, large-river wetlands. *J. Biosci.* **48**, 721–733.

Gasith, A. & Resh, V. H. 1999 Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. *A. Rev. Ecol. Syst.* **30**, 51–81.

Grimm, F. 1968 Das Abflußverhalten in Europa—Typen und regionale Gliederung. In *Wissenschaftliche Veröffentlichungen des Deutschen Instituts für Länderkunde, Neue Folge*, vol. 25/26, pp. 18–180.

Haines, A. T., Findlayson, B. L. & McMahon, T. A. 1989 A global classification of river regimes. *Appl. Geogr.* **8**, 255–272.

Harvey, B. C. 1987 Susceptibility of young-of-the-year fishes to downstream displacement by flooding. *Trans. Am. Fish. Soc.* **116**, 851–855.

Hughes, J. M. R. & James, B. 1989 A hydrolgoical regionalization of stream in Victoria, Australia, with implication for stream ecology. *Aust. J. Mar. Freshw. Res.* **40**, 303–326.

IUCN 2000 (Internation Union for the Conservation of Nature) *Vision for water and nature: a world strategy for conservation and sustainable management of water resources in the 21st Century.* Gland, Switzerland and Cambridge, UK: IUCN.

Junk, W. J., Bayley, P. B. & Sparks, R. E. 1989 The flood pulse concept in river–floodplain systems. In *Proc. Int. Large River Symp.* (ed. D. P. Dodge), pp. 110–127. Canadian Special Publication of Fisheries and Aquatic Science.

Knox, J. C. 1993 Large increases in flood magnitude in response to modest changes in climate. *Nature* **361**, 430–432.

Knox, J. C. 2000 Sensitivity of modern and Holocene floods to climate change. *Quat. Sci. Rev.* **19**, 439–457.

Knox, J. C. 2001 Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *Catena* **42**, 193–224.

Lins, H. F. 1997 Regional streamflow regimes and hydroclimatology of the United States. *Water Resources Res.* **33**, 1655–1667.

Loukas, A. & Quick, M. C. 1999 The effect of climate change on floods in British Columbia. *Nordic Hydrol.* **30**, 231–256.

Lytle, D. A. 1999 Use of rainfall cues by *Abedus herberti* (Hemiptera: Belostomatidae): a mechanism for avoiding flash floods. *J. Insect Behav.* **12**, 1–12.

Meffe, G. K. 1984 Effects of abiotic disturbance on coexistence of predator–prey fish species. *Ecology* **65**, 1525–1534.

Merritt, D. M. & Cooper, D. J. 2000 Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River basin, USA. *Reg. Rivers Res. Mngmt* **16**, 543–564.

Meyer, J. L., Sale, M. J., Mulholland, P. J. & Poff, N. L. 1999 Impacts of climate change on aquatic ecosystem functioning and health. *J. Am. Water Resources Assoc.* **35**, 1373–1386.

Molles, M. C., Crawford, C. S., Ellis, L. M., Valett, H. M. & Dahm, C. N. 1998 Managed flooding for riparian ecosystem restoration—managed flooding reorganizes riparian forest ecosystems along the middle Rio Grande in New Mexico. *Bioscience* **48**, 749–756.

Montgomery, D. R. & Buffington, J. M. 1998 Channel processes, classification, and response. In *River ecology and management* (ed. R. Naiman & R. Bilby), pp. 13–42. Springer.

Naiman, R. J. & Décamps, H. 1997 The ecology of interfaces: riparian zones. *A. Rev. Ecol. Syst.* **28**, 621–658.

Naiman, R. J., Magnuson, J. J., McKnight, D. M. & Stanford, J. A. 1995 *The freshwater imperative: a research agenda.* Washington, DC: Island Press.

NAST 2000 (National Assessment Synthesis Team) *Climate change impacts on the United States: the potential consequences of climate variability and change.* Washington, DC: US Global Change Research Program.

Nilsson, C., Xiong, S. J., Johansson, M. E. & Vought, L. B. M. 1999 Effects of leaf-litter accumulation on riparian plant diversity across Europe. *Ecology* **80**, 1770–1775.

NRC 1992 (National Research Council) *Restoration of aquatic ecosystems: science, technology, and public policy.* Washington, DC: National Academy Press.

NRC 1995 (National Research Council) *Wetlands: characteristics and boundaries.* Washington, DC: National Academy Press.

Petts, G. E., Möller, H. & Roux, A. L. (eds) 1989 *Historical change of large alluvial rivers: western Europe.* Wiley.

Poff, N. L. 1996 A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshw. Biol.* **36**, 71–91.

Poff, N. L. & Allan, J. D. 1995 Functional organization of stream fish assemblages in relation to hydrological variability. *Ecology* **76**, 606–627.

Poff, N. L. & Ward, J. V. 1989 Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Can. J. Fish. Aquat. Sci.* **46**, 1805–1818.

Poff, N. L. & Ward, J. V. 1990 The physical habitat template of lotic systems: recovery in the context of historical pattern of spatio-temporal heterogeneity. *Environ. Mngmt* **14**, 629–646.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B., Sparks, R. & Stromberg, J. 1997 The natural flow regime: a paradigm for riverine conservation and restoration. *Bioscience* **47**, 769–784.

Poff, N. L., Angermeier, P. L., Cooper, S. D., Lake, P. S., Fausch, K. D., Winemiller, K. O., Mertes, L. A. K., Oswood, M. W., Reynolds, J. & Rahel, F. J. 2001 Fish diversity in streams and rivers. In *Future scenarios of global biodiversity* (ed. F. S. Chapin, O. E. Sala & E. Huber-Sannwald), pp. 315–349. Springer.

Poff, N. L., Brinson, M. M. & Day Jr, J. W. 2002 *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States.* Arlington, VA: Pew Center on Global Climate Change.

Raat, A. J. P. 2001 Ecological rehabilitation of the Dutch part of the River Rhine with special attention to the fish. *Reg. Rivers Res. Mngmt* **17**, 131–144.

Resh, V. H., Brown, A. V., Covich, A. P., Gurtz, M. E., Li, H. W., Minshall, G. W., Reice, S. R., Sheldon, A. L., Wallace, J. B. & Wissmar, R. 1988 The role of disturbance in stream ecology. *J. N. Am. Benthol. Soc.* **7**, 433–455.

Reynard, N. S., Prudhomme, C. & Crooks, S. M. 2001 The flood characteristics of large UK Rivers: potential effects of changing climate and land use. *Climatic Change* **48**, 343–359.

Richards, C., Haro, R. J., Johnson, L. B. & Host, G. E. 1997 Catchment and reach-scale properties as indicators of macroinvertebrate species traits. *Freshw. Biol.* **37**, 219–230.

Richter, B. D., Baumgarten, J. V., Powell, J. & Braun, D. P. 1996 A method for assessing hydrological alteration within ecosystems. *Conserv. Biol.* **10**, 1163–1174.

Roth, N. E., Allan, J. D. & Erickson, D. 1996 Landscape influences on stream biotic integrity assessed at multiple spatial scales. *Landsc. Ecol.* **3**, 141–156.

Schumm, S. A. 1968 River adjustment to altered hydrologic regimen—Murrumbidgee River and paleochannels, Australia. US Geological Professional Paper 598, Reston, VA.

Schumm, S. A. & Lichty, R. W. 1963 Channel widening and flood-plain construction along Cimarron River in southwestern Kansas. US Geological Professional Paper 352-D, Reston, VA.

Scott, M. L., Friedman, J. M. & Auble, G. T. 1996 Fluvial processes and the establishment of bottomland trees. *Geomorphology* **14**, 327–339.

Senior, C. A., Jones, R. G., Lowe, J. A., Durman, C. F. & Hudson, D. 2002 Predictions of extreme precipitation and sea-level rise under climate change. *Phil. Trans. R. Soc. Lond.* A **360**, 1301–1311.

Sommer, T., Harrell, B., Nobriga, M., Brown, R., Moyle, P., Kimmerer, W. & Schemel, L. 2001 California's Yollo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* **26**, 6–16.

Sparks, R. E. 1994 Need for ecosystem management of large rivers and their floodplains. *Bioscience* **45**, 168–182.

Stanford, J. A. & Ward, J. V. 1993 An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. *J. N. Am. Benthol. Soc.* **12**, 48–60.

Stanford, J. A., Ward, J. V., Liss, W. J., Frissell, C. A., Williams, R. N., Lichatowich, J. A. & Coutant, C. C. 1996 A general protocol for restoration of regulated rivers. *Reg. Rivers Res. Mngmt* **12**, 391–414.

Townsend, C. R. & Hildrew, A. G. 1994 Species traits in relation to a habitat templet for river systems. *Freshw. Biol.* **31**, 265–275.

USGS 1999 (US Geological Survey) *Ecological status and trends of the Upper Mississippi River System 1998*. Report LTRMP 99-T001, La Crosse, WI.

Wolman, M. G. 1967 A cycle of sedimentation and erosion in urban river channels. *Geograf. Ann.* A **49**, 385–395.

Wootton, J. T., Parker, M. S. & Power, M. E. 1996 Effects of disturbance on river food webs. *Science* **273**, 1558–1561.