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Insight, part of a Special Feature on Restoring Riverine Landscapes

Process-Based Ecological River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages

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ABSTRACT. Human impacts to aquatic ecosystems often involve changes in hydrologic connectivity and flow regime. Drawing upon examples in the literature and from our experience, we developed conceptual models and used simple bivariate plots to visualize human impacts and restoration efforts in terms of connectivity and flow dynamics. Human-induced changes in longitudinal, lateral, and vertical connectivity are often accompanied by changes in flow dynamics, but in our experience restoration efforts to date have more often restored connectivity than flow dynamics. Restoration actions have included removing dams to restore fish passage, reconnecting flow through artificially cut-off side channels, setting back or breaching levees, and removing fine sediment deposits that block vertical exchange with the bed, thereby partially restoring hydrologic connectivity, i.e., longitudinal, lateral, or vertical. Restorations have less commonly affected flow dynamics, presumably because of the social and economic importance of water diversions or flood control. Thus, as illustrated in these bivariate plots, the trajectories of ecological restoration are rarely parallel with degradation trajectories because restoration is politically and economically easier along some axes more than others.

Key Words: *connectivity; flow dynamics; hyporheic zone; river restoration.*

INTRODUCTION

Connectivity is now widely acknowledged as a fundamental property of all ecosystems. The concept was introduced to ecology through landscape ecology as a factor explaining distribution of species (Merriam 1984, Moilanen and Nieminen 2002). However, definitions for this term vary widely and are often based either on metapopulation dynamics or continuity of landscape structure (Calabrese and Fagan 2004). In this paper, we concentrate on hydrologic connectivity (Ward 1989, Pringle 2003*b*) because it is arguably a defining feature of all riverine ecosystems. Pringle (2001:981) defined hydrologic connectivity as "water mediated transfer of matter, energy, and organisms within or between elements of the hydrologic cycle." Thus, in rivers, hydrologic connectivity refers to the water-mediated fluxes of material, energy, and organisms within and among components, e.g., the channel, flood plain, alluvial aquifer, etc., of the ecosystem. This hydrologic connectivity can be viewed as operating in longitudinal, lateral, and vertical dimensions and over time (Ward 1989).

The temporal dimension of connectivity is crucial. Temporal changes in connectivity underpin most river ecosystem processes, but were not incorporated within early static models of riverine ecosystems, e.g., the river continuum concept (Vannote et al. 1980), in which the roles of disturbance or flow regime were underestimated. More importantly, in river restoration, the recovery of lost linkages or disconnections is intended to occur over time, so the target endpoint is also likely to be temporally dynamic (Palmer et al. 2005). Therefore, to describe anthropogenic impacts and subsequent responses to restoration in rivers, visualizing changes in three-dimensional connectivity over time is useful.

In this paper, we focus on the relationship between hydrologic connectivity and flow variability, i.e.,

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change over time, using various examples to illustrate anthropogenic effects on longitudinal, lateral, and vertical connectivity in rivers worldwide. We propose a way of visualizing temporal changes in connectivity in these three spatial dimensions to provide a tool for managers and scientists aiming to assess the effect of anthropogenic degradation and assess the potential and ultimate efficacy of ecological restoration. Adequate visualization helps to enable evaluation of the potential for restoration with respect to connectivity and flow variability and can generate testable hypotheses about system response to restoration activities. The system response is illustrated as a trajectory over time and can be extended to a restoration of "processes" rather than simply desirable forms or habitats. Furthermore, as connectivity may occur to different degrees in each of these dimensions, visualization of system response is not limited to simply one or two dimensions, e.g., longitudinal and lateral linkages, but can integrate all three and even reveal their spatial and temporal interactions. We conclude that visualization of connectivity trajectories over time in river restoration ecology has heuristic value for generating further hypotheses and applied value for identifying and communicating restoration opportunities, goals, and efficacy.

Spatial and temporal connectivity in rivers

In the past 40 yr, broadscale theories of river ecosystem connectivity have evolved from an emphasis on longitudinal gradients (e.g., Illies and Botosaneanu 1963, Vannote et al. 1980) to include the lateral linkages with the floodplain (Amoros and Roux 1988, Junk et al. 1989), the riparian zone (Naiman and Decamps 1990), and the vertical connection with groundwater (Gibert et al. 1990, Vervier et al. 1992). The longitudinal, lateral, and vertical dimensions have been drawn together into a more collective concept only relatively recently (Stanford and Ward 1988, Ward 1989). It is now acknowledged that these vectors of hydrological connectivity and their associated variance underpin nearly all ecosystem processes and patterns in rivers at multiple scales (Townsend 1996, Ward et al. 2000, Poole 2002, Thorp et al. 2006) and that disconnection explains much of the ecological degradation of rivers (Wohl 2004).

Although connectivity has typically been considered in spatial terms, temporal changes are of comparable importance. We propose that connectivity is best considered in conjunction with system dynamics, i.e., changes in ecosystem attributes over space and time. These temporal-spatial relations have long been recognized in fluvial geomorphology (e.g., Schumm 1977), but have not been emphasized as strongly in the ecological literature until recently. The relationship between connectivity and ecosystem dynamics has been discussed in reference to such ecological phenomena as biodiversity maintenance (e.g., Liebold and Norberg 2004), nutrient cycling (Maltchik et al. 1994, Stanley et al. 1997), and food web structure (Closs and Lake 1994, Woodward and Hildrew 2002). Likewise, system dynamics can also be recognized not only for hydrologic variables like streamflow, but other parameters as well such as temperature, sediment, and trophic levels.

One vivid example of the dependence between hydrologic connectivity and dynamics, which depends both on topography and flow regime is the connectivity of floodplains and side channels with mainstem rivers. Connectivity with the mainstem can be reduced by levee construction, mainstem incision, or reduced floods downstream from dams, i.e., reduced flow dynamics, resulting in less frequent inundation of the floodplain and flow through side channels (e.g., Gergel et al. 2002, Henry et al. 2002). Channel incision, i.e., reduced lateral connectivity, and consequent increased channel capacity reduce the frequency and depth of floodplain inundation for the same flows delivered from upstream, and this loss of floodplain storage, in turn, can reduce the downstream attenuation of flood peaks, thereby reducing flow dynamics. This restricted lateral connectivity also decreases floodplain productivity, nutrient exchange, and dispersal of biota between the river and floodplain wetlands (Jenkins and Boulton 2003). The influence of flow on riverine assemblages (reviews in Galat et al. 1998, Bunn and Arthington 2002) and the threat posed by flow alterations to the ecological sustainability and functioning of rivers and floodplain wetlands has been increasingly recognized (Poff et al. 1997).

Changes in flow regime may restrict longitudinal connectivity in various ways. The physical barriers to migration of fish and other biota imposed by dams and weirs have long been recognized (Kingsford 2000*a*,*b*), but reduced flows can likewise render formerly passable reaches impassable, either by decreasing flows at waterfalls such that migratory fish can no longer navigate them or by completely drying up entire reaches of river, as occurs on the San Joaquin River of California because of diversions from Friant Dam (Cain 1997). In some rivers with anthropogenically reduced baseflows, dissolved oxygen levels fall to lethal levels in reaches affected by thermal discharges, e.g., Loire River, France, or dredging, e.g., the Lower San Joaquin River, California, preventing anadromous salmonids from migrating upstream to suitable habitats. Besides creating barriers to migration, water extraction can affect ecological integrity in regulated rivers through direct entrainment of organisms. In one of the main drainages of the Caribbean National Forest in Puerto Rico, water extraction removes more than 50% of migrating shrimp larvae, severely inhibiting their recruitment (Pringle and Scatena 1999).

Vertical hydrological connectivity is less readily apparent in rivers, and its reduction through human actions is seldom considered. Stream water flows into and out of permeable streambeds, i.e., downwelling and upwelling, respectively. In streams with strong vertical connections, patterns of upwelling, downwelling, and groundwater movement are complex and variable, driven by interactions between geomorphology and flow regime (Poole et al., *in press*). Bed permeability determines groundwater flow resistance and is largely a function of grain size and sorting, with clean gravels having the highest permeability. Hydraulic gradient drives groundwater movement and is largely a function of undulations in bed topography, such as pool/riffle sequences. Vertical connectivity can be reduced by physical barriers that reduce permeability such as siltation and the clogging of pore spaces of streambed gravels (Hancock 2002), or physical changes that reduce hydraulic gradients such as straightening and simplifying channel form, i.e., canalization. Vertical hydrologic connectivity can also be reduced by decreased flow dynamics and reduced hydraulic gradients. Reduced floods in mainstem rivers may no longer flush tributary-derived fine sediments that can accumulate on the bed and reduce permeability (Kondolf and Wilcock 1996).

Given the importance of interflow and groundwater upwelling to maintain discharge in many streams (Winter et al. 1998), human impacts on this linkage will influence surface water flow regimes, especially during times of low surface runoff. The hyporheic zone, i.e., the saturated zone beneath a stream that contains water derived from the stream, is closely linked with surface waters (White 1993). Downwelling stream water supplies dissolved oxygen, nutrients, and organic matter to the ecological communities in the hyporheos (Boulton et al. 1998), whereas upwelling water may supply surface waters with distinct water chemistry (Valett et al. 1994) and influence instream biota by enhancing the diversity of surface water habitat (Dent et al. 2000). The incubation of salmonid embryos in stream gravels depends on upwelling or downwelling groundwater, a critical component of a functional vertical stream system (Baxter and Hauer 2000). Despite these interactions, seldom do strategies for river rehabilitation explicitly consider the hyporheic zone or seek to restore lost vertical linkages with groundwater (Boulton, *unpublished manuscript*).

Connectivity in restoration

Connectivity is crucial in the context of restoration. Many reach-scale restoration projects have been unsuccessful because they were conceived and implemented in isolation from the larger catchment context (Frissell and Nawa 1992, Muhar 1996, Wohl et al. 2005). For example, instream structures used in some restoration projects have not been recolonized because of a limited pool of potential colonizers in nearby intact sites or because of barriers to dispersal of the colonizers (Bond and Lake 2003). Alternatively, the structure may be overwhelmed by sediment derived from upstream sources and carried downstream through the drainage network (Iversen et al. 1991).

As an example illustrating problems in connectivity in all three dimensions, the Merced River, California was dammed in the early 20th century, blocking salmon migration to upstream spawning areas, and interrupting transport of gravels to downstream spawning reaches. To compensate for loss of upstream spawning habitat, a hatchery was built below the lowest dam. To mitigate loss of spawning gravels below the dams, artificial riffles were constructed in 1990 to provide salmon spawning habitat. These riffles were designed to have wide, flat gravel beds, held in place by boulder weirs, to maximize the area of gravel bed falling within the range of preferred spawning depths and velocities during flows typical of the fall spawning season. However, such flat gravel beds are not found in natural rivers, and it is unlikely that they will be selected by salmon for spawning or for persistence. Because of their flat form, these artificial spawning riffles lacked pool/riffle sequences. Without these bed undulations to induce the downwelling and upwelling currents, characteristic of preferred spawning sites of many salmon and trout, fish were less likely to use the artificial riffles for spawning, and in fact, observed spawning, in the years after construction, was only about 10% of the anticipated use (Kondolf et al. 1996). This example illustrates the interactive effects of loss of different aspects of connectivity. A dam blocked salmon access to upstream spawning grounds and degraded downstream spawning areas by trapping gravel from upstream, i.e., reduced longitudinal connectivity. This restoration attempt involved excavating existing bed material and replacing with smaller gravel in flat beds that ignored the need for bed undulations to promote downwelling and upwelling, i.e., vertical connectivity. The small-sized newly placed gravel was easily eroded by the post-dam flow regime, ignoring system dynamics, washing it promptly downstream. The project also involved minor channel straightening and elimination of irregular channel margins to create a more canal-like reach, thereby reducing lateral connectivity (Kondolf et al. 1996).

Negative consequences of artificially increasing connectivity

Connectivity is most often considered as a positive attribute for riverine ecology, but connectivity need not always be high naturally, and increasing connectivity over natural levels may have negative consequences, e.g., on survival of native species. The opposite of connectivity, "isolation," can be an important factor influencing species distributions (Fausch et al. 2002, Moilanen and Nieminen 2002). Bedrock channels tend to have low vertical connectivity, and bedrock falls can serve as partial or complete barriers to fish migration. On tributaries of the Sacramento River in California, spring-run Chinook salmon (*Oncorhynchus tshawytscha*) can migrate past bedrock falls that are barriers to the fall-run Chinook salmon, allowing the spring-run to reproduce in isolation from fall-run. In Point Reyes National Seashore, California, native amphibians thrive in perennial stream reaches above a barrier impassable to salmonids, but are rare in reaches occupied by salmonids that prey on the amphibians (D. Fong, National Park Service, 2005, *personal communication*). Nonetheless, removal of natural barriers by blasting the bedrock is often recommended as an enhancement action to extend the range of salmon habitat (e.g., Flosi et al. 1998: VII-50), despite the evidence that such increased longitudinal connectivity could have negative consequences for other native species, e.g., amphibians, and for genetic diversity of spring- vs. fall-run salmon. Where groundwater is contaminated, high vertical connectivity can spread contaminants into surface waters (Hancock 2002). Irrigation return flow increases connectivity between irrigated agricultural fields and receiving waters, and these return flows have contaminated wetlands in the San Joaquin Valley of California and elsewhere (Pringle 2003*a*).

Many human activities enhance connectivity by providing ways for aquatic species to bypass natural biogeographic barriers to colonization (Rahel 2006). Such enhanced connectivity often has negative consequences by allowing invasive species to spread or by exposing endemics to new competitors. Of special concern are the transfer of organisms via ship ballast and the movement of organisms between formerly isolated basins via canals. In the North American Great Lakes, zebra mussel invaded via ballast water, and alewife invaded through canals (Mills et al. 1993). The potential migration of bighead carp and silver carp from the Mississippi River basin into the Great Lakes basin through the Chicago Sanitary and Ship Canal is currently of great concern because of the likely negative effects of these invasive species on fishery resources. The construction of electrified barriers to prevent the movement of these carp into the Great Lakes is essentially an attempt to restore the biogeographic isolation that historically existed between the basins (Rahel 2006). In some cases, naturally connected systems are being intentionally fragmented to prevent movement of undesirable invasive fish species. Examples include the use of dams to prevent sea lampreys from reaching spawning grounds in Great Lake tributary streams (Porto et al. 1999) and brook trout from invading streams inhabited by native cutthroat trout in the Rocky Mountain region (Novinger and Rahel 2003).

In general, any change to ecosystem processes or attributes, such as connectivity, is likely to benefit some organisms at the expense of others. Whether we consider these changes desirable depends on our values, e.g., protecting rare species, and is essentially a social question. Connectivity is not always good, nor always bad. For maximum ecosystem diversity and complexity, we can perhaps envision a range of spatial and temporal connectivity classes, which provides the widest range of environments for diverse organisms. Restoring the natural connectivity regime is as important as restoring flow regimes and other key aspects of river systems.

METHODS

From our collective experience in many parts of the world, we compiled wide-ranging examples of human-induced changes in connectivity and flow dynamics, and we sought a way to depict ecosystem changes as a function of these two attributes. From a list of over 50 potential case studies, we selected 23 with adequate information, representing a range of degradation trajectories, and when possible, having had restoration undertaken, thereby allowing us to compare restoration and degradation trajectories. We developed a descriptive model of change in three separate bivariate response spaces: longitudinal, lateral, and vertical connectivity, each plotted against flow variability. For case studies of human impacts over a wide geographic range, we plotted the general direction of change in hydrologic connectivity and flow variability associated with the human-induced change on each graph to represent a response space, and in the few cases in which restoration has been undertaken, the direction associated with the restoration (Figs. 1–3).

Describing connectivity or flow variation within a river system is difficult, in part because connectivity can be high at one scale and simultaneously low at another. An example may be a bedrock-dominated stream in a karstic region; at small scales, bedrock dominance limits vertical connectivity within individual reaches, but surface-groundwater connectivity is likely to be high at the regional scale, owing to strong connections between surface water and the underlying karst systems. To address this issue, we attempted to address connectivity and flow variation consistently. Longitudinally, we considered hydrologic connectivity between headwaters and the river mouth, and considered some cases in which the continuity of sediment transport in the river has been interrupted and then partially restored. Laterally we focused on near-river connections between the channel and riparian zone or flood plain. Vertically, we assessed exchange across the streambed between the channel and hyporheic zone. Finally, in assessing flow variation over time, we considered month-to-month flow variation, and considered the likelihood of temporal intermittency in flow to be an especially important indicator of variation in discharge.

RESULTS

For each longitudinal, lateral, and vertical dimension, we present a plot showing the degradation and restoration trajectories associated with each example. Descriptions of each river are presented in Appendix 1.

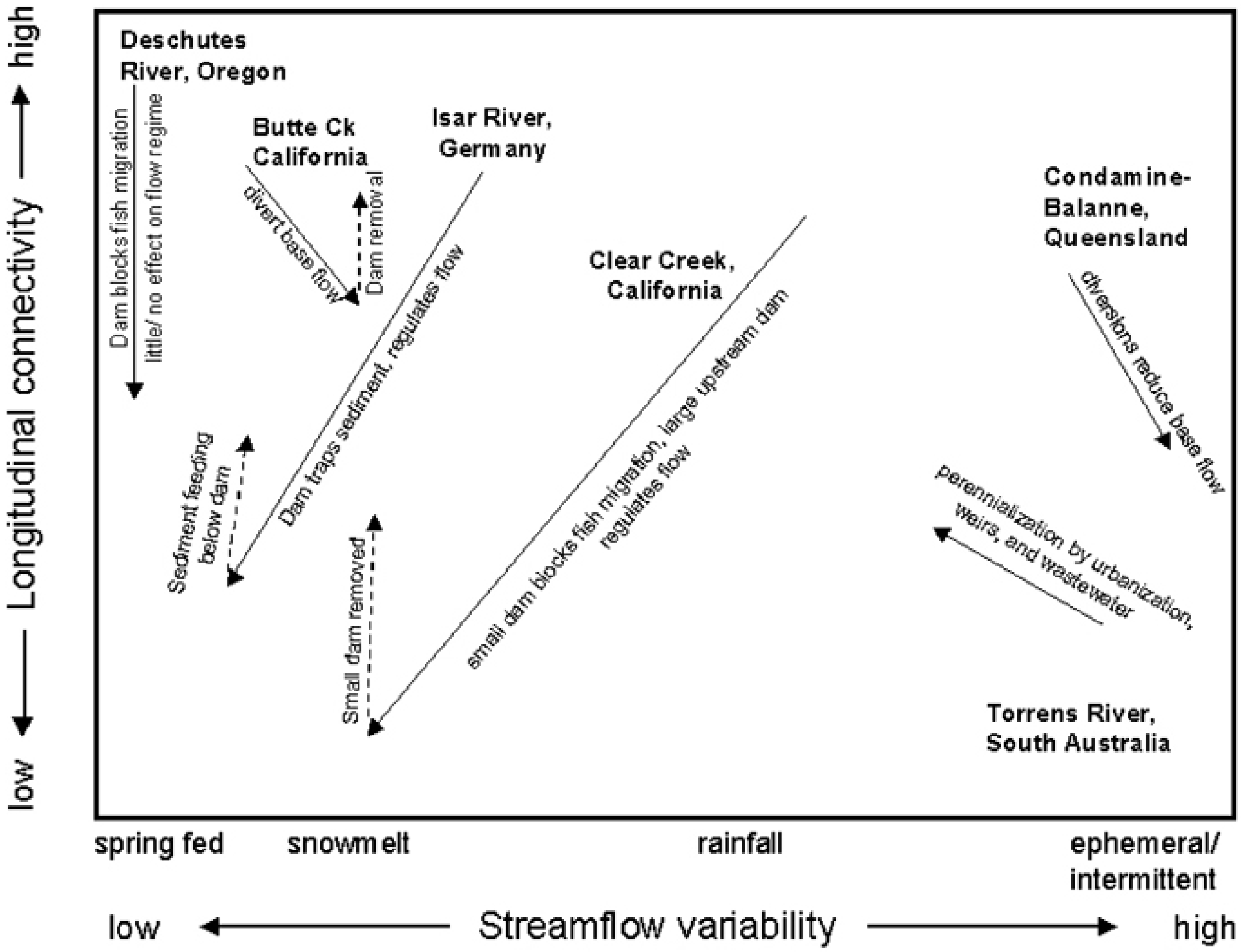
Longitudinal connectivity and flow dynamics

Figure 1 presents a diverse set of case studies in which longitudinal connectivity has been reduced by dams and diversions, and in one case, in the Torrens, increased by replacement of intermittency by perennial flow, i.e., perennialization. Flow variability was unchanged in Deschutes, increased in Butte and Condamine-Balonne, and decreased in Isar, Clear, and Torrens. In three examples, longitudinal connectivity has been partly restored by removing small dams, i.e., Clear, Butte, or restoring coarse sediment supply to the reach below the dam, i.e., Isar (Appendix 1).

Lateral connectivity and flow dynamics

As plotted in Fig. 2, lateral connectivity has been reduced by many mechanisms: (1) blocking side channels of the Pite; (2) levees cutting off overbank flooding and deposition in the Sacramento, Chorro, and Paroo; (3) cutting off meander bends in the Kissimmee; (4) channel incision in the Tama; and (5) reduced flood flows in the Trinity, Sacramento, South Platte, and Tama. The restorations have involved opening up side channels of the Pite, setting back or breaching levees on the Sacramento and Chorro, reactivating gravel bars in the Tama, and releasing higher flows from the reservoir on the Trinity. As a contrast, we also refer to an urban restoration project that involved the creation of parks along the South Platte. These parks, which provided benefits to the urban populace, did not affect connectivity or flow dynamics (Appendix 1).

Fig. 1. Solid arrows represent ecological degradation and dashed arrows represent restoration trajectories plotted on axes of longitudinal connectivity and flow dynamics. See Appendix 1 for a discussion of trajectories.



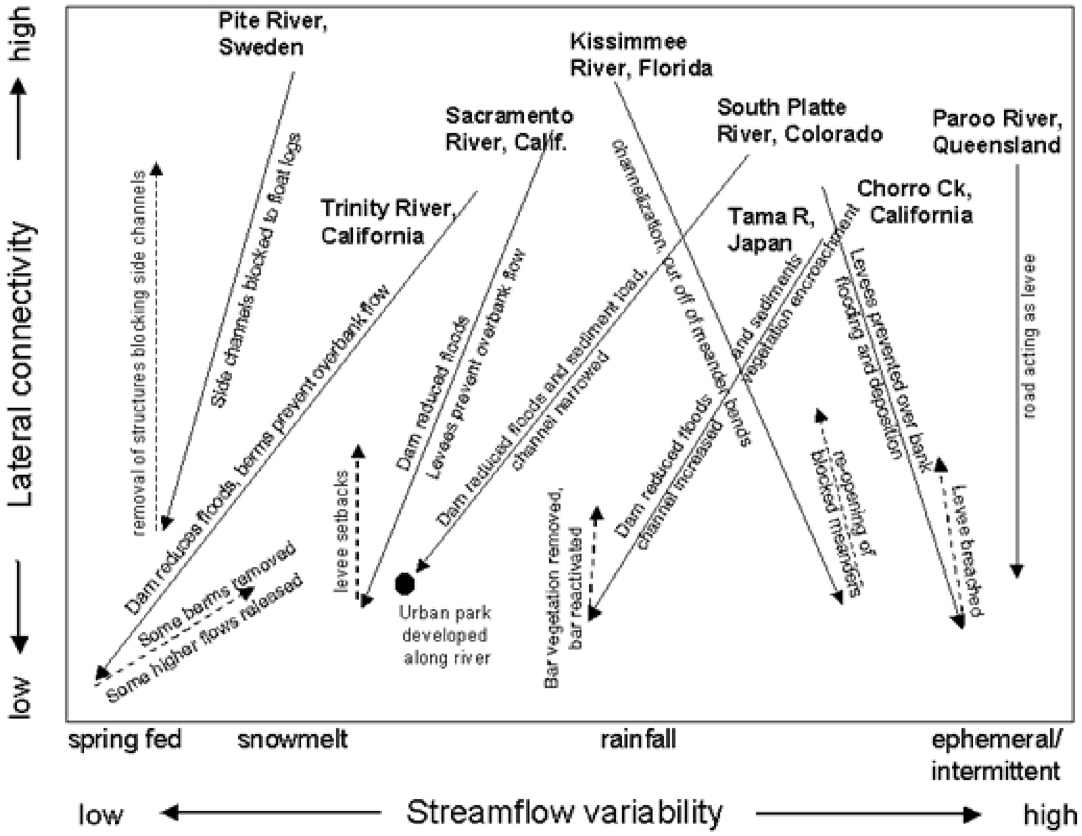
Vertical connectivity and flow dynamics

Case studies shown in Fig. 3 involve reduced vertical connectivity through channel simplification along the McCoy, deposition of fine sediment over formerly permeable beds in the Rhône and Creightons, drop in water table from pumping in the San Pedro, and lining the bed with concrete in the Los Angeles. Vertical connectivity artificially increased from water table rise, in turn caused by reduced evapotranspirative demand in the Rocky. Examples of restoration involved restoring channel complexity along the McCoy, excavating fine sediment from the Rhône, and reducing groundwater pumping in the San Pedro (Appendix 1).

Taking time into account: plotting change in three dimensions

In Figs. 1–3, we show vectors in three directions in three separate diagrams, but in reality these changes in various dimensions co-occur, and in some rivers,

Fig. 2. Solid arrows represent ecological degradation and dashed arrows represent restoration trajectories plotted on axes of lateral connectivity and flow dynamics. See Appendix 1 for a discussion of trajectories.



the interactions among the different dimensions will be important. To illustrate this, a three-dimensional plot for the Pite River (Fig. 4) shows the direction and trend of sequential changes resulting from construction of stone piers for log floating, a small dam, a larger dam, and finally removal of many stone piers. To generate this figure, we reviewed the historical context of major human activities along the river because they might have affected flow and connectivity, and classified their effects on longitudinal, lateral, and vertical linkages (Table 1). We then plotted these in three-dimensional space and illustrated the variability of the flow regimes as the size of the points defining each phase (Fig. 4). This complex plot illustrates changes in connectivity in three dimensions over time and its interrelationship with the flow regime.

DISCUSSION

Using the plots presented here, we suggest a structured way to examine and portray changes in ecological processes in rivers. The bivariate plots

Table 1. Pite River degradation and restoration: sequence of changes with connectivity expressed on a relative scale.

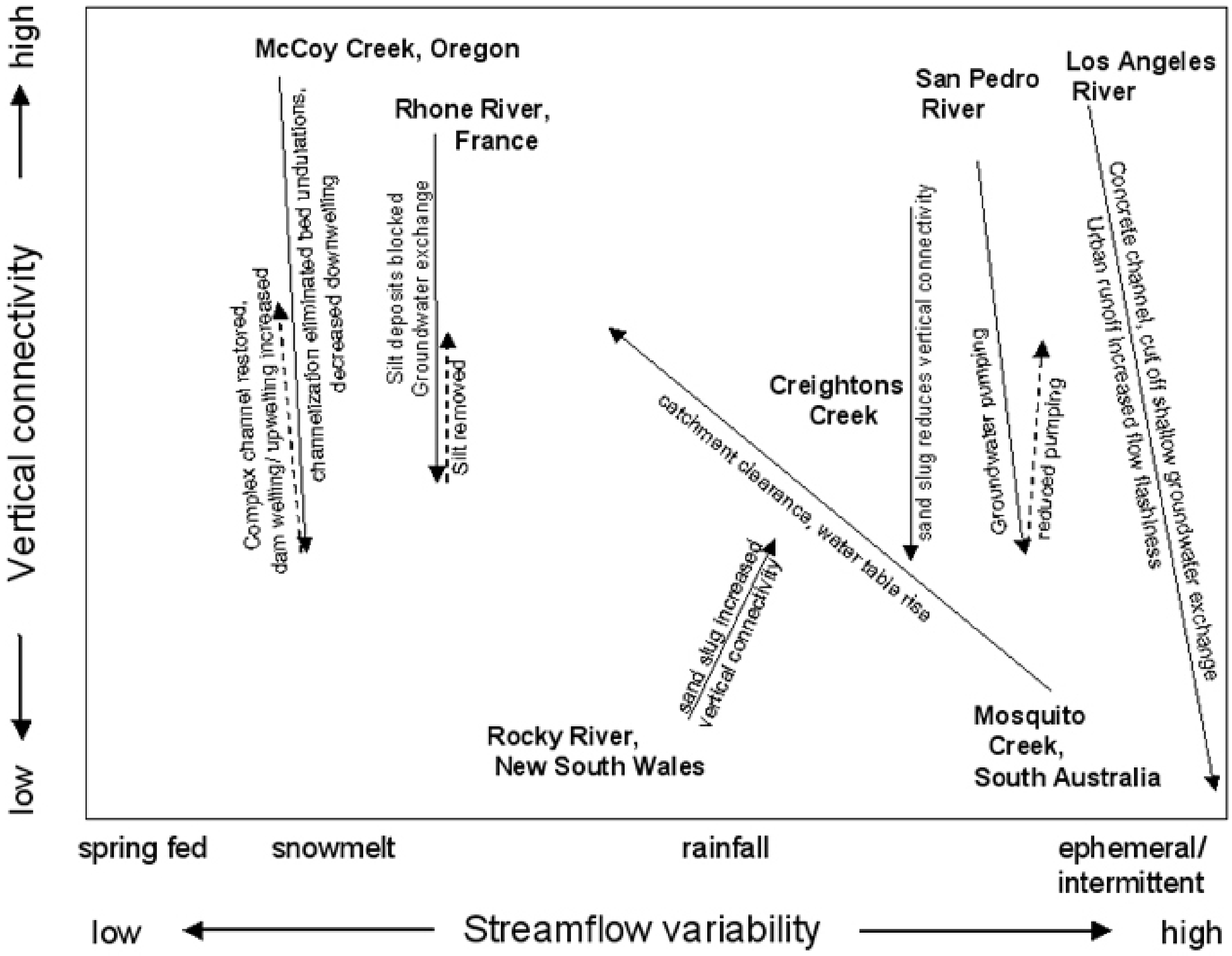
Driver	Longitudinal	Lateral	Vertical	Flow Variability
Predisturbance	very high	very high	high	medium
Stone piers	very high	medium	medium	medium
Small dam	medium	medium	medium	medium
Bigger dam	medium	medium	medium	low
Restoration: Remove stone piers	medium	high	high	low

help us apply ecological theory to river restoration by explicitly identifying directions of change along specific, albeit interrelated "axes." These simple descriptive models in bivariate response space serve to reveal relationships between connectivity and riverine dynamics. By plotting a specific river on a bivariate diagram, we are forced to do enough historical analysis to understand what has changed and to identify along what axes it may be possible to restore. For practitioners, such models may be useful to help put into perspective different types of human alterations and restoration approaches, and to specify constraints associated with flow variability and connectivity. Restoration can be understood in terms of the vector components of potential restoration trajectories, which in turn, can inform monitoring strategies and measurements of ecological success (Palmer et al. 2005).

Although not quantitative, these models focus on processes, in contrast to an overemphasis on form and pattern so common in the restoration literature and in and practice (Wohl et al., 2005). Creating form only, without restoring the processes to maintain it, implies a commodification of the ideal stream. This recalls Brautigan’s (1967) prophetic description of a used trout stream that was for sale at the Cleveland Wrecking Yard for $6.50 per linear foot. In Brautigan’s story, the salesman explained to the narrator, “We’re selling [a trout stream] by the foot length. You can buy as little as you want or you can buy all we’ve got left. A man came in here this morning and bought 563 feet. He’s going to give it to his niece for a birthday present” (Brautigan 1967:104). Although this may be a facetious example, there is still a tendency for river restoration strategies to be piecemeal and confined to limited sections. We hope that by illustrating flow dynamics and connectivity in three dimensions, river managers will more readily appreciate the importance of linkages at the catchment scale.

Our bivariate diagrams (Figs. 1–3) highlight the fact that restoration projects tend to involve changes to the physical form of rivers rather than to flow regimes because restoring flow regimes often requires removal or change in operation of dams, a process with both political and social consequences. For example, nearly all intentional dam removals to date have been on small dams with limited storage capacity or in cases in which reservoir sedimentation has reduced storage capacity (Doyle et al. 2003). These small dam removals have restored longitudinal connectivity, but have generally not significantly affected flow dynamics because larger dams remain in the drainage.

Fig. 3. Solid arrows represent ecological degradation and dashed arrows represent restoration trajectories plotted on axes of vertical connectivity and flow dynamics. See Appendix 1 for a discussion of trajectories.

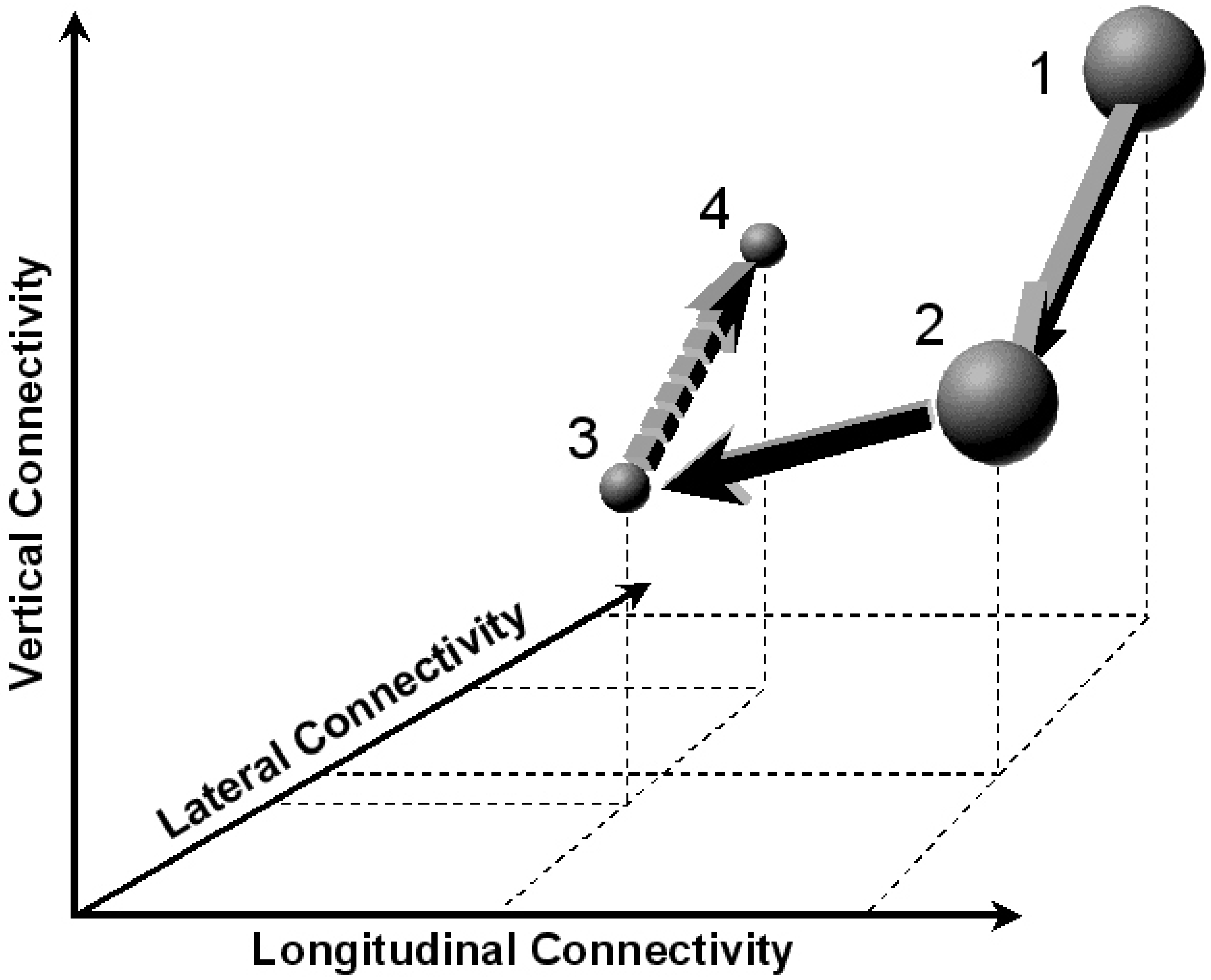


Restoring flow dynamics to drive ecological processes (e.g., Rood et al. 2003) has been less common. Examining the changes in a given river through these diagrams may also help answer the question, "When is restoration complete?” Knowing the history of how the channel became degraded can identify irreversible changes that would prevent restoration, at least in some dimensions (Kondolf and Larson 1995).

Limitations

The bivariate diagrams we propose are conceptual only, showing general trends of change along different axes. They could be improved by incorporating quantitative metrics. For example, along the x-axis of Figs. 1–3, flow variability could be represented as the ratio of Q100/Q2, i.e., the floods with return intervals of 100 and 2 yr, respectively, or Q2/baseflow, or another such ratio, depending on the most relevant hydrologic measure

Fig. 4. Three-dimensional representation of degradation (solid arrows) and restoration (dashed arrows) trajectories for the Pite River, Sweden, based on charting the strength of longitudinal, lateral, and vertical connectivity vectors (Table 1). The size of each point represents the relative variability in annual flow resulting at each phase, 1 though 4. Phase 1 represents pre-degradation; Phase 2, channel simplification and installation of revetments starting about 1870, to facilitate transport of logs to mill; Phase 3, establishment of impoundments, ca. 1930; and Phase 4, restoration via removal of revetments and emplacing structures to recreate complex in-stream habitat, ca. 2001.



for the ecosystem process of concern. Likewise, connectivity metrics, the y axis, could include radon concentration to assess relative contribution of groundwater to surface water, bed permeability as an indication of the strength of vertical water exchange, or shoreline length as an indication of lateral connectivity. By moving to quantitative metrics, it may be possible to make testable predictions.

The plots presented here show the changes as linear, when in reality changes in connectivity and flow dynamics may often be abrupt. Moreover, these plots show only the hydrologic changes that we expect will lead to ecosystem changes. Additional metrics could focus more on the ecological responses to changed connectivity such as exchange of organisms or retention efficiency (Sheldon et al. 2002).

Implications for setting goals

The three-dimensional plot (Fig. 4) serves to focus attention on changes in hydrologic processes within a river over time and makes plain the fact that most ecological restoration strategies regain only some fraction of the river's original ecological integrity. Rather than interpret Fig. 4 as suggesting that the goal of any restoration project should be to return the stream to its pristine state, we regard such a diagram as a means of identifying ecological restoration potentials and describing ecological restoration successes relative to a predisturbance state. Other considerations, e.g., maintenance or restoration of social or economic benefits, may legitimately constrain the amount of ecological restoration that is possible or even desirable on a given river. By allowing the visualization of desirable changes in ecosystem processes, Fig. 4 helps to prevent a narrow focus on preconceived visions of a desirable river structure.

The emphasis on process and historical evolution implied by these diagrams may help decision makers see that there is subjectivity in restoration goals. For example, the riparian forest of the Eygues River in southeastern France, identified as a key ecosystem by the European Union under the Natura 2000 program, is an artifact of reduced sediment yield from the catchment and 20th century narrowing of the unvegetated active channel (Kondolf et al. *in press*). Strategies to preserve the ecological functions of this riparian forest must account for evolving nature of the physical and ecological systems. Just to the north, the nearby Drôme River has experienced greater channel narrowing and incision due to reduced coarse sediment supply from its catchment. There, managers seek to increase the supply of coarse sediment in an effort to restore bed elevations. Ironically, the trajectory of this restoration effort is the polar opposite of restoration actions taken in North American catchments that widened due to catchment disturbance in the early 20th century, and where managers seek to reduce sediment loads and convert braided channels to narrow single-thread channels (Kondolf et al. 2002).

Visualization of connectivity and flow dynamic changes can improve restoration planning in a number of ways. First, it can encourage integration of process-based restoration strategies that are more apt to be self-sustaining and; therefore, less costly over the long term than attempts to impose and maintain a pre-envisioned channel structure. Second, ongoing, and epidemic reductions in native aquatic biodiversity in rivers and streams may be as much related to loss of ecosystem processes as it is to changes in habitat structure. Integration of process-based goals into restoration planning (Stanford et al. 1996) may be an important and underused tool for stemming biodiversity losses. Finally, development of a diagram such as Fig. 4 for any particular river encourages planners to undertake four tasks that are requisite for development of clear and accountable restoration strategies: (1) assessing historical conditions within a river; (2) developing a clear definition of "ecological degradation" in terms of changes in ecosystem processes; (3) identifying human activities that have contributed to existing ecological degradation; and (4) agreeing on which ecological processes are most the important for restoration and how much ecological restoration should be incorporated into the overall goal of the project. These complement the criteria for ecologically successful restoration of rivers proposed by Palmer et al. (2005) and Jansson et al. (2005).

We have focused on physical and ecological dimensions of restoration, but restoration is ultimately a social activity, undertaken because public and private resources have been allocated to that purpose. The visualization process that we propose does not incorporate social dimensions, but we hope these kinds of plots can inform public decisions about how restoration funds should be allocated to achieve the greatest ecological benefit. These plots could also serve as an educational tool for the public, illustrating progress during long-term rehabilitation programs and demonstrating why achievement of some goals may take a long time or whether they are even possible. Social scientists may be able to build on this visualization process to measure public involvement and approval of steps during the restoration process.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss2/art5/responses/

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Appendix 1. Descriptions of Case Studies Plotted in Figures 1-3

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