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Review

Improving restoration practice by deriving appropriate techniques from analysing the spatial organization of river networks

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ABSTRACT

Amendments to the water protection legislation in many countries have raised the need to develop prioritization strategies in river restoration. These political objectives need to be translated into applied methods of site selection. The high degree of heterogeneity within administrative boundaries makes the identification of sites challenging. Analysing data with computer software alone might not identify sites with the highest ecological recovery potential, as they might not take sufficient account of the complex ecological interplay over large spatial scales. In this literature study, the spatial organization of river networks (dendritic structure, unidirectional flow, species distribution) is discussed in the context of different restoration techniques and how efficiency is expected to vary within the network.

Although restoration planning must consider deficits on the reach scale, as well as catchment effects and develop suitable mitigation scenarios produced by the analysis, some general conclusions on the site-specific effectiveness of different restoration techniques can be derived from the spatial organization of river networks. Restorations in the headwaters are most suitable for improving fundamental ecological processes such as retaining nutrients and soils to improve water quality, buffering an increase of temperature by establishing riparian buffer-strips, and returning hydro-dynamic flow patterns to a more natural state by altered dam operation. Longitudinal connectivity is essential for many freshwater taxa and should be restored in a bottom-up direction, starting at the downstream ends of river networks or at species-rich nodes within the system. Habitat restorations and the re-establishment of a natural channel morphology throughout the network will aid ecological recovery, if species pools for re-colonization are close by and fundamental ecological processes support a recovery. To increase the success of future restoration efforts, branches of river networks should be seen as functional linked ecosystems, and therefore restoration efforts within one system should be more coordinated, rather than seeing every project as self-sufficient. There must be a shift from a tactical towards a strategic approach in river restorations.

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Introduction

The allocation of limited budgets to conservation and restoration projects is a problem for applied conservation management (Prato, 2007; Wilson et al., 2006). Many prioritization schemes in the past focused either on realizing projects with lowest costs or highest benefits (Ferraro, 2003) rather than combining both elements into cost-effectiveness approaches, which are now routine in applied restoration planning. Managers and scientists often disagree when setting priorities for river restoration. While managers focus on human needs before acknowledging ecological targets, scientists tend to ignore the role of humans in landscapes (Newson and Large, 2006). However, as humans are part of modern riverine landscapes, the aim should be to develop future scenarios for river restorations rather than following the 1:1 transfer of historic references. In the future, rivers should serve human needs (e.g. water supply, hydroelectric power generation, and recreation) while simultaneously meeting high ecological standards (Dufour and Piegay, 2009).

Prioritization guidelines should give decision support for selecting sites for ecological restorations in anthropogenically impaired environments. Suitable sites for restoration need to be identified over broad geographical scales. Map-based protocols (Peacock et al., 2012) or software-based analysis (Ball et al., 2009; Heiner et al., 2011; Stralberg et al., 2011) are common techniques used to identify restoration sites, within or between catchments. Both approaches presuppose a high spatial resolution of relevant data. Mathematical and statistical models that divide the target area into planning units (e.g. grid cells or connected areas of the same habitat type) to identify priority sites have been developed, and are continuously adapted to practical needs. However, relevant data are often not available at the spatial resolution needed (Palmer, 2009). Furthermore, computer models might not appropriately assess the recovery potential of stream sections, as their algorithms evaluate the data of planning cells individually. Compared to terrestrial ecosystems, riverine networks show a more intensive internal linkage (Vuilleumier et al., 2010), due to the continuous flow and the restrictions on organism movement within the dendritic structure of networks. Actual computer models might therefore not be the most valid tool for prioritizing sites, if the ecological interaction between planning units is not incorporated sufficiently (Proulx et al., 2005).

There is little scientific literature dealing with river restoration prioritization concepts. In addition to the software-based approaches, published prioritization guidelines are either limited to single restoration techniques, e.g. the reestablishment of longitudinal connectivity (Kemp and O'Hanley, 2010) or riparian reforestation (Kentula, 1997); the prioritization of restoration techniques on a reach-scale (Rheinhardt et al., 2007; Verdonschot and Nijboer, 2002); or a general, stepwise approach to analyse deficits and to restore ecological processes hierarchically with no specification of the spatial context (Roni et al., 2002, 2012). Though a deficit analysis on the catchment scale seems to be a necessary first step in the methodical prioritization approach, the capacity for ecological recovery (which depends on identified deficits) may vary between reaches, according to their position within the network. The site-specific efficiency is therefore expected to vary with the general position within networks and related processes. Efficiency is also an important characteristic for assessing the costs of restoration techniques. For the assessment of cost efficiency, the expected costs for restoration work need to be set in relation to the ecological and socio-economic benefit, e.g. the enhancement of biodiversity or the stimulation of ecosystem services. People benefit from improved ecosystem services, though approaches to estimate the economic value of those services have not yet been established, which makes cost-effectiveness approaches challenging (Aronson et al., 2010; Benayas et al., 2009). But information on the costs of restoration work are also scarce, notably lacking in the scientific literature, and would be expected to vary markedly between countries (Bullock et al., 2011). In general the cost-effectiveness of restoring deeply disturbed riverine ecosystem should be assessed, when a large number of ecological processes must be restored. Many restoration projects in the past have actively constructed in-channel habitats (Thompson, 2005; Wesche, 1985), rather than encouraging a self-restoring dynamic (Everard and Powell, 2002; Zalewski and Harper, 2001) by passive restoration techniques (e.g. removing stabilization structures). Though a self-restoring dynamic is expected to take longer before ecosystem recovery, it might be an alternative strategy to save costs and to encourage sustainable, self-dynamic ecosystems (Kail et al., 2007). Active restoration techniques are also more expensive than passive restoration, but a rapid recovery of ecosystem and the ecosystem services provided might be economically preferable (Acuña et al., 2013) depending on system-specific characteristics.

The limitation of many restoration projects to the reach scale (Bernhardt and Palmer, 2007; Kauffman et al., 1997) might be one reason why many restoration projects in the past failed to achieve the defined ecology goals (Alexander and Allan, 2007; Palmer et al., 2010; Roni et al., 2008). Other reasons for such failures might be that restoration measures are installed in systems with limited recovery potential (missing species pool for recolonization), the spatial extent of measures is inadequate, or measures are placed at unsuitable positions in the river network where they cannot capitalize their ecological power (Bond and Lake, 2003; Niezgoda and Johnson, 2005; Palmer et al., 2010). Knowledge of stream restoration practice is still evolving, and the expansion to the catchment perspective is beginning to play an important role in more recent restoration practice (Hillman and Brierley, 2005). Future stream restoration need to be more efficient, as funding is too limited to restore all degraded stream sections.

The present work produces recommendations on the effectiveness of restoration techniques in relation to the spatial position within stream networks in the industrialized world, taking into account anthropogenic constraints that cannot be reversed.

Spatial organization of river networks

Some basic processes in riverine ecosystems are comparable to terrestrial ecosystems, e.g. species and habitats often have a patchy distribution and the way patches are connected or separated from another has an effect on the exchange of species between sites (Wiens, 2002). But a more detailed view shows that stream and terrestrial ecosystems differ in many ways, largely due to the dendritic network structure of rivers, the unidirectional flow and that patches of species are distributed like pearls on a chain along the branches of river networks, which affects dispersal characteristics.

Dendritic structure

A dendritic ecosystem structure is unique to river networks, with the exception of rare ecosystems, such as caves or artificial hedgerows, which are organized in a similar way (Campbell