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Integrating and extending ecological river assessment: Concept and test with two restoration projects

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ABSTRACT

While the number of river restoration projects is increasing, studies on their success or failure relative to expectations are still rare. Only a few decision support methodologies and integrative methods for evaluating the ecological status of rivers are used in river restoration projects, thereby limiting informed management decisions in restoration planning as well as success control. Moreover, studies quantifying river restoration effects are often based on the assessment of a single organism group, and the effects on terrestrial communities are often neglected. In addition, potential effects of water quality or hydrological degradation are often not considered for the evaluation of restoration projects.

We used multi-attribute value theory to re-formulate an existing river assessment protocol and extend it to a more comprehensive, integrated ecological assessment program. We considered habitat conditions, water quality regarding nutrients, micropollutants and heavy metals, and five instream and terrestrial organism groups (fish, benthic invertebrates, aquatic vegetation, ground beetles and riparian vegetation). The physical, chemical and biological states of the rivers were assessed separately and combined to value the overall ecological state.

The assessment procedure was then applied to restored and unrestored sites at two Swiss rivers to test its feasibility in quantifying the effect of river restoration. Uncertainty in observations was taken into account and propagated through the assessment framework to evaluate the significance of differences between the ecological states of restored and unrestored reaches. In the restored sites, we measured a higher width variability of the river, as well as a higher width of the riparian zone and a higher richness of organism groups. According to the ecological assessment, the river morphology and the biological states were significantly better at the restored sites, with the largest differences detected for ground beetles and fish communities, followed by benthic invertebrates and riparian vegetation. The state of the aquatic vegetation was slightly lower at the restored sites. According to our assessment, the presence of invasive plant species counteracted the potential ecological gain. Water quality could be a causal factor contributing to the absence of larger improvements.

Overall, we found significantly better biological and physical states, and integrated ecological states at the restored sites. Even in the absence of comprehensive before-after data, based on the similarity of the reaches before restoration and mechanistic biological knowledge, this can be safely interpreted as a causal consequence of restoration. An integrative perspective across aquatic and riparian organism groups was important to assess the biological effects, because organism groups responded differently to restoration. In addition, the potential deteriorating effect of water quality demonstrates the importance of integrated planning for the reduction of morphological, water quality and hydrological degradation.
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1. Introduction

Freshwater biodiversity is threatened worldwide (Vorosmarty et al., 2010), and scenarios for the current century predict a continu-

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ous loss of biodiversity if human activities remain unchanged (Sala et al., 2000). To stop biodiversity loss in freshwater environments and to improve the ecological state of rivers, an increasing number of river restoration projects are undertaken (Bernhardt et al., 2005). However, the ecological effects of restoration are rarely assessed and only few of such assessments show an improvement (Palmer et al., 2010).

Studies quantifying the ecological state of rivers to assess the effect of river restoration often rely on one or just a few assessed organism groups, while studies using a comprehensive set of indicators are rare (despite the existence of such assessment protocols, see e.g. Hering et al., 2006; Woolsey et al., 2007), and terrestrial communities are often neglected. For this study, we selected five organism groups (fish, aquatic benthic invertebrates, aquatic vegetation, ground beetles, and riparian vegetation) to evaluate the ecological state of the rivers and to quantify the effect of restoration on aquatic and terrestrial communities. These organism groups reflect an important part of the biota living along and within rivers, and they are supposed to react to physical modifications in rivers induced by restoration measures (e.g. Jähnig et al., 2010; Januschke et al., 2011; Lorenz et al., 2012).

Integrative decision support methodologies for river management and for evaluating river restoration projects have been suggested (Beechie et al., 2008; Convertino et al., 2013; Corsair et al., 2009; Reichert et al., 2007, 2015), but are rarely applied in practice due to limited financial resources for monitoring. They rely on assessment protocols to evaluate the ecological state of rivers, which were not primarily designed for restoration (Bundi et al., 2000; Hering et al., 2004). Such protocols have the advantage that they can be applied to any kind of river management and support integrative river management by raising the awareness for other potential deficits than morphological ones, even when applied to restoration. On the other hand, modifications to such protocols may be needed to make them more sensitive to changes induced by restoration (Hering et al., 2006; Woolsey et al., 2007). Furthermore, uncertainty about observed or expected effects should be considered to evaluate the significance of changes.

To address these issues, we developed an integrative assessment framework based on value functions that transform environmental attributes measured in the field to degrees of fulfillment of a comprehensive, hierarchical set of ecological objectives. This framework provides a unified approach to all assessment areas, allowing us to quantify the overall ecological state of a river reach while still resolving assessments at lower hierarchical levels. The lower level objectives may be important for the analysis of causes of a bad state and for the design of measures for its improvement.

This study applies the approach developed for river morphology (Langhans et al., 2013) to a much more comprehensive set of assessment areas. With this approach we explicitly account for uncertainty about measured or predicted attributes of the river ecosystem by propagating this uncertainty to the calculated values. The framework is based on multi-attribute value theory, an important methodology for multi-criteria decision support (Dyer and Sarin, 1979; Eisenführ et al., 2010) that is increasingly used for environmental management (Reichert et al., 2015). Advantages of using this theory are that (i) it is based on axioms of "rational choice" which helps justifying decisions; (ii) it focuses explicitly on the objectives that should be achieved by a management decision (value focused instead of alternative focused thinking, Keeney, 1992); (iii) it is flexible regarding the mathematical formulation of preferences; (iv) it makes it possible to propagate uncertainty and to take risk attitudes into account (by extending value to utility functions, Dyer and Sarin, 1982); and (v) it naturally allows us to combine different assessment areas. In this unified framework, we combined physical, chemical and biological assessments to evaluate the overall ecological state of a river reach.

We addressed three goals in our study: 1) to construct a comprehensive ecological assessment procedure that considers the aquatic and the terrestrial parts of the river ecosystem based on physical, chemical and biological criteria, 2) to provide and apply a framework that considers uncertainty and can easily be integrated into decision support methodologies for river management, and 3) to test the suitability of the suggested approach for quantifying restoration effects on habitat diversity and on aquatic and terrestrial communities for two case studies in Switzerland.

According to ecological theory, habitat diversity promotes species diversity (Jähnig et al., 2009; Palmer et al., 2005, 2010). Thus, in the absence of other limiting factors, such as poor water quality and severe limitations to recolonization processes, we therefore expect that increasing instream habitat diversity by restoration promotes aquatic biodiversity (i.e. fish, benthic invertebrates, aquatic vegetation) (Lepori et al., 2005; Palmer et al., 2010). We also expect that enhanced flooding and morphological dynamics in the river floodplain by restoration increases the heterogeneity of the floodplain habitats and promotes terrestrial biodiversity (i.e. ground beetles, riparian vegetation) (Jähnig et al., 2009). In Europe, natural river corridors and floodplains are rare and threatened due to human alterations (Tockner and Stanford, 2002). Therefore, we expect that restoring alluvial habitats is favourable for threatened species living within and along rivers. However, dispersal limitations may be more severe for these species, preventing an increase in their presence at restored habitats. On the other hand, the creation of empty niches during the restoration process may lead to an increase in the presence of good colonizers, including alien species (Strayer, 2010). For these reasons, we included information about threatened and alien species in our integrative assessment procedure.

2. Material and methods

2.1. Study reaches and field study design

We studied the restored and unrestored reaches of two Swiss rivers (the Thur and Töss Rivers) to test the suitability of the assessment methodology described below for quantifying and valuing the effects of restoration. Both were highly channelized in the middle of the 19th century to increase flood security and to gain agricultural land. The natural river floodplain was disconnected and the rivers were reduced to straight channels. The restoration aimed at improving the hydromorphological conditions, first by lowering the floodplain by removing a layer of fine sediment, and second by removing the embankments to provide more space for the rivers (Pasquale et al., 2011; Schirmer et al., 2014). In both cases new gravel bars built-up (expected to be favorable to riparian vegetation and ground beetles) and the river shifted from a straight channel towards a more naturally braided river (in the Töss river, a short artificial structure was built at the upstream end of the widening to support the development of braided channels) with development of potential secondary channels absent before restoration (expected to be favorable to macroinvertebrates, fish and aquatic vegetation). Within each river, we studied a degraded and a restored reach. The restored reach at the Thur River is 1.5 km long and was restored in 2002. The restored reach at the Töss river is much shorter with 0.2 km length and was restored in 1999 (see Fig. A1 in the Supplementary material). In both cases, the degraded reach was representative of the river in the restored reach before restoration and located upstream (Fig. A1). The restored and degraded reaches were situated close to each other, with a distance of 650 m and 350 m for the Thur and Töss Rivers, respectively. In both rivers, no tributaries or differences in the chemical state occurred between the degraded and restored reaches. With this

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