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River restoration: morphological, hydrological, biogeochemical and ecological changes and challenges

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Abstract

River restoration is essential as a means to enhance river dynamics, environmental heterogeneity and biodiversity. The underlying processes governing the dynamic changes need to be understood thoroughly to ensure that restoration projects meet their goals. In particular, we need to understand quantitatively how hydromorphological variability relates to ecosystem functioning and services, biodiversity and (ground)water quality in restored river corridors. Here, we provide a short overview on the literature and present a study of a restored river corridor in Switzerland combining physical, chemical, and biological observations with modeling. The results show complex spatial patterns of bank infiltration, habitat-type, biotic communities and biogeochemical processes. In particular, we found an increase in taxonomic and functional diversity for earthworms, testate amoebae and bacteria in the restored part of the river. This complexity is driven by river hydrology and morphodynamics, which are in turn actively coupled to riparian vegetation processes. Given this complexity and the multiple constraints on the uses and management of floodplains, a multi-disciplinary approach is needed to monitor the success of restoration measures and to make recommendations for future restoration projects.

1 Introduction

Rivers have played a critical role in the development of human societies. Increases in demands on river use for transportation, energy, water and food supply were especially marked following the industrial revolution, often resulting in conflicting interests (e.g. Woolsey et al., 2007). Also, recurring flood events caused enormous damage to communities, infrastructure or farmland. Hence, in the past 150 yr, large portions of many rivers in Europe were engineered and regulated (e.g. Tockner et al., 2009). For decades, the underlying principle of engineered flood protection was to restrict the flooded areas by levees, with stabilized river banks and increased river flow to discharge flood water faster. While these measures were successful in protecting upstream areas, they endangered downstream regions through loss of retention areas, increase in river flow rates and faster arrival of peak flows causing even larger and more damaging floods than before engineering (e.g. Pinter, 2005). An additional consequence of this was degradation/erosion of the river beds leading to a deepening of channels and a reduction of suitable substrate for fish spawning (Kondolf, 1997).

Ecological conditions have dramatically changed in response to river regulation, both in the aquatic and terrestrial habitats of floodplains, reducing biodiversity (e.g. Palmer and Bernhardt, 2006; LeRoy Poff et al., 2007; Moyle and Mount, 2007). Floodplains are among the most threatened ecosystems worldwide (Tockner et al., 2010). In the past decade, it was foreseen that water demand and conversion of wetlands to agricultural, urban and traffic areas would increasingly compete with protection of aquatic ecosystems and preservation of ecological services (MEA, 2005). Biodiversity losses, including major decreases in fish and other aquatic life stocks in deteriorating river corridors (LeRoyPoff et al., 2006), have made it necessary to re-think the concepts of river exploitation (Arthingthon et al., 2006).

Over the last 20 yr, many projects have been envisioned in Europe to revitalize engineered river reaches as a measure to achieve good ecological status of water bodies as required by the EU Water Framework Directive (European Commission, 2000), while at the same time serving as flood protection measures for downstream river reaches. Swiss legislation requires river revitalization actions as part of flood protection measures (BWG, 2001). In the USA, legislative and policy-making processes for water promote restoration as an essential tool to enhance river dynamics (FISRWG, 1998). All legislative efforts and required actions ultimately aim to increase ecosystem heterogeneity and hyporheic exchange processes. Worldwide, the number of restoration projects, and use of public financial resources to fund these projects, have increased significantly during the past few years and are expected to rise further (e.g. Bernhardt et al., 2005; Nakamura et al., 2006; Palmer and Bernhardt, 2006; Woolsey et al., 2007).

We suggest that without an adequate understanding of the underlying hydrogeological and ecological processes together with sound performance control (e.g. Woolsey et al., 2007; Palmer et al., 2010), many restoration projects can be considered as large-scale field manipulations that lack effective strategies for achieving their desired goals or even a sound basis to assess whether goals have been met. The success of river restoration can be assessed using the concept of ecosystem services beneficial to humans (Fig. 1). In river corridors, regulation of runoff, provision of clean drinking water, cultural services such as recreation, as well as supporting services like soil formation, nutrient cycling, fish stocks, and habitat provision have to be considered (Pereira and Cooper, 2006). Functional biodiversity is both the consequence of habitat provision and a prerequisite for many ecosystem services (Kremen, 2005). Generally, restoration projects aim to maintain or increase biodiversity and ecosystem services (Benayas et al., 2009). However, some ecosystem services may be enhanced at the cost of others. For example, regulation of water quality by denitrification in riparian buffer zones may result in the formation of greenhouse gases (Verhoeven et al., 2006). It is therefore important to understand feedbacks among conflicting services and to set priorities.

Furthermore, a clear scientific knowledge of the river-river corridor-aquifer system is required to understand how to reduce flood risk while increasing other ecosystem services, such as sustaining a high taxonomic and functional diversity and providing clean drinking water. Fast river-water infiltration and short residence times within the riparian aquifer may endanger the quality of groundwater extracted by nearby pumping stations with respect to pathogenic fecal coliforms, harmful macronutrients, or micropollutants (Powlson et al., 2008). In Switzerland, this has led to conflicting legislation, requiring river restoration within flood protection measures, but prohibiting it close to existing drinking water wells (e.g. BUWAL, 2004).

If we accept that the key element of river restoration is to establish hydrological and morphological variability as a new dynamic equilibrium, river restoration can be assessed by answering the following key questions:

1. How stable are morphological patterns established by engineered restoration? Does the variability prevail over longer time scales or will homogenization of the river bed be fostered by the altered flow regime, which necessarily reflects engineering measures in the upper part of the catchment?
2. Does morphological variability guarantee an improvement in biodiversity for all taxonomic groups (i.e. from bacteria to macroscopic organisms)? Is it sufficient to create potential habitats by reestablishing the dynamism of erosion/sedimentation processes?
3. How does morphological variability affect biogeochemical transformations and associated ecosystem services, for example, enhanced ecosystem metabolism and organic carbon turnover, and microbial nitrate removal?
4. What are the potential adverse effects of river restoration? For example, endangerment of structures such as bridges and levees after removal of bank reinforcement, or limitations on use of near-river aquifers for drinking water provision because of the difficulty in predicting travel times through the riparian filter zone?

Here, we focus on concepts integral to river restoration and in particular report on a modification of a section of the Thur River, Switzerland (Pasquale et al., 2011; Schneider et al., 2011), which serves as a typical example for the evolution of a European perialpine river system. We illustrate how the detailed quantification of processes at the river/river corridor/groundwater interfaces can help to answer the questions raised above, and thus contribute to a successful restoration design. By these means, we facilitate knowledge transfer about controlling factors to other river systems undergoing restoration, which is crucial for a sustainable water supply and biodiversity in many countries.

2 Riparian and hyporheic processes

Natural river ecosystems are highly heterogeneous and can be regarded as spatially and temporally shifting mosaics of differently structured patches (i.e. areas that differ from their surroundings in structure or function; functional process zones – FPZ) (Thorp et al., 2006). Patches on which riparian vegetation develops are controlled by the hydrological regime of the river (Perona et al., 2009a), the sediment substrate (and thus the history of sedimentation, erosion and soil evolution) and the time since the patch was colonized (Thorp et al., 2006). Conversely, vegetation influences hydrological, chemical and morphological conditions via transpiration, root-microbe-soil interactions, and mechanical stabilization (Abernethy and Rutherfurd, 2001; Gyssels et al., 2005). The complex interactions between soil cohesion, soil-water content and chemistry, plant growth and soil organisms are thought to determine how and which vegetation develops on juvenile soils, and how resistant it is against minor floods. If time scales of vegetation evolution and morphodynamic processes are similar, vegetation grows appreciably between floods, and the life cycle of vegetation might influence river morphodynamics and vice versa (Perucca et al., 2007; Perona et al., 2012).

The functioning of a riparian zone strongly depends on the type and strength of the hydrological connectivity among FPZs (Fisher and Weiter, 2005), and on the vertical and lateral integration of the stream in the landscape through the flow path (Boulton, 2007). Restoration typically converts a channelized river section into a near-natural one composed of both FPZs created during or following the restoration and FPZs that existed before restoration.

Natural and restored floodplains offer a perfect setting to study the comparative responses of different organisms to perturbation. Indeed, aboveground and belowground communities are believed to show contrasting responses to perturbations. While aboveground diversity (e.g. vegetation) is expected to peak at the middle of the perturbation gradient (i.e. the intermediate disturbance hypothesis), the diversity of soil organisms is thought to increase linearly with decreasing perturbation (Wardle et al., 2004). A variety of different processes and interactions affecting ecosystem functions and services of river corridors has to be considered in the planning of restoration measures (Fig. 2). Riparian zone processes play a central role in river corridor restoration because they integrate river flow with corridor morphodynamics, soil processes, and riparian vegetation. Hyporheic exchange processes lead to filtration of particles, modulation of temperature fluctuations, and exposure of river water to subsurface microbial communities that are responsible for biogeochemical transformations. Because increased morphological variability in the river bed enhances hyporheic exchange, river restoration can increase the self-cleaning capacity of the river (Lefebvre et al., 2004). The discharge-modulated coupling of groundwater to overlaying soils can then form biogeochemical hotspots and moments of carbon and nitrogen turnover (e.g. Peter et al., 2012a,b; Shrestha et al., 2012).

Generally, river restoration represents a hydraulic alteration (Stromberg et al., 2007) and should ideally provide a change in land use in a catchment. The catchment hydrological response to land-use changes, which are overlaid on local responses due to river restoration, vary with catchment size, amongst other factors (Blöschl et al., 2007). On the other hand, further catchment urbanization can lead to increased sediment fluxes, to changes in water quality entering receiving waters or to changes in flood height (Smith et al., 2005; Rosenzweig et al., 2008). All these factors will influence the river restoration scheme to an extent that is unlikely to be quantifiable without numerical modeling at the reach scale. Similarly, prediction of the catchment hydrological response remains a significant challenge (Breuer and Huisman, 2009).

3 Case study: the Thur River restoration (Switzerland)

The formerly braided Thur River in NE Switzerland, which is characterized by a flashy flow regime, was channelized in the 1890s to protect the river valley against flooding. Since 1993, several 1–3 km long river sections were widened by removal of stabilizing elements to allow the formation of alternating gravel bars colonized by pioneer vegetation and to increase hydrological connectivity between the main channel and its riparian zone (Fig. 3).

In order to improve understanding of the coupled hydrological, biogeochemical, and ecological processes in river corridors, an interdisciplinary research program (RECORD: REstored CORridor Dynamics) was conducted using a restored and a channelized section of the Thur River corridor as test sites (Schneider et al., 2011). At these intensively instrumented sites, we studied geomorphodynamics, subsurface geological structure, river and groundwater hydrology, soil and groundwater biogeochemistry and terrestrial biodiversity. Such multidisciplinary and combined efforts have so far never been applied at a single site.

During the study, we developed and tested several methods and concepts to assess key processes or the impact of restoration on biodiversity:

1. Field experiments on vegetation establishment on river banks using transplanted willow cuttings supported by hydrodynamic modeling of the site (Schäppi et al., 2010; Pasquale et al., 2011) emphasized the need for a better understanding of interarrival flood and root growth time scales. We propose that this is best achieved by combining field (Pasquale et al., 2012) and laboratory experiments (Edmaier et al., 2011; Perona et al., 2012).

2. We established that geophysical crosshole and surface-based methods may offer high-resolution meter-scale, three-dimensional images of the effective porosity, distribution and the presence of fines at spatial scales ranging from tenths to hundreds of meters (Doetsch et al., 2010, 2012a; Coscia et al., 2011). This made it possible to postulate a likely limit between old fluvial deposits and those associated with deposition originating from the time the river was channelized (Doetsch et al., 2012a). Geophysical monitoring allowed 3-D imaging of groundwater flow patterns of infiltrating river water using crosshole geophysics (Coscia et al., 2012) and to investigate groundwater flow patterns at arbitrary locations using injections

of artificial saline tracers in combination with surface-based geophysics (Doetsch et al., 2012b).

3. In order to characterize hydrological exchange processes, time-series of two natural tracers (temperature and electrical conductivity) were recorded. This allowed for rapid detection of continuously fluctuating physical variables and for the calculation of seepage fluxes and vertical variations (Vogt et al., 2010a,b).

4. We studied the coupled impact of ecosystem configuration and discharge fluctuations on the transformations of organic carbon and nitrogen species in shallow riparian groundwater. The combination of geochemical and molecular biological analysis defined deep-rooting pioneer plants, exhibiting high-below ground organic carbon dynamics, as sources for bioavailable organic substrates to groundwater. Hence, the occurrence of those plants ultimately shapes subsurface heterotrophic metabolism and denitrification (Peter et al., 2012a).

5. We assessed the impact of river restoration on biodiversity of a broad range of taxonomic and functional groups of terrestrial organisms (vascular plants, invertebrates, testate amoebae and bacteria). This allowed us to assess patterns for individual groups (e.g. Fournier et al., 2012a,b), to compare the relationships between each group and ecological gradients or functional processes.

6. Earthworms and testate amoeba communities were evaluated for the first time as potential indicator groups of floodplain restoration. For both groups we tested for the first time indices based on functional traits, which more strongly correlated to measured environmental variables than classical species-based diversity indices (Fournier et al., 2012a,b).

7. We developed two methods for isolating nitrate from freshwater samples such as river, soil, and groundwater for nitrogen and oxygen isotope analysis (Huber et al., 2011, 2012a). The latter analyses are powerful tools for assessing sources and fluxes of nitrate in riparian systems.

8. A “Riparian Soil Model” was developed that allows modeling of carbon and nitrogen dynamics in riparian zones including soil–groundwater exchange (Brovelli et al., 2012). The model was successfully applied to reproduce soil respiration, organic matter stocks and inorganic nitrogen fluxes in the riparian forest of the test site (Batlle-Aguilar et al., 2012).

4 Lessons learned at the Thur River

Here we attempt to answer the questions raised in the introduction based on the results from the RECORD project and thus evaluate the advantages of an integrated and multidisciplinary approach at single sites.

4.1 How stable is the morphological variability established by restoration?

The evolution of riverbed morphology depends in general on coupled dynamics of sediments and colonizing vegetation as driven by river hydrodynamics (Perona et al., 2009b). Our experiments show that pioneering vegetation growing on gravel bars can develop vertical root density distributions, which depend on the distance between soil elevation and saturated water tables within the sediment (Pasquale et al., 2012). This highlights the root-anchoring mechanism and sediment stabilization, thus relating time scales of vegetation growth with those of hydrologic disturbances (Edmaier et al., 2011; Crouzy and Perona, 2012; Perona et al., 2012). Soon after restoration, FPZs may experience a transitory phase of coupled morphodynamics and ecosystem changes before a (statistically) stable configuration of the river corridor is reached. Since 2002, the restored Thur site has experienced large morphological changes triggered by either moderate or extreme flooding events (Fig. 4). This has resulted in uncontrolled bank erosion as portrayed in Fig. 5. This could create conflicts with land-owners and agricultural use and raise further questions about the ecosystem services and predictability of restoration-induced effects.

4.2 Does morphological variability guarantee an improvement in biodiversity?

Increasing biodiversity is a common goal of river restoration projects. However, it is not always clear if this goal is achieved (Palmer et al., 2010). Species richness of plants and soil organisms (earthworms, testate amoebae, bacteria) was higher in the restored section than in the control section (pasture) located directly upstream (Samaritani et al., 2011; Fournier et al., 2012a,b). Individual FPZ species richness was in most cases lower than in the control section, but the diversity of habitats created by the restoration provided a broader range of ecological niches thus allowing a higher overall diversity of organisms to colonize the area (Fournier et al., 2012a,b). Furthermore, colonization of FPZs by additional species is possible, which would further increase overall diversity in the restored section, but most likely not in the control section.

Beyond species richness, the identity of the species needs to be taken into consideration. The overall biodiversity of a river reach might not increase in response of river restoration: it might even decrease. However, if characteristic species of active floodplains are re-established following a river restoration project, this should be considered as a success. This is especially important given that many characteristic species of dynamic floodplains have become endangered. An illustration of this is the little ringed plover, which requires gravel bars for nesting. Following the restoration, this species returned to the restored Thur River reach after more than 100 yr of absence (Fig. 1b).

4.3 How does morphological variability affect biogeochemical transformations in the river corridor?

The spatial and temporal variability of organic carbon pools in soils and related fluxes were higher in the restored than in the channelized section. This functional variability was correlated to (i) the broader range of soil properties and flooding frequencies arising from the change in habitats from dynamic gravel bars to stable alluvial forests within the restored section of the Thur River floodplain, and (ii) the high spatial heterogeneity of soil properties and environmental conditions on the gravel bars (Samaritani et al., 2011). This suggests that restoration has led to a significant increase in soil functional diversity. These results are in line with previous reports that short-term inundations are important drivers of microbial habitat structure and function in floodplains (Wilson et al., 2011).

In a comprehensive study of nitrogen cycling in floodplain soils, we identified two FPZs in the restored section as hot zones of nitrogen turnover and removal (Shrestha et al., 2012): (i) the gravel bars, characterized by frequent inundation and high sediment deposition rates; (ii) the low-lying alluvial forest with a fine-textured soil where anaerobic microsites facilitated coupled nitrification-denitrification. By contrast, the soils of the embankment in the channelized section had comparatively small inorganic nitrogen pools and low transformation rates, particularly those related to nitrate production. This emphasizes the importance of environmental heterogeneity in creating sites of nitrogen buffering.

We found that restoration-induced soil-groundwater coupling is more important for subsurface nitrate removal than the nitrate removal capacity of local plant communities. In the restored section, we identified the discharge-modulated translocation of assimilable organic carbon from the unsaturated soil horizon to the saturated gravel zone as a key driver for groundwater organic carbon cycling and the formation of denitrification hot spots and hot moments (Peter et al., 2012b) confirming earlier observations (Schade et al., 2001; Clinton et al., 2002). Flood-induced water level changes are needed to exploit this coupling and to recharge the groundwater organic matter (OM) inventory with bioavailable substrates. Therefore, it appears that flood events, as triggers of transformation processes in the riparian zone, and morphological variability are of mutual importance for corridor-wide transformation processes.

4.4 What are the potential adverse effects of river restoration?

Vogt et al. (2010a) showed that, for the same distance to the main channel, groundwater propagated faster into the aquifer where the river has undergone restoration than in the channelized section where riverbed morphology was more uniform and a clogging layer existed. This effect could translate into potentially adverse impacts on groundwater quality due to faster river-water infiltration with shorter residence times within the riparian aquifer. This could endanger the quality of groundwater extracted in nearby pumping stations with respect to pathogenic fecal coliforms, harmful macronutrients, or micropollutants (including pharmaceutical, personal care products (Musolff et al., 2010) and pesticides). These pollutants undergo natural attenuation in the subsurface, but an understanding of the processes and flow paths is necessary.

Apart from the positive effect on nitrogen removal by denitrification, the fast nitrogen cycling in parts of the restored section has also some negative consequences. First, hot spots of N_2O (a major greenhouse gas) efflux can occur, in particular during the drying phase after major floods (Shrestha et al., 2012). Second, under unsaturated but sufficiently moist conditions, strong nitrification leads to the accumulation of high amounts of nitrate that are leached to the groundwater mainly during floods and in winter (Huber et al., 2012b). Hence, groundwater quality in near-river aquifers of restored river reaches could vary markedly because of the high spatial and temporal variability of both infiltration travel times and soil properties, in particular on gravel bars. Such considerations should be incorporated into relevant regulations.

The active geomorphodynamics which was created by the restoration action, as described above, improved the ecosystem. The larger diversity of habitats provided a broader range of ecological niches thus allowing a higher overall diversity of organisms to colonize the area. However, the larger geomorphodynamics may become critical when excessive erosion takes place. The Thur River provides a good example (Fig. 5) where in about five years the gradual formation of a (metastable) point bar on the left river bank has caused the removal of a large fraction of the riparian forest on the opposite bank. The river is now within 20 m of an agricultural field. Hence, a strategic balancing between protection and rehabilitation is needed.

4.5 What are the implications of our research for future restoration projects?

The planning of river restoration needs to assess the relative value of different ecosystem services and to address potentially conflicting goals. It appears that restoration can achieve the goals of sustainably increasing geomorphological and biological diversity mainly by creating a naturally developing and dynamic system of gravel bars. However, drinking water extraction from fluvial aquifers in the vicinity of rivers should be restricted to river reaches with stable conditions as in channelized sections or natural FPZs that are not well connected to the river. Our results thus support respective legislative measures (e.g. BUWAL, 2004).

On a different topic, the occurrence of greenhouse gas emission hot spots in dynamic FPZs of restored river reaches (Samaritani et al., 2011; Shrestha et al., 2012) could potentially compromise the climate regulation function of river floodplains. Furthermore, public acceptance of the restoration project was generally very positive during the first decade following the restoration of the Thur River. Regular educational and information efforts from local authorities and scientists involved contributed to creating a positive relationship with the local community. However, the increasing and visible threat of the changing river course (Fig. 5) will constitute a test of the tolerance of the local community to potential loss of agricultural land.

5 Conclusions

River–soil–groundwater interactions are the engines of riverine ecosystems and they respond at different temporal scales following restoration. Twenty years after restoring and widening a two km section of the Thur River in Switzerland, we identified the highest geomorphodynamics in revitalized reaches. Restoration led to an increase in taxonomic and functional diversity, which was mainly driven by short-term perturbations, such as periodic floods and inundations. Species richness of plants and soil organisms (earthworms, testate amoebae, bacteria) was higher in the restored section than in the control section (pasture) located directly upstream. Periodic flooding allows a balance between protection against flooding and rehabilitation to a more natural ecosystem in terms of ecology, hydrology and biogeochemistry. Nevertheless, repeated flooding may become critical if excessive erosion threatening valuable land takes place as experienced at the Thur River. This will test the tolerance of the community and the regulators on how far restoration can or will be accepted.

Increased river dynamics, higher infiltration rates and shorter residence times within the aquifer may endanger the microbiological and chemical quality of groundwater extracted in nearby pumping stations as pollutants undergo natural attenuation in the subsurface. Monitoring schemes in restored river corridors must therefore account for hydrological and biogeochemical dynamics. To conceptualize and track infiltrating river water moving through the groundwater systems, three-dimensional geophysical and hydrogeological investigations in combination with time-series analyses of natural tracers (temperature and electrical conductivity) are valuable. This allows for estimation of seepage fluxes and residence times, the characterization of vertical variations in the hydrological exchange processes, as well as the transformations of organic matter in the riparian groundwater. Here we found that groundwater quality in the restored river reach strongly varies because of the high spatial and temporal variability of both residence times and soil properties.

The spatial and temporal variability of organic carbon pools in soils and related fluxes were higher in the restored than in the channelized section. This suggests that restoration has led to a significant increase in soil functional diversity. Concerning the nitrogen cycling in floodplain soils, we identified two FPZs in the restored section as hot zones of nitrogen turnover and removal. Restoration-induced soil–groundwater coupling is more important for subsurface nitrate removal than the nitrate removal capacity of local plant communities. However, the fast nitrogen cycling in parts of the restored section has also some negative consequences. First, hot spots of N_2O efflux can occur, in particular during the drying phase after major floods. Second, under unsaturated but sufficiently moist conditions, strong nitrification leads to the accumulation of high amounts of nitrate that are leached to the groundwater mainly during floods and in winter.

Future research on restoration projects should include the evaluation of different ecosystem services against each other and the feedback mechanisms with global climate and society. There is growing need for innovative approaches to scale spatially and temporally heterogeneous data and achieve case-to-case measures of river restoration success. To accomplish this need, additional well-instrumented field observatories such as the RECORD field sites are required for comparisons and long-term monitoring.

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Fig. 1. Restoration enhances several aspects of ecosystem services: **(a)** recreational, where people regain contact with nature through sports and water-related activities (river flow is from right to left); **(b)** ornithological, favoring the return of long-disappeared bird species, e.g. the little-ringed plover; **(c)** educational, which ensures the build-up of awareness and sensitivity to ecological aspects in future generations; **(d)** functional biodiversity, where the reactivation of aquatic and semi-aquatic species (e.g. beavers) activity also drives the riverine ecosystem dynamics.

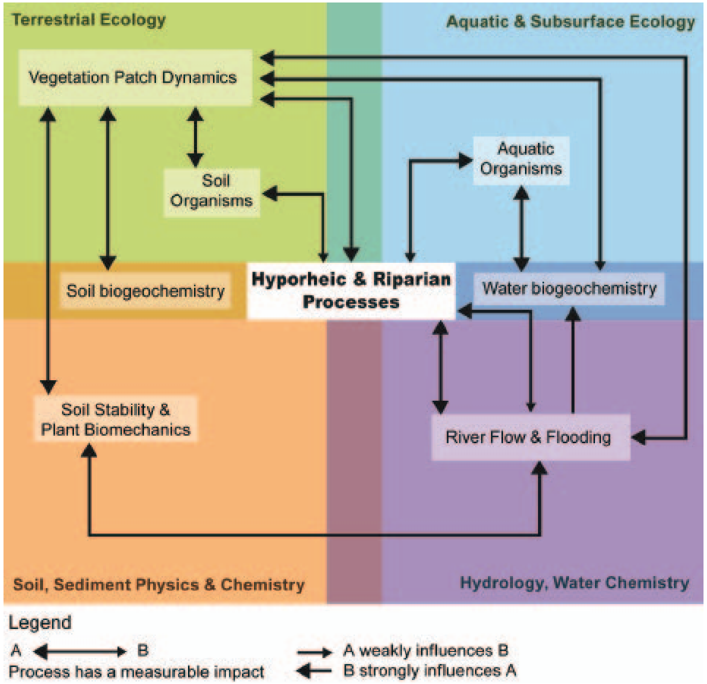
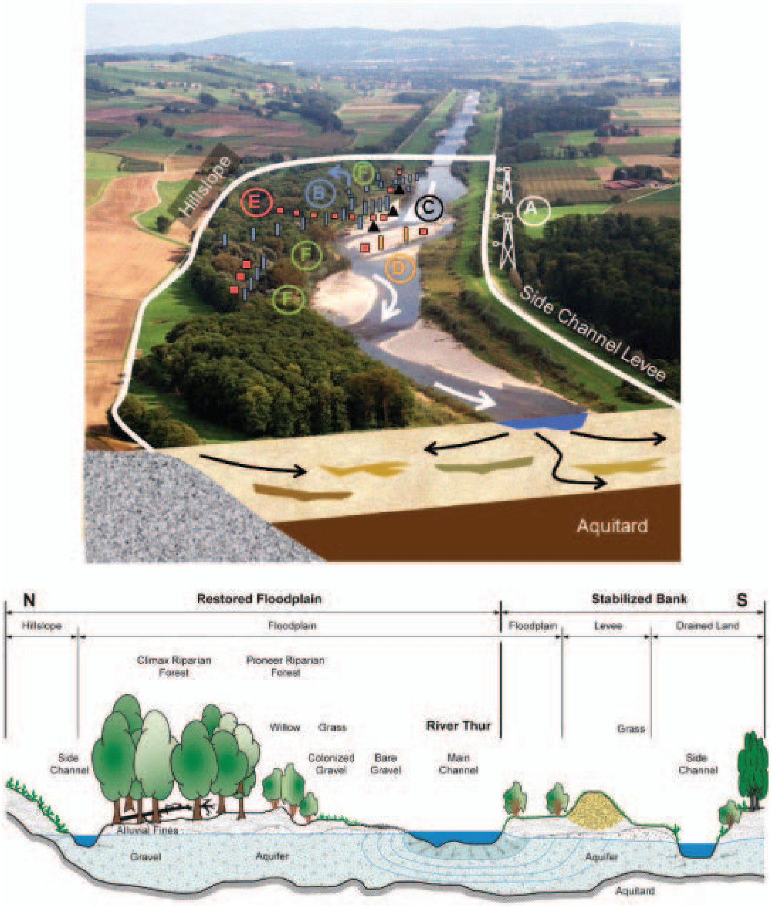


Fig. 2. Schematic overview showing scientific domains and related processes affecting ecosystem functions in river corridors that should be considered during restoration. Text labels represent processes that dynamically affect system functioning, lines represent connections between processes, and arrows indicate impacts of processes on each other (size of arrow heads indicates magnitude of impact).


Hillslope
E
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D
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Side Channel Levee
Aquitard
N
Restored Floodplain
Stabilized Bank
S
Hillslope
Floodplain
Floodplain
Levee
Drained Land
Climax Riparian Forest
Pioneer Riparian Forest
Willow
Grass
River Thur
Grass
Side Channel
Colonized Gravel
Bare Gravel
Main Channel
Side Channel
Alluvial Fines
Gravel
Aquifer
Aquifer
Aquitard

Fig. 3. Instrumented field site at the Swiss River Thur close to Niederneunforn (47°35.4′ N, 8°46.4′ E) in NE Switzerland with (A) observation towers including cameras, (B) piezometers and wells, (C) geophysical mapping, (D) measurements of meteorological parameters, (E) monitoring of soil parameters (for exact locations see Huber et al., 2012; Shrestha et al., 2013) and (F) biodiversity surveys (for exact locations see Fournier et al., 2012b). Empirical data gained from research at this field site are shared among all project partners through the database Swiss Experiment (www.swiss-experiment.ch). The picture was taken by BHAteam, Frauenfeld. The scheme below visualizes the specific parts of the RECORD field site. It shows a geological cross-section representing restored (left) and channelized (right) transects at the test site. The restored parts comprise gravel bars developed naturally after restoration, including (i) the gravel zone, sparsely colonized with pioneer plants, (ii) the grass zone, characterized by thick layers of young alluvial overbank sediments and densely colonized with mainly reed grass (Phalaris arundinacea), (iii) the willow zone, where alluvial sediments were stabilized during restoration by planting young Salix viminalis, and (iv) the alluvial forest dominated by ash and maple and growing on older alluvial sediments.

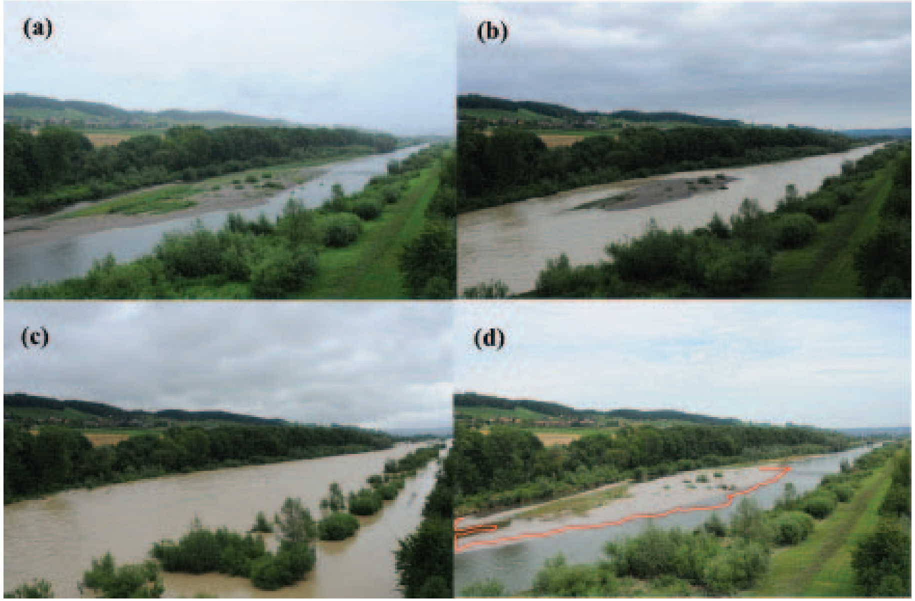

Fig. 4. Upstream view of the main island of the Swiss River Thur monitored with high-resolution remotely controllable digital cameras (see Pasquale et al., 2011 for details). The sequence **(a)**–**(d)** shows a compilation of the inundation dynamics during the flood in July 2009 (peak flow of 748 $m^3 s^{-1}$), which resulted in a complete flooding of the restored corridor **(c)**, causing substantial morphologic changes and removal of young vegetation **(d)**. The red contour line in panel **(d)** shows the comparison with the shoreline of the sediment bar before the flood **(a)** for the same flow rate.

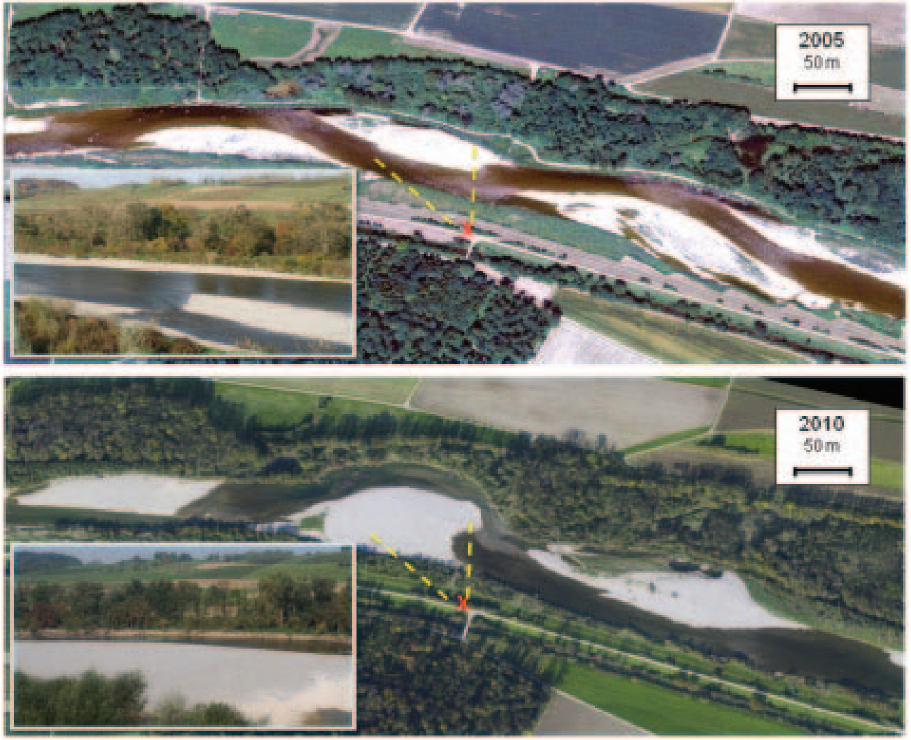

Fig. 5. Recent erosion: trouble brewing? Starting with the floods of 2010/2011 excessive erosion began in the area pointed out by the yellow dashed lines (river flow is from right to left). Large portions of the riparian forest were removed. The inserted pictures are taken at the locations of the red cross where an observation tower exists (see Pasquale et al., 2011).