Hydrol. Earth Syst. Sci., 18, 2449–2462, 2014
www.hydrol-earth-syst-sci.net/18/2449/2014/
doi:10.5194/hess-18-2449-2014

Hydrology and Earth System Sciences
Open Access

Morphological, hydrological, biogeochemical and ecological changes and challenges in river restoration – the Thur River case study

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Received: 18 July 2013 – Published in Hydrol. Earth Syst. Sci. Discuss.: 20 August 2013
Revised: 23 May 2014 – Accepted: 28 May 2014 – Published: 27 June 2014

Abstract. River restoration can enhance river dynamics, environmental heterogeneity and biodiversity, but the underlying processes governing the dynamic changes need to be understood to ensure that restoration projects meet their goals, and adverse effects are prevented. In particular, we need to comprehend how hydromorphological variability quantitatively relates to ecosystem functioning and services, biodiversity as well as ground- and surface water quality in restored river corridors. This involves (i) physical processes and structural properties, determining erosion and sedimentation, as well as solute and heat transport behavior in surface water and within the subsurface; (ii) biogeochemical processes and characteristics, including the turnover of nutrients and natural water constituents; and (iii) ecological processes and indicators related to biodiversity and ecological functioning. All these aspects are interlinked, requiring an interdisciplinary investigation approach. Here, we present an overview of the recently completed RECORD (**RE**stored **COR**ridor **D**ynamics) project in which we combined physical, chemical, and biological observations with modeling at a restored river corridor of the perialpine Thur River in Switzerland. Our results show that river restoration, beyond inducing morphologic changes that reshape the river bed and banks, triggered complex spatial patterns of bank infiltration, and affected habitat type, biotic communities and biogeochemical processes. We adopted an interdisciplinary approach of monitoring the continuing changes due to restoration measures to address the following questions: How stable is the morphological variability established by restoration? Does morphological variability guarantee an improvement in biodiversity? How does morphological variability affect biogeochemical transformations in the river corridor? What are some potential adverse effects of river restoration? How is river restoration influenced by catchment-scale hydraulics

Figure 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 for future generations; and **(d)** functional biodiversity, where the reactivation of aquatic and semi-aquatic species (e.g., beavers) activity also drives riverine ecosystem dynamics.

and which feedbacks exist on the large scale? Beyond summarizing the major results of individual studies within the project, we show that these overarching questions could only be addressed in an interdisciplinary framework.

1 Introduction

Over the last 20 years, revitalization of engineered river reaches has been established in Europe as a measure towards achieving a good ecological status of water bodies as required by the EU Water Framework Directive (European Commission, 2000) while protecting downstream river reaches from floods. Swiss legislation requires river revitalization actions as part of flood protection measures (BWG, 2001). These 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 over the past several 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; Kurth and Schirmer, 2014).

However, without an adequate understanding of the underlying physical, chemical, hydro(geo)logical, biological and ecological processes and without 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 (Wohl et al., 2005). Apart from considering the ecological status of the ecosystem itself, the success of river restoration can be assessed by evaluating ecosystem services beneficial to humans. Figure 1 exemplifies some services provided by river restoration. In general, these services include: regulation of runoff, provision of clean drinking water, cultural services (e.g., such as recreation), as well as supporting services (e.g., soil formation, nutrient cycling, fish stocks, and habitat provision) (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). Also, there is overall agreement that the inertia of the ecosystem to react to perturbations constrains the evaluation of restoration success (Palmer et al., 2005). 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. For example, fast river-water infiltration and short residence times within the riparian aquifer may threaten 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).

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; known as 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; Crouzy et al., 2013), 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). Soil cohesion, water content and chemistry, as well as the interactions between 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 (Gurnell, 2014). If the timescale of vegetation formation does not exceed the inter-arrival time of the major morphodynamic events, vegetation has a good chance to establish and grow. Generally, riparian zone processes play a central role in river corridor restoration because they couple river flow with corridor morphodynamics, soil processes, and riparian vegetation (Perucca et al., 2007; Perona et al., 2012; Camporeale et al., 2013). 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).

Natural and restored floodplains offer a suitable opportunity to compare responses of different organisms to perturbation. After restoration, former channelized river sections clearly appear to recover a near-natural status, composed of both FPZs created during or following the restoration and those that existed before restoration (Samaritani et al., 2011). However, 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 (intermediate disturbance hypothesis), the diversity of soil organisms is thought to increase linearly with decreasing perturbation (Wardle et al., 2004).

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 (e.g., Boulton et al., 1998; Kasahara and Wondzell, 2003; Hester and Doyle, 2008). Because increased morphological variability in the river bed enhances hyporheic exchange, river restoration may 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 hot moments of carbon and nitrogen turnover (e.g., Peter et al., 2012a, b; Shrestha et al., 2012, 2014).

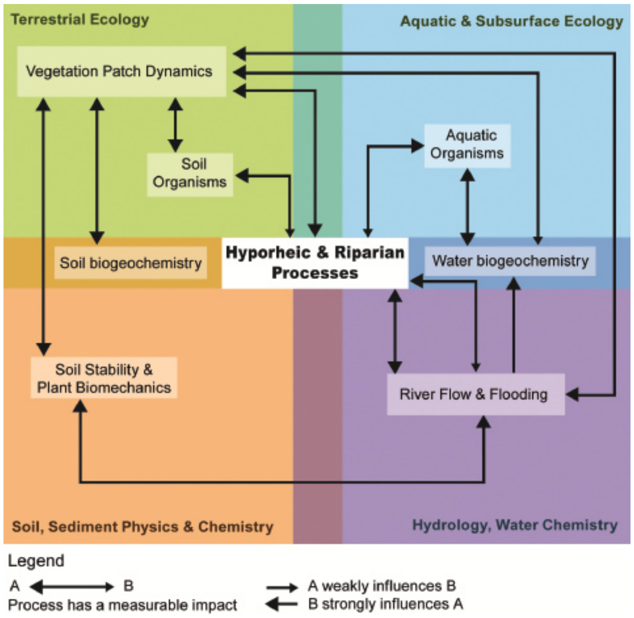

Figure 2. Schematic overview showing scientific domains and related processes affecting ecosystem functions in river corridors that should be considered during restoration. Text labels represent processes that dynamically affect system functioning, lines represent connections between processes, and arrows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

2 The RECORD Project at the Thur River (Switzerland)

The interdisciplinary RECORD (**RE**stored **COR**ridor **D**ynamics) project was aimed at understanding different processes and interactions affecting ecosystem functions and services of restored river corridors (see Sect. 1 and Fig. 2). Within the project's broad objectives, we focused on concepts integral to river restoration and in particular reported on the 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.

The formerly braided Thur River in NE Switzerland 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).

The perialpine Thur River drains a catchment area of 1730 km^2. It originates in an alpine region that reaches its highest point on Mount Säntis (2502 m above sea level). The Thur River is the largest river in Switzerland without a retention basin. This leads to a very dynamic discharge regime ranging from 3 to 1100 m^3 s^{-1} with an average of 47 m^3 s^{-1} (Diem et al., 2013b, 2014). The field site (Fig. 3) is located approximately 12 km upstream of the confluence with the Rhine River. In the western part of the field site, restoration measures were realized in 2002. Restoration measures were forbidden in the upstream section of the field site to protect the water quality at the nearby pumping station, where a pumping well supplies the nearby community of Niederneunforn with drinking water.

In order to improve understanding of how hydromorphological variability relates to ecosystem functioning and services, terrestrial biodiversity as well as ground- and surface

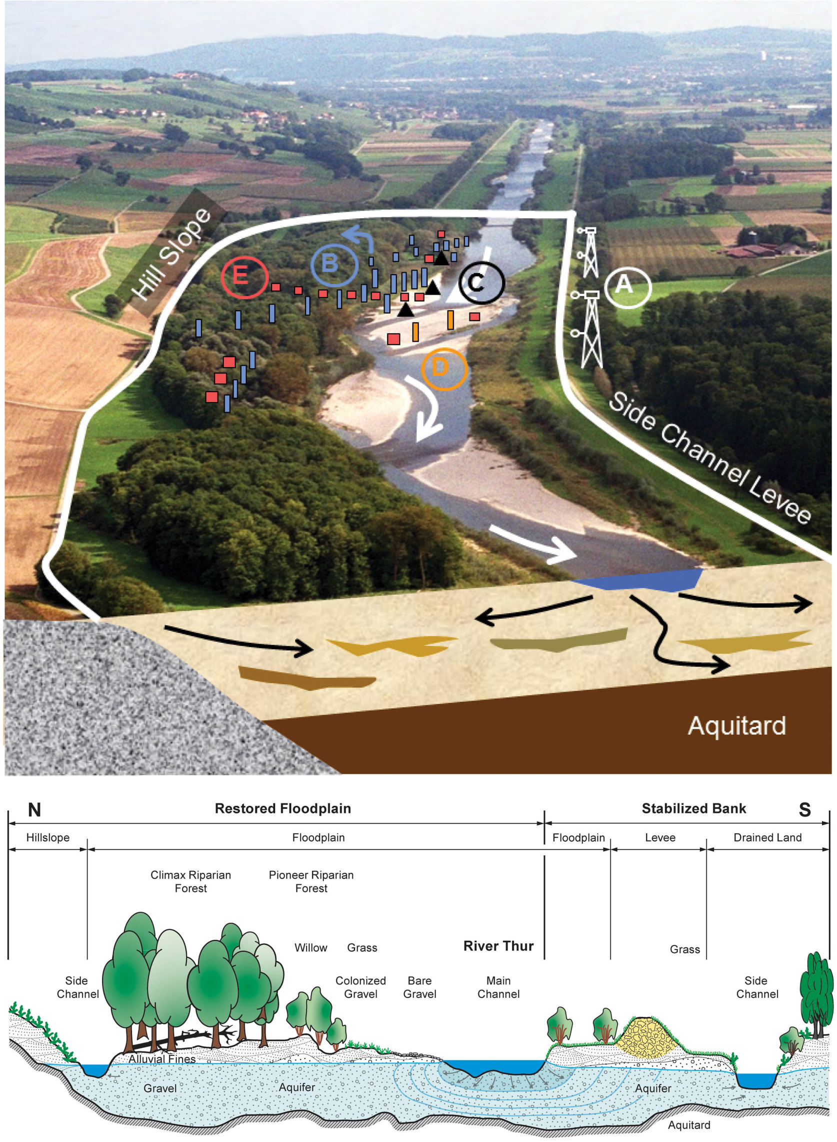

Figure 3. Instrumented field site at the Swiss River Thur close to Niederneunforn (47°35.4′ N, 8°46.4′ E) in NE Switzerland with **(A)** observation towers including cameras, **(B)** piezometers and wells, **(C)** geophysical mapping, **(D)** measurements of meteorological parameters, **(E)** monitoring of soil parameters (for exact locations see Huber et al., 2012; Shrestha et al., 2014) and **(F)** biodiversity surveys (for exact locations see Fournier et al., 2012b). 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 stabilized/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 canary 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.

water quality in restored river corridors, the RECORD project was conducted using a restored and a channelized section of the Thur River corridor as test sites. For this purpose, the field site was instrumented with measuring and monitoring devices to record aerial, water and soil variables (e.g., see Pasquale et al., 2011; Schneider et al., 2011; Fig. 3). In addition, more than 80 piezometers (2 inch) were installed during the project (Diem et al., 2013b, 2014).

At these intensively instrumented sites, we studied geomorphodynamics, the subsurface structure, river and groundwater hydrology, soil and groundwater biogeochemistry, terrestrial biodiversity as well as water quality. Such interdisciplinary and combined efforts have never been applied at a single site, but have proved useful in developing and testing several methods and concepts to assess key processes as well as the impact of restoration on biodiversity. To illustrate this we provide a few examples. Our studies on pioneer vegetation with subsequent development of river bars and islands, as well as our investigations on soil processes including carbon and nitrogen cycling would not have been possible in such a comprehensive way if we had not had temporally and spatially highly resolved information on river flow and water level data. The latter information, together with the detailed 3-D geophysical images of the subsurface, was crucial to construct a 3-D groundwater flow and transport model with a highly dynamic river boundary condition. This hydrogeological model then formed the basis for interpreting the dynamics of nutrient cycling and the fate of the investigated micropollutants. Also, the biological and ecological studies required insights into flood dynamics and water recession behavior over time to set sampling schedules and interpret the results. In the following, we present the main findings of and the interrelationships among the different sub-projects. For better readability, we subdivided the projects into three main research fields: (a) hydrologic, hydrogeological and physical investigations, (b) biogeochemistry: dynamics of organic carbon, nutrients and pollutants in groundwater and floodplain soils, and (c) biological and ecological investigations.

2.1 Hydrological, hydrogeological and physical investigations

The hydrological, hydrogeological and physical investigations are interrelated as described above, and have also laid the foundations for understanding the biogeochemical and ecological processes (see Sects. 2.2 and 2.3, respectively). The investigations carried out in the fields of hydrology, hydrogeology and physics include:

i. Field experiments to understand how pioneer vegetation becomes established on alluvial sediment forming river bars and islands. We proposed that the ratio of inter-arrival times of floods to the timescales of root growth determines the interplay between morphological and vegetation dynamics, and combined towards this end field and laboratory experiments. At the field scale, we used transplanted willow cuttings supported by hydrodynamic modeling of the site (Schäppi et al., 2010; Pasquale et al., 2013, 2014). At the laboratory scale, we performed controlled flume experiments to study the uprooting of seedling and pioneer vegetation using Avena Sativa as prototypical vegetation species (Edmaier et al., 2011; Perona et al., 2012). By comparing the histograms concerning the above- and below-ground characteristics of vegetation that is removed by floods, we found that there is a clear correspondence between the processes of vegetation uprooting by flow erosion at both scales (Crouzy et al., 2013). This is striking, if one considers that a complete mechanical similarity between the rescaled flume and the river is generally not possible when studying ecomorphodynamic problems. This notwithstanding, our results suggest that floods would operate as "natural filters" for the growing biomass, that is, they select which vegetation survives and which will be uprooted according to their biological (growth stage and location) and hydrological (magnitude, duration, interarrival time, and frequency) characteristics.

ii. In addition to the constantly changing riverbed environment, we had to assess the structure of the adjacent aquifer. For this, geophysical cross-hole and surface-based methods offered reliable high-resolution (meter-scale) three-dimensional images of effective porosity and presence of fines at spatial scales ranging from tenths to hundreds of meters (Doetsch et al., 2010b; 2012a; Coscia et al., 2011). It was then possible to postulate a likely limit between old fluvial deposits and those associated with deposition at the time when the river was channelized (Doetsch et al., 2012a). Geophysical monitoring allowed three-dimensional imaging of groundwater flow patterns that originate from infiltrating river water using cross-hole geophysics (Coscia et al., 2012b) or by using injections of artificial saline tracers in combination with surface-based geophysics (Doetsch et al., 2012b). We could also estimate groundwater velocities and image the hydraulic conductivity field by combining natural-tracer and hydraulic-tomography data with geophysical data in a joint inversion framework (Lochbühler et al., 2013). These interpretations were only made possible by modeling borehole effects (Doetsch et al., 2010a, b); incorporating known lithological interfaces (Coscia et al., 2011); and by employing dedicated filtering strategies to remove unwanted contributions to the geophysical monitoring data (Coscia et al., 2012a). We found that imaging techniques based on full-waveform inversion hold considerable promise, as they offer unprecedented resolution capabilities, but their reliability, especially in terms of the resolved electrical conductivity, is still a subject of ongoing research (Klotzsche et al., 2013). An investigation of the utility of self-potential monitoring to follow groundwater dynamics in the hyporheic zone was inconclusive, mainly because of thick clay deposits under the aquifer that led to very low electrical field strengths and, hence, low signal levels (Linde et al., 2011). Overall, the geophysical data and interpretations were crucial in constructing the 3-D hydrogeological model.

iii. Using the results of the work described above, we developed a 3-D hydrogeological site model to simulate groundwater flow and transport as well as interactions between ground- and surface water (Diem et al., 2014). The model input requires a proper definition of the river boundary conditions, with a detailed spatial and temporal distribution of river stage. Therefore, we developed two new methods to assign river stages for dynamic rivers that are based on measured data (Diem et al., 2013b). Comparing generated time series of water levels with those obtained by the hydraulic model as a reference, the new methods proved to offer an accurate and faster alternative with a simpler implementation. The developed 3-D hydrogeological site model including the dynamic river boundary condition proved to be crucial for the interpretation of the nutrient cycling and the micropollutant dynamics.

iv. A key parameter used in the assessment of bank filtration is the travel time of the infiltrated river water during the passage through the connected aquifer. For this, we analyzed time series of electrical conductivity (EC) in the river and adjacent groundwater observation wells to investigate travel times of young hyporheic groundwater (Vogt et al., 2010a). To quantify mixing ratios and mean residence times we performed a cross-correlation analysis and non-parametric deconvolution of the EC time series. Diurnal oscillations of EC observed in the river and in nearby observation wells facilitated the analyses of the temporal variation of infiltration. The range of travel times derived from diurnal and overall EC signals reflects different infiltration regimes such as low flow and flooding conditions (Vogt et al., 2010a).

v. In order to further 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 their vertical variations (Vogt et al., 2010b). These evaluations helped to validate the 3-D hydrogeological model.

vi. Based on the travel-time estimates from EC fluctuations in the river and in observation wells as described above, Diem et al. (2013c) were able to investigate the effects of temperature and discharge on degradation of natural organic matter during river infiltration. They developed a new modeling approach that allows efficiently estimating dissolved oxygen (DO) concentrations in groundwater from measured DO concentrations in the river under various temperature and discharge conditions (Diem et al., 2013a). The model is based on the stochastic–convective reactive approach and assumes a time-invariant lognormal travel-time distribution of the stream-tube ensemble connecting the river and a groundwater observation well. Dissolved oxygen consumption, resulting from aerobic respiration, is modeled by zero-order kinetics. According to high-resolution DO time series measured in the river and an adjacent observation well, the DO consumption rate appears to depend on river temperature and discharge.

2.2 Biogeochemistry: dynamics of organic carbon, nutrients and pollutants in groundwater and floodplain soils

For these investigations and the biological studies described in Sect. 2.3, we transferred the FPZ concept, introduced by Thorp et al. (2006) for the catchment scale, to the scale of a single reach and extended the concept of "functional" to ecological processes in addition to physical functioning of geomorphic and hydrologic forces (Samaritani et al., 2011).

i. We studied the coupled impact of ecosystem configuration in terms of FPZs and discharge fluctuations on the transformations of organic carbon and nitrogen species in shallow riparian groundwater and floodplain soils. In both systems, we combined geochemical, biochemical and molecular-biological analysis to identify biogeochemical processes as well as the responsible organisms and to determine process rates and element fluxes (Huber et al., 2012b; Peter et al., 2012a; Samaritani et al., 2011; Shrestha et al., 2012, 2014). The results are briefly discussed in Sects. 3.3. and 3.4.

ii. In the course of the latter investigations, we developed two methods for isolating nitrate from freshwater samples from the river, soil, and groundwater for nitrogen and oxygen isotope analysis at natural background levels (Huber et al., 2011, 2012a). Using these methods, we were able to find evidence of a significant contribution of archaeal ammonium oxidation in floodplain soils (Huber, 2012).

iii. In order to model the processes studied under (i), a "riparian soil model" was developed that allows predicting 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 storage and inorganic nitrogen fluxes in the riparian forest of the test site (Batlle-Aguilar et al., 2012).

iv. Micropollutant dynamics in groundwater were studied qualitatively and quantitatively using both spatiotemporally resolved sampling and single-well push-pull tests, followed by LC-MS/MS analysis (Huntscha et al., 2013). The information on flow dynamics and flow paths in the aquifer adjacent to the river provided by the 3-D flow and transport model (Diem et al., 2014) was pivotal to drawing conclusions about differences in degradation rates between the restored and the channelized section and their possible causes.

2.3 Biological and ecological investigations

Based on the comprehensive hydrological, physical and biogeochemical investigations, much more in-depth interpretation was possible for the biological and ecological studies. This is due to the fact that biological and ecological changes over the longer term greatly depend on the physical changes of the floodplain, the flow and flooding patterns, as well as on the changes in the subsurface biogeochemistry.

i. We assessed the impact of river restoration on the biodiversity of a broad range of taxonomic and functional groups of terrestrial organisms (vascular plants, invertebrates, testate amoebae, all soil micro-eukaryotes and bacteria). This allowed us to assess distribution patterns for individual groups (e.g., Fournier et al., 2012a, b), to compare the relationships between each group and ecological gradients (e.g., distance to the river and elevation as proxy to inundation frequency, water table depth) or functional processes (e.g., soil respiration, soil enzymatic activity) (Fournier, 2013; Samaritani, 2013).

ii. 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 (e.g., community weighted means of traits, functional dispersion), which more strongly correlated to measured environmental variables than classical species-based diversity indices (Fournier et al., 2012a, b).

iii. Diversity patterns differed among taxonomic groups (vascular plants, spiders, carabid and staphylinid beetles, isopods, diplopods and earthworms), functional groups (primary producers, herbivores, carnivores, decomposers), and among metrics (i.e., species richness, taxonomic and functional diversity metrics) indicating that different mechanisms contribute to shaping communities in this restored floodplain (Fournier, 2013). Overall, we could show that species richness was higher in the restored section in comparison to the channelized control section (pasture).

iv. Spatial and temporal patterns of bacteria and micro-eukaryotic communities were assessed in the main functional process zones (FPZs; colonized gravel, dense *Phalaris* grass communities, willow bush, mixed forest, willow forest and pasture) in winter, spring, summer and autumn. Bacterial communities differed primarily among seasons and within seasons among FPZs, while the opposite was observed for micro-Eukaryotes (Samaritani, 2013).

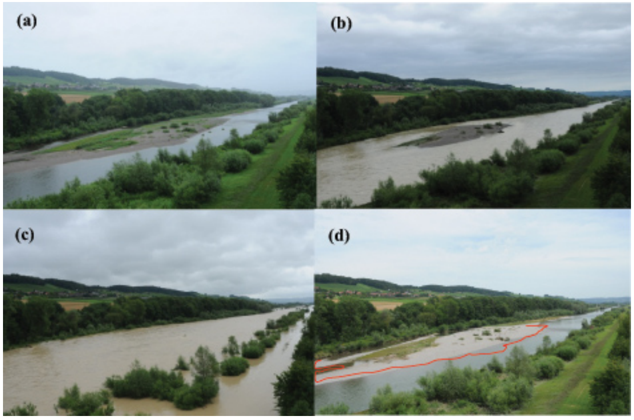

Figure 4. Upstream view of the main island of the Swiss River Thur monitored with high-resolution remotely controllable digital cameras (see Pasquale et al., 2011 for details). The sequence **(a–d)** shows a compilation of the inundation dynamics during the flood in July 2009 (peak flow of $748\,\mathrm{m}^3\,\mathrm{s}^{-1}$), 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.

3 Discussion of RECORD project results

Based on the work within the RECORD project described above, we here attempt to answer some basic questions concerning the evaluation of river restoration measures. We furthermore evaluate the advantages of an integrated and interdisciplinary approach at single sites.

3.1 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 stochasticity in the uprooting process of seedlings (Crouzy and Perona, 2012) is gradually replaced by delayed erosion mechanisms as plants increase their anchoring while growing. We found that vegetation (Salix) cuttings can tune their vertical root density distribution according to river fluctuations, notably to the distance between soil elevation and the saturated water table within the sediment (Pasquale et al., 2012, 2013). Together with the fact that uprooting can be delayed depending on flood duration and intensity, this root allocation strategy would allow plants to recover their anchoring in between floods. Timescales of vegetation growth, together with those of hydrologic disturbances (Edmaier et al., 2011; Crouzy and Perona, 2012; Perona et al., 2012), link the corresponding hydrologic and biological processes and contribute to the explanation of the presence of vegetation in patches reflecting local sediment morphology. At the reach scale, soon after restoration, FPZs may

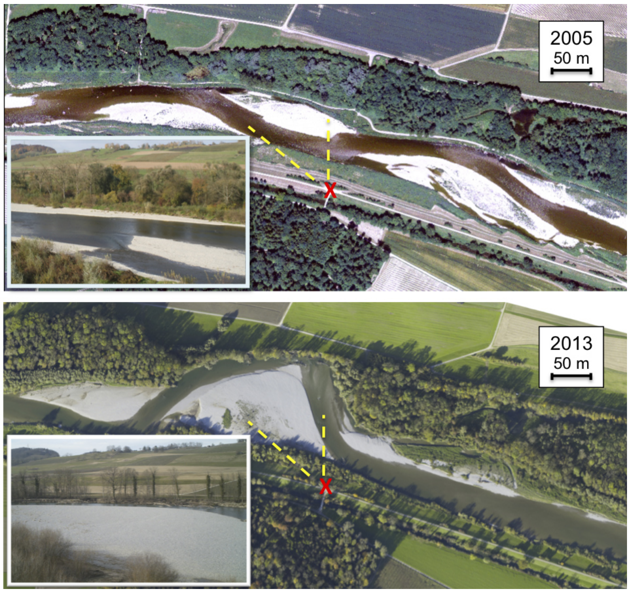

Figure 5. Recent erosion: trouble brewing? Starting with the floods of 2010/2011 excessive erosion began in the area pointed out by the yellow dashed lines (river flow is from right to left). Large portions of the riparian forest were removed. The inserted pictures are taken at the locations of the red cross where an observation tower exists (see also Fig. 3 and Pasquale et al., 2011).

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, as the left-hand side river bar at the river bend has gradually evolved into a point bar. However, this now relatively stable situation could create conflicts with land-owners and agricultural use and raise further questions about ecosystem services and predictability of restoration-induced effects.

3.2 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, arthropods, 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; Samaritani, 2013; Fournier, 2013). 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 to 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 years of absence (Fig. 1b).

3.3 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 low-lying alluvial forest with a fine-textured soil where anaerobic microsites facilitated coupled nitrification-denitrification; (ii) the gravel bars, characterized by frequent inundation and high sediment deposition rates. Here, major floods led to a strong stimulation of nitrogen mineralization due to temporary input of available organic matter, probably mainly related to the deposition of sandy sediments by the fast over-flowing water (Shrestha et al., 2014). This was followed by enhanced nitrification and denitrification during the drying phase with close coupling of the two processes supported by different redox conditions at the inside and outside of soil aggregates. 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 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 at other sites (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 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.

Pesticides and pharmaceuticals such as the herbicide 2-methyl-4-chlorophenoxyacetic acid and the pain killer diclofenac exhibited exceptionally short half-lives upon river water infiltration, demonstrating the great degradation potential for organic micropollutants in the hyporheic zone and the adjacent aquifer under aerobic conditions (Huntscha et al., 2013). The special importance of the hyporheic zone was indicated by the partial degradation of the corrosion inhibitor benzotriazol, particularly in the first few meters of the aquifer. Nevertheless, several micropollutants were persistent and reached the drinking water well, demonstrating the vulnerability of drinking water produced by river bank filtration. However, push-pull tests indicated faster degradation of phenoxy herbicides in the restored than in the channelized transects. We speculate that the improved micropollutant degradation in the restored river-groundwater system can be attributed to the higher spatial complexity, the respective higher diversity of microorganisms and thus better adaption to micropollutants, and to the higher amount of bioavailable organic matter, mentioned above, and thus higher microbial biomass. These hypotheses have to be tested by further studies.

3.4 What are 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 (Huntscha et al., 2013)). These pollutants undergo natural attenuation in the subsurface, but reduction of flow-path lengths and travel times due to river restoration may impair the completeness of degradation.

Apart from the positive effect on nitrogen removal by denitrification, the fast nitrogen cycling in parts of the restored section also has 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 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, more active geomorphodynamics may become problematic when excessive erosion takes place. For example, in 5 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 (Fig. 5). The river is now within 20 m of an agricultural field. Hence, strategic balancing between protection and rehabilitation is needed.

3.5 How is river restoration influenced by catchment-scale hydraulics and which feedbacks exist on the large scale?

River restoration determines hydraulic alteration (Stromberg et al., 2007), and should ideally provide a change in land use in a catchment. The hydrological response of the catchment to land-use changes, which are overlaid on local responses due to river restoration, varies 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 reach to catchment scales. To this regard, Fig. 6 shows an example of how the reach-scale hydrodynamic model BASEMENT (e.g., Schäppi et al., 2010; Pasquale et al., 2014) has been used to drive the bank stability model B-STEM 5.2 (e.g., see Simon et al., 2000) in order to simulate the erosion that took place at the outer bank of the river bend over the years 2009–2010 (Cattaneo, 2012). Despite several assumptions, the model calibrated on 2009 data suggests that flood events above an estimated threshold of $370\,\mathrm{m^3\,s^{-1}}$ were able, during the 2010 season, to drive an

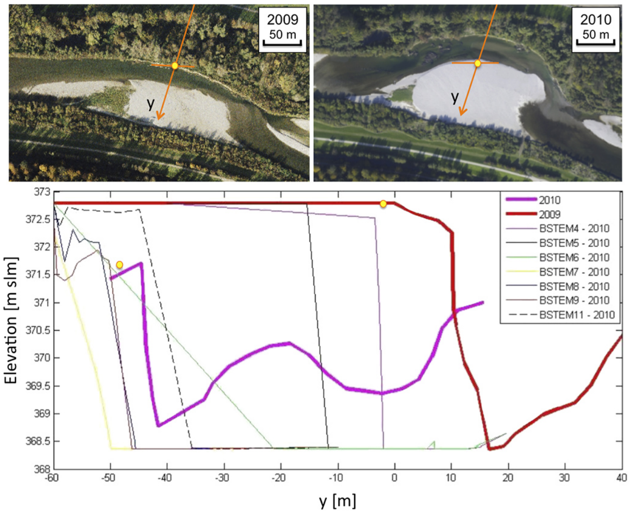

Figure 6. Aerial view of the river morphologies over the years 2009 and 2010 showing the impressive bank erosion that took place in the 2010 season (panels above, flow is from right to left). Yellow dots are correspondingly reported on the measured cross sections for both years, 2009 (thick red line) and 2010 (thick violet line), together with BSTEM model predictions of bank migration (below panel). Model names correspond to different model parameters (Schäppi et al., 2010; Pasquale et al., 2014). Model BSTEM9 produced the best compromise between lateral shift and surface bank erosion as a result of augmented water surface elevation at the outer bank based on BASEMENT flow velocity simulations.

impressive migration of the river bend, practically equal to the river width (e.g., circa 50 m). Possibly, this value would have been even larger without the presence of mature trees forming the historical forest on the right-hand side of the river bank. At a larger scale, prediction of the catchment hydrological response remains a significant challenge (Breuer and Huisman, 2009) and consideration of ecosystem dynamics at smaller scales must also be taken into account.

4 Implications of our work for future restoration projects and research

The planning of river restoration needs to assess the relative value of different ecosystem services and to address potentially conflicting goals. We suggest that restoration can achieve the goals of sustainably increasing geomorphological and biological diversity mainly by creating a naturally evolving 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 (e.g., channelized sections or natural FPZs that are not well connected to the river). Our results thus support respective legislative measures (e.g., BUWAL, 2004). Furthermore, 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.

At our Thur River field site, public acceptance of the restoration project was generally very high during the first decade following the restoration. Regular educational and information sessions from local authorities and scientists involved contributed to creating a positive relationship with the local community. But, 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. In this respect, researchers need to collaborate closely with river managers who have the important duty to communicate expected changes and potentially arising conflicts to society. Otherwise, future river restoration projects will remain large-scale field experiments with unknown outcomes. In addition, we need to acknowledge and communicate that river restoration projects might need a considerable amount of time, perhaps years or decades, until a new quasi-stable state is reached.

Recently, a large number of critical zone (CZ) scientists studying the chemical, physical and biological processes that modulate the earth's surface, argued that new observatory initiatives are required to build a holistic understanding of critical zone processes (Brantley et al., 2011). In the case of CZ observatories, there are several initiatives on the way. In the USA, six CZ observatories have been established. In Europe, scientists have received funding to create the SoilTrEC International CZO Network in collaboration with partners in the EU, China and the USA (Brantley et al., 2011).

We argue that the same sort of natural observatories and scientific networks are required to gain a holistic understanding of river restoration and the interrelated physical, chemical, biological and ecological processes. The RECORD project was a first attempt to shed light on different aspects of the system and many of the insights could not have been gained if researchers from different disciplines had not worked together and exchanged data and shared infrastructure. We tested hypotheses and developed models that were compared with new observations. When large disagreements were found, we further developed our models. If not, the models were ready to be tested at other sites with different settings and conditions.

We call for more interdisciplinary river restoration research projects which should ideally be undertaken on different sizes of rivers, different climate/altitude conditions and in various settings (e.g., urban and agricultural areas, in comparison to natural river reaches). This will help to broaden the dialog between researchers and stakeholders, advance our understanding of the complex river–river corridor–groundwater system and will help to communicate the newly gained knowledge to society.

5 Conclusions

River–soil–groundwater interactions are the engines of riverine ecosystems and they respond at different temporal scales following restoration. Twelve years after restoring and widening a 2 km section of the Thur River in Switzerland, we identified the principal geomorphodynamic processes along the investigated 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 system in terms of ecology, hydrology and biogeochemistry. Nevertheless, repeated flooding may become an issue if excessive erosion threatening valuable land takes place as experienced in 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 can have both negative and positive effects on the microbiological and chemical quality of groundwater extracted in nearby pumping stations. Monitoring schemes in restored river corridors must thus 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 estimating seepage fluxes and residence times, vertical variations in hydrological exchange processes, as well as the transformations of organic matter in the riparian groundwater. 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.

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

Without a holistic interdisciplinary effort, we will not be able to advance our understanding of the complex river–river corridor–groundwater system, especially when restoration measures are taken, and such river restoration projects will remain as only large-scale field experiments with an unknown outcome. An interdisciplinary approach will ensure a complete understanding on which to base effective management decisions.

Acknowledgements. This study was supported by the Competence Center Environment and Sustainability (CCES) of the ETH domain within the framework of the RECORD and RECORD Catchment projects (http://www.cces.ethz.ch/projects/nature/Record). Additional support was provided by Eawag, ETH Zurich, EPFL, WSL, University of Neuchâtel, and the Swiss NSF (206021-117370, 200021-113815, 200021-125273/1, 200021-129735, 200020-117513, 200020-143688). We are indebted to Marco Baumann and Andreas Scholtis and their colleagues from the Agency for the Environment, Canton Thurgau as well as collaborators from the Agency for Waste, Water, Energy, and Air (AWEL), Canton Zurich, and the Swiss Federal Office for the Environment for their valuable cooperation. We especially thank all our colleagues from the RECORD team and involved partners from the different ETH-associated research institutions. In addition, we thank the Associate Editor Insa Neuweiler and the four anonymous reviewers for their efforts that helped to considerably improve the manuscript.

Edited by: I. Neuweiler

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