Hydrol. Earth Syst. Sci. Discuss., 7, 8873–8912, 2010
www.hydrol-earth-syst-sci-discuss.net/7/8873/2010/
doi:10.5194/hessd-7-8873-2010

Hydrology and Earth System Sciences Discussions

Modern comprehensive approach to monitor the morphodynamic evolution of restored river corridors

N. Pasquale[1], P. Perona[1], P. Schneider[2], J. Shrestha[3], A. Wombacher[4], and P. Burlando[1]

[1]Institute of Env. Engineering, ETH Zurich, Switzerland
[2]EAWAG, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland
[3]WSL, Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland
[4]Dept. of computer Sciences,University of Twente, The Netherlands

Received: 27 October 2010 – Accepted: 2 November 2010 – Published: 16 November 2010

Correspondence to: N. Pasquale (nicola.pasquale@ifu.baug.ethz.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

River restoration has become a common measure to repair anthropogenically-induced alteration of fluvial ecosystems. The inherent complexity of ecohydrologic systems, leads to limitations in understanding the response of such systems to restoration over time. Up to now a lot of effort has therefore been dedicated worldwide to document the efficiency of restoration actions and to produce new effective guidelines that may help overcoming our deficiencies. At the same time very few attentions focused on illustrating the reasons and the use of certain monitoring and experimental techniques in spite of others, or in relation to the specific ecohydrologic process being investigated. The purpose of this paper is to enrich efforts in this direction by discussing the experimental setup that we designed and installed in order to accomplish some of the research tasks of the multidisciplinary scientific project RECORD (Restored Corridor Dynamics). Therein, we study the morphodynamic evolution of the restored reaches of River Thur near Niederneunforn (Switzerland), also in relation to the role of pioneer vegetation roots in stabilizing the alluvial sediment. In this work we describe and motivate the methodology chosen for monitoring the river morphodynamics, the dynamics of riparian and of in-bed vegetation and their mutual interactions, as well as the need of complementing such observations with experiments and with the hydraulic modeling of the site. We also discuss how the designed installation and the experiments integrate with the needs of other research groups within the project, in particular providing data for a number of investigations ranging from surface water to groundwater, soil moisture and vegetation dynamics.

1 Introduction

The water course of many rivers worldwide has been straightened and channelized in the past century for both hydraulic and socio-economic reasons such for instance, flood protection, land use changes, agriculture or spreading of infectious diseases (Lacey, 1930; Inglis, 1949; Brookes, 1988). However, it has later become clear that such corrections affected considerably the associated riverine ecosystem, which typically reacts to artificial perturbations on multiple time scales (Malmqvist and Rundle, 2002; Tockner and Stanford, 2002). For instance, straightening the water course affects quite rapidly (e.g., days, weeks) the river sediment dynamic, the lateral exchanges and connectivity with the floodplain, whereas the morphological changes and related effects in habitat availability and in local biodiversity occurs over longer temporal scales (e.g., months, years). In the last decade, many project of river restoration have started in order to bring local rivers back to a more natural appearance and thus to partially find a remedy to the consequence of large scale river straightening.

River bed and floodplain morphologies play a big role in determining the later connectivity between the main stream dynamic and the moisture condition of the side terraces which are critical for the ecotone development. Thus, changing river bed morphology by either artificial or natural widening actions is one of the most common restoration techniques for those rivers that in origin showed a braided morphology (Formann et al., 2004; Peter et al., 2006; Schweizer, 2007). To the purposes of this paper, we define river restoration as "the input actions that serve to trigger the fluvial ecosystem evolution toward a new self-sustaining statistical equilibrium (if existing)" (Wohl et al., 2005) or else "the complete structural and functional return of the river to a pre-disturbance state" (Cairns, 1991). Soar and Thorne (2001) notice that full-restoration to a *pre-disturbance* state is an ideal concept. Along with these concepts go the question of quantifying the restoration success (Peter et al., 2006; Schirmer et al., 2010), especially as far as coupled hydro-ecological processes are concerned. Useful hydrologic and ecologic indicators have been developed to evaluate the present riverine status (Woolsey et al., 2007), however today's literature about river restoration deals mostly with practical guidelines that have gradually been built on results, observations and lessons learnt by comparing pre- and immediate post restoration on case study (e.g., Mitsch, 2003). What is apparently missing are systematic studies addressing a mechanistic understanding of the evolution after restoration over longer periods. Densmore

HESSD
7, 8873–8912, 2010

and Karle (2009), for instance, recognize the value of long term monitoring of restored streams.

In this descriptive paper we discuss a comprehensive approach that we adopted to monitor the evolution of restored river corridors, specifically referring to the Thur River near Altikon, in Switzerland. We illustrate our monitoring strategy to study the morphodynamic evolution of the restored river reach, particularly addressing the role of riparian and in-bed vegetation. We describe the instrumentation details and the facilities available in the project RECORD, the foreseen experiments and both the hydraulic and morphodynamic modeling of the site. Since the installation started in 2008, the instrumentation has been providing data for formulating a mechanistic picture of a number of fundamental processes linking flow - sediment and vegetation dynamics, in particular as far as the role of root mechanical anchoring in stabilizing non-cohesive alluvial sediment is concerned. We provide here an essay of preliminary results and research potentials of the collected data.

This work is organized as follows: next Section gives a short overview about the Thur river history and hydrology. Section 3 depicts the reasons for a mechanistic understanding of restoration. Section 4 describes in detail our field installation, materials and methods adopted. Examples of application of the installed instrumentation together with some first results are described in Sect. 5. A constructive discussion with considerations for future analysis concludes this paper.

2 Thur River hydrology and history

The Thur River is a perennial river in the North-Eastern part of Switzerland (Fig. 1a, b). The catchment area is about 1750 km^2 and the river has a length of about 127 km. It is the longest river in Switzerland that flows continuously without any regulation by artificial reservoir or natural lakes.

The hydrologic regime of the river is nivo-pluvial with the characteristic presence of flash floods as neither lakes nor artificial reservoirs in the catchment attenuate the

HESSD
7, 8873–8912, 2010

discharge. In spring and autumn flood pulses are created as a combination of snow melt and intense precipitation. Discharge may increase dramatically within a few hours and trig both bed load and suspended sediment transport.

Originally, the lower river Thur showed a clear braided morphology (Fig. 1c). By the end of the 19th century the river was channelized like most major rivers in Europe to avoid frequent flooding and gain arable land. Such a 1st correction basically transformed the floodplain into a double trapezoidal channel with a 45 m wide low-water channel (flow capacity 230 m^3/s) with revertment and artificial floodplains (total flow capacity 1100 m^3/s) bordered by levees. Spacing between the levee crowns was 160 m and the vertical distance between riverbed and levee crown averaged 6 m. Failure of the levees during high magnitude floods in 1977 and 1978 resulted in enlarging levees and increasing channel capacity (today low channel and total flow capacities are about 300 m^3/s and 1300 m^3/s, respectively) by removing fluvial deposits from the forelands between the levee (Fig. 1d). Those river regulations have been causing depth erosion of the river bed. As a consequence, flood protection measures in Switzerland were adapted with respect to the gaining importance of ecological aspects thus leading to the 2nd Thur correction. Since 1993 this correction equally promotes river restoration and flood protection measures. In 2002, a 2 km long section of river Thur near Neunforn/Altikon (see the box in Fig. 1b) was restored by completely removing the northern foreland, so that the nearby alluvial forest became part of the active floodplain again. Soon, after restoration ended, this large widening forced the river to deposit its sediments forming typical alternate bar patterns, e.g. the preliminary river attributes (Trush et al., 2000) that are fundamental for the creation of physical habitats for pioneer species (Fig. 1e, f). With the support of Universities, Research Centers, and Zurich and Thurgau Cantonal Authorities, a comprehensive and multidisciplinary scientific project was funded (RECORD) in 2007 with the specific purpose of Assessing and Modeling Coupled Ecological and Hydrological Dynamics in the Restored Corridor (REstored COrridor Dynamics) (Schirmer et al., 2010).

HESSD
7, 8873–8912, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3 Science meets society: the need of a mechanistic understanding and research questions

As a starting point to construct the basis supporting the existence of mechanistic rules, we comment the aerial picture of the study area near Niederneunforn in 2005 (see Fig. 1f) i.e., soon after restoration works ended. The morphodynamic activity of the river rapidly generated the alternate bar configuration, a flow-sediment bedform instability well known in river mechanics (Ikeda et al., 1981; Colombini et al., 1987; Tubino and Seminara, 1990; Federici and Seminara, 2003). The natural formation of alternate bare bars and the formation of a diversity of habitats due to intense channel reworking with fast turnover rates attracted the scientific interest of ornithologists, ecologists, biologists, as well as the recreational sphere of local inhabitants. Among the somehow unexpected results of this restoration action there is the return of the "Little Ringed Plover". This bird specie preferentially breeds on bare or poorly vegetated alluvial sediment, and it visited the restored site after nearly 150 years from its disappearance from the region, i.e. the time when the 1st correction took place. Thus, the Thur River morphodynamics at medium-long terms after restoration in relation to the vegetation development on alluvial sediment will likely control the establishment of such a bird specie.

Apart of this interesting complementary aspect, water quality (Schneider et al., 2010), flood protection efficiency, long-term morphology of the river, biodiversity changes, etc. (Schirmer et al., 2010) are eco-hydrological processes all influenced by the river hydraulics and morphodynamics. Important research questions concern with understanding the active (biological) role of vegetation (e.g., Jang and Shimizu, 2007; Gurnell and Petts, 2006; Nat et al., 2002) in relation to river hydrology, specifically: (i) morphologic changes of the restored reach in response to hydrologic disturbances (ii) interactions between flow, sediment and local vegetation, and (iii) mechanical anchoring of vegetation roots and its contributions to morphodynamics (Fig. 2a).

A first quantitative analysis of the alternate bars pattern can be done as far as their wavelength λ is concerned. Both hydrodynamically based (e.g., Ikeda et al., 1981; Federici and Seminara, 2003) or empirically based (Leopold and Wolman, 1957) relationships would quite closely predict the typical periodicity that characterizes alternate bars, (e.g., Leopold and Wolman, 1957)

$$\lambda = 6.5 \cdot B^{1.1}. \quad (1)$$

If we measure the curvilinear distance between bars on the aerial picture (Fig. 1f, $\lambda = 560$ m) we come out with $B = 57$ m which is approximately the river width average between the straight and the restored reach. This is a first confirmation of the natural origin of the developed morphology. This stage of the system seems to suggest the tendency of the river to meandering if lateral banks or levee would be exceeded. A first research question therefore addresses the influence of vegetation roots in the movement of sediment, which may limit the migration of alternate bars. Indeed, mechanical anchorage is one of the main functions of plant roots (Fitter, 1987) and it gives strong contribution to soil reinforcement (Pollen and Simon, 2005; Pollen, 2007; Millar, 2000).

A second research question concerns the amount of vegetation that can colonize the bare sediments. In turn this is obviously related to the plant roots ability of anchoring to the alluvial non-cohesive soil. However, despite vegetation germinates on the bare sediment of the restored reach (see later Sections), it does not seems to colonize it and the gravel bars of the restored reach are still showing mainly seasonal vegetation about 6 years after restoration ended. Poorly vegetated sediment would in principle indicate a slow regeneration capacity as far as the creation of new terrestrial habitat is concerned.

4 Material and methods

One of the naturally formed sedimentary island of the Thur river constitutes the research area for the RECORD project in relation to the research questions identified in

HESSD
7, 8873–8912, 2010

the previous Section. The island is located in a slight river bend where the Thur passes through a rural agricultural area with many field crops and a riparian forest (Fig. 1f). The shape and size of such an island are obviously not constant, but changing because of erosion and aggradation induced by river hydrodynamic during floods. In order to quantitatively observe the morphodynamics we adopt an active monitoring strategy summarized in Fig. 2b. This figure illustrates the conceptual steps of the research strategy. The field installation consists of a meteo- and a soil moisture stations (see Sect. 4.1), both visible and IR cameras for terrestrial remote sensing (see Sect. 4.4) and three campaign of *Salix* cuttings transplantation on the island (see Sect. 4.6). Since the beginning we have also been taking advantage of the hydrological and topographic data provided by the Federal office for the Environment (FOEN) and of the aerial surveys. Meteo and soil moisture station, Salix cuttings and remote sensing together with a parallel project (Edmaier et al., 2010) are used for vegetation analysis. Topographic data such as river bathymetry (see Sect. 4.3) or DEM from aerial pictures, grain size distribution analysis (see Sect. 4.2) and hydrodynamic simulations (see Sect. 4.5) are used for morphological analysis. Results from vegetation response to river hydrology and the information about morphological changes (Fig. 2a) are then used to formulate a mechanistic model of non-cohesive soil reinforcement by roots (Fig. 2b).

4.1 Micro meteorological measurement and soil moisture

In order to monitor the micro meteorological variables necessary to compute a correct water balance of the reach scale we installed a complete meteo station (Campbell scientific, Fig. 3a) on a metal frame tower (see Fig. 3a) located on the top of the left side levee (Fig. 3c). The higher position of the tower with respect to the river corridor allows for measurements be representative of the mean micro meteorology surrounding the restored reach. The meteo station includes two sensors for air both temperature and relative humidity (at 2.5 m and 8 m above soil level), a complete solar radiation device (i.e., 4 components measured at 4 m above the ground), two wind flowmeters and an atmospheric pressure sensor. A pluviometer (OTT) completes the station. The

HESSD
7, 8873–8912, 2010

station is connected via optic fiber wires to a remote computer, located in a small hut one kilometer upstream on the levee (Fig. 3b, c). It is thus possible to remotely access the meteo station, download data in real time and eventually to reprogram the logger settings according to current needs. Our installation includes also a soil moisture station installed on the island (Fig. 3f, g), which is connected via wireless to a second tower (Fig. 3b). Soil moisture sensors (EC5 and TMC both from Decagon) measure soil moisture and temperature in four plots at three different elevations (20, 40 and 60 cm) below ground.

4.2 Sediment size and nutrient spatial distribution

Grain size distribution curves of the alluvial sediment forming the island have been obtained from six representative locations identified by simple visual survey (Fig. 4a). At each chosen location we took two samples, one on the surface and the second one about 40 cm underneath. Our purpose is to spatially identify and map sediment armoring and aggradation profiles (Lanzoni, 2000). Samples have been sieved to build common grain size distributions, which are shown in Fig. 4b, c. Generally, the sample taken on the surface (Fig. 4b) shows a higher percent of coarse sediments than the sample at 40 cm depth (Fig. 4c). Moreover in accordance with experimental observation reported by Lisle et al. (1991), Diplas and Parker (1992), Lisle and Madej (1992), Ashworth et al. (1992) the island is characterized by a longitudinal sorting. From coarse particle upstream we move to fine sand deposition downstream (Lanzoni, 2000), where also stratification is not evident anymore. Successive visual observation seemed to confirm this pattern, leading us to assume our grain size distribution substantially independent from the island morphological changes.

Sedimentation is the main source of fine materials and nutrients apportion. Hence, soil texture and nutrient content (organic carbon, nitrogen and phosphorus) in the lateral gravel bar upstream the island were measured in the context of another scientific Task of the project (Battle-Aguilar et al., 2010; Samaritani et al., 2010). In particular, six sampling plots were taken on the right hand side bar (from 50 to 150 m upstream

HESSD
7, 8873–8912, 2010

the island). As both the riverside bar and the island are formed by the same alluvial material, we expected that also the nutrient content is similar. However, six additional samples were taken from sparse location on the island inside the vegetation plots (see Sect. 4.6) to serve as control.

The collected soil samples were then dried at 40 °C and sieved at 2 mm for analysis of above-mentioned chemicals. Texture was measured using the pipette method (Gee and Bauder, 1986). Organic carbon and total nitrogen was measured in the elemental analyzer NC2500 (CE instruments, Italy) in finely ground fine soils (Walthert et al., 2010). Available phosphorus was measured colorimetrically by following the recommendation by Kuo (1996).

Eventually, both the island and the lateral bar showed similar amount of nutrients, represented by the spatial statistics of Table 1. The nutrient content in the gravel bar (exception made for Ammonium which was quite uniformly distributed) was spatially variable, but did not follow any particular pattern. Thus, the spatial variation in nutrient content suggests at the most that there are differences in both quantity and quality of sediment deposition within the gravel bar. For instance, the organic carbon and nitrogen content is known to be strongly related to soil texture whereas the quantity of sediment deposition is typically more important for phosphorus (Steiger and Gurnell, 2003). Although the nutrient content is lower than in other part of the floodplain (unpublished data), it is in normal range for the sediment deposits (Steiger and Gurnell, 2003). Hence, as far as the gravel bars and island are concerned, we conclude that the nutrient content of the fine material might not be the main limiting factor for plant growth in comparison with elevation and grain size, which might be more crucial (Gilvear et al., 2008).

4.3 Digital terrain model and cross sections

An important element in hydraulic and morphodinamic modeling is the availability of detailed topography data of the river bed and the floodplain area. The Federal Office for the Environment (FOEN), together with Canton Zurich and Canton Thurgau provides detailed cross section of the restored reach once a year. Surveys take place generally in late September–October, being the summer season characterized by the most important floods responsible of morphological changes. From annual LIDAR airborne flights, the corresponding Digital Terrain Model (DTM) is produced with a resolution 0.5 m. River bathimetry is obtained by manual cross sections measurements just few weeks after or before the aerial flight, depending of flow and weather conditions. Therefore, river bathimetry can be considered unchanged from the time the DTM was produced. Cross sections along the river are measured in average every 20 m. For each cross section, the river bed is measured every 50 cm.

Cross section data are then used to modify the DTM in order to properly include the river bathimetry. In particular, we use the method developed by Schaeppi et al. (2009), which requires as inputs: (i) cross section profiles data, (ii) a raster of the DTM that needs to be corrected and (iii) the definition of breaklines (Lane et al., 1994; Keim, 1999; Brasington et al., 2000). The algorithm is designed to deal with longitudinal unequally spaced cross section profiles. The program performs two linear interpolations in the lateral and longitudinal direction of the river. DTM grid points situated in between two adjacent cross section profiles are replaced by values obtained from cross section interpolation. This method was chosen because it is more robust than nonlinear ones and spline interpolations, which often introduce spurious oscillations due to not equally spaced data (Schaeppi et al., 2009).

4.4 Terrestrial and aerial photography

The high cost of aerial surveying makes it economically not feasible more than once a year. However, aerial photos are very important to monitor morphological changes and riparian vegetation patterns and evolution along rivers. Thus we are currently exploring the possibility to obtain such an information from terrestrial photography. This will have promising applications in the field of river hydraulic engineering and restoration. For instance, calibration of river hydrodynamic flow models is typically a difficult and demanding task. For different flow rates adequate information about the corresponding water depth should be obtained. The problem is thus twofold: many points are required, which makes the manual survey time demanding and practically impossible in the presence of high flow conditions or ecological constraints limiting the access to the area. Therefore, non invasive techniques are welcome.

Two boxes (Fig. 3d) are installed one on the top of each tower at 16 m above the levee level. Each box contains two digital cameras NIKON D300 shooting pictures in both the visible and the infrared ranges. Opportune combination of visible and IR images leads to the Normalized Difference Vegetation Index (NDVI) (Qi et al., 1994), which is useful to quantify vegetation patterns, growth and mortality. All digital cameras are connected to the remote computer, from which it is possible to change their shooting frequency, for instance to better capture flood events evolution. A remotely controlled motorized paraglider (Fig. 3e) equipped with a high resolution digital camera (NIKON D300) and a GPS is also used to detect important morphologic changes (Lejot et al., 2007) soon after a flood occurred and without waiting for the annual airborne LIDAR flight. Overall, our installation (Fig. 3) allows to test and improve a number of techniques based on pattern recognition analysis, which may help to calibrate both hydraulics and ecosystem models (Molnar et al., 2008; Perona et al., 2009a).

4.5 Hydrodynamic simulation

Numerical simulations of the river hydrodynamics allows to investigate the inundation patterns of any flow condition within the restored reach. To the purpose, the grid of the interpolated DTM (see Sect. 4.3) has first to be pre-processed in order to create a mesh. As mesh generator we use AQUAVEO SMS-10.1 which can create unstructured triangular mesh, suitable for fast and more efficient computing. For the hydrodynamic simulations we use the 2D shallow water model BASEMENT (Basic Simulation Environment). The software (open source under http://www.basement.ethz.ch) was developed at ETH Zurich (VAW, Laboratory of hydraulics, hydrology and glaciology), and uses the finite volume method to integrate the shallow water equations. The explicit Euler scheme used for the numerical solution is robust and allows to easily deal with both sub- and supercritical flow regimes. As a consequence, BASEMENT is a suitable code to perform hydrodynamic simulations covering the whole range of natural streamflows, as has recently been tested by (Ruf et al., 2008; Perona et al., 2008, 2009b,a).

4.6 Vegetation species and related experiments

Understanding the interaction between river hydrology and vegetation requires accurate monitoring about vegetation growth dynamic and survival. Among the dominant species that naturally vegetate the alluvial bars there are some bushes of different willows that grow via vegetative reproduction as well as from deposited and partially buried branches and trunks. Among the smaller plants are sticky weeds (*Galium aparine*) and small nettle (*Urtica urens*). Identified are most likely also dog mustard (*Erucastrum gallicum*), Himalayan Balsam (*Impatiens glandulifera*), and a butterbur species (*Petasites*). Willow species growing naturally on the island (via vegetative reproduction) are *Salix Alba* (White Willow), *Salix viminalis* (Common Osier) and *Salix nigricans* (Black Willow).

In march 2008 we began field campaigns of vegetation cutting transplantation. Each year a number of about 1200 cuttings of Salix Alba have been planted in early springtime. Cuttings are organized in plots with different density (9 plants m^{-2} and 16 plants m^{-2}). One plot is a regular square matrix (see box in Fig. 5) in which cuttings are planted in correspondence of the nodes. Plots are located all over the island surface (Fig. 5) in order to be stressed by different drought and inundation conditions. The location of single plots is decided also according to the shear stress patterns (Fig. 6) simulated by the numerical model (see Sect. 4.5). From year to year we change the location of the plots according to the information acquired during the former campaign either to validate previous observations or to increase the statistical significance of others. Periodic monitoring of the survival rates the main stem length and the number of branches for each cutting is regularly carried out every 15–30 days.

An accurate monitoring of the root-soil system is also done in order to identify factors linking root growth topological and functional differences in relation to topographic and hydraulic conditions (Waisel et al., 2002). Cutting samples are uprooted once a month at different plot locations and analyzed. The uprooting technique consists of three steps: first we dig a deep trench about 1 m beside the cutting. Second, we search for the deepest point of the root system. Third, in correspondence of roots and from below roots, we make the soil collapsing slowly in the trench and we remove it until the cutting is completely free. This "following the roots" technique allows us to uproot sample almost completely intact for our root analysis. The uprooted cuttings are first washed to remove the excess particles of soil and organic material. Then each cutting separately is layered down on a white sheet by re-arranging it to the on site roots distribution that we carefully reconstruct from pictures taken during the uprooting. Eventually, the root structure is photographed with a digital camera (Fujifilm, FinePix S9500) fixed on a tripod vertically above the ground. For image processing we developed and tested (Verones, 2009) a MATLAB script which allow processing both JPEG and TIFF images from a RGB image to a greyscale image. A gray scale threshold value between 0 (black) and 1 (white) defines whether a certain pixel is to be interpreted as a root or just empty space. We use the resulting matrix of ones and zeros to compute an empirical histogram of the root distribution (resulting from an average of three cuttings) with a chosen number of classes (see Sect. 5.4). An additional filter removes eventual "salt-and-pepper" noise (due for instance to dust or fine particles) and the degree of filtering can be chosen in the interface.

The last step of the root analysis is the quantification of the main morphological characteristic of the uprooted sample in space and time. To the purpose, roots are first cut away from the primary root (i.e., the cutting in our case, whose size is measured by hand) and then spread within a transparent tray (length 48 cm, width 32 cm, depth 1.4 cm) filled with water. The system is then scanned with an EPSON Expression 10000XL. This scanner uses one light source from below as by common flat-bed scanners and a second, additional light transparent unit (TPU) from above. The scanner is extra optimized for root images analysis by Regent Instrument, Inc. and a personal computer with Intel Core2 Duo CPU T7700 at 2.40 Ghz, 2 GB of RAM is used for the analysis. The scan is then analyzed by means of the commercial software WinRhizo (Regent Instruments, 2009), which is appositely designed for root images analysis, such morphology, topology and architecture. The software returns the total root length, average root diameter, surface area and volume of the root system and number of tips and forks of the roots in the morphology package. Compared to other softwares it gives more complete root morphological characterization (Himmelbauer et al., 2004). In addition, when working with abundant sample, WinRHIZO overlap algorithm enables increasing of the admissible scanning density (Himmelbauer et al., 2004).

5 Application examples and first results

Flood magnitude, frequency and duration are important parameters to understand plant growth and survival dynamics and mutual interactions with river morphodynamics. Whilst the return period of specific flow conditions can be estimated by flood frequency analysis, understanding spatial inundation patterns and consequent impacts on vegetation require integrating multiple sources of information. We hereby illustrate how we intend to pursue the goal by joining the results of hydrodynamic simulations, terrestrial photography and vegetation cutting experiments.

5.1 Modeling: river hydraulics and morphodynamics

A series of 2-D flow simulations at different flow rates for both the restored and the upstream straight reach allows to compute the both spatial and temporal variability of a number of flow indicators such, velocity components, water depth, water surface elevation, bed shear stress, etc. Over the course of the project we plan to perform flow simulations using different annual morphologies and flow conditions in order to establish a relationship between morphological and hydraulic variability and the related time dependency (see Sect. 6). As an example, Fig. 6 shows the simulated bed shear stress for a flood peak of 650 m^3/s over the 2005 topography. The shoreline of the

HESSD
7, 8873–8912, 2010

main island for a flow rate of 30 m^3/s is drawn in black. The spatial distribution of the bed shear stress for varying flow conditions allows to identify the location where critical conditions of incipient sediment motion (bedload) are first reached. For instance, the average grain size distribution curve of the surface sediment (see Sect. 4.2) gives d_{10} = 4 mm, d_{30} = 10 mm, d_{50} = 20 mm, d_{70} = 50 mm and d_{90} = 90 mm. From classic Shield analysis (e.g., Meyer-Peter and Müller, 1948) particles equal to 20 mm start to move for flows equal or greater than 200 m^3/s. For the simulated flow shown in Fig. 6 sediment material of size up to d_{90} is practically all mobilized from the highest stress region (red zones) to lower stress ones where sediment is eventually deposited according to local stress conditions. This picture would suggest a future of slow migration of the island toward the right-hand river side, i.e. according to the downstream migrating nature of alternate bars (Federici and Seminara, 2003). From the sequential analysis of successive morphologies over next years we expect to understand whether alternate "free" bars will gradually concentrate around the river bend thus assuming a punctual character eventually forced by the local river curvature (Tubino and Seminara, 1990). This will have important implication as far as the stability of the lateral banks (e.g., the right-hand side one in this case) is concerned.

5.2 Monitoring: use of terrestrial photography for pattern recognition and model calibration

Recognizing patterns automatically is relatively easy in the presence of well-defined objects and contrasting background colors, but this operation becomes rather difficult for open air or environmental photographs (e.g. of river corridors) where a multitude of colors, shadows, reflections and changing light conditions typically characterize the images. Our installation is a natural laboratory in this respect and has allowed us to start working in this direction (Fig. 7). For instance, we started with the already challenging task of recognizing water and non-water classes from digital photographs under changing light and surface albedo (e.g., due to either diurnal variability or bad

HESSD
7, 8873–8912, 2010

Monitoring restored corridor morphodynamics

N. Pasquale et al.

weather conditions like the presence of fog or snow). Water can then be removed and the exposed island surface computed and used for a multitude of purposes.

The approach that we have tackled consists of masking the images by ignoring the irrelevant parts like mountains and sky, for instance. Next, features are defined to describe properties of the image or the image content, like e.g. color values, gradients of neighboring pixels, or application specific information like a probability distribution of a pixel being water derived from the digital elevation model. The investigated features can be classified according to two orthogonal dimensions: (i) pixel based features and features derived from a group of pixels and (ii) time variant (derived from a time series of images) and time invariant features (derived from a single image). All collected features are then used in a supervised learning algorithm, which calculates the probability that a specific pixel belongs to the water class.

At present, this learning needs a training set of images to calculate the relation between the feature space and the two classes and to suggest how important a feature is for the classification. Time variant features (such as color values of water due to changing light conditions) require instead continues adaptation of the classifier to the most relevant selected feature in order to address the observation of highly variable condition/quality of the images and to adapt to changes in the environment. The evaluation of the proposed approach is done by classifying a test set having similar characteristic as the training set but being independent of it. The classification of water is in particular difficult in areas where vegetation is reflected in the water like e.g. in the water surface. To derive the time variant characteristics of these pixels, pixels in this area are sampled continuously. Since these samples are based on a specific position in the image the dislocation of the camera due to wind or maintenance operations effects the classification result negatively. Potentially a new initialization is required to determine new positions in the image for sampling. Figure 7 shows results of the learning process on two representative pictures at different discharges. If the training set of images is large enough, the error of the image processing is reasonable and comparable to any flow simulation numerical model. Our procedure is thus promising and its usefulness will be tested on a longer data record or on photographs from different locations and then used to build a non-invasive calibration technique for hydraulic models.

5.3 Experiments: above-ground vegetation dynamics

Data collected during monitoring campaigns together with aerial photographs allow to quantify vegetation plots growth (or mortality) rates, in relation to the natural river hydrologic regime. Figure 8 shows a representative data set of four plots in 2009. Each curve is the average behavior of all individual cuttings forming the plot. Plot 1 and plot 8 are located at high elevation, that is in a part of the island less frequently inundated. Their growth is practically monotonic. On the contrary, plot 19 is located at really low elevation and has been removed by the first big flood in June. In comparison with such two extreme situations, plot 21 (located at intermediate elevation) shows that in average it survives the season, despite some plants were either partially damaged or killed by the June flood.

From visible and IR pictures taken at the same time, we compute the NDVI index (Defries and Townshend, 1994; Wu and Tang, 2010), whose histogram for the part related to the island indicates the amount of water (<-0.3), soil ($-0.3 \div 0.1$) and vegetation (>-0.1). An exemplary result is shown in Fig. 9, which also illustrates the rationale for comparing different NDVI histograms throughout the season in order to obtain an information complementing that from field monitoring.

5.4 Experiments: root growth, anchoring and erosion dynamics

Salix are rather sensitive to prolonged droughts, but at the same time they are able to withstand long periods of submergence (Glenz, 2005; Glenz et al., 2006). Since our plots are spread on the island, they may experience both situations depending on river hydrology. Moreover, cuttings resistance to floods will eventually depend on their root architecture. Figure 10a shows the effect of a flood on a plot in 2009, which documents the plot survival despite the deep scouring of sediment around the cutting

HESSD
7, 8873–8912, 2010

(also notice the partially exposed root system). Although this picture reflects situation quite often observed in natural systems, it is quite difficult to obtain in experimental field campaigns. This partial erosion depicts therefore the type II mechanism of rooted sediment erosion conceptualized by (Edmaier et al., 2010). Notably, this also reflects the nonlinear role that a certain type of root architecture plays in locally stabilizing and anchoring the sediment.

Our research plan focuses precisely at understanding such dynamics better. In order to proceed we profit of the analysis of the nutrient content within the sedimentary bed. As previously discussed, data samples would suggest that the vertical root structure development should correlate to the statistical location of the saturated water table in the sediment. Since precipitation can be considered spatially homogeneous at the island scale, we assume soil moisture oscillations must depend on streamflow statistics. By means of the hydraulic model mentioned in Sect. 5.1 we simulate flow conditions ranging from the minimum recorded flow up to the one that completely inundates the island. Given the coarse size distribution of the alluvial material we expect the water front to infiltrate relatively quickly ($k = 2 \times 10^{-2}$ m/s) compared to the hydrograph dynamics. Therefore we assume the water table to propagate in quasi-steady state dynamic for common river hydrograph conditions. This allows us to obtain a "rating curve" of the island water table based on flow dynamics. This method is described in Schneider et al. (2010) together with its application in relation to groundwater issues. From flow frequency analysis we then obtain the (steady state) pdf of the saturated water table in the sediment at each plot location.

We link now the information from the root cutting analysis from regularly uprooted samples, together with the information of the water table in the sediment. This allows us to document the location of the maximum root density in relation to the most frequent location of the saturated water table (Fig. 10b). Such figure would seem to explain the relationship between roots and water table for plots depending on their location on the island. Obviously, for the time being our conclusion cannot go any further since a sequence of many years of analysis is needed in order to obtain comparable

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

7, 8873–8912, 2010

Monitoring restored corridor morphodynamics

N. Pasquale et al.

and statistically significant results. Our precise intention in the future is therefore to validate our conjecture from different plots around the island in order to define a suitable mechanistic rule of root development in relation to river hydrology in alluvial sediment. The presence of a possible scaling relationship would allow in the future to estimate at which depth cuttings are going to develop their root system, with obvious relevant application to restoration projects.

6 Discussion and conclusions

Hydrologic indicators of river restoration efficacy are based on flow variables such as flow depth, velocity, shore line length, exposed area, wet perimeter and their gradients under variable flow conditions (Emery et al., 2003; Clifford et al., 2005). Empirical approaches attempt to relate the form and shape of velocity and depth distributions to predictor variables that are relatively easy to determine (Lamouroux, 1995, 1998). A high spatial variability of these variables indicates areas with high habitat diversity (e.g., Lamouroux et al., 1992; Allan and Castillo, 2007). However this diversity can be maintained over time only if there are frequent disturbances such flood events that create or rework different morphologies.

Hereafter we propose a methodology to conceptually integrate the information conveyed from different ecohydrologic indicators into a single system trajectory showing how and toward which statistical equilibrium the restored system evolves to. To the purpose we draw a technique from classic mechanics, known as the "state space" (e.g., Sprott, 2003). The state space is a multidimensional space, the axis of which $(x_1(t), x_2(t), x_3(t), \ldots)$ represent the evolution of the system variables in time. Time does not appear explicitly in this space in that it is now a parameter of the dynamics. In our case, x_1 can be for instance flow velocity, x_2 water depth and x_3 the shoreline length for certain flow conditions. Let us imagine the situation from when restoration starts at time $t = t_0$, i.e. such as the case of the Thur river, and consider this as the initial state of the system. The river is in average straight as depicted in the exemplary panel of

HESSD
7, 8873–8912, 2010

Fig. 11.a. All state variables have average values $(x_1(t_0), x_2(t_0), x_3(t_0), \ldots)$ and this state corresponds to a single point in the state space. Then, by means of restoration works (e.g., in the Thur case the lateral banks are made erodible) the system starts to evolve in subsequent times under the action of floods, which reshape the river reach through erosion and aggradation, possibly forming alternate bars (see Fig. 1). At time $t = t_1$ the variables $x_1(t_1), x_2(t_1), x_3(t_1), \ldots$ identify another point in the state space corresponding to the actual river configuration and the associated ecohydrologic variables. Gradually, restoration leads to an evolution with more complex eco-morphologies characterized by different eco-hydrologic indicators, and possibly an accurate systematic monitoring allows identifying the related trajectory, as well as possible equilibrium (statistical) points (Argyris et al., 1994; Sprott, 2003).

As far as the Thur river is concerned, an example can be made by plotting flow velocities vs water depth for both the restored and the upstream straight reaches, i.e. assuming the latter as a reference of the pre-restoration situation. This plot is shown in Fig. 11b in relation to the topography of 2005. The higher spreading of points for the restored reach than for the straight one in low flow conditions illustrates the importance of restoration. That is, spatial variation in water velocity and depth are fundamental factors regulating ecosystems (Allan and Castillo, 2007). Benthic plants and invertebrates are indeed strongly influenced by these variables (Quinn and Hickey, 1994; Jowett, 2003) as well as fishes (Bovee, K, 1982; Jowett, 2003). Stewardson and MaMahon (2002) hypothesized the existence of two fundamental bivariate distributions, suggesting that one is characterized by a centered form with a positive correlation (Fig. 11b, c) resulting from significant cross channel effects and weak along-channel effects, while the other has a skewed shape (Fig. 11b, c) resulting from longitudinal bed undulations (e.g., pool-riffle sequences) and minimal lateral variation. Increasing the discharge results in a shift from a positively skewed (Fig. 11b) to a symmetric (Fig. 11c) distribution. At higher flow rate more and more fluvial forms are submerged, and the similarity between the restored and the non-restored reaches increases, i.e. as expected.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

7, 8873–8912, 2010

Monitoring restored corridor morphodynamics

N. Pasquale et al.

In this work, we described a methodology to integrate modern tools and instrumentation devices in order to quantify the evolution of restored river reaches. With specific reference to the Thur river, we provided some example from preliminary analysis, nonetheless letting now arise interesting questions about future morphodynamic scenarios after restoration. These involve: (i) the free evolution toward a multi-thread system therefore requiring levee and bank erosion; (ii) the (naturally) limited evolution to a constant river width reach characterized by a system of alternate bar forming, migrating and disappearing. On the basis of our preliminary observations the wavelength of the alternate bars in the restored reach is $\lambda \approx 600$ m, and their migration velocity $\frac{1}{2}\lambda$ in five years. However, understanding to which extent such a morphodynamics is influenced by vegetation, both as far as the role of the above and the below ground biomass is concerned, will depend on future monitoring and analysis of the collected data.

Acknowledgements. This study was financed by the Competence Center Environment and Sustainability (CCES) of the ETH domain in the framework of the RECORD project (Assessment and Modeling of Coupled Ecological and Hydrological Dynamics in the Restored Corridor of a River (Restored Corridor Dynamics), http://www.cces.ethz.ch/projects/nature/Record). We thank Romeo Favero, Ulrich Guettelmann, Robert Holzschuh, Andreas Scholtis, and Marco Baumann from AfU, canton Thurgau and Urs Spychiger, Franz Bieler, Kurt Nyfenegger, and Matthias Oplatka from AWEL, canton Zurich for their support and close cooperation. Thanks also to Francesca Casini, ETH Zurich, for helping with the grain size curve analysis, Francesca Verones, ETH Zurich, for testing the root analysis software and Sander Nouta,University of Twente, for pattern analysis.

HESSD
7, 8873–8912, 2010
Monitoring restored corridor morphodynamics
N. Pasquale et al.

References

Allan, D. J. and Castillo, M, M.: Stream Ecology: Structure and Function of Running Waters, vol. 125, Kluver Academic, Boston, 2nd edn., doi:10.1577/1548-8659-125.1.154, 2007. 8892, 8893

Argyris, J. H., Faust, G., and M, H.: An exploration of chaos: an introduction for natural scientists and engineers, North-Holland, 1st edn., 1994. 8893

Ashworth, P. J., Ferguson, R. I., and Powell, M. D.: Bedload transport and sorting in braided channels, in: Dynamics of gravel-bed rivers, edited by: Billi, P and Hey, RD and Thorne, CR and Tacconi, P, 497–515, John Wiley & Sons LTD, 1992. 8881

Battle-Aguilar, J., Brovelli, A., Luster, J., Shrestha, J., and Barry, D. A.: Carbon and nitrogen dynamics in a variably saturated soil profile. Model application to a restored Swiss riparian area, in preparation, 2010. 8881

Bovee, K, D.: A guide to stream habitat analysis using the in.-stream flow incremental methodology, Fish And Wildlife Services, Fort Collins, CO, US, 1982. 8893

Brasington, J., Rumsby, B. T., and McVey, R. a.: Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey, Earth Surf. Proc. Land, 25, 973–990, doi:10.1002/1096-9837(200008)25:9⟨973::AID-ESP111⟩3.0.CO;2-Y, 2000. 8883

Brookes, A.: Channelized rivers: Prospectives for Environmental Management, Wiley, John & Sons, 344 pp., 1988. 8875

Cairns, J.: The status of the theoretical and applied science of restoration ecology, The Environmental Professional, 13, 186–194, 1991. 8875

Clifford, N. J., Soar, P. J., Harmar, O. P., Gurnell, A. M., Petts, G. E., and Emery, J. C.: Assessment of hydrodynamic simulation results for eco-hydraulic and eco-hydrological applications: a spatial semivariance approach, Hydrol. Proc., 19, 3631–3648, doi:10.1002/hyp.5855, 2005. 8892

Colombini, M., Seminara, G., and Tubino, M.: Finite-amplitude alternate bars, J. Fluid. Mech., 181, 213–232, 1987. 8878

Defries, R, S. and Townshend, J, R.: NDVI derived land-cover classifications at global-scale, Policy, 15, 3567–3586, 1994. 8890

Densmore, R, V. and Karle, K, F.: Flood Effects on an Alaskan Stream Restoration Project: The Value of Long-Term Monitoring, J. Am. Water Resour. Assoc., 45, 1424–1433, doi:

10.1111/j.1752-1688.2009.00373.x, 2009. 8875
Diplas, P. and Parker, G.: Deposition and removal of fines in gravel-bed streams, in: Dynamic of gravel-bed rivers, edited by: Billi, P. and Hey, R. D., Thorne, C. R., and Tacconi, P., 313–329, John Wiley & Sons LTD, 1992. 8881
Edmaier, K., Molnar, P., Burlando, P., and Perona, P.: Uprooting of young riparian pioneer vegetation by flow: concepts, experiments and modelling, Hydrol. Earth. Syst. Sci., in preparation, 2010. 8880, 8891
Emery, J. C., Gurnell, A. M., Clifford, N. J., Petts, G. E., Morrissey, I. P., and Soar, P. J.: Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design, River Res. Appl., 19, 533–549, doi:10.1002/rra.744, 2003. 8892
Federici, B. and Seminara, G.: On the convective nature of bar instability, Journal Fluid Mech., 487, 125–145, doi:10.1017/S0022112003004737, 2003. 8878, 8879, 8888
Fitter, H.: An Architectural Approach to the Comparative Ecology of Plant Root Systems, New Phytol., 106, 61–77, 1987. 8879
Formann, E., Schober, S., and Habersack, H, M.: Monitoring and modelling of river widening processes in an Alpine river, in: Proceedings of the ninth international symposium on river sedimentation, Vols 1–4, 1627–1634, UNESCO, Int. Res. & Training Ctr. Erosion & Sedimentat, 2004. 8875
Gee, G, W. and Bauder, J, W.: Methods of Soil Analysis. Part I. Agron. Monogr. 9,, ASA and SSSA, Madison, WI, USA, 2nd edn., 1986. 8882
Gilvear, D., Francis, R., Willby, N., and Gurnell, A.: Gravel bars: a key habitat of gravel-bed rivers for vegetation, 2025, 677–700, doi:10.1016/S0928-2025(07)11154-8, 2008. 8882
Glenz, C.: Riparian forest dynamics in central Europe – Tool for decision-making in river restoration, Ph.D. thesis, 2005. 8890
Glenz, C., Schlaepfer, R., Iorgulescu, I., and Kienast, F.: Flooding tolerance of Central European tree and shrub species, Forest Ecol. Manag., 235, 1–13, doi:10.1016/j.foreco.2006.05.065, 2006. 8890
Gurnell, A. and Petts, G.: Trees as riparian engineers : The Tagliamento River, Italy, Earth Surf. Proc. Land, 31, 1558–1574, 2006. 8878
Himmelbauer, M. L., Loiskandl, W., and Kastanek, F.: Estimating length , average diameter and surface area of roots using two different Image analyses systems, Plant Soil, 111–120, 2004. 8887
Ikeda, S., Parker, G., and Sawai, K.: Bend theory of river meanders. Part 1. Linear develop-

HESSD
7, 8873–8912, 2010

N. Pasquale et al.

ment, J. Fluid Mech., 112, 363–377, 1981. 8878, 8879
Inglis, C, C.: The behaviour and control of rivers and canals (with the aid of models), Central Water Power, Irrigation and Navigation Research Station, Poona, India, Research pubblication 13 part 1, 1949. 8875
Jang, C, L. and Shimizu, Y.: Vegetation effects on the morphological behavior of alluvial channels, J. Hydraul. Res., 45, 763–772, doi:10.1080/00221686.2007.9521814, 2007. 8878
Jowett, I, G.: Hydraulic constraints on habitat suitability for benthic invertebrates in gravel-bed rivers, River Res. Appl., 19, 495–507, doi:10.1002/rra.734, 2003. 8893
Keim, R.: Digital terrain modeling of small stream channels with a total-station theodolite, Adv. Water Resous., 23, 41–48, doi:10.1016/S0309-1708(99)00007-X, 1999. 8883
Kuo, S.: Phosphorus, in: Methods of soil analysis: Part 3-chemical methods, Sparks, D. L., SSSA, Madison, WI, USA, 1996. 8882
Lacey, G.: Stable channel in alluvium, Proceedings of the institution of civil engineers, 229, 259–292, 1930. 8874
Lamouroux, N.: Predicting velocity frequency distributions in stream reaches, Water Resour., 31, 2367–2375, 1995. 8892
Lamouroux, N.: Depth Probability Distributions in Stream Reaches, J. Hydraul. Eng., 124, 224–227, doi:10.1061/(ASCE)0733-9429(1998)124:2(224), 1998. 8892
Lamouroux, N., Statzner, B., Fuchs, U., Kohmann, F., and Schmedtje, U.: An unconventional approach to modeling the spatial and temporal variability of local shear stress in stream segments, Water Resour. Res., 28, 3251–3258, doi:10.1080/07900629208722560, 1992. 8892
Lane, S. N., Richards, K. S., and Chandler, J. H.: Developments in monitoring and modelling small-scale river bed topography, Earth Surf. Proc. Land, 19, 349–368, doi:10.1002/esp.3290190406, 1994. 8883
Lanzoni, S.: Experiments on bar formation in a straight flume 2. Graded sediment, Water Resour., 36, 3351–3363, 2000. 8881
Lejot, J., Delacourt, C., Piégay, H., Fournier, T., Trémélo, M.-I., and Allemand, P.: Very high spatial resolution imagery for channel bathymetry and topography from an unmanned mapping controlled platform, Earth Surf. Proc. Land, 32, 1705–1725, doi:10.1002/esp, 2007. 8884
Leopold, B. L. and Wolman, M. G.: River Chanel Patterns: Braided, Meandering and Straight, 1957. 8879
Lisle, T. E. and Madej, M. A.: Spatial variation in armoring in a channel with high sediment

HESSD
7, 8873–8912, 2010

Monitoring restored corridor morphodynamics

N. Pasquale et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

supply, in: Dynamics of gravel-bed rivers, edited by Billi, P and Hey, RD and Thorne, CR and Tacconi, P, 277–293, John Wiley & Sons LTD, 1992. 8881
Lisle, T. E., Ikeda, H., and Iseya, F.: Formation of stationary alternate bars in a steep channel with mixed-size sediment - A flume experiment, Earth Surf. Proc. Land, 16, 463–469, 1991. 8881
Malmqvist, B. and Rundle, S.: Threats to the running water ecosystems of the world, Environ. Conserv., 29, 134–153, doi:10.1017/S0376892902000097, 2002. 8875
Meyer-Peter, E. and Müller, R.: Formulas for bed-load transport, Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research, 39–64, 1948. 8888
Millar, R. G.: Influence of bank vegetation on alluvial channel patterns, Water Resour. Res., 36, 1109, doi:10.1029/1999WR900346, 2000. 8879
Mitsch, W.: Ecological engineering: A field whose time has come, Ecol. Eng., 20, 363–377, doi:10.1016/j.ecoleng.2003.05.001, 2003. 8875
Molnar, P., Favre, V., Perona, P., Burlando, P., Randin, C., and Wolfgang, R.: Floodplain forest dynamics in hydrologically altered mountain river, Peckiana, 5, 17–24, 2008. 8884
Nat, D. V. D., Schmidt, A. P., Tockner, K., Edwards, P. J., and Ward, J. V.: Inundation Dynamics in Braided Floodplains : Tagliamento River , Northeast Italy, Ecosystems, 5, 636–647, doi: 10.1007/s10021-002-0170-0, 2002. 8878
Perona, P., Molnar, P., Savina, M., and Burlando, P.: Stochastic sediment – vegetation dynamics in an Alpine braided river, Sediment dynamics in changing environments (Proceedings of a symposium held in Christchurch, New Zeland), 266–274, 2008. 8885
Perona, P., Camporeale, C., Perucca, E., Savina, M., Molnar, P., Burlando, P., and Ridolfi, L.: Modelling river and riparian vegetation interactions and related importance for sustainable ecosystem management, Aquat. Sci., 71, 266–278, doi:10.1007/s00027-009-9215-1, 2009a. 8884, 8885
Perona, P., Molnar, P., Savina, M., and Burlando, P.: An observation-based stochastic model for sediment and vegetation dynamics in the floodplain of an Alpine braided river, Water Resour. Res., 45, 1–13, doi:10.1029/2008WR007550, 2009b. 8885
Peter, A., Kienast, F., and Woolsey, S.: A strategy to assess river restoration success, Archives de Science, 15, 643–656, 2006. 8875
Pollen, N.: Temporal and spatial variability in root reinforcement of streambanks: Accounting for soil shear strength and moisture, Catena, 69, 197–205, doi:10.1016/j.catena.2006.05.004, 2007. 8879

Pollen, N. and Simon, A.: Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, Water Resour., 41, 1–11, doi:10.1029/2004WR003801, 2005. 8879

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H., and Sorooshian, S.: A Modified Soil Adjusted Vegetation Index, Remote Sens. Environ., 126, 119–126, 1994. 8884

Quinn, J. M. and Hickey, C. W.: Hydraulic parameters and benthic invertebrate distributions in two gravel-bed New Zealand rivers, Freshwater Biol., 32, 489–500, doi:10.1111/j.1365-2427.1994.tb01142.x, 1994. 8893

Ruf, W., Foglia, L., Perona, P., Molnar, P., Faeh, R., and Burlando, P.: Modelling the interaction between groundwater and river flow in an active alpine floodplain ecosystem, Peckiana, 5, 5–16, 2008. 8885

Samaritani, E., Shrestha, J., Frossard, E., Mitchell, E., Fournier, B., Niklaus, P., Tockner, K., and Luster, J.: Spatio-temporal variability of soil carbon pools and fluxes among different functional processing zones in the floodplain of river Thur, In preparation, 2010. 8881

Schaeppi, B., Perona, P., Schneider, P., and Burlando, P.: Integrating river cross section measurements with Digital Terrain Models for improved flow modelling applications, Comput. Geosci., 2009. 8883

Schirmer, M., Durisch-Kaiser, E., Linde, N., Luster, J., Perona, P., Mitchell, E., Barry, D, A., Cirpka O, A., Schneider, P., Vogt, T., Burlando, P., Pannatier, E, G., Green, A., Hoehn, E., Hollender, J., Kipfer, R., Tockner, K., and Wehrli, B.: River restoration: Morphological, hydrological, and ecological changes, challenges and opportunities, in preparation, 2010. 8875, 8877, 8878

Schneider, P., Schirmer, M., Doetsch, J., Linde, N., Pasquale, N., Perona, P., and Cirpka, O. A.: Instrumentation Strategy for the Assessment of River-Groundwater Interactions in the Context of River Restoration, J. Hydrol., submitted, 2010. 8878, 8891

Schweizer, S. P.: Predicting the consequences fo river rehabilitation measures on morphology, hydraulics, pheriphyton and on invertebrates Zürich, Switzerland 2007, Ph.D. thesis, 2007. 8875

Soar, P. J. and Thorne, C. R.: Channel restoration design for mendering rivers, U.S. Army Engineer Research and Development Center, Vicksburg, Miss., 2001. 8875

Sprott, J. C.: Chaos and time series analysis, Oxford University Press, Oxford, UK, 1st edn., 2003. 8892, 8893

Steiger, J. and Gurnell, A. M.: Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France, Geomorphology, 49, 1–23, doi:10.1016/S0169-555X(02)00144-7, 2003. 8882

Stewardson, M. J. and MaMahon, T. A.: A stochastic model of hydraulic variations within stream channels, Water Resour. Res., 38(1), 1007, doi:10.1029/2000WR000014, 2002. 8893

Tockner, K. and Stanford, J.: Riverine flood plains: present state and future trends, Environ. Conserv., 29, 308–330, doi:10.1017/S037689290200022X, 2002. 8875

Trush, W. J., McBain, S. M., and Leopold, L. B.: Attributes of an alluvial river and their relation to water policy and management, P. Natl. Acad. Sci. USA, 97, 11858–11863, 2000. 8877

Tubino, M. and Seminara, G.: Free-forced interactions in developing meanders and suppression of free bars, J Fluid Mech, 214, 1990. 8878, 8888

Verones, F.: Experiments on Salix shoot and root growth on river alluvial sediment with programming for image analysis, Ph.D. thesis, 2009. 8886

Waisel, Y., Eshel, A., and Kafkafy, U.: Plant roots: The hidden half, Marcel Dekker, NY, 3rd edn., 2002. 8886

Walthert, L., Graf, U., Kammer, A., Luster, J., Pezzotta, D., Zimmermann, S., and Hagedorn, F.: Determination of organic and inorganic carbon, δ 13 C, and nitrogen in soils containing carbonates after acid fumigation with HCl, J. Plant Nutr. Soil Sci., 173, 207–216, doi:10.1002/jpln.200900158, 2010. 8882

Wohl, E., Angermeier, P. L., Bledsoe, B., Kondolf, G. M., Macdonnell, L., Merritt, D. M., Palmer, M. A., Poff, N. L., and Tarboton, D.: River restoration, Water Resour., 41, 1–12, doi:10.1029/2005WR003985, 2005. 8875

Woolsey, S., Capelli, F., Gonser, T. O. M., Hoehn, E., Hostmann, M., Junker, B., Paetzold, A., Roulier, C., Schweizer, S., Tiegs, S. D., Tockner, K., Weber, C., and Peter, A.: A strategy to assess river restoration success, Freshwater Biol., 52, 752–769, doi:10.1111/j.1365-2427.2007.01740.x, 2007. 8875

Wu, J. and Tang, A. D.: The influence of water conveyances on restoration of vegetation to the lower reaches of Tarim River, Environ. Earth Sci., 59, 967–975, 2010. 8890

Table 1. Nutrient content and soil type analysis results. Soil samples were dried at 40 °C, and then sieved at 2 mm.

	Units	Mean	SD
Sand	%	81	5
Silt+Clay	%	19	4
Organic carbon	gC kg^{1}soil	9.2	3.2
Total nitrogen	gN kg^{1}soil	0.6	0.2
Available phosphorus	mgP kg^{1}soil	24.9	8.7

HESSD
7, 8873–8912, 2010
Monitoring restored corridor morphodynamics
N. Pasquale et al.

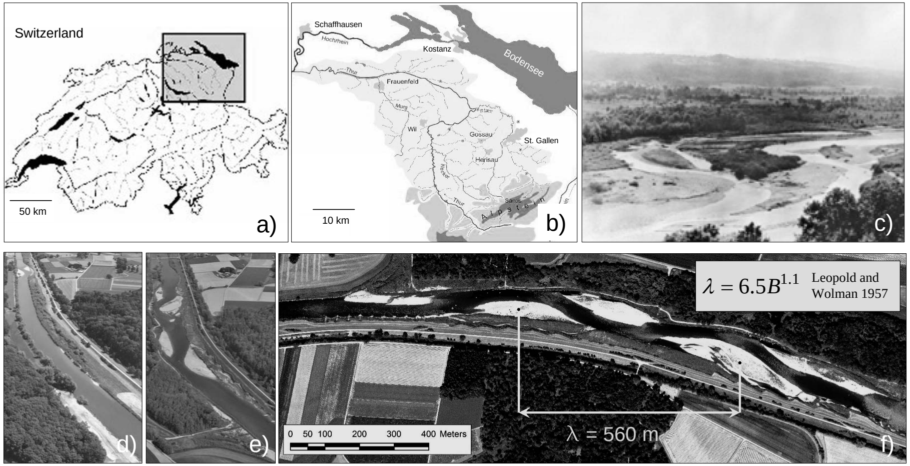

Fig. 1. Location of the river Thur in Switzerland **(a)** and river basin **(b)**. From a natural braiding state **(c)** the river was straightened **(d)** in the past century to improve flood protection, to increase agriculture areas and to reduce spreading of disease. As a consequence river bed faced serious erosion problems. After the restoration project started in 2002 the river naturally formed an alternate bar system **(e, f)**.

HESSD
7, 8873–8912, 2010

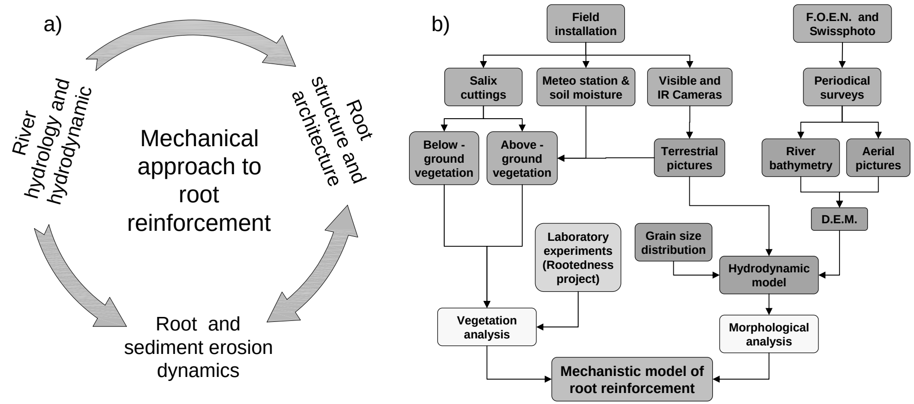

Fig. 2. River hydrology and hydrodinamics influence root structure and architecture together with sediment erosion and uprooting. The latters are also interconnected **(a)**. To reach a mechanical understanding of root reinforcement we follow the flow chart schema hereby represented **(b)**. Beginning from field installations, together with periodical survey and monitoring we make vegetation and morphological analysis. Coupling the two we aim at reaching a mechanistic model of root reinforcement of cohesiveless soil.

HESSD
7, 8873–8912, 2010

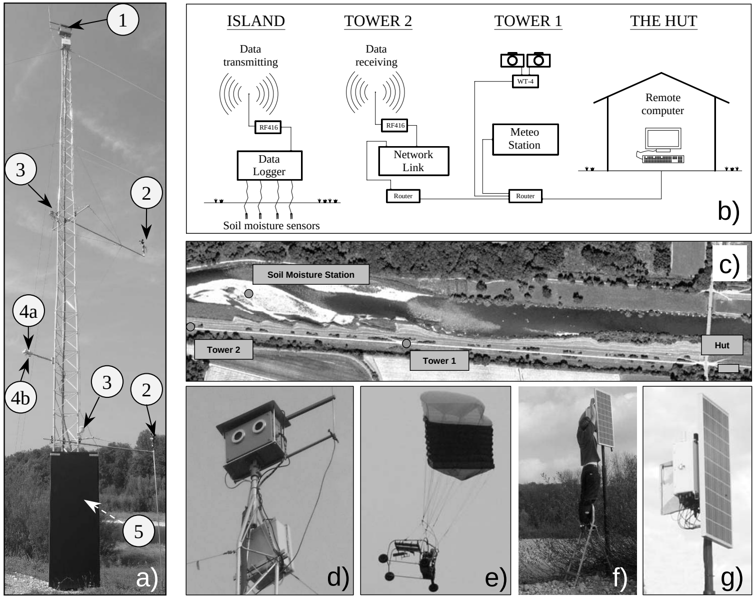

Fig. 3. Field installation: **(a)** shows the tower with the meteo station. 1 is the camera box **(d)**, box 2 are the two wind sensors, 3 are the two temperature and relative humidity sensors, 4a and 4b are the incoming and reflected radiation sensors respectively and 5 is the pressure sensor. Soil moisture station on the island transmits data via wireless to the second tower on the levee. The second tower has one box with two cameras and it is connected via optic wires to the first one where there there is also a camera box and the meteo station (b). The system is controlled by a computer located in a hut on the levee **(b, c)** and connected via optic fiber to the first tower (b). (d) shows the camera box. **(e)** is the motorized paraglider used for aerial pictures. **(f, g)** show the soil moisture station on the island and a particular of the solar panel used to charge the data logger battery.

HESSD

7, 8873–8912, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

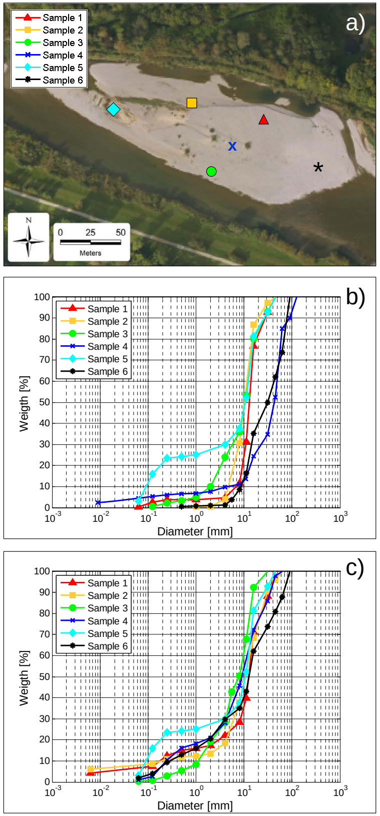

Fig. 4. Grain Size Distributions for six different locations on the main island **(a)**, for samples taken on the surface **(b)** and at 40 cm depth **(c)**. d_{50} and d_{90} are generally higher on surface layers (b) than at 40 cm (c). Surface samples (b) show also a higher spatial sediment sorting, from coarser material upstream (sample 6) to finer material downstream (sample 5). Sediment at 40 cm depth are more spatially similar and d_{50} is practically equal for all samples (c). Comparing (c) and (b) it is evident the vertical sorting typical of river bed forms.

HESSD
7, 8873–8912, 2010

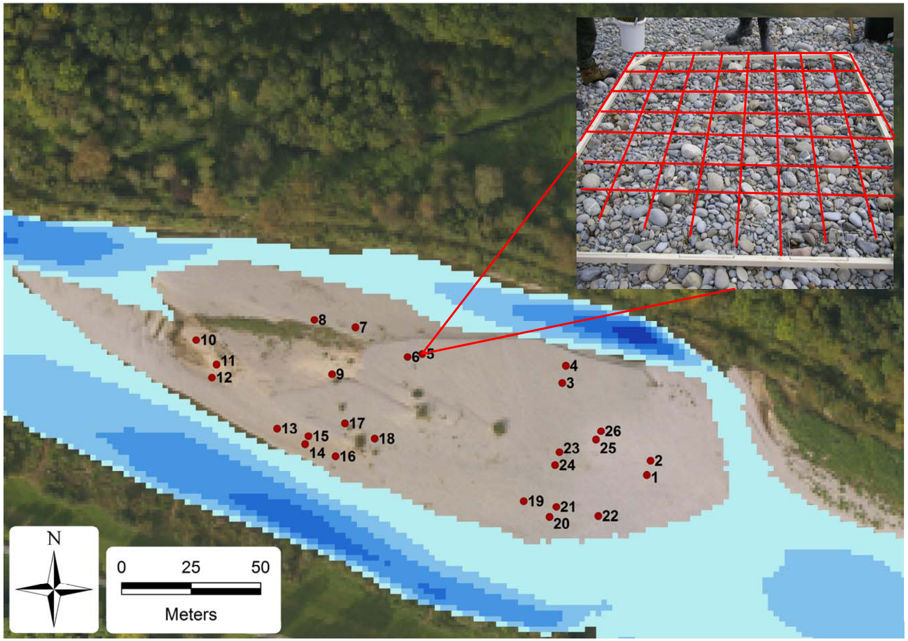

Fig. 5. Map of the study island showing the location of vegetation plot in 2009. Plot location is decided according mainly to hydraulic parameters (flow shear stress and velocity) and according to topography (elevation). The upper right corner box shows the matrix frame used for cutting plantation. One cutting is planted in the soil in correspondence of each node. We thus have a regular matrix which helps to identify cuttings position during monitoring.

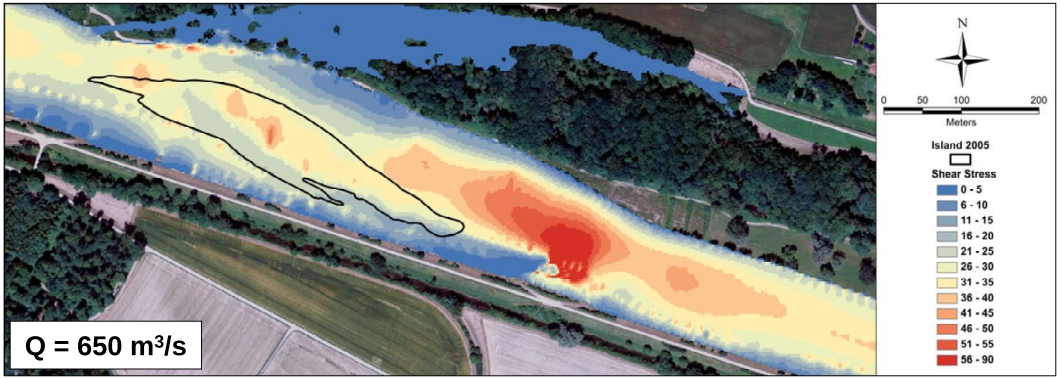

Fig. 6. Simulated bed shear stress produced by the maximum flow peak (corresponding to 650 m^3/s) registered in the range of time 2005–2006. Those kind of simulation have been used to decide the location of Salix plots as well as for morphodynamic analysis. In black it is shown the shoreline of the island for 30 m^3/s (2005).

HESSD
7, 8873–8912, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

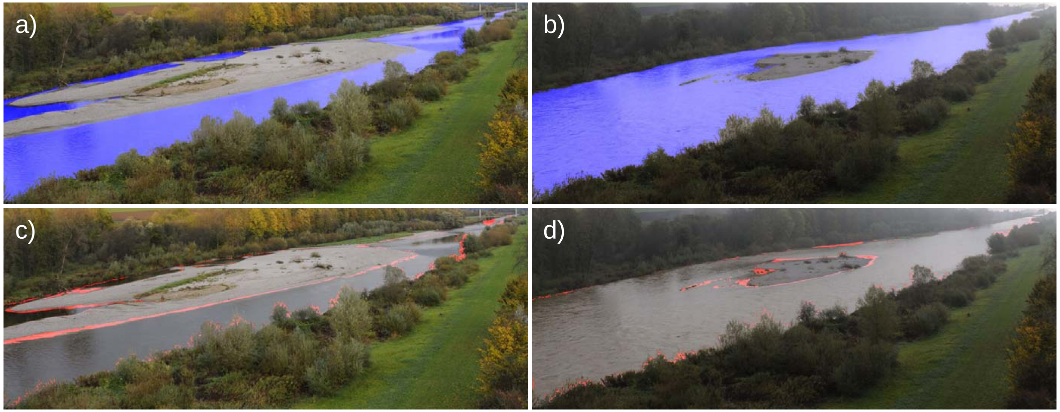

Fig. 7. We attempt to recognize water and non-water classes from digital photographs under changing light and surface albedo. Such conditions are typically due to either diurnal variability or bad weather conditions (e.g., like fog or snow). The approach consists of masking the images by ignoring the irrelevant parts like mountains and sky, for instance. Next, we define features which describe properties of the image or the image content, like e.g. color values, gradients of neighboring pixels. Specific information like a probability distribution of a pixel being water is derived from the digital elevation model. All collected features are used in a supervised learning algorithm, which calculates the probability that a specific pixel belongs to the water class. Two example pictures for low discharge (**a** and **c**) and high discharge (**b** and **d**) are shown. Blue is the detected water (a, b). Red are the classification errors (c, d).

HESSD

7, 8873–8912, 2010

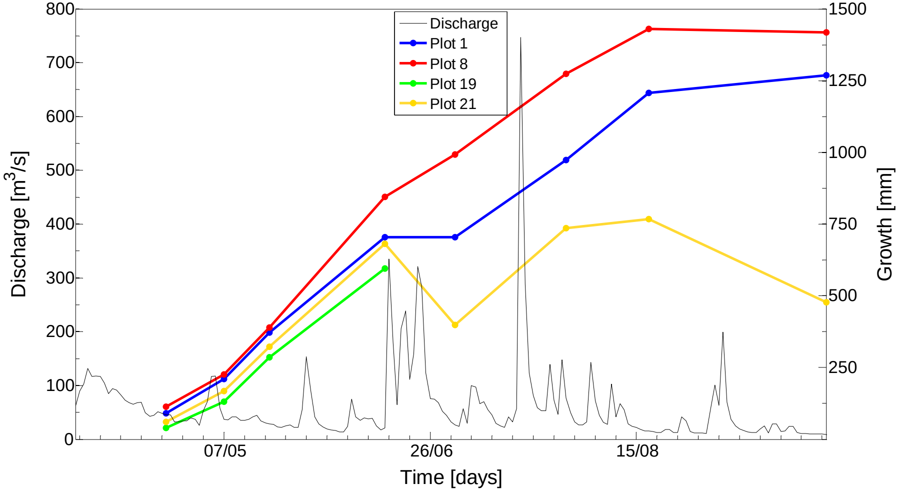

Fig. 8. High impulse natural floods are consider to be the main cause of mortality on such a gravel island. Plot 1 and 8 located at higher elevation are less frequently inundated and experience also lees stresses during floods. Their growth is therefore almost linear during the whole season. The effect of the hydrograph is more evident on plot 21 sited at lower elevation. In correspondence of the three consecutive peaks in June we register a negative growth for plot 21 (stems are broken). The same three floods cause the complete removal of all plot 19 cuttings, the one at the lowest elevation.

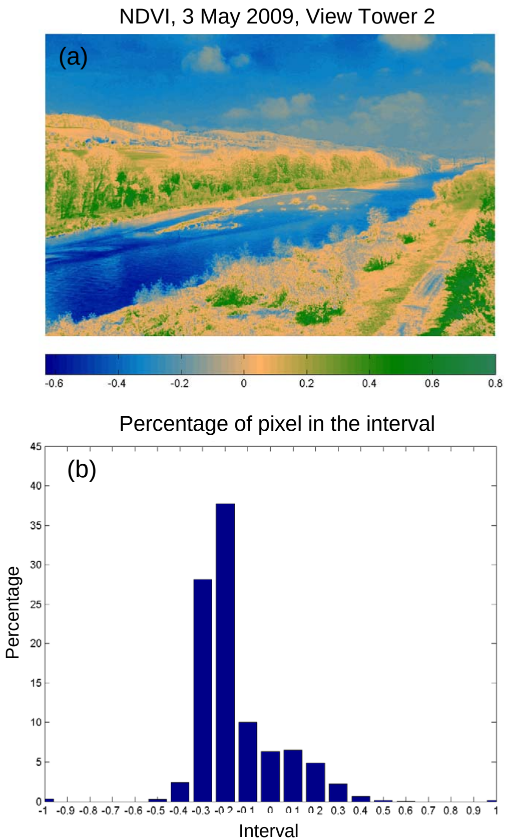

Fig. 9. NDVI picture of the field site **(a)** on 3 May 2009. Pixels between 0.1 and 0.8 correspond to vegetation cover, pixels ranging from −0.2 and 0.1 represents bare soil and values smaller than −0.2 water. NDVI images are used to compute the frequency (as a percentage) of vegetation, bare soil and water at a certain time **(b)**.

HESSD
7, 8873–8912, 2010

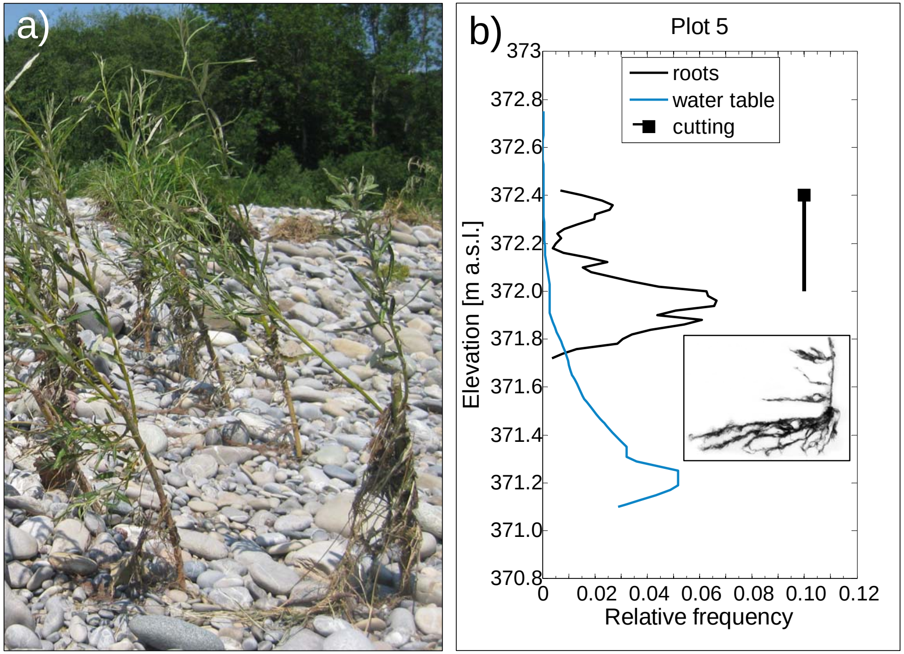

Fig. 10. Water flow during flooding produces high scouring of sediment. Consequently cutting roots are exposed **(a)**. This is the first stage for cutting removal. The deeper are roots the more a plot has chances to survive several flooding. It becomes thus important to study the position (in terms of relative frequency) of roots with depth and how the frequency is related to the water table **(b)**.

HESSD
7, 8873–8912, 2010

HESSD

7, 8873–8912, 2010

Monitoring restored corridor morphodynamics

N. Pasquale et al.

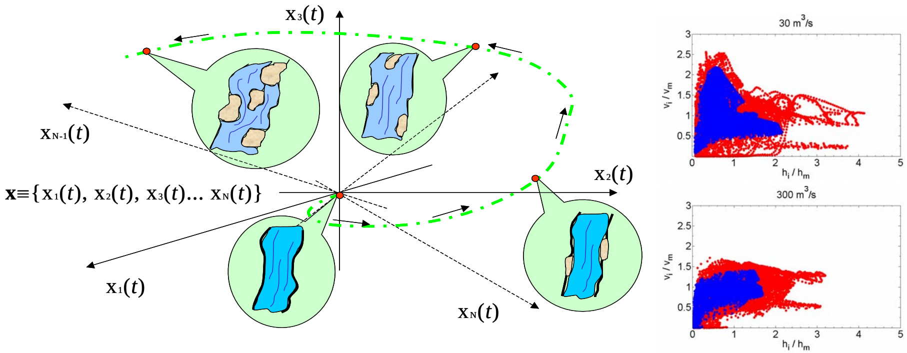

Fig. 11. Conceptual representation of the restored corridor evolution trajectory in the state space (left) assuming the variables $x_1(t), x_2(t), x_3(t), \ldots, x_N(t)$ as indicators representing the state of the system at successive time instants. State plane projection showing the spatial variability of the modeled hydraulic variables (h, v) for the straight (blue) and the restored (red) reaches at two different flowrates (right).