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Driving forces in a floodplain restoration project: interaction between surface water, groundwater and morphodynamic processes during an ecological flooding

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Abstract Erosion, transport and deposition of sediment play a major role in restoration projects and sustainable river management. The main driving variables, water and sediment dynamics resurrect the natural processes in "riverscapes" and floodplains. After the first flooding of a new river course in the floodplain along the River Danube between Neuburg and Ingolstadt (Germany) in 2010 (up to 5 m^3/sec), new morphological activity started instantly. However, intensive erosion rates were measured during the first two controlled ecological flood events with water discharges of 10 $m^3 s^{-1}$ and 20 $m^3 s^{-1}$. The relatively new river banks are prone to lateral erosion and during bankfull stages new undercut slopes have developed. To understand the processes in this new river channel, its development is being recorded by a package of methods such as terrestrial laser scanning (TLS) measurements.

Key words river restoration; floodplain; ground-based LiDAR; hydromorphology; monitoring

INTRODUCTION

Varying water levels and changing discharges with different flow conditions and directions are characteristic of floodplains. All these hydrological conditions directly influence the morphological processes in rivers, but also they have an effect on the riverine landscapes and their biocenoses. Hydrology is one of the key factors determining the type and function of floodplains. Two main parameters are the major sources of complexity in floodplains: (a) the hydrological connectivity, responsible for exchanges between landscapes and riverscapes, and (b) the energy of running water, responsible for the fluvial (morpho-) dynamics (Amoros & Bornette, 2002). Floodplains are complex and dynamic ecosystems and therefore hotspots of biodiversity (Tockner *et al.*, 2000; Ward *et al.*, 2002; Thorp *et al.*, 2006).

At the same time, this very dynamic and adaptable system surprisingly is one of the most imperilled, threatened and sensitive ecosystems on Earth. Slightest changes can have strong impacts not only on the wetlands themselves but even on adjacent catchments. Of the water discharge of the 139 largest river systems in North America and Europe, 77% is affected by fragmentation of river channels by dams and river regulation (Dynesius & Nilsson, 1994). Furthermore, all larger rivers were appreciably modified by a wide range of human activities (Petts *et al.*, 1989, Schiemer *et al.*, 1999). All these changes have greatly modified the magnitude, duration, and frequency, with which flood waters interact with the floodplain.

To diminish the negative effects of the regulations on one part of the Danube, the Bavarian water authority (co-financed by the Free State of Bavarian and the European Union) in 2010 reconnected a part of the Danube between Neuburg and Ingolstadt with its backwater (Bock *et al.*, 2006; Cyffka & Haas, 2008; Stammel *et al.* 2008, 2011). To monitor the effects of this reconnection, the Floodplain Institute, Neuburg and the Department of Applied Physical Geography of the Catholic University of Eichstaett established, in cooperation with eight other research institutes, a comprehensive and interdisciplinary monitoring programme (MONDAU, "MONitoringDonauAUen") including vegetation, fauna, hydrological and morphological data. Three different measures (new floodplain river, ecological flooding and groundwater drawdown) bring water and sediment dynamics back to the floodplain (cf. Fig 1). The dynamic interplay existing between terrestrial and aquatic components in floodplain ecosystems leads to a complex system. Thus, river dynamics, particularly lateral erosion, demolish and create diverse habitats that

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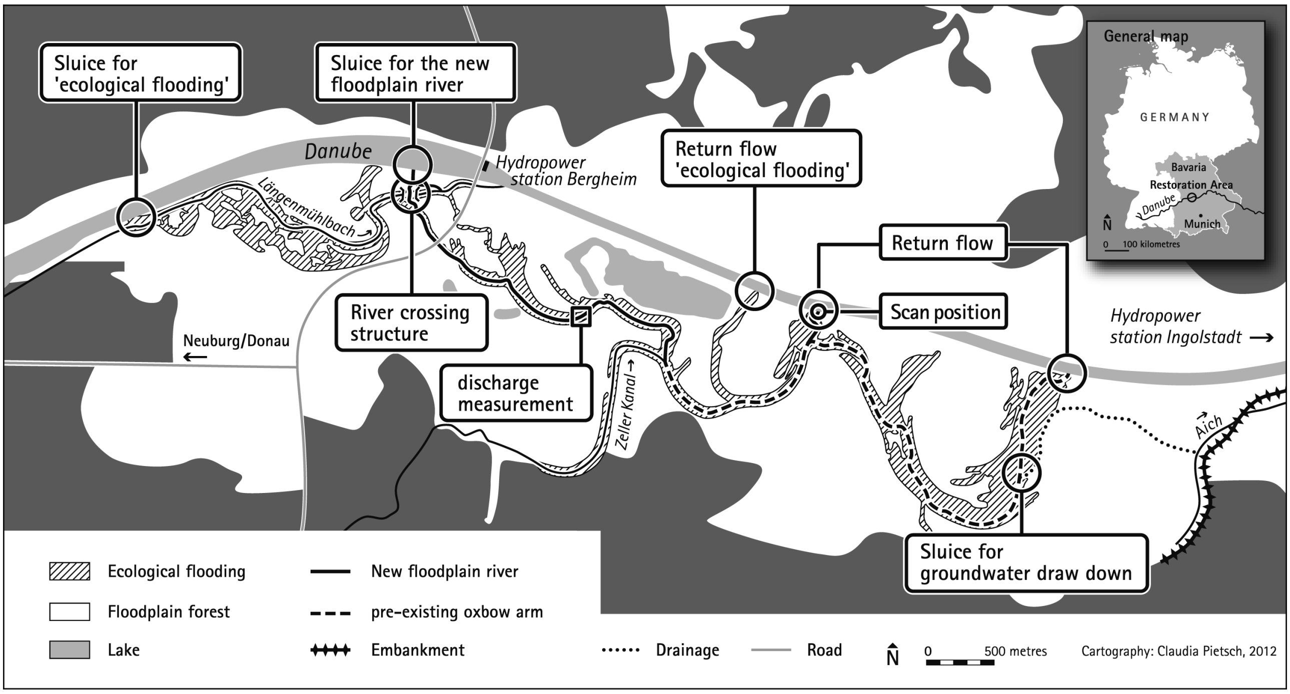


Fig. 1 Simplified map of the study area and location of the measures (new floodplain river, ecological flooding, groundwater drawdown) and study sites (gauging station "Hunters Bridge" for discharge measurement and one of the 64 scan positions at a selected hotspot "first return flow").

differ in their geomorphology (i.e. depth, width, length) and hydrology (i.e. temperature and flow velocity) and they are spatially distributed. During floods and bankfull discharges, especially, the force to develop river structure rises and the geomorphic changes are at their highest (Knighton, 1998). The first results of hydrological and geomorphic activity during a flood event in January 2012 are presented here.

STUDY SITE AND RESTORATION PROJECT

Study site

The project area is situated in the Upper Danube River reach (kilometres 2472 to 2464, 48°45′N, 11°16′E, small map in Fig. 1). The floodplain area of 1200 ha is located between two hydropower dams and still shows a high biodiversity (>1500 animal species, 400 of them threatened, and >500 plant species, 80 of them threatened; WWF, 1997). Two hundred years ago, river regulation and embankment resulted in only one straight channel. Therefore, the reduced connectivity between the Danube and its backwaters has fostered a strong tendency towards terrestrialization. In addition, a unification of the different vegetation types since 1969 has been monitored (Margraf, 2005). Interactions between factors are widespread, so flooding should not be regarded as the ultimate factor determining the presence of species, but nevertheless the hydrological dynamic is crucial.

Restoration project

The pre-restoration state, technical preconditions and first prognosticated expansions of the ecological flooding areas are described in detail by Bock *et al.* (2006), Cyffka & Haas (2008) and Stammel *et al.* (2008, 2011). A summary is provided here to permit an insight into the restoration measures and monitoring project.

To invert the impacts of the river regulations and to achieve the highest possible level of continuity for fish a new water course with alternating discharges of about 8.4 km length was created. The first 2.5 km, a completely new channel, was generated mainly following old (dry) meanders and river loops, whereas in its further course the new floodplain river follows temporary water bodies (floodplain ponds) and oxbow arms with slow flow velocity (cf. Fig. 1).

To create "natural site conditions" ecological flooding will take place over a second sluice approximately two to three times per year. A controlled amount of water up to 25 $m^3 s^{-1}$ will be discharged into the floodplain. The ecological flooding was designed both to bring water into the whole area, and to initiate erosion at the banks and bring new dynamics to the river channel. Maybe at selected sites a "reset" of the system will happen, e.g. when a gravel bar is completely renewed or newly formed at another place. Return flows and anticipated flooded area are shown in Fig. 1.

MATERIALS AND METHODS

The monitoring of abiotic processes (fluvial morphodynamic processes and groundwater monitoring) is the subject of subproject II (SP II) of the MONDAU joint project (Stammel *et al.*, 2011). The main objectives of SP II are to document and to analyse the abiotic changes in river morphology, sediment transport, water levels and flow velocities, soil moisture and groundwater, due to the restoration measures and provide this information for the other subprojects (cf. Stammel *et al.*, 2011). Therefore methods are used which range from water level measurements to discharge measurements, grain size analyses, cross-section measurements, and aerial photographs to ground-based LiDAR. Some are described below.

Hydrological measurements

Water level measurements Due to the complexity of the river and floodplain interconnection and the constraints specific to the project design (variable water runoff, bifurcation and junction, drainage channel), many water level gauging stations are necessary to document the variations in a satisfactory manner. Therefore water gauges with a pressure sensor and an internal datalogger (Diver-Suite, Schlumberger Water Services) were placed in observation wells distributed over the project area and record the water level at a 15-min time interval (Fig. 2). In addition to the automatic dataloggers, about 30 mobile scale slats are used during ecological flood events or groundwater drawdowns to improve the density of measurements of water level changes in different water bodies in the alluvial floodplain (Fig. 3). This time consuming technique is still a low cost and reliable method to complete hydrological data. The data produced were used to interpolate groundwater level (monthly) in the floodplain and, in combination with discharge measurements, to derive a stage–discharge relation for the channel system.

Discharge measurements Flow velocities and directions during "normal" conditions were measured with an electromagnetic velocity meter (FlowSens, SEBA Hydrometrie), which is common practice, especially in rivers of wadeable depth. During ecological flood events flow velocities and flow heights are very variable over short times, thus other methods are also needed to ascertain the current discharge heights. According to Day (1976) and Butterworth *et al.* (2000) salt dilution gauging by an uniformly mixed salt concentration with the streamwater can be precise to about 5%, equivalent to the accuracy of a current meter at a suitable cross-section. Hudson & Fraser (2005) give a good overview over this method. The "near-instantaneous slug method" with injection using salt in solution and dry salt has often been used for streamflow measurements (Moore, 2004). During peak discharge we injected the tracer from a small bridge and measured the concentration downstream using a conductivity meter with an integral data logger (time interval 1 s). Using these data the discharge was derived using the equation described in the work of Benischke & Harum (1990):

$$Q = \frac{M}{E \cdot \int_0^t (C - C_0)\,dt} \tag{1}$$

where Q is the discharge in L s^{-1}, M is the mass of salt in mg, E is a calibration factor in µS cm^{-1} × mg L^{-1} (gradient of the trend line between inserted salt and the conductivity; Benischke & Harum 1990), C is the conductivity in µS cm^{-1}, C_0 is the base conductivity in µS cm^{-1}, t is the transit time in seconds. Using the discharge measurements and the corresponding water level measurements, a stage–discharge relationship for every water gauge in the channel system of the project area was derived.

Geomorphic measurements using ground-based LiDAR

During the last decade the application of ground-based LiDAR data in geomorphology, and especially in fluvial research, has rapidly increased (Heritage & Large, 2009; Hohental *et al*., 2011; Wheaton *et al*., 2011), as high resolution digital terrain models (DEMs) can be used to quantify the change of fluvial landforms (Haas & Heckmann, 2007; Haas *et al*., 2011) and river morphology (e.g. gravel bars, bank failure and point bars) in a very accurate way (Wheaton *et al*., 2011).

Scanner system For the presented investigations we used the terrestrial laser scanner system Riegl LMS Z420i. This long-range 3-D laser scanner has a maximum measurement range up to ~ 700 m. The distance accuracy is 0.01 m (by single shot), by a scanning rate of 8000 pts s^{-1}. The system is operated by an external PC and the software Riscan Pro. To detect colour information, the scanner is equipped with a mounted digital SLR camera (Canon 350D, Nikon D70).

Data acquisition, processing and accuracy of the measurements To detect long-term surface changes the whole new dredged river course between the “river cross structure” and south of the big lake (Fig. 1) was scanned annually from a total of 64 scan positions with a resolution of 400 pts m^{-2}. Some geomorphic “hot spots” such as eroding banks and narrow channel reaches were scanned additionally at a much higher temporal resolution in order to detect short-term surface changes, e.g. during ecological floodings.

Here, the results of measurements on an eroding bank (high temporal resolution) at the first return flow before and during an ecological flooding event in January 2012 will be presented. For an accurate alignment of the single scan positions and the single time steps a huge number of tie points (reflector buttons with a diameter of 0.05 m and 0.1 m), mounted on unmoveable big trees or bridges, were used. The registration process of single scan positions and the post-process, including the manual correction of scans (removing “flying points” like birds or flies, and vegetation) is described in detail by Haas *et al*. (2011, 2012 – this issue).

The subsequent steps, e.g. filtering of vegetation and deriving of DEMs, is done using LIS Desktop/SAGA GIS (Haas *et al*., 2011, 2012 – this issue). The resolution of the derived DEMs varied between 0.05 m and 0.1 m for the “hot spot” surfaces, and 0.5 m to 1.0 m for the whole river course. Using the DEMs, the surface changes were derived by subtraction of the filtered DEMs of the single time steps (T_1, T_2, T_n) by a cut and fill analyses (*CutFill* in SAGA, Heckmann 2006). The uncertainty of the measurements was calculated following the work of Brasington *et al.* (2003) and Wheaton *et al.* (2010), as described by Haas *et al.* (2012 – this issue). The error of the measurements at the “hot spot” amounts to 0.014 m (2SD), thus surface changes below –0.014 m (–2SD) and + 0.014 m (+2SD) were not included in the volume estimation and were set to “no change” in the difference maps.

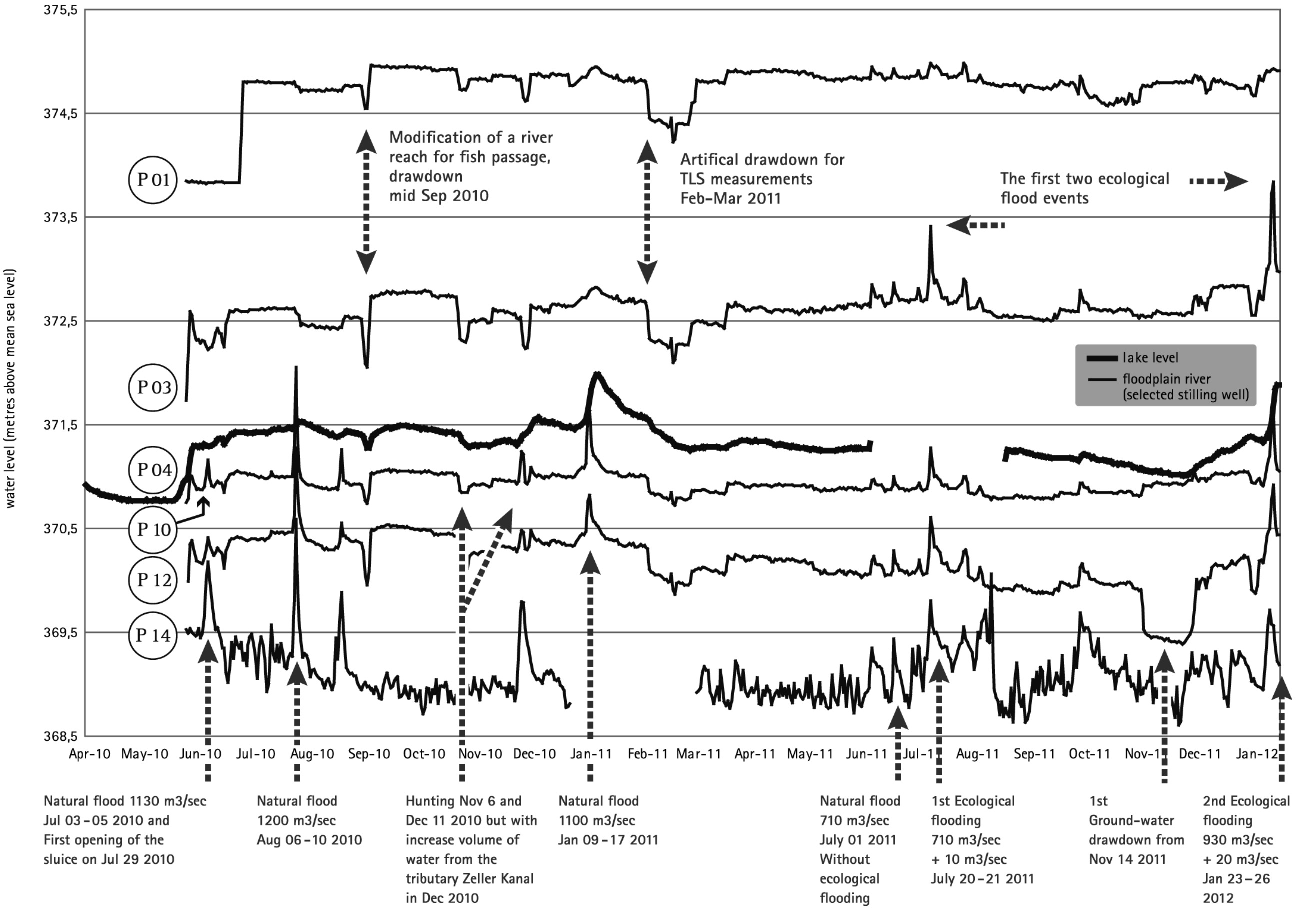
RESULTS AND DISCUSSION

Hydrology – ecological flood events

Since the first opening of the new river course on 29 June 2010 the first river reach has emerged to a “high structure habitat” with widths from 5 to 25 m and an average water depth of about 1.5 m at a mean discharge of 3 $m^3 s^{-1}$. Morphological structures and hydraulic parameters have developed. Plenty of woody debris has been deposited at different sites and has caused a high variability in morphological structures (sand ripples, gravel bars, or riffle and pools).

Two highlights occurred on 20 July 2011 and 1 January 2012 when the sluice was opened for 2 and 4 days, respectively (Fig. 2) and finally, after five years water came back to the floodplain (the last natural flood take place in 2005).

Whereas the first artificial flood (up to 10 $m^3 s^{-1}$, sluice for ecological flooding, Figs 1 and 2) merely restrained changes, self-development and river dynamics could be observed in January 2012. A regulated volume of water (from 12 to 20 $m^3 s^{-1}$) passed the sluice between the 23rd and 26th. After about six hours the water level in “Längenmühlbach” reached the top of the terrain threshold and the water conjoined with the floodplain river. Then, some hours later bankfull discharge in most reaches of the river course could be noticed; the channel was filled up to the tops of the banks and water level rises could also be noticed at the automatic gauging stations and mobile scale slats (Figs 2 and 3).



Modification of a river reach for fish passage, drawdown mid Sep 2010

Artifical drawdown for TLS measurements Feb–Mar 2011

The first two ecological flood events

Natural flood 1130 m3/sec Jul 03 – 05 2010 and First opening of the sluice on Jul 29 2010

Natural flood 1200 m3/sec Aug 06 – 10 2010

Hunting Nov 6 and Dec 11 2010 but with increase volume of water from the tributary Zeller Kanal in Dec 2010

Natural flood 1100 m3/sec Jan 09 – 17 2011

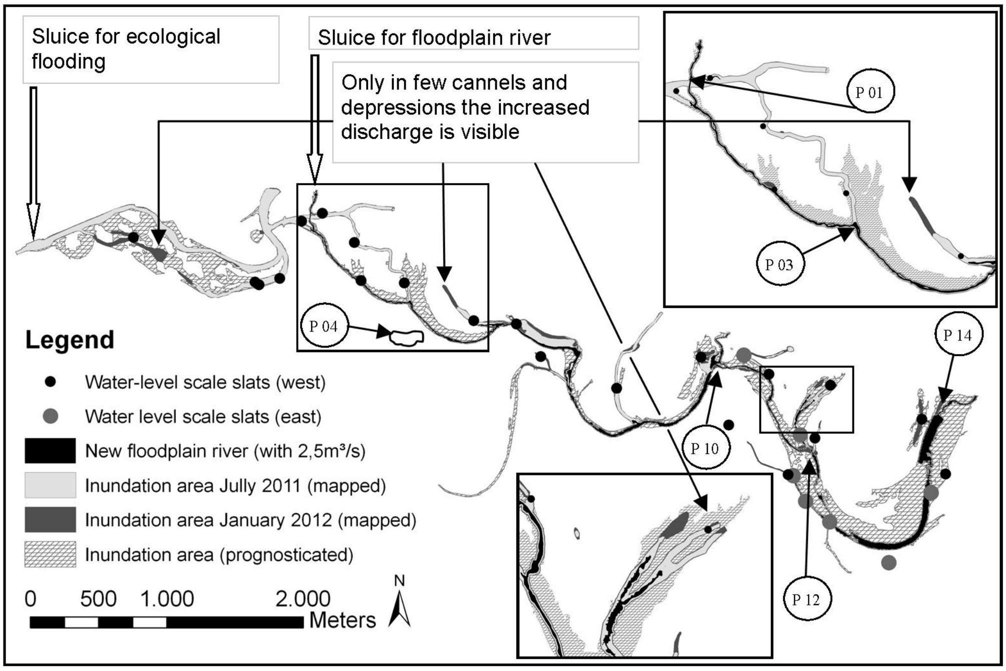
Natural flood 710 m3/sec July 01 2011 Without ecological flooding

1st Ecological flooding 710 m3/sec + 10 m3/sec July 20 – 21 2011

1st Ground-water drawdown from Nov 14 2011

2nd Ecological flooding 930 m3/sec + 20 m3/sec Jan 23 – 26 2012

Fig. 2 Surface-water stages at selected stilling wells (location cf. Fig. 3) in new floodplain river and a lake-level hydrograph (bold line, P04) (April 2010 through January 2012). Water-level hydrographs show differences and commonalities along the river course. Variations are clearly visible, e.g. rises due to natural or ecological flooding or declines due to groundwater lowering or manmade drawdown for hunting or scientific surveys.



object	**area in m^2**
New Floodplain river (calc. with < 2,5 m^{3}s^{-1})	155,121
New Floodplain river (calc. with > 3m^{3}s^{-1})	215,791
Längenmühl-bach	27,474
Zeller Kanal	9,722
Inundation area ecological flood (July 2011)	503,398
Inundation area ecological flood (Jan 2012)	653,608
Inundation area ecological flood (prognosticated)	1.367,277

Fig. 3 Inundation area during ecological flood events and scale slats distribution. Table on the right shows the calculated water area of selected water bodies in m^2. Note the differences between forecasted and mapped expansion.

Such a high runoff indicates the condition of incipient flooding and also influences the shape and size of the channel. During such flood events, when the erosive power of the discharge is greatly increased, dramatic changes in the form of the channel can occur, and large amounts of geomorphological work can be performed (Knighton, 1998; Charlton, 2008). Numerous flows during the year are limited inside the channel; only high flows overtop the river banks and overflow the surrounding areas. Both ecological floodings remained more-or-less within the trenched channel. Only at a few points did overtopping happen (Fig. 3).

One reason for this is the water loss in the adjacent environment. Exfiltration in riverine landscapes is difficult to estimate. In soils of low permeability, a long flooding period is required to achieve significant groundwater recharge. But in coarse alluvial deposits, which are laid down in an earlier phase of floodplain development, the groundwater exchange can influence the water regime distinctively. Discharge measurements (Fig. 1) on 25 January show a decrease of the total water amount from about 25 m^3 s^{-1} (sluice ecological flooding about 20 m^3 s^{-1} + sluice floodplain river 5 m^3 s^{-1}, cf. Fig. 1) to 11.2 m ^{3} s^{-1} (gauge Hunters Bridge). Both in Figs 2 and 3 the water loss is visible. This is demonstrated most clearly in Fig. 2 with P04, the lake level hydrograph. Figure 3 shows a flat water expansion. All the waterbodies, either surface water connected or ephemeral groundwater-fed, contribute to a total inundation area of 65 ha.

Geomorphic measurements using ground-based LiDAR

The morphology at the return flow "ecological flooding" has changed significantly since the beginning of the restoration project and a high structural variability in morphological features has emerged. Two processes of river bank erosion mainly erode the bank at the return flow: (a) bank scour (direct removal of bank material by the physical action of flowing water), and (b) mass failure (bank erosion through sliding, following undercutting by the river). Gravel bars, small islands and a small temporary terrace were generated during the last flood event. Two point bars arose inside a meander and deflected the flow initiating further bank failure on the other side where a trail was undermined. The river was widened at a cross-section some metres downstream.

The power of an increase of discharge volume up to 5 m^3 s^{-1} is sufficient for self-development with natural dynamics. Thus, when the erosive power of the flow is greatly increased, there can be dramatic changes in the channel form (Knighton, 1998; Charlton, 2008). Rapid changes in bank erosion, especially during ecological flooding events, can be recorded. Formann (2007) documented a reduction of channel changing processes after one year, and Hooke (1995) after two to three years, followed by stabilization after six to eight years.

Within this contribution we present the geomorphic activity on the erosion bank (Fig. 4), which we have recorded with ground-based LiDAR since February 2011. This was done at different spatial resolutions to document the long-term (by periodic scans) and short-term changes (by ecological flooding). Thus for this investigation site (Fig. 1) a total of 11 single scans are available (3 long-term and 8 short-term during the 2nd ecological flooding). Figure 4 shows a photograph and the derived surface changes to the erosion bank from the first scan on 18 February 2011 until the ecological flooding on 23 January 2012, and during the ecological flooding (23–26 January 2012). It is clearly visible that there has been very intense erosion since the beginning of the restoration project that led to a back shifting of the erosion bank by up to 7.2 m (Fig. 5). The total lost volume at this site amounts to 197.6 m^3 and most of the eroded material has been directly transported into the Danube (Fig. 5).

Our results show that the adaptation of the channel and meander geometry is not yet complete; in fact the natural stable tendencies are still at their beginnings. In particular, the high discharges during the ecological flooding between 23 and 26 January 2012 led to very intense geomorphic activity that is 1.4 times higher than during 18 February 2011 and 23 January 2012 (Table 1), including the first and less intense ecological flooding on 20 July 2011 (Fig. 2).

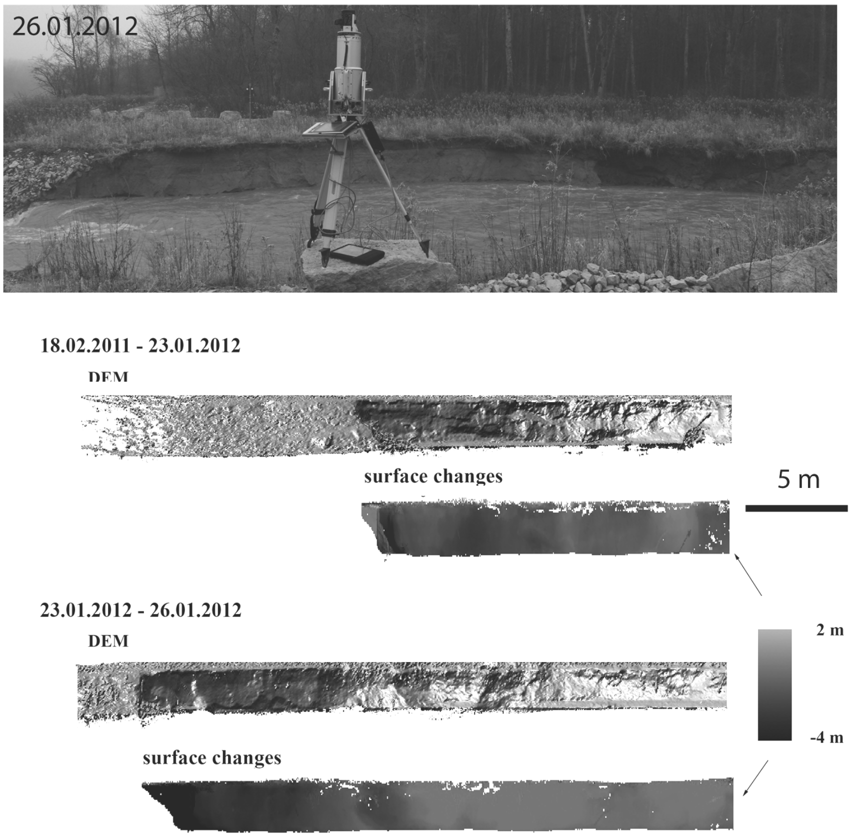


Fig. 4 Photograph of the erosion bank and surface changes on this erosional "hot spot".

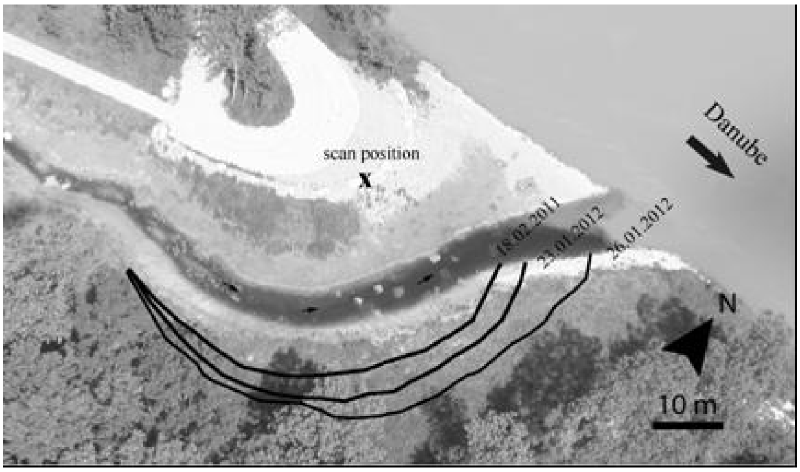


Fig. 5 Back shifting of the erosion bank at the first return flow between 18 February 2011 and 26 January 2012. Aerial photograph, Haas (July 2010).

Table 1 Eroded material volume at the first return flow between 18 February 2011 and 26 January 2012 based on LiDAR measurements

			Ecological flooding II							
Date	18.2. 11 07.4. 11	07.4. 11 23.1. 12	23.1. 12 24.1. 12	24.1.12 25.1.12	25.1.12				25.01.12 26.01.12	Total
Time				14:11	14:23	14:37	15:09	15:15		
Erosion in m^3	3.15	80.28	0.69	84.56	2.35	4.12	3.19	5.59	13.64	197.57

CONCLUSION

Our investigations during recent years document a high variability in hydrological and morphodynamic processes, especially during higher runoffs, which are triggered by ecological floodings. These alterations can only be documented by a wide range of sophisticated methods and "dynamic" adjustment of the materials and techniques deployed. Thus, adaptation to the floodplain processes is required for comprehensive floodplain monitoring. Morphological changes at the local scale are difficult to forecast and monitoring that is only based on field measurements always provides limited spatial information, depending on time and scale. But our first results clearly show that ground-based LiDAR especially turns out to be applicable to document the channel deformations in space and time. However, further investigations, including traditional field monitoring methods (e.g. GPS measurements, cross-section measurements, etc.) as well as e.g. multi-temporal aerial photographs by an UAV (unmanned, uninhabited or unpiloted aerial vehicle), are necessary to complete the described first results and therefore are still in progress.

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