FLOODPLAIN RESTORATION ON THE UPPER DANUBE BY RE-ESTABLISHING BACK WATER DYNAMICS: FIRST RESULTS OF THE HYDROLOGICAL MONITORING

Peter Fischer and Bernd Cyffka

With 7 figures and 3 tables
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Summary: Reactivation of hydrological dynamics is an essential part within restoration projects especially on floodplains. Frequently, oxbows are reconnected or former flood channels are supplied with water again. This can be accomplished for example by lowering spillway weirs, slit dams or widening of passages. In highly developed areas with various stakeholder interests and different types of land use the floodplain often is connected with the river via controllable sluices. This contribution explains the importance of a controlled water management of sluice gates for the interplay between river and an artificially connected floodplain. First results of the hydrological monitoring can be achieved by the interpretation of hydrographs and ground water levels as well as mapping surveys of flooded areas with a GPS. The functionality and effectiveness of restoration measures implemented in the research area on the Upper Danube between Neuburg and Ingolstadt are assessed and discussed. It is possible to point out that the different types of land use (forestry, nature conservation, water management and hydropower) within a river and its adjacent floodplain can only be brought together by an optimized control of the restoration measures themselves. The possibilities and constraints of an optimum discharge control, the major objective of this research, are discussed.

Zusammenfassung: Im Rahmen von Renaturierungsprojekten in Auen kommt der Reaktivierung der Wasserstandsdynamik eine entscheidende Bedeutung zu. Nicht selten werden Altarme wieder angeschlossen oder ehemalige Flutrinnen wieder mit Wasser versorgt. Dies kann z.B. durch Absenkung von Überlaufschwellen, Dammschlitzungen oder Aufweitung von Durchlässen erfolgen. In Gebieten mit hoher Siedlungsdichte und diversen Nutzungsinteressen kann die Aue über steuerbare Bauwerke wieder an den Fluss gekoppelt werden. Wie wichtig das Management von Abflüssen bei steuerbaren Ausleitungsmengen ist, zeigt der vorliegende Beitrag. Hierbei werden über die Interpretation von Wasserstandsganglinien und Grundwasserständen an unterschiedlichen Auengewässern und über eine flächenhafte Kartierung von Überflutungsflächen mit GPS erste Rückschlüsse auf die Funktionalität und Effektivität von den im Untersuchungsgebiet der südlichen Donauauen zwischen Neuburg und Ingolstadt durchgeführten Renaturierungsmaßnahmen gezogen. Dabei zeigt sich, dass sich die vielfältigen konkurrierenden Nutzungen (Forstwirtschaft, Naturschutz, Wasserwirtschaft und Energieerzeugung aus Wasserkraft) an einem Fluss und seiner angrenzenden Aue nur durch eine optimierte Steuerung der Renaturierungsmaßnahmen vereinen lassen. Die Möglichkeiten und Beschränkungen einer optimalen Steuerung des Abflusses, das wesentliche Ziel der Untersuchung, werden beschrieben.

Keywords: River restoration, floodplain, ecological flooding events, hydrology, monitoring, Danube, Germany

1 Introduction

The Water Framework Directive sets the ambitious goal of attaining ‘good status‘ for Europe’s rivers by 2015. According to the German National Strategy on Biological Diversity rivers and their floodplains and alluvial meadows will be protected in their function as an environment (also for human) and the typical variety of nature-like landscape in Germany will be guaranteed by 2020 (BMU 2007). Measures to restore rivers and floodplains will play a key role in the future development of inland water habitats; measures of this kind are enhanced in the implementation of the Water Framework Directive as well (Lüderitz and Jüpner 2009; BMU 2010). This can only be achieved if floods, varying groundwater levels, stream stage and last but not least riverbed dynamics are regarded as natural processes in water courses and their floodplains. They are elementary components of these ecosystems (Bunn and Arthington 2002; Jacobson and Faust 2014).

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Hydrology is one of the key factors determining the type and function of floodplains and thus alternating water levels are the driver of riparian ecosystems. Fluctuation of water and groundwater levels and particularly flood events affect and support the development and growth of typical fauna and flora on a floodplain. All water bodies there (oxbows, floodplain ponds, backwaters and branches) have for the most part a surface or subsurface hydraulic connection. Seasonal or episodical inundations are an essential requirement of maintaining the function of rivers and conserving the sediment dynamics in the river channel itself and its associated floodplain. This natural dynamics creates gravel and sand bars in the channel; deposits of fine sediment load along rivers renew sediments and soils in floodplains and thus fresh habitats are generated. The two overarching regulative factors of channel morphology and floodplain are sediment and water.

These dynamics, triggered by water, turns floodplains into hotspots of biodiversity (Tockner et al. 2000; Ward et al. 2002; Thorp et al. 2006). This complexity is due to the interaction between several processes, which operate at different spatial and temporal scales between different compartments. For example, alternating discharge and flood events create a shifting mosaic of aquatic, semiaquatic and terrestrial habitats that are spatially and temporarily connected. On the very same spot the living conditions can change rapidly from beneficial to life-threatening. Under certain circumstances on a floodplain two varying 'states' of the same place can show bigger differences than two different neighbouring places (Dörfer 2000).

More than in other ecosystems processes and effects in floodplains are determined by their interaction, both with each other and with the surrounding areas (Tockner et al. 1998). In the past, several river corrections were made, which disturbed the natural linkage of the river and its floodplain. This loss of interaction is most frequently conceptualized as connectivity (Amoros and Bornette 2002). The four dimensions of hydrological connectivity can be distinguished in: longitudinal, lateral, vertical and temporal connectivity (Ward 1989; Wiens 2002; Kondolf et al. 2006). For the aspects discussed in this paper all four dimensions are important. Longitudinal connection which links hydrology, geomorphic processes and morphology along the length of a river is described by the River Continuum Concept (Vannote et al. 1980). The lateral aspect is characterized by permanent and/or episodic linkages between the river or stream and the various associated waterbodies located on the floodplain. The Flood Pulse Concept (Junk et al. 1989; Junk and Wantzen 2004) focuses on the lateral exchange of water, nutrients and organisms between the main river and its floodplain especially through recurring inundations and possible periods of droughts. Tockner et al. (2000) made the next step forward in the concept. They suggested extending the Flood Pulse Concept to temperate areas and taking into account the pulsing of river discharge below overbank flow ('flow pulse' versus 'flood pulse') as well as the processes that determine the degree of hydrological connectivity. The vertical connectivity includes exchanges between the surface and groundwater via infiltration or exfiltration, depending on water levels mostly in the main river (Gibert et al. 1990; Kondolf et al. 2006), but also in a dominant bypass or tributary like in this project. The 'Hyporheic Corridor Concept' of Stanford and Ward (1993) integrates the ground water into the ecology of river systems, while it highlights the significance of interplay between river floodplain and ground water variation. The three-dimensional effect of the water, i.e. the river (longitudinal), the floodplain (lateral) and groundwater (vertical) is extended by the temporal dimension. This contribution focuses on the short term changes particularly during diverse restoration measures, in our case the most powerful ones being 'ecological floodings', controlled floods of up to 30 m^3/s of water. During an 'ecological flooding' the floodplain receives a controlled water supply via a sluice. The water is mainly led along the stream Ottheinrichbach and inundates the floodplain partly (cf. Fig. 1).

In Germany the floodplains of the larger rivers (Rhine, Danube) have lost on average two-thirds of their former dimension and in many reaches about 80 to 90% of their original extent. Even the remaining active floodplains, which more or less have retained their dynamics, are often under agricultural use (28%) or lost their habitat function otherwise. The status report on German floodplains shows that only 0.1% to 0.2% of the former geomorphologic floodplain is currently covered by near-nature floodplain forest (Brunotte et al. 2009). The need to restore rivers or streams as a part of the landscape is generally accepted. However monitoring programs are rare because common evaluation methods are still under development (Stewardson et al. 2004; Kondolf et al. 2007; Scholz et al. 2009) and 'highly political'. Different objectives require different evaluation methods and the establishment of consistent criteria for success (Poff et al. 2003; Baker and Eckerberg 2013).

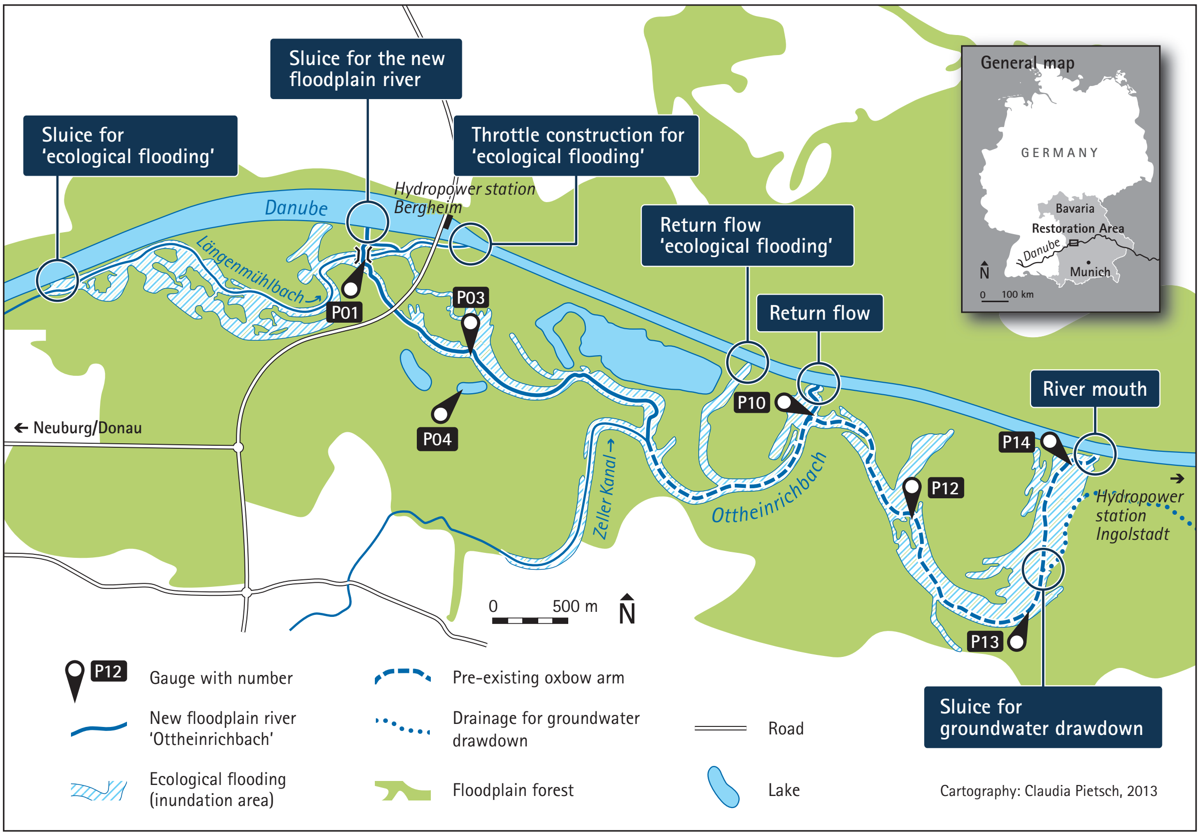

Fig. 1: Simplified map of the project area and location of the restoration measures (new floodplain river, sluices for ecological flooding and forecast inundation area, groundwater drawdown) and selected stream gauges

When dammed-up rivers are reconstructed, it is of great importance to keep in mind the reaction time of rivers to changes in their environment (Wilcock 2012). Therefore, the understanding of the channel evolution is indispensable. Rivers and their surrounding floodplains can only be restored or revitalized when the hydrological and geomorphological dynamics are considered (Sear 1994; Kondolf 1998; Schiemer et al. 1999; Wiens 2002). In the worst case ineffectiveness, failures and great expenses, like Snyder (2012) already mentioned, can occur with unreflecting channel reconstruction. Successful floodplain restoration involves linking the activities and knowledge of all participants and stakeholders (Stewardson et al. 2004; Palmer et al. 2005). One of the challenges of an inter-disciplinary restoration experiment and monitoring project like MONDAU (see below) is combining all the different views and opinions and transferring the results into one target course for a sustainable development of the project.

Many different factors have to be considered, when floodplain restorations are implemented. One main focus of this study is the question of how many and of what kind of factors, from a hydrological point of view, should be considered. Especially the controllable discharge of the new floodplain river is a sensitive tool either for floodplain dynamics or stakeholders' interests. The aim of this contribution is to detect the interaction of hydrological components and analyse the success and the spatial dimension of effects of the restoration measures. Insufficient water means insufficient dynamics on the floodplain. On the other hand, too much water could cause damages for the several stakeholders, first of all for land owners and forestry. The main question is: 'How many water is necessary on the floodplain' to bring back former ecosystem functions? Considering the special combination of restoration measures there are no experiences from other projects and there is no knowledge about short and long term changes in floodplain ecosystems in response to these/comparable management actions.

2 Restoration and monitoring

Within the framework of the restoration project 'Dynamic Development of Danube Wetlands between Neuburg and Ingolstadt' on the Upper

Danube (funded by the Free State of Bavaria and implemented by the Bavarian State Office for Water Management Ingolstadt) eight working groups of different scientific disciplines have been working on a large monitoring project ('MOnitoring DonauAUen', MONDAU), funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Stammel et al. 2012). They investigate the changes evoked by the restoration measures which were designed to bring back new dynamics to the floodplain and to reconnect it with the Danube in order to optimize floodplain ecological functioning (Cyffka and Haas 2008; Stammel et al. 2012).

In particular the control of the hydrologic variables and their effects on the biotic system, especially on the role of development of habitats, are part of subproject II „Fluvial Morphodynamics, Soil Moisture and Groundwater". These complex interrelations take place at different spatial and time scales, from short term response during single floods to long term response of the seasonal flow conditions. The effects can range from single unconnected pools up to large inundated areas on the floodplain during floods.

2.1 Project area

The study site is located on the right side of the Upper Danube River reach (between river kilometre 2473 to 2464, 48°45' N, 11°16' E) with a catchment area of approx. 20,000 km^2 (which refers to the gauging station Ingolstadt), and is situated in the south of Germany (Bavaria) between Neuburg a. d. Donau and Ingolstadt (Fig. 1). The project area with the riparian forest is 1,200 ha of size. A high biodiversity has been detected by WWF (1997) and Margraf (2005).

The river regulation in combination with intensive hydropower utilization affects strongly the conditions of the Danube (BMU and BfN 2009). Also the floodplain between Neuburg and Ingolstadt has severely been influenced by the river straightening during the 19th century and the construction of two hydropower dams in the 1970s and was widely disconnected from the hydrologic dynamics of the stream. The typical self-development of the Danube river bed is prevented or at least decisively limited (Schlegel 2000). The nowadays monotonous channel structure and standardized flow conditions have led from a formerly dynamic to rather a stable and well-balanced situation.

2.2 Hydrological characteristics

The discharge regime of the Danube is considerably marked by the first two main tributaries (river Iller with 54.5 m^3/s, gauge Wiblingen and river Lech 114 m^3/s, gauge Augsburg (mean annual discharge) (HND 2013). An effect that overlays the natural regime is the linking of all transverse structures and the hydropower dams which regulate the discharge in all three rivers (Iller, Lech, Danube) and therefore the flow conditions in the bypass 'Ottheinrichbach' as well. The regulation starts at the reservoir 'Forggensee' of the river Lech which is 178 river kilometres upstream, and continues with 44 transverse structures between the outlet sluice and Bergheim hydropower station.

2.3 Restoration measures and water management

The hydrological conditions in the research area are influenced by (a) structures like sluices and bridges and (b) the management of the water volume. The three main restoration measures are:

- the creation of a permanent bypass river called 'Ottheinrichbach' with a discharge from 0.5 up to 5 m^3/s (discharge adapted to the Danube, but controlled by a sluice, no overflow sills) .Within the first 2.5 km a complete new nature-like channel was carved into the alluvial sediments. The following 6 km the river uses pre-existing water bodies like former oxbows.
- 'ecological floodings' (discharge of up to 30 m^3/s, equally controlled by a sluice, depending on a peak discharge of the Danube of 600–1000 m^3/s (see Tab. 1).
- groundwater drawdown in the eastern project area during low water conditions (Danube runoff <150 m^3/s). A sluice (Fig. 1) in combination with flash board weirs and a diversion trench allows a lowering of the groundwater level to amplify the hydrological dynamics.

Some more detailed description of the whole restoration project, management and monitoring programme is made by Cyffka and Haas (2008), Stammel et al. (2012) and Fischer et al. (2012). However, all measures and outlet sluices, in particular the regulation of discharge is attached to prerequisites which arise from different forms of land use (hydro power and forestry) and official requirements.

Tab. 1: General hydrological characteristics of the Upper Danube between Neuburg and Ingolstadt (gauge Ingolstadt, cf. HND 2013) and of the new bypass 'Ottheinrichbach' with its floodplain

Danube	
Watershed	20,000 km^2
River kilometre	2,457.80 km
Mean discharge (annual)(1924-2008)	
MNQ (low water)	130 m^3/s
MQ (mean)	285 m^3/s
MHQ (high water)	920 m^3/s
HQ1	1,000 m^3/s
HQ5	1,320 m^3/s
Start/end point (min) ecological flood	600 m3/s
End point (max) ecological flood	1,000 m^3/s
Start/end point (min) groundwater drawdown	150 m^3/s
Ottheinrichbach	
Floodplain and project area	1,200 ha
River length (total)	8.4 km
Mean discharge (2010-2012)	3.1 m^3/s
Mean depth (new constructed reach)	74.4 cm

The following are to be mentioned:

a) The Danube discharge up to 550 m^3/s is used for power generation at the hydropower plant Bergheim, so ecological flooding begins from more than 600 m^3/s.
b) Generally regulated Danube runoff via all dams including the tributaries.
c) Restrictions because of hunting (less water during hunting season).
d) Streets, dirt roads and bridges fix the water course or disconnect old channels. The maximum volume of water is limited by some bridges as well.
e) Legal regulations for flood protection.
f) All sluices are controlled. The sluice for ecological flooding is controlled by semiautomatic operation due to liability issues.

All these constraints are considered by a planning permission and this decision fixes the discharge regulation as already pointed out.

3 Methods/field measurements

In highly dynamic environments the monitoring requires a degree of flexibility. On the one hand, it is common to use a huge number of methods and tools which vary accordingly to the objects and scale. On the other hand, if it is necessary you combine this or change practice during a survey. Even actually fix gauging stations or cross section poles must sometime move in high dynamic systems. Therefore, a 'dynamic method mix' is used (Fischer and Cyffka 2013) to monitor the hydrological conditions in the channels and on the floodplain itself (cf. Tab. 2).

Due to the complexity of the river and floodplain interconnections and the constraints specific to the project design (variable runoff, artificial bifurcation and confluence, drainage for groundwater drawdown and other structural measures), a large number of water level gauging stations is necessary to document the variations in a satisfactory manner. To develop a sufficient understanding for the hydrological processes es-

Tab. 2: Objects, expectations and methods of the hydrological monitoring programme

Objects	Expectations	Methods/Tools	Log interval	Number
surface water				
stream gauge (new floodplain river)	increase of water levels in the bypass river up to a mean flow	stream gauges (pressure transducer) provide accurate measurements of water levels and temperature,	15 min	12
lake level	increase of lake levels	loggers measure lake level stages and temperature	15 min	2
stream gauge (new floodplain river, Längenmühlbach and Zeller Kanal)	increase of water levels in rivers, with strong regionally depending stages	loggers from external operators	15 min–3 hours	12
stream gauge (Danube)	no changes, depending from the runoff regime and impoundment	high temporal resolution measurements at the barrages Bergheim and Ingolstadt from the hydro-power company and 2 further gauging stations (water authority)	30 sec.	4
water gauge (various floodplain water bodies, like side arms, oxbows and temporarily inundated areas)	increase and decrease of water levels in all flood-plain waterbodies	mobile measuring poles at selected sites with dataloggers used during ecological flood events or groundwater draw-down	15 min	about 30
groundwater				
groundwater level	rise and fluctuation of groundwater level	gauging stations from external operators	3 hours	16
groundwater level	rise and fluctuation of groundwater level	groundwater level gauge and temperature	15 min–1 hour	9
discharge and velocity	increase of variability in discharge and mean velocity (from 0.05 to >~1.5 m/s)	discharge and velocity measurements at selected sites and event-related with a flow meter	–	119
		with salt tracer dilution	–	3
		with a Qliner during the 9th flood event by the water authority	–	5
inundation area	increase of regularly flooded areas according to the forecast areas	GPS mapping during and after the event Aerial photos with an UAV and GIS mapping	–	during and after every flood event

pecially during flood events, neither inspections in a clearly separated space (one water body or river segment), nor snapshots are enough. With a specially designed high resolution water-level network (altogether 85 gauging stations, see Tab. 2) the dynamics within riparian habitats can be analysed properly. For example: according to events (flooding or groundwater drawdown) mobile pressure sensors at measuring poles are distributed at special sites in the project area. This is an effectual expanding of the water level network, because the data loggers can be distributed and collected before and after an event and can be inserted according to the measure where they are most needed. Large scale mapping by a drone (unmanned aerial vehicle, UAV), and field mapping at the mesoscale with tablet PC and GPS/dGPS during and after flood events, identified the flooding areas as well. Further methods such as velocity and discharge measurements complete the hydrological research work.

4 Results

Since the first startup of the Ottheinrichbach on 29 June 2010 nine ecological flood events and two groundwater drawdowns took place. The monitoring results document high variability in hydrological processes, especially during flood events. In table 3 some facts about the flood events are listed, only two of them took longer than 4 days.

4.1 Stationary gauges in the floodplain river

The selected hydrographs shows the dynamic in the river (cf. Fig. 2) and the floodplain waterbodies (cf. Fig. 3, 4). Natural small floods (from 700 m³ up to 900 m³ discharge in the Danube) like the floods during the third quarter of 2010 as well as human driven flow changes released by hydraulic engineering or scientific investigations, can be read from the hydrographs in Figure 2. Some of the most striking events are marked by arrows and show the reaction of the water level to the performed changes. The bottom line recorded at gauge P14 corresponds to the Danube water level (218 meters to the river mouth) and is clearly influenced by hydropeaking and backwater dynamics of the Ingolstadt hydropower dam. Only a high-temporal resolution of every single graph can show the real conditions at the relevant spot and deliver important knowledge for the fine tuning of the discharge amounts and the hydrologic connectivity.

4.2 Mobile gauges in oxbows and temporary waterbodies

Figure 3 shows the water level curves of the mobile gauges for the period of the 7th ecological flood event (from 23.12.2012 to 27.12.2012). The increase of water level (a) as well as the maximum amplitude could be clearly observed. The

Tab. 3: Ecological flood events since the beginning of the monitoring programme and peak discharge for gauge Neuburg (HND 2013) (for a detailed description of the level classifications see Fischer and Cyffka (2013)

Ecological flood	Date	Duration [hours]	Peak discharge [m³/s]	Volume of water [m³]	Level
EF 1	20.07.–21.07.2011	23.5	710	1,269,000	1
EF 2	23.01.–25.01.2012	52.5	910	4,734,000	2
EF 3	13.06.–14.06.2012	19.75	700	1,737,000	1
EF 4	10.10.–11.10.2012	31.0	770	3,240,000	2
EF 5	17.12.2012	4.0	600	432,000	1
EF 6	18.12.2012	20.0	620	2,160,000	1
EF 7	23.12.–27.12.2012	97.5	825	10,530,000	3
EF 8	06.01.–08.01.2013	21.0	770	2,268,000	1
EF 9	04.02.–07.02.2013	98.0	910	10,584,000	3

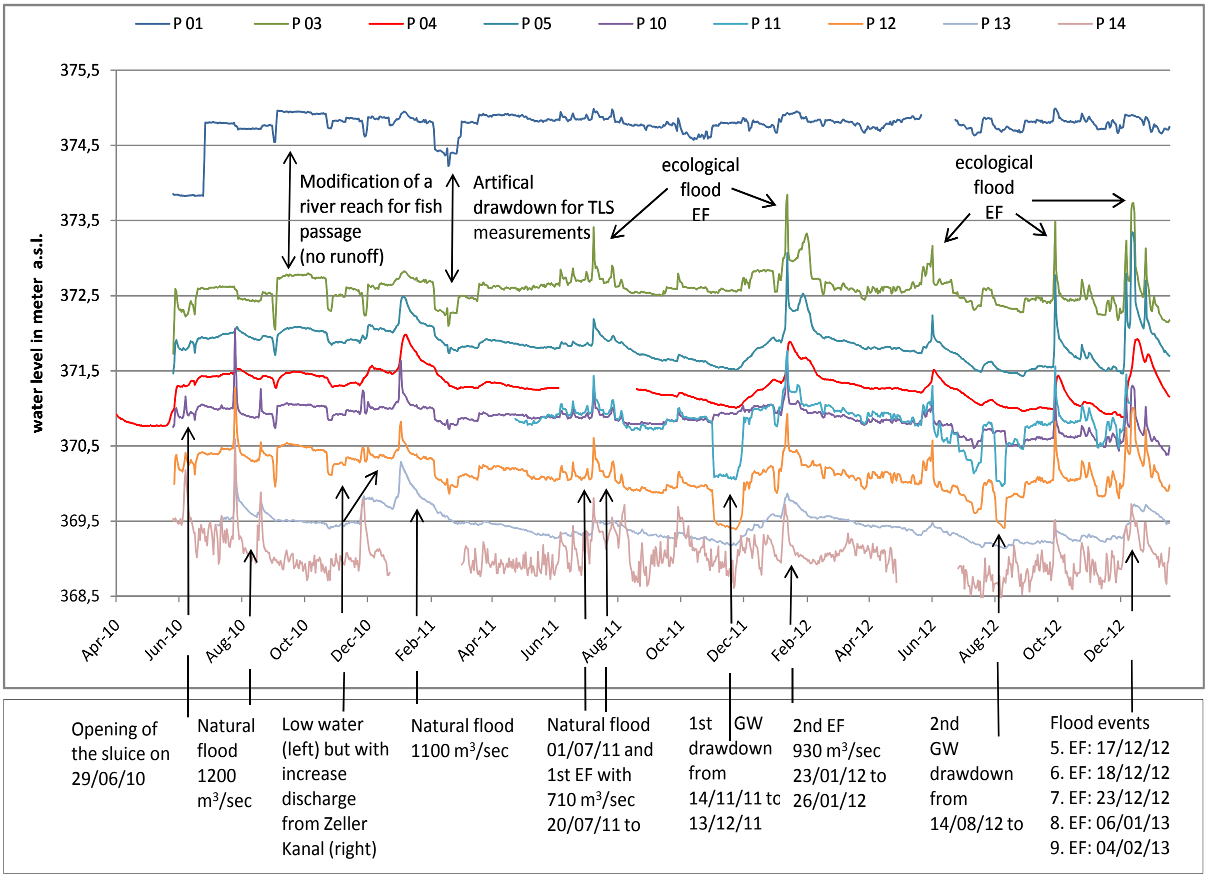

Fig. 2: Stream stages at selected gauging stations (location cf. Fig. 1) in the new floodplain river and a lake-level hydrograph (red line, P04) (April 2010 to January 2013). Water-level hydrographs show differences and commonalities along the river course. Variations are clearly visible, e.g. rise due to natural or ecological floodings or declines due to groundwater drawdown

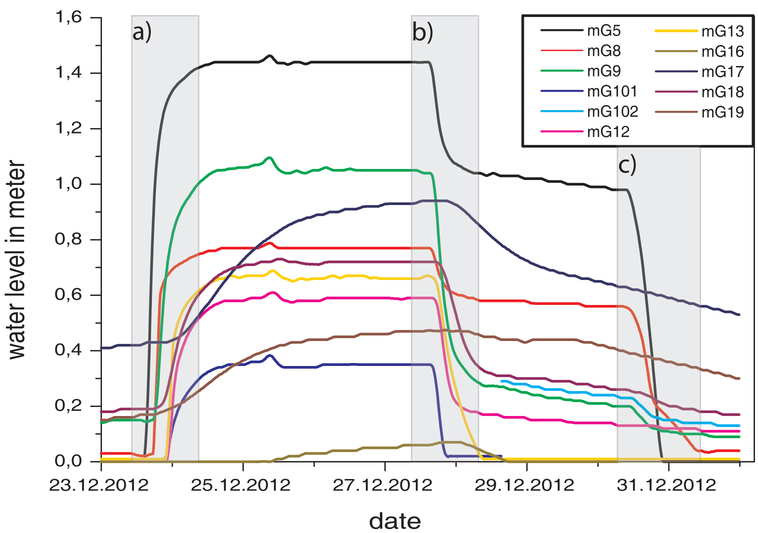

Fig. 3: Hydrographs of mobile water gauges during the period of the 7th ecological flooding from 23.12.–31.12.12. By moving the mobile gauge 10(1) towards another site 10(2) at the end of the ecological flooding ('dynamic method mix') more information about the water level changes could be gained, because an extended time period of recording is granted at the new location

closing of the sluice after the Danube water level decreased under 600 m^3/s on 27th of December at 15:30 pm (b) is visible and also a further decline (c) after opening the throttle construction on 30th of December at 11:00 am (see Fig. 1) in the Längenmühlbach river. The plateau phase from 24th of December 2012 to 27th of December 2012 shows that the water level would not become higher regardless of the duration of the flooding. The water levels cannot rise because they are limited on the one hand by the available water volume of just 30 m^3/s and on the other hand by the Danube stream stage itself (cf. Fig. 7). It can be derived that the duration of the event has no effect on an extension of the inundation area within the current structural design, the relief situation and the control configuration. The management of the buildings and the reaction of the water levels can again be read in the listed graphs (cf. Fig. 3). The reaction of gauges towards surface water (directly) or water in flood channels that are connected to the bypass Ottheinrichbach is clearly visible. Typical for gauges at these places is the quick and immediate reaction to the flood as well as to the control of the discharge amounts which are regulated by the sluice. Examples for these gauge locations are number 5, 8 and 9 (Fig. 2 and 5). Gauges only indirectly bound to the Ottheinrichbach react with a time lag e.g. in backwater areas, cf. gauge 18, or by rushing out water in depressions, cf. gauge 17 or 19 (cf. Fig. 3, 4 and 6).

The combination of groundwater drawdown and ecological flooding leads to a fluctuation of water levels of up to 1.32 m respectively 0.30 m (see Fig. 4). Depending on the location values of over 1.70 m can be recorded. The second groundwater drawdown at gauge E with an amplitude of 0.62 m shows that also in the backwater system a high surface hydrologic connectivity exists. The disconnected waterbodies (plesio- and paleopotamon) according to the typology formulated by Amoros et al. (1987) show a similar reaction (cf. gauge A and D).

4.3 Groundwater gauges

Groundwater level changes of all 9 groundwater gauges (GWG) from 2007 to 2012 are shown in figure 5. The amplitude of the groundwater level changes during the measuring period is about 2.04 m (mean

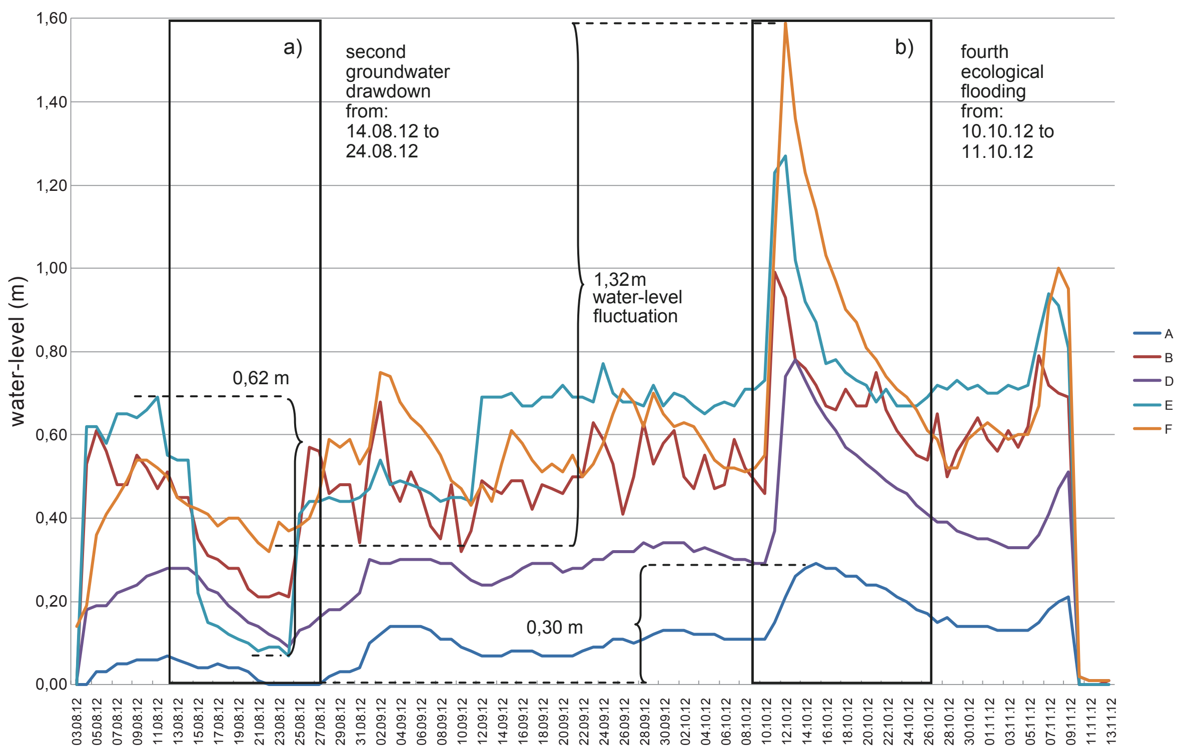

Fig. 4: Hydrographs (daily mean) of the mobile water gauges for the second groundwater drawdown (a) and the fourth ecological flooding (b)

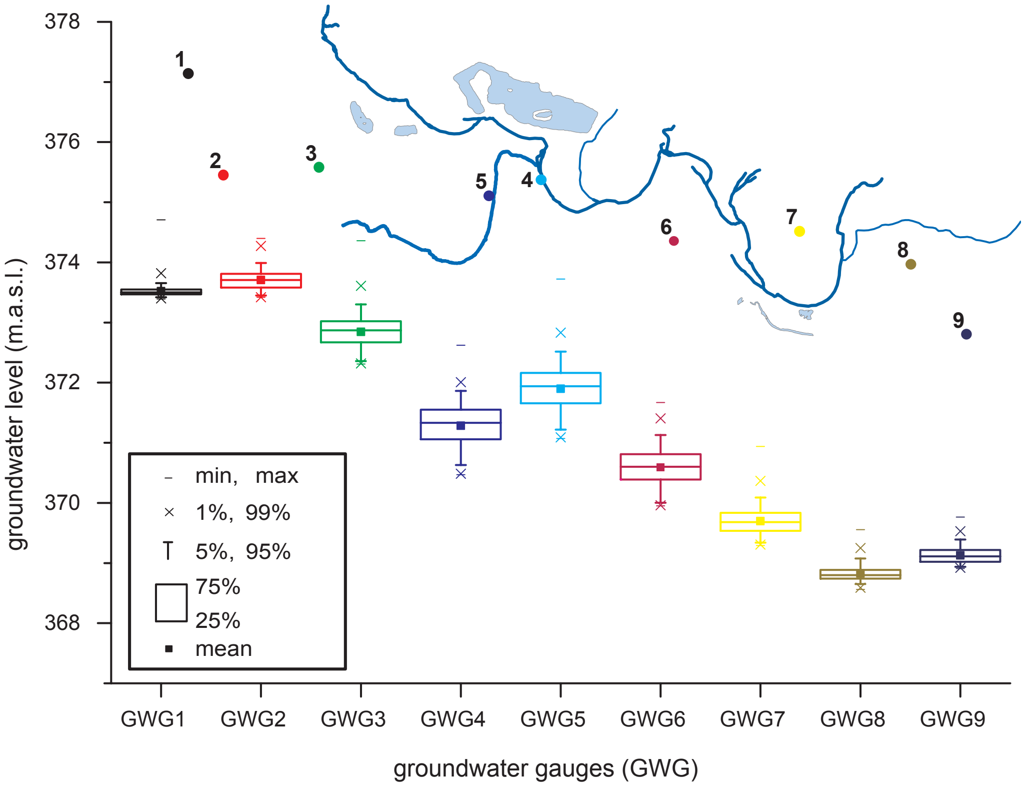

Fig. 5: Groundwater level changes in the riparian forest (measuring period 2007–2012) and location of gauging stations. GWG Nr. 4 with 10 m is very close to the new bypass river. Data source: Bavarian State Office for Water Management Ingolstadt

value) for the stations, which are close to the bypass river (GWG 3-7) and 1.03 m for the rest in the east or west part of the project area. The highest groundwater levels before the restoration measures were implemented were recorded in March and April, the lowest in October. With the opening of the bypass river in June 2010 a fundamental shift to higher levels took place. The maximum value in the measuring period from 2007–2013 was recorded at GWG 4 with 372.62 m (mean: 371.28) during a natural flood in January 2011. Nowadays the ecological floods generate the peaks with just approx. 20 cm less than the maximum peak in 2011, e.g. during the second flood in January 2012 with 372.43 m.

The GWG 3-6, the locations with the smallest distance to the new bypass river show the biggest variations with amplitudes up to 2.65 m (GWG 5), while at GWG 7 with 1.0 m less, the influence of the restoration measures subsides quite clearly. With increasing distance the groundwater oscillation declines to 0.85 m recorded at GWG 9.

From April to November the groundwater levels decrease in the floodplain to a minimum state. The minimum groundwater level of 370.48 m in the late autumn 2008 recorded at GWG 4 is about 1 m less than in 2011 with 371.30 m or 2012 with 371.00 m (increase of groundwater level, due to the restoration measures).

4.4 GPS mapping of inundation areas

With GPS and dGPS mappings carried out so far, the changes triggered by the measures can be captured and documented. Particularly in the zones with changing water levels, where water discharge variations are clearly visible, the expansion of the inundation area could be mapped. For the project area the expansion of the flood surfaces can be estimated very well (Fig. 6). To this day, all 'ecological floodings' that took place have stayed behind the forecast of about 138 ha of inundated area. Up to now just 86 ha could be reached, but for successful floodplain restoration a wide-area inundation is necessary.

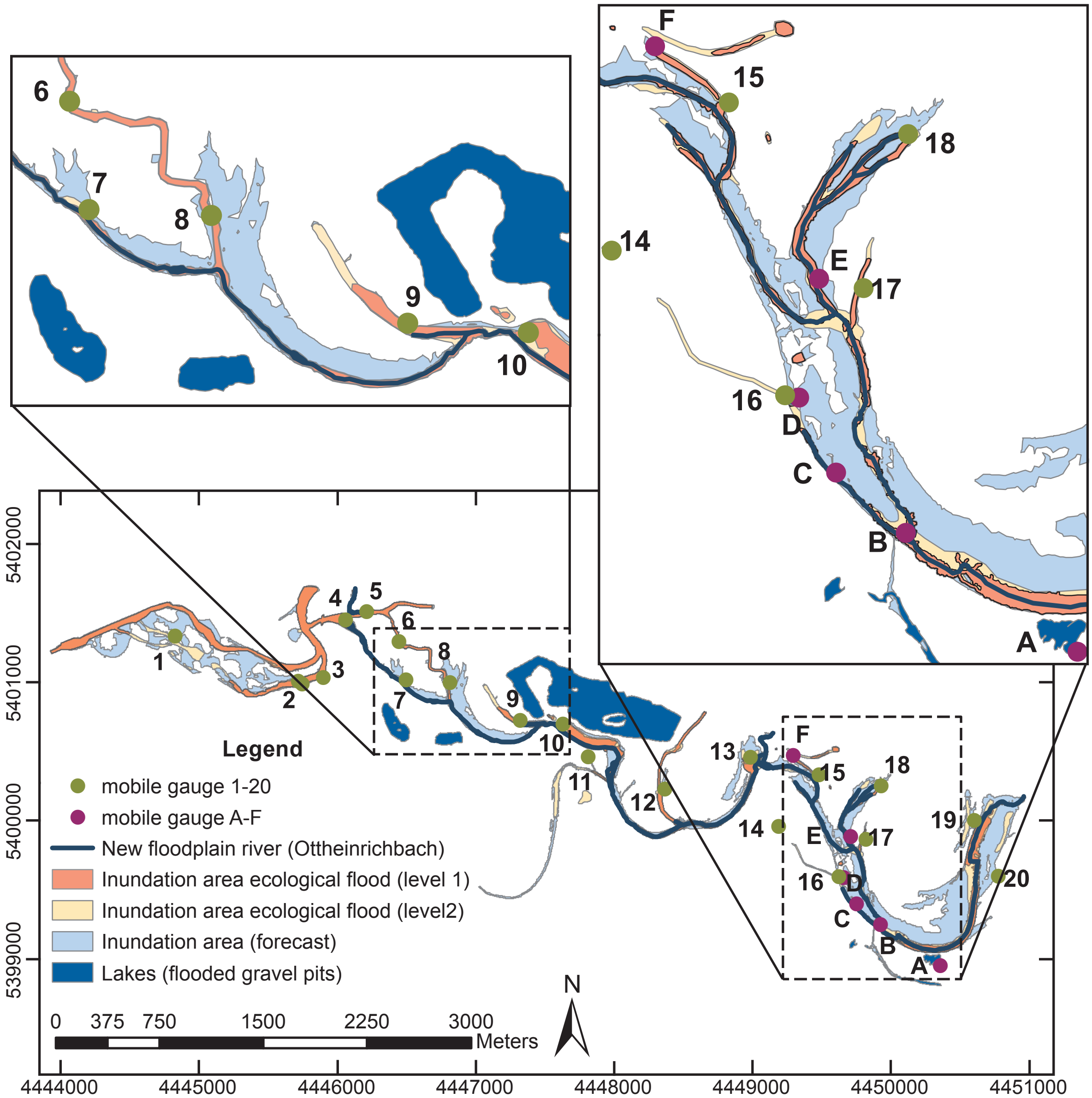

Fig. 6: Inundation area during ecological flood events (level 1 and 2, see Tab. 3) and distribution of mobile gauges. Note the differences between forecast and mapped extent of the inundation area

5 Discussion

Our first results show some interesting facts related to the restoration measures and differences between natural flood events and controlled ecological floodings. Under natural conditions, high discharges overtop the river banks and inundate widespread areas of the surroundings along the river course. However, all ecological floodings so far have stayed more or less inside the bed of the bypass river. Only at a few points an overtopping has happened (cf. Fig. 6). One reason for small flooded areas is the water loss in and through the gravel beneath the streambed into the groundwater, detected at several gauges. In coarse alluvial deposits the exfiltration of water can influence the water regime distinctively (Winter et al. 1999; Gröngröft et al. 2000; Hancock et al. 2005). Discharge measurements during flood events show a decrease of the runoff in the bypass along the water course (Fischer et al. 2012). The exfiltration in the hyporheic zone and the surrounding area is visible most clearly in figure 2 at P04, where a lake level change can be detected at a small lake (with a distance of approx. 75 m from the new water course) after opening the new floodplain river and as well during all other stream breathings. Only some hours after opening the sluice for the very first time the lake level hydrograph rose up to an approx. 0.55 m higher new mean water level. Similar water level increase could be documented in polder systems (LfU and GWD 1999) and during flood events (Heiler et al. 1995; Scholz et al 2009). The other way round, during low stream stages the lake levels decline. Van Geest et al. (2005) show that lake level fluctuations during non-flood conditions also are largely driven by groundwater connection to the main channel. The bypass river is in close hydraulic contact with the surrounding groundwater through well water-permeable gravel bodies (fluvio-glacial sediments) what could be already documented by mobile gauges. The groundwater in the adjoining floodplain is also influenced by the partly fluctuating water levels (Gibert et al. 1990; Kondolf et al. 2006) and the distance to the main channel (Heiler et al. 1995; Van Geest et al. 2005). At locations particularly influenced by the variable water levels, the discharge in the Ottheinrichbach leads to a strongly variable groundwater table and it shows a good connectivity. The groundwater fluctuations can be restored by the measures, but stay behind the dynamics before regulation and barrage construction (Schlegel 2000). Wide areas are only influenced by groundwater, without surface water contact. Another reason for the slight overtopping is the limited water volume (30 m³/s) and the short duration of the flood events themselves (Tab. 3). Also not negligible is that water inflow occurs just at one point.

At least the decisive limiting factor is the water level in the Danube (see Fig. 7). Decreases in duration of inundation caused by water-level decline in a river are well described by Light et al. (2006). In addition, hydrologic connections between river and backwaters become shorter and less frequent when river stages are lowered by incision (Shields et al. 2009). As a consequence, quantity and quality of floodplain habitats have degraded, and riparian forests are changing in response to drier conditions. As Light et al. (2006) correctly described, water-level decline caused by channel change is probably the most serious anthropogenic impact. The same has also occurred on the Danube river and its floodplain. All the water bodies, either surface water or ephemeral groundwater-fed ones are connected with the Danube. If the stream stage is too low, the Danube acts like a drainage and sucks all water out of the floodplain area. The lower the water level in the Danube, the more serious the situation is. Hence, if the water level in the Danube is lower than about 850 m³/s, no 'real' backwater dynamics are possible and all the water passing the sluice gate runs through the bypass river as bankfull or sub-bankfull flow and returns into the Danube. The flow is dependent on connectivity with the main river channel (Lizotte et al. 2012) and essential for the viability of the populations of floodplain species (Bunn and Arthington 2002). However, the impacts (on water quality and ecological status) of increased connectivity on floodplain backwaters are not well understood so far (Acreman et al. 2007).

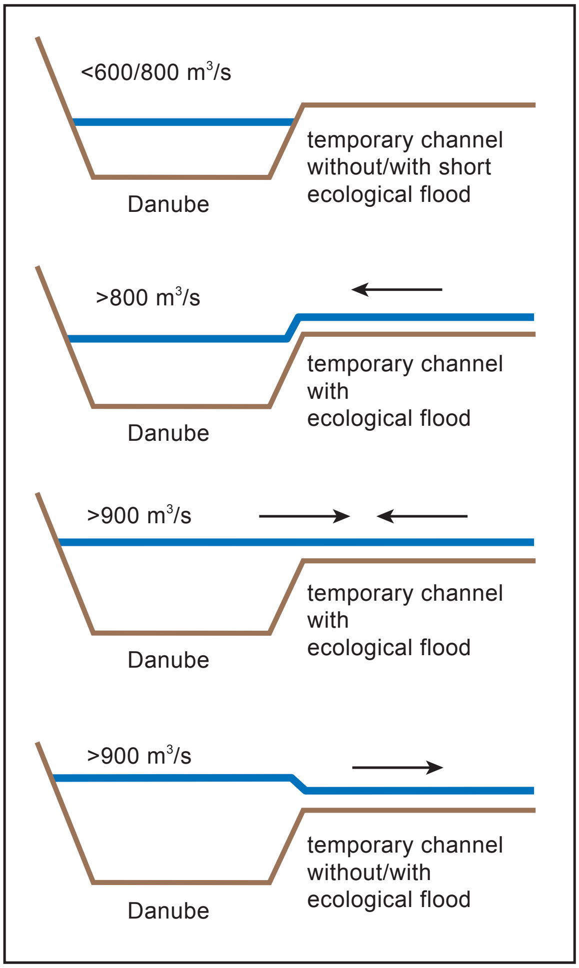

Fig 7: Schematic illustration of the different stream stages in the Danube and linkages (modes of hydrological connectivity) with the floodplain at the 'return flow 'ecological floodings' (see Fig. 1.). Very similar conditions can be assumed for the other return flow and the river mouth

Nevertheless, to achieve the maximum ecological benefit it requires an adjusted control within the scope of the given range, i.e. to generate an optimum discharge for nature-like ecosystem functions in time, duration, frequency and magnitude by controlling the sluice gates without an economic and water law infringement. For this reason, different control options should be given for all three sluice buildings ('ecological flooding'), new floodplain river and groundwater drawdown, see figure 1. Different ways of controlling and water management have to be tested before guidelines can be established. In some cases intrinsic ecosystem characteristics can cause problems in setting up these control options. Depending on the target species (aquatic or terrestrial) the regulation is particularly contradictory (Tockner et al. 1998; Amoros and Bornette 2002). Thus, for fish a specific minimum water level must remain in the channel, so that neither water shortages originate nor shallow areas in the spawning grounds dry out. In contrast to this, some botanical species, well adapted to changing water levels like softwood species and others require intermittent lower water levels. The present project and management programme is based on the axiom to restore and keep ecological processes (Tockner et al. 1998; Kondolf et al. 2006) not to support target species. So, for us it is very important to learn more about the hydrological connectivity and the effects of various regulated water levels on flora and fauna.

The basic requirements for a natural development of the new water course have thus far been created by the technical restoration measures in the Danube floodplain. At most places along the new water course typical processes for rivers and the important discharge variations and even groundwater fluctuations could equally be initiated. But for a comprehensive floodplain restoration it seems to be too little water. The dynamics of water levels and discharge variations which are crucial for a near-natural floodplain development (Amoros and Bornette 2002) can only be reached for the Ottheinrichbach and surrounding areas. All three measures, especially in combination, create more dynamic in water level fluctuations than one measure alone.

In combination with the limiting factor, the regulated water level in the receiving water, no backwater dynamics and adequate hydrologic connectivity is possible. Sub-bankfull flow in a new water course which is carved into the recent floodplain can only reach the surroundings, deposition of fine sediments and nutrients does not take place. If a near to nature water course, with changing water levels is built, parameters like precipitation or discharge of uncontrolled rivers in the catchment area or a goal-oriented runoff management by ecological requirements should be of paramount importance. The investigations show that a better understanding of the interplay of groundwater and surface-water in combination with geomorphological processes of the floodplain is needed especially by restoration projects with controllable water volumes. The very limited practical experience in restoring floodplains in the described way necessitates a stepwise approach for discharge regulation.

6 Conclusion and implications for river restoration

It may be concluded that it is not so easy to restore floodplains along regulated rivers just with some technical measures and a bit of water. Successful floodplain restoration needs some more efforts especially when several stakeholder interests and other non-ecological factors (Palmer et al. 2005) have to be considered. Especially the controllable discharge of new bypass rivers is a sensitive and disputable tool. If we know at what time how much water is necessary to bring back former dynamic and allow the restored or new river to be a resilient self-sustainable system, it would be much easier to find the best discharge control for involved parties and at least for floodplain communities. But, at this stage of knowledge, it is not possible to give a universal declaration for man-controlled amount of water in case of floodplain restoration because they are always site-specific and fundamental principles should be considered:

- The more non-natural the discharge regime is and the more hydraulic engineering measures are used for restoration, the more important the management gets. Additional numerous claims of utilization (see chapter 3) limit wider inundation areas by a narrow framework of conditions with regard to time and water volume.
- Ecological engineering, e.g. the creation of undercut slopes, gravel bar, and dead wood structures, is not enough to revitalise ecosystems. Rather the dynamic processes leading to these structures must be promoted. This aspect, already promoted by the general implementation of the restoration project, could be supported by the monitoring results.

- Calculations and models, which were created and worked out at the planning and construction phase of restoration measures, must be adapted after a certain period of time to actually the occurred environmental changes, which are the result of the self-development of the river and its floodplain. The process of adaption is not usual along with restoration measures in Germany. Typically restoration measures are set up without monitoring and/or adaption.
- For future restoration projects with controllable sluices the water volume and its management must be seen as an important aspect for the development of floodplain habitats. This generally logical aspect becomes more important with more divers land use and conservation requirements.
- It should be considered that accomplishing the aimed increases in flood magnitude and duration will require more than just a simple increase of water volume. It's rather a question of how a better control of the sluices is possible to improve the natural conditions on the floodplain

Last but not least a comprehensive success concerning floodplain dynamics as well as nature conditions on the floodplains requires freedom of decision-making and clear communication channels to decide, 'when, how, where, and to which amount' water is available for the restoration process. Successful floodplain restoration involves comprehensive information of all participants and stakeholders.

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Authors

Peter Fischer
KU- Eichstaett-Ingolstadt
Applied Physical Geography
Aueninstitut Neuburg
Ostenstraße 18
85072 Eichstätt
Germany
peter.fischer@ku.de

Prof. Dr. Bernd Cyffka
KU- Eichstaett-Ingolstadt
Applied Physical Geography
Aueninstitut Neuburg
Ostenstraße 18
85072 Eichstätt
Germany
bernd.cyffka@ku.de