The influence of changes in flow regime caused by dam closure on channel planform evolution: insights from flume experiments

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Abstract

Constructions of dams influence river courses by cutting off sediment delivery and altering flow regime. We conducted flume experiments to study how sediment starvation, flow deficit and occurrence of series of floods with sediment load influence the evolution of channel planform. Results indicated that reduced flow caused a transition from a braided to incised single-thread planform with remains of inactive channels. The planform resembled rivers suffering from flow reduction caused by dams and constructions of irrigation canals (e.g., Central Platte River, USA). Simulation of series of floods with no sediment delivery caused the formation of an anabranching planform with incised main channel, alluvial islands, and side channels active at high flows. This evolution corresponds to river courses altered by sediment starvation and series of floods (e.g., the lower Drava River, Hungary). Floods with delivery of fines created a single-thread, incised channel with terraces along banks. Such channels are formed by rivers closed by dams, and compensating sediment deficit by sediment load from tributaries and/or floodplains (e.g., the Green River, USA). The flume tests demonstrated how flow and sediment deficit influence river channels and that the potential for restoration strongly depends on possibilities for the activation of sediment supply. However, restoration of pre-dam conditions is often impossible owing to other hydro technical works and land use changes. The highest restoration potential refers to the rivers compensating sediment delivery blocked by dams with tributary and floodplain resources.

Keywords River planform · Human impact on fluvial systems · Dam construction · Flume experiments

Introduction

What is the reason for the great diversity of river channel patterns? What are the factors that influence river channel evolution? These questions have troubled fluvial geomorphologists and river engineers for a long time, hence a large number of research studies have been devoted to this topic. Many river courses are subjected to changes in the flow magnitude, and sediment transport. These changes may be the natural features of a hydrological regime, and can

be characterized by cyclic (seasonal) character. However, in many cases such changes are caused by anthropogenic actions such as dam closure, sand mining and constructions of drainage or irrigation canals (e.g., Surian 1999; Rinaldi 2003; Horn et al. 2012; David et al. 2016; Słowik et al. 2018). Global damming of rivers resulted in changes that have no reference in the evolution of rivers in the past. Most frequent changes caused by dam closure are the reduction of flow magnitude and peak discharges, elimination of upstream sediment delivery, and bed incision (Williams and Wolman 1984; Grant et al. 2003; Pets and Gurnell 2005). These changes affect the life of communities dependent of river resources such as seasonal flooding (Nguyen et al. 2016; Latrubesse et al. 2017, 2020) and the presence of fish habitat (e.g., Pasha et al. 2015). Further dam constructions will seriously affect the life of people in developing countries (Cutler et al. 2020). Sediment starvation caused by dam closure exerted an impact on sedimentation in coasts

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and deltas (Syvitski and Kettner 2011; Kondolf et al. 2014; Nguyen et al. 2016).

Rivers were subjected to various the human-induced changes prior to dams constructions. For instance, the incision of the lower Drava River (Hungary) was started by channel straightening in the eighteenth century. This process was enhanced by dams constructions since 1958. The effect was the exposure of channel bars, which, in turn, caused vegetation encroachment, stabilization of bars and formation of alluvial islands (Kiss and Balogh 2015; Słowik et al. 2018). Rivers may react in a variety of ways to dam closure. For instance, sediment starvation caused by dam construction may be compensated by delivery from tributaries and/or valley floor and slopes [e.g., Dean and Schmidt 2013, Rio Grande (USA); Grams and Schmidt 2002 and 2005, the Green River (USA)].

Three methods are used commonly for the determination of the factors that influence river planforms evolution: (i) field surveys, (ii) numeric modelling, and (iii) laboratory experiments. Each of the methods has its own limitations and advantages. Field research allows for the collection of huge amount of data; however, the collected information may often be the record of the joint influence of a number of both natural and human-induced factors. Flume experiments are burdened by scaling issues (cf. Kleinhans et al. 2014). Certain parameters like grain size of the modeling media, cannot be scaled down. This shortcoming, however, can be partially overcome and compensated with higher slopes to increase the mobility of coarser sediment (Peakall et al. 1996; Kleinhans 2010).

Numerical modelling can be fully controlled. This limits the reality of obtained results, although, with increasing computational capacity, numerical simulations are becoming more and more useful for modelling the behavior of complex systems of river channels in large spatial and temporal scales (e.g., Nicolas et al. 2013; Schuurman and Kleinhans 2015; Yang et al. 2017; Weisscher et al. 2019).

Flume experiments are useful tools to test the influence of erosion and deposition processes on river behavior despite elimination of other factors occurring in real rivers. Laboratory tests have been applied to model channel evolution since the late 1800s. The largest flume ever built has been the downscaled replica of the Mississippi River, constructed in 1944 to support flood control planning and procedures along the river (Foster 1971). Leopold and Wolman (1957) applied a constant discharge and sediment feed to simulate the evolution of a braided stream. Struiksma et al. (1985) used curved flumes, characterized by various sinuosity and radii of curvature, to study changes in morphodynamics of bedforms and flow structure in meandering channels. Schumm and Khan (1971) analyzed the effect of slope on river pattern, then later (1972) the combined effect of slope and sediment load. They found that there is a close relationship between

slope and sediment load concentration. With low slope, river channels remain straight. With increasing slope and sediment load, the planform is transformed from straight to sinuous, and then to a braided pattern. Schumm and Khan (1972) also found that channel patterns do not change progressively but quickly when reaching a critical erosional and/or depositional thresholds. They also discovered that the presence of silts in sediments added to a river bed contributes to the formation of meanders. Hundey and Ahmore (2009) used constant flow, sediment feed and slope to determine relations between channel width and the formation of confluences, bifurcations and channel bars in braided rivers. Van Dijk et al. (2012, 2013) transversely moved the inlet point and added fines (silt-sized silica flour) to the flume to simulate conditions necessary for the formation of meanders and cut-offs. Their flume tests allowed for determining the influence of upstream flow perturbations and delivery of fines on the formation of an actively migrating meandering planform. They demonstrated that vegetation is not an essential factor on the formation of meandering rivers. Métivier et al. (2016) found that river channels widen due to increased sediment transport. When the channel reaches a given threshold width it is transformed into an unstable braided river.

Recent studies used close range photogrammetry for the monitoring of morphological changes during flume experiments, including the simulation of forming floodplain sedimentary architecture (van de Lageweg et al. 2013, 2016). Generation of 3D models at specified time intervals was found to be an efficient way measuring the topographic changes of channels and bedforms in flumes (Leduc et al. 2019). Norizan et al. (2016) analyzed the effect of alternating flooding and non-flooding events on channel evolution, employing close range photogrammetry for recording changes during flume experiments.

The main goal of our study was to determine the influence of sediment starvation, flow deficit and occurrence of series of floods on the evolution of channel planform. Our study is based on flume tests that allowed for a simulation of effects of alternating flows and channel incision on channel planform evolution. The research tasks included: (i) to track the evolution of river planform in various flow and sediment delivery conditions, and (ii) compare the results of the flume experiments with the evolution of real river courses. Previous research based on flume tests aimed, e.g., to simulate the influence of vegetation on bank stabilization and formation of a meandering planform (Tal and Paola 2007; Braudrick et al. 2009), and the influence of flow variability and presence of fines on the prevention of erosion and bank stabilization (Métivier et al. 2016), and formation of meandering rivers and cutoffs (e.g., Schumm and Khan 1972; van Dijk et al. 2012, 2013; Li et al. 2019). In our flume tests, we decreased the magnitude of discharge (test 1), simulated flood events by temporal increase of the flow (test 2), and

floods accompanied by additional sediment load (test 3) to track processes taking place in rivers affected by such events.

Research methods–setup of flume experiments

The flume tests were carried out using the PTETHYS (Project for Tectonical and Hydrological Simulations) flume at the University of Pécs (Fig. 1). The flume can be adjusted and tilted both around its longitudinal (7.5°) and transversal axes (up to 10°) and has adjustable push-blades both vertically and horizontally. Six sections can be moved vertically and it has 4 push-blades which allows lateral deformation. These adjustments enables the execution of various experiments including tectonic and morphological processes. These motions are controlled by computer-governed electro-engines. Thus water and sediment could leave the flume only through a sink in its downstream part (Pirkhoffer et al. 2014).

The experimental area is 4.2×2.5 m, which can hold up to 2500 kg of sediment. For modeling purposes a 1 m wide section of the entire flume was used where the bottom was made of plexiglass and for the lateral constraints of the flow wooden boards were used (see Fig. 1). The bottom of the flume was also secured using plexiglass to prevent the infiltration. Discharge was measured and regulated by a flow meter.

Three experiments, simulating downstream hydrological impacts of dam operations, and sediment delivery scenarios, were conducted. All the experiments were started with a straight channel (3 cm deep and 5 cm wide). The material used in these experiments is color-coded; the colors of grains indicate grain size. Coarse grains are grey ground basalt (1.0 mm) and black andesite (0.8 mm). The 0.6 mm diameter grains are of red marble and the 0.2 mm diameter are of beige limestone. Particle-size distribution of the experimental material is shown in Table 1. When scaling down the material placed in a flume to the volume of the flow used in experiments, sediment mobility may be low or below the threshold of motion (cf. Kleinhans et al. 2014). Therefore, we used in our flume tests relatively high slopes (from 1° to 5°) compared to these occurring in real rivers. This allowed for the activation of sediment transport in our flume tests, and resulting changes in the channel morphodynamics and planform.

During the flume tests, pictures of planform changes were taken every 60 s using 8 Canon EOS 1100D (4 Samyang 16 mm $f/2.2$ and 4 Sigma 24 mm $f/1.4$ objectives) cameras installed on a system of cantilevers above the experimental area. They are connected to a computer with USB ports, so images are taken with each camera concurrently. Pictures are overlapping by 80%, allowing the calculation of

3D models of the planform. Ten markers (ground control points) were used as reference in the experimental area and their coordinates were measured by a Sokkia total station in a local coordinate system. This way the resulting 3D models are in the same coordinate system and distances can be determined. For image processing Agisoft Metashape 1.5.3 was used, which is used for the calculation of orthophotos and digital elevation models using the synchronous images. Digital elevation models were processed in ArcMap 10.6.2. Based on the obtained models, cross-sections illustrating channel planform changes in selected stages of the flume tests were obtained.

All the flume tests started with a straight channel, and a certain time was needed for the channel to evolve to a state with active morphodynamics, in conditions of decreasing discharge or sediment deficit. Therefore, the detailed analysis of the channel planform changes refers to part of the conducted experiments; changes of the planform in flume test 1 were shown between 30 and 70 min. since the activation of the straight channel. Periods between 45 and 68 min of the experiments were analyzed for flume tests 2 and 3 (Fig. 2), to compare the morphodynamics in conditions of subsequent floods, and floods with additional flow and sediment delivery volume.

Test 1–simulation of decreased discharge on planform evolution

The experiment was conducted as follows (Fig. 2a):

- a 1.5 l/min discharge was set to flow through a straight channel (duration: 35 min),
- the discharge was decreased to 1.0 l/min (duration: 20 min)
- the flow was decreased again to 0.5 l/min (duration 20 min).

During the test the slope of the flume was constant (3°).

Test 2–simulation of influence of subsequent floods and increased slope on planform evolution

The experiment was carried out in the following way (Fig. 2b):

- the slope was successively increased from 1° to 5° in 0.5° intervals. Each of the intervals lasted 10 min.
- during each of the intervals the flow was changed as follows: 2.5 l/min–duration 1 min, 1.5 l/min – duration 4 min, 2.5 l/min–duration 1 min, 1.5 l/min–duration 4 min (Fig. 2b). The aim was to simulate sequences of floods occurring in the Drava valley after 1989 when

Main elements of the construction of the PTETHYS flume.

PTETHYS flume used for experiments

The flume filled with sand material during one of tests. White plates in lateral parts of "floodplain" are markers necessary to integrate photos from cameras into one image.

Set of cameras (marked by white arrow) to image particular stages of the flume tests

Fig. 1 Images illustrating the construction of the PTETHYS flume

Table 1 Grain-size properties of sediments used in the flume tests

Fraction	Percentage
1–2 mm	0.34615
500–1 mm	66.57948
355–500 μm	18.21738
250–355 μm	7.20981
100–250 μm	4.56918
< 100 μm	0.8901

the construction of the lowermost dam near Botovo was completed.

Test 3—simulation influence of floods with sediment load and increased slope on planform evolution

In the third of the experiments, the slope was increased as in test 2. However, the 1 min intervals of increased flows

were enhanced by adding 1 l of water with 20 g of sediments of diameter < 250 μm (Fig. 2c) during each of the floods. The additional volume of water (1 l) was selected as higher volumes would cause too intensive eroding of the sediments placed in the flume, and lower volumes would not exert a visible influence on the evolution of simulated channel planforms.

As we treated sediments placed in the flume by the volume of water with no sediment load (tests 1 and 2) or such load was added only during simulated flood events, the simulated channel planforms were eroded by downstream propagating erosion. The erosion formed a straight channel cutting along fluvial forms shaped in the flume. These changes appeared after 70 min. of each of the tests (Fig. 2). We could not extrapolate the pace of the downstream erosion observed in the flume to the propagation of river bed incision occurring in real rivers downstream of dams.

Fig. 2 Setup of the flume experiments

Results

Evolution of channel planform in flume test 1

The first of the experiments was conducted at a constant slope (3°). The discharge at the start of the flume test measured 1.5 l/s (Fig. 3). In such conditions the river bed evolved from a straight channel, through the formation of a sequence of alternate bars, to a sequence of side bars. The largest of them has been preserved in the upstream part of the flume (Fig. 3a–d). Moreover, a bifurcation was formed on the left side of the floodplain. The bifurcation conveyed part of the flow through two channels. After 30 min of the experiment the channel planform was braided with three mid-channel bars, two side bars “attached” to the banks, and the bifurcation consisting of two channels (Fig. 3a; Table 2).

After decreasing the flow to 1.0 l/s, the bifurcation became temporarily inactive (Fig. 3b). 5 min after the decrease of the flow (40 min of the test) the flow was conveyed by a single channel characterized by a sequence of alternating side bars (Fig. 3b). At 50 min. of the test, the flow was directed to one of the channels forming the bifurcation (Fig. 3c1). The flow was conveyed by this channel to the floodplain. This was caused by in-channel deposition, resulting in the formation of a channel bar that blocking the main channel (Fig. 3c1). This is illustrated by a shallow cross-section of the main channel (see line I in Fig. 3). However, this was a short-duration event. At 55 min. of the test, the flow in the main channel was reactivated (Fig. 3c2). The overbank flow was discontinued but the floodplain remained saturated; water was stagnating on its surface downstream of the bifurcation (Fig. 3c2).

After further decrease of the flow to 0.5 l/s, the flow was conveyed through the main channel. The incision of the main channel propagated downstream (Fig. 3d). This is also illustrated by cross-sections of the main channels in lines I and III (see cross-sections in Fig. 3). Channel incision also commenced in the downstream part of the flume. In this way the side bars situated at both sides of the main channel were positioned at a higher level in relation to the incised main channel, and became inactive (Fig. 3d; Table 2). At the same time, bifurcation also became inactive. This is marked by a deposition in one of the bifurcating channels after 55 and 70 min of the test (see cross-section II; Fig. 3). However, the line illustrating the channel bottom after 70 min. is probably elevated, possibly owing to reflections from surface water.

Evolution of channel planform in flume test 2

During the first 45 min of the test the planform evolved from a straight to braided planform with downstream

migrating mid-channel bars. The barforms were inundated during a flood event simulated in 45 min of the test at a slope of 3° . The flow commenced over the entire width of the channel, and the channel was widened (Fig. 4a). In the following period of a low flow, four channel bars were exposed (Fig. 4b).

After increasing the slope to 3.5° , the channel bars were eroded during a flood at 50 min. of the flume test (Fig. 4c). The first flood at a slope of 3.5° caused the formation of scour channels in the channel bar in the middle part of the flume (Fig. 4d). In periods of low flows, the side channels became inactive, and the channel bars were exposed. This is expressed by an increase in the surfaces of channel bars in this period (see diagram in Fig. 4). The channel bar exhibited a characteristic undulating surface with inactive scour channels (Fig. 4d). Moreover, three channel bars with adjacent side channels were formed in its downstream part. The channel was successively widened.

During the second flood at a slope of 3.5° (55 min of the test; Fig. 4e) a set of scour channels was formed by the overbank flow that inundated the floodplain along the right bank. The scour channels were reactivated and the bar in the middle part of the flume was divided into three smaller barforms (Fig. 4e). This is also illustrated by cross-sections II and III (Fig. 4h). All the barforms were inundated during the flood and the channel width increased. This is also indicated by a decrease in the number of barforms (see Fig. 4g).

The flood simulated at 55 min. of the experiment caused the incision of the main channel (see cross-section I; Fig. 4h). In the following period of low flows (58 min. of the test; Fig. 4f), side channels located between channel bars and bank were inactive as they were situated at a higher level than the main channel (see cross-sections II and III in Fig. 4h). The second of the floods left a number of channel bars separated from the floodplain by side channels, also in the downstream part of the flume (cross-sections IV and V; Fig. 4h). Their total surface increased by close to 100% (from 0.08 to 0.148 m²) compared to the previous period of low flows (Fig. 4g). In the upstream part of the flume, three bar cut by scour channels merged into one; the traces of the scour channels have been preserved in the “alluvial island” surface (see Fig. 4f and cross section II and III). Since the island existed until the bankfull stage was exceeded, the channel planform may be defined as anabranching (cf, Nanson and Knighton 1996). Nanson and Knighton (1996) define the anabranching planform as “a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull”. This meets the conditions obtained in the laboratory tests except for vegetation impact. This means that this type of channel planform can also be formed without the presence of vegetation.

Fig. 3 The evolution of channel planform at decreasing discharge (flume test 1). **a** A braided planform after 30 min of the experiment, with a bifurcation conveying part of the flow by two channels, **b** after the flow decrease the flow commences through a single channel, **c1** reactivation of the bifurcation due to in-channel deposition, **c2** return

of the flow path to the main channel, **d** the planform become morphologically inactive; the flow is too weak to transport sediments and make any changes in the planform. **e** cross-sections illustrating evolution of channel planform during the experiment

Table 2 Review of experimental settings and obtained channel planforms in the present study and earlier flume experiments

Experimental study	Simulated flow and sediment regime	Obtained results
Our study	Decreasing the volume of discharge from 1.5 to 0.5 l/min, no sediment feed Successive increase of slope. Simulation of floods by increasing flow to 2.5 l/min in 4 min. intervals, no sediment feed Successive increase of slope. Simulation of floods enhanced by adding additional volume of water with suspended material. No sediment feed except for the floods	Formation of braided planform and bifurcation (1.5 l/min). Temporary in-channel deposition and directing the flow to bifurcating channel (1.0 l/min). Incision of the main channel and deactivation of the bifurcation (0.5 l/min) Formation of anabranching planform consisting of one main channel, alluvial islands, and side channels activated in periods of high flows Formation of single-thread channels with terraces in periods of low flows. Erosion of terraces and formation of channel bars at high flows
Li et al. (2019)	Replication of a meander from the middle Yangtze River (China), series of tests with discharge from 0.5 to 3.0 l/s, no sediment feed, and three slopes (from 0.8 to 1.7%)	Formation of neck cutoff at the higher-magnitude discharges (2.0–3.0 l/s). The cutoff commences in short time, favored by a high difference on water levels on both sides of meander neck
Van Dijk et al. (2012, 2013)	Van Dijk et al. (2012) Constant discharge of 1.0 l/s. Constant sediment feed (sand and fines silica flour). Transverse movement of the inflow point simulating upstream perturbations Van Dijk et al. (2013) long period of low flows and short flood, constant sediment feed, adding fines to the inflow at high flows to simulate influence of fines on planform changes	Formation of a dynamic meandering planform evolving through lateral migration and chute cutoffs Addition of fines influenced the formation of a meandering planform evolving through chute cutoffs
Tal and Paola (2007)	Periods of low and high flows. Constant sediment feed. Introducing vegetation during periods of low flows	Influence of low and high flows regime, and development of vegetation cover, on transition from braided to a stable sinuous planform
Schumm and Khan (1972)	Constant discharge, increasing the slope and sediment load Adding suspended sediment load	Transition from a straight channel at low slopes, through a meandering thalweg, to a braided planform at high slopes Formation of static meandering planform
Leopold and Wolman (1957)	Constant discharge, slope and sediment feed	Formation of braided planform

Fig. 4 Channel planform changes during a sequence of floods and increasing slope (flume test 2). The diagram in Fig. 5g shows changes in the surface of bars during particular stages of the experiment

The final products of the flood were exposed in a period of low flows (Fig. 4f; Table 2):

- channel bars with traces of scour channels in the middle and downstream part of the flume. They are also illustrated by cross-section II (line II; Fig. 4h).
- all the channel bars separated from the banks by side channels
- the sequence of floods simulated in the experiment caused a successive increase of bar surfaces (see a diagram in Fig. 4); during floods the bars were reworked or inundated whereas in periods of low flows the amount of bars increased owing to conveying the flow by incised main channel.
- the test at 3.5 and 4.0 degrees also shows that together with the repeated sequence of high flows and river bed incision the process of bar merging, the formation of alluvial islands and repeated activation/deactivation of side channels propagated downstream.
- owing to the successively increased surface of channel bars, the hierarchy of channels (one main channel and

a number of side channels active at high flows), and their persistence until the overbank flow occurred, the obtained channel planform can be defined as anabranching.

Evolution of channel planform in flume test 3

As in the previous tests, the evolution of the planform started with a straight channel, and downstream migration of alternate bars. When the slope was increased to 3.0°, channel bars were formed during a flood at 45 min. of the experiment in the middle part of the flume (see Fig. 5a, b, and cross sections III and IV; Fig. 5h). Terrace levels were present in the upstream and downstream part of the flume (cross-sections I and VI; Fig. 5h). In period of low flows that followed the flood (48 min. of the test, Fig. 5b), the surface of terrace levels increased (see Fig. 5h and cross-sections – Fig. 4h). The terraces were situated at a higher level due to channel incision.

At a slope of 3.5°, channel bars were formed again during the first of the simulated floods (Fig. 5c). In the following

Fig. 5 Channel planform changes during a sequence of floods with delivery of fines, and increasing slope (flume test 3). The planform evolved through channel incision, and formation of terraces along

period of low flows they were separated from banks by side channels (Fig. 5d). The side channels were inactive at low flows. However, the channel bars and the side channels were eroded by the second flood at 55 min of the test (Fig. 4e). In the following periods of low flows the flow commenced through a single channel with adjacent terraces and a single channel bar (Fig. 5f).

When the slope was increased to 4°, the terraces were eroded, and two channel bars appeared during the first flood in the 60 min of the test (Fig. 5i). In period of low flows (62 min of the test; Fig. 5j; Table 2) the planform returned to the incised single-thread channel near-continuous terraces. The process of eroding of the terraces and formation of bars during floods, and deposition along banks and formation of terrace levels at low flows, is illustrated by cross-sections I–VIII (Fig. 5m). The erosion of the terraces was repeated by the second flood at this slope (Fig. 5k). This flood event also caused the formation of an alluvial island characterized

banks. The terraces were eroded by subsequent floods, during which channel bars were formed

by undulating surfaces owing to the formation of scour channels. The island is well seen during the periods of low flows (Fig. 5l), when the scour channels were inactive. In these periods, the main channel returned to the incised, sinuous planform.

Compared to test 2, the delivery of fines during each of the floods influenced a deposition along the channel banks resulting in the formation of the terrace levels. This is confirmed by relatively small changes in the total surface of bars during test 3 in relation to experiment 2 (see diagram in Fig. 5g).

Discussion

Our experiments allowed for the simulation of processes taking place in rivers affected by flow reduction (Fig. 3), sediment-starved regimes (Fig. 4), and rivers where sediment

Fig. 5 (continued)

load is delivered during floods (Fig. 5). Previous flume studies demonstrated the influence of vegetation cover (Tal and Paola 2007; Braudrick et al. 2009), upstream perturbation (van Dijk et al. 2012), and presence of fines (Schumm and Khan 1972; van Dijk et al. 2013) on the formation of meanders (see Table 2). We have proved in laboratory test 2 that

series of floods can lead to the formation of an anabranching planform, and this can happen without the presence of vegetation and input of fines. Series of floods alternating with periods of low flows trigger the formation and coalescence of channel bars, formation of side channels and scour channels within the alluvial islands are sufficient for

the formation of anabranching planforms. This is confirmed by examples of real dryland river courses evolving without vegetation (e.g., Li et al. 2015). In the case of Rio Capilla the discharge regime was characterized by seasonal occurrence of floods the result of natural hydrological regime, not dam closure. The influence of series of floods on the development of anabranching planform with meandering anabranches was also demonstrated in the study of Słowik (2018) in the middle Obra River valley (Poland).

Similar to flume tests conducted by Leopold and Wolman (1957), and Schumm and Khan (1972), we observed the formation of alternate bars, that later merged into larger bedforms. Schumm and Khan (1972) observed merging of channel bars and formation of alluvial islands, however, without the main incised channel. This is because they used a constant discharge and sediment feed that caused the widening of the channels near the alluvial islands (Schumm and Khan 1972). We applied variable flows, successive increase of the slope and no sediment feed in test 2 and this resulted in the formation of an anabranching planform characterized by the main incised channel and side channel active at high flows (Fig. 4f; Table 2).

The addition of fines during floods simulated in test 3 caused the formation of terrace levels along a single-thread channel in periods of low flows (Fig. 5j). This is not in agreement with the results shown by Schumm and Khan (1972), and van Dijk et al. (2012), possibly owing to the fact that they applied a constant feed of fines. Van Dijk et al. (2012) applied delivery of fines along with transverse moving of the inflow point. These settings caused the formation of migrating meanders and chute cutoffs. In our test 3, the inflow point was fixed in one place, and this resulted in the formation of a straight single-thread channel with terrace levels on its both sides (Fig. 5j). Similarly to laboratory tests performed by Li et al. (2019), our experiments exhibited increased eroding and reworking of channel banks when increasing the slope and discharge (tests 2 and 3; see, e.g., Figs. 4c and 5i).

Types of rivers simulated in flume experiments

These experiments allowed for simulation of the evolution of the following types of rivers:

- rivers unable to rework and convey sediment sources available in floodplains. They evolve from wide channel belts comprising of a number of channels to a single-thread course with traces of inactive channels preserved in the floodplain. The main reason is a decrease in the flow magnitude caused by constructions of dams, systems of irrigation canals and use of water for municipal needs. The evolution of the channel pattern in flume test 1 is similar to changes in the course of the central Platte River

(USA) (Horn et al. 2012). Before dam construction, the river exhibited a high-energy braided planform evolving in a 1.3 km wide channel belt (see archival image from 1938 in Fig. 6). Dam closure, preceded by the construction of irrigation channels and diversion dams, caused a reduction of discharge, decrease of channel width from 25 to 50% and turned the channel into a single thread and anabranching planform, with a number of inactive channels (Horn et al. 2012) (see Fig. 6 for a comparison of the flume tests with changes of the real river course). Another example are rivers of northern Italy, affected by dam closure, sediment mining and channelization. These actions resulted in severe narrowing of active channels, producing inactive channels belts downstream of dams (cf, Surian and Rinaldi 2003; Surian et al. 2009). Possibilities of restoration in such cases are low in the above cases as dam constructions were accompanied or had been preceded by a number of other actions (mentioned above) that reduced water resources.

- rivers with a single incised channel, and alluvial islands and side channels situated at a higher level of the floodplain (Fig. 7). In such river courses, series of floods with limited or no sediment load cause bed incision, and formation of channel bars. The bars merge and, as the main channel continues to incise, are stabilized by vegetation and become alluvial islands. Side channels are activated by high flows or become part of the floodplain if the continued incision of the channel prevents this activation. Such an evolution describes rivers that were altered by dam constructions hence reducing bed load transport. This is the case, e.g., of the lower Drava River (Hungary) (Słowik et al. 2018), Rhone River (France) (Provansal et al. 2014), Garonne River (France) (David et al. 2016), Vistula River (Poland) (Gierszewski et al. 2015 and 2020) and the Arno River (Italy) (Rinaldi 2003). Some actions aiming to restore the activity of side channels and groundwater supply are undertaken in these river courses (e.g., the lower Drava River Lóczy et al. 2014). However, the success of these undertakings strongly depends on availability of sediment and water resources in river basins.

The second flume experiment allowed for simulation of such an evolution in conditions of frequent floods, and accompanying sediment starvation and bed incision. The obtained channel planform changes are similar to these observed in a real river course the lower course of the Drava River (Hungary) (cf, Słowik et al. 2018). The river was altered by dam construction and earlier human-induced changes (channel straightening in the eighteenth and nineteenth century) (Słowik et al. 2018). The variability of water levels after closure of the lowermost dam in

Fig. 6 A comparison with channel planform obtained in flume test 1 with channel pattern changes of the central Platte River (USA)

1989 (Fig. 7a) was reflected in the experiment by series of high flows (Fig. 7b). These conditions resulted in the formation of channel bars and bed incision, which resembles similar processes after straightening of the Drava River bed in the eighteenth century (see Fig. 7c, d). Next, the planform evolved through continued incision of the main channels, formation of alluvial islands with scour channels formed by floods, and side channels active a high flows (Fig. 7e, f) similar to the lower Drava (cf, Słowik et al. 2018).

- rivers evolving through the formation of terrace levels and sediment benches causing channel narrowing (Fig. 8). In many cases the deposition is the effect of lowering the magnitude of flow and upstream sediment delivery owing to dam closure. The sediment deficit is compensated by sediment resources from tributaries and floodplain. If the flow volumes are smaller compared to these prior to dam closure, the channel narrows owing to the formation of the terraces and benches. In this group of rivers, restoration potential is the highest compared to rivers simulated by experiments 1 and 2, as these courses

have the highest ability to return to pre-dam conditions using their tributary and floodplain sediment resources.

Flume test 3 simulated a sequence of floods, enhanced by addition of surplus flow and the load of fines. The resulting formation and reworking of terrace material (part of which was built of fines), and channel bars in periods of floods, resemble to river valleys influenced by delivery of sediments from tributaries and/or floodplain. They may be also formed by controlled floods delivering sediment load in water courses altered by dam closure. The case of the Green River (USA) downstream of Three Gorges Dam (Fig. 8c) is the example of a real river course characterized by channel narrowing, and formation of elongate patches of floodplain along active channel by post-dam floods, and sediment delivery from floodplain, valley slopes and tributaries (cf, Grams and Schmidt 2002, 2005; Grams et al. 2019) (see also Fig. 8c). Peak flows were reduced from 500–600 m³/s in a pre-dam period to 200–300 m³/s after dam closure. Mean discharge decreased from 200–300 m³/s in a pre-dam period to 100–200 m³/s after dam construction (see Fig. 2 in Grams and Schmidt 2005). The

Fig. 7 Changes in water levels in the lower course of the Drava River (a) and variability of flows simulated in flume test 2 (b). Channel bars formed in an incised channel after 48 min of flume test 2 (c), and bar-forms in the course of the Drava River (Hungary) in 1816 after channel straightening (d). The planform was redrawn from a historical

maps from the second Habsburg military survey available at mapire.eu. e set of channel bars and alluvial islands formed after 68 min of the experiment, f anabranching planform of the modern lower Drava River

Fig. 8 Channel planform in flume test 3 and its similarity to morphodynamics of the Green River (USA) during floods and at low water levels

main difference between the Green River planform and flume test 3 is that the Green River evolves in dominantly depositional conditions (Grams and Schmidt 2005), and the channel in the flume evolved through incision, and downstream transfer of sediments. This downstream transfer commenced through a sequence of depositional and erosional events (terrace formation in periods of low flows and reworking of these terraces by floods causing movement of the material forming these terraces further downstream).

The dynamics of the planform simulated in the flume resembles the course of the Rio Grande (USA) (Fig. 8d). Its channel planform evolves through narrowing interrupted by large controlled floods causing “reset” of channel morphology was observed in the course of the Rio Grande (USA) (Dean and Schmidt 2013). Dean and Schmidt (2013) reported that after such a flood the river bed aggraded and benches built of fine sediments were formed along the banks. The third of conducted flume tests also resembles the course of the Colorado River (USA) downstream of Glen Canyon Dam (cf, Grams et al. 2007). After dam closure, the river

bed incised that caused abandonment and stabilization of previously active sandbars (Fig. 8e).

Implications for river restoration

The conducted experiments reveal the main effects of dam constructions on the evolution of rivers: decrease of discharge (demonstrated in test 1) and elimination of sediment supply (test 2). There are very few rivers (simulated by test 3) that can compensate such a loss by supply from floodplain resources or tributaries (e.g., the Green River, USA).

Dam removal seems to be a remediation for rivers affected by the loss of flow simulated in test 1 (Fig. 9). However, the success of such actions depends on a number of factors such as, e.g., dam height, reservoir size, the strategy of dam breaching, amount and grain-size of sediment in a dam reservoir, and rate and grain-size of sediments transported downstream (Foley et al. 2017). Elimination of dams restores the connectivity of sediment transfer and flow (cf. Foley et al. 2017). On the other hand, failure in the strategy of a dam removal brings new hazards and negative consequences, i.e.,

Fig. 9 Types of channel planforms simulated in the flume tests, potential actions and effects of restoration

intensive downstream deposition of sediments and contaminants accumulated in the reservoir. So a restoration through a dam removal should be a result of earlier analysis/tradeoff counting positive and negative effects of such an intervention. One should realize that the new post-restoration system is not synonymous with pre-dam conditions (cf. Foley et al. 2017). Furthermore, local communities are sometimes against such actions, as they perceive the modern landscape of small dams and artificial lakes as a traditional/historical one (the case of New England, USA; Fox et al. 2016). This shows the importance of social aspects as river restoration results in changes in the land use, for instance, from agricultural areas to riverine wetlands. And such a change affects everyday's life and work of local communities.

In the case simulated by test 2 (e.g., the Drava River, Hungary), entraining floodplain resources to complement sediment starvation would be a good solution (Fig. 9). Such a solution would temporally prevent further incision of the main channel and resulting isolation of the side channels. The third of the experiments show that regular delivery of fines helps maintaining a stable planform in periods of low flows, even if the alluvial forms are eroded by high flows. This shows the importance of maintenance of restoring

sources of sediment delivery to support a restoration of pre-dam river morphodynamics. In river courses that compensate sediment load caused by dam closure by delivery from tributaries and/or floodplains (Fig. 9) a potential for restoration is the highest. This is possible until this delivery is maintained by protecting the tributary valleys from further hydro-technical works and land use changes.

Conclusions

Flume experiments were conducted to study the influence of flow reduction, sediment deficit, and series of floods with sediment load on the evolution of channel planform. In conditions of flow reduction (experiment 1) the channel planform evolved from braided to single-thread with traces of inactive bifurcating channels. A simulation of series of floods with no sediment load (experiment 2) resulted in the formation of an anabranching planform with side channel active at high flows. The third experiment, in which each of the simulated floods delivered sediment load, allowed for the formation of a single-thread incised channel with terraces

formed along banks in period of lower flows and reworked by the floods.

The experimental results maintain a number of elements of the evolution of real river courses. Flume test 1 shows behavior of river courses affected by dam closure and constructions of irrigation canals resulting in flow reduction (Central Platte River, USA). Here possibilities for restoration are the lowest owing to significant changes caused not only by dam closure but also other significant land use changes. The anabranching planform formed in flume test 2 resembles sediment-starved rivers downstream of dams, like, e.g., the lower Drava River (Hungary). In this case, going back to pre-dam conditions is impossible. The success of restoration, aiming to maintain the activity of the multi-channel pattern formed after dam closure, depends on availability of sediment and water resources. Flume test 2 also showed that vegetation is not necessary condition to form an anabranching planform. This is confirmed by the presence of real anabranching river in non-vegetated areas (e.g., Rio Capilla, Bolivia). The single-thread planform with terraces obtained in flume test 3 is similar to river courses altered by dams but affected by controlled (or tributary) floods with sediment load (Colorado River, USA; Green River, USA). Here possibilities of potential restoration of river forms and processes are the highest as these rivers compensate the loss of sediments caused by dam constructions with delivery from tributaries and floodplains.

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