Erosion, transport and deposition of a sediment replenishment under flood conditions

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24.07.2020

Abstract: River reaches downstream of dams with constant residual discharge often lack sediment supply and periodic high flows due to dam sediment retention and flow regulation, respectively. To test a novel multi-deposit methodology for defining environmental flows, activating dynamics of river morphology downstream of dams, a flood was released from Rossens Dam in Switzerland. This event was combined for the first time with a multi-deposit configuration of sediment replenishment consisting of four artificial deposits allocated as alternate bars along the river banks as a restoration measure. To validate the sediment transport behaviour observed in laboratory tests, stones were equipped with RFID PIT tags, a fix-antenna was installed at the river bed and a mobile antenna was used to allow the investigation of erosion, transport and deposition of replenished sediments. The extension of the erosion period was determined for the tracked stones and average transport velocities were found on the order of 10^{-3} m/s. To estimate the erosion efficiency of the flood, defined as the eroded tagged stones compared to the released water volume, the hydrograph was divided in different periods: rising limb, constant peak discharge, decreasing limb. During the rising limb of the flood, which lasted for 20% of the total flood duration, more than 40% of the PIT tags were transported. The defined *erosion efficiency* is a measure to support the hydrograph design of artificial flood releases at dams. The deposition of tagged stones resulted in a repeating cluster formation as expected from previous laboratory experiments, creating an increase in hydraulic habitat diversity. The analogy of results from field and laboratory experiments confirmed the robustness of the multi-deposit sediment replenishment method. Combined with the gained knowledge of the erosion efficiency, results could spark further application and research of multi-deposit sediment replenishment techniques as a habitat oriented river restoration measure.

Keywords: sediment transport, river morphology, RFID PIT tags, river restoration, sustainable hydropower management, artificial flood release

Introduction

Flow and sediment regimes are two key drivers of morphology and functioning in riverine ecosystems and associated floodplains (Poff et al., 1997; Wohl et al., 2015) that host a large variety of habitats (Sparks 1995; Allan and Castillo 2007; Stähly et al. 2019a). Storage dams have severe impacts on these drivers, causing residual flow conditions due to flow regulation and, in the case of hydropower dams, hydropeaking conditions through energy production (Magilligan and Nislow, 2005; Moyle and Mount, 2007). Large reservoirs retain almost all coarse sediment transported by rivers. The sediment continuum is often completely interrupted in long reservoirs (Schleiss et al., 2016; Warner, 2012). The absence of periodic flood events and sediment supply leads to incision of downstream river beds, loss of fluvial connectivity and, over time, to colonialization of biotopes (e.g. gravel bars) by species that prefer a more static environment such as hardwoods that are limited in dynamic riverine systems.

Reservoir flushing is required to ensure a sustainable dam management, thus dam operators do it periodically (Kantoush and Schleiss, 2009; Schleiss et al., 2016). Such flushing operations can be designed to restore sediment dynamics and associated ecological functions in residual flow reaches (Cross et al., 2011; Kondolf and Wilcock, 1996; Konrad et al., 2011; Loire et al., 2019; Poff et al., 1997; Poff and Schmidt, 2016). An example of this is the extensive long-term study of artificial flood releases at the Spöl river, Switzerland, which has been conducted since 2000 and has changed the diversity of macroinvertebrates (Robinson, 2012; Robinson et al., 2018; Robinson and Uehlinger, 2008). Artificial flood releases have been widely studied all over the world (Konrad et al., 2011). Where feasible, sediment should be added to such

artificial floods to restore river dynamics and hydraulic variability; so-called sediment replenishment. This is also a widely applied technique without artificial flood releases (Arnaud et al., 2017; Gaeuman, 2012; Gaeuman et al., 2017; Hassan and Zimmermann, 2012; Heckmann et al., 2017; Wilcock et al., 1996).

Lately, extensive joint research efforts were performed to study erosion, transport and deposition processes of sediment replenishment in the laboratory (Battisacco, 2016; Battisacco et al., 2016; Cui et al., 2003; Friedl et al., 2018; Sklar et al., 2009). Friedl et al. (2018) looked at rivers with a gentle slope (0.17%) and investigated erosion processes of different dimensions of a single artificial deposit adjacent to the river bank. This is a common practice in sediment replenishment (Kondolf, 1997), and they came up with a method to predict the erosion rate of such a single deposit replenishment. Battisacco (2016), on the other hand, investigated the replenishment of sediments for steep rivers with a bed slope of 1.5%. The study focused on the transport and deposition of sediment replenishment in the downstream river. The results were promising for a multi-deposit replenishment configuration with an alternate bar arrangement. The deposition of the replenished material in the downstream reach resulted in a repetitive pattern of sediment clusters, leading to an increase in morphological diversity (Battisacco et al. 2016; Juez et al. 2016; Stähly et al. 2019b). However, the detailed erosion, transport and deposition processes have not been studied in the field, and is the aim of the presented research here.

Sediment transport processes can be investigated in the field using Radio-Frequency IDentification technology, RFID (Brousse et al., 2019; Lamarre et al., 2005; Olinde and Johnson, 2015; Slaven et al., 2014). Passive

Integrated Transponder (PIT) tags have been successfully used in sediment replenishment projects. Tags are fixed inside stones with little effort and can then be detected with an antenna (Lamarre and Roy, 2008; MacVicar and Roy, 2011; Nathan Bradley and Tucker, 2012). Thus far, RFID PIT tags proved to be a useful technology in up to waist-deep water (Hassan and Roy, 2016; Liébault et al., 2012). Studies in different fluvial environments resulted in recovery rates from around 10% in larger to over 85% in smaller rivers (Arnaud et al., 2017; Brenna et al., 2019; Lamarre et al., 2005; Schneider et al., 2010). PIT tags are relatively inexpensive, allowing the use of several hundreds of such tags. A large quantity of PIT tags can compensate for the difficulties of recovering them. Compared to active RFID tags, passive tags have a short detection distance. Furthermore, PIT tags have an “unlimited” life time since they do not include a battery. This allows long-term studies and giving still useful results if certain tags left the study perimeter, destroyed, or lost.

Research objectives

In the framework of an artificial flood release, the erosion, transport and deposition of a multi-deposit sediment replenishment, previously analyzed in laboratory experiments and promising an increase of morphological diversity, was investigated outside of the laboratory, using RFID PIT tags. Besides the investigation of the different processes, the field experiment was also compared with the laboratory tests of Battisacco et al. (2016). The analysis of the erosion efficiency for different periods of the flood hydrograph (percentage of eroded stones divided by the percentage of the released amount of water) provided useful information for the practical application of artificial flood releases and

sediment replenishment below dams. Aspects of the artificial flood can be found in the supplementary data S1-2.

Study area

The study took place at the Sarine River in western Switzerland. The Sarine is a bed-rock alluvial river that originates upstream of Lac de Snin at the Sanetsch at 2252 m a.s.l. It drains a catchment of 1900 km² into the Aare, which is a tributary of the Rhine. Six reservoirs for hydropower production are located along the 125-km long river, resulting in a regulated flow regime. In 1948, an 83-m high arch dam was constructed in Rossens, creating the over 13-km long Lac de la Gruyre, with a reservoir volume of 200 million m³. The dam is located in a pre-alpine valley leading to a relatively long reservoir that completely interrupts the sediment continuum. The downstream floodplain is located in a natural landscape of a 100-m deep incised and 40 to 100 m wide canyon. The canyon is surrounded by agriculture and small villages. Man-made structures in the floodplain are limited to a handful of buildings and some gravel roads and hiking paths. The absence of flood events and interruption of sediment supply reduced sediment dynamics and enhanced channel incision, resulting in a lateral disconnection of the floodplain (see *supplementary data S3*). Vegetation colonized the gravel bars, which are now populated with willows and hardwood (Dring et al., 2018; Milani et al., 2018).

A residual discharge of 2.5 – 3.5 m³/s is released at Rossens Dam, creating a 13.4-km long by-pass reach until the outflow of the powerhouse in Hauterive (see Figure 1a). There, four Francis turbines release up to 75 m³/s into the Sarine during electricity production.

A large-scale field experiment was launched in 2016 to simulate a dynamic flow and sediment regime in the Sarine floodplain. Flood frequency and magnitude decreased in this river segment since the construction of Rossens Dam. The median of the maximal measured discharge at the gauging station in Fribourg decreased from 304 m³/s (pre-dam period 1911-1947) to 165 m³/s (recent decades 1990-2016). There are two small tributaries between the power station in Hauterive and the gauging station in the city of Fribourg.

Restoration framework

Multi-deposit replenishment configuration

The replenishment was added in four artificial deposits of sediment and placed in the river at the coordinates 46°45'29.21"N / 7°06'11.47"E. The configuration was an adaptation to field conditions of the sediment replenishment successfully tested previously in flume experiments. Numerous multi-deposit replenishment configurations were tested in the flume and the selected setup led to a formation of clusters like alternate bars and hence increased habitat diversity (Battisacco et al., 2016). Figure 1b provides a top-view of the multi-deposit configuration in the Sarine, and Figure 2 an example of one artificial sediment deposit. The main specifications of the field and laboratory experiments are given in Table 1. The replenished sediment was excavated from the adjacent alluvial forest on the orographic right side of the river. Thus, we could assume that the sediment replenishment has the same grain size distributions as the river bed subsurface. The sediment was distributed in the river without sorting. The excavated material was composed of characteristic grain sizes $d_m = 57$ mm and $d_{90} = 113$ mm. The d_{90} corresponds to the grain size of the armor layer in the river bed.

The grain size distribution was determined by analyzing 21 samples using pebble counts (Fehr, 1987) and photo sieving from BASEGRAIN (Stähly et al., 2017). The fine sediment for d_m and d_{90} was estimated as 25% (Fehr, 1987). Where the sediment was excavated, ponds with still water were created, serving additionally as habitats for amphibians and other species (*see supplementary data S4*).

[Figure 1]

[Figure 2]

[Table 1]

Artificial flood release

The artificial flood release was led by cantonal authorities in collaboration with the research institutes École Polytechnique Fédérale de Lausanne, Swiss Federal Institute of Aquatic Science and Technology, University of Zurich and Zurich University of Applied Sciences, as well as with the participation of engineering offices (Pronat, Hydrique), NGO's and the dam owner (Groupe e).

A slightly right-skewed hydrograph had a gradual increase up to a peak discharge of $195 \text{ m}^3/\text{s}$, corresponding to a two-year flood, was released from Rossens Dam on 14 September 2016 and lasted about 28 hours (Figure 9 and Table 4). The main purpose was to clean the river of excess algae, hence flip each stone of the bed surface once. This gave us the opportunity to test the behavior of this multi-deposit sediment replenishment in the field and to study its local impact. Given the initial flood purpose, the threshold for the destruction of the armor layer in the river bed was not exceeded to a large extent.

According to studies done by engineers, the critical discharge for onset of movement is some $150 \text{ m}^3/\text{s}$ for a diameter corresponding to d_{90} . To initiate

sediment transport, the shape of the hydrograph was chosen accordingly; peak discharge was kept for two hours with a gradual decrease.

Methodology

Sediment tracking system

A total of 489 cobbles, divided in d_m and d_{90} , were collected in the field, drilled, the hole filled with an RFID PIT tag of 32 mm and 23 mm length (depending on stone size) and sealed with silicon (Arnaud et al., 2015; Cassel et al., 2017b). The modal diameter d_m was chosen to represent the entire grain size distribution and d_{90} for characterizing the armor layer of the river bed, if there was an armor layer. The shape characteristics of the equipped stones was different between d_m and d_{90} . Despite the small variation in b -axis, the weight varied significantly, especially for d_{90} . Most d_{90} stones were disc-shaped, while the shape of d_m stones were more diverse (Figure 3a-c). With the software S2_Util (Texas Instruments TIRIS, Version 1.20), tags were programmed with a unique identification number. After measuring the three axes and the weight of the tagged cobbles, they were distributed equally in three layers (surface, 0.5 m – 1.0 m and ca. 1.5 m) in the four artificial deposits (Figure 1b).

About 100 m downstream of artificial deposit IV, a pass-over loop fix-antenna was mounted across the river, perpendicular to the main flow direction (Schneider et al., 2010). The antenna consisted of a single loop multiple strand cable with a diameter of 16 mm², protected by a rubber hose (Figure 4). The hose was fixed with cable straps close to the river bed at 1-m long armoring irons that were vertically installed into the river bed every meter. Prior to its installation, the antenna shape was optimized to a length corresponding to the

local river width of about 25 m. The optimal antenna surface of 25 m x 0.3 m resulted in a detection distance of up to 1.5 m under dry conditions. Installed in the river, the detection range under water did not exceed 0.3 m. The loss of detection distance may likely be from the limited structural rigidity of the antenna respectively its fixation at the river bed.

[Figure 3]

[Figure 4]

In addition to the fixed antenna, a mobile antenna was used for RFID PIT tag detection after the flood. The mobile antenna consisted of a 1.5 m long pole and 0.7 m diameter ring attached at the end, both made of plastic (S5). Inside the ring, a double loop of 4 mm² multiple-strand cable formed the antenna resulting in a maximal detection distance of some 0.60 m. The electro-magnetic components are carried in a back pack. When detecting a PIT tag, the antenna made a noise and the tag ID was shown on the screen. Both antenna systems worked with a 12 V 7.0 Ah battery. The electromagnetic components, such as the PIT tags, Tuning Board, HDX Reader and Control board are products from OREGON RFID, Portland, USA. The PIT tags work at a low frequency of 134.2 kHz, allowing detection in submerged conditions.

With the help of the self-made mobile RFID antenna, the location of tagged stones could be detected after the flood event and their locations were recorded with a differential Global Navigation Satellite System (GNSS, model TOPCON HiPer Pro) with an accuracy of a few centimeters. The location of origin (x_0) and deposition (x_d) for tagged stones could therefore be captured with a precision of ca. 1 m due to the antenna-size. The location of the fix-antenna (x_a) was known. In addition, the replenishment zone was defined,

covering the influence area of the artificial deposits where flow varies highly. It reaches from the upstream end of artificial deposit I until one river width downstream of artificial deposit IV (x_e). The definition of this spatial division is given in Figure 5.

[Figure 5]

Knowing the location of deposition of a tagged stone (x_d), the time it ceased moving (t_d), the time it passed the antenna (t_a) and the location of the antenna (x_a), an average transport velocity (v_d) for each stone that passed the fix-antenna can be estimated for the distance between the fix-antenna and the location of final settling (Eq. 1). This measured average transport velocity, referred to as virtual velocity v_d , is the average of a series of bouncing and stopping processes within the interval of x_a and x_d in the allocated time period (Hassan et al., 1991). On the other hand, the velocity upstream of the antenna (v_a) can be calculated (Eq. 2), using the time and location at the antenna (t_a, x_a) with its departing location (x_0) and earliest possible moment for erosion (t_0), which depends on the discharge. The erosion time (t_e) indicates the time a tagged stone is transported out of the replenishment zone and can be obtained by Equation 3 and the estimation of the erosion velocity v_e according to Equation 4 (see Figure 6). The erosion times are visualized in a survivor plot (Davison and Hinkley, 1997), allowing the determination of the erosion-effective periods during the flood event as well as the corresponding sedigraph. The sedigraph represents the time-series of the erosion of the tagged stones and combined with the released volume the *erosion efficiency* is calculated ($eeff$, see Equation 5). The $eeff$ is defined as the ratio between the percentage of

eroded tags in a certain time period (Δt_i) and the percentage of released water during the same time period.

$$v_d = \frac{x_d - x_a}{t_d - t_a} \quad (1)$$

$$v_a = \frac{x_a - x_0}{t_a - t_0} \quad (2)$$

$$t_e = t_d - \frac{x_d - x_e}{v_d} \quad (3)$$

$$v_e = \frac{x_e}{t_e} \quad (4)$$

$$eeff_i = \frac{\text{Eroded tags (during } \Delta t_i) \text{ } [\%]}{\text{Released water volume (during } \Delta t_i) \text{ } [\%]} \quad (5)$$

276

277 [Figure 6]

278 **Critical discharge to determine t_0 and t_d**

279 The critical discharge for the d_m and d_{90} on each artificial deposit was
 280 determined using a numerical 2D-flow-model in BASEMENT (see
 281 www.basement.ethz.ch). The node spacing in the wetted area was 2 m, and
 282 calibration was done with the maximum water depth observed during the flood
 283 event. The river bed was modelled as a fixed bed and the artificial deposits with
 284 a mixed grain size, with both diameters, 57 mm (d_m) and 113 mm (d_{90}). Two
 285 different sediment transport equations were applied (Meyer-Peter and Müller,
 286 1948; Parker, 1990) to observe the incipient motion of the grain sizes at each
 287 artificial deposit based on the shields criteria. The globally smallest critical
 288 discharge was used as the deposition criterion on the decreasing limb of the

hydrograph (*more information in the supplementary data S8*). The resulting discharges are given in Table 3.

Comparison with the laboratory experiments

To compare the experiment with the laboratory findings, the deposition pattern of the replenished sediment was analysed using two metrics that were investigated by Battisacco et al. (2016): the occupation ratio along the channel (OCR) and the different wavelengths of the OCR longitudinal distribution, which represents a measure of the reoccurrence of sediment clusters. In the laboratory experiments, the OCR is defined as the percentage of red pixels (red pixels = replenishment) in an analyzed cross-section with the interval size of one pixel x (Eq. 6). In the field, the OCR was calculated based on the number of tagged stones found in a certain river interval (X). Therefore, the length of the river was fragmented into 5-m-intervals between the downstream end of artificial deposit IV and the last tagged stone found (see Figure 7). To normalize the data and allowing comparison with the laboratory data, the maximal number of tagged stones detected in a 5-m-interval was taken (Eq. 7). The periodicity in the longitudinal direction of the river can be calculated with the Fourier transformation of the OCR (Stoica et al., 2005). A more detailed calculation procedure of OCR and periodicity is given by Battisacco (2016).

$$OCR_{x,lab} = \frac{\sum \text{red pixels in a cross section}}{\sum \text{pixels in a cross section}} \quad (6)$$

$$OCR_{X,field} = \frac{\sum \# \text{ of tagged stones in a 5 m interval}}{\sum \text{maximal \# of tagged stones recovered in a 5 m interval}} \quad (7)$$

Results

Sediment tracking

From the 489 RFID tagged stones placed in the artificial deposits, 277 were found and localized with the mobile antenna after the flood event (Stähly et al., 2018). Out of these 277 stones, 166 were located in the river and 111 in the remaining part of the partially eroded artificial deposits. From these 166 stones, 84 were detected downstream of the replenishment zone. Air images revealed that artificial deposit I, II and IV were only partially eroded (Figure 7). Stones from artificial deposit I and III were transported the furthest, stones from artificial deposit II the least (Figures 7 and 8). The maximal recorded travel distances reached 286 m (d_m) and 278 m (d_{90}) and the mean distances 100 m (d_m) and 65 m (d_{90}). No PIT tagged stone from the top-layer in artificial deposit I and from the bottom-layer of artificial deposit IV was recovered after the flood event. Independent of the artificial deposit, PIT tags located in the bottom layers were transported over the shortest distances. The pass-over loop fixed antenna detected six stones having the origin of artificial deposit I or III (Table 2).

[Figure 7]

[Figure 8]

[Table 2]

Erosion time and average transport velocity

From the six PIT tags equipped stones registered at the pass-over loop fixed antenna only two could be used to calculate the erosion time (Eq. 1-4). Tags with the ID 16 and 364 were not located after the flood pulse (Table 2). ID 271 was trapped by a large rock in the river 3 m downstream of the antenna, and

332 therefore could not be considered as a representative transported stone. Once
 333 the flood passed and the discharge was low, tag ID 325 was registered.
 334 However, the stone must have arrived hours before at that location since it was
 335 registered at the residual flow of $3.5 \text{ m}^3/\text{s}$. It is likely that the antenna did not
 336 work properly when stone 325 arrived. Therefore, the analysis was done based
 337 on the information of stones with ID 367 (d_m) and 73 (d_{90}). For the analysis of
 338 the virtual velocities, values for critical discharge were taken based on the
 339 numerical model results (see Table 3). Based on field observations, we
 340 considered it not accurate to use these results. The artificial deposits were
 341 located after a right river bend causing an increased erosion of artificial deposit I
 342 and III (Bathurst et al., 1977; Termini, 2004). We therefore exchanged the
 343 values between the artificial deposits (Table 3). The lowest critical discharges
 344 ($29 \text{ m}^3/\text{s}$ d_m and $84 \text{ m}^3/\text{s}$ d_{90}) were allocated to artificial deposit III, the second
 345 lowest (34 and $106 \text{ m}^3/\text{s}$) to artificial deposit I, and the highest to artificial
 346 deposit II (72 and $137 \text{ m}^3/\text{s}$). For artificial deposit IV, the average value of the
 347 critical discharges from artificial deposit I and II were taken
 348 ($106/2 + 137/2 = 122 \text{ m}^3/\text{s}$). The virtual velocity v_d resulted in $3.1 \cdot 10^{-3} \text{ m/s}$ for
 349 tag ID 367 (d_m) and $4.6 \cdot 10^{-3} \text{ m/s}$ for tag ID 73 (d_{90}). These two values were then
 350 assigned to all 84 tagged stones that were transported further than the lower
 351 boundary of the replenishment zone, allowing the calculation of the erosion time
 352 t_e for each tag (Figure 9). The most effective erosion occurred after the
 353 discharge reached $175 \text{ m}^3/\text{s}$. Once the discharge passed its maximum and
 354 decreased, the erosion diminished quickly and equalled zero once the
 355 discharge was below $126 \text{ m}^3/\text{s}$. The sedigraph in Figure 9 indicates high erosion
 356 mainly when the discharge increased. Four periods of steep increase in

discharge until 12h, intermediated by constant discharge periods, are observed. About 40% of the stones were transported during these periods of steep increase of the discharge, which represented only 20% of the water released. If we include the whole rising limb (considering also the constant hydrograph periods), 51% of the stones were transported. During the constant peak discharge 24% of the stones were transported and 25% during the decreasing limb which corresponded to 44% of the released water. This is associated with an erosion efficiency ($eeff$) of 2.16 for the steep increase of the discharge, 1.60 for the peak discharge and 0.57 for the decreasing limb.

[Table 3]

[Figure 9]

[Table 4]

Comparison with laboratory experiments

Since the replenishment was not fully eroded (Figure 7), it was compared with an intermediate result of the laboratory tests (Figure 10a). The laboratory experiments lasted until all artificial deposits were eroded. Therefore, the picture taken after 60 min in the laboratory experiment and corresponding to the field observation was chosen for the OCR and the periodicity analysis (one test took 180 min, *more information in the supplementary data S6*). The laboratory data resulted in a non-stationary periodicity at a normalized distance x/w equal to 2.5 with the strongest signal at time step 105 min (Figure 10b). The signal decreases with increasing experiment time. The results of the Sarine have a pronounced peak at $x/w = 4.2$ with small signals at shorter distances.

[Figure 10]

Discussion

Sediment tracking technique

The fixed installed antenna did not work properly during the whole event. Post-flood investigation revealed that the system with the wire in the hose was not rigid enough to resist surface flow velocities of above 2 m/s. The strong forces and high shear stress acting at the bottom of the Sarine during the flood event changed the shape of the antenna permanently and with it the electromagnetic field. The antenna is tuned for a certain shape and the electromagnetic field around the antenna may decrease and eventually disappear if the antenna-shape changes (Arnaud et al., 2015; Schneider et al., 2010). Despite all the vertically installed metal rods staying in place, the hose was detached from some rods and the cable straps broke, resulting in a high flexibility of the antenna shape. A relatively flexible system as the one used here has the advantage that it tolerates a certain amount of impact by rolling, jumping and sliding rocks, whereas a complete rigid structure may completely break after impact and no data would be collected. Furthermore, if the bed is eroded below the antenna, a flexible system is more tolerant to such processes. The pass-over loop fixed antenna used here demonstrates that despite the high impact, the antenna worked at least partially during the flooding such that six PIT tags could be registered. In total, 36 PIT tag equipped stones were localized with the mobile antenna after the flood downstream of the antenna, but 212 stones remain missing.

From the 489 PIT tag equipped stones, 57% were localized with the mobile antenna. In similar studies, significantly higher recovery rates were

observed (Hodge et al., 2011; Liébault et al., 2012; Nathan Bradley and Tucker, 2012). There are multiple limitations why the 57% recovery rate was not higher:

1. The mobile antenna had a detection distance of up to 0.6 m, causing the PIT tags that remained in the mid (0.5-1 m) or lower layer (ca. 1.5 m) of the artificial deposits to be out of the electromagnetic field of the mobile antenna. This also can occur for transported PIT tags which were buried in a lower layer in the river bed. This is probably the most relevant reason for not recovering all tags.
2. PIT tag signal collision (Chapuis et al., 2014). At 134.2 kHz, PIT tags do not have an anti-collision protocol. The signal of PIT tags located about 0.3 m to each other may collide (Cassel et al., 2017a).
3. The size of the tag (32~mm and 23~mm PIT tags) and the orientation of the PIT tag relative to the antenna influence the detection range (Arnaud et al., 2015, 2017).
4. The deep scour in the bed downstream of the fixed antenna, where the river has a slight bend. In this area, the water depth is more than 4 m and thus cannot be accessed with the mobile antenna (Figure 7). All tagged stones that settled in this pool could not be located after the flood event.
5. The fact that stones traveled further than the area that was searched with the mobile antenna. After the furthest downstream stone was detected, another 100-m reach was searched with the mobile antenna without detecting any further PIT tags. The dry area on the floodplain, where water passed during the flood event, also was searched for PIT tags. It is likely that there were stones transported significantly further

downstream. There are 38 PIT tagged stones from artificial deposit I and III that were eroded in the top-layer of artificial deposit I and never found after the event (see Figure 8a). It was likely that they traveled further downstream than the searched area or stopped in the scour as mentioned above.

Erosion time and incipient motion

Considering the deposition map, there is no significant transport of the tagged stones transversal to the flow direction (Figure 7). The PIT tagged stones from artificial deposit I and III settled near the left bank and those from artificial deposit II and IV near the right bank of the river. This indicates that bend-related effects (e.g. secondary currents) are of low importance downstream of the replenishment zone, hence supports the choice of the replenishment zone (Figure 5).

The analysis of the erosion time underlies some uncertainties. First, we have the critical discharges for onset of movement. It is not exactly known when the artificial deposits started to erode, since the field observations and the results of the numerical modeling are not concluding. However, the maximum chosen critical discharges reflect the findings of the sediment restoration report of the Sarine. The report concludes that a grain with a characteristic diameter of 50 mm moves at a discharge of 70 to 100 m³/s and that the armor layer in the residual flow segment of the Sarine breaks up at a discharge of 150 m³/s (DAEC, 2014; Jäggi and Hunziker, 2002). Second, most of the PIT tagged stones were disc-shaped and the ratio between the different axes varied significantly in the Zingg diagram (see Figure 3c, Benn and Ballantyne, 1993; Bunte and Abt, 2001; Zingg, 1935). The stone shape has a strong influence on

transport behavior. Differences in particle shape and size favor burial and overlapping due to imbrication of stones when they settle. These effects have been studied in the application of image based surface sampling methods (Graham et al., 2010; Stähly et al., 2017) and contribute to the limited recovery rate. Particles with the same b -axis are transported at a significantly smaller discharge when they are disc shaped and not rod-like shaped. The different shapes result also in a large variation of volume and the weight of the tagged stones (see Figure 3a-b). The average weight for a d_{90} stone is 1700 g, and varied between 720 and 3500 g (d_m : 250 g, 110-570 g). The volume of a stone and therefore also its weight, have a key influence on the critical incipient motion of a particle, and a further reason why effective discharge for erosion varies from stone to stone. Since the weight of ID 367 is above average (328 g vs 250 g; $d_m = 57$ mm) and of ID 73 below average (1202 g vs 1700 g; $d_{90} = 113$ mm), the erosion curve in Figure 9 could be shifted if measured for stones with different characteristics.

Despite these uncertainties of the definition of the erosion time of a tagged stone and differences between laboratory and field conditions, the sedigraph and survivor analysis presented in Figure 9 are in good agreement with observations from the laboratory experiments (Battisacco, 2016) and observations at the Spöl (Robinson, 2012). This may indicate the robustness of the methodology. Leopold et al. (1965) identified that bankful discharge is the effective discharge for morphological change, corresponding to a flood event with a return period of 1.5. Surian et al. (2009) observed a significant change in the geomorphology of side-channel by floods with a return period <1 year in the Tagliamento river. During the artificial flood, the surrounding floodplain was

inundated at limited locations and a freeboard of 1 m was observed at artificial deposits in the Sarine (S7). Therefore, we conclude that the low submergence of artificial deposits was the main reason why artificial deposits were partially eroded. Artificial deposit submergence is a main driver of the erosion of the multi-deposit configuration as revealed in the laboratory results for different hydrographs (Battisacco, 2016). In the laboratory study, complete erosion of the artificial deposits was observed shortly after the peak discharge passed for a right-skewed hydrograph. For a left-skewed hydrograph, meaning the peak of the hydrograph arrives after 50% of the event time, the erosion of the four artificial deposits may be completed before the peak arrives.

Sorting of settling sediment on the surface of the artificial deposits limited the further erosion of the artificial deposits during constant or decreasing discharge during the event (Powell, 1998). This transversal sediment fining is shown in Figure 11. Whenever the discharge was constant for more than one hour (see rising limb), the erosion of tagged sediments from the artificial deposits was low or even zero (at 60 m³/s, 108 m³/s and 140 m³/s), what is observed in the sedigraph and the ϵ_{eff} (Figure 9 and Table 4). Therefore, it may be assumed that temporary armor layers formed during the event on the artificial deposits (Parker and Sutherland, 1990). This explains to a certain extent why sediment was not eroded from the residual part of the replenishment once peak discharge passed. In addition to this armoring, the artificial deposits were already partially eroded after the peak passed, resulting in a reduced concentration of flow to the middle of the channel. Hence, the bed shear stress is lower for the same discharge compared to the beginning of the artificial flood event in the replenishment zone.

[Figure 11]

Comparison with laboratory experiments

Artificial deposit III was clearly more eroded than the other artificial deposits (Figure 7). This was due to the flow concentration caused by artificial deposit I and II towards the middle of the river. The laboratory study by Battisacco (2016) revealed that erosion started at artificial deposit III (S6). The final situation of the field experiment (Figure 7) was comparable with the resulting state of the laboratory experiments after 60 min (S6). After starting at artificial deposit III in the laboratory, it continued at artificial deposit IV, II and I. In the field experiment, however, artificial deposit I was eroded similarly or even more than artificial deposit II and IV. Nevertheless, after 60 min, the two situations were quite similar, with the only difference that artificial deposit IV was less eroded in the field (Figure 7). As observed in the laboratory experiments, erosion also happened in two directions in the Sarine. Lateral erosion occurred along the artificial deposit length and vertical erosion from the top to the bottom of the artificial deposits. This is confirmed by the transport of stones initially placed in the bottom of artificial deposit II and the miss of top-layer stones of artificial deposit I (Figure 8).

The field experiment cannot be considered as an exact up-scaling of the laboratory setup. A scaling of the dimensions and positioning of the artificial deposit in the river was normalized to the river width as close as possible to the laboratory study (Table 1). Despite the differences between this prototype and the laboratory experiment, the resulting erosion and deposition patterns are similar. A periodicity was detected in both experiments what may be an indication of the robustness of the approach with the four alternate artificial

deposits. The periodicities at short distances (Figure 10b) are significantly smaller than the detected periodicity at a distance of 4.2 times the river width. In the laboratory results, the replenished sediment spread over a longer normalized distance than in the Sarine (Figure 10a). This can be explained with different boundary conditions such as the heterogeneous geomorphology found in the river, the sediment size, and the hydrograph. Important is the similar development of a distinctive periodicity and not the same location of it. However, the total reach length is about 10 times the river width in the field and 30 in the laboratory. Therefore, the peak observed in the periodicity of the analyzed river reach may still change, if the analyzed reach length would be similarly to the laboratory, corresponding 900 m length. The periodicity peak in the river depends largely on the geomorphological structure, in the Sarine this is likely connected with the sinuosity of the river. Furthermore, it must be highlighted that a higher recovery rate of the PIT tagged stones may cause a different periodicity.

Conclusions

For the first time, erosion and deposition processes of a multi-deposit sediment replenishment with four artificial deposits arranged as alternate bars were investigated by stone tracing techniques during an artificially triggered flood in the Sarine River in Switzerland. A similar configuration of the replenishment with four artificial deposits as alternate bars adjacent to the river banks was investigated in laboratory experiments prior to this event, which allowed comparison. The field experiment underlines the laboratory findings in terms of erosion, transport and deposition processes. This sediment replenishment methodology may therefore be an interesting alternative to frequently applied

replenishment techniques (Ock et al., 2013), since the cluster formation in the sediment deposition led to a significant increase in the diversity of aquatic habitats in the restored river reach (Döring et al., 2018; Stähly et al., 2019a). Further, erosion of the material starts at a lower discharge caused by the flow concentration to the river center by geometry. The analysis of the erosion efficiency *eeff* contributes to the definition of hydrographs of future artificial floods. This knowledge can be transferred to other rivers. Such a combined technique comprising of environmental floods and sediment replenishment may result in a smaller volume of released water, reducing restoration costs.

Acknowledgments

In the framework of their master thesis, Jonas Durand-Gasselin and Anthony Maître contributed to the field work and analysis. Elena Battisacco gave advice in the field work preparations and post-treatment of data and took images. Kevin Gianom, Matthias Thalmann and Diego Tonolla helped during the flood event. Professor Anthony Davison from EPFL provided his expertise for the analysis of the erosion time including survivor analysis. The authorities of the Canton of Fribourg and the hydropower plant operator Groupe e included us in the planning process and financed the artificial deposits. The construction company Brodard Services put into place the sediment deposits. This research project was part of the National Research Programme "Energy Turnaround" (NRP 70, www.nrp70.ch) of the Swiss National Science Foundation (SNSF, Project No. 153972). The first author has a complementary by the Swiss Federal Office of Energy (SFOE, Project No. 501673-01).

Data availability

Further information concerning this study is given in the supplementary data.

The datasets analyzed during the current study are available from the
corresponding author on reasonable request.

Conflict of interests

The authors declare no competing interests.

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841 Table 1. Characteristics of the laboratory and field replenishment experiments.

Parameter	Unit	Laboratory	Field
Mean channel slope	[-]	1.5%	0.3%
Hydrograph peak discharge Q	[m ³ /s]	0.031	195
Hydrograph skewness	[-]	highly left-skewed	slightly right skewed
Channel-bed width B	[m]	0.40	30
Channel-bed width at peak discharge	[m]	0.46	35
Average deposit length L	[m]	0.75	22
Average deposit width W	[m]	0.13	8
Average deposit height H	[m]	0.07	1.5*
Total replenishment volume	[m ³]	0.028	1000
90%-quantile of the diameter d_{90}	[mm]	6.95	113
Dominant diameter d_m	[mm]	4.89	57
Ratio d_{90} / d_m	[-]	1.42	1.98

842 *The average deposit height in the field experiment was not constant.

843 Table 2. Information about the six stones detected with the field loop antenna.
844 bot = bottom level; mid = middle level; top = top level of initial placement in the
845 artificial deposit of origin. NaN as a result of the further travel distance (x_d-x_a)
846 indicates that the tagged stone was not located after the flood event. The
847 detection time refers to on-site time on 14 September 2016 except for tag ID
848 325 recorded on the following day.

Tag ID		16	271	367	73	364	325
Deposit of origin	[-]	III	I	III	III	III	I
Level placed	[-]	mid	bot	mid	top	mid	mid
Type	[-]	d ₉₀	d _m	d _m	d ₉₀	d _m	d _m
Tag size	[mm]	32	32	23	32	23	23
Diameter (b-axis)	[mm]	122	58	55	117	56	59
Stone shape	[-]	disc- shaped	rod- like	spherical	rod- like	disc- shaped	spherical
Weight	[g]	2251	236	328	1202	361	299
Detection time	[hh:mm]	18:25	19:37	19:39	19:44	19:53	10:11 (+1)
Detection duration	[s]	33	4	0.9	145	9.1	79
Further transport (x_d-x_a)	[m]	NaN	3	88	87	NaN	0

849

850 Table 3. Critical discharges taken for the estimation of virtual velocity and
 851 erosion time. Values used for the calculation were chosen based on the
 852 numerical model results and field observations. As a deposition criterion, the
 853 smallest discharge taken for the incipient erosion was used for each artificial
 854 deposit.

	Incipient motion Q				Deposition Q	
	Model results		Used values			
	d _m	d ₉₀	d _m	d ₉₀	d _m	d ₉₀
	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]	[m ³ /s]
Deposit I	72	137	34	106	84	29
Deposit II	72	106	72	137	84	29
Deposit III	34	106	29	84	84	29
Deposit IV	29	84	53	122	84	29

855

856

857 Table 4. Erosion efficiency (*eeff*), hydrograph information as well as
 858 interpretation of the sedigraph and Figure 9.

	Eroded stones		Period	Released water		<i>eeff</i>
	[%]	[Number of tags]		volume		
	[%]	[Number of tags]	[hh:mm]	[mio m ³]	[%]	[-]
Steep increasing	41	34	06:30	1.79	19	2.16
periods						
Increasing limb	51	43	10:30	3.79	41	1.24
Constant peak	24	20	02:00	1.40	15	1.60
discharge						
Decreasing limb	25	21	15:30	4.07	44	0.57
Total	100	84	28:00	9.26	100	1.00

859

Erosion, transport and deposition of a sediment replenishment under flood conditions

Survey of the combination of sediment replenishment with an artificial flood as a measure to increase habitat suitability

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24.07.2020

Figure 1. (a) Location of the sediment replenishment. (b) Configuration of the four artificial sediment deposits in the Sarine river, indicated with the orange square in a. The distance between the artificial deposits was about a deposit length L , the shift between the artificial deposits on the left and the right bank is half a deposit length. The height of the artificial deposits was about 1.5 m above the initial river-bed. W is the deposit width. The numbering refers to the name of the artificial deposits from upstream to downstream: artificial deposit I, II, III and IV. Geodata © Swisstopo (left) and Research unit Ecohydrology, ZHAW (right).

Figure 2. View from artificial deposit III upstream towards artificial deposit I at the day of installation. The replenished sediment was directly excavated from the adjacent floodplain without sorting. Image: Elena Battisacco.

Figure 3. Physical properties of the stones equipped with RFID PIT tags. (a) Weight distribution; (b) b-axis distribution; (c) shape classification after Zingg (1935); most stones were disc-shaped.

Figure 4. Installed pass-over loop fixed-antenna in the Sarine river. The single loop cable was installed for protection inside a garden hose. The hose was fixed with cable straps to 1-m long vertical armoring irons installed in the river bed every meter. The antenna had a surface of $25 \times 0.3 \text{ m}^2$. Image: Elena Battisacco.

Figure 5. Concept and sketch of the longitudinal scales. The replenishment zone is shaded, artificial deposit III and IV dark grey. x_0 = original position where a tagged stone was put in the artificial sediment deposit; x_e = downstream end of the replenishment zone; x_a = location of the pass-over loop fix-antenna; x_d = final position where a tagged stone was found after the flood event with the mobile antenna.

Figure 6. Concept of the estimation of the average sediment transport velocity or virtual velocity (v_d) and erosion velocity (v_e). x_0 = original position where a tagged stone was put in the artificial sediment deposit; x_e = downstream end of the replenishment zone; x_a = location of the pass-over loop fixed-antenna; x_d = final position where a tagged stone was found after the flood event. t_0 = time of erosion; t_e = time of leaving the replenishment zone; t_a = time of passing the pass-over loop fixed-antenna; t_d = time the stone stopped moving.

Figure 7. Field sketch: The exposed dry surface of the four artificial deposits before (air-image background) and after (colored areas) the artificial flood event. The residual flow discharge was $3.5 \text{ m}^3/\text{s}$ when the air-image was taken before the flood event and $2.5 \text{ m}^3/\text{s}$ when the dry surface was measured after the flood event. The 5-m-intervals with RFID PIT tag equipped sediments recovered after the flood event are noted. Based on this count, the OCR was calculated (see Figure 10a). Geodata © Research unit Ecohydrology, ZHAW.

Figure 8. Transport distances from 159 of the 166 transported stones. The initial position of six stones was not clear. Stones from artificial deposit I and III were transported further than the others.

Figure 9. The erosion time represents the time that the 84 stones needed to leave the replenishment zone, on 125 PIT tagged stones recovered downstream of deposit IV. The survivor function (Davison and Hinkley 1997) indicates the proportion of stones remaining in the replenishment zone (84 stones = 100%). To cluster the data, a censored analysis was done assembling all PIT tag-equipped stones leaving the zone within a change in discharge of 15 m³/s or higher. The sedigraph (shaded) represents the derivative of the survivor function, indicating the percentage of moved stones (84) that left the replenishment zone in a certain time interval, based on the virtual velocity analysis. It serves for illustrative purposes and does not refer to a y-axis, highest point is at 0.14.

Figure 10. (a) Occupation ratio density (OCR) of the field experiment in the Sarine and the evolution of the laboratory experiments. Lab 60-120 are the results from the laboratory experiment after 60 min, 90 min, etc. (b) Periodicity was calculated based on the signal power of the OCR. The two datasets were both normalized to be comparable in the same plot. The analyses are based on 125 PIT tagged stones.

Figure 11: View from artificial deposit I towards upstream. An armoring of the residual artificial deposit was observed. The armoring was sorted with large stones in the bottom (left), where the submergence was higher and cobbles (right) where the submergence was smaller. Image: Severin Stähly.