PHYSICAL MODELING OF ARTIFICIAL RIVER REPLENISHMENT TECHNIQUES TO RESTORE MORPHOLOGICAL CONDITIONS DOWNSTREAM OF DAMS

BATTISACCO, E.[(1)], MAIRE A. [(2)], FRANCA, M.J. [(3)] & SCHLEISS, A.J.[(4)]

[(1)] *École Polytecnique Fédérale de Lausanne, Lausanne, Switzerland,,*
elena.battisacco@epfl.ch

[(2)] *École Polytecnique Fédérale de Lausanne, Lausanne, Switzerland,,*
adrien.maire@epfl.ch

[(3)] *École Polytecnique Fédérale de Lausanne, Lausanne, Switzerland,*
mario.franca@epfl.ch

[(4)] *École Polytecnique Fédérale de Lausanne, Lausanne, Switzerland,*
anton.schleiss@epfl.ch

ABSTRACT

First applied in the 1980's, the artificial replenishment of sediments is one technique proposed to solve the problem of sediment deficit downstream dams. The present experimental research aims at improving the technique of river replenishment and at providing an engineering answer and framework for its application. A systematic series of laboratory tests are run to understand the hydrodynamics of the river flow when the replenishment technique is applied. Erodible volumes, with different lengths (occupancy of the replenishment volume is 1/3 of the channel width) and submergence conditions (100% and 130% submergence of the replenished volume), reproducing sediment replenishments volumes, are placed along a channel bank. Different geometrical combinations (single volume, double aligned volumes, double aligned half-volumes, double alternated half-volumes) of erodible sediment volumes are tested. The influence of discharge, the distance travelled by the eroded sediments and the time evolution of the erosion process are presented and discussed.

Keywords: River replenishment, Sediment supply, Erosion of sediment

1. STATE OF THE ART

In the downstream reaches of dams, the solid transport is altered by the dam presence. Regardless their purpose, every dam traps the sediments upstream, especially during floods, in other words dams constitute an obstacle to natural sediment transport (Brandt 2000, Petts et al. 2005, Grant et al. 2013). The absence of sediment transport induces many negative changes in rivers. A tendency to bed erosion, a consequent generation of an armoured layer and a coarsening of the bed and a depletion of fish habitats have been observed (Kondolf 1997). Moreover, the lack of solid transport has morphological effects on downstream dam reaches, related to riverbed incision, bank instability and changes in channel width. The above-mentioned changes have a negative influence also on the present ecosystem along the river, inducing a loss in the aquatic and riparian habitats with consequences on the water quality (Power et al. 1996, Merz et al. 2006, Kantoush 2010). Due to the sediment transport reduction downstream of dams and to the armoured riverbed, the possibilities for fish spawning are limited.

In order to supply sediments lacking in the downstream reaches, one of the most efficient proposed method is the replenishment of sediments also called gravel augmentation. The artificial addition of sediments into the rivers has the main purpose to recreate a natural solid transport (Balland 2004). Nowadays, the method is more often applied considering a specific grain size distribution (Wheaton et al. 2004, Gaeuman 2008). The replenishment of sediments technique has been used since the 80's in the United States in more than 17 river reaches below dams (Kondolf et a. 1991, Gaeuman 2012). The initial purpose was to add coarse sediments in order to recreate artificial spawning riffles intended to keep the spawning zone in place and also to improve salmonid spawning habitats. Many other experiences have been carried out also in Alpines Rivers in Germany and in Switzerland (Zeh and Donni 1994), and in several Japanese rivers in order to understand the complex geomorphological processes occurring in rivers and to provide an engineering answer to the application of this technique. Most of the field experiences show a complete erosion of the replenished volume and, through a monitoring campaign; effects of improvement were observed in riverbed formations and materials, benthic organisms and algae (Kantoush et al. 2010, Sumi et al. 2011). Nevertheless, few of the experimentations were not successful because the grains were not mobilized or transported by the flow (Kantoush et al. 2010, Sumi 2009). On the Rhine River downstream of Iffezheim dam, in Germany, the approach has resulted successful in reducing further incision of the riverbed (Kuhl 1992, Kondolf and Minear 2004). The in-situ experimentations have demonstrated that the added sediments did not help in creating durable spawning grounds and it is necessary to add continuously additional material (Sumi et al. 2009, Kantoush and Sumi 2010, Ock et al. 2013, Pulg et al. 2013). Despite the good promising results obtained, it is still necessary to work in order to improve the replenishment of sediments technique (Kondolf 1997, Kantoush et al. 2010).

In this context, the purpose of these laboratory tests is to evaluate the influence of discharge and to investigate how the erosion phenomena acts on the simulated replenishment volume. The replenishment volume is placed along the bank before the water starts to flow on the flume and the test is stopped when either the volume is completed eroded or the erosion process became to be too much time consuming. The submerge condition demonstrated to be influent on determining the erosion process, like multiple volumes showed to be easier erodible than a single volume.

2. EXPERIMENTAL SETUP

The test were ran in two geomorphological identical parallel flumes of 15 m long and 1.2 m width each one (Figure 1). The width of channel bed is 0.4 m and the bank slope is 2:3 (height : length). A pump spilling water from the inlet basin upstream, throughout the flume, supplies the water that reaches the outlet basin placed downstream. The discharge is regulated by an automatic control system.

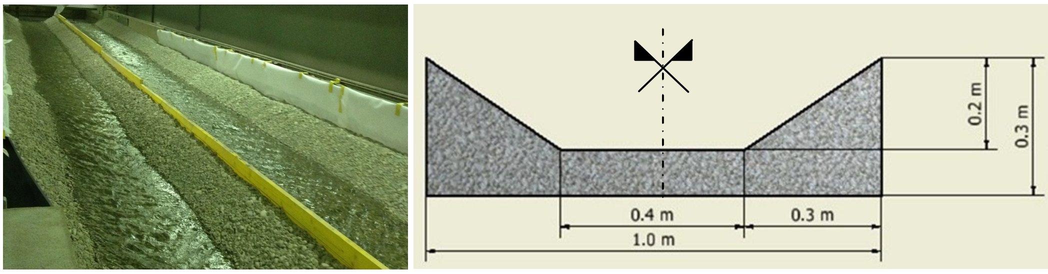

Figure 1. Left: picture of the laboratory facility; Right: sketch of the channel section.

The grain size distribution, used for the channel bed and for the gravel forming the banks, is chosen considering an average distribution typical for the alpine rivers, as proposed by Hersberg (2002) (

Figure **2**, left). In order to simulate an armored bed, a constant discharge was spilled into the flume washing out the smaller particles. The replenishment volumes are composed by grains having a smaller grain size distribution, varying between 5 mm and 8 mm. The choice takes into account the ecological needs for fishes spawning grounds, scaled down to the laboratory conditions. In order to perform a photo analysis of the morphological evolution during time, the grains composing the replenishment volumes were painted in red (Figure 2, right). The data analysis is performed by photo treatment as follows: detection of red pixels, subtraction of occupied surface by red grains, definition of the eroded surface and calculation of the travelled distance in time.

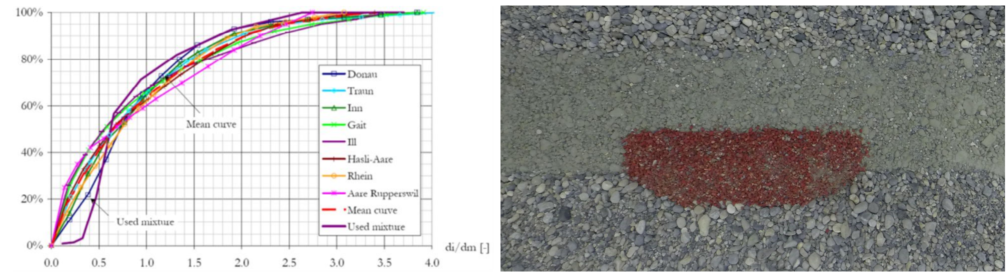

Figure 2. Left: normalized average grain distribution for alpine rivers and for the mixture used in the experiments; Right: replenishment volume made with colored sediments placed in the channel.

Single and multiple replenishment volumes were reproduced and tested on the flume as shown in Figure 3. In particular, four configurations were tested: single volume, double half aligned, double half alternated and double aligned (not shown in Figure 3). “Aligned” refers to volumes placed along the same bank, while “alternated” considers the volumes placed on opposite banks. In case of two single volumes places on the channel bank, the configuration is called “double”, while “half” indicates that the total amount of grains on the channel is equal to one single volume. In both cases, the distance between volumes is equal to the replenishment volume length. The discharge imposed upstream of the channel is indirectly determined by the submergence condition. The replenishment volume height is set constant, but the water height varies from a condition of completely submergence (100% of the volume is covered by water) to over submergence (130% of the volume is covered by water).

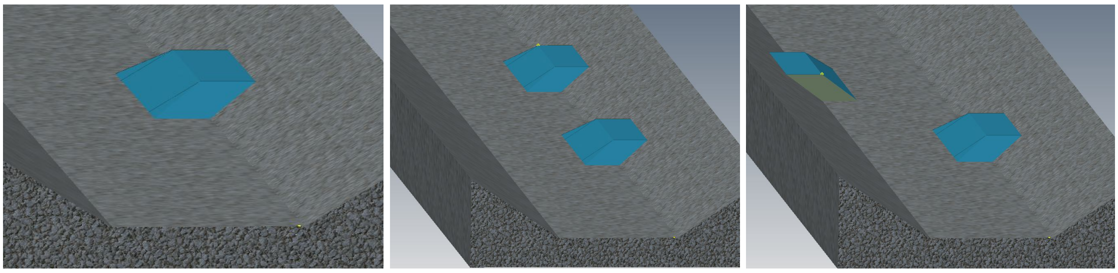

Figure 3. Representation of replenishments placed in the channel with the following configurations: left: single volume; middle: double half aligned volumes; right: half alternated volumes.

3. PRELIMINARY RESULTS

The replenishment of sediment technique is still considered a new methodology to solve the problem of lack of sediments downstream of dams and that explains the absence of universal parameters to be taken into account in the analysis of such technique. As preliminary results, the first analysis considers the following parameters characterizing the evolution and efficiency of the application of the replenishments: the average distance, the ratio perimeter-surface and the action distance. The average distance represents the distance travelled by sediments from the upper control section and the mobility of grains considering the time evolution. The ratio between perimeter and surface considers the total sum of elements perimeter and total sum of elements surface. The latter parameter proposes a way to evaluate the maximum distance until which the replenishment can be considered efficient.

The configurations with half volumes and single volumes use the same amount of replenishment sediments, and the results show a slight difference in the average distance and action distance obtained. Nevertheless, the case with two half aligned volumes performs longer distance ran by the eroded grains which are spread also along the channel width (

Figure 4). The influence of the initial amount of sediments and their configuration play an important role: a larger quantity of grains runs longer distance and it is faster eroded by water in case of aligned volumes. In case of double volumes, the upstream replenishment plays as an obstacle for the water flow, which accelerates the flow inducing erosion of the downstream volume in less time compare to a single volume.

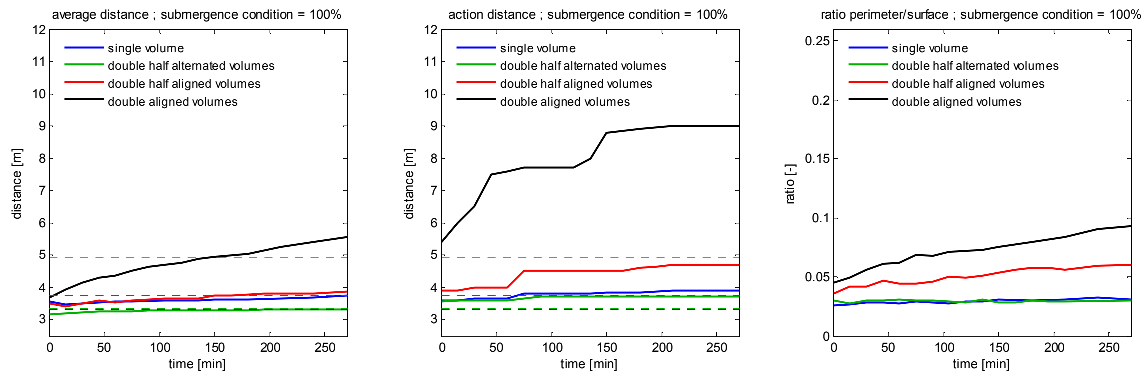

Figure 4. Average distance, action distance and ratio perimeter-surface for submerge condition of 100%.

A higher submerge condition reduces the experimental time. The completely submerge condition (100%) is not enough for obtaining neither the same distance travelled by grains nor the same rate of erosion performed by the over submerged condition (130%) (Figure 5). The effect of submergence is most evident for two half aligned volumes: the maximal average distance achieved with 100% after four hours is overcame almost completely with 130%. Moreover, the action distance is almost doubled in one half of the experimental time (Figure 5).

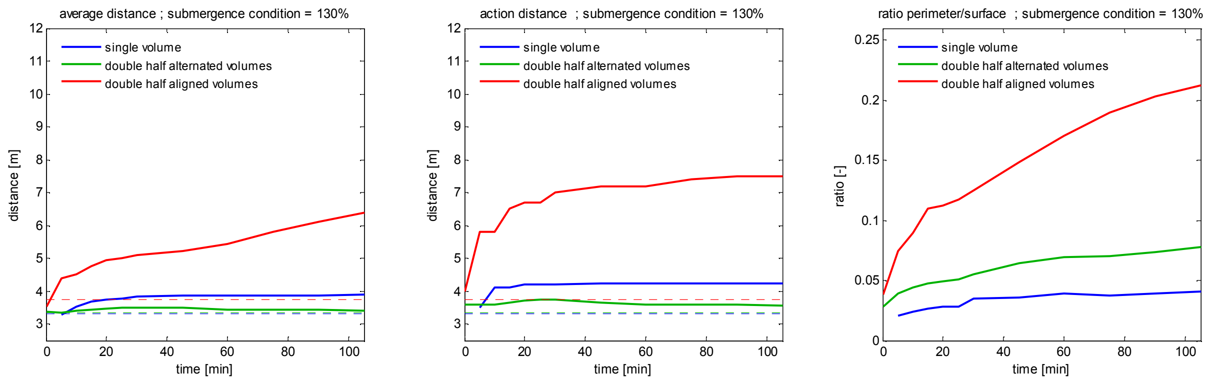

Figure 5. Average distance, action distance and ratio perimeter-surface for submerge condition of 130%.

4. CONCLUSIONS

Through a series of systematic tests in laboratory, this research aims at studying the technique of river replenishment to understand the hydrodynamic changes once the replenishment is added into the reach, providing general recommendations for further applications of the method. The tests carried out deal with erodible volumes and different geometrical configurations, experienced with two submerged conditions. The preliminary results show that no morphological bed forms are yet created by the artificial gravel injection. An increased total amount of grains is necessary in order to achieve the results. The presence of one single volume placed along the bank is not significant in changing the flow behaviour, permitting a rapid erosion of the volume replenishment and consequent spread of this with no consequence in downstream valley. The introduction of a second volume showed interesting results. The flow behaviour is influenced by the upstream bed narrowing, and the replenishment placed more downstream is rapidly eroded by water, which has been accelerated by the replenishment volume. The erosion process and the action distance prone to be speed up by a higher water depth, almost halving experimental time in case of multiple aligned volumes. The real water behaviour and the turbulent water motion still needs to be deeply investigated.

ACKNOWLEDGMENTS

The research is financed by FOEN (Federal Office for the Environment, Switzerland).

REFERENCES

Balland P. (2004). "Impacts des barrages sur les milieux physiques et biologiques." *Ingénieries – Supplément* 38: 23-32.
Brandt SA. (2000). "Classification of geomorphological effects downstream of dams." *CATENA* 40(4): 375-401.
Gaeuman D. (2008). "Recommended quantities and gradation for long-term coarse sediment augmentation downstream from Lewiston Dam". *TRINITY RIVER RESTORATION PROGRAM*, U.S. Department of the Interior Bureau of Reclamation.
Grant GE., Schmidt JC.and Lewis SL. (2013). "A Geological Framework for Interpreting Downstream Effects of Dams on Rivers". A Peculiar River, *American Geophysical Union*: 203-219.
Hersberger DS. (2002). "Wall roughness effects on flow and scouring in curved channels with gravel bed". Faculté Environnement Naturel architectural et Construit. Lausanne, Switzerland, Écoe Polytechnique Fédérale de Lausanne. Grade de docteur ès sciences techniques, Laboratory of Hydraulic Constructions, EPFL-LCH (Thesis 2632).
Kantoush SA. and Sumi T. (2010). "River Morphology and Sediment Management Strategies for Sustainable Reservoir in Japan and European Alps". *Annuals of Disaster Prevention Research Institute*, Kyoto University. Kyoto, Kyoto University.
Kantoush SA., Sumi T. and Kubota A. (2010). "Geomorphic response of rivers below dams by sediment replenishment technique". *River Flow 2010* K. Dittrich, Aberle & Geisenhainer (eds). Braunschweig, Gernany.
Kantoush SA., Sumi T., Kubota A and Suzuki T. (2010). "Impacts of sediment replenishment below dams on flow and bad morphology of rivers". *First International Conference on “Coastal Zone Management of River Deltas and Low Land Coastlines “.* Alexandria, Egypt.
Kantoush SA., Sumi T., Suzuki T. and Murasaki M. (2010). "Impacts of sediment flushing on channel evolution and morphological processes: Case study of the Kurobe River, Japan". *River Flow 2010* K. Dittrich, Aberle & Geisenhainer (eds). Braunschweig, Gernany.
Kondolf GM. (1997). "HungryWater: Effects of Dams and Gravel Mining on River Channels." *Environmental Management* 21(4): 533–551.
Kondolf GM. and Matthews G. (1991). "Management of coarse sediment in regulated rivers of California". *Technical Completion Report*. 1991.
Kondolf GM. and Minear JT. (2004). "Coarse Sediment Augmentation on the Trinity River Below Lewiston Dam: Geomorphic Perspectives and Review of Past Projects". *TRINITY RIVER RESTORATION PROGRAM*.
Kondolf GM. and Wolman MG. (1993). "The sizes of salmonid spawning gravels." *Water Resources Research* 29(7): 2275-2285.
Kuhl D. (1992). "14 years artificial grain feeding in the Rhine downstream the Barrage Iffezheim". *5th International Symposium on River Sedimentation*, Karlsruhe, Germany.
Merz JE., Pasternackc GB. and Wheaton JM. (2006). "Sediment budget for salmonid spawning habitat rehabilitation in a regulated river." *Geomorphology* 76(1-2): 207-228.
Ock, G., Sumi T. and Takemon Y. (2013). "Sediment replenishment to downstream reaches below dams: implementation perspectives." *Hydrological Research Letters* 7(3): 54-59.
Petts GE. and Gurnell AM. (2005). "Dams and geomorphology: Research progress and future directions." *Geomorphology* 71(1-2): 27-47.
Power ME., Dietrich WE. and Finlay JC. (1996). "Dams and Downstream Aquatic Biodiversity: Potential Food Web Consequences of Hydrologic and Geomorphic Change." *Environmental Management* 20(6): 887-895.
Pulg U., Barlaup BT., Sternecker K., Trepl L. and Unfer G. (2013). "Restoration of Spawning Habitats of Brown Trout (Salmo Trutta) in a Regulated Chalk Stream." *River Research and Applications* 29(2): 172-182.

Sumi, T. and S. A. Kantoush (2011) "Integrated Management of Reservoir Sediment Routing by Flushing, Replenishing, and Bypassing Sediments in Japanese River Basins." *8th International Symposium on Eco-Hydraulics* (ISE 2010), COEX, Seoul, Korea, pp. 651-673.

Sumi, T. and S. A. Kantoush (2011). "Sediment management strategies for sustainable reservoir." *Dams and Reservoirs under Changing Challenges*.– Schleiss & Boes (Eds)

Sumi, T., Kobayashi K., Yamaguchi K. and Takata Y. (2009). "Study on the applicability of the asset managment for reservoir sediment managment". Commission Internationale des Grands Barrages, Vignt *Troisième Congrès des Grands Barrages*, Brasilia, Brasilia.

Sumi, T., Kotsubo H., Kido k., Kubota A., Yoshikoshi I., Sandanbata I., Temmyo T., Kodaka S. (2009). "Primary treatment of dredging system for dam sediment replenishing to the river". Commission Internationale des Grands Barrages, Vignt *Troisième Congrès des Grands Barrages*, Brasilia, Brasilia.

Wheaton, J. M., Wheatonab JM., Pasternackc GB. And Merz JE. (2004). "Spawning habitat rehabilitation – II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A." *International Journal River Basin Management* 2(1): 21-37.

Zeh, M. and W. Donni (1994). "Restoration of spawning grounds for trout and grayling in the river High-Rhine." *Aquatic science* 56(1).