Contact:
sara.venuleo@fhnw.ch
silas.unrau@fhnw.ch

Investigating river-restoration-effects on riverbed-stability by physical modelling

Authors: Silas Unrau[1], Sara Venuleo[1], Guido Derungs[2], Henning Lebrenz[1]

[1]University of Applied Sciences and Arts Northwestern Switzerland, Institute of Civil Engineering, Hydraulic Engineering and Water Management, Switzerland

[2]Tiefbauamt Basel-Stadt, Dufourstrasse 40, 4001 Basel, Switzerland

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Introduction

River revitalization can sometimes directly on indirectly affect flood-safety. In this study we present a case study which investigated if **sediment replenishment could threaten the stability of the revitalized riverbed.** Specifically, our results concern the "Wiese Vital" project, a restoration project of the river Wiese in Switzerland (Basel). This project aims at revitalizing the riverbed while ensuring flood safety and improving the protection of Basel's drinking water supply. With these objectives, the original riverbed will be replaced by an artificial coarse sediment layer which protects the integrity of a fine filter preventing undesirable water infiltrations into the aquifer (source of Basel's drinking water).

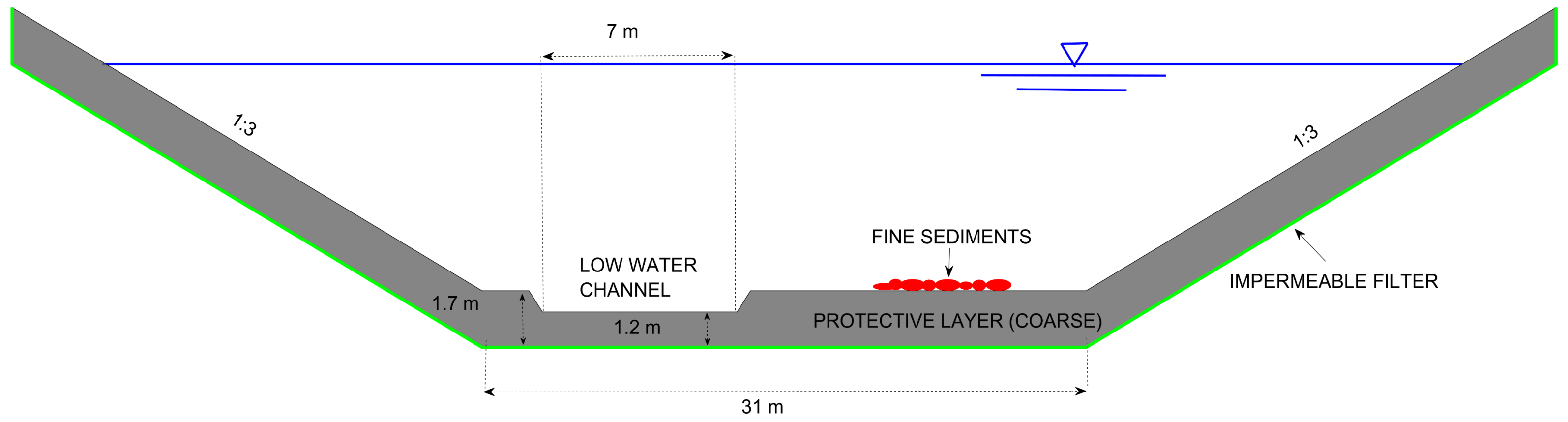

Figure 1: Planned, typical cross-section of the river Wiese (dimensions given on a natural scale)

The artificial coarse layer will consist of a mixture of sediments with a grain size between 32 mm and 200 mm and a characteristic diameter (d_m) of 100 mm. This granulometry isn't the ideal spawning habitat for Salmons, which prefer a finer bed surface (7-47 mm, Kondolf and Wolman 1993). To re-create a spawning habitat more suitable for indigenous species, fine sediments will be artificially placed over the revitalized riverbed. On the other hand, the addition of these sediments could threaten the stability of the new river-bed. Indeed, finer sediments replenishment has previously been shown to increase the mobility of the coarse sediment fraction (Jackson and Beschta 1984; Venditti et al. 2010, Houssais and Lajeunesse 2012). For example, Wilcock and Kenworthy (2002) and (Wilcock & Crowe, 2003) showed that the incipient shear stress can decrease by a factor of 3.5 and 2, respectively, as the percentage of surface covered by fine sediments increases. In addition, the mixing of fine and coarse sediment grains could alter the bed granulometry only in its most superficial part or over the entire depth (Dudill, Frey, and Church 2017; Gibson et al. 2009). These premises raised the concern that fine sediment replenishment could threaten the stability of the new Wiese riverbed.

Objectives:

The aim of this study was to investigate the **response of the coarse protective layer to the addition of fine sediments.** To achieve this, its stability was tested before and after the replenishment of fine sediments.

Methods:

A **physical model in scale 1:20** was used for our investigations. The model scale was chosen respecting space constraints and aiming at minimizing scale effects at a discharge having return period 100 years (HQ100). An **undistorted Froude model** was chosen, maintaining similarity in all geometric ratios model-Nature and using the natural water and sediment densities. To avoid scale effects due to viscous forces, such model should be operated in turbulent (Re>2300) and hydraulically rough conditions (Re*> 70) (Henry and Aberle 2018). Figure 2 shows that the coarse sediments have grain Reynolds number (Re*) larger than 70 both at model and Nature scale, thus scale effects can be excluded for what concerns the coarse sediment fraction. On the other hand, the fine grains Re* is lower than 70 (Re*=60 at HQ100, Re*=53 at HQ10, Re*=44 at HQ1).

Therefore, in our model, especially at lower discharges, the onset of fine sediment motion occurs earlier than in Nature and the transport rate of fine sediments may be larger. On the other hand, scale effects do not alter the fine-coarse grains mixing processes, being these dependent on geometric ratios between grains sizes (which remained unvaried in the model).

Scenarios HQ10 and HQ100 were run in absence and presence of fine sediments, which were colored using red acrylic spray and added in the model, forming six lateral embankments (see Figure 3). A sequence of smaller discharges were run to achieve a sufficient degree of mixing before running again HQ10 and HQ100.

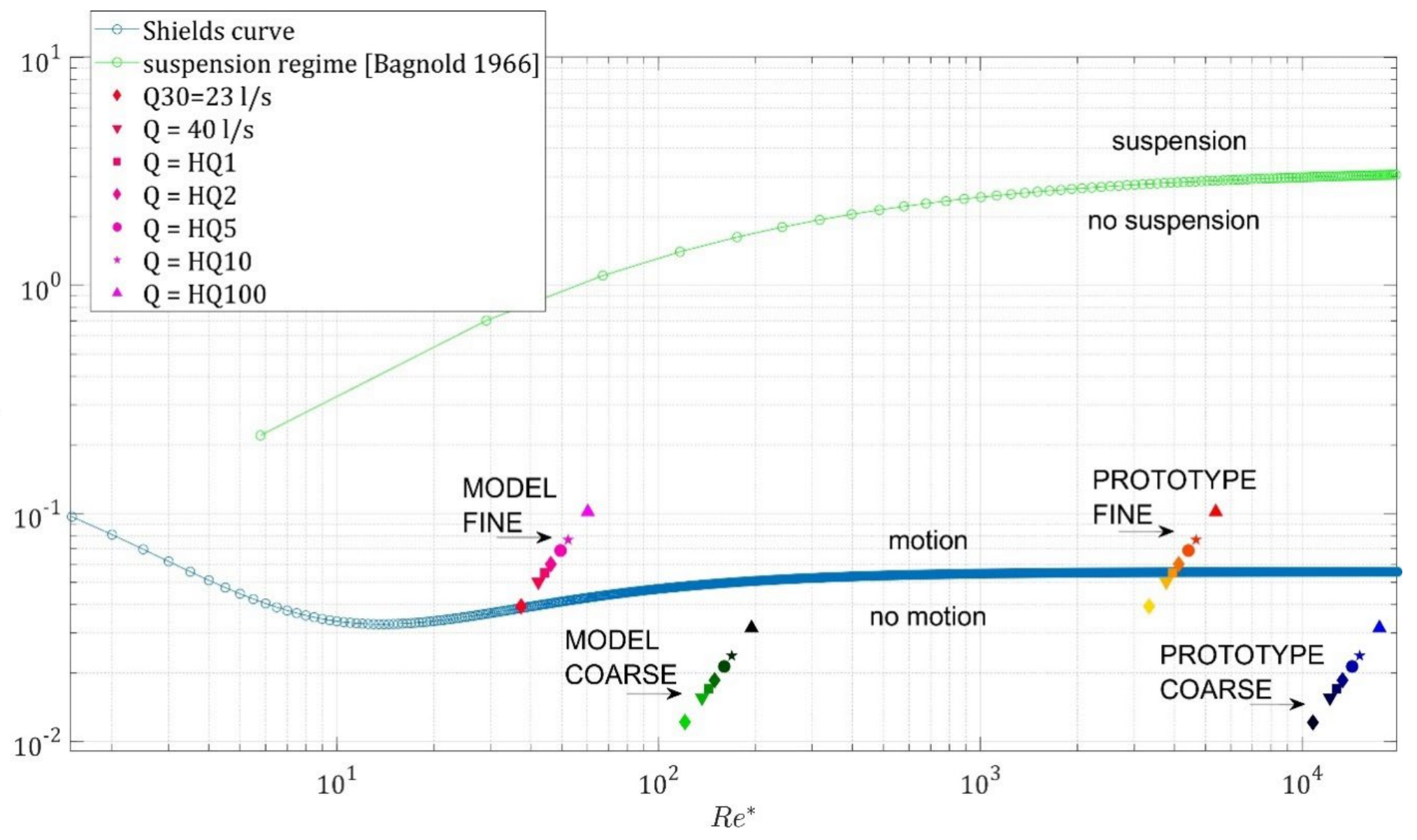

Figure 2: Extended Shields diagram

	Experiment Name	Scenario	Discharge [l/s]
1	HQ10	Constant: HQ10	Q = 97.8
2	HQ100	Hydrograph: HQ100	Qmax=173.3
Addition of 180 kg of fine sediments in six lateral embankments			
Mixing sequence	Q30_withFS	Constant: Q<HQ1	Q = 40
	HQ1_withFS	Constant: HQ1	Q = 48.9
	HQ2_withFS	Constant: HQ2	Q = 58.8
	HQ5_withFS	Constant: HQ5	Q = 78.3
	Addition of 22.7 kg of fine sediments		
	HQ2_withFS(2)	Constant: HQ2	Q = 58.8
	Addition of 10.1 kg of fine sediments		
	HQ5_withFS(2)	Constant: HQ5	Q = 78.3
3	HQ10_withFS	Constant: HQ10	Q = 97.8
4	HQ100_withFS	Hydrograph: HQ100	Qmax=173.3
5	HQ100_withFS(2)	Hydrograph: HQ100	Qmax=173.3

Table 1: Sequence of experiments.

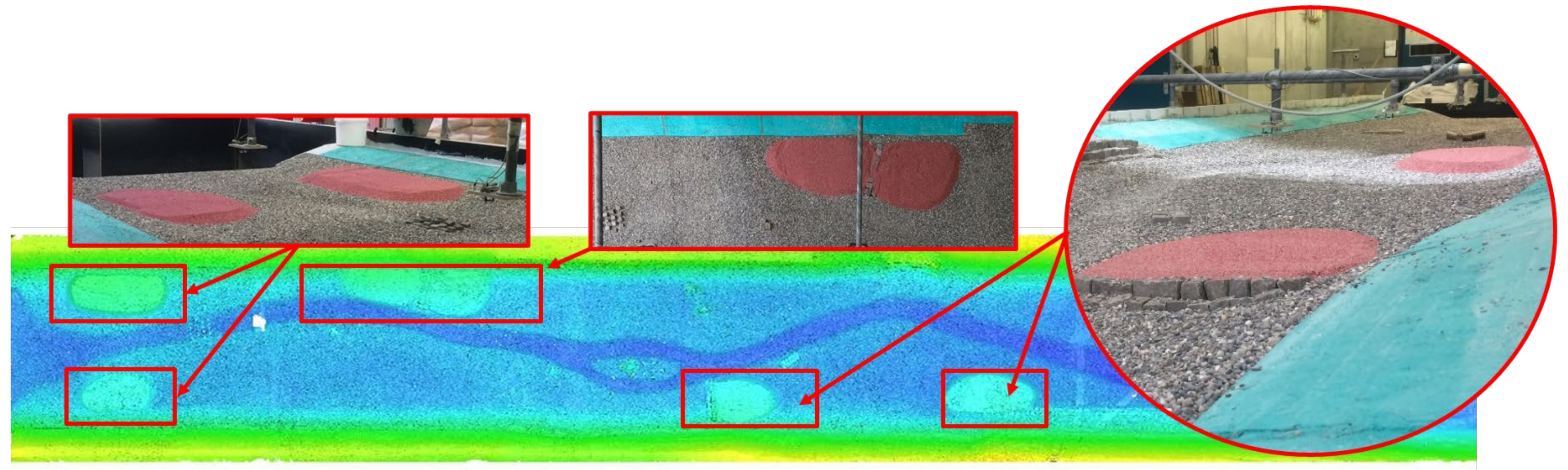

Figure 3: Scan of the model and location of the six later embankments before the mixing.

During the experiments, water level and discharge measurements were acquired. Two GoProHERO 8 cameras were used to monitor the spreading and mixing of the fine sediments over the original bed-surface. A LEICA RT360 laser scanner was used to scan the bed surface, before and after each experiment, to monitor the sedimentation and scour depth evolution. Finally, after each experiment, the sediment mass fallen in the outlet pool was collected, dried, and weighted to obtain a rough estimation of the bed load transport rate.

Results

Table 2 shows that, for the same discharge scenario, the water level decreases in presence of fine sediments. Correspondingly, the depth-averaged velocities are larger. This is due to **an average decrease in surface roughness** due to the mixing of the fine and coarse fraction. An image-analysis technique, based on Color-Based Segmentation was used to compute the percentage of bed surface mixed with fine sediments, which increased from 10% to about 70% (after HQ100(2)), as shown in Figure 4. The same image-analysis technique allowed estimating the surface d_m. After each scenario, a bed probe was collected and analyzed: **a small drop of the bed $\mathbf{d_m}$** was observed, but the variation of the bed composition mainly concerned the most superficial layer. The largest observed **mixing depth was 2 cm** (after HQ100(2)). The formation of a bridge layer, due to the relative size of coarse and fine sediments ($d_{15,coarse}/d_{85,fine} = 1.37$ and $d_{m,coarse}/d_{m,fine} = 3$), probably prevented a deeper infiltration. In presence of fine sediments, isolated coarse grains were observed to occasionally move at discharge Q: HQ5 < Q < HQ10 ($\tau^*_{CR} = 0.018$), while before the sediment replenishment coarse grains were entrained into motion only at HQ10 < Q < HQ100 ($\tau^*_{CR} = 0.045$). These observations confirm previous findings (Wilcock & Crowe, 2003) and can be explained by: 1) the hydraulic smoothing of the bed and increase in near-bed flow velocities; 2) the increment of coarse grains flow-exposure and the drop of the pivot angle they must rotate to be entrained in the flow; 3) the decrease of detrainment locations.

	without fine sediments		with fine sediments				
	HQ10	**HQ100**	**HQ1**	**HQ2**	**HQ5**	**HQ10**	**HQ100**
Q [l/s]	97.8	173.3	48.9	58.8	78.3	97.8	173.3
h [m]	0.132	0.167	0.094	0.106	0.116	0.127	0.165
V [m/s]	0.481	0.614	0.388	0.436	0.460	0.500	0.627
FR [-]	0.422	0.480	0.403	0.429	0.432	0.449	0.493
Re [-]	4.89E+04	7.88E+04	2.82E+04	3.55E+04	4.09E+04	4.87E+04	7.95E+04

Table 2: Main time and space-averaged hydraulic variables characterizing each experiment.

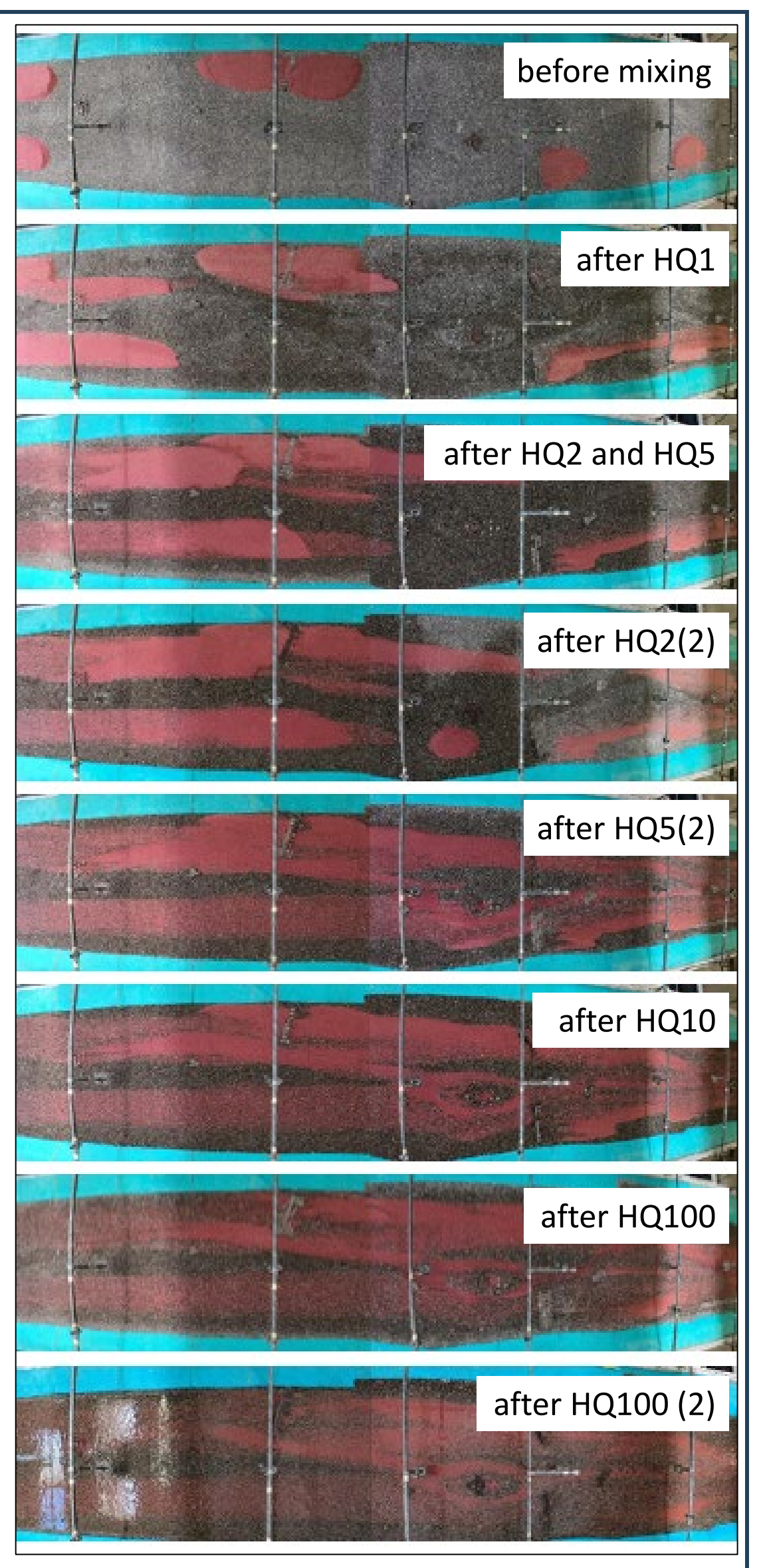

Figure 4: Chronological sequence showing the mixing evolution and the increase of the fraction of bed-surface covered by fine sediments.

After high discharge scenarios, local erosion was observed especially at the planned ecological structures (see Figure 5). The extent of the scour depth at these locations increased up to 70% at HQ10 and up to 800% at HQ100 after the addition of fine sediments.

The measured bed load transport was compared to an estimation based on Wilcock and Crowe (2003) model which depends on the estimated characteristic surface diameter d_m. The comparison is shown in Table 3 and, for discharges with smaller scale effects, it is satisfactory.

Discharge scenario	Measured [kg]	d_m [mm]	Predicted [kg]
HQ1	6.7	1.55	2.8
HQ10	8.9	1.60	12.1
HQ100	28.1	1.79	22.3
HQ100 (2)	21.7	1.68	21.5

Table 3: Comparison between the measured bed-load and the one predicted according to Wilcock and Crowe (2003)

Figure 5: Examples of local scour after HQ100

Conclusions

The main results of our experimental work showed that:

- The addition of fine sediments (spawning substrate) modified the granulometry of the coarse protective layer but only up to a third of its thickness: due to the relative size of the coarse and fine sediments a deeper infiltration is not expected. However, at high flows (i.e. Q>HQ100), the process of "kinetic sieving" might increase the mixing depth.
- During smaller flood events, fine sediments were transported into the low-water channel. This may endanger the achievement of the minimum flow depth required for ecological reasons and thus represents a possible negative outcome.
- The addition of fine sediments increased the mobility of the coarse protective layer. However, it did not prove to be critical for its stability.
- Local erosion can significantly augment in presence of fine sediments.
- The transport model of Wilcock & Crowe (2003) was successfully applied to estimate the shear stress at incipient motion and the model bedload transport. Nevertheless, results strongly depends on the surface d_m, which has high spatial and temporal variability and is difficult to be estimated in the field.

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References

- Kondolf, G. Mathias, and M. Gordon Wolman. 1993. 'The Sizes of Salmonid Spawning Gravels'. Water Resources Research 29(7):2275–85. doi: 10.1029/93WR00402.
- Dudill, Ashley, Philippe Frey, and Michael Church. 2017. 'Infiltration of Fine Sediment into a Coarse Mobile Bed: A Phenomenological Study'. Earth Surface Processes and Landforms 42(8):1171–85.
- Gibson, Stanford, David Abraham, Ronald Heath, and David Schoellhamer. 2009. 'Vertical Gradational Variability of Fines Deposited in a Gravel Framework'. Sedimentology 56(3):661–76.
- Henry, Pierre-Yves, and Jochen Aberle. 2018. Hydralab+ Deliverable D8.3 Protocols for Scaling Morphodynamics in Time.
- Houssais, M., and E. Lajeunesse. 2012. 'Bedload Transport of a Bimodal Sediment Bed'. Journal of Geophysical Research: Earth Surface 117(F4).
- Jackson, William L., and Robert L. Beschta. 1984. 'Influences of Increased Sand Delivery on the Morphology of Sand and Gravel Channels'. JAWRA Journal of the American Water Resources Association 20(4):527–33. doi: 10.1111/j.1752-1688.1984.tb02835.x.
- Venditti, J. G., W. E. Dietrich, P. A. Nelson, M. A. Wydzga, J. Fadde, and L. Sklar. 2010. 'Mobilization of Coarse Surface Layers in Gravel-Bedded Rivers by Finer Gravel Bed Load'. Water Resources Research 46(7). doi: https://doi.org/10.1029/2009WR008329.
- Wilcock, P. R., and J.C. Crowe. 2003. 'Surface-Based Transport Model for Mixed-Size Sediment'. Journal of Hydraulic Engineering 129(2):120–28. doi: 10.1061/(AS CE)0733-9429(2003)129:2(120).
- Wilcock, P. R., and S. T. Kenworthy. 2002. 'A Two-fraction Model for the Transport of Sand Gravel