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# Incision and width changes caused by dam removal. Experiments and data analysis

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ABSTRACT: Dam removal may cause severe disruptions to the river, both upstream and downstream of the former location of the dam. The aim of the paper is to study the physical response to dam removal in the former deposit upstream. Specifically, the goal is to analyze bed profile evolution and the associated change in channel width. An experimental investigation has been carried out to study these topics. The experiments consisted of (i) a study of the delta front progradation within the impoundment and (ii) a set of runs in which profile and planform changes caused by dam removal were continuously monitored. All experiments were performed in a tilting flume filled with a non-uniform sediment mixture made of sand and gravel. The dam itself was made of three slats that were sequentially removed, allowing the remaining height to control the response of the river to removal. During the early stages of each removal, a narrowing process was observed while in more advanced phases, channel widening was reported. Narrowing-widening process was linked to bed erosion. The bed degradation process has been satisfactorily reproduced by a set of empirical equations that describe (i) bed erosion through foreset slope evolution and (ii) sediment discharge downstream.

*Keywords: Dam removal, Incision, Degradation, Experiments, Transport of sediment mixtures.*

## 1 INTRODUCTION

Many dam reservoirs are filled with sediment to the verge of being useless (there is not enough water storage capacity for design purposes). Moreover, some other dams are close to the end of their life-span (Evans et al., 2000). In those cases, dam retirement can be considered a tool for sediment managers, ASCE (1997), Graf (2002). Actually, a number of dams have already been removed (550 in the United States in the last 20 years, Granata et al., 2007) and some others are under study for removal. Although there are many reasons for removal, river restoration is one of the common goals pursued when a dam is removed (Cantelli et al., 2007).

However, dam removal perturbs the existing new eco-system both downstream and upstream of former dam location (at least during the early stages after dam retirement). Dam removal provokes ecological, morphological, and even social and economic impacts that must be addressed (Graf, 2002). Many studies have focused on the ecological impacts (Bednarek, 2001, Cheng et al., 2006) while others have studied the geomorphic impacts of dam removal (Doyle et al. 2003, Cheng and Granata, 2007). Although much effort has been exerted in the understanding of these impacts, there is still much concern regarding biological, chemical and physical impacts of removing dams (Shuman, 1995). Among others, an important issue that has not been properly quantified is the sediment transport rate released downstream after removal of a dam of given height. The role played by the grain size distribution of the upstream sediment deposit in these processes is still unknown (ASCE, 1997).

Cantelli et al. (2004) performed a set of runs to study the degradation process in the sandy deposit upstream. They observed that the very early stages of the degradational process were first accompanied by a relatively rapid reduction of the channel width (erosional narrowing). Hereafter, a slow increase in width accompanying degradation (erosional widening) was observed. These findings were contradictory to those which assumed that channel widens as bed degrades, whatever the incisional rate is (Doyle et al., 2003).

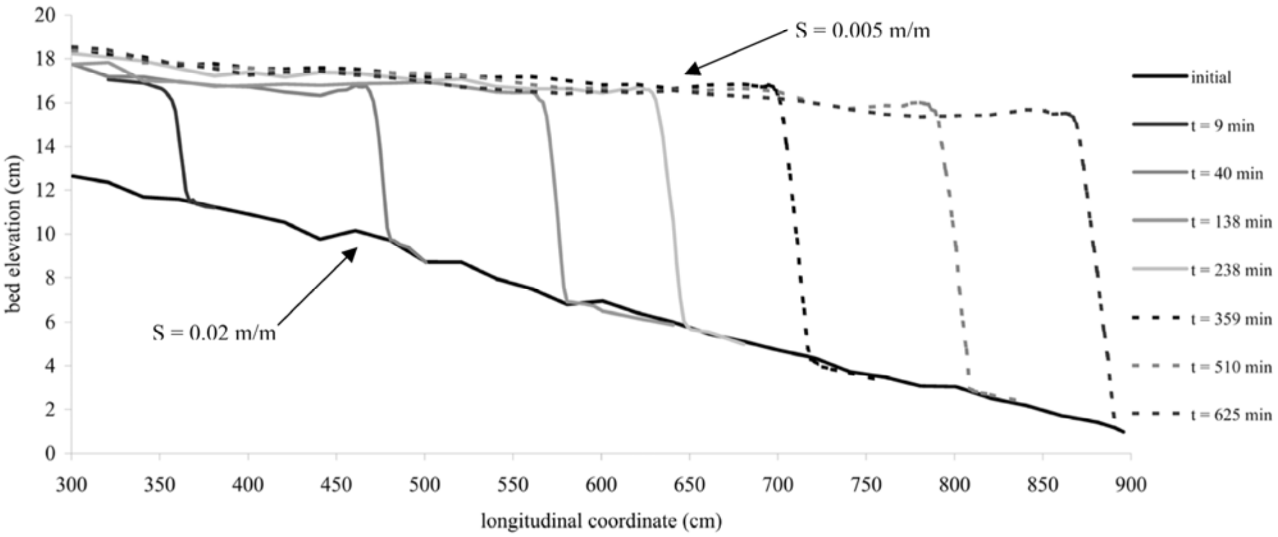


Figure 1. Delta progradation profiles of run 2, obtained by averaging data from the four probes across the flume.

The main goal of this investigation is (i) to check the previous results in uniform sand on the coupled incision and width changes (Cantelli et al. 2004) now in a mixed bed, and (ii) to obtain a set of experimental data about the degradational process in the deposit upstream of the dam location and about the sediment transport rates released downstream. A set of runs have been performed to study these objectives.

## 2 DESCRIPTION OF THE EXPERIMENTAL SET-UP AND PROCEDURES

The experiments were carried out in a 12m-long, 0.60m-wide rectangular tilting flume. The sediment feeder was placed within the first 2 meters of the flume. The initial bed slope was 0.02 m/m for all experiments. The bed material was composed of a sediment mixture of $D_g$ = 3.39 mm and $\sigma_g$ = 1.8, where subscript *g* denotes they were obtained by geometric calculations. The specific gravity of the mixture was 2.58, bed porosity was 0.35 and $D_{90}$ was 7.83 mm. The dam was located 9 m from the inlet of the flume.

Two types of experiments were carried out. The first type modeled the creation of a delta upstream of the dam (by filling the impoundment with the sediment mixture), while the second focused on studying erosional processes due to dam removal. The latter experiments were performed in a staged way: the dam was not removed all at once. Instead the dam consisted of three slats of 4 cm height stacked vertically, removed sequentially in such a way bed incision upstream was controlled by the remaining dam below. The total dam height above the bed was 12 cm.

Water discharge was measured with an electromagnetic flowmeter. In the progradation experiments, sediment was introduced by means of a sediment screw-type feeder at a constant rate. Table 1 shows the main characteristics of all experiments. Dam removal experiments were performed without sediment feeding.

Table 1. Main characteristics of the experiments carried out

| run | type | $Q_w$ | $Q_s$ |
|---|---|---|---|
| | | $m^3/s$ | kg/s |
| 1-2 | Progradation | $47\cdot10^{-3}$ | $1.33\cdot10^{-2}$ |
| 3 | Dam removal | $2.0\cdot10^{-3}$ | 0 |
| 4 | Dam removal | $2.5\cdot10^{-3}$ | 0 |
| 5 | Dam removal | $3.5\cdot10^{-3}$ | 0 |
| 6 | Dam removal | $4.0\cdot10^{-3}$ | 0 |

### 2.1 *Progradational experiments*

The flume upstream of the dam was uniformly filled with the mixture up to a depth of 0.1m prior to the experiments. Sediment feeding into the flume at the specified rate and water pumps were switched on simultaneously. Bed profiles were measured with the aid of 4 ultrasonic transducer probes (see Wong et al., 2007), located at 13.5, 24.5, 35.5 and 46.5 cm with respect to one side of the flume. So, four bed profiles were simultaneously measured. The frequency of profile measurements decreased as the run progressed: delta progradation rates were much faster at the beginning of the run than at the end. The spatial distribution of measurements was increased at the junction between the topset and the foreset in order to appropriately capture the foreset slope. Figure 1 shows an average bed profile evolution for run 2.

Water and sediment discharges were chosen in such a way that the obtained topset slope was close to 0.005 m/m (the one that would be used for dam removal experiments). Moreover, in order for the filling not to take too long, the sediment feed rate was set to $1.33\cdot10^{-2}$ kg/s. With this in mind and with the aid of previous experiments carried out with the same facility and mixture (Viparelli et al., 2008), water discharge was set equal to 47 l/s. These two discharge values were in equilibrium with the chosen slope of 0.005 m/m. The run was ended when the lowest part of the foreset reached the dam. As is seen in Figure 1, more than 10 hours were needed to completely fill the reservoir. The progadational experiment was repeated twice (runs 1 and 2) to check for consistency.

### 2.2 *Dam removal experiments*

The delta geometry formed in test 1-2 was manually reproduced without taking into account the stratigraphy occurred in the filling process of the impoundment. Topset slope was approximately set equal to 0.005 m/m. As before, the entire length of the flume was filled with a 0.1m-deep layer of the sediment mixture, both upstream and downstream of the dam location. At that station, a 0.1m-high base dam was emplaced as a base, taking care to ensure that the three stacked, removable slats above, were completely horizontal in the cross-section.

In order to make sure that the degradation process would develop in the center of the deposit, a small pilot channel was dug, with widths of 24.1-34.6 cm depending on the flow rate, calculated according to Parker (1978). The depth of this small channel was between 1.4 cm and 1.7 cm. In Figure 2, the initial configuration of dam removal runs is illustrated.

Figure 2. Initial configuration (run 3) with the 3 slats that are to be removed and the small pilot channel.

Bed elevations were measured by means of 20 rulers driven in the deposit both upstream and downstream of the dam. The ruler closest to dam was located at station 8.75 m, i.e. 0.25 m upstream of the dam. Between that and station 6.95 m, 10 rulers were spaced as 0.20 m. Between x = 6.95 m and x = 4.15 m 7 rulers were driven in so as to be equally spaced. Farther upstream three more rulers were placed spaced 0.50 m out until reach station 2.65 m. Finally, 6 more rulers were driven in until reaching station 11 m downstream of the dam.

Incisional process at stations close to the dam occured relatively fast, especially during early stages. This was the reason why bed profile was laterally recorded by means of three video cameras. Each one recorded the evolution of three rulers, so that the nine rulers closest to the dam were video-monitored. Bed elevation at other stations were visually measured once incision reached them.

In order to measure changes in channel width, two more video cameras were placed above the flume. Thus a zenithal view of the flume was obtained. Only the closest sections to the dam were recorded. The first video camera recorded stations between 8.75 m and 8.35 m, i.e. the flume between the first three rulers. The second video camera recorded the width evolution of 5 more rulers upstream. Thus water widths between stations 7.35 m and 8.75 m were video monitored.

As noted above, 3 slat removals were sequentially carried out in each run. Before removing the first slat, water flow occupied not only the central channel but also the two "adjacent" floodplains so water spilled over the entire length of the dam. Thus, during the first seconds of the experiment, the floodplain stations farthest downstream were washed away.

There was no sediment feeding in all runs. Initial conditions were such that there was no sediment transport on the topset deposit. Once the first slat was removed rapid incision was observed at stations close to the dam. The body of water between the foreset and the dam (see Figure 2) was quickly filled with sediment coming from the floodplain and the central pilot channel.

Channel incision progressively caused all the water to concentrate into the pilot channel. So, just a few seconds after a slat was removed, all water spilled over the remaining dam through this central channel region. As degradation progressed upstream water flow became confined to the central channel at upstream stations.

The 2$^{nd}$ and 3$^{rd}$ slats were removed when bed elevation changes downstream were minor and when it was visually observed that sediment transport rates upstream were much lower than the initial rates, respectively.

## 3 EXPERIMENTAL RESULTS

Experimental results obtained from dam removal experiments are shown below. These results are analyzed in terms of bed elevation evolution, top width changes, foreset slope evolution as an empirical way to describe the degradational process upstream of the dam and finally sediment transport rates.

## 3.1 *Bed profile evolution*

Bed evolution after each removal of the 4 runs has been analyzed. Under the steady flow assumptions (for which a diffusive equation of bed evolution can be formulated), it is already known that degradational profiles upstream of a bed-level lowering follow an upward-convex pattern.

After each slat removal, bed degradation progressed upstream. During the first stages of the process, the bed profile showed an upward-convex trend: bed slope increases downstream toward the former dam location. However, this convexity disappears as time goes by (Fig.4), even eventually showing some upward-concavity. It is thought that this is due to an increase in water discharge per unit width: recall that at the beginning of the experiment, water flowed over the two adjacent floodplains as well as in the pilot channel. But as time passes, the incised channel was able to convey all the water flow. Thus, there was a mobile transition zone (migrating upstream) in which water stopped filling the whole width, and flow concentrated in the incising channel. Within this transition zone there was an increase in unit water discharge. And, even though solid discharge rises as well, the absolute increase in unit discharge is much larger, so that bed slope decreases in the streamwise direction, i.e. the bed profile is concave upwards. Figure 3 shows a sketch of how flow concentration is produced in a half cross-section of the flume.

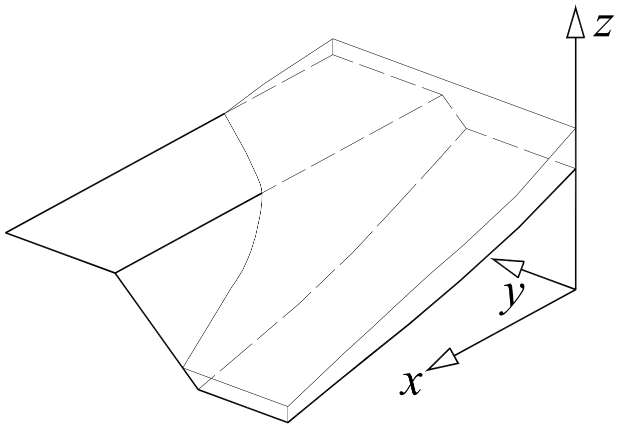


Figure 3. Sketch of flow concentration between two half cross-sections. Vertical dimensions are exaggerated. For the sake of simplicity, bed width is kept constant.

The incision during the convex upwards phase (that can be associated to a diffusive evolution of bed elevation) did not affect all sections from the beginning. In Figure 4, the longitudinal evolution of run 3 has been plotted. It can be seen how the incision process evolves after the 1st and 2nd slat removals (between t = 0 s and t = 900 s for the first one and between t = 900 s and t = 1800 s for the second one).

The first two removals, especially the second one, can be considered as base-level lowering experiments: bed elevation downstream of the dam after removal did not affect how incision is produced upstream, because of the height of the remaining dam. On the contrary, after 3rd removal sediment released after previous dam slat removals, caused the degradation process upstream to be affected by the downstream bed elevation profile. This is the reason why all analyses have been done in terms of the first two removals.

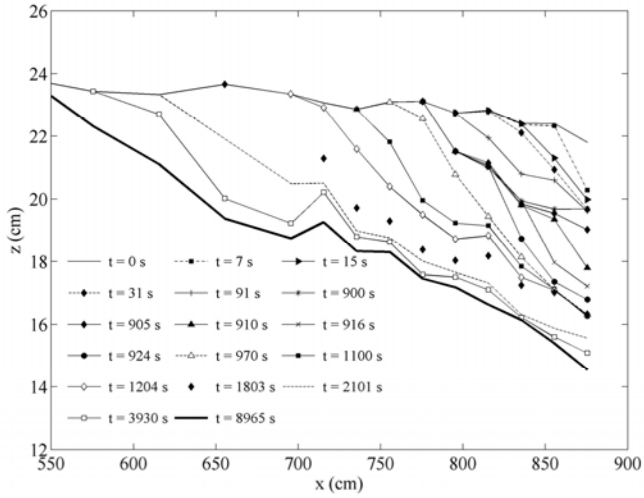


Figure 4. Bed profile evolution for run 3. The first slat removal took place at t = 0. The second slat was removed at t = 900 s and third one at t = 1800 s. Water flowed from the left to the right.

## 3.2 *Channel width changes*

Water surface width (top width) was obtained from video frames recorded by the two zenithal cameras. All four experiments were analyzed, including top width evolution after the 3rd removal. Major changes were produced during the first two removals, for which a common trend was observed.

After the 1st dam removal, channel narrowing was observed. Indeed an upstream-migrating channel-narrowing perturbation was observed in all runs. This process had been previously noticed by Cantelli et al. (2004) in dam removal experiments with uniform sand. As an example, Figure 5 is a plot of the top width evolution of 4 cross-sections after the 1st slat removal in run 3.

Channel narrowing proceeded upstream (convection) i.e. a section located farther upstream needed more time to be affected by the width disturbance. Moreover, the speed of width change depended on how close to the dam the section was: the closer to the dam the faster it narrowed. But this initially rapidly narrowing section later widened, until eventually recovering the initial width of the pilot channel, or becoming even wider. Upstream sections maintained a narrowed width until next slat was removed. Maximum amplitudes of narrowing range between 3.7 cm and

4.5 cm, during the 1st dam removal. No trend in the maximum amplitude of width perturbation as a function of water discharge was found. (It is thought instead that it depends on the slat height, instead). However, it was observed that the location of maximum narrowing does depend on the water discharge: the higher discharge, the further upstream from the dam it occurred.

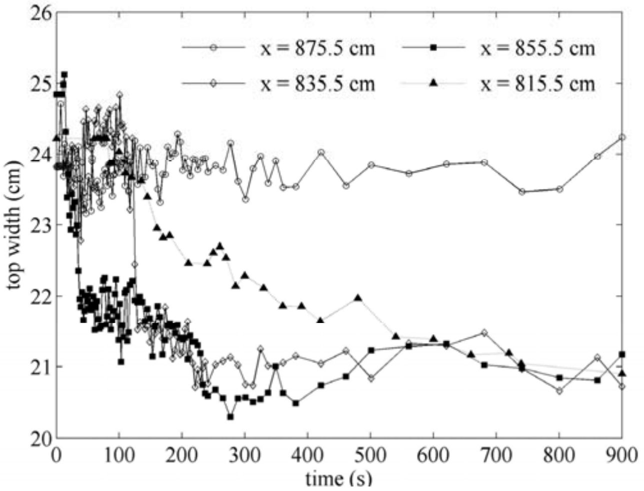

Figure 5. Evolution of 4 cross-sections named after their abscissa, following 1st slat removal of run 3.

Width evolution after the 2nd removal showed a slightly different behavior than the one illustrated above. We must distinguish between sections already affected by the 1st slat removal and those that remained unaffected. (a) The former ones underwent a similar narrowing in magnitude than that produced after 1st removal. However, they widened during a relative short period of time (between 100 and 200 s after the slat is removed). (b) The latter sections behaved in the same way as those affected by the 1st removal: they narrowed and keep this narrowing after the 3rd removal. The first trend can be seen in Figure 6, in which the width change with respect to the top width at time t = 900 s (i.e. just after 2nd removal) for run 3 is shown. As before, an upstream convection of width perturbation was observed, but also a damping of its amplitude as time passed. That is, sections farther upstream needed more time to be affected by narrowing, and amplitude of width disturbance was less once they noticed it. These two features can be clearly seen in Figure 6, for instance by comparing water width changes between stations 875 cm and 835 cm.

In Figure 6 it is seen how sections widened once they reach a minimum width, as well. Two different widening mechanisms were observed: (i) mass failure and (ii) bank erosion produced by excess bank shear stress. The widening process in station 875 was produced through mass failure while in sections further upstream, i.e. station 835, it was produced mainly by excessive shear stress in the bank. The difference between these two mechanisms can be seen in Figure 6 by the slope of the top width change: a steeper slope corresponds to widening through mass failure (i.e. sudden increase in water width) while a milder slope indicates bank erosion.

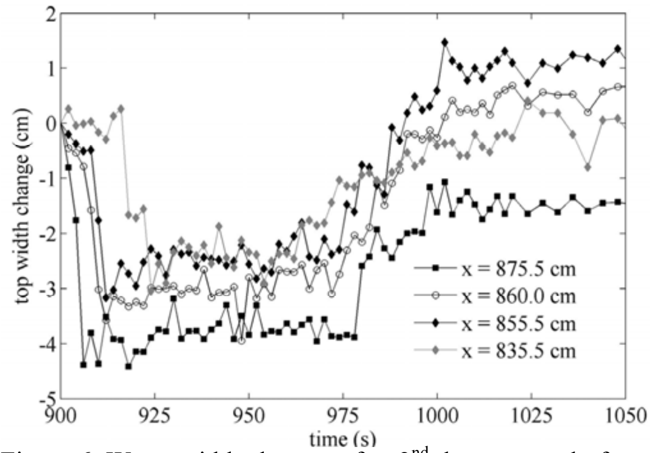

Figure 6. Water width changes after 2nd dam removal of run 3 for 4 cross-sections named after their abscissa. Coupling bed elevation and top width evolution.

We analyzed coupled changes in bed elevation and top width. We used data corresponding to run 4. As before, we distinguish between the 1st and 2nd removal.

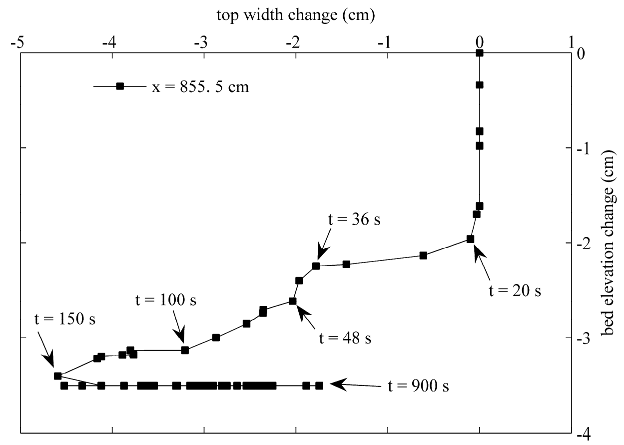

Figure 7. Changes in top width (abscissa) together with bed elevation (ordinate) in run 4 for cross-section 855.5 cm.

Bed evolution after 1st slat removal can be divided into 5 consecutive phases. However, if a particular section is located far upstream, these five phases may not be totally accomplished: there is not enough time between the 1st and the 2nd removal for the effects to propagate sufficiently far upstream.

The 1st phase consists of a strong degradation, but almost no change in channel width. The time elapsed during this phase strongly depends on how far the section is from the former dam location (the farther the longer). The 2nd phase consists of a moderate erosion accompanied by a strong narrowing. Afterwards, during the 3rd phase the bed erosion rate increases while the narrowing rate decreases. During the 4th phase there is little change in bed elevation, while the cross-section attains maximum narrowing. From this point and during the last phase, the section begins to widen without much change in bed elevation. These coupled trends of bed and top width have been plotted in Figure 7 for cross-sections 855.5 cm.

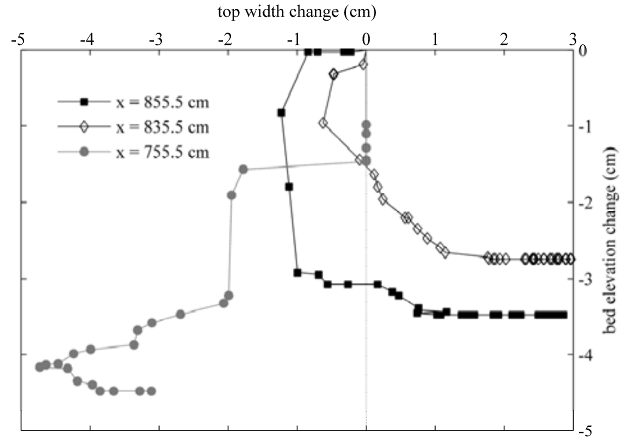


Figure 8. Changes in top width (abscissa) together with bed elevations (ordinate) after 2nd slat removal in run 4, for 3 cross-sections.

As before, after the 2nd removal, all sections that were not affected by the 1st dam removal behave in the same way as the sections affected before. For example, see section x = 755.5 cm in Figure 8. Note that incision at this station is larger than the slat height that is removed. This is only possible because it did not undergo erosion during the 1st removal, so that when erosion reached that station the cumulated bed elevation change at the outlet was 8 cm (twice the slat height). However, sections that were affected during the 1st removal evolved in a slightly different way: the section narrows until reaching a minimum top width, after which it widens together with some degradation.

All this process of degradation with narrowing and widening can be gathered in a global trend that includes a relatively quick 1st phase of degradation with narrowing followed by a 2nd phase in which degradation is minor and is accompanied by widening. The latter phase is much longer than the former. This global trend has been observed in all 4 runs carried out.

### 3.3 *Foreset slope evolution*

The time evolution of the foreset slope is modeled here, assuming that it is a straight line passing through the top of the remaining dam. That is, this point acts as a fulcrum, around which the line rotates. If the time evolution of this foreset slope is known, the process of degradation upstream of the dam is be easily evaluated assuming the topset slope is also known.

We have analyzed the process during the 2nd dam removal. The foreset slope at different times for the four experiments was obtained by least squares fitting. In order to deal with all four experiments, a dimensional analysis has been carried out. The variables involved in this analyses are: $S$, $S_0$, $t$, $Q_w$, $B_{b0}$, $H$, where $S$ the foreset slope, $S_0$ the former bed slope, $t$ is the time at which the slopes are obtained, $Q_w$ is the water discharge of each run, $B_{b0}$ is the initial width of the channel and $H$ the height of the removed slat. We denote $S'$ as the difference between the foreset slope and the former slope $S_0$. The foreset slope should tend to the former slope $S_0$ at the end of the experiment, so $S'$ will tend to zero. Choosing $H$ and $t$ as the main variables, $S'$ can be described as a function of two dimensionless parameters:

$$\hat{t} = \frac{tQ_w}{H^3}, \quad \hat{B} = \frac{B_{b0}}{H} \tag{1}$$

in such a way that the foreset slope can be defined as $S = f\left(\hat{t}, \hat{B}\right) + S_0$. This formulation of dimensionless time makes possible comparison between foreset slopes belonging to different experiments: the degradation in a run with high discharge is faster than with that low discharge.

Figure 9 illustrates the foreset slope $S$ as a function of dimensionless time $\hat{t}$ for all runs. In this plot, different trends depending on the flow rate are not observed. Rather, all data seems to collapse in a single curve. When dimensionless time tends to infinity, the foreset slope tends to 0.02 m/m, which corresponds to the bed slope prior to the creation of the deposit upstream of the dam.

If it is assumed that a power function of dimensionless time and dimensionless width can describe the foreset evolution, a general expression for the slope can be proposed:

$$S\left(\hat{t}, \hat{B}\right) = a_1 \hat{t}^{b_1} \hat{B}^{c_1} + S_0 \tag{2}$$

where coefficients $a_1$, $b_1$ and $c_1$ are obtained by least squares fitting. The obtained values are respectively: $a_1$ = 1.16, $b_1$ = -0.46 and $c_1$ = 0.08. It seems that foreset slope depends weakly on dimensionless width (though this parameter varied very little in the experiments). If this variable is dropped out from the analysis and the fitting is repeated, the new coefficients are: $a_1$ = 0.99 and $b_1$ = -0.46, which are very close to those obtained immedlately above. A good agreement is observed for relatively steep to mild values of the foreset slope while the equation seems to overpredict the slope for the initial stages of the dam removal process (those that produce very steep slopes). That is, the modified equation (2) predicts during the early stages a slower process of erosion than the actually observed.

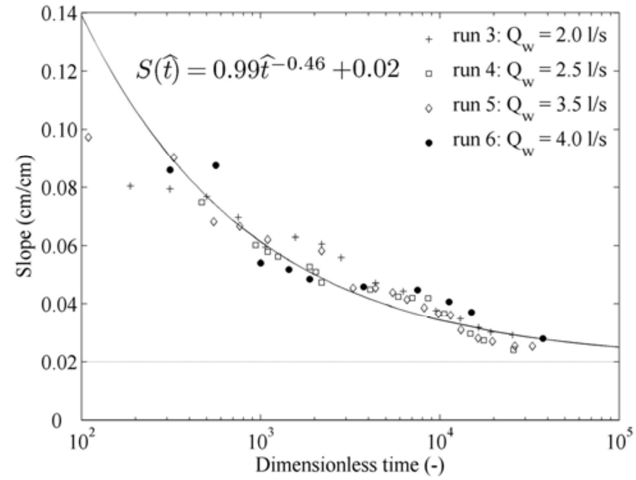


Figure 9. Calculated foreset slopes for all runs after the 2nd removal as a function of dimensionless time defined in (1).

## 3.4 *Sediment transport rates*

Once bed elevation and top width change are known, sediment discharge can be obtained by a volumetric calculation. There are several possibilities for calculation, mainly regarding water width change: for instance, if a particular cross-section widens, an extra amount of sediment coming from the banks has to be added. Theoretically, one cross-section can widen or narrow (in the transverse direction), and also aggrade or degrade. This gives 16 combinations of calculation if a control volume bounded by two consecutive cross-sections is considered. However, the most relevant possibilities are those that involve degradational processes. In case of widening, volume calculation must account for the material coming from the entire height of the bank (not only the depth of bed degradation). Obviously, this bank gets higher as bed degrades.

Maximum sediment discharge at the outlet largerly depends on the height of the slat that is removed. In these experiments, this value is more or less constant for all runs, because the slats are always 4 cm high. If bed width were kept constant during the whole degradational process, the total evacuated sediment volume out would depend on the difference between the initial and final bed slopes. The latter is a function of the boundary conditions, sediment and water discharge. It should also be noted that time at which the final configuration is reached is highly dependent on water discharge.

Sediment discharges at the outlet have been obtained by volumetric calculations. Higher sediment transport rates were observed for runs with higher water discharges. Sediment volume calculated after the 1st slat removal is shown in Figure 10. The asbscissa shows is dimensionless time defined by equation (1). The volume follows the same curve for the early stages of the process in all four experiments. However, as time goes by, every run develops a unique curve.

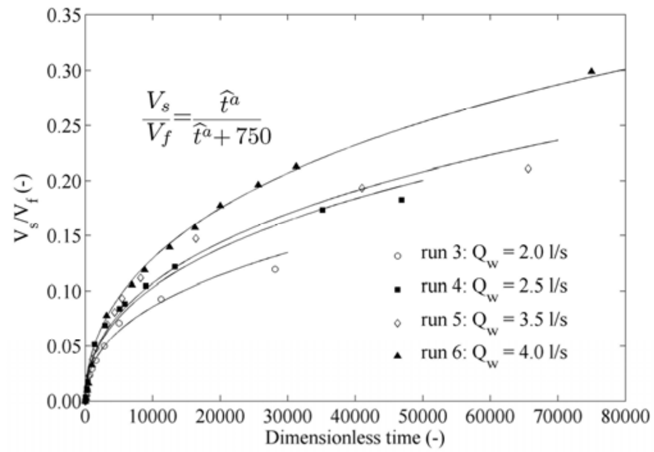


Figure 10. Dimensionless sediment volume (as a fraction of the total volume of the delta) released at the position of the dam for all four experiments carried out. A single expression that describe the volume is presented as a function of parameter *a*.

Figure 10 also shows the equation that has been fitted to predict the sediment volume released downstream after a removal:

$$\frac{V_s}{V_f} = \frac{\hat{t}^a}{\hat{t}^a + 750} \tag{3}$$

The expression (3) depends on one hand on the parameter $a$ and on the other on the final volume $V_f$ that would theoretically be released. Both of these parameters are shown in the equation directly on the figure. The latter parameter roughly depends on the geometry configuration (dam height, bed slopes, etc). The former depends only on the water discharge, $Q_w$ as:

$$a = 1.0 \cdot Q_w^{0.12} \tag{4}$$

Once the sediment volume is known, dimensional sediment discharge $Q_s$ can be obtained by just taking the derivative of the equation (see Figure 10):

$$Q_s = K_Q \frac{a\hat{t}^{a-1}}{\left(\hat{t}^a + 750\right)^2} \tag{5a}$$

where dimensional coefficient $K_Q$ is given by

$$K_Q = 750 \frac{Q_w V_f}{H^3} \tag{5b}$$

The volumetric methodology used to compute total sediment discharges enables us to obtain the contribution of the discharge coming from the banks. This ratio has been calculated and integrated to get an averaged value for the 1st and the 2nd dam removal period. It is found that that for the first removal the material coming from the banks represents 5.5% of the total sediment; this proportion rises to 18.2% for the second dam removal period. This order-one difference is produced because during the first period, as noted above, there is no channel widening (the bed degrades and narrows and the narrowing is maintained) while in the second period there is rapid recuperation of width after some narrowing in the closer sections to the dam location.

## 4 CONCLUSIONS

A set of experiments on dam removal with sediment mixtures is presented. The dam was removed in a staged way by dividing the entire height of the dam into three stacked horizontal slats. Each slat was sequentially removed once morphological changes induced by the previous removal, both upstream and downstream of the dam, were minor.

During the early stages after a given removal,bed profiles showed an upward-convex trend, whereas as water concentrates into the central pilot channel, bed exhibited an upward-concave profile later on. It is suggested that this change is caused by flow concentration from the floodplain into the channel.

In all dam removal experiments, the width change associated to bed degradation followed a similar trend: sudden narrowing that it is approximately kept constant after the 1$^{st}$ removal and sudden narrowing followed by slow widening as run proceeds after the 2$^{nd}$ one.

It is found that the foreset time evolution/dissection after dam removal, i.e. the upstream degradation rates, can appropriately be described by a power function of a dimensionless time that accounts for water discharge and dam height.

Finally, some expressions are given to describe temporal evolution of the sediment volume (and sediment transport rate) released downstream after removal, as a function of the two main variables involved in the process: height and flow rate. Good results are obtained when comparing experimental data and results with the mathematical expressions, even though the lack of data does not allow us to validate these latter equations.

## ACKNOWLEDGEMENTS

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