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Generation of autogenic knickpoints in laboratory landscape experiments evolving under constant forcing.

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ABSTRACT

The upward propagation of knickpoints in the long profiles of rivers is commonly related to discrete changes in tectonics, climate or base-level. However, the recognition that some knickpoints may form autogenically, independently of any external perturbation, may challenge these interpretations. We investigate here the genesis and dynamics of such autogenic knickpoints in laboratory experiments at the drainage basin scale, where landscape evolved in response to constant rates of base-level fall and precipitation. Despite these constant forcing, we observe that knickpoints regularly initiate in rivers at the catchments' outlets throughout experiments duration. Their propagation rate does not decrease monotonically in relationship with the decrease in drainage area as predicted by stream-power based models, but first increases with a peak retreat rate in the mid-part of catchments. Their initiation coincides with rivers narrowing and increasing their shear stress. Then, rivers widening leads to a decrease in shear stress and incision rate below the base-level fall rate once knickpoints have propagated upward, creating an unstable situation that ends up with the formation of a new knickpoint. We propose a new model of cyclic generation of autogenic knickpoints controlled by river width dynamics. It illustrates the need to consider autogenic processes in the generation of knickpoints and for deciphering variation of tectonic and climatic processes from landscape records.

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1 Introduction

Knickpoints in rivers are discrete zones of steepened bed gradient that are commonly observed in their long profiles. Although they occasionally occur due to changes in bedrock properties (e.g. Duvall et al., 2004), in many cases they are dynamical features that propagate upstream along the drainage network of landscapes (Whipple and Tucker, 1999; Kirby and Whipple, 2012; Whittaker and Boulton, 2012; Yanites et al., 2013). In this last case, they are commonly considered as formed in response to variations in external forcing such as uplift rate, sea-level or climate. According to a stream-power based celerity model (SPCM), their upstream propagation rate is predicted to depend non-linearly on drainage area (a proxy for discharge; Crosby and Whipple 2006; Berlin and Anderson, 2007), implying a monotonous decrease of retreat rate as they propagate upstream. This property can be used for example to invert their present location for dating the external perturbation responsible for their formation (Crosby and Whipple 2006; Berlin and Anderson, 2007). A recent experimental study however pointed out a potential inadequacy of this model when the upstream decrease in discharge is counterbalanced by the adjustment of the river width, resulting in a constant knickpoint retreat rate (Baynes et al., 2018). Some other studies also pointed out some limitation of SPCM to predict the actual propagation of knickpoints when the role of sediment supply is not considered (Cook et al., 2013).

Unlike the commonly accepted idea that knickpoints are symptomatic of changing external forcing (e.g. Crosby and Whipple 2006; Berlin and Anderson, 2007; Kirby and Whipple, 2012; Whittaker and Boulton, 2012; Mitchell and Yanites, 2019), several studies pointed out that they could also be autogenic, that is to say internally-generated without any variation in boundary condition (e.g. Hasbargen and Paola, 2000, 2003; Finnegan and Dietrich, 2011). Their consideration should then be crucial for retrieving changes in external forcing from analysis of knickpoints observed in landscapes. Autogenic knickpoints has been observed for example in experimental drainage basins forced by constant rate of base-level (BL) fall by Hasbargen and Paola (2000). In their experiments, successive knickpoints initiated despite constant forcing, even when landscapes were at steady-state. Internal processes may also complexify the propagation of knickpoints as shown in flume experiments by Cantelli and Muto (2014) and Grimaud et al. (2016) who observed that a single discrete event of BL

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drop may result in the propagation of multiple knickpoints. Other flume experiments show that some knickpoints may generate autogenically along a river profile from the amplification of local instabilities (Scheingross et al., 2019).

We consider here the generation and dynamics of autogenic knickpoints in laboratory-scale drainage basins experiments forced by constant rate of BL fall and steady precipitation. We observe that successive knickpoints initiate near the outlet and propagate within drainage basins and propose a new model of autogenic knickpoint initiation and propagation driven by downstream river width dynamics.

2 Methods

Landscape experiments have been used successfully to explore how tectonics and climate impact erosion processes and the evolution of topography under controlled conditions (e.g. Hasbargen and Paola, 2000; Bonnet and Crave, 2003; Lague et al., 2003; Turowski et al., 2006; Bonnet, 2009; Singh et al., 2015; Sweeney et al., 2015; Moussirou and Bonnet, 2018). This approach allows the observation of complex dynamics that are difficult to simulate numerically and sheds new light on the way natural landforms may evolve. The experiments presented here have been performed using a new setup specifically designed to investigate landscape evolution under controlled BL fall (Fig. 1; see also Fig. S1 in the Supplemental Material). The facility is a box with dimensions 100 x 55 cm filled with silica paste. At its front side, a sliding gate, 41 cm-wide, drops down at constant rate, acting as the BL. During a run, runoff-induced erosion occurs in response to steady artificial rainfall (95 $mm.h^{-1}$) and BL fall. Then, some incisions initiate along the BL and propagate up to a complete dissection of the initial surface, which consists on a plane with a counterslope of ~3°, opposite to the BL-side. This allows to create a water divide between incisions that develop along the BL-side and the initial surface. The use here of a large gate on the BL-side of the setup constitutes a major difference compared to previous similar catchment-scale experiments of Hasbargen and Paola (2000, 2003), Bigi et al. (2006) and Rohais et al. (2012). In these experiments, a single outlet location was actually pinned due a narrow gate, which also

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set the river width at the outlet. Unlike these experiments, the setup use here allows experimental rivers to freely evolved, with their width not being constrained by such a narrow gate.

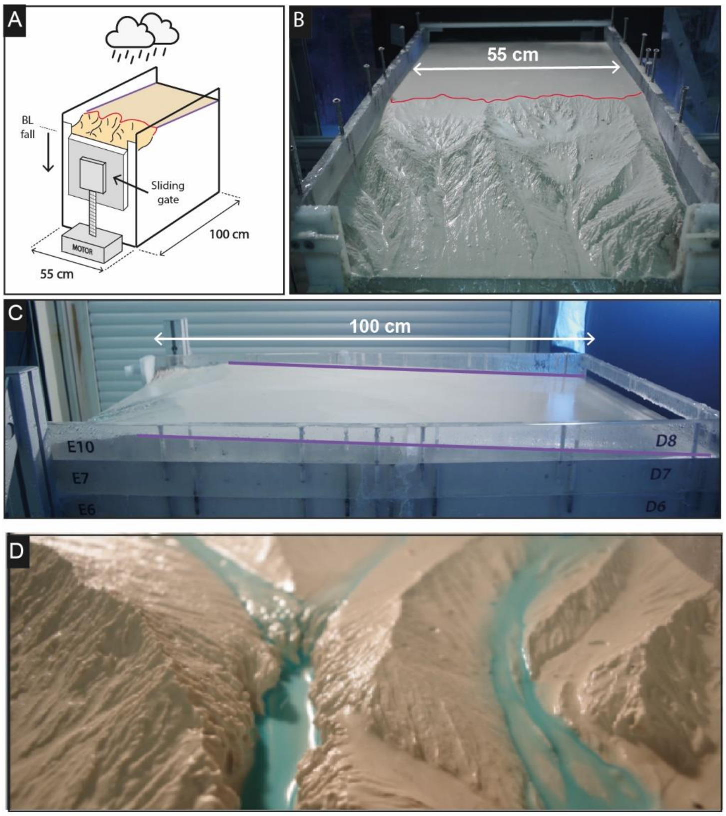

***Figure 1**. Experimental setup. Purple and red lines show respectively the counter-slope of the initial topography and the main water divide. (A) Sketch of the erosion box with the sliding gate, 41 cm wide, used to drop down base level (BL). (B), (C) Front and side photographs (experiments MBV07 at 525' and MBV06 at 185'). (D) Photograph of a typical knickpoint studied here.*

Experiments were stopped every 5 min to digitize the topography using a laser sheet and to construct DEMs with a pixel size of 1 mm. Due to the large number of DEMs per experiment, about 200, river long profiles and knickpoints were extracted based on a semi-automatic procedure. For this purpose, we first extracted long profiles by considering the lowest elevation on the successive rows of each DEM

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within a 20 cm-wide swath that included the main river and then by plotting it against distance down the long axis of the box. This procedure has already been applied in analysis of experiments by Baynes et al. (2018) and Tofelde et al. (2019). It may result in a slight overestimation in channel slope because it does not consider the obliquity of channels within the box in the distance calculation nor their sinuosity, however these effects are of minor influence here, most of channels being straight and roughly parallel to the long side of the box. In a second step, we computed the elevation difference between each successive pairs of longitudinal profiles and we identified knickpoints by considering peaks in erosion with values above the steady erosion amount defined by the rate of base-level fall (Fig. 2). We carefully verified manually that this procedure allows to define knickpoints correctly and we investigated in particular how the procedure performed according the time interval chosen between successive profiles. We found that knickpoint retreats were generally too small to produce well-defined erosional peaks when we considered the highest time-resolution of 5 minutes, which lead us to track knickpoint positions at a time-interval of 10 minutes. Thanks to this approach, we built a first rough catalogue of knickpoints positions over time that we subsequently rearranged manually by gathering together the successive positions of each individual knickpoint. We then complemented the database by computing incremental retreat rate of knickpoints from their successive positions.

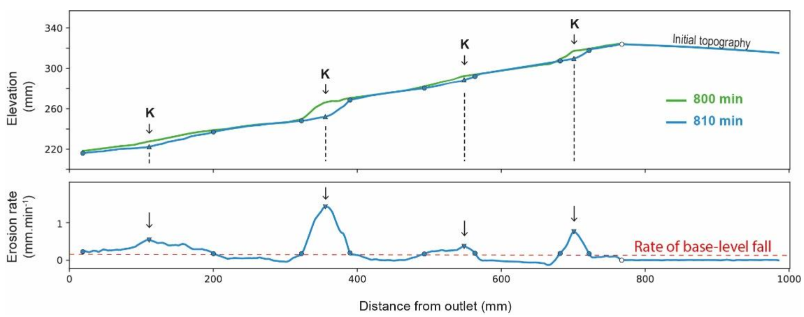

***Figure 2**. Graph showing two successive long profiles of experiment MBV07 taken at 10 min interval (top) and corresponding erosion rate profile (bottom). Triangles illustrate the position of erosional peaks taken as knickpoint position (black arrows). Red dashed line shows the rate of base-level fall.*

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DEMs were also used to compute hydraulic information (water depth, river width, discharge and shear stress; see Supplemental Material) using the Floodos hydrodynamic model of Davy et al. (2017; see also Baynes et al. (2018, 2020) for previous use of Floodos for analyzing laboratory experiments). Floodos is a precipiton-based model that calculates the 2D shallow water equations (SWE) without inertia terms, from the routing of elementary water volumes on top of topography. The output of floodos are maps of water depth, velocity and shear stresses. We ran Floodos on successive DEMs of experiments by considering spatial distribution of precipitation, then generating several output raster products at the pixel size, including water depth, unit discharge and bed shear stress that were then used for computation of hydrologic parameters (river width, specific discharge and shear stress). The solution of the SWE depends on the friction coefficient (C) that depends on water viscosity only for laminar flow; its theoretical value is ~2.5 x 10^6 $m^{-1}.s^{-1}$ at 10°C (Baynes et al., 2018). To ensure that Floodos outputs (e.g. water depth raster maps) calculated using this value are consistent with actual experiment hydraulic conditions, we injected dye in the rainfall water during a run to catch the actual extent of water flow and make rivers visible (see Fig. 2 and Fig. S2). A visual comparison with Floodos results shows a good match between model outputs and experimental results, which validates the numerical method and the expected theoretical friction coefficient C (Baynes et al., 2018). River widths were extracted from DEMs by considering water depth maps and a threshold depth between channels and hillslopes. Floodos routing procedure calculates water depth from precipitation over the totality of the topography, on hillslopes as well as in channels, river banks corresponding to sharp variations in water depth. During runs, the actual water depth in rivers is very low, of mm-scale, and very difficult to measure without introducing any perturbation in the flow. Thus, the water depth threshold was estimated by varying this threshold over a DEM and by comparing the corresponding extent of rivers with actual extent of water flow as viewed by injecting red dye in the water used to produce the artificial rainfall (Fig. 3). A good visual agreement was obtained for a threshold value between 0.1 and 0.5 mm, and a mid-value of 0.3 mm was consecutively used for determining river widths.

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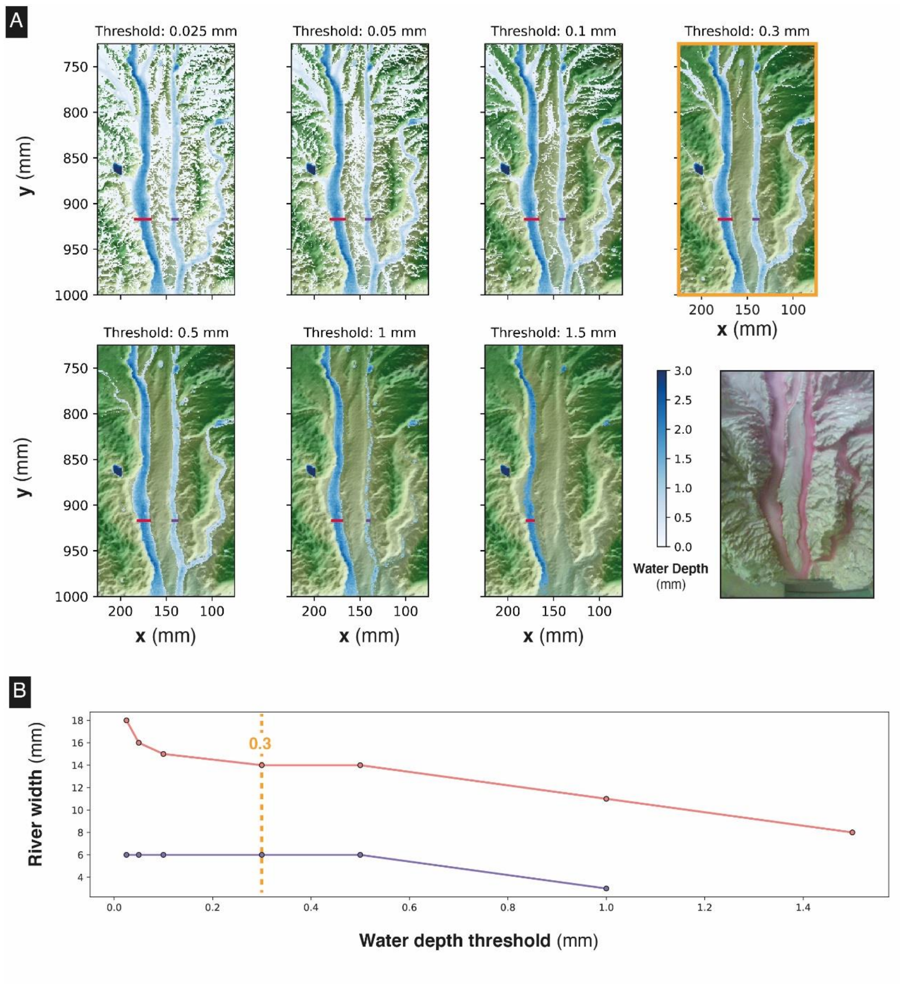

Figure 3. *Impact of water depth threshold used to delineate river boundaries on estimated river widths, considering a friction coefficient C of 2.5 x* 10^6 m^{-1} s^{-1}*. A. Map views of water depths (blue colors) superimposed to DEM, for water depths threshold values between 0.025 and 1.5 mm. Red and purple lines show corresponding river widths for two rivers. Photo on the bottom right shows the active river width during the corresponding experimental run (pink colors; "control run"), viewed by injecting red dye in the water used to generate the artificial rainfall. B. Corresponding local river widths for the two sections shown by red and purple lines. The use of a low water depth threshold value (e.g. 0.025 mm; top left) leads to the inclusion of large areas of thin water depth in the "wetted area" considered as rivers and then to unrealistic large rivers in comparison with actual rivers observed in the control run.*

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On the opposite, considering large threshold value (e.g. 1.5 mm) results in narrow rivers, or even in the absence of rivers when maximum computed water depth is lower than the threshold used. A threshold value of between 0.1 and 0.5 mm shows a good similarity between rivers on water depth map and the control run. Here, a mid-value of 0.3 mm has been chosen for computing river widths.

3 Results

3.1 Dynamics of knickpoints retreat

We present here results from 3 experiments, MBV09, MBV07 and MBV06, performed with different rates of BL fall, of respectively 5, 10 and 15 $mm.h^{-1}$ (Table 1). In each experiment, BL fall induces the growth of drainage networks by headward erosion and the progressive migration of a main water divide (Fig. 4). The migration rate of the divide is constant in each experiment (Fig. 5 and Table 1), but increases from 25 to 66 $mm.h^{-1}$ for increasing rate of BL fall. Figure 6 shows the evolution of the longitudinal profile of the main river investigated in each experiment, as well as topography of the initial surface, the profiles being colored according to the experimental runtime. These stacks illustrate the growth of rivers as they propagate within the box. Longitudinal profiles show alternations of segments with low and higher slopes, the later defining knickpoints that propagate upward, some profiles showing even several knickpoints that retreat simultaneously. Knickpoints regularly initiate at the outlet throughout the duration of the runs in all experiments, and propagate upward until they reach and merge with the divide. The mean retreat velocity of knickpoints varies between experiments from 73 ± 50 to 183 ± 94 $mm.h^{-1}$ (Table 1) and increases in average as a function of the rate of BL fall. Data suggest a non-linear relationship however complementary experiments would be necessary to constraint this dependency. To investigate the propagation of the knickpoints, we show in Figure 7 the successive alongstream position of each knickpoint over experimental runtime, as well as the position of the water divide in the box as already reported in Figure 5. In order to be able to compare the dynamics of knickpoints within an experiment regardless of the stage of water divide retreat into the box, the position of knickpoints (distance to outlet, D) has been normalized to the position of the divide, hereafter referred

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to as normalized distance to divide (nDD; nDD=0 at outlet and nDD=1 at the divide; Figure 2). Lines of isovalue of nDD considering an increment of 0.1 are also shown in the space-time diagrams in Figure 7. To a first order, the trajectories of each knickpoint are very comparable within an experiment whatever regardless the stage of retreat of the water divide and the size of the catchment. Visually for example, in the space-time diagrams there is no systematic variation in the general slope of the successive knickpoint trajectories over time, as the rivers expand, that would indicate a change in mean knickpoint velocity in relation to the change in the river length and catchment size. An inflection of trajectories is visible for many knickpoints when they are close to the divide, for nDD > ~0.8 (Figure 7), which indicates that they slow down as they approach the divide. The opposite is observed for some knickpoints when they are close to the outlet, for nDD < ~0.2 / 0.3, with some trajectories suggesting, on the contrary, an acceleration (Figure 7). These suppositions are supported by the detail analysis of retreat velocity data shown in Figure 8. For each experiment, we show in Figure 8A the stack of successive retreat velocities of each individual knickpoint according to nDD, *i.e.* according to their propagation between the outlet and the divide. The envelopes draw a bell-shaped distribution for each experiment, which indicates that retreat velocities are maximum when knickpoints are located at a mid-distance between the outlet and the divide, for central values of nDD, between 0.4 and 0.6. Figure 8b provides summary statistics of retreat velocities at 0.1 intervals of nDD considering all knickpoints in each experiment. Both the mean and median values show higher rates of retreat when knickpoints are in the central section of rivers, and conversely lower rates near the outlet (nDD < 0.2 / 0.3) when they initiate and start to propagate and when they approach the divide (nDD > 0.8), as suggested by trajectories shown in Figure 7. Then, these data indicate that after their initiation near the outlet, knickpoints first accelerate up and reach their maximum retreat rate in the central part of the catchments before to decelerate as they approach the divide. It is worth noting that this specific distribution of knickpoint retreat rates is observed regardless of the progress of the experiments and the advancement stage of incision and divide retreat into the box. This applies both to rivers in the early stages of evolution of experiments, when they are short, and to very large rivers at the end of evolution of the experiments.

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Table1. Parameters of experiments

Experiments	Base Level Fall (mm/h)	Precipitation rates (mm/h)	Duration Time (min)	nDDvmax	Mean Knickpoints retreat rates (mm/h)
MBV06	15	95	1065	0.52	183.571 ± 93.784
MBV07	10	95	1200	0.57	164.789 ± 74.8374
MBV09	5	95	1455	0.54	73.127 ± 50.0142

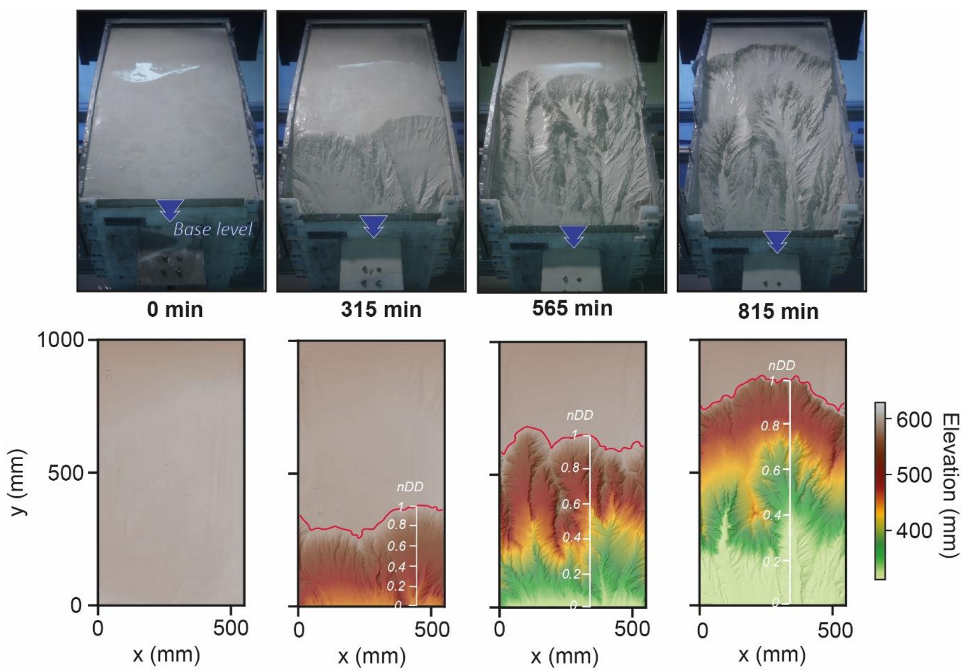

***Figure 4**. Photos and corresponding DEMs of experiment MBV06 at four runtimes. Note the propagation of the divide through the erosion box (red line) and the drop of the sliding gate used for falling base-level. The normalized distance to divide (nDD, see text) used to follow the position of knickpoints during runs is shown superimposed to DEMs.*

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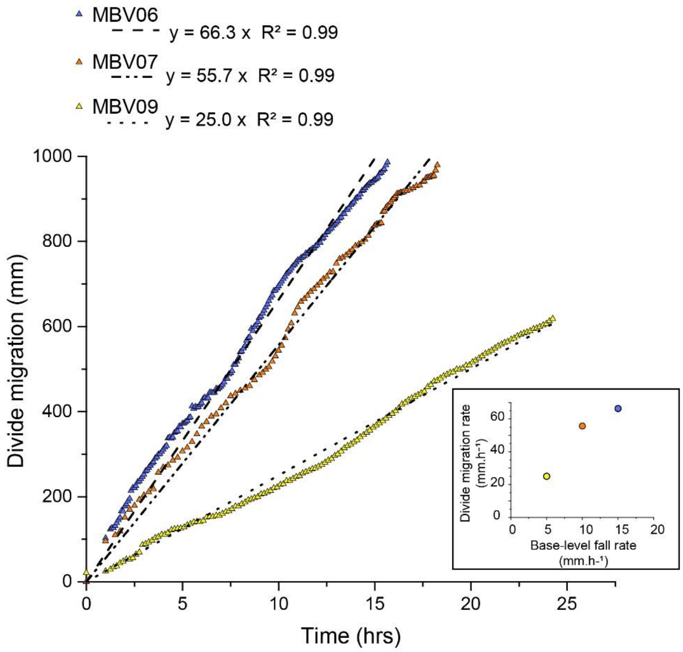

211 ***Figure 5***. *Evolution of the water divide position within the erosion box for the three experiments.*

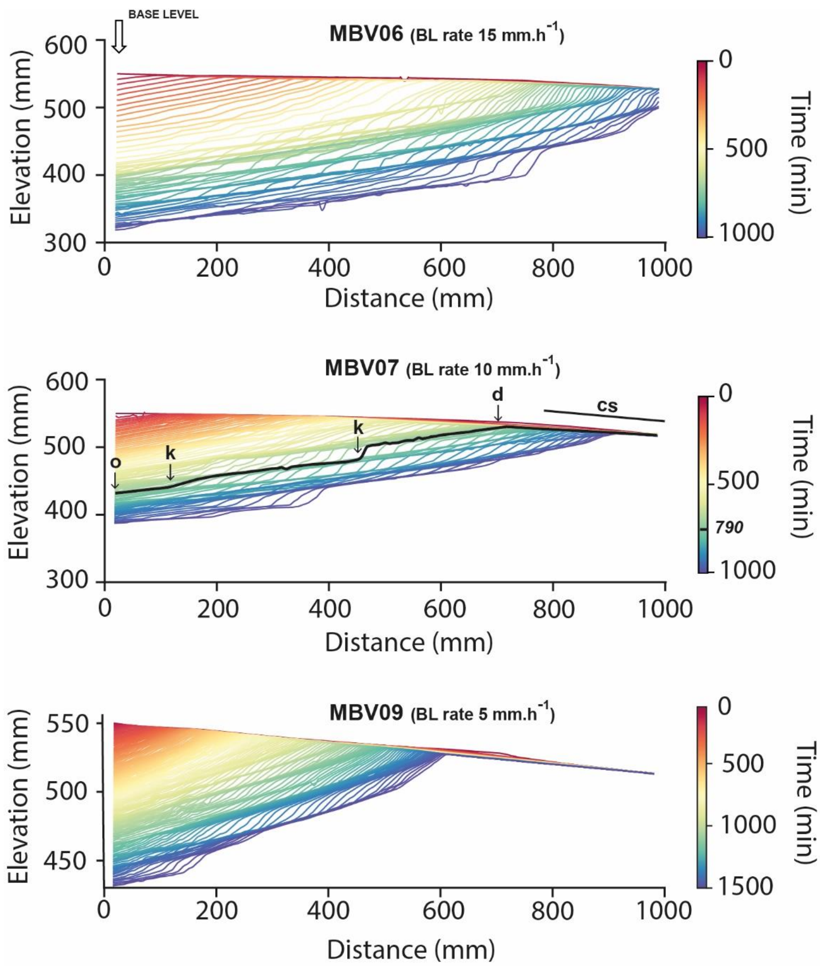

Figure 6. *Successive river long profiles of experiments, shown here every 10 min. Each long profile is colored according to experimental runtime. The sliding gate (BL) is to the left. Note the initial counterslope (cs). Black thick line on MBV07 is the long profile at t=790', illustrating the outlet (o), knickpoints (k), and water divide (d).*

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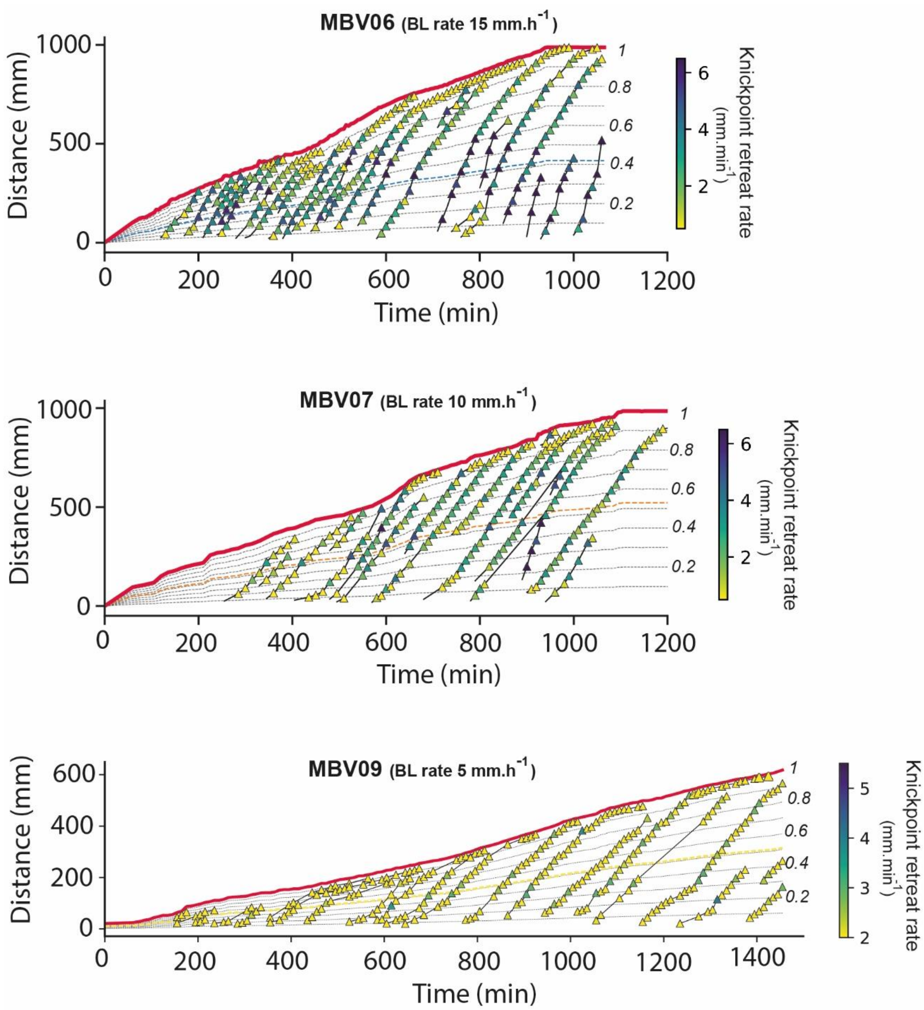

__Figure 7.__ Space-time diagrams showing the propagation of the water divide (red line) and successive trajectories of knickpoints (triangles). Symbols color shows instant (10 min) knickpoints retreat rate. Thin dashed lines show the normalized distances to divide (nDD).

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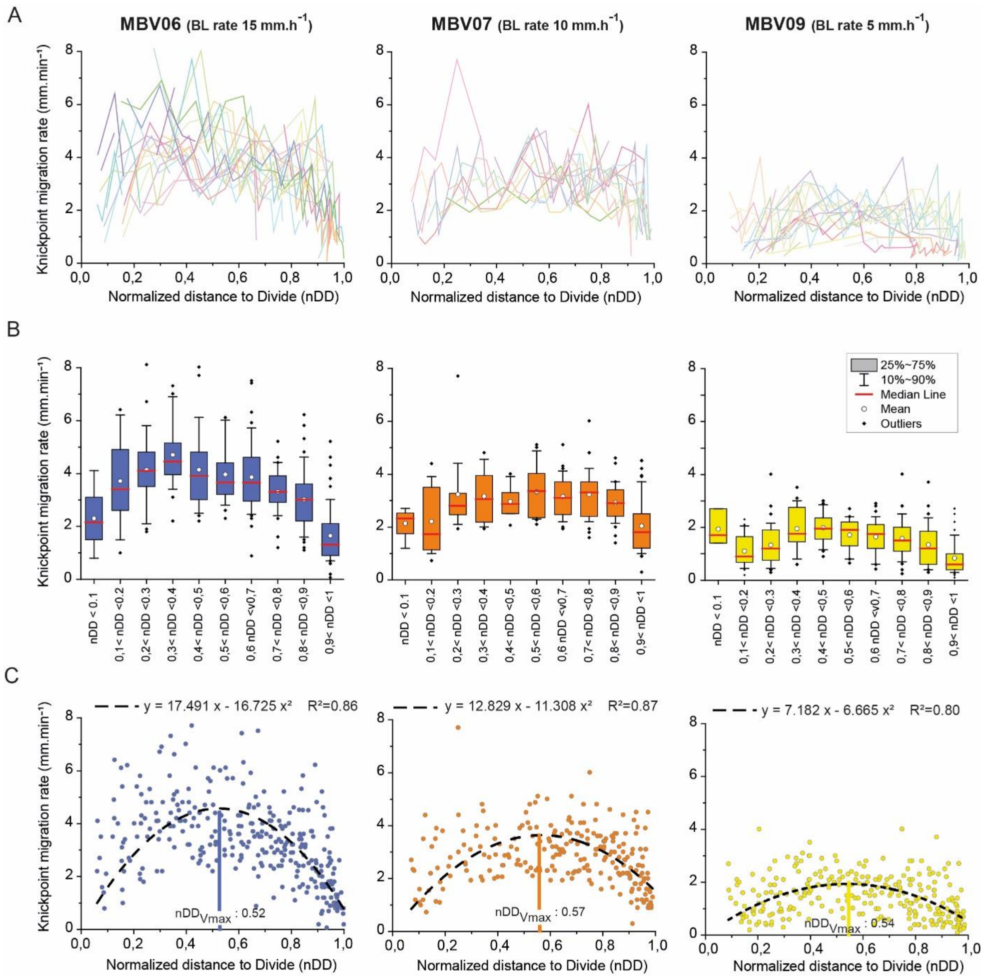

Figure 8. *(A) Knickpoint retreat rates according to the normalized distances to divide (nDD) for each knickpoint of experiments. Each color line corresponds to an individual knickpoint of the space-time diagram in Fig. 7. (B) Summary statistics of retreat rates for nDD intervals of 0.1. (C) Plot of all knickpoints retreat rates for each experiment. Black dashed line shows the second order polynomial fit to the data used to define the normalized longitudinal distance of maximum velocity of knickpoints (nDD_{Vmax}).*

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Studies that investigated knickpoints retreat at catchment-scale demonstrated that their velocity decreases as they propagate upstream due to the progressive reduction of the upstream drainage area and water discharge (e.g. Crosby and Whipple, 2006. Berlin and Anderson, 2007). The pattern of velocity distribution that we document here is not consistent with this finding because we observe here an increase in knickpoints velocity in the early stage of their propagation. To evaluate this effect in our experiments, we investigated the dependency between retreat velocities and discharge by cutting the dataset into two parts corresponding to the different regimes identified above. For this purpose, we considered a second order polynomial fit to the data shown in Figure 8 and used the inflexion to define a normalized longitudinal distance of maximum velocity of knickpoints (Fig. 8C) referred to as nDD_{Vmax} in the following. This value is very similar between experiments, of 0.52 to 0.57 (Table 1). Data above nDD_{Vmax} (Figure 9) allows to consider retreat rates against more two orders of magnitude of unit discharge (total discharge normalized to river width). They do not show a clear tendency of increasing rate with discharge as expected, although a rough positive correlation could be defined, following a power law with an exponent of 0.25. Data below nDD_{Vmax} show 3 distinct fields without any clear trend with discharge. The restricted range of discharge data however limits the analysis.

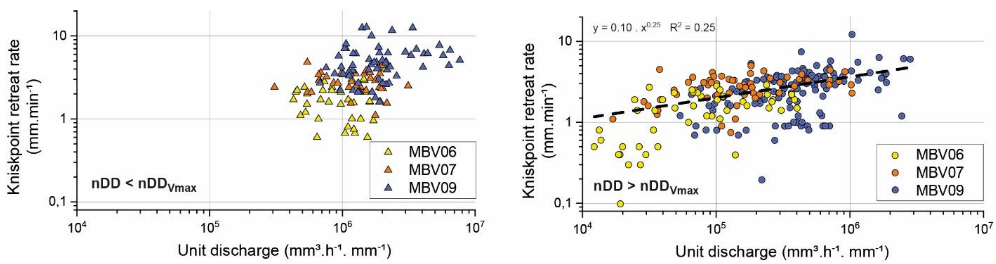

Figure 9. *Relationship between knickpoints retreat rates and unit discharge (discharge/width) for nDD < nDD_{Vmax} (left) and nDD > nDD_{Vmax} (right).*

3.2 Knickpoints initiation

To illustrate how knickpoints initiated near the outlet, we consider here a 120 minutes-long sequence of channel evolution in experiment MBV06 from experimental runtime 880 to 1000 minutes, during which

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two knickpoints successively initiate and propagate upward. Figure 10 shows 5 min intervals sequence of downstream longitudinal profiles, 40 cm-long, showing their initiation and propagation as well as the evolution of a channel cross-section located at 8 cm from the box boundary. Some photos and perspective views of the corresponding DEMs also illustrate the evolution of the channel. Complementary data are shown in Figure 11: variations over time of channel width (Fig. 11A) and unit water discharge (Fig. 11B) at the cross-section location as well as summary statistics of normalized elevation changes (Fig. 11C) and shear stress (Fig. 11D) for all pixels across the section. On the graph shown in Figure 11C, normalized values of 1 indicate erosion at the same rate than base-level fall and then steady-state conditions. Values > 1 or <1 indicate respectively higher and lower erosion rate than BL fall rate. Negative values indicate sedimentation. The sequence starts with a regular profile at runtimes 880 and 890 min once a knickpoint has already retreated, still visible upstream (Figure 10A). The channel is 23 to 25 mm wide (Fig. 10B and 11A) and unit discharge is about $1.5.10^{6}$ $mm^{3}.h^{-1}.mm^{-1}$. Erosion in the channel is in average lower than BL fall as normalized erosion is <1 for most pixels along the section (Fig. 11B). Then, the first knickpoint initiates and starts to retreat. The channel narrows, being ~15 mm wide at 905 min (~60 % decrease), before to subsequently widens once the knickpoint has retreated, at 910 min at the location of the section surveyed (Fig. 10B). The narrowing phase goes with an increase in unit discharge (Fig. 11B) and with an enhanced erosion well above the BL fall rate, up to 4 times this rate in average at 900 min (Fig. 11 C), with extremes as high as 8 times the BL rate. Once this first knickpoint has retreated, unit discharge decreases as the channel subsequently widens, to reach a width of 25 cm to 28 cm between 925 and 930 min (Fig. 11A) while a new regular profile, i.e. without any slope break, established at 930 min (Fig. 10A). The normalized erosion across the section decreased below the BL value (Fig. 11C), with mean erosion rates value of 0.53, 0.36 and 0.76 times below the BL rates between 915 to 925 min. Longitudinally, the profiles stack together downstream the knickpoint following its retreat from 895 to 925 min (Fig. 10A), which also indicates minor vertical erosion here once the knickpoint has retreated despite the ongoing falling base-level. A second knickpoint then initiated at 935 min and propagated upstream in a similar way, until establishment of a new regular profile at 980 min (Fig. 10A). The passage of this second knickpoint also coincides with a narrowing of the channel, being ~15 mm wide on the cross-section shown here (Fig.

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10B and 11A), a rise in the unit discharge and with an increase of the normalized erosion above the BL rate (Fig. 11C). It is followed again by a phase of widening to reach a width to around 30 / 35 mm once the knickpoint has propagated upstream and by a decreasing erosion below the BL fall rate (Fig. 11C). Note that at 975 min, sedimentation took place on a large part of the surveyed section (mean normalized erosion rate is 0.1 and median is -0.25): Figures 10B and 11C. Again, the longitudinal profiles stack together downstream the knickpoint (Fig. 10A). Figure 11D provides summary statistics of shear stress exerted on the channel bed for all pixels along the channel section. The values of shear stress show a quite large variability at the scale of the cross-section, with the median and maximum values increasing however in phase with the passage of knickpoints. Then once passed, shear stress values decrease as the river widens. This sequence illustrates that the rivers are never in equilibrium at the 5 min time-scale, but continuously oscillate over time between periods of disequilibrium during which erosion in wide channels goes at a slower rate than the BL and periods of knickpoint propagation with enhanced erosion and increased discharge in narrower rivers, erosion being well above the BL rate along the knickpoint segment. These knickpoints then propagate upward up to the divide as discussed previously (Fig. 6). Although erosion appears to be fundamentally punctuated over time, considering all erosion rates data across the investigated cross-section and for the whole sequence shown here gives an average normalized erosion rate closed to unity (0.99) which indicates that these oscillations take place however around an average steady state over the long time-scale (erosion rate equal to BL rate). It indicates that enhanced erosion above the BL value during the retreat of knickpoint compensates the delay in vertical erosion that accumulates between two successive knickpoints, while rivers are defeated in following BL fall.

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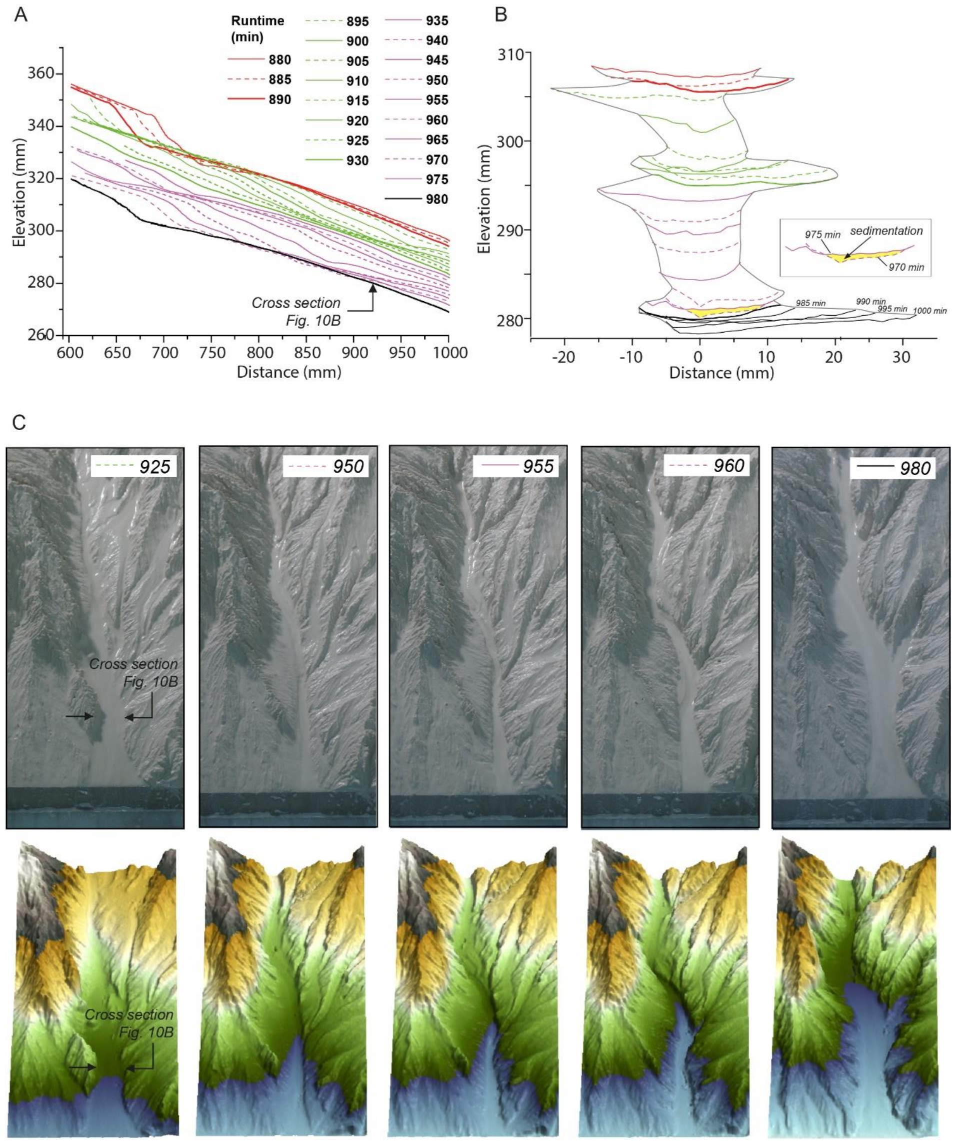
300 

301 ***Figure 10.*** *(A) Successive longitudinal profiles (downstream section) of the investigated river in*
302 *experiment MBV06, corresponding to the sequence hydro-geomorphic parameters shown in Figures 11*
303 *and 12. Propagation of the first (K1) and second (K2) knickpoints is shown in blue and orange colors*
304 *respectively (see text). (B) Time evolution of successive cross-sections of the channel at 80 mm from the*
305 *outlet. (C) Photos and perspective views of DEM at five time-steps.*

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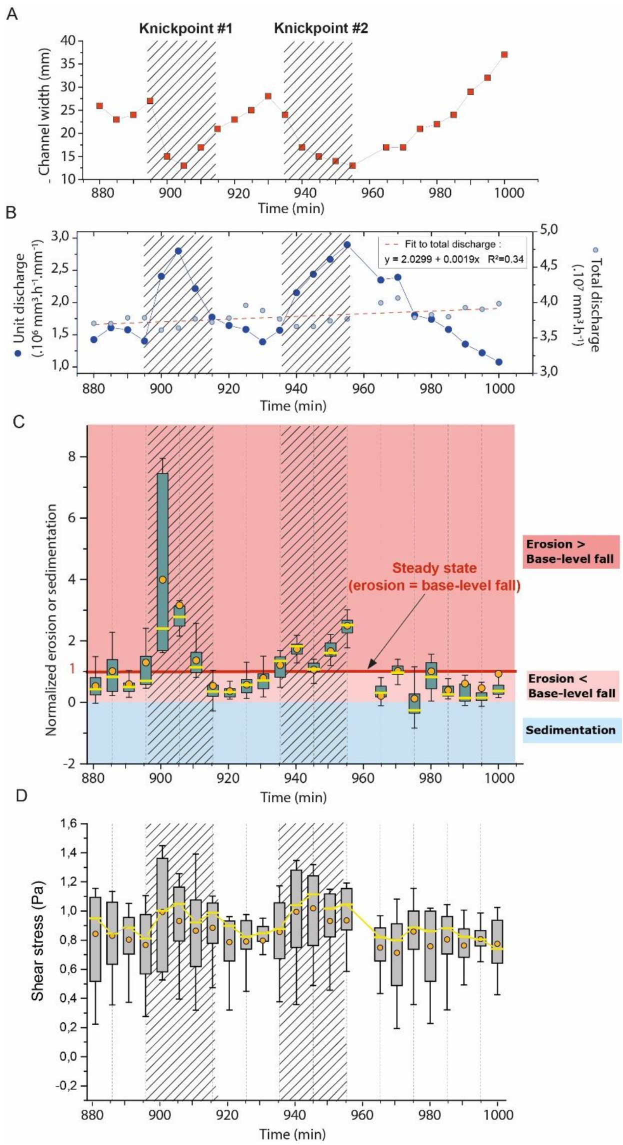

Figure 11. *Time-series at 5 min interval of river width (A) and unit and total discharge (B) for the channel in experiment MBV06 shown in Figure 10B. Time-series of box-and-whisker plots of normalized elevation changes (C) and shear stress (FD) for all pixels across the section. Orange solid circles and yellow lines show the mean and median values respectively. Edges of the boxes indicate the 25th and 75*th *percentiles. Crosshatched areas indicate the passage of knickpoints.*

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To complement cross-section data, we show in Figure 12 how parameters vary longitudinal by considering four stages, two before (925 min) and after (975 min) the passage of the second knickpoint and two during its retreat (945 and 950 min). Note that at 925 min, the first knickpoint (K1) has just passed upstream the investigated profile and is responsible for the enhanced normalized erosion and increased shear stress between distance 800 to 650 mm. Similarly, at 975 min the second knickpoint (K2) is still in the upstream part of the profile, between distance 700 to 650 mm. We also reported the longitudinal variations in river width, shear stress and normalized erosion along the profiles. At runtimes 925 and 975 min, after the passage of a knickpoint, erosion is below the BL rate along all the profiles down the knickpoints, with even localized sedimentation at 975 min between 805 and ~950 mm. These sections are characterized by low shear stress values, being between 0.5 and 1 and by rivers that widen downward (around 0.7 mm/cm). On the opposite, during the passage of a second knickpoint (K2) at runtimes 945 and 950 min, mean shear stress increases locally at the knickpoint location, being > 1 and the normalized erosion overpasses the BL rate there. These knickpoint segments are characterized by a narrowing of the rivers as already shown previously. The data illustrate that erosion mainly occurs during periods of knickpoint retreat though a combination of local steepening of the profile and narrowing of the river, resulting in an increase shear stress. On the opposite, once a knickpoint has and between the passage of two successive knickpoints, erosion decreases significantly and does not longer compensate the BL fall. These periods of defeated erosion are characterized by low bed shear stress values in wide rivers, that widen downward.

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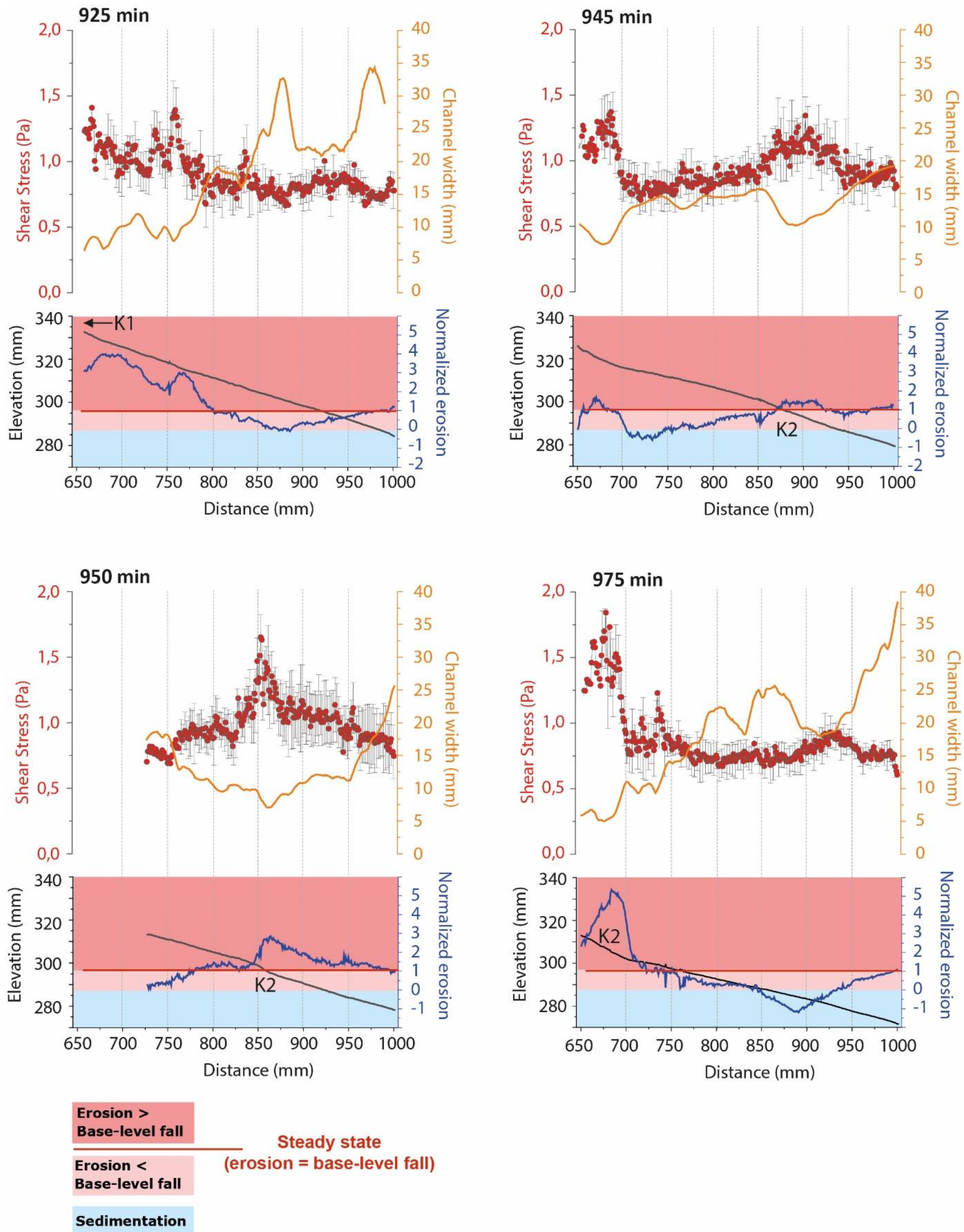
333 

334 ***Figure 12.*** *Longitudinal trends of hydro-geomorphic parameters in experiment MBV 06 at runtimes*
335 *925, 945, 950 and 975 min (see text for comments). K1 and K2: first and second knickpoints discussed*
336 *in the text (see also Fig. 10A).*

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4 Discussion and conclusions

Our experiments illustrate the generation and retreat of successive knickpoint waves that traveled across the landscape during the growth of drainage networks. They formed throughout the duration of experiments regardless of the steadiness of the precipitation and BL fall rates and of the homogeneity of the eroded material. Consequently, these knickpoints were autogenically generated (Hasbargen and Paola, 2000), arising only from internal geomorphic adjustments within the catchments rather than from variation in external forcing. Our observations appear very similar to those of Hasbargen and Paola (2000, 2003) and Bigi et al. (2006) who also reported the generation of successive knickpoints in landscape experiments evolving under steady forcing (rainfall and BL fall rate), throughout the duration of the runs. These authors mentioned that their initiation was not "*attributed to abrupt base-level drops, because the outlet drops continuously*" (Hasbargen and Paola, 2000) as in our study. Unlike our experiments, which mainly consider the growth phase of the drainage networks, experiments reported in Hasbargen and Paola (2000, 2003) and Bigi et al. (2006) considered the propagation of knickpoints after the phase of network growth, while their system was at steady-state in average (mean catchment erosion rate equal to BL rate). Then, given that the size of their experimental catchment was steady over time and given the steady rainfall rate, they were able to rule out variations of water discharge over time as the main driver for the generation of their knickpoints. On the opposite, in our experiments the size of catchments continuously increased over time, and thus the water discharge. However, this does not appear as the main factor controlling knickpoints initiation for several reasons. First, as we already mentioned, knickpoints arose at all stages of network growth and divide retreat, for both small and large rivers (Fig. 7), and thus whatever the range of water discharge at outlet. Second, the migration of the water divide related to drainage network growth occurred steadily and roughly at a constant rate during an experiment (see Figures 5 and 7), and then the size of the catchments and the related increase in water discharge. Then, we can rule out abrupt variations in discharge as the driving mechanism for knickpoint initiation. Last, knickpoint initiations occurred at a higher frequency than the increase in water discharge that results from catchment expansion and divide migration. For example, in addition to unit discharge, we also reported on Figure 11C the variation in total discharge during the 120 min-long sequence of knickpoint initiation discussed previously. The total discharge rose from 3.7 10^7 to 4.0 10^7 $mm^3.h^{-1}$ in 120 minutes representing a ~ 8% increase, which is relatively low compared to the ~100 % increase of unit discharge during the passage of a knickpoint. For all these reasons we conclude that the change in catchment size was not the main driver of successive knickpoints initiation in our experiments, which occurs at a higher frequency.

Admitting that the initiation of successive knickpoints was not related to changes in external factors and catchment size over time, it is then necessary to consider internal geomorphic processes as driving mechanisms. The detailed sequence of knickpoints initiation and propagation discussed above clearly shows enhanced incision above BL fall during the periods of knickpoints propagation. This occurred through local steepening of the longitudinal profile and narrowing of the river, these two factors leading to an increase in unit discharge and bed shear stress along the knickpoint section. Several studies already documented how steepening and narrowing act together for increasing river incision rate (e.g. Lavé and Avouac, 2001; Duvall et al., 2004; Whittaker et al., 2007; Cook et al., 2013), which is what we also document here. The particularity of the rivers in our study however lies in the phase of post-knickpoint retreat. Actually, immediately after the retreat of a knickpoint, erosion was inhibited downstream and rivers no longer incised despite the ongoing BL fall, until the passage of a new knickpoint. Although clearly shown in the sequence detailed previously (Figs. 10 to 12), this was a general behavior that concerned the three experiments presented here and their whole longitudinal profile, not only their downstream part as in the sequence discussed above. Actually, this systematic defeat in erosion downstream the knickpoints is inherent to the geometry of the stacks of all successive longitudinal profiles of each experiment shown in Figure 6. In most cases, profiles downstream retreating knickpoints stack on top of each other, as illustrated schematically on Figure 13A, which indicates minor or no erosion downstream the knickpoints. In the case of continuous adjustment of rivers to BL fall downstream knickpoints, the geometry of profiles should rather shows a pattern as illustrated in Figure 13B. The pattern of profiles evolution over time documented here is usually observed following a sudden and finite drop in BL (Finnegan, 2013; Grimaud et al., 2016) and to our best knowledge this is the first time here that such geometry is documented in the case of a continuous BL fall. This particular pattern

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is explained by the decrease in erosion rate downstream the retreating knickpoints which finally acts as if the BL was not falling continuously at a constant rate but dropped regularly step-by-step. Therefore, understanding the systematic occurrence of successive knickpoints in our experiments requires to understand why erosion rate dropped downstream of knickpoints following their retreat. After the passage of knickpoints, we systematically observe a widening of the rivers, as also documented in natural systems (e.g. Cook et al., 2014; Zavala-Ortiz et al., 2021) and a decrease in the bed shear stress. Because an increase in channel width over time will inevitably reduce the bed shear stress if discharge and river gradient remain constant (Fuller et al., 2016), we propose that widening was the main factor responsible for the decrease in shear stress and erosion rate after the passage of a knickpoint, and then for the occurrence of the successive autogenic knickpoints. Demonstrating the sole effect of river width on bed shear stress and erosion rate is complicated by covariations of these factors with river slope and variations of discharge related to connection of tributaries. This can be discussed however on the basis of the sequence discussed previously, particularly at runtime 925 min between the passage of two successive knickpoints (Figs. 10 and 12). At that time, the profile of the river had a roughly constant slope, without any slope break (Fig. 14) and no major tributary connected (Fig. 10) that could change significantly the water discharge. As illustrated in Figure 12, this river segment was characterized by widening and decreasing shear stress downward. Then, as shown in Figure 14 we can document here a decrease in shear stress that was only the result of the widening of the river downward. This observation supports our hypothesis that defeated erosion downstream the propagating knickpoints was mainly due to the widening dynamics of the experimental rivers.

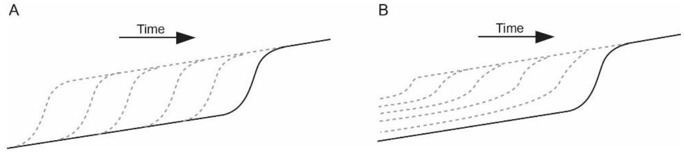

Figure 13. *Sketches illustrating the difference in the geometry of successive longitudinal profiles following the retreat of a knickpoint depending on whether fluvial incision in inhibited (A) or not (B) downstream of the retreating knickpoint.*

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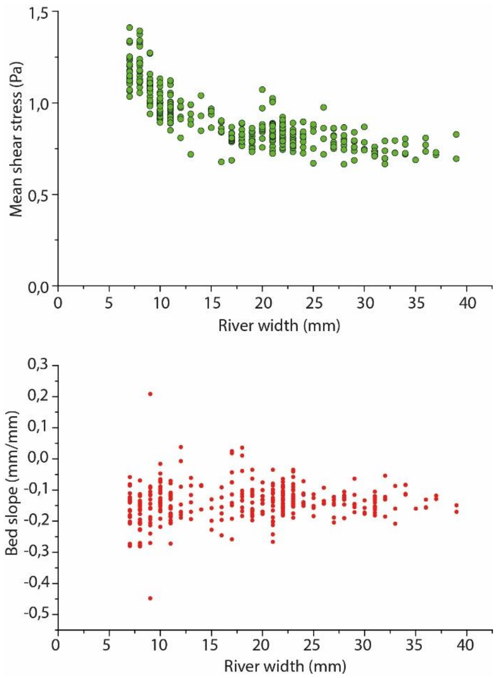

Figure 14. *Top: river bed shear stress according to river width in the downstream section, 40 cm-long, of experiment MBV06 at runtime 925 (see also Fig.12). Bottom: corresponding slope of the river bed.*

The set of experiments presented here illustrates the initiation and propagation of successive knickpoints during the growth of drainage networks and progressing enlargement of catchments, under constant external forcing. From the detailed analysis of their initiation and propagation, we propose that they formed autogenically, in response to variations in river width. We show that once knickpoints had retreated, unit discharge, shear stress and incision rate all decreased downstream while the rivers widened, resulting in a state where incision no longer counterbalanced the BL fall. We propose that rivers widening downstream the retreating knickpoints is the main mechanism responsible for the decrease in incision rate through its feedback on unit discharge and shear stress. This results in an unstable situation that ends up with the initiation and propagation of a new knickpoint and a sequence of river narrowing, increasing shear stress and incision rate. Then, incision of rivers in these experiments appears to be fundamentally discontinuous despite continuous forcing, and we highlight downstream

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river width dynamics as the main driver. Unlike studies that documented how river narrowing leads to an increase in shear stress and incision rate (Lavé and Avouac, 2001; Duvall et al., 2004; Whittaker et al., 2007; Cook et al., 2013) we propose that the opposite, river widening, is potentially responsible for a decrease in erosion rate downstream a retreating knickpoint, leading ultimately to the generation of a new knickpoint. This specific mode of autogenic knickpoints initiation result in an upward dynamic of retreat that is not conventional, as we observe that they first accelerate during the first step of their propagation before to decelerate in a second time as they approach the divide. Actually, studies that investigated knickpoints retreat at catchment-scale due to a single drop of base-level (due to a fault that displaced the river bed or to a capture for example) show that their velocity decreases as they propagate upstream due to the progressive reduction of the upstream drainage area and water discharge (e.g. Crosby and Whipple, 2006. Berlin and Anderson, 2007). The specific mode of retreat dynamics that we document here is likely the consequence of their specific mode of initiation. Although further studies should be conducted on this question, we found that the maximum retreat velocity (which scales with the rate of BL fall) occurs in the mid of the catchments in all our experiments, whatever the rate of BF fall and the length of the rivers. This appears as a key element for understanding the dynamics of these knickpoints.

Knickpoints are commonly linked to variations in tectonics or climate through their influence on base level and/or sediment supply (e.g. Whipple and Tucker, 1999; Crosby and Whipple, 2006; Kirby and Whipple, 2012; Whittaker and Boulton, 2012). The recognition that knickpoints may be generated autogenically in relationship to river width dynamics is then of first importance for investigating how tectonics and climate impact landscape and erosion. The generation of autogenic knickpoints has already been observed in experiments that evolved under steady forcing (Hasbargen and Paola, 2000, 2003; Bigi et al., 2006) and ascribed to water flow close to critical conditions by Hasbargen and Paola (2000). Our model is consistent with this proposition. By performing such exploratory experiments, we do not pretend to reproduce natural landscapes in the laboratory because of important scaling issues (see Paola et al., 2009 for an extensive reflection on this matter) but rather to highlight and document complex system behaviors under controlled conditions that could provoke further investigations. For instance, the dynamics observed here could not be reproduced in numerical simulations based on a classical Stream Power Incision model that would not integrate a dynamic width (see Lague, 2014), which appears as key ingredient here and supports ongoing investigations on this topic (e.g. Turowski, 2018; Croissant et al., 2019; Baynes et al., 2020).

Author contributions. SB designed the experimental device. LdL, SB and AG built the experimental setup and carried out the experiments. LdL analyzed the data with the help of SB and PhD. All authors discussed the data. LdL and SB wrote the manuscript with input from AG and PhD.

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References

Baynes, E.R.C., Lague, D., Attal, M., Gangloff, A., Kirstein, L.A., and Dugmore, A.J.: River self-organisation inhibits discharge control on waterfall migration: Scientific Reports, v. 8, p. 2444, doi:10.1038/s41598-018-20767-6, 2018.

Baynes, E.R.C., Lague, D., Steer, P., Bonnet, S., and Illien, L.: Sediment flux-driven channel geometry adjustment of bedrock and mixed gravel–bedrock rivers: Earth Surface Processes and Landforms, v. 45, p. 3714–3731, doi:10.1002/esp.4996, 2020.

Berlin, M.M., and Anderson, R.S.,: Modeling of knickpoint retreat on the Roan Plateau, western Colorado: Journal of Geophysical Research, v. 112, p. F03S06, doi:10.1029/2006JF000553, 2007.

Bigi, A., Hasbargen, L.E., Montarani, A., and Paola, C.: Knickpoints and hillslope failure: Interactions in a steady-state experimental landscape, *in* Willet, C.D., Hovius, N., Brandon, M.T., and Fisher, D.M., eds. Tectonics, Climate and Landscape evolution: Geological Society of America Special paper 398, p. 295-307, doi:10.1130/2006.2398(18), 2006.

Bonnet, S.: Shrinking and splitting of drainage basins in orogenic landscapes from the migration of the main drainage divide: Nature Geoscience, v. 2, p. 766–771, doi:10.1038/ngeo666, 2009.

Bonnet, S., and Crave, A.: Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climatic uplift of topography: Geology, v. 31, p. 123–126, doi: 10.1130/0091–7613, 2003.

Cantelli, A., and Muto, T.:Multiple knickpoints in an alluvial river generated by a single drop in base level: experimental investigation: Earth Surface Dynamics, 2, 271-278, doi:10.5194/esurf-2-271-2014, 2014.

Cook, K.L., Turowski, J.M., and Hovius, N.: A demonstration of the importance of bedload transport for fluvial bedrock erosion and knickpoint propagation: Earth Surface Processes and Landforms, v. 38, p. 683–695, doi:10.1002/esp.3313, 2013.

Cook, K.L., Turowski, J.M., and Hovius, N.: River gorge eradication by downstream sweep erosion: Nature geoscience, doi:10.1038/NGEO2224, 2014.

Croissant, T., Lague, D., and Davy, P.: Channel widening downstream of valley gorges influenced by flood frequency and floodplain roughness: Journal of Geophysical Research-Earth Surface, v. 124, p. 154–174, doi:10.1029/2018JF004767, 2019.

Crosby, B.T., and Whipple, K.X.: Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand: Geomorphology, v. 82, p. 16–38, doi:10.1016/j.geomorph.2005.08.023, 2006.

Davy, P., Croissant, T., and Lague, D.: A precipiton method to calculate river hydrodynamics, with applications to flood prediction, landscape evolution models, and braiding instabilities: Journal of Geophysical Research-Earth Surface, v. 122, p. 1491–1512, doi:10.1002/2016JF004156, 2017.

https://doi.org/10.5194/esurf-2021-50
Preprint. Discussion started: 28 June 2021

Duvall, A., Kirby, E., and Burbank, D.: Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California: Journal of Geophysical Research, v. 109, p. F03002, doi:10.1029/2003JF000086, 2004.

Finnegan, N.J.: Interpretation and downstream correlation of bedrock river terrace treads created by propagation knickpoints: Journal of Geophysical Research-Earth Surface, v. 118, doi:10.1029/2012JF002534, 2013.

Finnegan, N.J., and Dietrich, W.E.: Episodic bedrock strath terrace formation due to meander migration and cutoff: Geology, 39, 143-146, doi:10.1130/G31716.1, 2011.

Fuller, T.K., Gran, K.B., Sklar, L.S., and Paola, C.: Lateral erosion in an experimental bedrock channel: The influence of bed roughness on erosion by bed load impacts: Journal of Geophysical Research-Earth Surface, v. 121, p. 1084-1105, doi:10.1002/2015JF003728, 2016.

Grimaud, J.-L., Paola, C., and Voller, V.: Experimental migration of knickpoints: influence of style of base-level fall and bed lithology: Earth Surface Dynamics, v. 4, p. 11–23, doi:10.5194/esurf-4-11-2016, 2016.

Hancock, G.S., and Anderson, R.S.: Numerical modeling of fluvial strath-terrace formation in response to oscillating climate: Geological Society of America Bulletin, v. 114, p. 1131-1142, 2000.

Hasbargen, L.E., and Paola, C.: Landscape instability in an experimental drainage basin: Geology, v. 24, p. 1067-1070, 2000.

Hasbargen, L.E., and Paola, C.: How predictable is local erosion rate in erosional landscape ? *in* Wilcox, P.R. and Iverson, R.M., eds., Prediction in Geomorphology: American Geophysical Union Geophysical Monograph 135, doi:10.1029/135GM16, 2003.

Hilley, G.E., and Arrowsmith, J.R.: Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California: Geology, v. 36, p. 367-370, doi:10.1130/G24517A.1, 2008.

Kirby, E., and Whipple, K.X.: Expression of active tectonics in erosional landscapes: Journal of Structural Geology, v. 44, p. 54–75, doi:10.1016/j.jsg.2012.07.009, 2012.

Lague, D.: The stream power river incision model: evidence, theory and beyond: Earth Surface Processes and Landforms, v. 39, p. 38–61, doi:10.1002/esp.3462, 2014.

Lague, D., Crave, A., and Davy, P.: Laboratory experiments simulating the geomorphic response to tectonic uplift: Journal of Geophysical Research-Solid Earth, v. 108, doi:10.1029/2002JB001785, 2003.

Lavé, J., and Avouac, J.P.: Fluvial incision and tectonic uplift across the Himalayas of central Nepal: Journal of Geophysical Research-Solid Earth, v. 106, p. 26561–26591, doi:10.1029/2001JB000359, 2001.

Mitchell, N.A., and Yanites, B.J.: Spatially variable increase in rock uplift in the Northern U.S. Cordillera recorded in the distribution of river knickpoint and incision depths: Journal of Geophysical Research: Earth Surface, v. 124, 1238-1260, doi:10 .1029/2018JF004880, 2019.

Moussirou, B., and Bonnet, S.: Modulation of the erosion rate of an uplifting landscape by long-term climate change: An experimental investigation: Geomorphology, v. 303, p. 456–466, doi:10.1016/j.geomorph.2017.12.010, 2018.

Paola, C., Straub, K., Mohrig, D., and Reinhardt, L.: The “unreasonable effectiveness” of stratigraphic and geomorphic experiments: Earth-Science Reviews, v. 97, p. 1–43, doi:10.1016/j.earscirev.2009.05.003, 2009.

Rohais, S., Bonnet, S., and Eschard, R.: Sedimentary record of tectonic and climatic erosional perturbations in an experimental coupled catchment-fan system: Basin Research, v. 24, p. 198–212, doi:10.1111/j.1365-2117.2011.00520.x, 2012.

Scheingross, J.S., Lamb, M.P., and Fuller, B.M.: Self-formed bedrock waterfalls: Nature, v. 567, p. 229–233, doi:10.1038/s41586-019-0991-z, 2019.

Singh, A., Reinhardt, L., and Foufoula-Georgiou, E.: Landscape reorganization under changing climatic forcing: Results from an experimental landscape: Water Resources Research, v. 51, p. 4320–4337, doi:10.1002/2015WR017161, 2015.

https://doi.org/10.5194/esurf-2021-50
Preprint. Discussion started: 28 June 2021

Sweeney, K.E., Roering, J.J., and Ellis, C.: Experimental evidence for hillslope control of landscape scale: Science, v. 349, p. 51–53, doi:10.1126/science.aab0017, 2015.

Tofelde, S., Savi, S., Wickert, A. D., Bufe, A., and Schildgen, T. F.: Alluvial channel response to environmental perturbations: fill-terrace formation and sediment-signal disruption. Earth Surface Dynamics, v. 7, p. 609-631, doi:10.5194/esurf-7-609-2019, 2019.

Turowski, J.M.: Alluvial cover controlling the width, slope and sinuosity of bedrock channels: Earth Surface Dynamics, v. 6, p. 29–48, doi:10.5194/esurf-6-29-2018, 2018.

Turowski, J.M., Lague, D., Crave, A., and Hovius, N.: Experimental channel response to tectonic uplift: Journal of Geophysical Research-Earth Surface, v. 111, doi:10.1029/2005JF000306, 2006.

Whipple, K.X., and Tucker, G.E.: Dynamics of the stream-power river incision model: Im- plications for height limits of mountain ranges, landscape response timescales, and research needs: Journal of Geophysical Research, v. 104, p. 17,661–17,674, 1999.

Whittaker, A.C., and Boulton, S.J.: Tectonic and climatic controls on knickpoint retreat rates and landscape response times: Journal of Geophysical Research, v. 117, F02024, doi:10 .1029/2011JF002157, 2012.

Whittaker, A.C., Cowie, P.A., Attal, M., Tucker, G.E., and Roberts, G.P.: Bedrock channel adjustment to tectonic forcing: Implications for predicting river incision rates: Geology, v. 35, p. 103, doi:10.1130/G23106A.1, 2007.

Yanites, B.J., Ehlers, T.A., Becker, J.K., Schnellmann, M., and Heuberger, S.: High magnitude and rapid incision from river capture: Rhine River, Switzerland: Journal of Geophysical Research, v. 118, 1-25, doi:10 .1002/jgrf200567, 2013.

Zavala-Ortiz, V., Carretier, S., Regard, V., Bonnet, S., Riquelme, R., and Choy, S.: Along-stream variations in valley flank erosion rates measured using 10Be concentrations in colluvial deposits from canyons in the Atacama Desert: Geophysical Research Letters, 48, doi:10.1029/2020GL089961, 2021.