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Research paper

Impact of flow variability and sediment characteristics on channel width evolution in laboratory streams

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ABSTRACT

Alluvial rivers are shaped by sequences of water flows excavating their channels. Observations show that besides the magnitude, the frequency and duration of streamflow oscillations might also be important for the river channel formation. In addition, the river morphology appears influenced by both size and degree of uniformity of the sediment. Nevertheless, many morphodynamic studies still represent the flow regime with a single value of the discharge, often corresponding to the bankfull condition, and the sediment with its median grain size. This work investigates the effects of streamflow variability and sediment characteristics on channel width formation, analysing the evolution of experimental streams with different sediments and discharge hydrographs. Results show that the formative condition of the channel width is not the geometric bankfull flow but a rather frequent peak flow. Remarkably different channel configurations arise from different sediment characteristics in the laboratory, where sediment non-uniformity produces more stable banks.

Keywords: River morphodynamics; channel width; streamflow variability; bankfull discharge; sediment gradation; laboratory experiments

1 Introduction

Water flow governs the river channel formation through sediment entrainment, transport and deposition. Discharge variability affects the sediment mobility in time and space, resulting in vertical and horizontal sorting (e.g. Nicholas et al., 2016; Surian, Mao, Giacomini, & Ziliani, 2009) and bed topography adaptation (e.g. Dodov & Fofoula-Georgiou, 2005; Huthoff, Van Vuren, Barneveld, & Scheel, 2010). Each value of the discharge contributes to the evolution of river channels in a different way (Lane, Richards, & Chandler, 1996). The influence

of variable flow regime on channel-width adjustment, through its effects on bank erosion and accretion rates, has been identified from field data (e.g. Hooke, 2006; Nanson, 1980; Provansal et al., 2010) and in numerical modelling (e.g. Asahi, Shimizu, Nelson, & Parker, 2013). Flow variations affect the pore water pressure in river banks, enhancing bank erosion and river widening (e.g. Khan, Mwelwa-Mutekenya, Crosato, & Zhou, 2014; Rinaldi, Casagli, Dapporto, & Gargini, 2004). Opposite (indirect) effects are related to riparian vegetation, since plant growth on river banks and floodplains strongly depends on the alternation of high and low flows (e.g. Tsujimoto, 1999). Riparian

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vegetation has shown to affect flow field, as well as sediment and bank processes, with important consequences for the river morphology (Corenblit et al., 2011; Gurnell, Bertoldi, & Corenblit, 2012; Hickin, 1984). In particular, as a result of riparian vegetation growth, river channels become narrower and deeper (e.g. Crosato & Saleh, 2011; Tal & Paola, 2010; Villada Arroyave & Crosato, 2010). In this context, it appears important to include both discharge and sediment variability in morphodynamic studies. Nevertheless, it is often accepted assuming a single value of the discharge, referred to as the “formative discharge” or “dominant discharge”, and representing bed sediment by its median diameter (e.g. Surian, 1999).

The concept of a channel-forming discharge, Q_f , lies on the assumption that one single discharge may be capable of reproducing the same channel morphology (for instance width, depth and slope) as the natural hydrograph (e.g. Copeland, Soar, & Thorne, 2005; Emmett & Wolman, 2001; Pickup & Warner, 1976; Prins & de Vries, 1971). Most common approaches determine the formative discharge, Q_f , as the one having a certain return interval, Q_{Tr} , as the effective discharge, Q_{eff} , or as the bankfull discharge, Q_{bf} , (e.g. Blom, Arkesteijn, Chavarrias, & Viparelli, 2017; Shields, Copeland, Klingeman, Doyle, & Simon, 2003). While the discharge associated to a return interval is only obtained from data-based statistical analyses, the effective discharge, Q_{eff} , is defined as the flow that moves the largest amount of sediment over time (Wolman & Miller, 1960). In contrast, the definition of bankfull discharge, Q_{bf} , is not unique (see for instance Rosgen & Silvey, 1996). Nevertheless, it is widely accepted that the bankfull discharge corresponds to the maximum flow rate that can be conveyed by a channel without overflowing (Emmett & Wolman, 2001; Leopold & Maddock, 1953; Parker, 1979; Williams, 1978). Assuming the bankfull discharge, Q_{bf} , as the formative one, Q_f , is the most common approach. This is adopted, for instance, in many stream restoration projects (e.g. Biedenharn, Copeland, Thorne, Soar, & Hey, 2000; Kondolf, Podolak, & Grantham, 2013), even if field measurements have shown that this discharge might not represent the formative condition (e.g. Kondolf, Smeltzer, & Railsback, 2001). The bankfull discharge is traditionally derived from channel geometry and bed characteristics (e.g. Leopold & Maddock, 1953), and this is here referred to as “geometrical bankfull discharge”, from flow duration curves (e.g. Li, Czapiiga, Eke, Viparelli, & Parker, 2015; Naito & Parker, 2016; Nixon, 1959), or from a combination of discharge with a certain recurrence interval and basin drainage area (e.g. He & Wilkerson, 2011; Wilkerson, 2008).

Several empirical relationships have been proposed to derive the equilibrium geometry of alluvial channels as a function of bankfull discharge, sediment median grain size and other parameters, based on the so-called “regime theory” developed by Kennedy (1895) and Lacey (1929). This theory has been applied to gravel-bed rivers (e.g. Bray, 1982; Garde, Prakash, & Arora, 2001; Kaless, Mao, & Lenzi, 2014; Millar, 2005; Parker,

Wilkerson, Paola, Dietrich, & Pitlick, 2007), sand-bed rivers (e.g. Wilkerson & Parker, 2011) or both (e.g. Brooker, 2010; Eaton & Church, 2007). Contrastingly, studies dealing with the effects of streamflow variability on channel geometry are scarce. Yu and Wolman (1987) introduced the variability of streamflow in an extended version of the regime theory in such a way that increased streamflow variability would lead to narrower channels. However, this hypothesis has never been validated so far. Visconti, Camporeale, and Ridolfi (2010) suggest that increased streamflow variability might indeed result in narrower channels, but their experiments, carried out to study pseudo-meandering initiation, offer only a weak support of it. Pizzuto (1986) studied the effects of streamflow variability on the bankfull depth of sand-bed rivers, finding that an increase of discharge variability results in deeper channels, but in general, questions about the effects of discharge variability on river channel geometry remain unsolved.

In addition to the poor understanding of the effects of streamflow variability, studies assessing the consequences of using uniform sediment instead of graded sediment for morphodynamic predictions are scarce as well, especially with respect to the river channel formation (Parker, 2008; Powell, 1998). Focusing on the study of bar and planform development, mobile-bed experiments have been carried out with the addition of cohesive sediments highlighting the differences between the patterns obtained with and without adding cohesive material (e.g. Peakall, Ashworth, & Best, 2007; van de Lageweg, van Dijk, & Kleinhans, 2013; van Dijk, Lageweg, & Kleinhans, 2013). However, morphodynamic experiments focusing on the channel width formation using different bed-material sediment sizes are lacking. Recently, Singh, Crosato, Giri, and Hicks (2017) highlighted the importance of using variable discharge and considering sediment gradation to investigate the evolution of gravel-bed rivers using numerical models. The interaction between variable discharge and sediment characteristics appears therefore key to explaining the geometry of this type of river channels.

The objective of this contribution is to analyse the effects of both variable discharge and varied sediment characteristics on channel formation by performing a large series of small-scale laboratory experiments. We focus on the channel width, a key aspect of the morphological evolution of channels that has not been systematically studied yet. As bank processes are not completely well described in morphological numerical models yet (Siviglia & Crosato, 2016), laboratory studies seem to be an appropriate tool to start tackling some of the unsolved questions regarding the channel width formation. Although the possibility of measuring flow properties in small-scale laboratory flumes is limited, laboratory experiments constitute a relevant and versatile tool in morphodynamic studies since they provide important information on the governing morphodynamic processes (Kleinhans et al., 2014; Paola, Straub, Mohrig, & Reinhardt, 2009). However, despite the spectacular resemblance of real-world systems obtained by performing

small-scale experiments, questions about the upscaling of laboratory results are inevitable. The performed experimental tests consist in following the channel evolution of small streams for different combinations of discharge variability and sediment characteristics till achievement of morphodynamic equilibrium. Discharge regimes include constant as well as variable discharge hydrographs, with different peak frequencies and intensities, but maintaining the same average flow, chosen as the initial geometrical bankfull discharge. Four different sand types are considered, differing in their median grain size and degree of uniformity.

2 Materials and methods

2.1 Experimental set-up

The experiments were carried out in a tilting mobile-bed flume 1.25 m wide and 2.2 m long built at the Environmental Fluid Mechanics Laboratory of Delft University of Technology without sediment feeding or recirculation (Byishimo, 2014). The flume was filled with a 0.20 m thick layer of sand in which an initial straight narrow channel was excavated; see Fig. 1.

Four different sands were used. The grading of the sediments is here represented by their sorting index, I , given as:

$$I = 0.5 (D_{84}/D_{50} + D_{50}/D_{16}) \quad (1)$$

where D_x is the diameter of the grain size exceeding $x\%$ of each sediment sample. The grain size distribution and grading characteristics of the used sand samples are shown in Fig. 2 and listed in Table 1. Samples S1 and S2 correspond to rather uniform (well-sorted) sands whereas samples S3 and S4 to graded (poorly sorted) sand mixtures. Sediment samples S2 and S3 differ primarily in their sorting degree, with median diameters of similar size, S2 being a well-sorted sand and S3 being a poorly sorted sand mixture.

In order to minimize the effects of inflow and outflow at the upstream and downstream boundaries, coarse material was placed near the inlet and outlet to locally fix the local bed (see points 1 and 2 in Fig. 1).

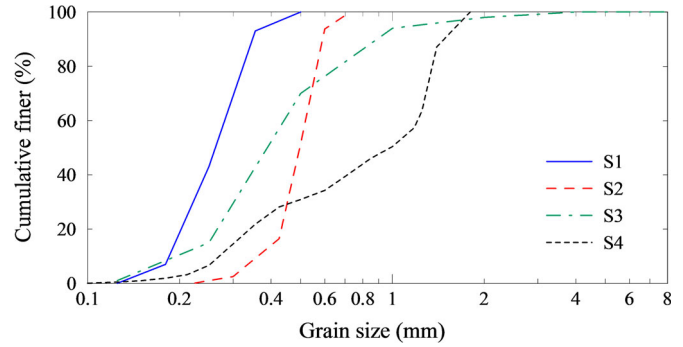


Figure 2 Grain size distributions of the sand samples used in the experiments

Table 1 Characteristics of sand samples

| Sample | D_{50} (10^{-3} m) | I |
|--------|-------------------------|------|
| S1 | 0.26 | 1.26 |
| S2 | 0.50 | 1.20 |
| S3 | 0.40 | 1.84 |
| S4 | 1.00 | 2.26 |

2.2 Experimental procedure

All experimental tests, differing in the sand used, started with the same constant flow, Q_f , equal to $0.1 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$. This was applied to a 3 cm wide, B_0 , and 2 cm deep, H_0 , straight channel with mobile bed, erodible banks and initial longitudinal slope equal to 1% (Stage 1 in Fig. 3a). Q_f was approximately

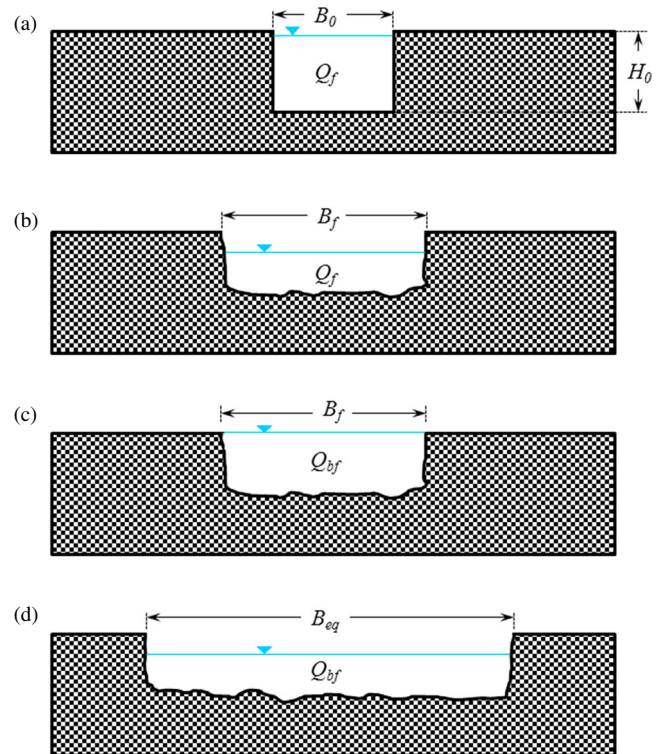


Figure 3 Experimental procedure subdivided in stages (a) 1, (b) 2, (c) 3 and (d) 4

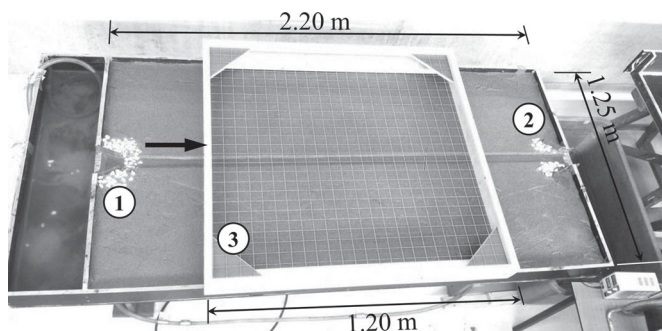


Figure 1 Experimental set-up at starting conditions: (1) inlet; (2) outlet; (3) net used for visualization

Table 2 Initial sediment-specific flow properties for a discharge Q_f , equal to $0.1 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$

| Property | S1 | S2 | S3 | S4 |
|--------------|------|------|------|------|
| H_0/D_{50} | 76.9 | 40.0 | 50.0 | 20.0 |
| θ | 0.47 | 0.24 | 0.30 | 0.12 |

the bankfull discharge of the initial channel, although small differences could be found for the different sediments, due to different bed roughness. Table 2 summarizes the relative roughness, H_0/D_{50} and the initial sediment-specific Shields parameter, $\theta = U^2/(C^2 \Delta D_{50})$, where U is the mean flow velocity, C is the Chézy coefficient, Δ is the relative density of the sediment, and D_{50} is the mean diameter of each sediment sample. The initial values of flow resistance, represented by the Chézy coefficient, Reynolds (R) and Froude (F) numbers were the same for all tests, namely $28.3 \text{ m}^{1/2} \text{ s}^{-1}$, 3100 and 3.5, respectively.

This first part of the experiments primarily allowed estimating the effects of sediment characteristics on channel formation, since all tests had the same initial and boundary conditions. At the achievement of the equilibrium width, B_f , being the width at the end of the widening process (Stage 2 in Fig. 3b), the discharge was increased to the value Q_{bf} (Stage 3 in Fig. 3c), corresponding to the new geometrical bankfull discharge. This allowed immediate observation of the difference between formative and geometrical bankfull discharge for each sand used. Starting from the obtained equilibrium configuration, a constant or variable flow was then imposed for 3.5 h, a duration that was found to be long enough for the achievement of a new equilibrium width, B_{eq} (Fig. 3d, Stage 4). All imposed hydrographs had Q_{bf} (geometrical bankfull) as average discharge (note that Q_{bf} was sediment-specific). Stage 4 allowed estimating the effects of high and low flow sequences, differing in intensity and frequency but having the same average discharge, on channel width formation for each sediment type.

Due to channel widening and water depth reduction, the flow properties changed over time. Froude numbers increased, whereas Reynolds numbers and Shields parameters decreased, resulting in reduced sediment mobility. Notwithstanding this, sediment was always mobile in all experimental tests. Figure 4 shows magnitudes and frequencies of the five imposed variable hydrographs, whereas Table 3 lists their values relative to the bankfull discharge Q_{bf} . The constant hydrograph, named H0, consisted of uniform flow equal to Q_{bf} . Hydrographs H1 and H2 alternated the same low and high discharges, but with different frequencies and durations. Hydrograph H3 presented decreased high flow frequency with an extended low-flow duration. In this case, the low-flow rate was adapted to maintain an averaged discharge equal to Q_{bf} . Hydrographs H4 and H5 had the same high flow frequency as H1 and H2, but with smaller discharge variations. These two hydrographs were applied only to the sediment samples S3 and S4.

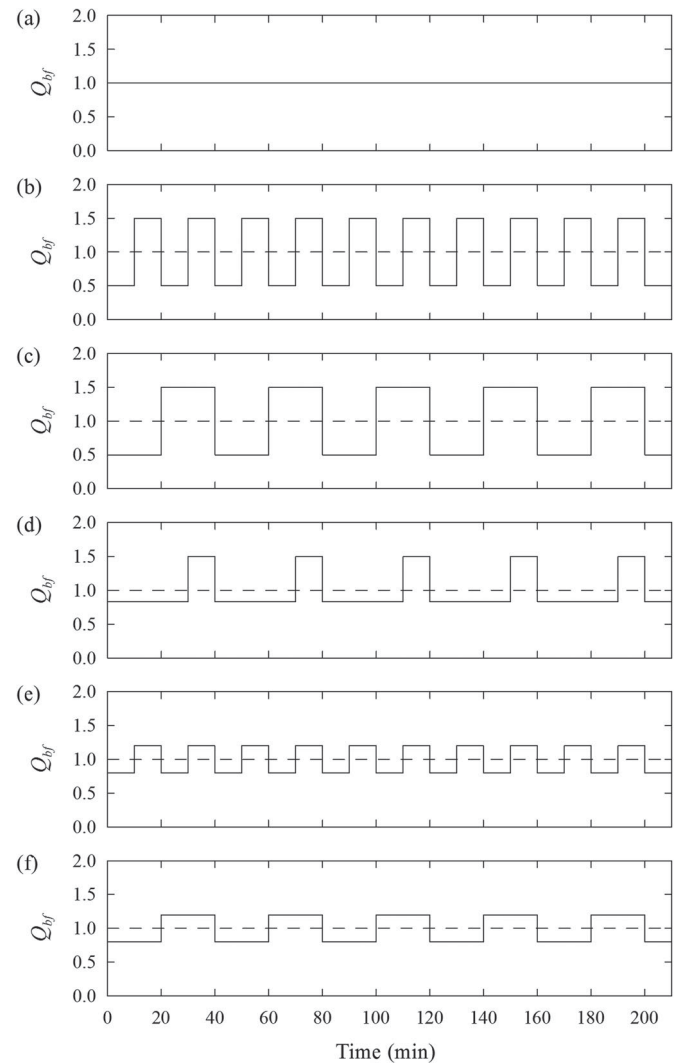


Figure 4 Flow hydrographs considered in the tests expressed as a function of the bankfull discharge, Q_{bf} , (a) H0, (b) H1, (c) H2, (d) H3, (e) H4, and (f) H5. See flow conditions in Table 3

Table 3 Flow conditions characterizing the imposed discharge hydrographs

| Hydrograph* | Q_{low} | $\Delta t_{Q_{low}}$ (min) | Q_{High} | $\Delta t_{Q_{High}}$ (min) |
|-------------|---------------------|----------------------------|---------------------|-----------------------------|
| H0 | Q_{bf} | — | Q_{bf} | — |
| H1 | $0.50 \cdot Q_{bf}$ | 10 | $1.50 \cdot Q_{bf}$ | 10 |
| H2 | $0.50 \cdot Q_{bf}$ | 20 | $1.50 \cdot Q_{bf}$ | 20 |
| H3 | $0.83 \cdot Q_{bf}$ | 30 | $1.50 \cdot Q_{bf}$ | 10 |
| H4 | $0.80 \cdot Q_{bf}$ | 10 | $1.20 \cdot Q_{bf}$ | 10 |
| H5 | $0.80 \cdot Q_{bf}$ | 20 | $1.20 \cdot Q_{bf}$ | 20 |

*Hydrographs H4 and H5 were applied only to sediment samples S3 and S4.

To reduce the influence of the up- and downstream boundary conditions, the channel width was measured at three cross-sections located in the middle area of the flume, being 1.2 m long. A 5 cm square grid frame (indicated by number 3 in Fig. 1) covered the measurement area, helping in the monitoring of the channel evolution. Data collection consisted of recording

water flow and channel evolution with a high-resolution camera located above the flume. Image analysis techniques were applied to the recorded videos to extract the width at several cross-sections each 5 min. The channel width was then derived by spatially averaging the measured width values and its value was plot as a function of time to analyse its evolution and to assess the achievement of equilibrium conditions. Due to the scale of our set-up, water depth and slope measurements were only possible at the beginning of the experiment.

3 Results

A high rate of sediment transport was observed at the beginning of each test, but sediment movement drastically reduced as a response to channel widening. In our experiments, the channel formation process was governed by bank erosion, which produced high rates of sediment inputs to the system, so that even if the flume lacked sediment recirculation and feeding devices, the sediment influx from bank failure prevented channel incision and led to small bed aggradation instead, slightly adjusting the slope in each experiment (see Fig. 5). No bedforms were observed during the experiments; however, for the fine and well sorted sediment, sample S1, some scour holes formed during the experiments. Sediment was transported as bedload, which alternated from high mobility during peak flows to close to initiation of motion during low-flows. Therefore, the experimental channels, as most available small-scale experiments, qualitatively reflected some dynamics of gravel-bed rivers with banks and bed made of similar materials.

3.1 Effects of sediment characteristics on equilibrium channel width

Table 4 lists the values of the equilibrium channel widths, B_f , obtained for the different sediments with the initial (formative) discharge, Q_f . Although maintaining the same discharge, as well as boundary and initial conditions, a different equilibrium width was obtained for each sediment type. In this case the differences are minor (all the widths fall in the range 9.3–9.8 cm), which is due to the relative small value of the formative discharge resulting in low sediment entrainment rates. However, these small differences in channel geometry resulted in larger variations of bankfull discharges, Q_{bf} (Table 4).

The values of the equilibrium channel widths, B_{eq} , obtained at the end of each test for all hydrographs and sediments are shown in Table 5. For all sediments, the largest widths were obtained with hydrograph H1 (highest discharge variability) and the smallest ones with the constant discharge, hydrograph H0. The comparison between the channels formed in sediments S1 and S2, both rather uniform materials (well sorted) but with different median grain size ($D_{50S2}/D_{50S1} = 1.92$), shows that a smaller sediment size produced wider channels. Sands with similar median grain size but different sorting characteristics

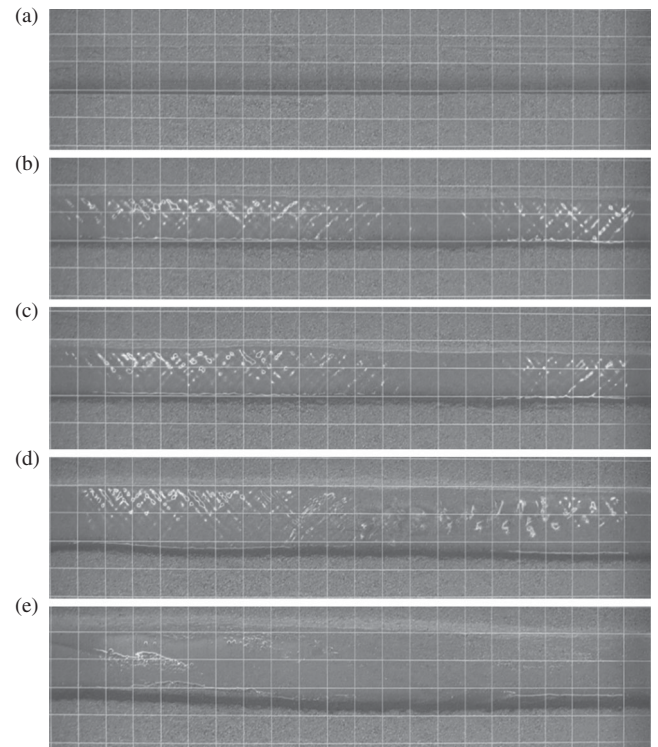


Figure 5 Channel width evolution with sediment S4 ($D_{50} = 1.0 \times 10^{-3}$ m) and discharge hydrograph H3 at: (a) T = 0 min ($B = 0.093$ m), (b) T = 15 min ($B = 0.105$ m), (c) T = 30 min ($B = 0.107$ m), (d) T = 60 min ($B = 0.137$ m), and (e) T = 150 min ($B = 0.153$ m). The flow conditions are listed in Table 3 and the hydrographs are shown in Figure 4

Table 4 Equilibrium channel widths, B_f , and bankfull discharges, Q_{bf} , for the four sediment samples obtained after the first constant flow equal to $0.1 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$

| Sample | B_f (m) | Q_{bf} ($10^{-3} \text{ m}^3 \text{ s}^{-1}$) |
|--------|-----------|---------------------------------------------------|
| S1 | 0.0983 | 0.27 |
| S2 | 0.0953 | 0.25 |
| S3 | 0.0923 | 0.20 |
| S4 | 0.0930 | 0.23 |

Table 5 Summary of the equilibrium channel-width for the considered flow conditions

| Sediment sample | B_{eq} (10^{-2} m) | | | | | |
|-----------------|-------------------------|------|------|------|------|------|
| | H0 | H1 | H2 | H3 | H4 | H5 |
| S1 | 20.0 | 24.3 | 24.0 | 20.7 | – | – |
| S2 | 16.8 | 19.0 | 18.3 | 17.2 | – | – |
| S3 | 12.7 | 17.0 | 16.2 | 15.3 | 14.7 | 14.5 |
| S4 | 13.0 | 16.2 | 15.5 | 15.3 | 14.7 | 14.5 |

(samples S2 and S3, $D_{50S3}/D_{50S2} = 0.8$) show that a higher degree of sediment non-uniformity produced narrower channels. Notwithstanding an important difference in sediment size ($D_{50S4}/D_{50S3} = 2.5$), affecting entrainment, transport and deposition of bed and bank material, the channels excavated in

sediments S3 and S4 have similar if not identical widths (Table 5). This can be explained by a similarly low bank erodibility. A relatively strong increase in bank stability appears related to the relatively large sediment gradation of these two sediment mixtures. The explanation can be found in the higher sediment density and smaller pore volumes of poorly sorted sands with respect to uniform sands, resulting in higher apparent cohesion.

3.2 Effects of streamflow variability on channel formation

Figure 6 depicts the temporal evolution of channel width produced by hydrographs H0, constant discharge equivalent to bankfull discharge Q_{bf} , listed in Table 4. The new equilibrium width was reached almost at the same time (1.5 h) in all cases.

The temporal channel evolution obtained with hydrographs H1 to H3 (Table 3) are presented in Fig. 7–9, respectively. These figures and the comparison between the values listed in Table 5 for each sediment type show that, in general, discharge variability has a strong effect on channel width formation, which appears dominated by the peak discharges. As a result, all variable hydrographs produced wider channels than the constant

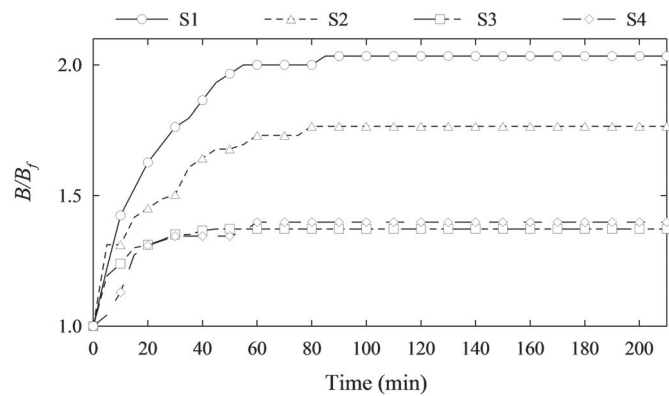


Figure 6 Dimensionless channel-width evolution as a function of time resulting from hydrograph H0 (uniform bankfull discharge)

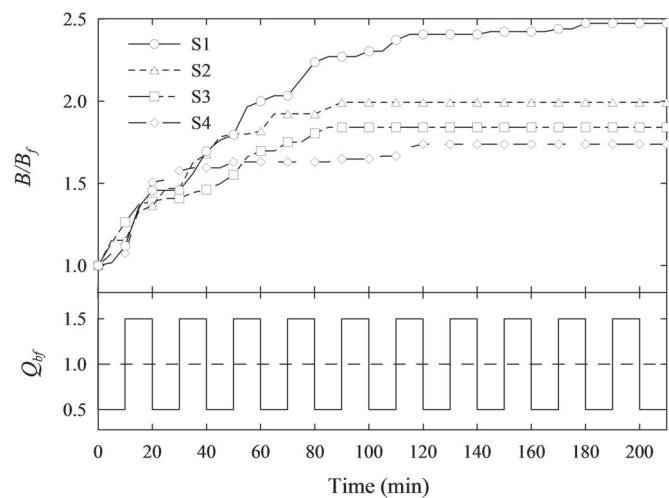


Figure 7 Dimensionless channel-width evolution as a function of time resulting from hydrograph H1 (top) and discharge variation (below) as a function of bankfull discharge

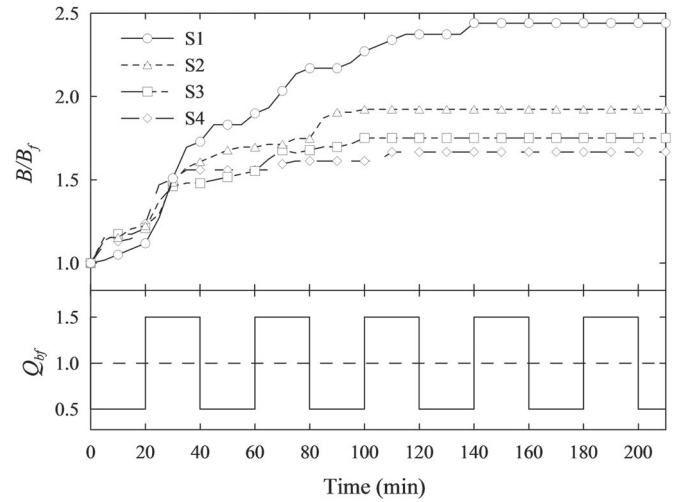


Figure 8 Dimensionless channel-width evolution as a function of time resulting from hydrograph H2 (top) and discharge variation (below) as a function of bankfull discharge

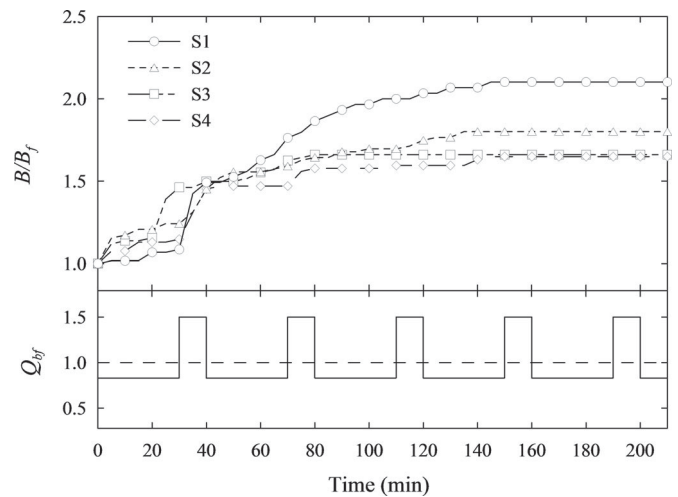


Figure 9 Dimensionless channel-width evolution as a function of time resulting from hydrograph H3 (top) and discharge variation (below) as a function of bankfull discharge

(bankfull) discharge; the higher the peak discharge the wider the channel. For the same values of high and low flows, larger widths were obtained for higher frequency of discharge variations (compare the results of H1 with the results of H2; Table 5). The differences between the results for non-uniform samples, S3 and S4, are smaller than those obtained for uniform sediments; an aspect here attributed to the relatively high bank resistance observed for non-uniform sediment (Section 3.1).

It is important to mention here that the geometrical bankfull discharge experimentally derived for each sediment at the start of this experimental phase always exceeded the initially imposed (formative) discharge Q_f ($0.1 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$) by a factor of 2–3 (Table 4). The channel obtained by applying the bankfull discharge was therefore always much wider than the original one (compare the widths obtained by Q_f to the ones obtained by Q_{bf} , in the first columns of Tables 4 and 5, respectively). This means that the geometrical bankfull discharge is

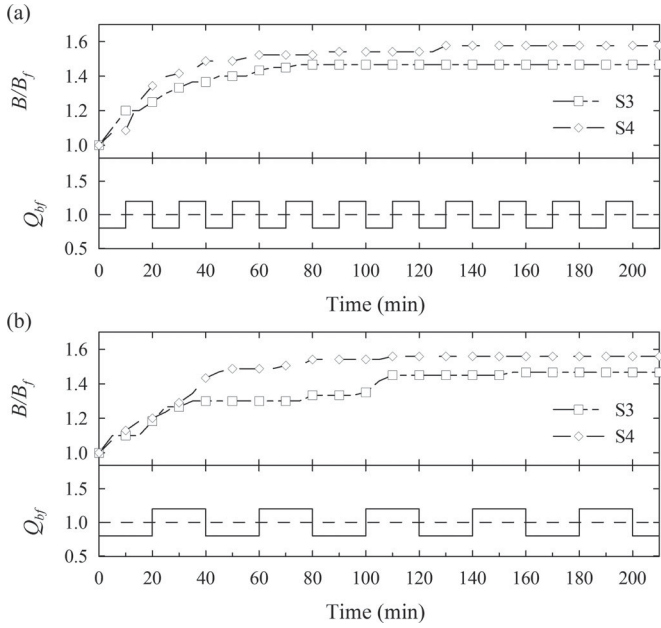


Figure 10 Dimensionless channel-width evolution as a function of time for the sediment samples S3 and S4 with the hydrographs: (a) H4 and (b) H5

not the formative condition of alluvial channels that are excavated through sediment as a result of bed and bank erosion. At the end of each experiment, after 3.5 h of variable flow, the channel cross-section was not completely filled by the flowing water, even at peak conditions. This means that the geometrical bankfull discharge of the final channel configuration would exceed even the imposed peak flows.

Hydrographs having the same frequency as H1 and H2, but smaller discharge variation (H4 and H5), were additionally imposed to sediment samples S3 and S4, both poorly sorted (non-uniform) materials, but with different median grain sizes. The results are shown in Fig. 10. The final widths are rather similar, which means that the effects of peak frequency and duration are small.

Figure 11 presents the channel width evolution obtained with all hydrographs for sediment sample S4. This figure clearly illustrates the effects of streamflow variability on channel width

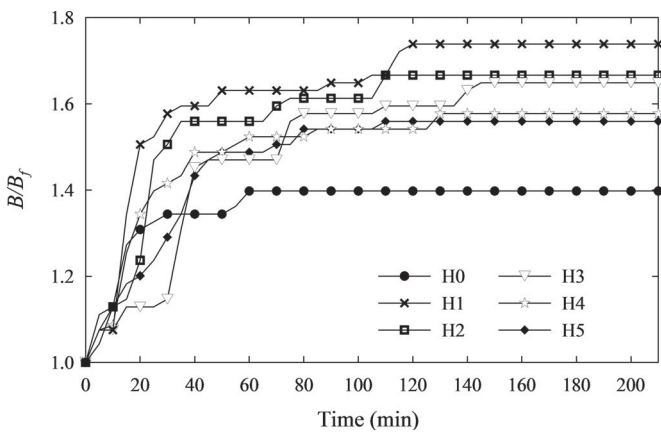


Figure 11 Dimensionless channel width evolution as a function of time for all the considered the hydrographs on the sediment sample S4

evolution. It is now evident that hydrograph H1, characterized by the highest variability, in terms of both intensity and frequency, resulted in the largest channel. Higher frequency of peak discharges resulted in larger channels (compare the results of hydrographs H1 and H3). The same frequency with smaller flow variation produced narrower channels (compare the results of H1 with H4 and H2 with H5 in Fig. 11). The smallest channel was produced by the constant discharge H0. The observed trends apply also to the other sediments (Section 3.2).

4 Discussion

The results obtained in this work are presented in the way adopted by Parker et al. (2007) to allow for comparison with their field data analysis. For that purpose, we define the dimensionless channel width as:

$$\tilde{B} = (g^{1/5} B) / Q^{2/5} \tag{2}$$

Assuming that the median grain size of the sediment at the bed surface is equivalent to the median size of the sediment samples used in the experiments ($D_{s50} = D_{50}$), the dimensionless discharge is defined as:

$$\tilde{Q} = Q / (\sqrt{g D_{50} D_{50}^2}) \tag{3}$$

Figure 12 plots dimensionless channel width against dimensionless discharge for the conditions at the end of Stage 1 and Stage 4. For the conditions at the end of Stage 1, two discharges are considered: the initial (formative) discharge, Q_f (red dots) and the geometrical bankfull discharge, Q_{bf} (black dots), whereas the channel width is the one at the end of that Stage, B_f (Fig. 3b). For the conditions at the end of Stage 4, two discharges are considered: Q_{bf} for the hydrographs with constant discharge (red dots) and Q_{High} (peak discharge) for the hydrographs with

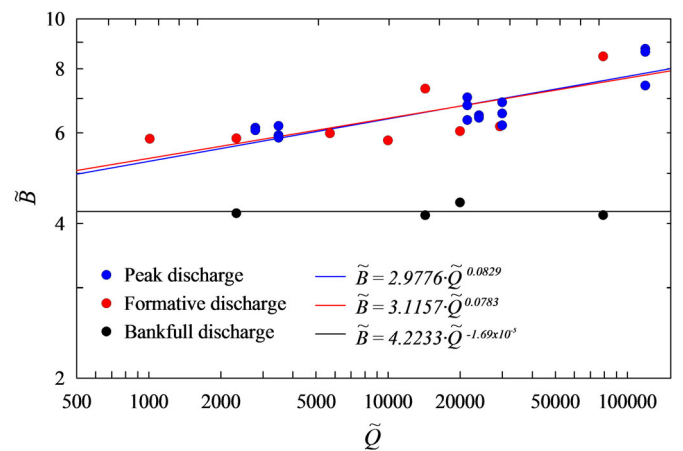


Figure 12 Dimensionless width versus dimensionless discharge. Black dots and black trend line: width versus geometrical bankfull discharge. Red dots and red trend line: width versus constant formative discharge. Blue dots and blue trend line: equilibrium width versus peak discharge (variable discharge cases)

variable discharge (blue dots), whereas the width is represented by the final equilibrium width, B_{eq} (Fig. 3d). Equations presented in Fig. 12 were obtained by applying a standard linear regression procedure, computing uncertainties at the 95% confidence level.

In Fig. 12 the red dots represent the cases with a constant formative discharge, to be distinguished from the cases with variable discharge (blue dots) for which the formative condition is assumed to be represented by the peak flow.

The trend lines obtained with either the formative constant discharges (the only cases in which we could surely quantify the formative discharge are the tests with constant flow) or the peak discharges are very similar and strongly resemble the one found by Parker et al. (2007) for single-thread gravel-bed rivers “at bankfull conditions”:

$$\tilde{B} = 4.63 \tilde{Q}^{0.0667} \quad (4)$$

The dimensionless width appears independent from the geometrical bankfull discharge (horizontal trend line), demonstrating once again that the geometrical bankfull discharge cannot represent the formative condition, at least in our experiments. In Parker et al. (2007), the “bankfull conditions” are represented by the two-year flood flow and not by the geometrical bankfull discharge, as reported in the papers they cite (see for instance Bray, 1975, 1982; Kellerhals, Neill, & Bray, 1972; Parker, 1979). The strong similarity between our trend lines and the one derived by Parker et al. (2007) for single-thread gravel-bed rivers (Fig. 12) suggests that the evolution of our small alluvial systems can be assumed to be representative of some dynamics of real-scale gravel-bed rivers, particularly the ones related to the channel width formation, despite of the limitations related to the small size of the facility used.

Our experimental results do not support the extended regime relationship developed by Yu and Wolman (1987), since all hydrographs with variable discharge produced wider channels than those with constant discharge, even if the average discharges were identical. On the contrary, it is shown with our experiments that the equilibrium width for hydrographs with variable discharges can be obtained from a formative discharge corresponding to the peak of the hydrograph, instead of the average (bankfull) discharge.

With the same starting and boundary conditions, different sediments resulted in different equilibrium channels. In particular, poorly sorted sandy materials resulted in relatively high bank stability, producing more stable and narrower channels. Uniform sands resulted in much wider systems. Smaller sediment sizes produced wider channels as well. These findings show that width and planform of laboratory streams depend on both gradation and size of sediment. However, in our experiments the effects of grain size became negligible for the poorly sorted sediments, since channel widening was strongly limited by increased bank resistance. The experiments showed also that a low-sinuosity meandering stream with relatively stable banks can be obtained in the laboratory using a poorly-sorted sandy

mixture. Adding cohesive material, like kaolinite, is not necessary as shown in previous works (e.g. Kleinhans et al., 2010; van de Lageweg et al., 2013; van Dijk et al., 2013). However, this is true only for small-scale streams with small water flows.

Future laboratory works including variations of bank resistance are required to clarify the role of bank soil properties on the channel width evolution. Larger experimental facilities would also be preferable, since they allow measuring flow and bed properties with more accuracy. Considering more realistic hydrographs is also encouraged, as the assumed flow hydrographs do not reflect the natural regimes observed in rivers (e.g. Gunsolus & Binns, 2016; Huthoff et al., 2010).

5 Conclusions

As flow and sediment are important interacting factors governing the river channel formation, we carried out a series of laboratory experiments to study the effects of streamflow variability and sediment characteristics on river channel width. The study was conducted in a small-scale mobile-bed flume, in which identical initial straight channels excavated in different sediments evolved as a result of different discharge regimes.

Maximum channel widening was obtained from the combination of fine uniform sand and relatively frequent sequences of high and low flows. Minimum widening was obtained with poorly sorted sand and constant discharge. Higher frequency of peak discharges resulted in wider channels, but in general the channel-width formation was mostly affected by the peak flow intensity.

The results of our experiments show that the geometrical bankfull discharge is much larger than the formative one and produces excessively wide channels. The trend line dimensionless-width versus dimensionless-discharge obtained with the formative, constant discharges resembles the trend line obtained using the peak discharges when considering the variable flow regimes. This allows the conclusion that the peak flows represented the formative conditions of our small alluvial systems in case of variable discharge.

Comparing our experimental results with the results of Parker et al. (2007), who derived a very similar trend line for real rivers based on their two-year flood flow, we conclude that the formative condition of single-thread gravel-bed river channels is not their geometrical bankfull discharge, but rather a relatively frequent peak flow. These findings stress the need to distinguish the geometrical bankfull discharge from the formative condition and to avoid relating any peak discharges with given return times to the bankfull state.

Furthermore, the similarity of the trends found in this study with data from single-thread gravel-bed rivers shows that our experiments can be assumed to represent some dynamics of real-scale gravel-bed rivers, particularly the ones related to the channel width formation, despite the limitations of the size of the facility used.

An additional finding of this study is that the channel width increases with increasing discharge variability, which is according to expectations but conflicting with what has been previously proposed in the literature (e.g. Yu & Wolman, 1987).

Finally, the results of this research emphasize the role of bank erodibility for the formation of river channels, as high sediment gradation, resulting in apparent cohesion at the small flume scale, dominated the channel formation of our laboratory streams by limiting their widening.

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Notation

| | |
|-----------------------|--------------------------------------------------------------------------------|
| D_x | = diameter of the grain size exceeding x% of a sediment sample (m) |
| I | = sorting index (–) |
| Q_{Low} | = low discharge considered in the hydrographs ($m^3 s^{-1}$) |
| Q_{High} | = high discharge considered in the hydrographs ($m^3 s^{-1}$) |
| $\Delta t_{Q_{Low}}$ | = duration of the low discharge considered in the hydrographs (min) |
| $\Delta t_{Q_{High}}$ | = duration of the high discharge considered in the hydrographs (min) |
| Q_f | = formative discharge ($m^3 s^{-1}$) |
| Q_{eff} | = effective discharge ($m^3 s^{-1}$) |
| Q_{Tr} | = discharge associated to a return interval, Tr ($m^3 s^{-1}$) |
| Q_{bf} | = bankfull discharge ($m^3 s^{-1}$) |
| \tilde{Q} | = dimensionless discharge (–) |
| B_0 | = width of the initially constructed straight channel (m) |
| B | = channel width (m) |
| B_f | = equilibrium channel-width obtained with the formative discharge, Q_f (m) |
| B_{eq} | = equilibrium channel-width obtained with the bankfull discharge, Q_{bf} (m) |
| \tilde{B} | = dimensionless width (–) |
| Tr | = return interval (years) |
| H_0 | = depth of the initially constructed straight channel (m) |

| | |
|------------|-----------------------------------------------------------------|
| F | = $U/(gH_0)^{1/2}$ = Froude number (–) |
| U | = mean flow velocity ($m s^{-1}$) |
| R | = UH_0/ν = Reynolds number (–) |
| Q | = flow discharge ($m^3 s^{-1}$) |
| θ | = $U^2/(C^2 \Delta D_{50})$ = Shields parameter (–) |
| g | = acceleration due to gravity ($m s^{-2}$) |
| C | = Chézy coefficient ($m^{1/2} s^{-1}$) |
| D_{50} | = median grain size (m) |
| Δ | = $(\rho_s - \rho)/\rho$ = relative density of the sediment (–) |
| ν | = kinematic viscosity of the fluid ($m^2 s^{-1}$) |
| ρ | = density of the fluid ($kg m^{-3}$) |
| ρ_s | = density of the sediment ($kg m^{-3}$) |
| D_{50Sx} | = mean grain size of sample Sx (m) |

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