Impact of flow variability and sediment characteristics on channel width evolution

Vargas-Luna, Andrés; Crosato, Alessandra; Byishimo, Protogene; Uijttewaal, Wim

DOI
10.1051/e3sconf/20184005044

Publication date
2018

Document Version
Final published version

Published in
E3S Web of Conferences

E3S Web of Conferences **40**, 05044 (2018) https://doi.org/10.1051/e3sconf/20184005044
River Flow 2018

Impact of flow variability and sediment characteristics on channel width evolution

Andrés Vargas-Luna[1,2,*], *Alessandra Crosato*[3] , *Protogene Byishimo*[2] , and *Wim Uijttewaal*[2]

[1]Pontificia Universidad Javeriana, Cra. 7 No. 40-62, Bogotá D.C., Colombia
[2]Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands
[3]IHE - Institute for Water Education, PO Box 3015, 2601 DA Delft, The Netherlands

Abstract. Alluvial rivers are shaped by sequences of water flows excavating their channels. Observations show that besides the magnitude, also the frequency and duration of streamflow oscillations might be important for the river channel formation. In addition, the river morphology appears influenced also 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.

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 and bed topography adaptation. Each value of the discharge regime contributes to the evolution of river channels in a different way [1]. 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 [2] and in numerical modelling [3]. Flow variations affect the pore water pressure in river banks, enhancing bank erosion and river widening. 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 [4].

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 [5]. Most common approaches determine the

* Corresponding author: avargasl@javeriana.edu.co

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}. Assuming the bankfull discharge, Q_{bf}, as the formative one, Q_f, is the most common approach.

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 [6]. Morphodynamic experiments focusing on the channel width formation using different bed-material sediment sizes are also lacking. Recently, [7] 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 explain 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, 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, yet laboratory experiments constitute a relevant and versatile tool in morphodynamic studies since they provide important information on the governing morphodynamic processes.

2. Materials and methods

2.1. Experimental setup

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 [8]. 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.

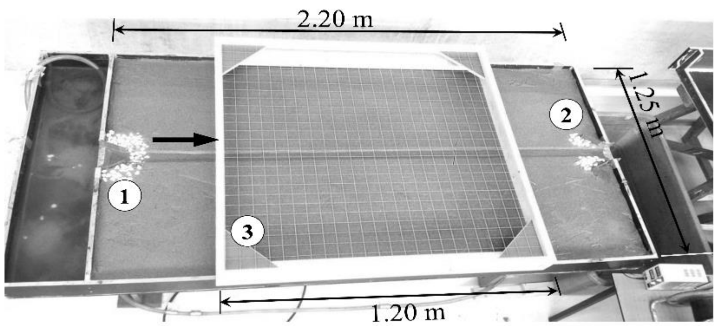

Fig. 1. Experimental setup at starting conditions: (1) inlet, (2) outlet, and (3) net used for visualization.

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

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

where Dx is the diameter of the grain size exceeding x % of each sediment sample. The grain size properties and grading characteristics of the used sand samples are 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.

Table 1. Characteristics of sand samples.

Sample	D_{50} (mm)	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 0.1l/s. 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. 2a). Q_f was approximately 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 in m/s, C is the Chezy's coefficient in $m^{1/2}/s$, Δ is the Relative density of the sediment (-), and D_{50} is the mean diameter of each sediment sample in m. The initial values of flow resistance, represented by Chezy's coefficient C, Reynolds, R, and Froude, F, numbers were the same for all tests, namely 28.3 $m^{1/2}/s$, 3,100 and 3.5, respectively.

Table 2. Initial sediment-specific flow properties for a discharge Q_f, equal to 0.1l/s.

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

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 this the width at the end of the widening process (Stage 2 in Fig. 2b), the discharge was increased to the value Q_{bf} (Stage 3 in Fig. 2c), corresponding to the new geometrical bankfull discharge. This allowed to immediately observe 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 hours, duration that was found to be long enough for the achievement of a new equilibrium width, B_{eq} (Fig. 2d, 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, *F*, increased, whereas Reynolds numbers, *R*, and Shields parameters, θ, decreased, resulting in reduced sediment mobility. Notwithstanding this, sediment was always mobile in all experimental tests. Table 3 lists the values of high and low flows 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.

Table 3. Flow conditions characterizing the imposed discharge hydrographs.

Hydrograph*	Q_{low}	Δt Q_{low} (min)	Q_{High}	Δt 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 this 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 minutes. 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 setup, 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. 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.

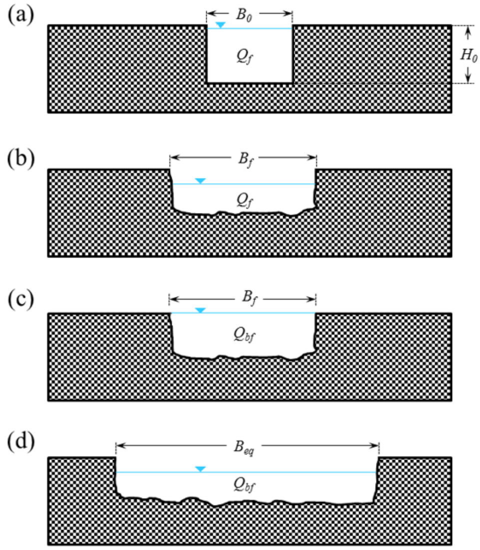

Fig. 2. Experimental procedure subdivided in stages (a) 1, (b) 2, (c) 3 and (d) 4.

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}.

For all sediments, the largest widths were obtained with hydrograph H1 (highest discharge variability) and the smallest ones with the constant discharge, hydrograph H0 (See Table 3). The comparison between the channels formed in sediments S1 and S2, both rather uniform materials (well sorted) but with different median grain size ($D_{50\ S2}$ / $D_{50\ S1}$ = 1.92), show that a smaller sediment size produced wider channels. Sands with similar median grain size but different sorting characteristics (samples S2 and S3, $D_{50\ S3}$ / $D_{50\ S2}$ = 0.8) show that a higher degree of sediment non-uniformity produced narrower channels. Notwithstanding an important difference in sediment size ($D_{50\ S4}$ / $D_{50\ S3}$ = 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. 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.

All variable hydrographs produced wider channels than the constant (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).

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 (0.11/s) by a factor 2 to 3. The channel obtained by applying the bankfull discharge was therefore always much wider than the original one. This means that the geometrical bankfull discharge is not the formative condition of alluvial channels that are excavated through sediment as a result of bed and bank erosion.

Figure 4 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 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.

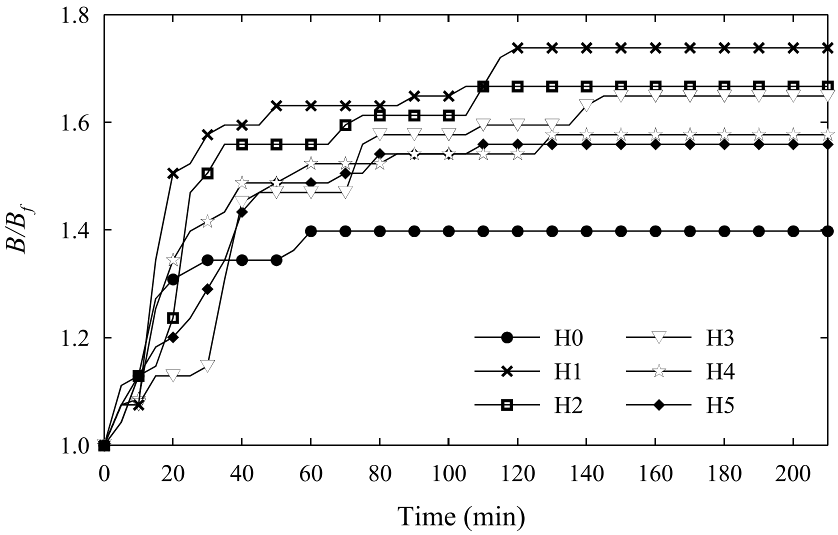

Fig. 3. Dimensionless channel width evolution as a function of time for all the considered the hydrographs on the sediment sample S4.

The results obtained in this work are presented in the way adopted by [9] to allow for comparison with their field data analysis. For that purpose, we define the dimensionless channel width as:

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

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:

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

Figure 4 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

 https://doi.org/10.1051/e3sconf/20184005044

bankfull discharge, Q_{bf} (black dots), whereas the channel width is the one at the end of that Stage, B_f (Fig. 2b). 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 variable discharge (blue dots), whereas the width is represented by the final equilibrium width, B_{eq} (Fig. 2d).

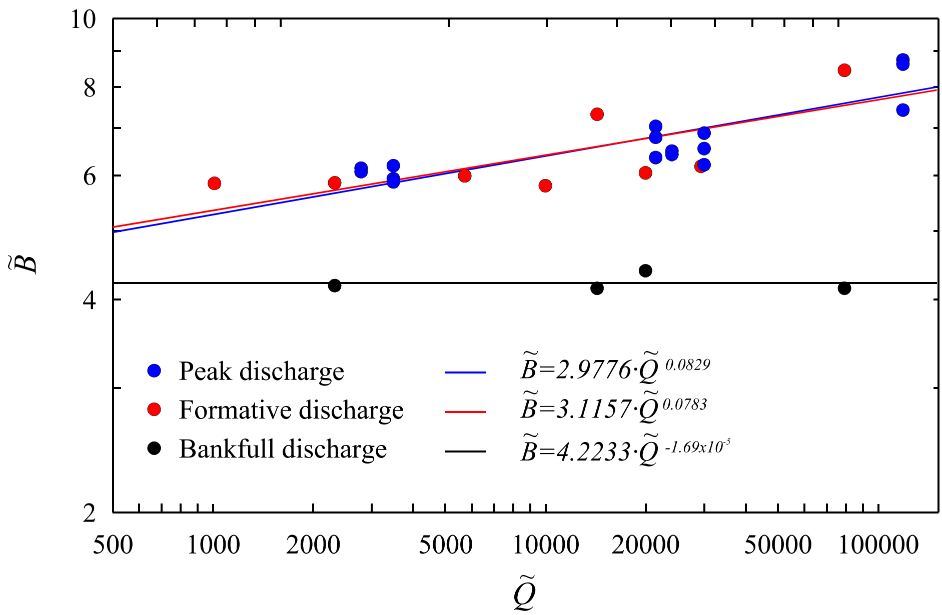

Fig. 4. Dimensionless width vs dimensionless discharge. Black dots and black trend line: width vs geometrical bankfull discharge. Red dots and red trend line: width vs constant formative discharge. Blue dots and blue trend line: equilibrium width vs peak discharge (variable discharge cases).

In Fig. 4 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 [9] for single-thread gravel-bed rivers “at bankfull conditions”.

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 [9], the “bankfull conditions” are represented by the 2-year flood flow and not by the geometrical bankfull discharge, as reported in the papers they cite. The strong similarity between our trend lines and the one derived by [9] for single-thread gravel-bed rivers (Fig. 4) 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.

4. 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 vs 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 concluding 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 by [9], who derived a very similar trend line for real rivers based on their 2-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 show 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 of the limitations of the size of the facility used.

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.

References

1. S.N. Lane, K.S. Richards, J.H. Chandler, Geomorphology **15**, 1 (1996)
2. G.C. Nanson, Sedimentology, **27** 1 (1980)
3. K. Asahi, Y. Shimizu, J. Nelson, G. Parker, J. Geophys. Res-Earth **118**, 1-22 (2013)
4. N. Surian, Earth Surf. Proc. Land. **24**, 12 (1999)
5. A. Prins, M. de Vries, *Proceedings of the XIVth IAHR Congress* (1971)
6. Parker, G. In Garcia, M. (Ed.) Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. ASCE Manuals and Reports on Engineering Practice No. 110, 165–251 (2008)
7. U. Singh, A. Crosato, S. Giri, M. Hicks, Adv. Water Resour. **104**, 127–144 (2017)
8. Byishimo, P. (2014). Effects of variable discharge on width formation and cross-sectional shape of sinuous rivers. Master Thesis, UNESCO-IHE, Institute for Water Education, Delft, The Netherlands.
9. G. Parker, P.R. Wilcock, C. Paola, W.E. Dietrich, J. Pitlick, J. Geophys. Res-Earth, 112 F4 (2007)