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Crosato, Alessandra

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On the factors governing river morphology with a look on how rivers adapt to climate

Alessandra Crosato[a,b]
[a]IHE Delft Institute for Water Education, Department of Water Resources and Ecosystems, Westvest 7, 2611 AX Delft, the Netherlands
[b]Delft University of Technology, Dept. of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, the Netherlands

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Introduction

River morphology can be described at different scales: at the basin scale we distinguish the river network; at the reach scale the planform, the slope and average features, such as the width and bankfull water depth; at the cross-section scale the transverse variations of river bed topography; and at smaller scales we observe bedforms and sediment grains. What are the factors that influence the river mophology at the different scales? Does climate govern these factors and if climate changes, how does the river react?

This review addresses these important questions, focusing at the reach and cross-section scales. Important knowledge gaps are related to the channel width formation, a key factor for river morphology. Several predictors based on field data relate the equilibrium width to bankfull discharge, sediment size, vegetation and bank resistance. However, it is not clear if the river width also depends on the conditions at the start of the morphological process. An example are rivers that adapt their morphology after their water and sediment discharge regimes have been altered by an external factor, such as a dam of a change in climate. Does the morphology of these rivers depend also on their previous width?

Theoretical background

Assuming morphodynamic equilibrium, the combination of water and sediment balances, momentum equation for water, and a sediment transport law allows deriving slope and average water depth of river reaches as a function of discharge Q_W, sediment transport rate Q_S, sediment size D_{50}, hydraulic roughness C (Chézy), and channel width B (Jansen et al., 1979). Applying Engelund and Hansen's (1967) formula (sand-bed rivers), the equilibrium slope i is given by:

$$i = K\left(\frac{1}{Q_W}\right)\left(\frac{Q_S^3 D_{50}^3 B^2}{C}\right)^{1/5} \qquad (1)$$

where coefficient K depends on gravity and the mass densities of water and sediment.

The value of longitudinal slope is often used to predict the channel planform, i.e. meandering (smaller than a threshold value), braiding or in between. Several empirical formulas have been derived based on field data (e.g. Leopold and Wolman, 1957). A physics-based approach considers the number of bars in the channel cross-section. Re-writing the formula of Crosato and Mosselman (2009), and assuming that central bars form the limit between meandering and braiding, it is possible to derive a threshold slope i_{cr}, in a way similar to other predictors:

$$i_{cr} = 11.75\left(\frac{h}{B}\right)^2\left(\frac{u}{\sqrt{gh}}\right)\left(\frac{C}{\sqrt{g}}\right)\sqrt{\Delta\frac{D_{50}}{h}} \qquad (2)$$

with h = water depth, u = flow velocity, g = acceleration due to gravity and Δ = relative sediment mass density under water. This relation extends Parker's (1976) predictor, who derived i_{cr} as a function of width-to-depth ratio and Froude number. Both approaches highlight the role of width-to-depth ratio and thus of the channel width, assumed known. Their application needs to be coupled to a width predictor, but existing ones perform poorly. Width predictors relate to bankfull conditions and have the general form:

$$B = f(Q_W, D_{50}) \qquad (3)$$

According to Parker et al. (2007) for sand-bed rivers the bankfull width increases if the discharge increases and decreases if sediment size increases.

Factors influencing the channel width

Riparian vegetation plays an important role in bank erosion and accretion. Its growth on river floodplains and emerging bars is able to reduce the river braiding degree and width (e.g. Crosato and Samir-Saleh, 2011). However, unvegetated bank material resistance has similar, even stronger, effects on river width (Fig. 1).

Figure 1. Channel development from straight in the laboratory with two different sediments: uniform sand (top) and poorly sorted sand behaving as cohesive at the flume scale (down).

In sand-bed rivers with vegetated floodplains, vegetation density strongly impacts the channel width (Fig. 2), whereas discharge rather affects the water depth (Crosato et al. 2022).

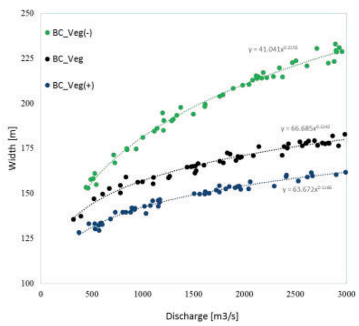

Figure 2. 2D Delft3D reproduction of Pilcomayo River. Channel width as a function of discharge and floodplain vegetation density (Grissetti-Vázquez, 2019).

Paudel et al. (2022) show that the final width of gravel bed rivers without floodplain vegetation hardly depends on initial channel width. It rather depends on boundary conditions, especially sediment input. During the transition period, however, the width is most of the time very different from the final one. With densely vegetated floodplains and a fixed amount of sediment input, instead, Munir et al. (2023) found a dependency on initial width. Possibly, for these systems the transition period is much longer than for rivers with unvegetated floodplains. In all other cases, different initial geometries lead to final widths having the same order of magnitude. The results of these studies only partly support the use of empirical formulas derived from natural rivers supposed in equilibrium, considering that with vegetated floodplains the transition period might be very long. Finally, Vargas-Luna et al. (2019) and Naito and Parker (2020) show that the formative discharge should not be derived from bankfull geometry, as it is rather a frequent flood.

Role of climate

Climate governs the river discharge regime, sediment input and riparian vegetation. Climate change has thus a strong influence on river morphology.

If the climate becomes warmer and wetter, we can expect higher discharges and vegetation density with less sediment input, and the river to become narrower, deeper with gentler slope and less bars, and a more sinuous planform.

If the climate becomes warmer but drier, we can expect lower discharge and vegetation density with higher sediment input, and the river to become wider, shallower, and steeper, with more bars and increased braiding degree.

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* Corresponding author
Email address: a.crosato@un-ihe.org (A.Crosato)