Advances in Water Resources 93 (2016) 156–165

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Ecomorphodynamic approaches to river anabranching patterns

Benoît Crouzy [a,*], Fabian Bärenbold [a], Paolo D'Odorico [b], Paolo Perona [a]

[a] Group of Applied HydroEconomics and Alpine Environmental Dynamics, IEE, EPFL-ENAC, Station 2, Lausanne, CH 1015, Switzerland
[b] Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, USA

ARTICLE INFO

Article history:
Available online 21 July 2015

Keywords:
Riparian vegetation
Physical model
Neural model
Stability analysis

ABSTRACT

We investigate the influence of vegetation on river morphological instabilities using an analytical framework. We first discuss the important role of the hydrological (flooding frequency) and biological (vegetation development rate) timescales. As long as the changes in riverbed morphology and vegetation over an interval comprising one flood and one low-flow period are small, we show that it is possible to simplify the description of a vegetated river with non-constant discharge. We propose physically-based and effective (neural) models for the feedback between vegetation and morphodynamics. Physically-based approaches use equations of morphodynamics extended to account for the interplay between flow, sediment and vegetation dynamics. While their foundation is solid, a physically-based description is only feasible for simple vegetation cover (grass to shrubs). For complex vegetated obstacles we present as an alternative effective approaches, explicitly including interactions (local and non-local) between obstacles. We focus on the role of vegetation in the emergence of ridge patterns observed in the presence of an ephemeral flow and correspondingly derive a set of conditions for patterns.

1. Introduction

Riparian vegetation and its couplings to river morphological evolution have recently triggered an increased research activity: field studies [1], laboratory experiments [2,3] and models [4,5] have shed a new light on the complexity of the feedback between biological and morphological processes. There has been a change of paradigm [6,7] in the description and modeling of riparian vegetation, going from the view of vegetation as a static element part of a classic hydraulic model [8,9] to a more complex viewpoint where vegetation dynamics is fully considered [6,10–13]. The historical tendency to either neglect the presence of biomass in rivers or disregard its dynamical character was the expression of the difficulty to present a comprehensive framework and account for all the ecological and geomorphological processes occurring within the river (eco)system.

While recent research (for a review, see [1,4]) has partly filled this gap, stability analysis of morphological equations [14] including the dynamics of vegetation and the feedback between biological and river processes (flow and sediment) has not been explored yet. Classically, linear stability analysis of morphological equations has been a tool of choice for explaining universal river features. We shall not attempt a comprehensive review here but one may cite for example works on the instability toward ripples and (anti-) dunes [15], alternate/multiple bars [16] and meanders [17–19].

In this work, we use classic stability analysis in order to study the emergence of vegetated patterns in two models for the evolution of riparian vegetation. We begin with a physically-based approach in the form of an extension of standard morphological equations [14] (shallow water equations + Exner) to include the evolution of vegetation and the feedback between riparian vegetation and river morphodynamics. The use of a physically-based description is feasible only for the most simple situations. We therefore propose the alternative of using a lumped model for the evolution of the biomass, which allows us to include effects such as scouring around a vegetated patch (increased local velocity and/or turbulent kinetic energy, denoted TKE hereafter) or the presence of a sediment tail behind a permeable vegetated obstacle [20,21]. As case study, we focus on the role of vegetation in the formation of anabranching ridge patterns observed in various fluvial environments.

In Fig. 1, we present two contrasting examples for such patterns, corresponding to the simple vegetation cover and the more complex vegetated obstacles mentioned above. Anabranching patterns (Fig. 1, upper panel) consisting of stable ridges dividing the main channel were described in the Marshall River [22–24] (Australia, NT) and the formation of those patterns was explained using classic hydraulic arguments (optimization of the bedload transport capacity) [25,26] or conceptual models [22,27]. In the lower panel of Fig. 1 we show rills observed on a river bar of the Thur River (Switzerland). The type of vegetation cover is very different in the two rivers: in the

* Corresponding author. Tel.: +41 797048633.
E-mail address: crouzy@gmail.com, benoit.crouzy@epfl.ch, benoit.crouzy@a3.epfl.ch (B. Crouzy).

http://dx.doi.org/10.1016/j.advwatres.2015.07.011
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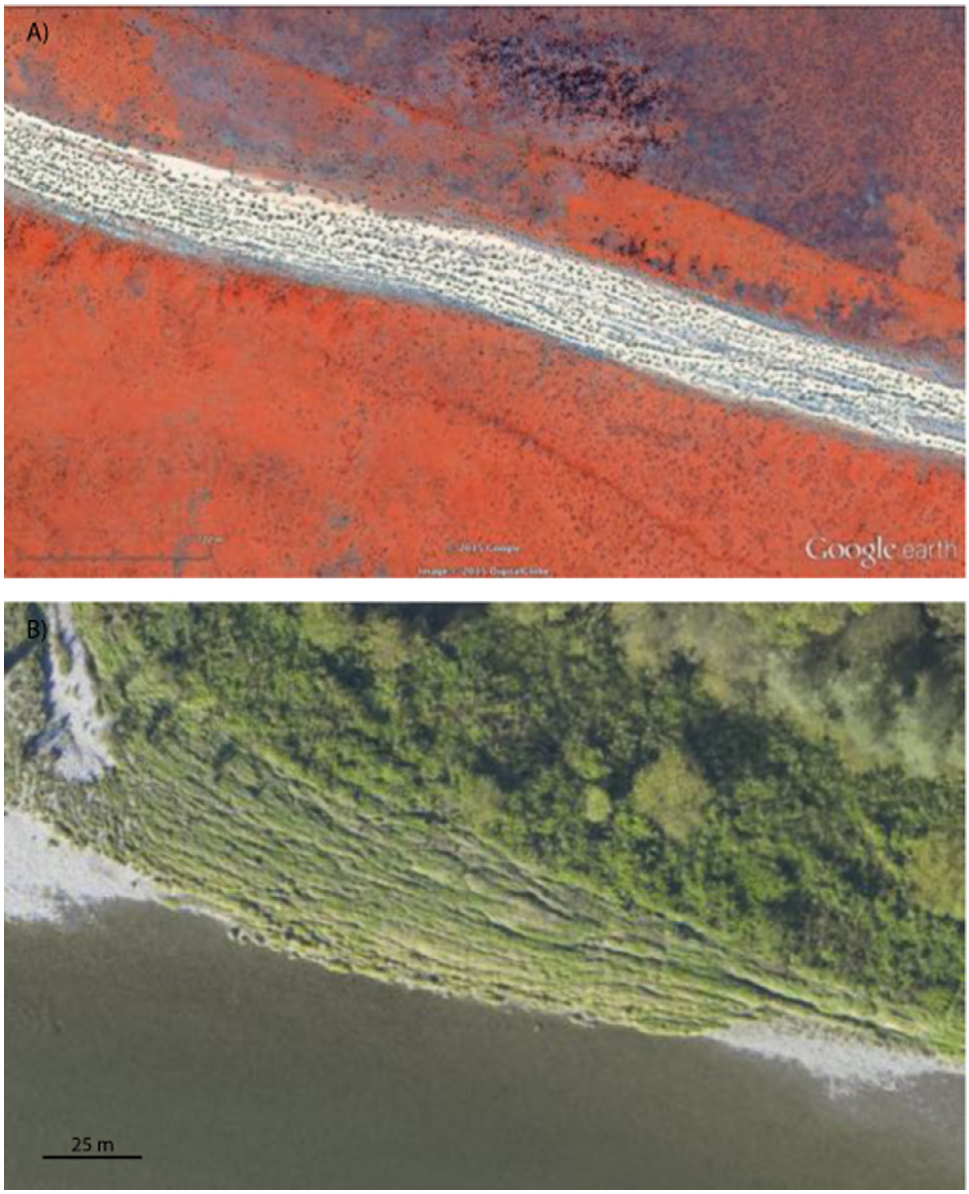

Fig. 1. Examples of anabranching patterns emerging in two contrasting fluvial environments: (A) anabranching of the entire river bed (Marshall River, Australia, NT) and (B) rills observed on a bar of the Thur River, Switzerland.

Marshall river we have well-developed tall-shrubs and trees (teatrees and river red gums), while grass grows on the bar depicted in the lower panel of Fig. 1. Common to those two environments is the presence of an ephemeral flow resulting either from the ephemeral character of the river (Marshall River) or the position (elevated bar) within the riverbed (Thur River). Another similitude is the presence of low cohesive sediment causing significant biomass mortality. The ephemeral flow allows for a feedback loop between ecological and morphological processes: changes in riverbed morphology are typically faster than the development of vegetation but are only taking place during flow events. As suggested by [13] and empirically investigated by [3,28], the feedback loop is only observed for a certain window of ratios between the frequency of flooding events and the development rate of vegetation. For too rare flooding events the vegetation grows out of scale compared to the uprooting capacity of the floods. Conversely, very frequent events completely uproot all the vegetation present in the channel.

The paper is organized as follows: in the next Section we show how it is possible under certain assumptions to reduce the description of the vegetation dynamics in the presence of a variable discharge to an equivalent situation with constant flow; in Section 3 we present the stability analysis of a physically-based ecomorphodynamic model for the emergence of vegetated river patterns, focusing on the asymmetry of the patterns; in Section 4 we present an effective model that allows us to describe the interactions among complex vegetated obstacles in a river; we then perform the stability analysis of this model; in Section 5 we discuss our results and the domain of validity for the two approaches we propose; finally, Section 6 concludes the work.

2. Hydrological and biological timescales

Before turning to the modeling framework for the feedback between the evolution of the biomass and the morphodynamics (flow and sediment dynamics), we discuss here the important role of the characteristic timescales for the biological and hydrological processes. In typical field situations, one observes that the dynamics of vegetation development is much slower than the morphodynamics.