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Numerical study on river bar response to spatial variations of channel width

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ABSTRACT

Managing river bar formation in alluvial channels remains a challenging issue related to the need to free intakes, improve navigation and optimise river restoration works. This work studies the effects of locally varying the channel width on bar formation to see whether channel widening and narrowing could be feasible bar control measures. The investigation focuses on steady (hybrid) bars, the most common type of bars in lowland rivers. Several numerical experiments are performed using a two-dimensional physics-based finite-difference code. Model simplifications include capacity-limited sediment transport, uniform grain size and constant discharge. Previous tests on field and experimental data show that the simulations of the relevant processes are realistic. The results indicate that the formation of steady alternate bars downstream of lateral structures occurs at a distance that depends on the local width reduction and that narrowing the channel for a distance of 10 times the original width appears sufficient to locally suppress alternate bars. A symmetric inflow forces the formation of symmetric bed topography, as for instance a flat bed or central bars. Similarly, an asymmetric inflow forces asymmetric bed topography, as alternate bars. Upstream flow asymmetries disrupt the symmetry of central bars leading to a compound bed configuration characterised by a dominant wandering channel, a common feature in wide lowland rivers. Central and alternate bars are found to coexist even if bar stability theories predict the development of alternate bars only. These results are promising and raise fundamental questions, but need experimental and field confirmation.

1. Introduction

Bar formation in rivers is an important issue for many river training and rehabilitation projects whose success depends on proper management of bars. An example is given by the Waal River in the Netherlands. This river has been intensely trained over the last two centuries to prevent ice growth in winter and to allow proper navigation conditions by channel narrowing and regular dredging. The consequences of these interventions include the desired reduction of the number of bars in the river main channel [46], but also undesired channel erosion that progresses upstream [52]. Another example of the need for bar management can be found in the Po River near Boretto (Italy), where the Moglia Secca water intake is obstructed by a persistent bar formation [10]. In this case, bar suppression or reallocation would be desirable to enable regular water withdrawal. Finally, on the Emme River in Switzerland, bars were reconstructed as part of a restoration project together with main channel widening [44].

Bars are large sediment deposits whose length scales with the channel width and the height with the water depth, primarily resulting in two-dimensional features.

Following stability analyses in the 1970s and 1980s (e.g. [5,8, 23,28,38,56,60]), bars on river beds have commonly been divided into “free bars” and "forced bars" (e.g. [49]). This terminology has become problematic, because river beds basically present three types of bars: point bars and other local bars, free bars arising from inherent morphodynamic instability, and non-migrating bars forced by a local non-migrating perturbation but giving rise to a free morphodynamic response in a larger area [42]. We propose a new terminology that describes both the appearance (phenomenology) of the bars and the mechanism of their formation and growth. This terminology attempts to resolve the existing ambiguities, and provides rigorous definitions based on mathematical descriptions and thorough experimental and field observations.

First of all, it is useful to make the phenomenological distinction between local and periodic bars. Local bars are large deposits of sediment, scaling with the river width, which are forced by a permanent finite deformation of the water flow. This type of deformation can be

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caused by a natural bend, a channel width variation, or a structure like a groyne. Parker and Johannesson [39] referred to these bars earlier as “curvature-driven bars”, since the most common bars belonging to this type are point bars inside river bends. These bars are here categorised by mechanism as “forced bars”, because their existence depends on the presence of forcing and their size is proportional to the forcing.

Periodic bars are large deposits of sediment whose formation depends on morphodynamic instability, and they do not arise if the system is outside the instability range. Based on mechanism, we can distinguish two types of periodic bars: “free” and “hybrid”. Free bars arise within the mophodynamic instability range of the system as soon as a perturbation of the flow or bed level is present. They do not require any type of forcing for their formation, and are in general migrating. Their initial wavelength corresponds to the wavelength of the maximum initial growth rate from linear stability theory, but differs from their final wavelength (as observed in the experiments of e.g. [13,24,27,32]).

Hybrid bars arise from morphodynamic instability [56], but they also require the presence of forcing, which has the effect of fixing their phase at a certain location along the river axis. The fixing of phase prevents hybrid bars from migrating and therefore fixes their celerity as zero. The amplitude and wavelength of hybrid bars are not proportional to the forcing, but are determined by the morphodynamic instability. The initial wavelength and growth rate of hybrid bars correspond to bars with zero celerity by the linear stability theory. Hybrid bars usually take longer than free bars to grow to their final amplitude because the initial growth rate is generally smaller than the maximum value from the linear stability theory. Their final wavelength is generally longer than the initial value [12]. A common earlier term for hybrid bars is “forced bars” (e.g. [49]), stressing the fact that hybrid bars require forcing. Another earlier nomenclature [12] stresses the fact that hybrid bars require morphodynamic instability and includes them in the category of "free bars". The term “hybrid” expresses more clearly that these bars have both forced and free aspects.

There are different types of forcing that can fix the phase of hybrid bars. One type, used in laboratory experiments, is that the bed level at the upstream boundary is maintained at a fixed value. Another possibility is that a forced bar can act as a (large) perturbation, generating hybrid bars. The forced bar can be obtained for instance by placing a groyne. This bar is local with size proportional to the forcing. Hybrid bars arise, either only downstream or also upstream [64], if the system falls within the morphodynamic instability range [56]. These bars are hybrid in nature, with the phase fixed by the first local (forced) bar. They are non-migrating, with initial wavelength equal to the value that gives a zero celerity in linear stability theory. Similarly, river bends can force the formation of point (local) bars at the inner side, which may be accompanied by periodic (hybrid) bars if the system is morphodynamically unstable [56].

Table 1 illustrates the bar characteristics and mechanisms leading to their formation, together with common definitions.

There may be from one to several periodic bars in a river cross-section leading to different hydrodynamic and morphodynamic behaviours. The number of bars in transverse direction is represented by the "bar mode", i.e. the number of half-transverse wavelengths (e.g. [18]): a bar mode equal to one indicates alternate bars (Fig. 1a), a bar mode equal to two indicates central bars, whereas larger bar modes indicate multiple bars (Fig. 1b). As pointed by Engelund and Skovgaard [19], Parker [38], Fredsøe [23], and Crosato and Mosselman [11], the channel planform of a river (meandering or braiding) can be related to the presence or absence of free bars and their mode (Fig. 1).

The current knowledge of periodic bar formation includes linear theories that describe the morphological trends at the first stages of the bar development based on stability analyses. These theories allow establishing whether bars would form in the river channel and which bar mode can be expected (e.g. [7,18,23,38]). Seminara and Tubino [50] defined a marginal stability curve separating the conditions in which a certain bar mode grows (unstable conditions leading to bar formation) from the conditions in which the same bar mode decays (stable conditions leading to the restoration of a flat channel bed). The major parameter governing the bar instability phenomenon is the channel width-to-depth ratio. For every value of this parameter above the critical one, an entire range of bar wavelengths may become unstable.

Most linear bar-stability theories assume incipient bars to appear simultaneously along the channel with the same amplitude. This is a rather restrictive assumption since the stability range is in fact larger, as shown by Struiksma et al. [56] for non-migrating bars. Furthermore, linear stability theories assume that the bars that appear are the ones characterised by the largest growth rate [60], which is true only for the initial stages of the bar development, whereas in the later stages bars typically elongate ([12] and [13]).

Free bars can be non-migrating or migrating. Non-migrating bars with constant amplitude in longitudinal direction are called "resonant". Blondeaux and Seminara [5] introduced this term for alternate bars, but it can be used also for the other bar modes. Migrating bars mostly travel in downstream direction, but at "super resonant" conditions bars may migrate in upstream direction too [64]. The migration celerity is therefore another parameter that characterises bars, in addition to their mode, wavelength, height and growth rate. There is a relation between bar size and bar celerity [15], so non-migrating bars present wavelengths that are two to three times larger than the most commonly observed migrating bars [37].

Linear theories were found to have a fairly good agreement with experimental data in terms of bar wavelength, celerity and the critical conditions for the formation of alternate bars [27,32]. However, they are strictly valid only for the first development stage of bars, and as a consequence, linear theories cannot predict the characteristics of fully-developed bars. Furthermore, the choice of the closure relationships used in the derivation of the linear theories has a fundamental role in the accuracy of the results [27]. Weakly non-linear theories allow explaining further developments of bars [8,25,45] and can be used to predict the final bar height [8], but are restricted to conditions close to the critical point, characterised by a specific width-to-depth ratio.

The success of river engineering and restoration projects depends on the ability to anticipate the long-term development of the channel bed, which is dominated by the subsequent stages of the bar development. In particular, engineers and river managers need anticipating where bars and pools will be located, which bar mode will dominate the river channel in the end, and whether there will be forced, free, hybrid or a combination of bar types in the system. At present, this can only be assessed by means of long-term laboratory experiments or by using physics-based numerical models that take into account all the non-linear terms in the morphodynamic equations that describe the flow field and the channel bed evolution. Using a two-dimensional finite-element numerical model, Defina [15] showed qualitative agreement with the experimental observations of Fujita and Muramoto [24] regarding the evolution of bars from an inception phase towards a dynamic equilibrium phase. Defina’s model was able to reproduce different bar wavelengths with the corresponding bar migration celerity while growing in amplitude as they propagate downstream. It is important to note here that numerical tests are not confined to the study of alternate bars (e.g. [54]) but include also braided systems, characterised by multiple bars (e.g. [36,48]). Regarding experimental studies, only a few investigated the long-term bar development [12,13]. In general, the shortcomings of laboratory experiments lie in the difficulty to upscale the results to real river cases, the limited availability of large facilities to minimise scale effects, the test duration and the associated costs. Nevertheless,