INTRINSIC STEADY ALTERNATE BARS IN ALLUVIAL CHANNELS

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1. Introduction

Alternate bars in straight alluvial channels can be migrating or steady. The steady ones are a key ingredient in present-day explanations of river meandering. The currently accepted view is that bars can only be steady if channel widening slows down bar migration or if bars are forced by a steady local perturbation. However, Crosato & Desta (2009) find in flume experiments and numerical computations that steady bars are also present in cases of migrating bars in narrower channels without permanent forcings. Mosselman (2009) proposes a theoretical explanation for this. The findings turn out to meet resistance because they do not fit well in established theories. This paper reviews theories on bars and river meandering, describes the findings of Crosato & Desta (2009) and Mosselman (2009) in more detail and addresses some of the objections raised.

2. Explanations of river meandering

(*This section has been adapted from Mosselman, 2009*)

River meanders have intrigued generations of researchers. Natural rivers usually develop a windy course because of irregularities in the terrain, but despite those random irregularities they often evolve into regular meander geometries. Yet more intriguing is that initially straight alluvial channels develop into meandering courses. Up to the 1970s, this was even called "mysterious" (e.g. Lebreton, 1974). Some researchers proposed that meandering resulted from an inherent instability of the system of water and sediment motion, potentially understood from a stability analysis, but others invoked Earth rotation or extremal hypotheses to explain the onset of meandering.

Research in the 1970s and 1980s established stability analysis as the firmest basis to explain river meandering. Two distinct approaches emerged: a bar theory and a bend theory. The bar theory considers the stability of the alluvial bed and shows that this bed may develop into a pattern of alternate bars. At the pools between these bars, near-bank flow velocities and water depths are higher and may thus give rise to localised bank erosion, transforming an initially straight channel into a sinuous one. The bend theory considers the planform stability of a straight channel and shows that any infinitesimal perturbation of the channel centre-line leads to the development of meanders. The problem was that the bend theory implicitly assumed bars, but that the corresponding wave length was much larger than the wave length of alternate bars with fastest growth according to the bar theory. Olesen (1984) argued, however, that the alternate bars with the largest growth rate are migrating so fast that they lead to uniform bank erosion rather than localised bank erosion if the banks are not easily erodible. The result is channel widening rather than channel meandering. Olesen proposed that steady alternate bars offer a more adequate explanation for the formation of meanders. Apart from being a condition for localised bank erosion, steady bars with a natural (eigen) wave length also produce a form of self-excitation in incipient meanders, because bars forced by channel curvature excite the natural wave length of the steady bars responsible for the bank erosion that curves the channel. The explanations thus arising found the widest support, as stability analysis is based on validated physical concepts of water and sediment motion.

For the corresponding literature, reference is made to Rhoads & Welford's (1991) review of the development from mystery to physics-based understanding. These authors conclude that the bar and bend theories based on stability analysis hold great promise for a universal theory of meander initiation, although the theories are not without shortcomings and a universal theory has yet to emerge. They also rightly emphasize that the bar and bend theories show helical flow to be irrelevant for the initiation of meandering, despite suggestion of the opposite in widespread conceptual models. In one respect, however, Rhoads & Welford miss a point. They state that the notion of a migrating doubly harmonic infinitesimal perturbation in the bar theory is less intuitive than that of a local random perturbation, and that bar theory provides no explanation for the origin of these perturbations. However, the doubly harmonic infinitesimal perturbation is not used as a *forcing* of the system, but as a way to describe the *effects* of perturbations, using the Fourier theorem that any arbitrary bed topography that might arise in response to perturbations, can be represented by a sum of such harmonic functions.

Accepting Olesen's (1984) argument that steady alternate bars are needed to explain the onset of meandering, the question becomes where these steady bars come from if the fastest growing alternate bars are migrating. Two different explanations based on linear stability analysis were offered simultaneously by Blondeaux & Seminara (1985) and Struiksma et al (1985). This gave rise to a debate between what Parker & Johannesson (1989) term the "Genova School" and the "Delft School" (or "Dutch School" in the terminology of Seminara & Tubino, 1992). The Genova School argued that migrating alternate bars slow down and evolve into steady bars as a channel widens due to bank erosion. The spatial damping of the bars was found to vanish at the corresponding width-to-depth ratio, which means that the self-excitation of steady bars recognised earlier leads to resonance. The Delft School argued that any steady local perturbation gives rise to the formation of steady bars. Experimentally, both mechanisms have been shown to produce steady bars. The wave lengths of the two types of steady bars are equal at the point of resonance. The debate was not on the occurrence of these mechanisms, but on the question as to which mechanism is the most fundamental one, in the sense that it represents an *intrinsic* instability without the need of external forcings. The Genova School considered the steady local perturbation of the Delft School to be such an external forcing. The Delft School, however, maintained that channel widening to a resonant width-to-depth ratio could only represent a peculiar case, as most meandering rivers do not have a resonant width-to-depth ratio. A single steady local perturbation was considered to be a less stringent prerequisite than the widening till achieving resonant conditions.

Other research refined the picture. Flume experiments by Fujita & Muramoto (1985), as reported by Nelson & Smith (1989), showed that migrating alternate bars become slower and longer as they develop towards a finite amplitude. Nonlinear computations by Nelson (1990) confirmed the elongation. This reduced the gap between the short migrating alternate bars that grow fastest and the long steady alternate bars needed for the onset of meandering, although it did not bridge the gap fully. Hall (2004) found from a weakly nonlinear stability analysis of unsteady flow that interaction of discharge variations and migrating alternate bars produced a steady sinusoidal structure of the bed, which he suggested to be relevant to meander formation. However, the discharge variations can still be seen as an external forcing and meanders are known to form at constant discharge as well.

3. Findings presented at RCEM Symposium in Argentina in 2009

New findings on the occurrence of steady bars were presented at the 6th IAHR Symposium on River, Coastal and Estuarine Morphodynamics (RCEM 2009) in Santa Fe, Argentina, from 21 to 25 September 2009. Crosato & Desta (2009) presented numerical simulations in which steady bars appeared also at non-resonant conditions in the absence of any steady local perturbation. Rapidly growing migrating bars developed first, but longer slowly growing steady bars evolved subsequently and dominated the final bed topography. Crosato also reported a laboratory flume experiment at Delft University of Technology, just completed and not described in the proceedings, in which steady bars evolved in the same manner as in the numerical simulations. Mosselman (2009) proposed a theoretical explanation for this intrinsic instability of steady bars, based on a crude linear analysis.

The findings aroused resistance because they do not fit well in established theories. It was suggested that the laboratory experiments had not been carried out well and that the numerical computations had been affected by reflecting boundaries. However, these comments were ruled out by the careful set-up of the research as well as the observed bed evolution. The experimental and numerical evidence thus remained strong.

Mosselman's (2009) crude theoretical analysis was criticized because he introduced temporal variations of bar wave length at the end of his mathematical derivation instead of including it from the start. This criticism was right, although such crude back-of-the-cigar-box calculations may still reveal glimpses of true physical behaviour. The basic idea of the analysis was that steady bars might also result from a small-amplitude unsteadiness in the system. For unsteadiness due to discharge variations, this complied with Hall's (2004) weakly non-linear finding that the interaction of discharge variations and migrating alternate bars produces a steady sinusoidal structure of bed topography. Hall's structure, however, does not represent an *intrinsic* instability, because discharge variations can still be seen as an external forcing. Mosselman argued that the small-amplitude unsteadiness can also be ascribed to the mere presence of migrating alternate bars, as confirmed by Crosato & Desta's (2009) experimental and numerical findings. Hence, if migrating alternate bars are an *intrinsic* instability of alluvial channel beds, steady bars are an *intrinsic* instability too.

Since steady bars are seen as a prerequisite to explain meandering of alluvial rivers, the findings imply that neither resonant width-to-depth ratios nor steady local perturbations are necessary conditions for the onset of river meandering. These findings remain controversial for the time being. The research will be continued to find either further confirmation or evidence of the contrary.

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