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Field-scale experiment on migrating bar dynamics: Preliminary analysis

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ABSTRACT: Within the Dutch research project 'Valley wide meander restoration' six restored streams will be monitored over a 2-year period. The monitoring program aims at understanding initial morphological processes and the associated ecological developments. The present study focuses on the morphodynamic developments that took place after the completion of one of the restoration projects. The morphology and hydraulics of the field sites are evaluated using sequential GPS-surveys, discharge records and information from sediment samples. The present contribution concerns the Hooge Raam, where a new channel is constructed parallel to the stream that was to be restored. The channel was designed to investigate the autogenous formation of a meandering channel from an initially straight reach, designed based on hydraulic geometry relations. Eight months after construction of the stream, alternating bars emerged in the downstream part of the stream. Analysis of ten successive bed level surveys about two months apart shows channel bar migration and an increase of both the bar height and their wavelengths. Bar wavelength is increasing in time until it reaches an equilibrium value. The dynamics of both migration speed and bar height respond to the dynamics in the varying discharge.

1 INTRODUCTION

Several types of rhythmic patterns can develop on sandy beds. Alternating bars are amongst the largest free bed forms observed in fixed-bank rivers and channels. Laboratory research has shown that starting from a plane bed, the bed morphology evolves to an asymmetrical pattern of bars growing alternately from the banks, which are readily in equilibrium with the steady flow and sediment transport conditions (Federici and Paola 2003). During this evolution process, the alternating bars increase both in length and in height. Bar lengths are proportional to their width and bar heights scale with flow depth. Alternating bars are generally asymmetrical in along-stream cross-sections, they may or may not have an avalanche face on the downstream side, and generally migrate in the downstream direction (Bridge 2003).

Investigation of the development of meandering rivers has mainly been restricted to modeling and laboratory studies. Within meander models a distinction can be made between linear (Ikeda et al. 1981; Johannesson and Parker 1989; Zolezzi and Seminara 2001) and nonlinear models (Howard and Knutson 1984; Stølum 1996; Blanckaert and de Vriend 2003). Two basic assumptions are made within these models: (1) the river discharge is always assumed to be constant, and (2) the shallow water approximation allows the flow field to be solved using a 2-D depth-averaged scheme. (Camporeale et al. 2007) concluded that non-linear models have a similar quantitative behavior as their linear counterparts, which supports the use of linear theories to model the long-term evolution of meandering rivers. Despite these general remarks confirming that the linear theories provide a valid means of modeling meander dynamics, applications to real-world systems are rare.

Mathematical meander models offer insight in the primary governing processes of meander dynamics, but lack the predictable power to give them practical use. This has lead to the revival of laboratory studies of river landscapes over the past decade. Laboratory-scale river meanders can develop within hours. The type of sediment plays a major role in creating meanders at the lab-scale. (Federici and Paola 2003) showed that a meandering planform will form after some time, but that it eventually evolves into a braided river pattern. Basically, this is caused by excessive erosion of the cohesionless banks. Several sediment mixtures were used to produce meanders, e.g. solely cohesive material (Friedkin 1945; Schumm and Khan 1971), the inclusion of silica flour (Peakall et al. 2007) and seeding with alfalfa (Gran and Paola 2001; Tal and Paola 2010). Still some major difficulties have to be overcome within experimental meander research, which relate to scaling effects, upstream sediment feeding and consolidation of bed material.

Considering the long time-scales involved in river evolution, and the scale effects of laboratory meanders, we intend to focus on small natural fluvial channels, which can be analyzed in their full geographical complexity. Both the temporal and spatial scales of streams are in between the scales of laboratory experiments and river dynamics, which renders them suitable for field experiments on the initiation of meandering. This is not to say that the mechanics of stream morphodynamics can be readily translated to rivers, since vegetation, trees in particular, have a relatively great influence on the morphology of streams.

In this paper we present preliminary results of the initial morphological response of a straight stream. Eight months after the construction of the stream the first alternating bars appeared. Bar heights and wavelengths are recognized from the longitudinal data, and migration speeds are determined.

2 MATERIALS & METHODS

The stream under study is named the Hooge Raam (51° 42′ 56″N, 5° 42′ 7″E), a tributary of the river Meuse, see Figure 1 (a). In the summer of 2009, a stream restoration project was finished over a length of 1 km. The downstream part of this project was restored based on so-called re-meandering, where the old meander planform before straightening of the stream was restored. In the upstream part, however, a wide, shallow, rectilinear channel was created with the purpose of autonomous meander initiation. This part of the stream serves as the experimental part of the project. The length of the experimental reach is 700 m, and the initial channel slope is 1.7 m/km. The channel has a constructed width of 7.2 m and a depth of 0.4 m, which were based on general hydraulic geometry relations. The bed sediments consist of cohesionless fine sands, with a median grain size of 210 µm.

In this contribution, we focus on the downstream part of the experimental reach, indicated in Figure 1(a) with alternating bars (light gray area). A regular pattern of alternating bars has formed in this part of the channel. In the upstream part of the channel, dense vegetation growth resulted in an irregular bed morphology, without a clear pattern of alternating bars. Figure 1 (b) and (c) show two aerial photos of the study area, where the water is flowing from top to bottom. Panel (c) shows this clear pattern of alternating bars, whereas in panel (b) this pattern is not apparent. The sudden change in vegetation may relate to differential nutrient supply from the neighboring agricultural lands.

This paper mainly focuses on the morphological development of the channel bed. Therefore, bed elevation data of 10 GPS-surveys are analysed. The bed elevation data were collected using RTK-GPS equipment (Leica GPS 1200+). The RTK-GPS equipment is able to measure a point in space with an accuracy of 1–2 cm. The number of points collected during each individual survey ranged from 600–2250, with an average of 1900 point-measurements. The collected data are interpolated on a grid using nearest neighbor interpolation , with a grid spacing of 0.2 m. Since the data were collected in cross-sections, an anisotropic factor of 4 is used within the interpolation routine, to account for the dispersion of the collected data in the longitudinal direction.

Besides the bed elevation data, discharge data are used to relate the dynamics of the alternating bars to dynamics in discharge. Discharge data are collected upstream of the reach using a measurement weir (see Figure 1 (a)), with a sampling frequency of one hour. The discharge station was constructed about 4.5 months after the stream restoration project was completed.

The development of the alternating bars will be studied using some geometrical parameters. These parameters cannot be extracted directly from the data. First, the average longitudinal channel slope was subtracted from the data. The bar height, for instance, is determined relative to the channel slope. Second, the data are filtered using a loess regression algorithm (Tate et al. 2005), adopting a bandwidth of 2.6 m. Figure 2(a) shows the results of the filtered data, the channel gradient and the low-passed filtered data resulting from the loess regression. Figure 2(b) shows the same data after the channel slope was subtracted. The figure shows zero-crossings were easily found after routines were applied to the interpolated data. The location of local extremes (bar crests and troughs), which are used in the subsequent analysis, are also well-retained after application of the regression model.

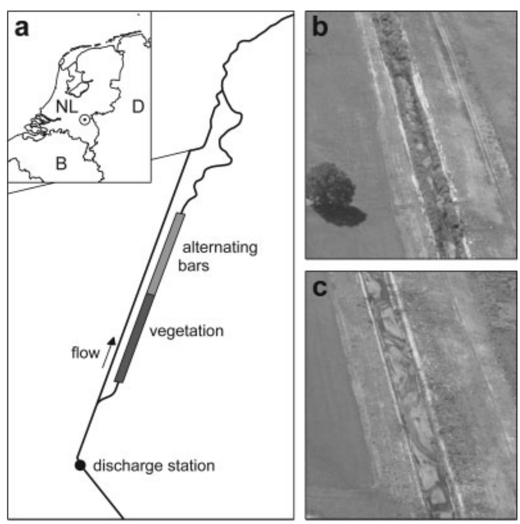

Figure 1. Overview of the study area: (a) the location of the study area in the Netherlands and a sketch of the channel reach under study, (b) aerial photo of the vegetated area and (c) aerial photo of the alternating bar area.

The geometrical parameters used in this study are bar height, wavelength and migration speed. The bar height and wavelength are defined according to (Ikeda 1984). The bar height (H_B) is defined as the difference between the height of the bar crest and the lowest point in the cross-sectional direction. The wavelength (λ) is defined as the distance between two successive bar troughs. The migrations speed (u_{bar}) is defined as the distance travelled by the bar in longitudinal direction divided by the time between two successive surveys. The position of the bar is defined as the average between two successive bar troughs.

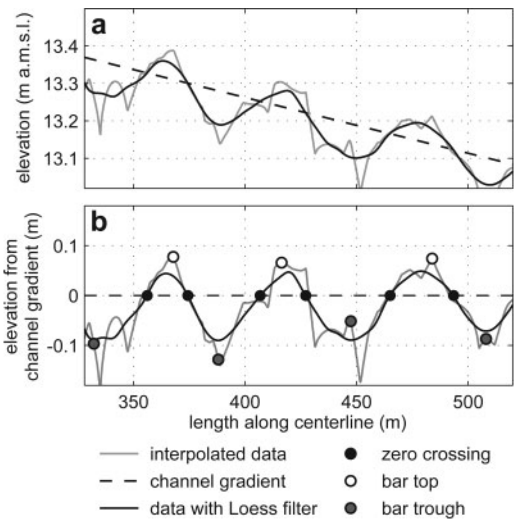

Figure 2. Example of calculations performed on the longitudinal profile to extract the position and magnitude of the bar tops and bar troughs: (a) shows the longitudinal profile with interpolated data, channel gradient and loess regression applied to the data with elevation in meters above mean sea level (a.m.s.l.) and (b) showing the same data with elevation relative to the channel gradient. (b) also shows the position and magnitude of the bar tops, bar troughs and zero crossings.

3 RESULTS

Here we present data from ten surveys, where the first survey was performed 246 days after construction of the stream. Figure 3 shows the interpolated data of all ten surveys. Water is flowing from the bottom to the top. In this figure, the data were corrected for the channel gradient, this means that elevation is relative to the channel gradient. From the first survey, on the left side of the figure, the individual bars can be distinguished relatively easily. As time evolves, however, the morphology of the channel increases in complexity. Bars appear to grow both in length and in height. Besides, bars seem to be connected and disconnected from each other, one time step after the other.

The complexity of the channel morphology makes it difficult to determine the geometrical parameters described above. Therefore, the geometry of all individual bars are studied based on longitudinal transects on either the left or the right side of the channel. In total seven bars are identified, which appear in the data from all ten surveys; four on the left side and three on the right side of the channel. From these seven bars the bar height, wavelength and migration speed are determined and will be discussed in the next section.

Figure 4 shows the results of the evolution of the bar wavelength (a), bar height (b), migration speed (c), and discharge (d), since the construction of the channel. The bar wavelength appears to increase in time and levels after the fifth survey to an average wavelength of 68 m. The bar height, on the contrary, does not evolve to a constant value. The evolution of the bar height shows an increase from the second to the fourth survey, stabilizes and decreases again after

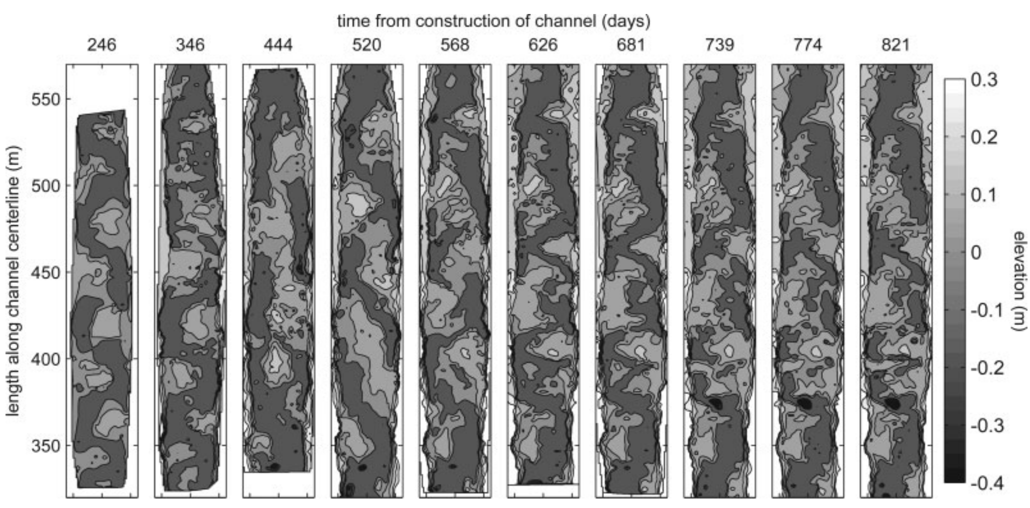

Figure 3. Interpolated data from all ten GPS-surveys, with elevation corrected for the channel gradient. Water is flowing from the bottom to the top.

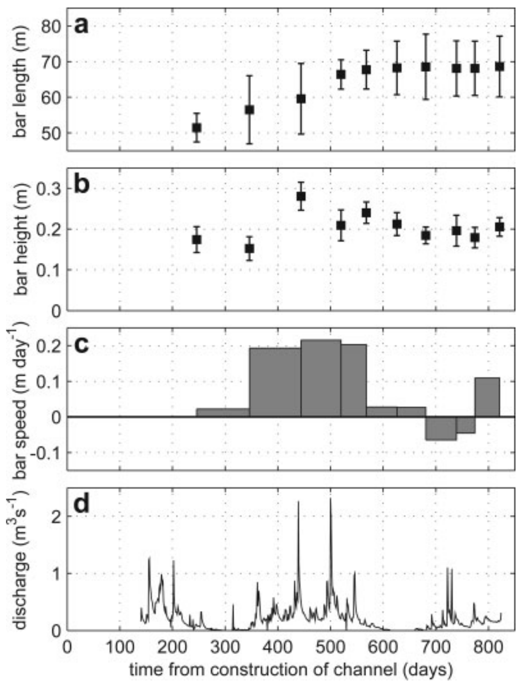

Figure 4. Evolution of (a) the bar length, (b) bar height, (c) migration speed, and (d) discharge since the construction of the stream. The length of the error bars in panel (a) and (b) are defined with the standard deviation divided by the square root of the number of bars (std/$\sqrt{n}$).

the fifth survey, where a slight increase is visible after the sixth and ninth survey. When comparing the bar height with the discharge series, it appears that the bar height responds to the dynamics of the discharge. The increase in bar height from the second to the fourth survey may be caused by the increase in discharge in this period. The same holds for the decrease in bar height after the fifth survey.

Bar migration speed is determined for each of the nine intervals between the ten GPS-surveys, and over the complete surveying period. Figure 4 (c) shows the migration speed of the nine intervals. The migration speed varies within the surveying period, and takes an average of 8 cm day^{-1}. A maximum was observed in period 3, when the migration speed amounted to 22 cm day^{-1}. This value is comparable with the values found in periods 2 and 4. Periods 7 and 8 show negative values for the migration speed, which may indicate the bars were migrating in upstream direction at a rate of a few cms day^{-1}. This may be an artefact of the method used to determine the position of the bars, i.e. as the average of the upstream and downstream bar trough. This method is prone to local variations in the bed elevation, which occur for instance when a local minimum arises upstream from the bar trough of a previous survey. Based on results obtained from the method applied, the bar would have migrated in upstream direction, whereas only a local scour hole has emerged upstream from this bar. An improved algorithm is under construction to eliminate these kinds of errors.

Discharge characteristics of all intervals have been derived from the data shown in panel (d) of Figure 4. The average discharge during the surveying period was 0.18 m^{3}s^{-1}. A the maximum discharge peak amounted to 2.32 m^{3}s^{-1} and occurred in period 3. The highest migration rates were observed in periods 2 through 4. During these periods, the average discharge was well above the averages during all other periods. The same holds for the maximum discharge. Further analysis on the dynamics of the discharge is planned to show how bar migration rates relate to discharge.

4 CONCLUSIONS

We argue that analysis of small streams can bridge the gap between laboratory experiments and field-scale studies of meandering. The time scales for the appearance of morphological features like alternating bars are in the order of months. Regarding spatial scales, many streams are small enough to perform a GPS-survey within one day with a resolution high enough to make a detailed elevation model. Besides, the data presented also shows that the morphodynamics of this small stream is of such an extent that each survey shows changes caused by the varying discharge. Small streams are thus suitable to study the initial response of fluvial systems under varying discharges.

Data is presented of a stream showing the appearance of alternating bars 8 months after construction of the stream. Successive bed level elevation models are analyzed, aiming to retrieve bar characteristics and migration speeds. A preliminary analysis demonstrates the alternating bars migrate in downstream direction, at a time-varying rate. Several well-known features of migrating bars are identified, such as an increase of both the bar height and the wavelength with time. Bar height covaries with discharge and migration speeds also show an apparent response to discharge variation. The causal relation between both bar height and migration speed, on the one hand, and discharge, on the other hand, will be subject of further analysis. Besides, a method will be developed to determine the longitudinal position of the bars, since the current method is prone to small variations of the bed elevation data.

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