Dune morphology and hysteresis in alluvial channels during long-duration floods revealed using high-temporal resolution MBES bathymetry

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ABSTRACT: This paper quantifies how dune morphology changes through flood hydrographs by using high spatial- and temporal-resolution bathymetric data and robust computational analysis methods to produce probability density functions of dune morphology. This quantification aims to provide a better understanding of dune hysteresis by examining river bathymetry from a 16 km reach of the River Waal, Netherlands, in a 6-month time series of bi-weekly multibeam echo sounder surveys. Parameterization includes dune height, wavelength, leeside angle and leeside shape, to assess dune kinematics and hysteresis during different flood hydrographs.

1 INTRODUCTION

In rivers and man-made channels, flow discharge may fluctuate across a range of time scales – from diurnal to seasonal – but is often most pronounced in hydrographs that encompass long-duration floods (weeks to months). Under these varying flows, bedforms can be created and modified by the flow without achieving an 'equilibrium' state (Ten Brinke et al., 1999). A lag between changes in flow and the morphological response of the bedforms, termed bedform hysteresis, is commonly present. Importantly for channel management and navigation, critical water depths may be reached for inland shipping since dunes may grow larger during floods, but often experience a lagged decay in size during lowering water levels (Ten Brinke et al., 1999; Wilbers & Ten Brinke, 2003). There is also a growing consensus that dunes possess a more flattened shape, and lower leeside angle, than previously assumed in large rivers and that such dunes do not exhibit a region of permanent flow separation downstream of the dune (Roden, 1998; Kostaschuk, 2000; Best & Kostaschuk, 2002; Motamedi et al., 2012, 2014; Lefebvre & Winter, 2016; Lefebvre et al., 2016; Kwoll et al., 2016). This different leeside shape thus questions traditional ideas of flow interactions with dunes, where flow separation in the steep dune leeside leads to energy loss (form drag) that increases flow resistance and energy expenditure within the flow.

The shape of dunes also has the potential to change through the adaptation of dune morphology to the flow, as well as the interaction between neighbouring dunes (Reesink et al., 2018). In variable flow conditions, smaller superimposed dunes can also exist with large dunes (Allen & Collinson, 1974; Allen, 1978; Reesink et al., 2018). As these smaller, superimposed dunes migrate and climb up the stoss side of larger host dunes, they can modify the shape of the larger dunes by eroding the crest and eventually descending down the leeside of host dunes, thus lowering the leeside angle (Allen, 1978; Amsler & Schreider, 1999). In the process of small dune migration up the stoss side of the larger dune, the small dunes can also intermittently increase the leeside angle of the host dune when their leeside is aligned with the crest of the larger dune. This intermittent increase in leeside angle has been observed from ripple - dune interactions in laboratory experiments and might be reflected in other observations as 'superelevation' of the crest, which occurs at time scales of 5 - 15 min (Reesink & Bridge 2007; Reesink et al., 2018; Baar & Cisneros, in review). Smaller dunes may also run into, and amalgamate with, larger dunes, leading to large morphological change and complexity for those larger dunes (Allen & Collinson, 1974; Allen, 1978). Thus, whilst previous work has shown that variable flow conditions may cause dunes to increase and decrease in size, the response of dune shape, and specifically leeside angle, to variable flow conditions has not yet been quantified, despite the fact that the leeside has been shown to be of major importance to the flow field over alluvial dunes (Kostaschuk, 2000; Best & Kostaschuk, 2002; Motamedi et al., 2012, 2014; Lefebvre & Winter, 2016; Lefebvre et al., 2016; Kwoll et al., 2016). Understanding such bedform response may also offer important information in teasing out the possible processes of dune formation and dune-dune interactions. This paper aims to investigate dune morphological response to natural variations in flow during a flood in a major navigation channel.

2 MBES DATA

Until recently, temporally abundant river bathymetric data were not available, but with the need for accurate riverbed topography to assess dredging locations for safer navigation, the River Waal has been surveyed once every two weeks since 2005. These data, along with hydrographs measured at stations along the river, are now available through the Dutch Ministry of Infrastructure and the Environment, Rijkswaterstaat, and Deltares, which offers a unique opportunity to investigate dune morphodynamics under variable flows over long periods of time (weeks to months) (Fig.1). These bathymetric data were obtained using a multibeam echo sounder (MBES) over a period ranging from 1 to several days per survey. Time series MBES data in 2010-2011 were analyzed (Fig. 1), yielding 12 bathymetric maps that reveal the morphologic response in the Waal River at two weekly time steps through a compound, long-duration flood, lasting ~6 months and reaching peak flow of *c.* 6,000 m^3s^{-1} (3x the average flow discharge) (Fig.1).

3 METHODS

A bedform analysis (Cisneros et al., in prep.; Baar & Cisneros, in review.) was implemented on all 12 river bathymetric surveys of the River Waal. This method measures dune morphology by running automated profile line measurements spaced at the resolution of the bathymetric grid (0.5 m grid cells) across the width of the surveyed area and interrogates the value of each data point along each dune profile (Cisneros et al., in prep.). Thus, dune height, wavelength, leeside angle, and leeside shape (location of

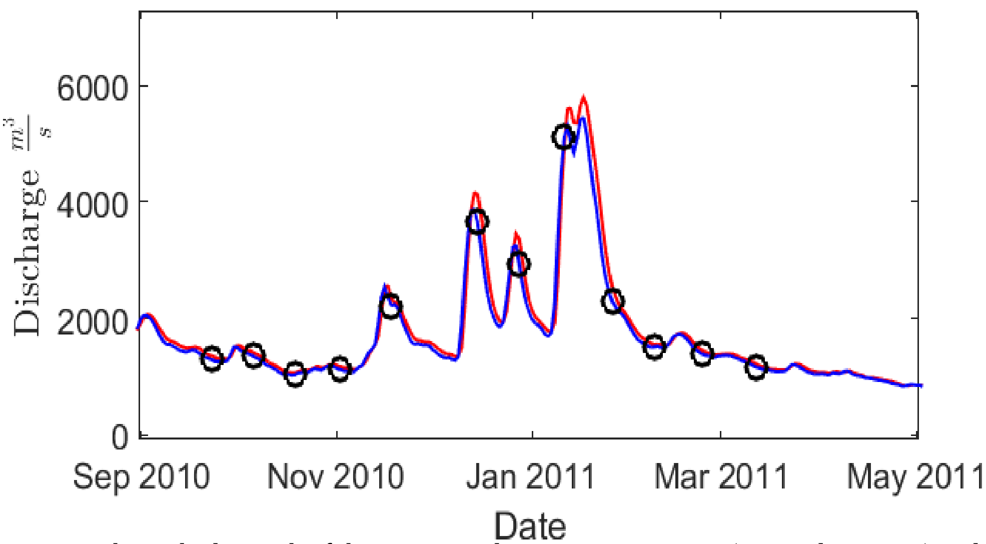

Figure 1. Discharge hydrograph of the River Waal at stations upstream (Pannerdense Kop) and downstream (Tiel) of the survey area, with the survey dates throughout the flood denoted by black circles.

possible brink points or changes in slope), as well as the flow depth for each dune, are measured along its width, thereby quantifying the morphology of the dunes and indicators of dune shape complexity in the streamwise and spanwise directions.

4 RESULTS AND DISCUSSION

From the bedform analysis method, ~100,000 measurements of dune morphology were made for each survey date through the flood. Distributions of the mean and maximum leeside angle (Figure 2) represent all measured values of the average slope of the leeside (mean) and the singular, maximum slope on the leeside (maximum) of each dune. In this plot, the shapes of the distributions appear similar and the peaks of the distributions fall in the same ranges. A normal probability density function was also fitted to each of the distributions. These data (Table 1) show that the shape of the distributions changes through the flood. Notably, at the peak of the flood, on January 11, 2011, the shape parameters of the distribution indicate that the mean and maximum distributions are shifted to higher values (μ is 13.48° & 19.26°, for mean and maximum angle, respectively). After the peak of the flood, on January 26th, 2011, a long tail on the high end of the distribution of maximum leeside angles is present and demonstrates that more dunes with higher angle leesides exist at this time, even though the majority of leeside angles are lower (mean value of 16.65°).

In addition, dune height, wavelength, and aspect ratio (height/wavelength) were quantified through time (Figure 3). A sharp distinction between dunes was observed between the northern and southern parts of the river, with large dunes in the north and small dunes in the south. Thus, analysis of the data was split between the dunes occupying the north and south of the channel, using a channel centreline for differentiation. This north-south division has been previously noted by Wilbers & Ten Brinke (2003), irrespective of any natural bends in the channel. The northern and southern dunes react differently to the changes in flow (Figure 3). Initially, the dunes on both sides of the channel grow in height with increasing discharge, but during the falling stage of the flood (after January 11, 2011), the northern dunes decay in size at a much slower rate than the southern dunes. Thus the heights of the northern dunes are lagged behind changes in river flow during the falling stage, with dunes being higher during the falling stage than the rising stage. In terms of dune wavelength, the northern and southern dunes also possess different responses through the flood. The northern dunes are shorter in wavelength during the rising stage and longer during the falling stage, whereas the southern dunes show the opposite behaviour.

Table 1. The shape factors (μ = mean & σ = sigma) of the probability density function normal fit to the mean and maximum angle distributions for each survey.

Date	Mean (μ)	Mean (σ)	Max (μ)	Max (σ)
Sept. 23, 2010	10.79	4.20	14.92	5.59
Oct. 6, 2010	10.93	4.64	14.95	5.70
Oct. 19, 2010	10.79	4.02	14.56	5.09
Nov. 2, 2010	10.87	4.13	14.62	5.01
Nov. 18, 2010	11.73	4.50	16.43	5.41
Dec. 15, 2010	13.39	4.55	19.19	5.28
Dec. 26, 2010	12.80	4.44	18.22	5.28
Jan. 11, 2011	13.48	4.03	19.26	4.65
Jan. 26, 2011	11.70	4.63	16.65	6.16
Feb. 8, 2011	10.34	4.18	14.01	5.49
Feb. 23, 2011	10.53	4.00	14.14	4.99
Mar. 12, 2011	10.66	3.77	14.22	4.63

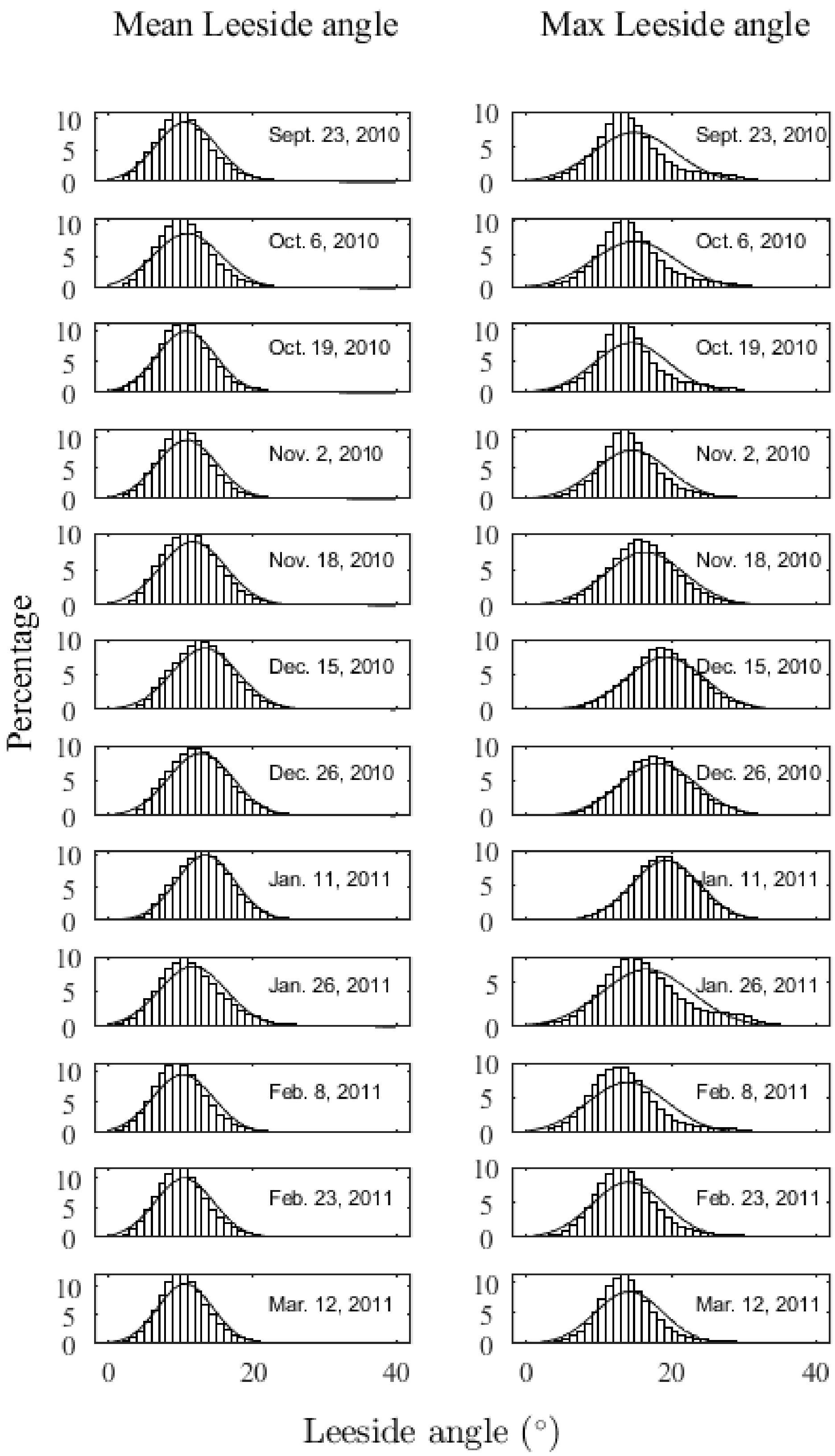

Figure 2. The distributions of mean and maximum leeside angle representing all dunes measured across the river width for each survey date. Note each distribution represents ~100,000 data points. Black lines are normal pdf's fitted to each distribution.

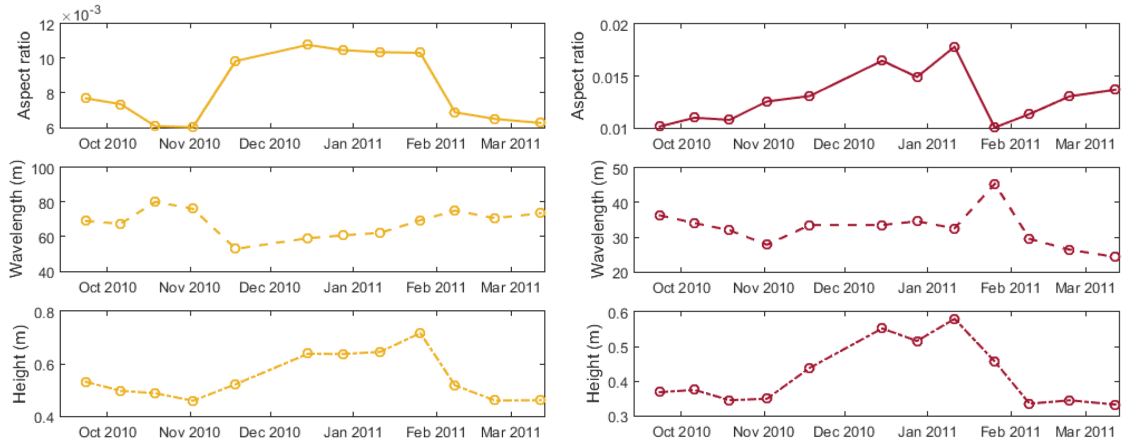

Figure 3. Dune population characteristic values (mean values) of aspect ratio, wavelength, and height determined for each survey through the flood for northern (yellow) and southern (red) dunes.

The northern dunes range in their mean wavelength by 30 meters through the flood, with the southern dunes range being 20 meters, but the change between successive surveys is only a few meters, i.e. the rate of change is relatively mild (Figure 3). One exception occurs in the southern dunes immediately after the peak of the flood, on January 26th 2011, when the wavelength increased from ~30 meters to the maximum wavelength during this time, ~50 meters, and then decreased just as abruptly by the following survey date. This time represents a period of large change in the morphology of the southern dunes – the dunes almost double in wavelength and then decrease in wavelength by a factor of 2. In addition to dune height and wavelength, their aspect ratio is also plotted in Figure 3 and shows how the height and wavelength change together through the flood. Overall, the aspect ratio thus increases and decreases through the rising and falling stage, but the aspect ratio notably remains constant in the northern dunes during the peaks of the flood, which corresponds to discharges greater than 2,000 m^3s^{-1} (Figures 1 and 3).

5 CONCLUSIONS

Dune morphology was measured in the River Waal over a 16 km reach using MBES bathymetric data taken every 2 weeks through a long-duration (6-month long) flood. During this flood, three major morphological features are apparent:

1. Dune leeside angles are largest during the peak of the flood. Such an increase in leeside angle during the flood peak suggests more significant contributions to flow resistance by dunes, and changing leeside angle should be considered in future flow models.
2. Dunes grow and decay in size in the northern half of the channel, whereas in the southern half dunes show little to no hysteresis in dune height and wavelength. Previously, the hydrodynamic effects of laden ships travelling eastbound (on the south side of the river) and unladen ships travelling westbound (on the north side) have been proposed to explain such a distinction in dune scale. This hypothesis is now under investigation by comparing this bathymetry against ship tracks with information on ship loading.

3. Large morphological change occurs immediately after the peak of the flood in the southern dunes, where wavelength firstly increases and then decreases by a factor of two. This may indicate possible amalgamation and splitting processes are occurring at this time for the southern dunes.

These preliminary findings demonstrate how the distributions of the dune dimensions and population characteristic values can be used to make morphologic and process-based interpretations of dune response during a long-duration flood, which may not be apparent by an analysis of solely mean values. It is clear that the former approach is required to more fully quantify dune-flow hysteresis, and its effects, over the temporal scale of a flood wave.

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