The response and hysteresis of alluvial dunes under transient flow conditions

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Abstract

Bedforms perpetually adjust to spatially non-uniform and temporally unsteady flow conditions, with marked changes in flow causing hysteresis-effects in bed response. The rates and styles of adjustment are likely to differ depending on the relative magnitudes of changes in water surface slope, and thus bed shear stress, and flow depth. Slope and depth are likely to be temporally disconnected during the passage of flood waves, but also vary in spatially in their magnitude, for instance between the thalweg and shallower parts of the channel. This paper describes the first of a series of experiments set up to identify the relative roles of slope and flow depth for the morphodynamic adjustments of dunes under a range of transient flow conditions. Initial results suggest that the morphodynamics of dune growth and decay are controlled by four key factors: i) the bedform stability range, ii) spatial variability in bedform stability, iii) bedform kinematics, iv) the relative magnitudes of water surface slope and depth. Bed morphology was most sensitive to changes in water depth. In particular, the development of trains of superimposed bedforms on the stoss of larger dunes was observed following an increase in water depth and not in decreasing water depths. This association suggests that an abundance of superimposed bedforms is not unique to dune decay by cannibalisation, but related to a disequilibrium between dune geometry and the flow over the stoss slope. Fuller understanding of the causes for, and constraints on, dune adaptation to changing flows requires robust quantification of the flow field over out-of-equilibrium dunes.

1. INTRODUCTION

Bedforms in river channels perpetually adjust to non-uniform and unsteady flow conditions, with marked changes in flow causing hysteresis-effects in bed roughness, sediment transport rates and morphodynamic adjustments. Recent work indicates that the reduction in dune size through cannibalization (e.g. Kleinhans, 2002) by smaller superimposed dunes differs fundamentally from bedform amalgamation during dune growth (Coleman and Melville 1994; Raudkivi and Witte, 1990). Such differences are consistent with changes in water-surface slope and absolute flow depth being out-of-phase with one another during

the passage of a flood wave (Figure 1). Water-surface slope commonly increases during the arrival of a flood wave, such that the maximum bed shear stress precedes the maximum water level for a given flood (Van Rijn, 1994). In contrast, water surface slope and bed shear stress decline prior to absolute flow depth during falling stage (Figure 1). The separation of water surface slope and depth supports a separation of '*true hysteresis*' of different bedform growth and decay processes (Martin and Jerolmack, 2013), '*rate-dependent hysteresis*' related to the time needed for bedform adaptation to reach an equilibrium form (Paarlberg et al., 2010; McElroy and Mohrig, 2007), and '*naturally variability*' in dune geometries (Parsons

et al., 2005; Rubin and McCulloch, 1980). The shape of flood waves and the phase-relation between water surface slope and water depth varies between floods from highly asymmetrical flash-floods to monthly changes in base-flow. In addition to such temporal variability related to flood waves, the magnitudes of changes in flow depth and water surface slope differ i) within a river channel between the deeper areas, such as the thalweg, and shallower areas such as bar tops where depth increases are much larger, and ii) along a the course of a river from steep and shallow tributaries to a comparatively deep and low-gradient river mouth. In order to understand the morphodynamic response of river beds to transient flows, it is necessary to identify the mechanisms of erosion and deposition associated with adaptions to changing water depths and water surface slopes.

This paper presents preliminary results from a series of laboratory experiments in which bedform response was measured for different magnitudes of changes in water depth and discharge (flow velocity).

2. METHODS

A recirculating flume 16m long, 2m wide and 0.5m deep was constructed in the Total Environment Simulator in The Deep at the University of Hull, UK. The flume contained a sand bed with a D_{50} of 239µm. The experimental runs covered a range of transient conditions, where the magnitudes and rates of change in discharge (and hence flow velocity) and depth were carefully controlled and systematically increased and decreased. In this paper, we present data from: 1) an increase water depth for a fixed discharge; 2) a decrease in water depth for a fixed discharge, 3) an increase in discharge for a fixed water depth, and 4) a decrease in discharge for a fixed water depth. Water-depth and water surface slope were measured along the flume at 2Hz using 7 wave height probes. Flow velocity was measured at 25 Hz with 4 ADV's set at 40% of the water depth at 4 locations in the test section to provide an approximation of the depth average flow velocity. Froude numbers were calculated using the depth-averaged flow velocity measured with the 4 ADVs. Bed elevation was measured over a 5 m test

section at repeat intervals of 7.5 and 300 s throughout the 120 hrs of experiments using a multi-frequency (1, 2 and 4 MHz) acoustic backscatter profiler that measured bed elevation together with suspended sediment concentration. Vertical resolution of the bed elevation measurements was 2.5 mm and horizontal resolution was 5 mm.
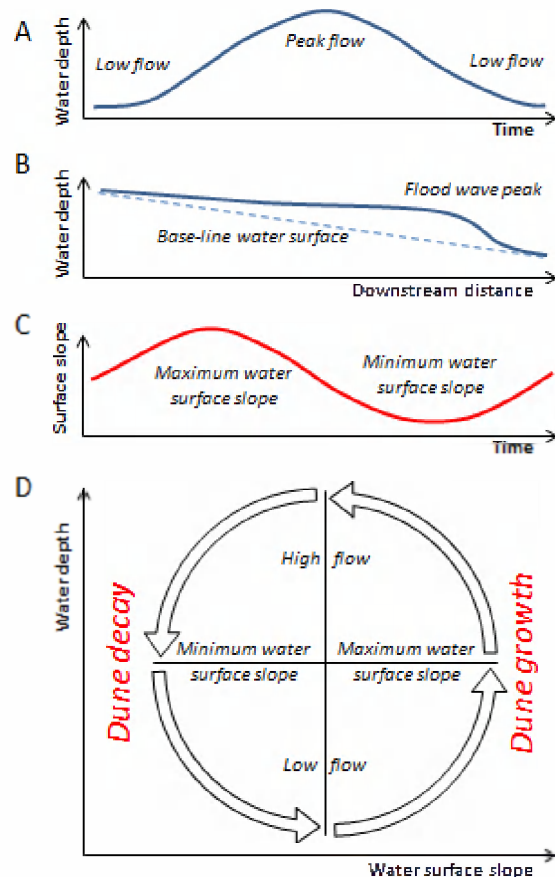

Figure 1. The passage of a flood wave at a location over time (A) and at a time over a downstream distance (B): both result in a water surface slope (C) that is out-of-phase with water depth at a location (A). This depth-slope association affects the nature of alluvial dune growth and decay in unsteady flows (D).

3. RESULTS

Four step-wise changes in flow conditions (Figure 2) are described herein to illustrate differences in bedform adaptation that were observed during the experiments for:
1) an increase in flow depth
2) a decrease in flow depth

3) a decrease in discharge (flow velocity)
4) an increase in discharge (flow velocity)
The flow was kept within the limits of the stability range of dunes. The effects on the morphology of these changes in flow are then compared below.

3.1. Increase in flow depth

An increase in water depth was followed by a decrease in dune migration rate, a decrease in trough scour, and the development of trains of superimposed bedforms on the stoss slopes of two dunes (Figure 2A, Label 2). The presence of these two new clusters of smaller superimposed bedforms was also linked to preceding merger of bedforms upstream (Figure 2A, Label 1). The superimposed bedforms gradually decreased in number and increased in height and length until the dune-bed had re-established itself at a new condition. Dune trough scour decreased following the increase in flow depth (Figure 2A, Label 3). The depth increase presented here was a 30% increase in flow depth, from 0.175 to 0.225m. This increase in flow depth caused a decrease in water surface slope from $-1.9 \pm 0.6 * 10^{-3}$ to $-1.2 \pm 0.4 * 10^{-3}$ and a decrease in the Froude number from 0.59 to 0.50.

3.2. Decrease in flow depth

A decrease in water depth was followed by an increase in trough scour (Figure 2B, Label 4) and a lengthening of the dunes (Figure 2B, Label 5). Trains of superimposed bedforms remained absent during the decrease, and merger of bedforms was not followed by the development of superimposed bedforms on the downstream bedforms. The decrease in flow depth presented here was a reversal in flow depth from 0.175 back to 0.225m. This decrease in water depth caused an increase in water surface slope from $-1.6 \pm 0.5 * 10^{-3}$ to $-2.3 \pm 0.8 * 10^{-3}$, and an increase in the Froude number from 0.46 to 0.58.

3.3. Increase in discharge (flow velocity)

An increase in flow velocity was followed by an increase in dune migration rate, an increase in scour depth (Figure 2C, Label 4) and crest height of the dunes (Figure 2C, Label 6), and a reduction in the number and size of superimposed bedforms. The increase in discharge (velocity) presented here, from 1.8 to 0.2 m s^{-1} at a fixed water depth of

0.175 m caused an increase in water surface slope from $-1.4 \pm 0.5 * 10^{-3}$ to $-2.1 \pm 0.8 * 10^{-3}$ and an increase in the Froude number from 0.49 to 0.53.

3.4. Decrease in discharge (flow velocity)

A decrease in flow velocity was followed by a decrease in dune migration rate and an increase in the number superimposed bedforms (Figure 2D, Labels 1-2). The development of a train of superimposed bedforms occurred in an area where the crest-to-crest distance had increased following the merger of bedforms upstream. The decrease in discharge presented here, from 2.2 to 2.0 m s^{-1} at a fixed water depth of 0.175 m caused a decrease in water surface slope from $-1.6 \pm 0.8 * 10^{-3}$ to $-1.4 \pm 0.7 * 10^{-3}$ and a change in the Froude number from 0.56 to 0.52.

4. DISCUSSION

4.1. Bedform adaptation and bedform stability in spatially variable flow

The causal association of bedform response to changes in flow is complicated by naturally occurring variability in bed morphology at different locations in the stability range of dunes (Van den Berg and Van Gelder, 1993) and dune kinematics (Gabel, 1993; Leclair and Bridge; 2002). For example, the distinct increase in superimposed bedforms (Figure 2, Label 2) occurred following decreases in dimensionless bed shear stress and hence the bed becoming nearer to the stability range of ripple-covered beds. Under these conditions, closer to the stability range of ripple-covered beds, flow can be hydraulically smooth locally on dune stoss slopes even though time- and space-averaged flow remains hydraulically rough (Bridge, 2003; Reesink and Bridge, 2009). Such localised hydraulically smooth flow allows ripples to develop, and potentially even persist, outside their stability field if the separated flow in their lee is sufficiently erosive. Thus, dune adaptation is likely to vary depending on bedform stability, which varies spatially over bedforms that are sufficiently large in size.

4.2. Bedform adaptation, local flow conditions and dune kinematics

In addition to differences in bedform stability, the development of trains of superimposed bedforms was associated with preceding merger of dunes upstream from the newly developed bedforms (Figure 2, Label 1). The merger of two bedforms generates a gap in the crest-to-crest spacing of the primary bedforms. Trains of superimposed bedforms form preferentially in such enlarged areas of flow deceleration. Thus, the results indicate that antecedent bed morphology and kinematics affect the location and frequency of processes such as cannibalisation of large dunes by smaller bedforms.

4.3. Superimposition as an adaptation mechanism

Superimposition of bedforms, like other changes in bedform geometry, is non-unique and occurs naturally in any dune population. However, increased superimposition of smaller bedforms on dunes has been described as a mechanism for growth by amalgamation (Raudkivi and Witte, 1990), as a mechanism for decay by cannibalisation (Kleinhans, 2002; Martin and Jerolmack, 2013), and as a characteristic of the re-establishing boundary layer on the stoss slope (Rubin and McCulloch, 1980). Superimposed bedforms can significantly increase bed roughness through modification and interactions of coherent flow fields over bedforms of various scales (Fernandez et al., 2006). Despite their importance, the hydrodynamic controls that allow superimposed bedforms to develop and persist on dune stoss slopes are poorly constrained. In these experiments, the development of superimposed bedforms occurred primarily following a decrease in flow competence, forming on stoss slopes in areas where the crest-to-crest distance was relatively high. Overall dune dimensions ultimately increased as a consequence of the increase in flow depth (Figure 2A). Conversely, initial increase in dune length observed in decreased flow depths were not associated with increased bedform superimposition. Thus, the results of the experiments suggest that an abundance of superimposed bedforms is not unique to dune decay by cannibalisation, but related to a disequilibrium between primary dune geometry and flow over the stoss slope.

4.4. Separate effects of water depth and water surface slope?

The magnitudes of adaptation effects (increased superimposition, trough scour, increase in crest height, bedform lengthening) were more pronounced for the changes in water depth compared to the changes in discharge/velocity (Figure 2), even though all the investigated changes represented significant steps within the stability range of dunes. Flow velocity and water depth have different effects on the geometry and strength of the separated flow and re-establishing boundary layer (Balachandar et al., 2007), and such differences may explain the differences in bed response to changing flow. Further research is needed to improve our understanding of out-of-equilibrium flow over dunes, in particular the nature of the separated flow and re-establishing boundary layer on the stoss of downstream bedforms (Unsworth et al., this volume) and its role in initiating and sustaining, or supressing, superimposed bedforms.

5. CONCLUSIONS

The absolute and relative magnitudes of water surface slope and water depth differ spatially along river channels and temporally between different flood waves. These temporal changes are known to exhibit significant out-of-phase behaviour in which maximum water surface slope precedes maximum water depth. In the experiments presented herein, the morphodynamics of dune growth and decay are attributed to four factors: i) the bedform stability range, ii) spatial variability in bedform stability, iii) bedform kinematics, and iv) the relative magnitudes of water surface slope and depth. Morphology was more sensitive to changes in water depth than flow velocity. In particular, the development of trains of superimposed bedforms on the stoss of larger dunes was observed following an increase in water depth as opposed to a decrease in discharge, and was associated with areas of flow deceleration that were enlarged by preceding merger of dunes. This association suggests that an abundance of superimposed bedforms is not unique to dune decay by cannibalisation, but related to a disequilibrium between primary dune geometry and flow over the stoss slope. Fuller understanding of the causes for, and constraints on, dune adaptation to changing

flows awaits quantification of the flow field over out-of-equilibrium dunes.

6. ACKNOWLEDGMENT

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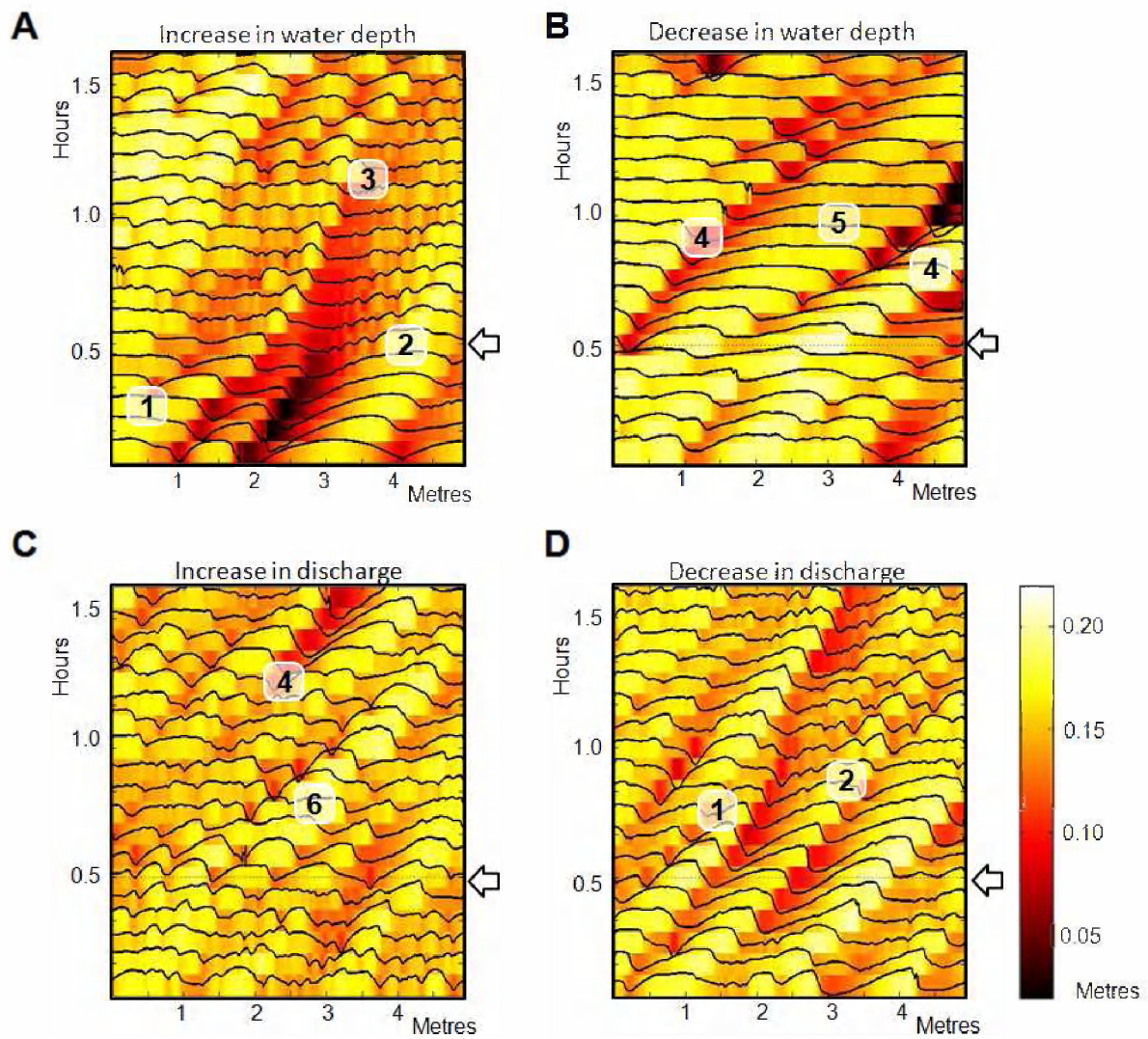
Figure 2. Plots of consecutive bed elevation profiles over time: A) an increase in water depth, B) a decrease in water depth, C) an increase in discharge, and D) a decrease in discharge. The background-colour represents bed elevation. Arrows indicate the point of change, and labels indicate the effects of this change on the morphology: 1) dune merger, 2) increased superimposition of bedforms, 3) decreased trough scour, 4) increased trough scour, 5) lengthening of dunes, and 6) increased dune height.