Morphodynamics of supercritical-flow bedforms using a depth-resolved computational fluid dynamics model

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Introduction

Unidirectional, overall supercritical, free-surface flow over a sediment bed leads to the formation of supercritical bedforms as cyclic steps and antidunes. For the first time, a depth-resolved numerical model is employed to simulate the behaviour of the sediment bed and flow at these conditions. Many morphodynamic aspects of supercritical flow bedforms are still poorly understood. This study aims to provide more insight into the processes associated with the inception and evolution, temporal and spatial, of these bedforms, the focus herein will be on cyclic steps.

The development of bedforms caused by water flowing supercritically at the beach - Waimea River Hawaii, (image by QuickSilver)

Methods: the model

A turbulent, supercritical, sediment-laden flow over an erodible bed is simulated using MassFLOW-3D and the kernel code FLOW-3D. FLOW-3D uses a multiphase Reynolds-Averaging Navier-Stokes (RANS) model in combination with a built-in scour model, an RNG k-epsilon turbulence model and a fractional area/volume obstacle representation (FAVOR) that allows rendering of intra-cell geometries.

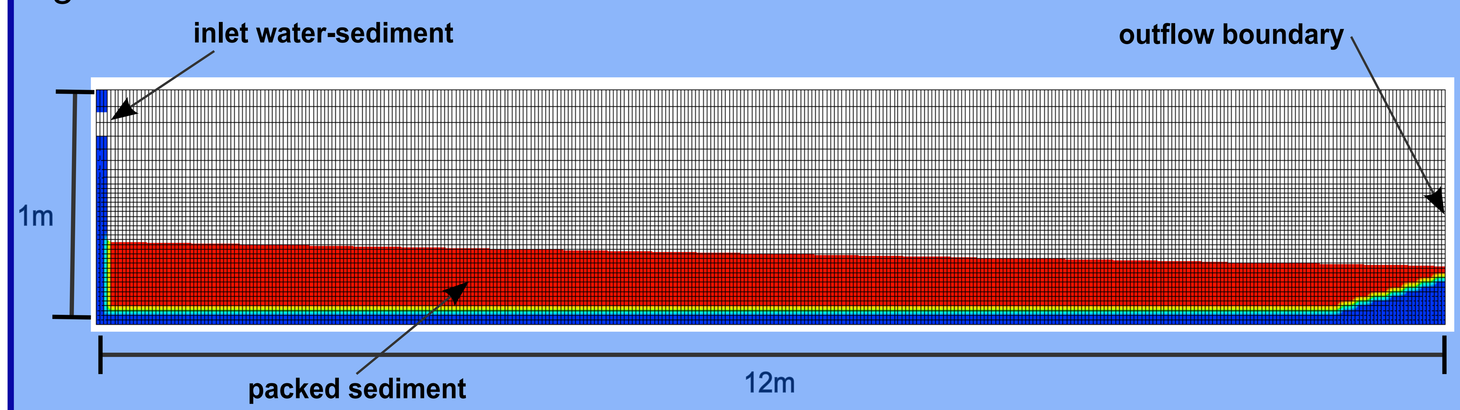

Figure 2: the setup of the simulation in FLOW-3D

Bedform stability

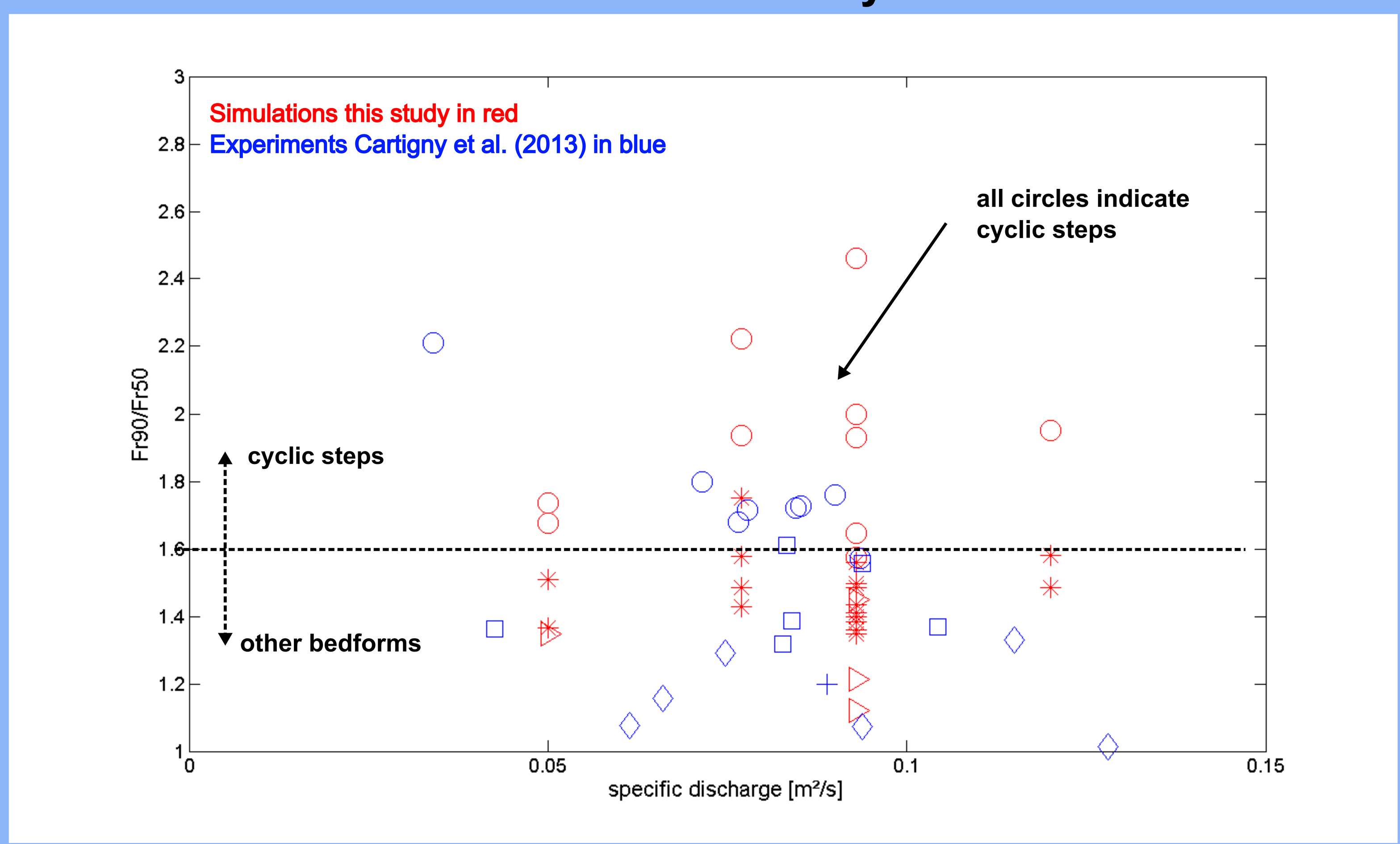

Figure 3: A bedform stability diagram showing the ratio of 90th percentile Froude number over median Froude number versus specific discharge (discharge per unit width). Data from this study and from experiments of Cartigny et al. (2013). Circles indicate cyclic steps, stars are undefined supercritical bedforms, squares are chutes-and-pools, plus-signs are unstable antidunes, diamonds stable antidunes and triangles indicate a flat bed.

Fr_{90}/Fr_{50}-values of more than 1.6 are indicative of cyclic steps in this bedform stability diagram. This also appears to be the case when changing other independent variables, such as grain size and inlet sediment concentration. This constraining value may be a helpful tool in paleoflow reconstruction.

Velocity field and sediment concentrations over a cyclic step

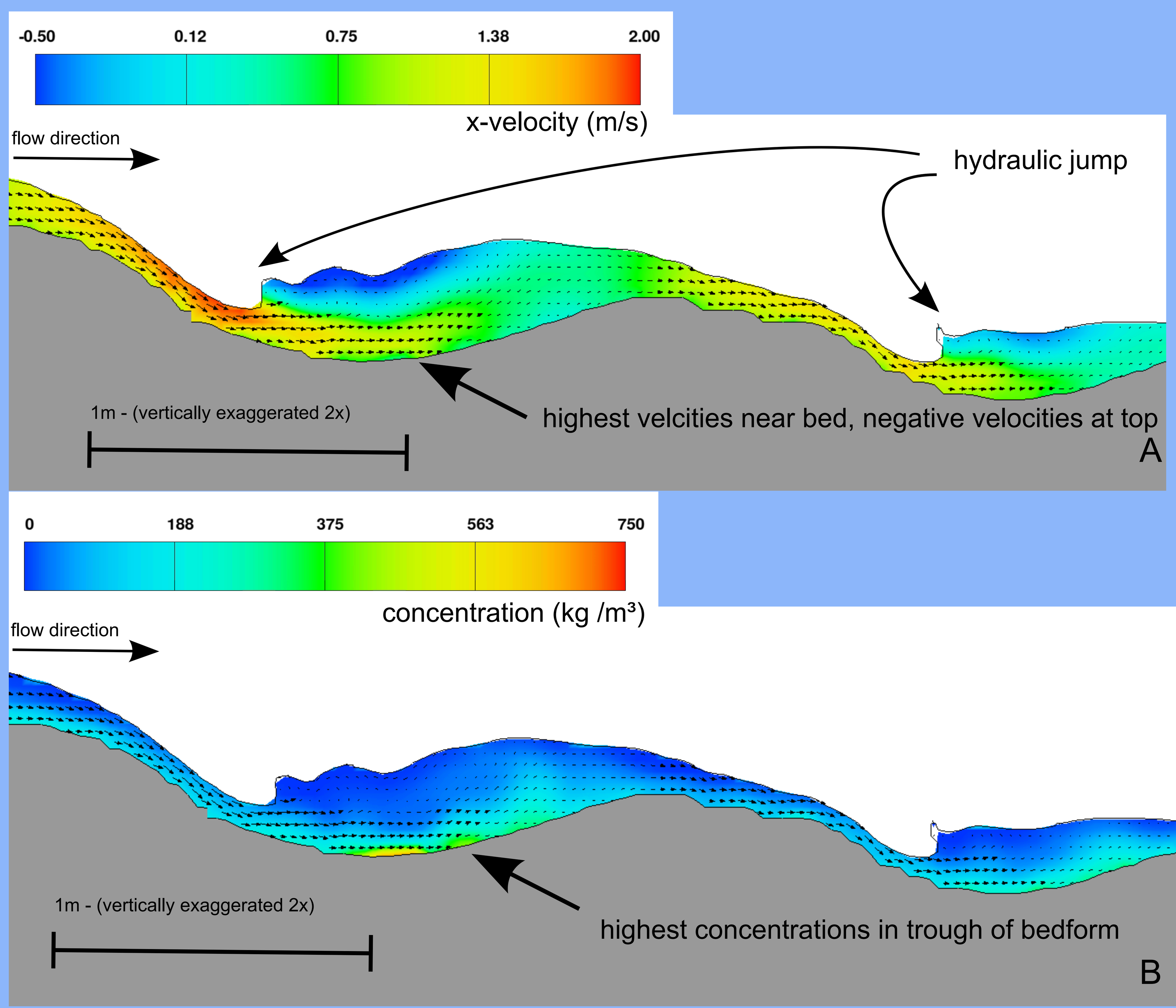

Figure 4: A snapshot of x-directed velocity over a cyclic step (A) and sediment concentration over a cyclic step (B)

Highest flow velocities are found at the lee-side of a cyclic step and at the bottom of the current at the start of the stoss-side. Negative flow-velocities -upstream directed velocities- are found just downstream of hydraulic jumps. Highest sediment concentrations are found just downstream of the hydraulic jump, near the bed in the trough of the bedform, as the near-bed flow-velocity starts to decrease.

Averaged properties over a cyclic step

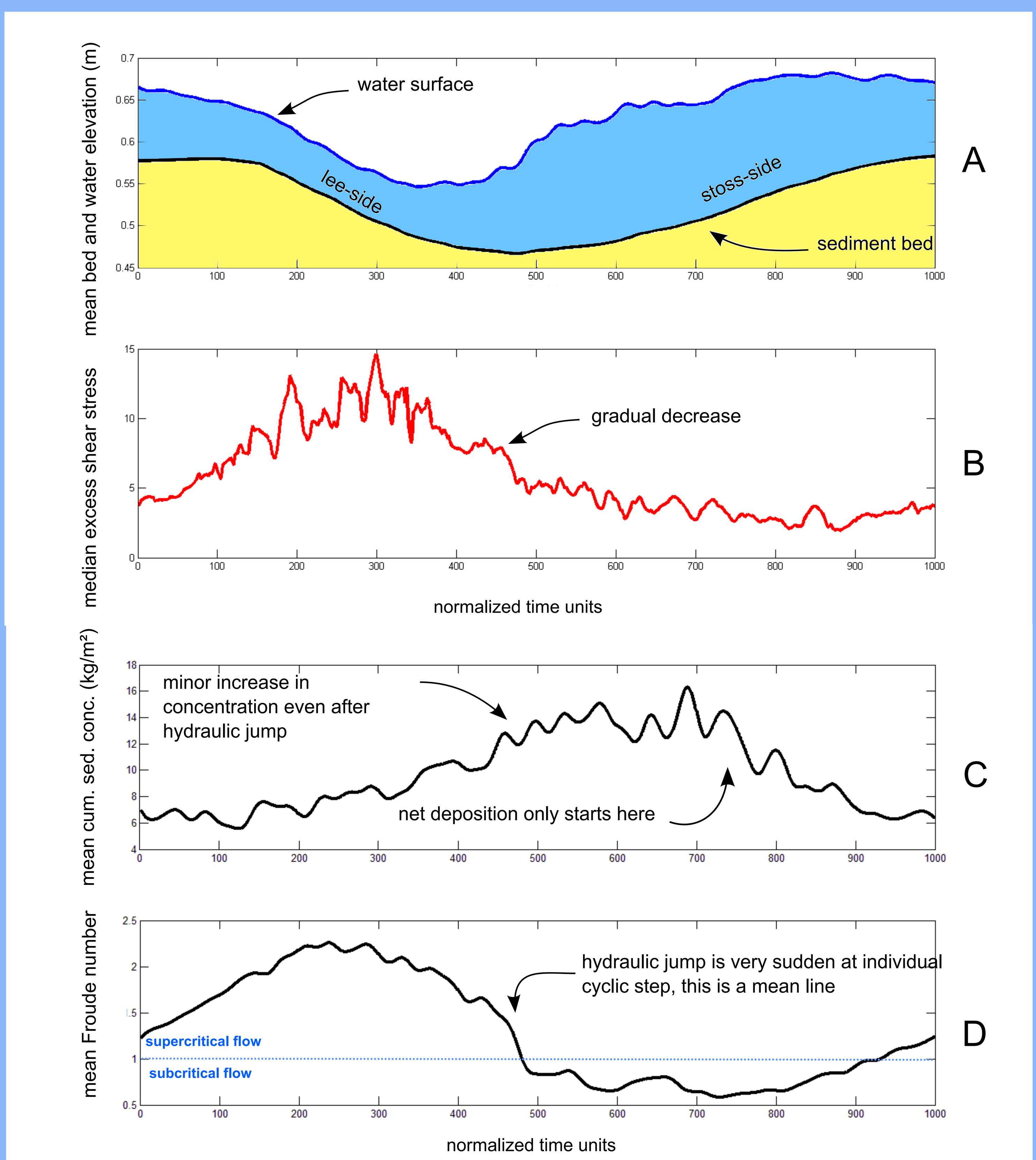

Figure 5: the mean free-surface and bed height (A), median excess shear stress (B), mean cumulative sediment concentration -depth integrated sediment concentration- (C) and mean Froude number (D). Versus a normalized time, the means are based upon the data of 29 individual cyclic steps from one single simulation. This is time series data on a fixed location. The rate of migration of the cyclic steps is in the order of 120 seconds.

The excess shear stress drops off slowly after the hydraulic jump, causing the sediment concentration to only decreases at the equivalent of about 30 seconds after the hydraulic jump.

Bed-evolution and deposits

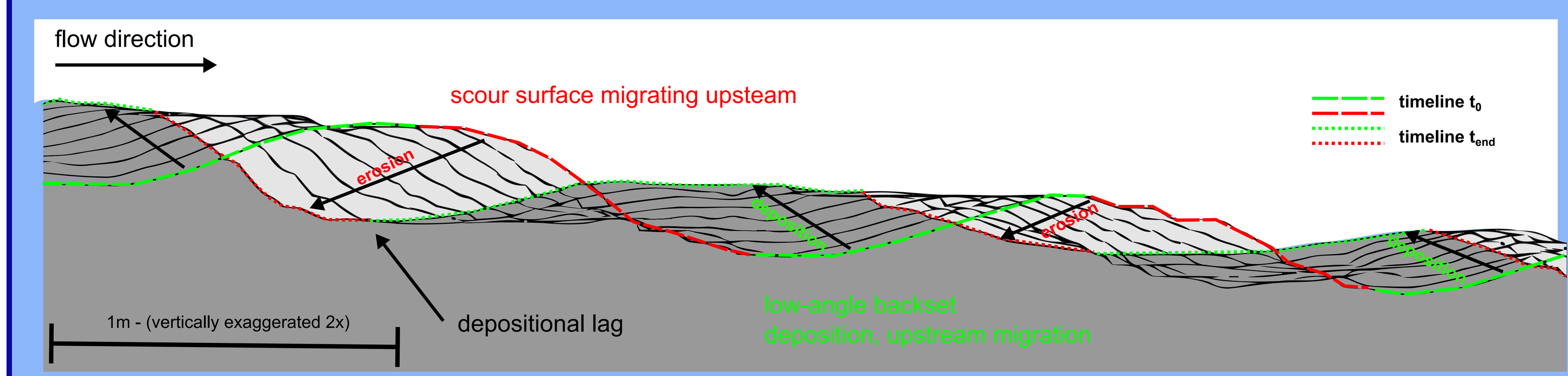

Figure 6: the evolution of the bed over time, the black lines are 8-second time-lines

Erosion takes place on the lee-side of the bedform, while deposition takes place on the stoss-side in low-angle backset laminations causing an overall upstream migration of the cyclic steps. The majority of deposits are formed at the last two-thirds of the stoss-side.

Conclusions

- Velocity structure downstream of hydraulic jump: highest velocities near bed, negative velocities at top of flow.
- Shear stresses remain high, only dampen out gradually downstream of hydraulic jump.
- Sediment concentration drop lags with respect to hydraulic jump.
- Depositional lag of about $^1/_2$ m or 30 s, most deposits at downstream two-thirds of stoss-side of a cyclic step.
- Interaction between erosion and depostion creates low-angle, upstream migrating backsets, cross-cut by erosional surface.
- Fr_{90}/Fr_{50}-ratios larger than 1.6 are indicative of a cyclic step morphology.
- It is possible to model cyclic steps using a depth-resolved model: MassFLOW-3D or FLOW-3D.

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