TOPOGRAPHIC EVOLUTION OF SANDBARS: FLUME EXPERIMENT AND COMPUTATIONAL MODELING

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Abstract Measurements of sandbar formation and evolution were carried out in a laboratory flume and the topographic characteristics of these barforms were compared to predictions from a computational flow and sediment transport model with bed evolution. The flume experiment produced sandbars with approximate mode 2, whereas numerical simulations produced a bed morphology better approximated as alternate bars, mode 1. In addition, bar formation occurred more rapidly in the laboratory channel than for the model channel. This paper focuses on a steady-flow laboratory experiment without upstream sediment supply. Future experiments will examine the effects of unsteady flow and sediment supply and the use of numerical models to simulate the response of barform topography to these influences.

INTRODUCTION

Barforms function as resistance elements in rivers and influence the distribution of depths and velocities, substrate character, water-surface elevations, and sediment transport. Consequently, the spatial and temporal evolution of barforms has implications with regard to in-channel habitat, risk for flooding, and the transport and storage of pollutants adsorbed to bed sediment. Flume studies have been conducted to examine the formation of free bars (Fujita and Muramoto, 1985; Fujita, 1989). Numerical modeling techniques have also been used to simulate the development of barforms in straight laboratory channels (Nelson, 1990; Takebayashi et al., 2001). Further work directed toward field-scale evaluation of these models is hampered by the fact that field data sets to test sandbar evolution algorithms are often difficult to collect given the detailed spatial and temporal resolution required. Additionally, because natural flow events are inherently unpredictable, antecedent channel topography immediately before a flow event may not be available.

Increasingly, adaptive management programs are motivating research into sediment transport dynamics. These programs are implementing flow releases to meet a variety of objectives, including releases to satisfy biological needs or for channel maintenance. Recent releases of water into the Colorado River in Grand Canyon have provided data sets to evaluate sediment transport in lateral separation zones (Logan et al., 2010, this volume). In the coming years, pulse flows are also planned to be released in the Platte River, Nebraska for the purpose of creating and maintaining avian sandbar habitat (Platte River Governance Committee, 2006). These releases will also provide unique opportunities to test barform evolution models with field data. In the interim, laboratory experiments, such as those described in this paper, can be used to gain confidence in the use of and limitations of numerical models for predicting sandbar evolution.

LABORATORY EXPERIMENT

Flume experiments were conducted in a 6-m long by 1.2-m wide tilting flume at the United States Geological Survey's (USGS) Geomorphology and Sediment Transport Laboratory (GSTL) in Golden, Colorado (Figure 1a). Water is pumped from the tail tank and manual valves can be used to direct the flow through the 9.5-cm and 3.5-cm diameter pipes that lead to the upstream end of the flume. The larger diameter pipe can convey flows up to 12 Ls^{-1} and the smaller can convey up to 5 Ls^{-1}. The flow in each pipe can be modulated with a ball valve controlled by a motorized actuator. The flow rate in each pipe is also separately monitored with a flow meter. The electrical current output from the flow meter is transmitted to a signal-conditioning connection block that is in turn sent to a computer where the current is converted to a flow rate. The flow rate is displayed in real time and stored as a file. The National Instruments LabVIEW ™ programming language was used to interact with the flow meters, valves, and additional flume instrumentation (National Instruments, 2005). LabVIEW ™ is a graphical environment that allows users to develop measurement, test, and control systems for laboratory instrumentation using simple icons and wired linkages. The software interface allows users of the flume to visualize the flow output on a graph, and control the position of the actuator and the flow rate. This can be done interactively by adjusting a slider graphic or using a feedback subprogram that reads the current flow, compares the value to that which is read from an input file, and either closes or opens the valve to adjust the flow. In this manner hydrographs can be preprogrammed for flume experiments.

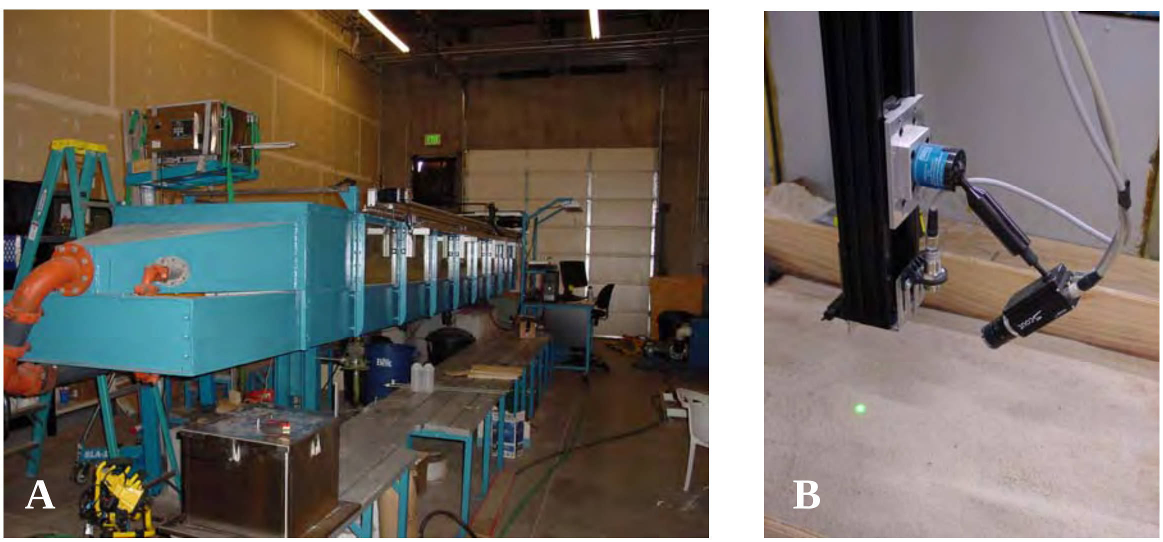

Figure 1 (A) Photograph of the channel evolution flume at the USGS Geomorphology and Sediment Transport Laboratory. (B) Topographic measurement system.

Measurements of bed-surface topography during flume runs where water depths are less than a few centimeters are challenging to accomplish. Marti and Bezzola (2006) used a motorized traverse with a laser and ultrasonic sensor to map sand-surface topography in their flume experiments. A similar optical triangulation system was developed at the GSTL to automate measurement of sand-surface topography and water-surface elevation in the flume (Figure 1B). The system includes a green wavelength laser (532 nm) mounted vertically on a traverse. The traverse is controlled by stepper motors and can be programmed to execute any three-dimensional motion. For our application, a zigzag scan pattern in the y (perpendicular to the flow in the flume) and x (parallel to the flow in the flume) directions was programmed. The traverse can send a transistor – transistor logic (TTL) pulse after any number of steps of the motor. The stepper motor in the y-direction was programmed to pulse every 1 cm as it traversed the flume. The TTL pulses are sent to a 659 by 494 pixel monochromatic Gigabit Ethernet (GigE) camera to trigger an exposure. The camera is mounted at an approximately 50 degree angle to the laser (Figure 1B). Each frame is saved as a time-stamped digital image and is also analyzed in real time to determine the location of the laser spot. A calibration was developed to relate the elevation of the laser spot relative to the flume datum to the pixel height in an image. Because the position of the laser spot is refracted when it is submerged, an ultrasonic sensor was used to measure the water-surface elevation at each camera exposure. When the sensors are in motion an elevation measurement is made every centimeter in the y-direction (transect). After a transect is completed in the positive y-direction the traverse is moved up the flume 10 centimeters. The next transect is surveyed in the negative y-direction and the traverse moves up the flume 10 centimeters. This pattern is repeated until 60 transects are surveyed. The traverse then returns to its initial position at the downstream end of the flume 9 minutes from when the survey was initiated. Figure 2 shows maps of bed topography made with the survey system. Figure 3 illustrates an individual transect surveyed at a location 3 meters in the x-direction.

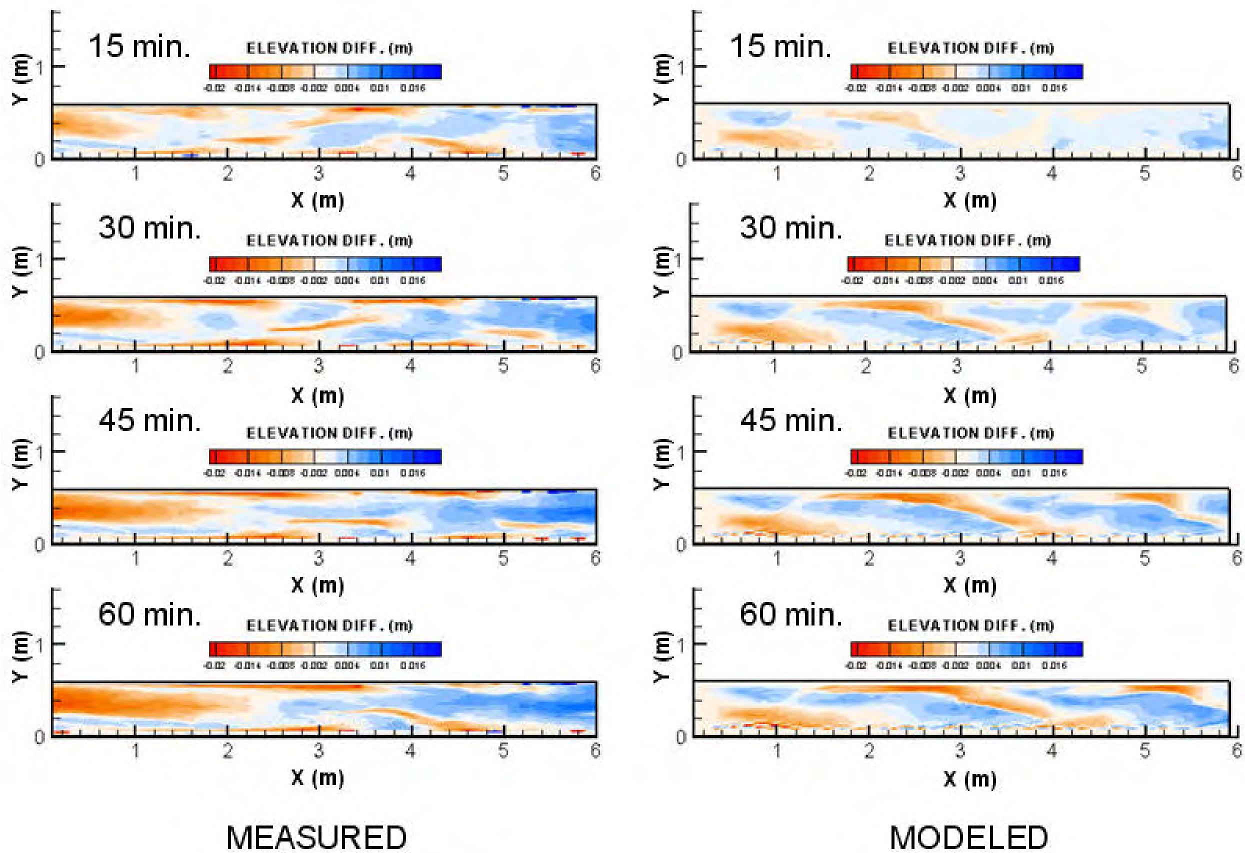

Figure 2 Comparison of experimental and modeled topographic changes from a plane bed. Flow is from left to right.

Steady-Flow Experiment Parallel walls 0.5 m apart were affixed to a false floor built within the flume and sealed with silicone to prevent leakage along the edges. The flow was baffled to remove turbulence at the upstream end of the flume and was allowed to enter the flume over a fixed weir. At the downstream end of the flume an adjustable weir was used to set the water-surface slope. Pool filter sand (d_{50} = 0.6 mm) was placed in the flume and screeded at a slope of 1/80, identical to the water-surface slope, and the plane bed was allowed to evolve over one hour without upstream sediment feed and at a constant discharge of 1 Ls^{-1}. During the flume run the traverse mapped the topography in 15-minute intervals (Figure 2). Water-surface elevations were also collected to aid in roughness calibration for the numerical modeling. The sediment exiting the downstream end of the flume was captured to determine the transport rate over the experiment (60 g/min).

NUMERICAL MODELING

Flow and Sediment Transport with Morphologic Evolution of Channels (FaSTMECH) (Nelson et al., 2003) a numerical flow model with sediment transport and channel evolution capabilities, was executed within the USGS Multi-dimensional Surface-Water Modeling System (MD_SWMS) (McDonald, et al., 2001, 2006). FaSTMECH is a quasi three-dimensional flow model that (1) solves the vertically and Reynolds averaged Navier Stokes equations on curvilinear, orthogonal coordinate system and (2) combines that solution with vertical structure and secondary flow computations in order to develop a 3-dimensional flow field prediction. Computations of the bed load and total load are used with the flow solutions at each time step to evolve the channel bed. The FaSTMECH model allows specification of input hydrographs and computes the flow solution in a step-wise steady-state manner, meaning the flow is treated as quasi-steady. Sediment transport can be computed with either the Engelund-Hansen or the Yalin equation and the model operates on the assumption that sediment is supplied at the upstream end at a rate equal to its transport capacity.

Steady Flow Modeling The topography in the flume surveyed at time 0, the plane bed, was used as an input data set to the MD_SWMS interface. A channel centerline was digitized and a 0.02-m by 0.02-m grid was created. The raw topographic data were mapped to the numerical grid using a template method, which is similar to nearest neighbor algorithm (McDonald et al., 2006). Channel boundaries in the model were refined to closely follow the vertical side walls. The downstream water-surface elevation and a drag coefficient were determined from the flume measurements. The FaSTMECH model was run to simulate 1 hour of steady discharge at 1 L/s. The Yalin sediment transport equation was used assuming a uniform grain size of 0.6 mm and the channel bed was allowed to evolve. Figure 2 illustrates the predicted channel topography over the simulation in 15-minute intervals. Figure 3 shows individual transects that were extracted from the model grid at various times in the simulation.

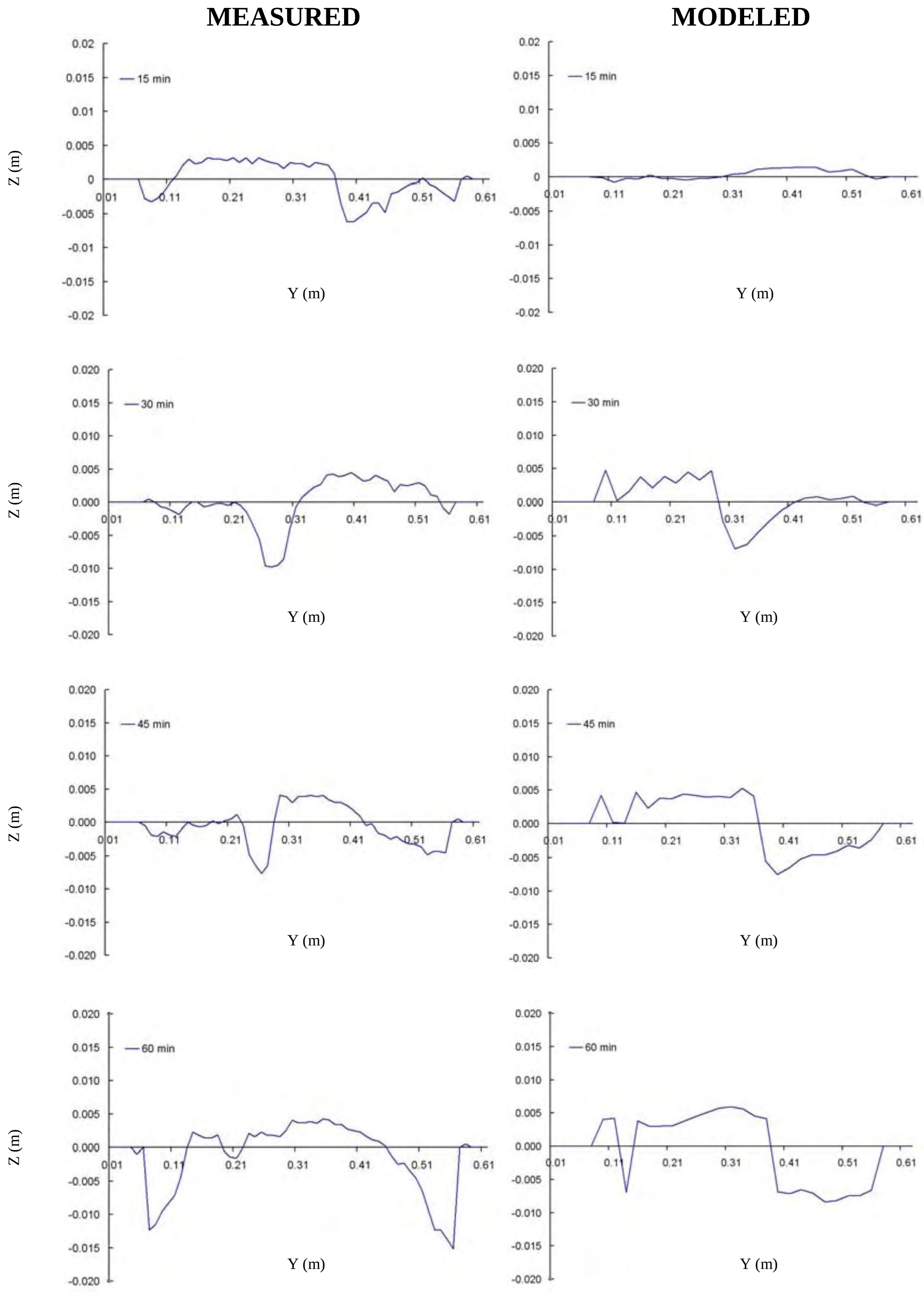

Figure 3 Comparison of measured and modeled changes from a plane bed at a transect located at 3 meters.

DISCUSSION

A scour area was observed to form early in the run at the upstream end of the flume (red color in Figure 2). This was because sediment was not supplied at the upstream end of the flume. This upstream scour area persisted and increased in length as the run progressed. Additional channels appeared along each sidewall and these alternated with a single channel located approximately near the center of the flume. This channel pattern is best illustrated by the topography that was measured after 45 minutes and resembles the mode 2 bars illustrated by Fujita (1989). Aggradation was also measured at the downstream end of the flume, appearing early in the run and persisting throughout the experiment. To minimize the influence of the upstream and downstream boundaries on sandbar development, a transect was selected at the midpoint of the flume for detailed examination (Figure 3). At 15 minutes into the run, 3 channels had formed along the transect and a depositional area had formed between 0.12 and 0.38 m. After 30 minutes the high and low areas along the transect had alternated or switched sides, with a large channel between 0.21 and 0.31 m and a crest between 0.32 to 0.54 m. After 45 minutes the large channel persisted but was accompanied by another channel between 0.42 and 0.56 m. At the conclusion of the experiment two dominant channels were observed along the side walls. This symmetrical pattern also is indicative of the mode 2 bars illustrated by Fujita (1989).

In the numerical simulation a scour area also formed at the upstream end of the flume and progressed downstream over time. However, once the channel pattern developed after 30 minutes it did not change as dramatically as the observations (Figure 2). After 15 minutes the numerical model predicted a relatively small amount of deposition and degradation along the transect as compared with the measurements (Figure 3). This could be attributed to the rapid initial scour at the flume upstream boundary stimulating the planform evolution. As the simulation progressed to 30 minutes, a channel developed near 0.29 to 0.41 m and also an area of deposition developed between 0.10 and 0.30 m. The relative bar heights and channel depths in the model simulation were similar to the observations after 45 minutes but with a lower mode. At the conclusion of the numerical simulation, a secondary channel began to develop at 0.13 m. However, neither of these channels proved to be as deep as those observed at the conclusion of the flume run.

The FaSTMECH model operates on a number of assumptions including uniform grain size and equilibrium transport at the upstream and downstream end. Sandbar evolution measured in the flume was more dynamic than that simulated by the model and the amplitude of scour was greater, consistent with the lack of upstream sediment supply. Once the channel pattern was established in the model it became reinforced through time as opposed to the flume observations, which showed migration in channel position through time. Sidewall boundaries in the model must be treated carefully as instabilities were found to occur if these interfaces were not well defined. The MD_SWMS software enables editing of topographic surfaces and grid adjustment for the FaSTMECH model. Shallow water depths were also found to cause model convergence issues. For this reason when the depth in a node became less than 0.0008 m it was made dry and removed from the computation.

CONCLUSIONS

The FaSTMECH numerical model was used to simulate the initial development of sandbars in a laboratory channel. Model predictions indicated an alternate bar morphology, whereas observations of laboratory evolutions indicated higher mode sandbars. Examination of a topographic transect located away from the boundaries also showed differences in mode and a more dynamic morphologic response of the laboratory channel. Boundary effects exert a tremendous influence on the temporal and spatial development of laboratory barforms. These effects are difficult to minimize in a flume of this relatively short length. The model assumed hydraulically limited sediment supply, while the experiment had no upstream sediment supply – this appears to play a significant role in the differences observed between the two cases. Future experiments will attempt to evaluate the effect of upstream sediment supply on the development of flume barforms. These experiments will also serve to characterize the topographic variability of the sandbars created in flume runs. Additional flow and channel evolution models will be evaluated with an emphasis on the types of transport equations used and the effect of structured and unstructured numerical grids.

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