EFFECT OF UPSTREAM SEDIMENT SUPPLY AND FLOW RATE ON THE INITIATION AND TOPOGRAPHIC EVOLUTION OF SANDBARS IN LABORATORY AND NUMERICAL CHANNELS

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Abstract The evolution of barforms from a bed of uniform sediment and changes in sediment storage were measured in a laboratory flume and simulated numerically. Flume experiments were conducted with several upstream sediment supplies and flow conditions. For the sediment supply rates (no upstream supply, equilibrium supply, and 133, 166, and 200 percent of the equilibrium supply) and flow rates examined, the plane bed tended to evolve into mid-channel bars early in the runs ~15 minutes. As the flume experiments progressed, the bed transitioned to a lower mode configuration of alternate bars or a single-thread meandering thalweg. Increasing the upstream sediment supply to 133 percent or more of the equilibrium rate, increased the height and volume of deposited sediment relative to experiments conducted at the equilibrium rate and those experiments without sediment supply. Experiments conducted at flow rates of 0.5 and 1.0 L/s without sediment supply demonstrated that an increase in flow corresponded to a greater volume of erosion. A coupled two-dimensional flow and sediment transport model, Nays2DH, was used to simulate the evolution of bed topography for three sediment supply rates. We compared the morphodynamics and sediment storage predicted by Nays2DH for two initial bed conditions: one set of calculations used a plane bed with a small upstream perturbation as the initial bed condition, and the other set used the bed topography measured 15 minutes after the start of the flume run. Whereas initializing the model with measured flume topography provided a somewhat better analog to the final evolved morphology, predictions of sedimentation were not substantially improved over simulations using the plane bed as the initial condition.

INTRODUCTION

Flow and sediment management have been identified as tools to rehabilitate river corridors impaired by upstream regulation (National Research Council, 1999; U.S Department of Interior, 2006). Management strategies may be directed toward increasing the height of fine-grained deposits along channel margins or increasing barform heights for the preservation or enhancement of in-channel habitat. A number of adaptive management programs are in place in the United States that have objectives related to geomorphic change. A few examples of these programs are the Colorado River in Grand Canyon, the Trinity River in California, and the Platte River in Nebraska. In the case of the Platte River, the Bureau of Reclamation and U.S. Fish and Wildlife Service have identified short duration near-bankfull flows from 1 to 3 days in duration to test the ability of these flows to scour vegetation and build ephemeral sandbars to benefit
nesting species of concern (the least tern and the piping plover, U.S. Department of the Interior, 2006). Sediment augmentation has been recently used in the Platte River to offset reduction in sediment supply created by a clear water return from an upstream hydropower canal. The Platte River Recovery Implementation Program (PRRIP) initiated a pilot study aimed at adding 100,000 tons of sediment to the Platte River (PRRIP, 2014). Due to the magnitude and cost of adaptive management programs, predicting the outcome of management actions becomes an important means to design strategies to achieve the desired goals economically and effectively.

Predicting river response to different physical stimuli can be a difficult task. One of the tools available to river scientists is numerical models that can simulate morphologic change in rivers resulting from various management scenarios, including hydrograph change and sediment input. However, the detailed field information required to run, calibrate, and verify these models may be unavailable, potentially incomplete, or difficult to collect. Specifically, river bed topography before, during, and after flow manipulation may be lacking, as might information regarding the sediment supply rate during the management activities. Additionally, it is not always clear if a model has a range of applicability that encompasses the physical settings of the problem at hand.

Flume experiments have been used by researchers as a means to understand and observe channel evolution processes (Fujita and Muramoto, 1985; Fujita, 1989; Germanoski and Schumm, 1993; Marti and Bezzola, 2006; Madej et al., 2009). Flume experiments can also provide the data necessary for input, calibration, and verification of morphodynamic models (Jang and Shimizu, 2005; Takebayashi and Okabe, 2009). Combining numerical and physical modeling, therefore, offers a more comprehensive approach to predicting the outcomes of river management actions for at least two reasons. It can identify and provide a means to assess conditions that drive model predictions and provide a better understanding of the physical processes involved.

The intent of this paper is twofold. First, we discuss a series of flume experiments designed to explore the effect of upstream sediment supply and discharge alterations on erosion and deposition patterns in a straight channel with an initial plane bed. Second, we applied a coupled flow and sediment transport model to simulate and predict the morphologic changes observed in the flume. The flume experiments were conducted to address how the magnitude of upstream sediment supplied influenced the spatial and temporal patterns of erosion and deposition in a straight channel. In addition, we wanted to understand the effect of flow rate on the deposition and erosion patterns in a coarse, bedload dominated system. These effects are related to many types of management actions and, in particular, are directly relevant to those actions that involve manipulating flow and sediment supply to achieve bar formation. The numerical experiments were conducted for model testing and validation, and to gain an understanding of the influence of boundary conditions (input sediment load and initial topography) on predictions of channel evolution.
METHODS

**Flume Experiments** Over 30 flume experiments were conducted at the U.S. Geological Survey’s Geomorphology and Sediment Transport Laboratory in Golden, CO using a 7-m long and 1.2-m wide tilting and recirculating flume. The flume slope was set to 1.25 percent. Vertical plywood walls were attached to the flume bed to restrict the width of the test channel to 0.50 m and the flow in the flume was adjusted with a computer controlled valve. The sediment used in the experiments was a well-sorted sand $d_{50} = 0.6$ mm, $\sigma = \sqrt{D_{84}/D_{16}} = 1.2$. Sediment was introduced at the upstream end of the flume using a motorized sediment feeder. Higher sediment supply rates were achieved by augmenting the feeder supply by manually distributing sand evenly across the upstream end of the flume. We determined the sediment transport rate for a given flow by trapping sediment at the downstream end of the flume at that flow over a set time interval and weighing the dried material. The mean equilibrium transport rate measured for a 1L/s flow was approximately $3.3 \times 10^{-3}$ kg/s. The bed of the test channel was screed at the beginning of each experiment and the initial plane bed topography of the test channel was surveyed. Topographic surveys were repeated at 15-minute intervals over the duration of each experiment. We used a topographic measurement system that included a motorized traverse that spanned the width and length of the flume, a laser mounted to the traverse with its long axis pointing perpendicular to the flume bed, and a video camera oriented to capture an oblique image of the laser spot on the sand. Details of the mapping system are presented in Kinzel and others (2010). During the experiments it was necessary to drain the flume before the bed was surveyed. This was because the refraction of the laser through a small depth of water (< 0.01 m) could not be compensated for accurately, due to the inability to resolve distinct water surface and bed reflections in the images. An ultrasonic sensor was integrated to detect the water surface. The water-surface elevation was measured with the ultrasonic sensor at the end of each flume run.

A series of flume runs was conducted to evaluate channel response to varying sediment loads at a similar discharge. A discharge of 1.0 L/s was used for each of these experiments and with sediment supply rates equal to 0, 100, 133, 166 and 200 percent of the equilibrium transport rate. Each experiment lasted 2 hours to allow sufficient time for the sediment to move through the test section located between 2 and 4 m downstream of the most upstream transect measured. A series of flume runs was also conducted at 0.5 and 1.0 L/s without sediment supply to examine the change in morphology and sedimentation from clear-water flow alteration.

Plots of volumetric change as a function of the vertical deviation from the initial plane bed were made by determining the volume in 1-mm elevation bins within the test section of the flume. The test section was positioned to minimize the effect of the flume boundaries (upstream entrance and downstream tailgate) on the erosion and deposition patterns in the flume.

**Numerical Modeling** We used a two-dimensional, depth averaged, unsteady, coupled flow and sediment transport model, Nays2DH Version 1.0, to try to reproduce the spatial and temporal evolution of barforms observed in the flume experiments and the concomitant changes in sediment storage. Nays2DH is based on the numerical solution of the shallow water equations in a curvilinear orthogonal, structured grid and is a combination of two models: Nays2D and Morpho2D (iRIC Project, 2014). Nays2D is described in Shimizu (2002) and Takebayashi (2005) and Takebayashi and Okabe (2009). Nays2DH is one of the models in the
international River Interface Cooperative (iRIC) software, described by Nelson and others (2010). The software is available at no cost and can be downloaded from http://i-ric.org/en/introduction. A general curvilinear coordinate system is used in Nays2DH. For our straight channel simulations we used a numerical grid with 0.02 m x 0.05 m grid cells in the stream-normal and stream-wise directions. Model inputs included the initial bed topography of the flume, downstream water-surface elevation, flow rate, and hydraulic roughness in the form of Manning’s n. Nays2DH assumes a non-slip condition along the side-wall boundary.

Nays2DH supports both bedload and suspended sediment transport, and can perform calculations on uniform and mixed-grain sediment beds. The sediment bed in the flume was modeled with a uniform grain diameter of 0.6 mm. Nays2DH uses either the Meyer-Peter Müller (1948) or Ashida and Michiue (1972) equation to compute bed load transport. In our simulations, the Ashida and Michiue equation was used. The bedload transport vector was calculated using the Watanabe formula (Watanabe et al., 2001).

Two sets of model simulations were carried out. In the first set, a common technique to perturb the numerical calculation and stimulate the development of bar morphology from the initially plane bed was used. This technique uses a plane bed topography for the initial condition, and places a rectangular region with a slightly higher bed elevation (bump) at the upstream end of the model domain (Jang and Shimizu, 2005). In the second set of simulations, the flume topography measured after 15 minutes into the run was used directly as the initial condition for the bed topography.

Other modeling experiments were performed to examine the influence of secondary flows on the morphodynamics. Secondary (helical) flows can be treated in Nays2DH by using one of two approaches. One option involves solving an equation for depth-averaged vorticity in the streamwise direction. The other option allows the user to directly specify the strength of secondary flows. This parameter controls the near bed velocity and the direction of bedload transport:

\[
\tilde{u}_b^n = \tilde{u}_b^s N^* \frac{h}{r_s}
\]  

(1)

Where: 
\(\tilde{u}_b^n\) = the near-bed velocity in the transverse direction  
\(\tilde{u}_b^s\) = the near-bed velocity in the stream-wise direction  
\(N^*\) = the strength of secondary flows, =7 per Engelund (1974))  
\(\frac{h}{r_s}\) = the ratio of the depth to the radius of streamline curvature
RESULTS

**Sediment Experiments** Our first experiments demonstrated, albeit somewhat intuitively, that if we supplied sediment at the equilibrium transport rate, the flume channel would degrade less and build bars to higher elevations than without sediment supply. Subsequent experiments demonstrated it was necessary to increase sediment supply 133 percent or more of the equilibrium transport rate for bars to be built to higher elevations than those built with the equilibrium rate. The change in elevation from the initially plane bed for three sediment supply rates and sedimentation after 2 hours with a flow of 1 L/s are shown in figure 1.

![Figure 1](image)

Figure 1 Changes in the bed elevation of the flume, in meters, measured over 2 hours with a flow of 1.0 L/s and sediment supplied at (A) the equilibrium transport rate (B) no upstream supply and (C) double the equilibrium transport rate. Plot showing erosion and deposition volumes measured in the test section as a function of elevation for the various supply rates after 120 minutes (D).

The differences between the supply rates are most discernable in the upper portion of the flume. For the flume run conducted with the equilibrium transport rate (Fig. 1A), the net change in the volume of the test section was a relatively small gain of 358 cm$^3$. The undersupply run (Fig. 1B) was dominated by erosion in this section and the net change in sediment volume in the test section was a loss of 1768 cm$^3$. The run with twice the equilibrium transport rate (Fig. 1C) resulted in a delta at the upstream end of the flume that continued to propagate downstream as
the experiment progressed, resulting in a net increase in sediment volume of 2273 cm$^3$ in the test section.

The morphology of the runs shown in figure 1 could be classified as alternate bars with deeper regions periodically forming along opposing channel walls. A volumetric change plot, which is computed over the inner third of the flume (test section) also highlights differences between the 3 sediment supply rates (Fig. 1D). The volume and height of deposition is highest for double the equilibrium supply rate, whereas the volume of erosion is highest when sediment is not supplied. Not surprisingly, supplying sediment at the equilibrium transport rate shows more equivalent volumes of erosion and deposition.

**Flow Experiments** A series of experiments was conducted to simulate the effect of flow regulation on channel morphology. These experiments are analogous to river reaches that have experienced alterations in flow due to dams or diversions. Two discharges were examined in detail, 0.5 and 1 L/s. Multiple runs were conducted for each discharge without upstream sediment supply and each lasting a duration of 1 hour.

Figures 2A and 2B illustrate the topographic changes that were measured for Run 3 (1 L/s) and Run 9 (0.5 L/s). The experiments conducted at 1.0 L/s displayed a similar pattern of channel evolution. Typically the channel formed higher mode bars during the initial 15 minutes of the experiment (Fig 2A). Following the 15-minute survey, when flow in the flume resumed, the channel evolved to have a more meandering pattern in which the main thalweg was found along alternating sides of the flume. The experiments conducted at 0.5 L/s (Fig. 2B) initiated bed forms in the first 15 minutes that, based on visual inspection, were less symmetric and of lower relief than the higher mode bars that developed early in the 1.0 L/s experiments. The initiation and progression of upstream erosion during the 1-hour flume run was also less clearly defined for the lower 0.5 L/s flow. Volumetric plots of the elevation changes after 1 hour for each run at 0.5 and 1.0 L/s show variability among each flow rate (Fig. 2C).
Figure 2 Changes in the bed elevation of the flume, in meters, measured over 1 hour for two flow rates (A) Run 3 at 1 L/s and (B) Run 9 at 0.5 L/s. Plot showing the erosion and deposition measured in the test section for various flow rates after 1 hour (C).

The greatest disparity in sedimentation between the flow rates was observed in the amount of erosion; the height of bar forms were rather consistent. The higher discharge caused more total erosion and erosion to lower elevations. This morphologic response is akin to that of a flushing event wherein water devoid of sediment is released into a channel from a dam or hydropower return canal.

**Nays2DH Simulations** The roughness value used in Nays2DH was determined by calibrating the water-surface elevation measured at 2 hours into the flume run with the model predicted water surface. This water-surface elevation was influenced by drag from bedforms created during the flume run, but acknowledging that drag changed because of bed evolution we reasoned this profile was most appropriate for calibration. The best calibration (root mean square error of 0.001 meter between measured and modeled water-surface elevations) was found using a Manning’s n of 0.03. While Nays2DH can accept varying sediment supplies at the upstream end by specifying the ratio of supplied sediment transport to the equilibrium rate, there is presently no ability to input a transport rate to exactly match observations. We found better agreement in transport rate with our observations using the Ashida Michiue equation (~2.0 x10^{-3} kg/s, i.e., 60.6 percent of the measured transport rate of the flume experiments) rather than the Meyer-Peter Müller equation (~2.0 x10^{-2} kg/s, an order of magnitude greater than Ashida Michiue), which is expected as the latter was developed for fine gravel. Modeling experiments were conducted to compare two approaches for inducing bed instability and initiating bar development in a straight channel. Model results using an initial plane bed with a small bump placed immediately upstream as input are shown in figure 3. Figure 4 shows the outcome from using the flume topography measured at 15 minutes as the initial bed condition.
Figure 3 Changes in bed elevation predicted by Nays2DH using a plane bed with upstream perturbation as input and sediment supplied at (A) the equilibrium rate, (B) 0 percent of the equilibrium rate, and (C) 200 percent of the equilibrium rate. Plot showing erosion and deposition volumes predicted by Nays2DH in the test section as a function of elevation for the various supply rates after 2 hours (D).
Figure 4 Changes in bed elevation predicted by Nays2DH using the antecedent bed topography in the flume measured at 15 minutes as input and sediment supplied at (A) the equilibrium rate, (B) 0 percent of the equilibrium rate and (C) 200 percent of the equilibrium rate. Plot showing erosion and deposition volumes predicted by Nays2DH in the test section as a function of elevation for the various supply rates after 2 hours (D).

Including secondary flows by computing the depth-averaged vorticity in the streamwise direction resulted in excessively weak alternate bar formation that did not match experimental results. Using the second option and increasing the strength of the secondary flow parameter $N^*$, from the default value of zero, was shown to induce more substantial variations in bed morphology and sediment storage. However, because we were simulating flow in a straight flume channel, we reasoned that adjusting this parameter was somewhat subjective and more justifiable for stronger meander bends, therefore the results are not discussed here. Nays2DH also is able to simulate periodic boundary conditions. If periodic boundary conditions are used, the sediment and hydraulic conditions calculated at the downstream end of the model domain are applied to the upstream end. However, in the present version of Nays2DH if periodic boundary conditions are enabled the supply of sediment at the upstream boundary cannot be changed from the equilibrium condition. Therefore, to ensure consistency among all supply rates modeled, we disabled this boundary condition for all runs.
DISCUSSION AND CONCLUSIONS

Two sets of flume experiments were carried out: one set with increasing sediment supply, the other with clear-water inflow at different flow rates. In conjunction these two sets of runs show the separate effects of flow rate and sediment supply changes on the morphologic evolution of a plane-bed channel. These experiments were conducted to illustrate and explore basic morphologic responses and serve as simple analogs to river management activities. The sediment supply experiments (Fig. 1) indicated that it was necessary to increase the supply at or above 133 percent of the equilibrium rate to appreciably increase bar heights. Although all runs showed both degradation and bar formation, the height of the bedforms was greater and degradation was smaller for the higher sediment supply rate (Fig. 1D), highlighting the role of sediment transport in bar formation and maintenance. In the clear-water flow experiments without upstream sediment supply, greater flow rates induced increased bed degradation, but did not contribute to the creation of bed forms with higher elevation (Fig. 2). This observation corroborates the idea that increased transport capacity (i.e., higher flow rates) must be accompanied by increased sediment availability in order to create and maintain higher bars and topographic relief.

The Nays2DH numerical model was used to simulate the conditions employed in the laboratory flume. The principal difficulties in the modeling effort were to accurately compute the sediment transport rates and to determine the ideal starting bed conditions for the onset of plane bed instability. Therefore, the primary causes for the differences between the physical flume experiments (Fig. 1) and the numerical simulations (Figs. 3 and 4) may be attributed to the boundary conditions supplied to the model. The initiation of morphologic evolution using an initially plane bed with an artificial perturbation produced higher mode bars at the end of the simulations than did predictions using the natural perturbations present in an antecedent flume topography, which more closely resembled the alternate bar or single-thread meandering morphology observed in the flume.

The initiation and progression of the scour under the no supply case was more pronounced using the antecedent bed condition over the plane bed topography but did not advance downstream to the extent of the flume observations. In addition, the delta predicted at the upstream end of the flume for each modeled over supply case was higher than observed in the flume. These observations indicate the transport rate calculated by the model was not sufficient in either input condition to advance these features, and it may be a direct consequence of the use of the Ashida and Michiu transport equation, which was shown to underestimate the equilibrium transport rate of the experimental conditions by over 39 percent.

The erosion and deposition volumes predicted by either input bed condition were about the same for the equilibrium supply case. For the under supply case, both models over predicted aggradation and under predicted degradation. Turning to the over supplied case, the plane bed input condition under predicted aggradation, whereas using the antecedent topography as input under predicted the degradation. Thus, it can be concluded that although using a natural perturbation produced a morphology that was more analogous to the final evolved flume topography, the transport rates predicted by the model were not sufficient to match the sedimentation observed in the test section. As above, the likely explanation is that the transport
rate computed by the model was less than that of the experiments. Unfortunately, Nays2DH does not at present offer a means to scale existing transport equations to match the observed conditions.

Future work will include comparing the flume experiments and, ultimately, morphologies from river management experiments with predictions from other models in iRIC. These models offer different approaches to sediment transport modeling, such as other transport equations, and can account for three-dimensional flow effects. While resulting in somewhat more computationally expensive models, inclusion of additional boundary conditions (e.g. side wall friction) and three-dimensional simulation of the flow structure and its influence on sediment transport can provide more accurate representation of the dynamics of channel evolution.

REFERENCES


