COMPUTATIONAL MODELING OF BEDFORM EVOLUTION IN RIVERS WITH IMPLICATIONS FOR PREDICTIONS OF FLOOD STAGE AND BED EVOLUTION

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Abstract Uncertainties in flood stage prediction and bed evolution in rivers are frequently associated with the evolution of bedforms over a hydrograph. For the case of flood prediction, the evolution of the bedforms may alter the effective bed roughness, so predictions of stage and velocity based on assuming bedforms retain the same size and shape over a hydrograph will be incorrect. These same effects will produce errors in the prediction of the sediment transport and bed evolution, but in this latter case the errors are typically larger, as even small errors in the prediction of bedform form drag can make very large errors in predicting the rates of sediment motion and the associated erosion and deposition. In situations where flows change slowly, it may be possible to use empirical results that relate bedform morphology to roughness and effective form drag to avoid these errors; but in many cases where the bedforms evolve rapidly and are in disequilibrium with the instantaneous flow, these empirical methods cannot be accurately applied. Over the past few years, computational models for bedform development, migration, and adjustment to varying flows have been developed and tested with a variety of laboratory and field data. These models, which are based on detailed multidimensional flow modeling incorporating large eddy simulation, appear to be capable of predicting bedform dimensions during steady flows as well as their time dependence during discharge variations. In the work presented here, models of this type are used to investigate the impacts of bedform on stage and bed evolution in rivers during flood hydrographs. The method is shown to reproduce hysteresis in rating curves as well as other more subtle effects in the shape of flood waves. Techniques for combining the bedform evolution models with larger-scale models for river reach flow, sediment transport, and bed evolution are described and used to show the importance of including dynamic bedform effects in river modeling. For example calculations for a flood on the Kootenai River, errors of almost 1m in predicted stage and errors of about a factor of two in the predicted maximum depths of erosion can be attributed to bedform evolution. Thus, treating bedforms explicitly in flood and bed evolution models can decrease uncertainty and increase the accuracy of predictions.

INTRODUCTION

Engineers and scientists are frequently asked to make predictions of water-surface elevation, flow patterns, sediment transport and morphologic evolution in rivers. Because of this demand, a great deal of time and effort has been invested in developing sophisticated models for river reaches that predict these quantities. These models are based on the well-known principles of conservation of mass and momentum and range from relatively simple 1-d models for water-surface elevation all the way to turbulence-resolving three-dimensional mobile bed models.

However, across the range of model complexity, the largest sources of model uncertainty tend to be the same. These primary sources of uncertainty arise from two model inputs: channel bathymetry and roughness. Uncertainty arising due the measurement error and lack of spatial resolution in channel bathymetry are not dealt with in this paper, but it is worth noting that such uncertainties are becoming far less common than in the past due to improvements in river surveying techniques; many current river bathymetry data sets are collected with multibeam acoustic techniques or airborne bathymetric (green) LiDAR, both of which can produce high-resolution accurate data. Given the advancements in bathymetric measurement techniques, the specification of roughness is almost certainly the greatest source of uncertainty in current river models. Typically, roughness is set by choosing a value of any of a variety of parameters that characterize roughness, including drag coefficient, Manning's n, the roughness length z_0, Chezy coefficient, and others. All of these parameters provide some kind of relation between velocity and bed stress, so they are extremely important for predicting the stage that a given discharge of water will produce in a given channel. Similarly, for sediment transport and bed evolution models, the specification of roughness must include some consideration of how friction or total stress is distributed into form (or pressure) drag on bed and bank features and how much is actually available as skin friction stress (the local stress that actually characterizes sediment motion). When specifying roughness, researchers typically use a great deal of empirical information relating roughness to bedform size, grain size, channel form, and so forth in order to make the best possible choice. In many cases this is relatively straightforward, but in others it is very difficult and uncertain, so that model predictions are not reliable. In some cases, it is possible to use measured information about water-elevation and velocity to calibrate roughness in models; this is the preferred method in most situations, but it restricts reliable model applications to flows that have been measured in detail.

Uncertainty in roughness is a major barrier to modeling predictions in rivers with bedforms that evolve over flood hydrographs, because in that situation roughness changes with time, so even if measurements were available for calibration at a given flow, those data would not necessarily be useful for calibrating roughness for any other flow. In addition, because the bedforms respond over some period of time, bedforms may have different shapes and sizes at a given flow depending on the preceding flows, so the roughness at any time is not uniquely related to discharge. The so-called "washout" of bedforms is a common extreme example of this nonuniqueness; for that case, the roughness can change dramatically because bedforms are present on the rising limb but absent on the falling limb of the hydrograph, so there is significant hysteresis of the stage-discharge rating curve.

In this paper, a method to resolve the uncertainty associated with roughness specification in rivers with evolving bedforms is presented and applied to a reach of the Kootenai River in Idaho, USA. The method is only approximate, as it does not explicitly calculate bedform behavior within a river morphodynamics model, but it does allow for prediction of roughness and form drag associated with bedform change over a flood hydrograph, and as such it can help reduce the uncertainty in river model predictions. The model is based on the combination of two models: (1) a typical multidimensional model for river flow, sediment transport, and bed evolution, and (2) a model for bedform growth and evolution. These two models are coupled only through the input conditions to the separate models and through specification of roughness and form drag.

METHODS

The method described here is a direct extension of recent progress that has been made in the development and testing of models for the evolution of bedforms, including research reported by Tjerry and Fredsoe (2005), Giri and Shimizu (2006, 2007), Niemann et al. (in press) and Shimizu et al. (in press). In the models presented in these papers, the evolution of bedforms is treated by combining detailed computational models for flow and turbulence over bedforms with sediment-transport models in order to predict bedform response. This is precisely the same idea used in river flow and morphodynamics models, but the time and length scales of the bedform models are typically much smaller. This might lead one to think that incorporating bedform dynamics in river reach models is simply a matter of using smaller space and time steps in existing computational models. However, this is not really the case, as most river reach models are still hydrostatic and do not predict flow separation in the streamwise-vertical plane; this is a fundamentally important part of the accurate prediction of bedform form drag. Even for the case of river reach models that are fully three-dimensional, it is currently impractical to reduce time and length scales of computation to those required for bedform modeling. Thus, the method described here uses a bedform model to compute the bedform behavior for selected two-dimensional "slices" of the flow over bedforms in the river, and then uses the computed roughness and form drag as input to the larger scale river reach model.

Bedform Model

The bedform model used for this work was described by Giri and Shimizu (2006) and has been tested against flow, form drag and direct numerical simulation results by Nelson et al. (2005) and against flow and bed morphology data by Giri and Shimizu (2006) and Giri et al. (2007). The flow model is based on the computational solution of the two-dimensional Reynolds-averaged Navier-Stokes equations with a nonlinear k-ε closure; Nelson et al. (2005) compared this method to pressure and velocity data measured over dunes with a laser-Doppler velocimeter and pressure transducers and found the model performed well, predicting the details of velocity structure very well and matching pressure such that computed form drag was within less than 10% of the measured value. Model results were also compared to computational results obtained using a 3-dimensional simulation (LES) and the closure model performed almost as well as the LES with much lower computational cost. The sediment-transport model used is based on the sediment pickup model described by Nakagawa and Tsujimoto (1980) for bedload transport and an advection-diffusion model for suspended sediment. For the suspended-sediment calculation, the lower boundary condition was treated using a flux version of the reference concentration equation given by Smith and McLean (1977); results were also developed using the equation of Itakura and Kishi (1980) but the results were very similar. For further description of the computational technique and the boundary-fitted coordinate system, the reader is referred to Giri and Shimizi (2006). Giri and Shimizu (2007) compared morphologic predictions of the model to flume experiments and empirical results for bedform geometry and found that the model reproduced observation of bedform geometry reasonably well; Shimizu et al. (in press) also showed that the model could produce bedform washout at high flows and could accurately predict rating curve hysteresis. Thus, the model has been verified both for accurate prediction of the measured flow field and also for accurate prediction of bedform morphology for a wide range of flows.

River Model

The river reach model used for the prediction shown below is the Flow and Sediment Transport with Morphologic Evolution of Channels (FaSTMECH) model developed at the United States Geological Survey (USGS) and supported by staff at the USGS Geomorphology and Sediment Transport Laboratory (GSTL). The details of the modeling approach are described in Nelson and McDonald (1997) and Nelson et al. (2003). The model is currently available within a comprehensive user's interface (the USGS Multi-Dimensional Surface Water Modeling System, MD_SWMS) and a detailed manual (McDonald et al, 2006). This model and the interface are open source and in the public domain; the model and user's interface along with tutorials and manual can be downloaded at wwwbrr.cr.usgs.gov/gstl.

The FaSTMECH model is based on a quasi-three-dimensional model for flow in rivers, where quasi-three-dimensional indicates that the model determines flow routing using a two-dimensional (vertically averaged) flow model but solves for primary vertical structure and secondary flows using simplified versions of the three-dimensional momentum equations along with a simple eddy viscosity turbulence closure. This flow solution is combined with a variety of bedload and total load equations to predict sediment transport in rivers. Computed sediment-transport fluxes are used in the so-called Exner equation expressing conservation of sediment volume along with an assumed time step to predict bed evolution. This relatively simple modeling approach has been applied and tested on a wide variety of rivers by USGS researchers and other river scientists around the world.

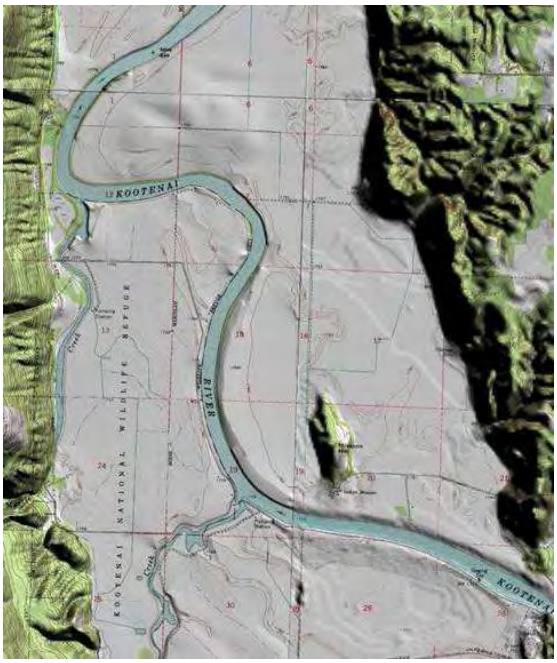
Model Coupling

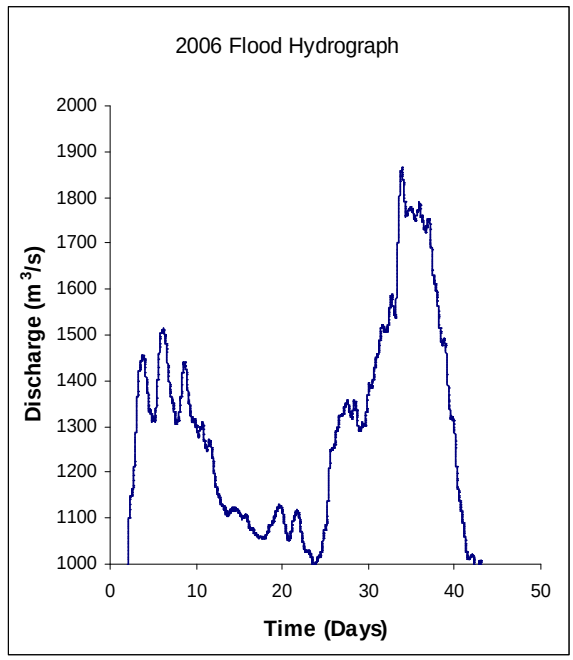
The bedform model is applied either by starting with a flat bed and computing the equilibrium bedform shapes and sizes or by using measured bedform heights and wavelengths. Given the discharge time series, the model predicts the effective roughness of the bed, including both skin friction and form drag, given only the bed grain size and the channel slope. Thus, the model predicts the total drag as well as portioning between form drag and skin friction. Given the total drag and the unit discharge, this allows computation of any of the common roughness parameters; for the case of the FaSTMECH model, this is typically expressed in terms of a drag coefficient relating the depth-averaged flow to the total bed stress. Notably, this drag coefficient will be a function of time if the bedforms are evolving. The computed drag and the form drag correction ratio can then be introduced into the larger-scale river model in order to investigate the effect that the evolving bedforms have on the river model results. This coupling is very simple, and does not require that the models be run in a linked fashion through time. As bedforms may vary spatially, bedform model results may be run for a variety of areas or "slices" of the river to develop a temporally and spatially varying set of drag values. Furthermore, if the variation in drag produces alterations in the routing of the flow, the bedform model results can be recomputed iteratively as necessary. In practice, it appears that only one or two iterations are required for simple channels.

Field Application

In order to test the approach described above, calculations were carried out for a reach of the Kootenai River in Idaho, USA. The reach of interest is meandering with a sand bed and relatively uniform quasi-two-dimensional bedforms. This reach is the subject of an ongoing study to investigate sturgeon habitat and the impacts of Libby Dam upstream in Montana. In 2006, the largest flood since the emplacement of Libby Dam in 1972 occurred. A map of the

study reach and the 2006 flood hydrograph are shown in Figure 1 (a) and (b), respectively, and typical bedforms are shown in both a contour plot and a linear "slice" of the bed in Figure 2 (a) and (b), respectively. Because of existing detailed bathymetric surveys and the lack of bedform observations for this 2006 high flow, this presents an ideal opportunity to test the approach described here against observations of water-surface elevation and bed evolution.





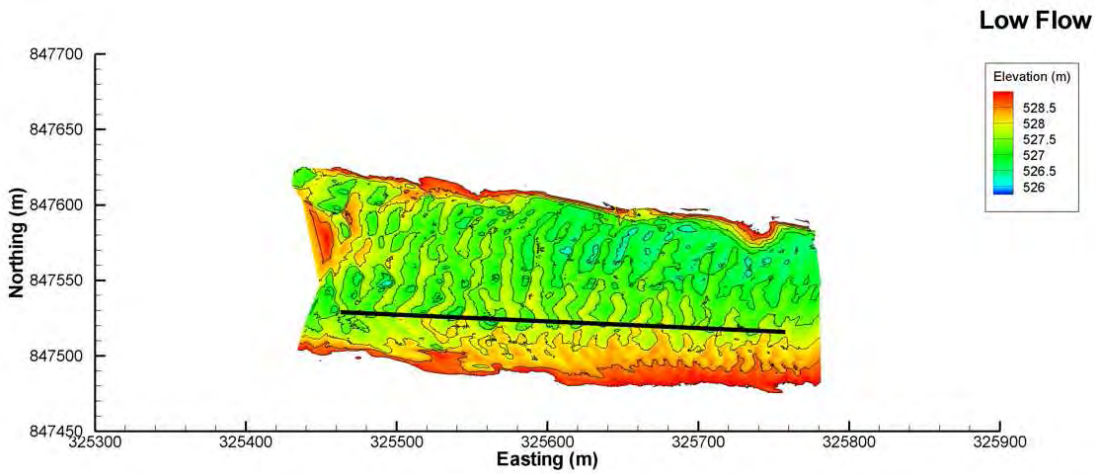
a) b)

Figure 1(a) Map of the Kootenai study reach and (b) 2006 flood hydrograph

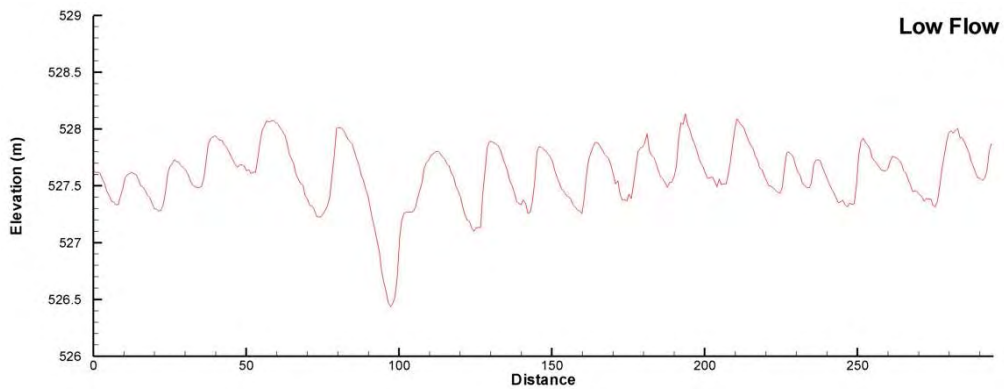
RESULTS AND DISCUSSION

Using the bedform model along with the hydrograph shown in Figure 1(b) and the observed average wavelength and height of the low flow dunes, the roughness of the bed and the evolution of the bedforms over the hydrograph were computed. Various other calculations evaluating roughness at other lower flows were also carried out but are not reported in this short paper. At the initial flood flow of 1000 m^3/s, roughness initially increased, but as flow increased, the suspended sediment concentration increased dramatically and the bedforms began to decrease in height, resulting in decreasing roughness and form drag. At the time of the first peak at 1500 m^3/s, the bed was essentially flat, resulting in very low drag coefficients and no appreciable form drag.

In order to examine the results from using the predicted roughness from the bedform model, FaSTMECH was used to predict flow and bed evolution over the 2006 flood hydrograph using both roughness and form drag values predicted by the bedform model and those determined from roughness calibration at lower flows. Figure 3 shows the water-surface elevations predicted using the two roughness models compared to measurements at 1500 m^3/s. The roughness values predicted by the bedform model result in dramatically better predictions for water-surface elevations, despite the fact that the same (measured) lower boundary condition on stage was used in both model results.



a)



b)

Figure 2 (a) Contour plot of multibeam acoustic data showing bedforms patterns and (b) transect of data along line shown in (a). Data courtesy of Gary Barton, USGS Idaho Water Science Center.

In Figure 4, bed change predictions for the case of the bedform model roughness and form drag are shown for one of the meander bends along with the results using the low-flow calibration. Observations made after the flood indicate maximum scour in pools on the order of 3 meters, which is in good agreement with the bedform model results. Neglecting the dynamic bedform effects overestimates the form drag and results in less scour and fill than is actually observed. Both this and the water-surface elevations demonstrate the potential value of using the bedform model to develop roughness and form drag estimates for larger scale river models. Bedform observations for the highest flows during the flood are not available, so this work awaits further corroboration with more detailed data, but the results strongly suggest that the bedform model is correctly predicting bedform behavior.

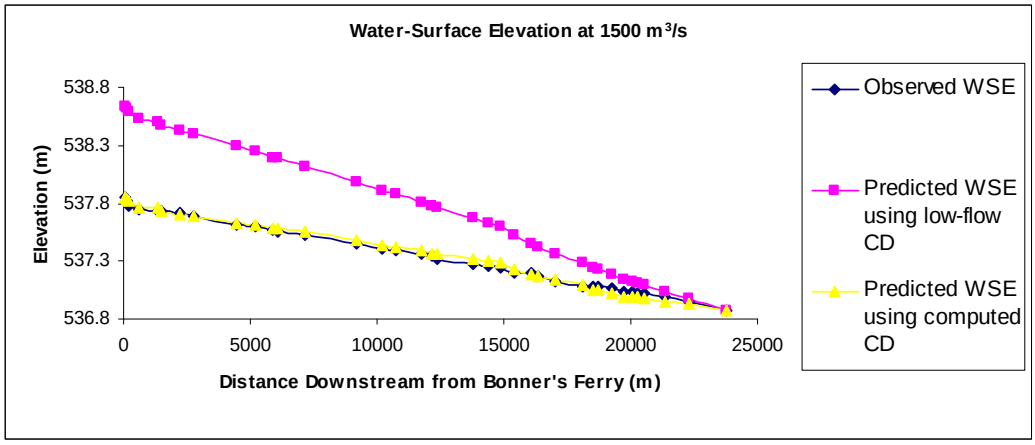
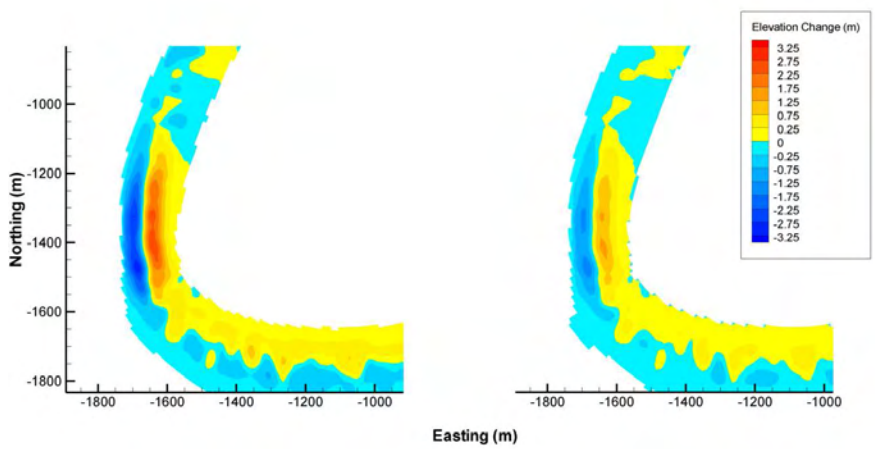


Figure 3. Predicted vs measured water-surface elevation using model and low-flow calibration.



(a) (b)

Figure 4. Morphologic change using roughness and form drag from the (a) bedform model and (b) low-flow calibration.

CONCLUSIONS

Although the methodology briefly described in this short paper is simple, it can potentially decrease uncertainty in the application of computational models for river flow and morphodynamics by reducing errors in roughness and form drag. In some situations, this correction may be relatively small and can be accounted for using simple empirical methods. However, in situations where discharges change rapidly and/or over a wide range, empirical methods are insufficient because they assume flows that are at or close to equilibrium. For those cases, coupling a bedform model that is primarily two-dimensional in the horizontal-vertical plane with a river model that is primarily two-dimensional in plan view can yield good results, as shown here. Although further verification of the bedform model over controlled flows would be desirable (and is currently planned by these authors), the demonstration offered here shows the

potential of this approach. Although continued testing and refinement is required, the method outlined in this short paper represents the foundation of a first-principles approach to predicting roughness and flow patterns for arbitrary hydrographs in sand-bedded channels.

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