Modeling Surface-Water Flow and Sediment Mobility with the Multi-Dimensional Surface-Water Modeling System (MD_SWMS)

The Multi-Dimensional Surface-Water Modeling System (MD_SWMS) is a Graphical User Interface for surface-water flow and sediment-transport models. The capabilities of MD_SWMS for developing models include: importing raw topography and other ancillary data; building the numerical grid and defining initial and boundary conditions; running simulations; visualizing results; and comparing results with measured data.

Surface-Water Model

- FaSTMECH - 2D vertical average and quasi-3D general steady-state flow.

Applications:

- Flood reconstruction.
- Habitat analysis.
- Instream-flow requirements.
- Bridge-pier analysis.
- Sediment mobility.

Capabilities:

- Import, view, and edit ancillary scatter data sets.
- Interactively build data sets for the computational grid, material properties, and boundary conditions.
- Specify model parameters and run the model.
- Visualize model results.
- Compare model results to measurements.

Requirements:

- Topography suitable for multi-dimensional models.
- Single thread channel at the upstream boundary.
- Measured water-surface elevations for model calibration.
- Measured velocity for model verification.
- Downstream stage and discharge for flows of interest.

MD_SWMS Version 1

The U.S. Geological Survey's (USGS) Multi-Dimensional Surface-Water Modeling System (MD_SWMS) is a pre- and post-processing application for computational models of surface-water hydraulics. The system is both a tool and framework that provides an easy to use interface to a variety of environmental hydraulic models.

The tool is a Graphical User Interface (GUI) (McDonald and others, 2005) that allows the modeler to build and edit data sets of the modeling system's computational surface-water models. The framework links the GUI tool with the modeling applications. New applications can be adapted to the framework through modification of the input and output software routines. In this way, MD_SWMS is flexible and generic, easily incorporating new models and avoiding the necessity of writing a new GUI for each modeling application.

The GUI tool is a sophisticated 1, 2, and 3-dimensional interactive GUI (fig. 1) that is used to build and visualize all aspects of computational surface-water applications. Surface-water modeling is a process whereby the modeler builds the grid, applies boundary conditions, runs the simulation, and evaluates the results. The MD_SWMS GUI tool facilitates this process by providing an easy way to apply this process iteratively until a useful result has been obtained.

The Computational Fluid Dynamics General Notation System (CGNS) is used to provide the framework for incorporating surface-water models into MD_SWMS. CGNS is a database developed to assist the exchange of data between aerodynamic Computational Fluid Dynamic (CFD) applications and it consists of two parts: (1) a standard format for recording the data, and (2) a software interface that reads, writes, and modifies data in that format (Legensky and others, 2002; http://www.cgns.org). CGNS provides a bridge between MD_SWMS and its environmental surface-water applications in the following ways:

- All data designed in the MD_SWMS GUI tool is written to a CGNS database including descriptions of the computational grid, boundary conditions, initial conditions, and application specific parameters.
- Modeling applications in MD_SWMS read from the CGNS database to initialize and run the model after which the model solution is appended to the database.
- The model solution is then read by MD_SWMS for visualization, analysis, and verification.

The CGNS framework is used to separate the GUI from the computational models, which allows MD_SWMS to be a single tool that can be used with many applications.

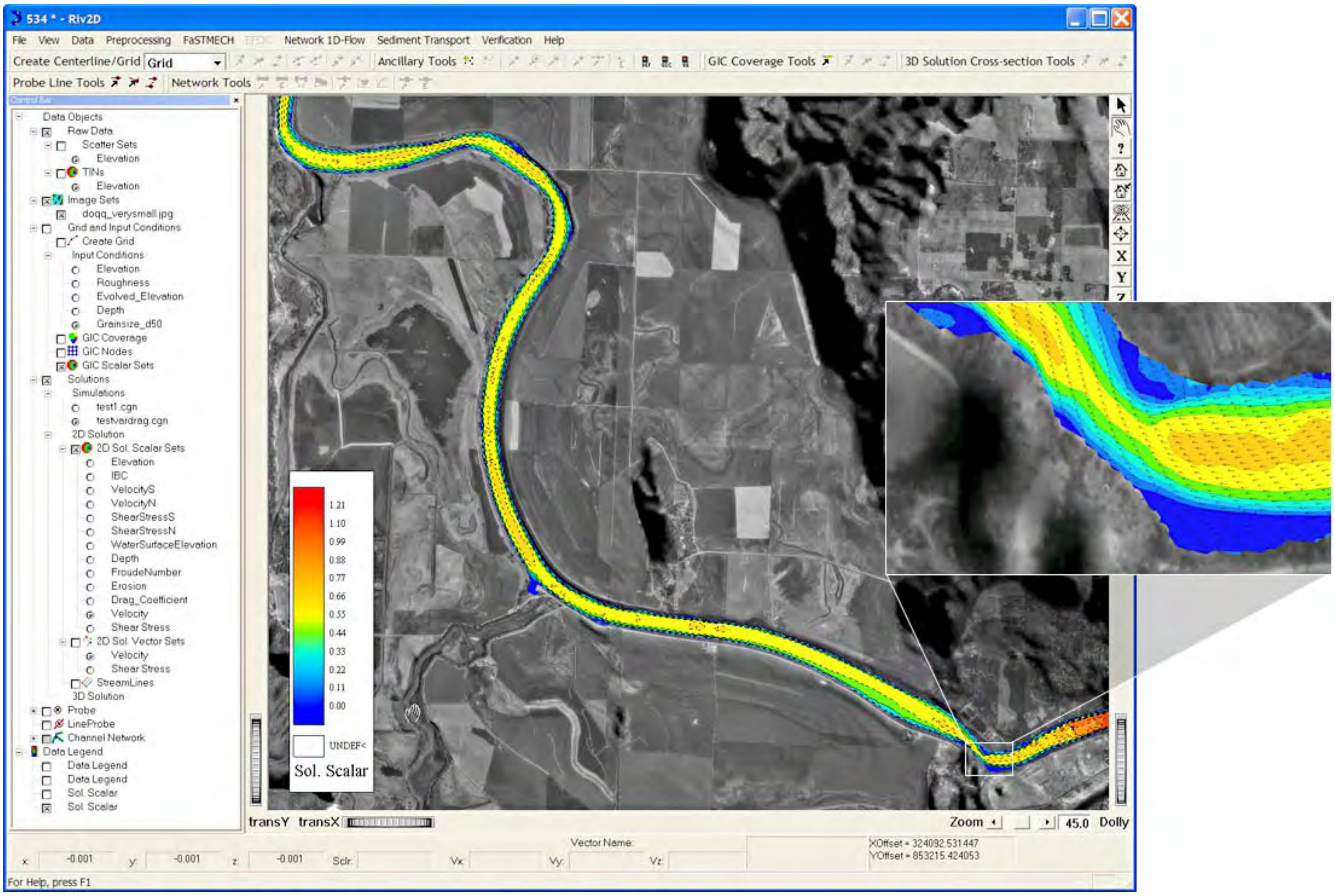


Figure 1. The MD_SWMS GUI tool shown with an application of the Kootenai River, Idaho. The GUI features menus, toolbars, treeview of data objects loaded into the project, graphics view with tools for zooming and panning, status bar and probe bar for dynamic feedback of data values. The main panel of the application shows a portion of a 10-kilometer reach of the Kootenai River with a model prediction of velocity overlain on a georeferenced digital orthoquad. A detail (inset) of the solution shows the complicated flow pattern in a sharp bend of the river. Velocity magnitude is shown by color and velocity vectors are shown in black.

Multi-Dimensional Surface-Water Modeling

Multi-dimensional models are used where spatially distributed values of velocity, depth, water-surface elevation, or bed-shear stress are required. Applications include flood-flow predictions, flood reconstruction, in-stream flow requirements, habitat analysis, and sediment transport.

A series of technological advancements have made the use of multi-dimensional surface-water models more efficient in terms of time and ultimately cost. These advancements include modern computing, new channel mapping methods using survey grade global positioning systems (GPS), and velocity mapping using acoustic Doppler current profiler (ADCP) linked with GPS. The majority of effort in using multi-dimensional models is in the collection of field data, especially bathymetry at suitable scales; that is, scales corresponding to scales of the desired results. Field surveys of water-surface elevations and velocity are used for model calibration and validation. These data are now efficiently collected using roving or boat-mounted systems.

MD_SWMS Applications

Version 1 contains a single steady-state model of flow, FaSTMECH, developed at the USGS (Nelson and others, 2003). Future plans and additions are discussed later in the text. Here we present a variety of applications that have been modeled using FaSTMECH within MD_SWMS.

Flow Modeling

Basic output from a hydraulic model such as water-surface elevation, depth, and velocity magnitude and direction can be used by engineers in the design and location of bridge piers. MD_SWMS was used to model the 100-year recurrence interval flood on the Tanana River in Alaska to aid in the relocation and realignment of the Alaska Highway Bridge over the Tanana River, near Tok, Alaska.

Bridge designs are required to accommodate 100-year recurrence interval and to withstand the associated streambed scour around bridge piers. An initial step in the design is selecting a location that will have low susceptibility to general scour over a range of hydraulic conditions. If properly designed, the location, dimensions, and alignment of bridge piers can reduce the potential for local streambed scour at the piers. An extensive bathymetric data set and a properly calibrated hydrodynamic model are needed to design a sound structure.

Detailed topography, water-surface elevations, and velocity were collected in a 1.5-kilometer reach of the Tanana River that spanned the existing bridge and a potential downstream location for the new bridge. The model was first calibrated to a measured flow discharge of 725 m^3/s (cubic meters per second), by adjusting the roughness or flow resistance in the model so that the simulated and measured water-surface elevations matched. The observed spatial pattern of velocity magnitude and direction with the simulated values were compared (fig. 2).

A model of the 100-year recurrence interval discharge of 1,452 m^3/s (fig. 3*A*) was then calculated by using the calibrated parameters and a starting water-surface elevation calculated with a one-dimensional model. Simulated flow angle of attacks, on the existing bridge piers, which are used to calculate the susceptibility to bridge pier scour, increased from 38 to 45 degrees on the left bank pier and from 45 to 55 degrees on the right-bank pier. A second hypothetical simulation (fig. 3*B*) of this discharge was run with the existing piers removed from the channel. Flow directions from this scenario can be used to determine channel flow angle of attack on piers for the replacement bridge. Simulated velocity magnitude and direction,

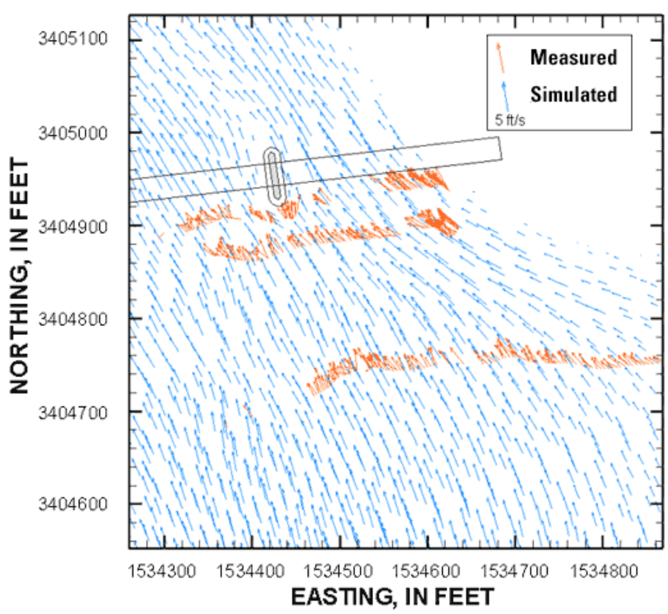
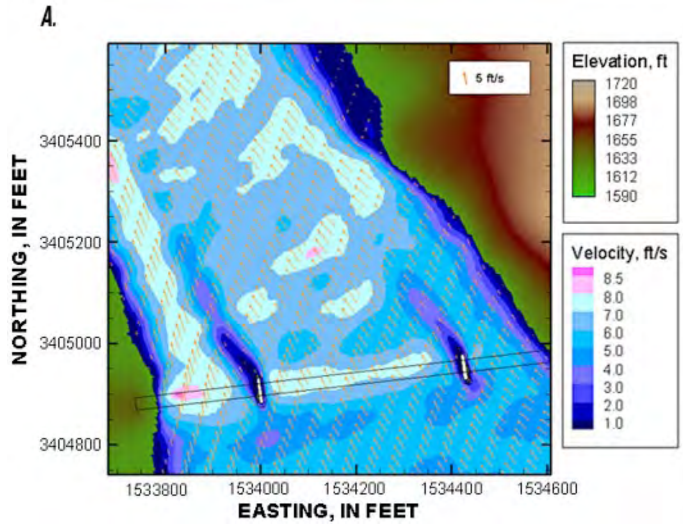


Figure 2. Comparison of simulated and measured velocities for the 780 m^3/s calibration flow. The velocity was measured along traverses by using an ADCP; three seperate traverses across the river are shown. Measured velocities represent the velocity at a point in space and time compared to simulated velocities, which represent an average. Therefore, the measured velocities are expected to have more variability than the simulated velocities.



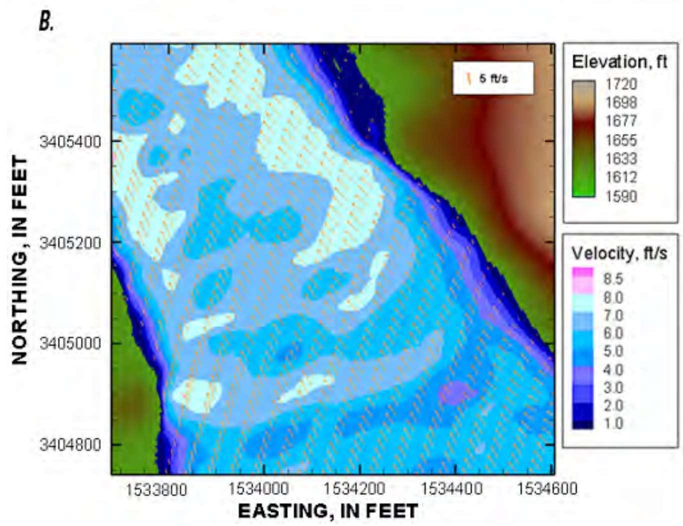


Figure 3. Velocity vectors and contours of velocity for the simulation of the 100-year recurrence interval discharge with (A) the existing bridge piers and with (B) the existing piers removed.

water-surface elevations, and flow angles of attack from these simulations will aid engineers in the design of a new bridge in the event that the existing bridge is removed from the channel. Conaway and Moran (2004) provide a more detailed description of this project.

Sediment-Mobility Modeling

Sediment mobility can be used to establish the flow necessary to maintain the geomorphic characteristics of a channel (Nelson, 1996). The Deer Flats Wildlife Refuge on the Snake River, Idaho, consists of many islands that provide diverse riparian habitat for nesting birds. Channel islands usually are separated from the banks of the river by a relatively swift main channel and a slower secondary channel. Sedimentation in the secondary channels can result in attachment of the island to the bank. Removing sediment from the secondary channels is necessary to maintain the island and nesting habitat.

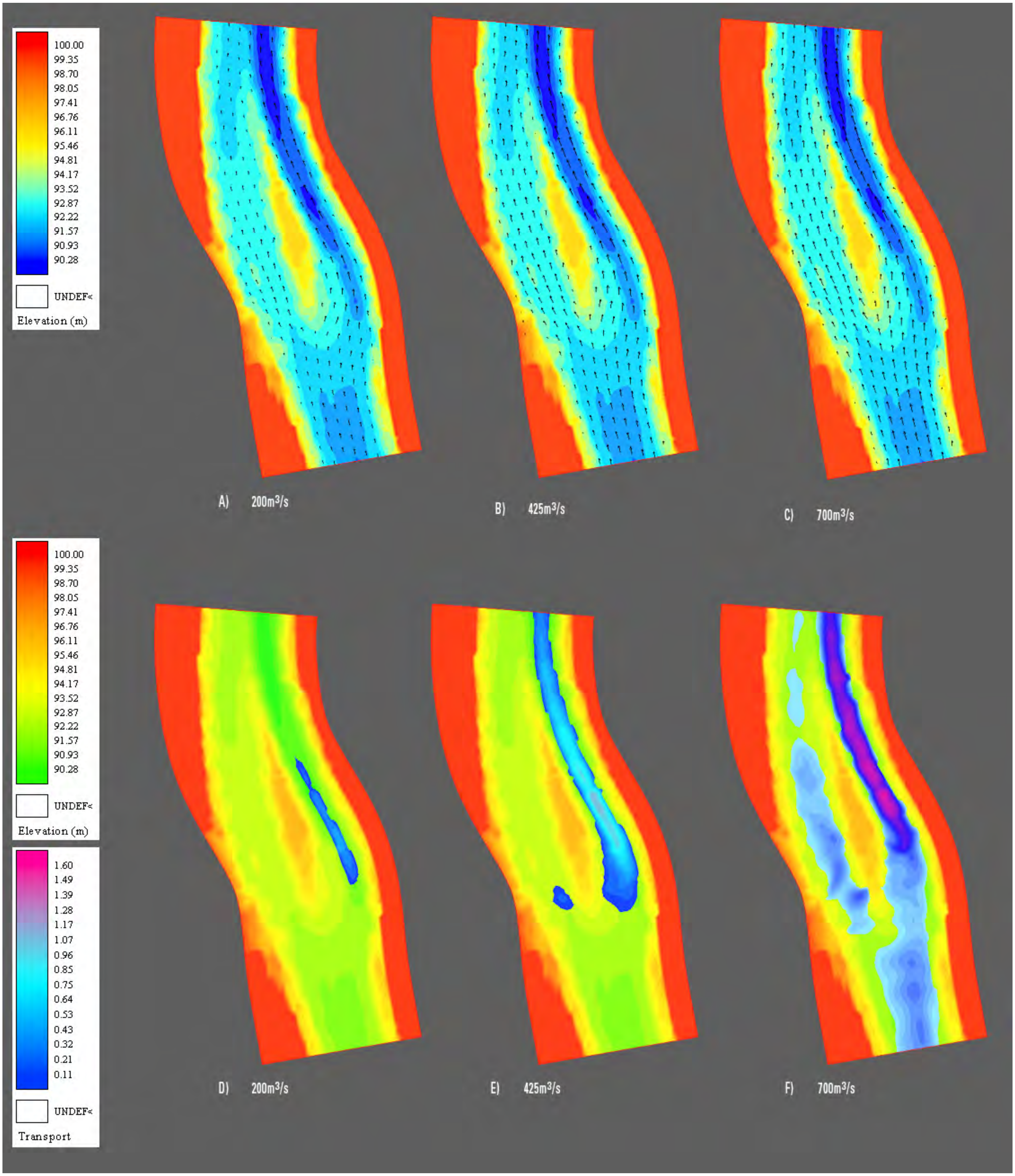


Figure 4. Model solutions for the Snake River sediment-mobility model. The topography and velocity vectors for three discharges of (a) 200, (b) 425, and (c) 700 m^3/s show the increasing magnitude and inundation of the island in the center of the channel. In general, the flow rate in the back-bar channel to the left of the island is slower than the main channel. The transport strength for each of the three discharges is shown in d-f respectively. At increasing discharge, flow rates are sufficient to mobilize coarse sediments in a larger area of the backbar channel. The highest discharge (700 m^3/s) is necessary to remove coarse sediments and maintain flow in the backbar channel.

To simulate flows needed to maintain the secondary channels, a two-dimensional model is required that can resolve the flow routing around an island and the spatial distribution of bottom shear stress. For preservation of channel islands, the variations of flow and shear stress with discharge are crucial. The modeled channel consists of a main channel along the river right side of the island and a shallow low-velocity secondary channel. Bottom shear stress and hence sediment transport capacity of the secondary channel generally is much lower than the main channel. Figure 4*A-C* shows the topography and velocity vectors for three discharges—200, 425, and 700 m^3/s. During periods of relatively low discharge, fine sediment accumulates in this channel. Over time, in the absence of higher flows, this channel may become completely blocked with sediment.

To identify the flow that can prevent long-term aggradation in the secondary channel requires, knowledge of the bed material within the reach is required. The bed material in this example reach is composed primarily of coarse gravel that is rarely mobile, even at relatively high discharge. However, fine sediments are supplied by tributaries and bank failure, and these fine sediments are deposited in the interstices of the gravel in regions of low flow. The principal condition for maintaining the secondary channel is removal of the fine material. In the presence of mixed grain sizes, this requires flows that are at a minimum, capable of moving the coarser material at very low transport rates.

For the Snake River example, the low-velocity channel contains gravel approximately 2 centimeters in size. The initiation of motion for this size is expected to occur at a bottom shear stress of 10 newtons per meter squared. Using this value, it is possible to compute the transport rate, defined as the simulated bottom shear stress normalized by the critical shear stress minus unity. When the bottom shear stress equals the critical shear stress, the transport rate is zero and when the bottom shear stress is twice the critical value the transport rate is one. Results for the transport strength are shown in figure 4 for the same series of discharge used to show the flow velocity. For the 200 m^3/s discharge, the coarse material moves in the main channel only. At 425 m^3/s movement is very limited in the secondary channel, and by 700 m^3/s, coarse material moves throughout the secondary channel. Thus, by using the computational flow solution, it is possible to conclude that flows of approximately 700 m^3/s are required to produce gravel movement and maintain the secondary channel free of sediment.

Habitat Modeling

Each spring more than 0.5 million sandhill cranes and a few endangered whooping cranes use the Central Platte River Valley, Nebraska, as critical staging habitat during their northern migration. During their spring visit, most cranes roost in the central Platte River, standing on submerged sandbars from dusk until dawn each night. Over the last century, upstream water-resource development has affected the delivery of water and sediment to the central Platte River, removing high flows and decreasing the supply of fine sediment. These changes have resulted in channel incision and vegetation encroachment along the riparian corridor, both of which tend to stabilize sand bars and banks; the once wide and shallow channels of the Platte River have narrowed and deepened, and their beds have become significantly coarser (Kinzel and others, 1999). The changes in river morphology in part are believed to have altered the nocturnal roosting habitat used by cranes.

To gain an understanding of how the changing river morphology affects the roosting habitat, MD_SWMS was used to simulate crane habitat at the Rowe Sanctuary on the Platte River. Roosting sites were surveyed by using infrared video, and the channel morphology and hydraulics (depth and velocity) were compared to MD_SWMS simulations (fig. 5*A, B*). The crane roost maps defined from the infrared video were overlain on the flow modeling results to identify the ranges in depth and velocity preferred by roosting cranes (fig. 6). Cranes generally prefer to roost in water depths less than 0.40 meter with velocities less than 0.70 meter per second. The habitat value was then computed by applying the depth and velocity preferences over a range of simulated streamflows (fig.7).

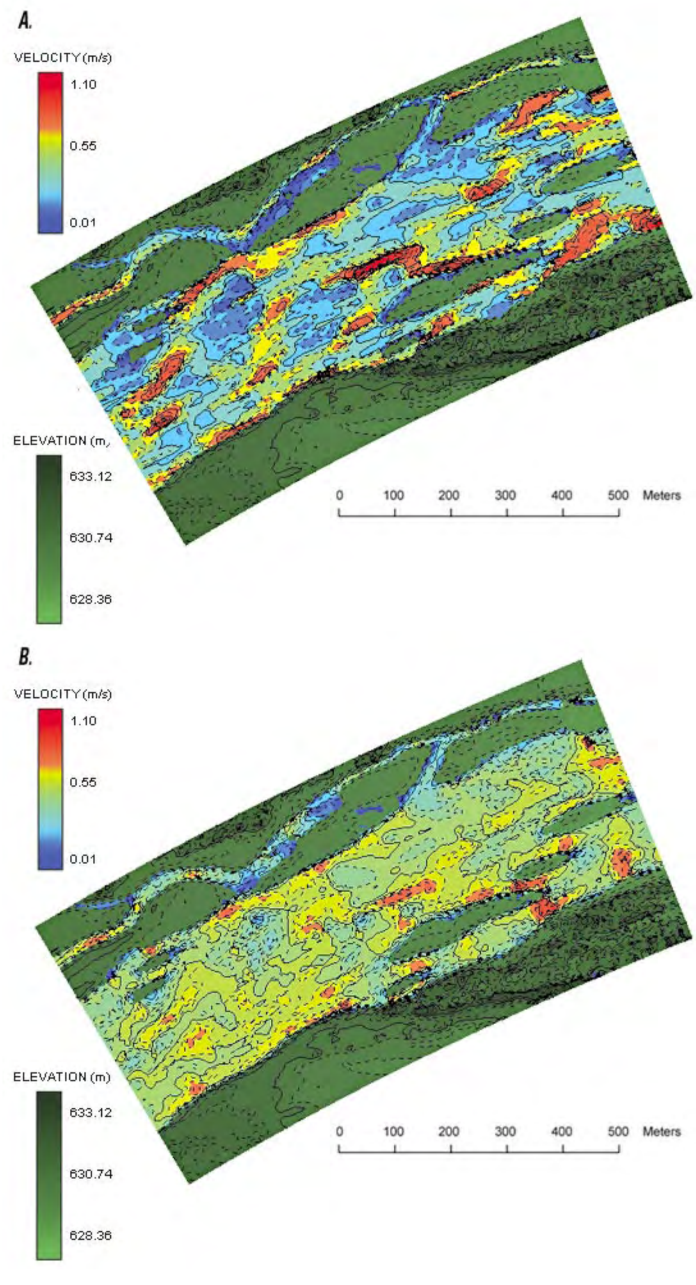


Figure 5. Output of multi-dimensional hydraulic model showing the (a) depth distribution and (b) velocity magnitude along the Rowe Sanctuary study reach for a streamflow of 37 m^3/s.

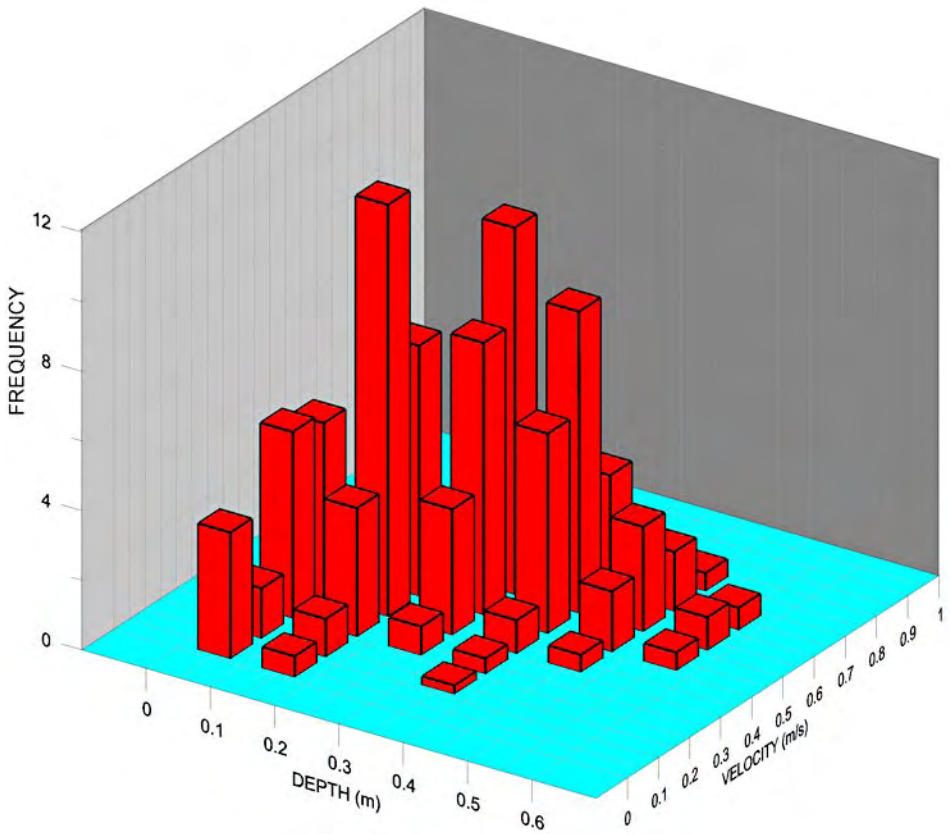


Figure 6. Histogram showing ranges of depths and velocities used by roosting cranes in the Rowe Sanctuary study reach.

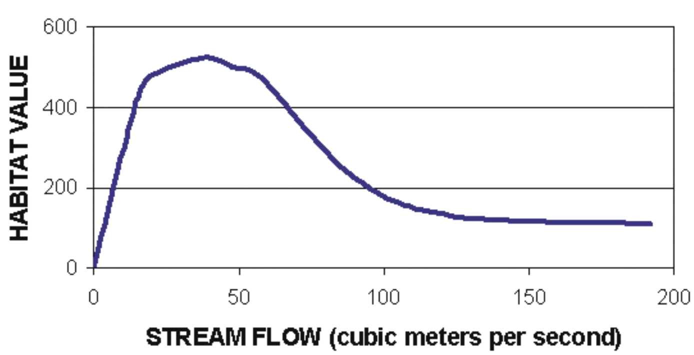


Figure 7. Habitat value over a range of stream discharge at the Rowe Sanctuary study reach.

Figure 6 indicates that, based on the observed habitat preferences, the greatest quantity of available roosting habitat occurs at the Rowe Sanctuary when the streamflow in this channel is about 37 m^3/ s. It is important to realize that these model results were computed by assuming the riverbed is fixed and immobile. In actuality at high streamflows, sand could be deposited on the submerged sandbars and increase their elevation, which may increase the quantity of available habitat. Investigating these effects would require modifying the model to incorporate sediment transport and verifying what influence this may have on the sandbars. For more information on this project, see Kinzel and others (2005).

Future Additions

Work on the FaSTMECH model is ongoing and includes the addition of time-stepping through variable discharge using the steady-state approximation and sediment-transport and channel-evolution modules. System for Transport and River Modeling (STORM), a general coordinate system two-dimensional unsteady flow model is currently (2005) in development (Simões and McDonald, 2004) and is planned to be included in the MD_SWMS system.

Availability

MD_SWMS is available from the web at http://wwwbrr.cr.usgs.gov/projects/SW_Math_mod/OpModels/MD_SWMS/index.htm

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References Cited

Conaway, J.S., and Moran, E.H., 2004, Development and calibration of two-dimensional hydrodynamic model of the Tanana River near Tok, Alaska: U.S. Geological Survey Open-File Report 2004-1225, 22 p.

Kinzel, P.J., Nelson, J.M., Parker, R.S., Bennett, J.P., and Topping, D.J., 1999, Grain-size evolution of the Platte River, 1931-1998, *in* Proceedings of the 10th Platte River Basin Ecosystem Symposium, February 23-24, 1999, Kearney, Nebraska, p. 9-14.

Kinzel, P.J., Nelson, J.M., and Parker, R.S., 2005, Assessing sandhill crane roosting habitat along the Platte River, Nebraska: U.S. Geological Survey Fact Sheet 2005-3029, 2 p.

Legensky, S.M., Edwards, D.E., Bush, R.H., Poirier, D.M.A., Rumsey, C.L., Cosner, R.R., and Towne, C.E., 2002, CFD General Notation System (CGNS)—Status and future directions: American Institute of Aeronautics and Astronautics Paper 2002-0752.

McDonald, R.R., Nelson, J.M., and Bennett, J.P., 2005, Multi-dimensional surface-water modeling system user's guide: U.S. Geological Survey Techniques and Methods, 6-B2, 136 p.

Nelson, J.M., 1996, Predictive techniques for river channel maintenance: Water, Soil, and Air Pollution, v. 90, p. 321-333.

Nelson, J.M., Bennett, J.P., and Wiele, S.M., 2003, Flow and sediment-transport modeling—Tools in fluvial geomorphology: England, Wiley, p. 539-576.

Simões, F.J., and McDonald, R.R., 2004, A modeling system for 2D flow in surface waters, *in* Advances in Hydro-Science and Engineering VI, ed. by M.A. Altinakar and others: Proceedings of the 6th International Conference on Hydroscience and Engineering, Brisbane, Australia, May 31-June 3, 2004.