Chapter 3.—Advanced Tools for River Science: EAARL and MD_SWMS

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Abstract

Disruption of flow regimes and sediment supplies, induced by anthropogenic or climatic factors, can produce dramatic alterations in river form, vegetation patterns, and associated habitat conditions. To improve habitat in these fluvial systems, resource managers may choose from a variety of treatments including flow and/or sediment prescriptions, vegetation management, or engineered approaches. Monitoring protocols developed to assess the morphologic response of these treatments require techniques that can measure topographic changes above and below the water surface efficiently, accurately, and in a standardized, cost-effective manner. Similarly, modeling of flow, sediment transport, habitat, and channel evolution requires characterization of river morphology for model input and verification. Recent developments by the U.S. Geological Survey with regard to both remotely sensed methods (the Experimental Advanced Airborne Research LiDAR; EAARL) and computational modeling software (the Multi-Dimensional Surface-Water Modeling System; MD_SWMS) have produced advanced tools for spatially explicit monitoring and modeling in aquatic environments. In this paper, we present a pilot study conducted along the Platte River, Nebraska, that demonstrates the combined use of these river science tools.

Introduction

In many western rivers in the United States, changes in flow and sediment regime caused by water-resource development, landscape modification, or climatic factors have altered in-channel and riparian habitat conditions. As a consequence, recovery programs in these river basins for species with endangered or threatened designations have adopted adaptive management (Holling, 1978) as a strategy toward habitat enhancement and species recovery. To function effectively and iteratively, adaptive management in aquatic environments requires monitoring programs that include geomorphic, hydrologic, and biological components. Ground surveys have traditionally been used to collect these monitoring data at sampling points, often using statistical methods to determine the locations, spacing, or frequency of these measurements. Although discrete sampling has utility and practicality, it does not completely represent the aquatic ecosystem that is continuous with spatial gradients in habitat quality and quantity. These gradients are determined by a variety of physical and biological factors and include the degree of connectivity/isolation brought about by the presence of disturbance and topological features in the landscape.

Spatial monitoring in the form of remote sensing has been seen as an innovative alternative to conventional monitoring approaches (Walters, 1997). Remote sensing commonly is used to delineate landscape features for river studies, with aerial photography being the most ubiquitous acquisition. In addition to feature data, high-resolution and high-quality three-dimensional topographic datasets are being increasingly sought by river scientists seeking to understand and model the complex relationships between ecological processes, channel form, flow, and sediment supply. Desire for this level of topological characterization in rivers and the difficulties associated with using discrete conventional survey methods have motivated researchers to investigate photogrammetric, passive optical, and active remote-sensing techniques. Examples of these methods include those of Hicks et al. (2001) (airborne laser scanning, photogrammetry, and passive optical) and Westaway et al. (2003) (photogrammetry and passive optical). Despite these efforts, simultaneous and integrated measurement of both terrestrial and submerged topography, channel topography, in rivers using a single remote sensor and technique has been a challenging goal.

Airborne laser scanning or Light Detection and Ranging (LiDAR) technology has become readily available for detailed terrestrial surveys of large areas. However, the use of LiDAR in rivers typically has been confined to overbank areas (Bowen and Waltermire, 2002), because the near-infrared wavelength commonly used in these lasers is strongly absorbed and attenuated in water. Within the last decade, large-footprint, high-powered bathymetric LiDARs developed for coastal applications have been used in rivers (Tiffan et al., 2002; Hilldale and Raff, 2008). The tradeoff between laser power and eye safety in these LiDARs results in sampling footprints on the order of meters, a design suitable for surveying coastal areas but less optimal for narrow river channels.

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Experimental Advanced Airborne Research LiDAR

Recently, the National Aeronautics and Space Administration (NASA) developed the Experimental Advanced Airborne Research LiDAR (EAARL) sensor (Wright and Brock, 2002). The instrument initially was designed for surveying coral reefs in relatively clear water. The relatively low-power, small-footprint laser (about 20 cm), which operates in the blue-green spectral region with a short (about 1 nanosecond) pulse width at a high sampling rate with temporal waveform capture, has demonstrated considerable promise for simultaneous acquisition of in-channel and adjacent floodplain topography (Kinzel et al., 2006; McKean et al., 2008). The system is operated from a Cessna 310 platform at a nominal altitude of 300 m and uses a kinematic global positioning system (GPS) and an inertial measurement unit to geolocate each laser spot. The EAARL instrument suite also has two cameras to facilitate the interpretation of the digital topographic data. Digital images acquired with a high resolution (about 20 cm per pixel at 300-m flying height) color infrared (CIR) camera are co-registered with the laser-derived topographic data. It also has a lower resolution red, green, and blue (RGB) camera (about 80 cm per pixel), which is tightly coupled to a digital image player within its processing software, Airborne Lidar Processing System (ALPS), allowing instant access to any photograph by clicking on an image of the flight track (fig. 1). ALPS is an open-source software written in the Yorick and TCL/TK programming languages and runs on a Linux operating system (Nayegandhi et al., 2006). Processing algorithms in ALPS are used to detect peaks and inflections in the time history of the backscattered laser intensity (waveforms). The algorithms enable measurement of the range of the aircraft to the first-surface encountered, the bare-earth surface, and surfaces below the water. These data can be exported from ALPS for use in mapping, statistical, or modeling software.

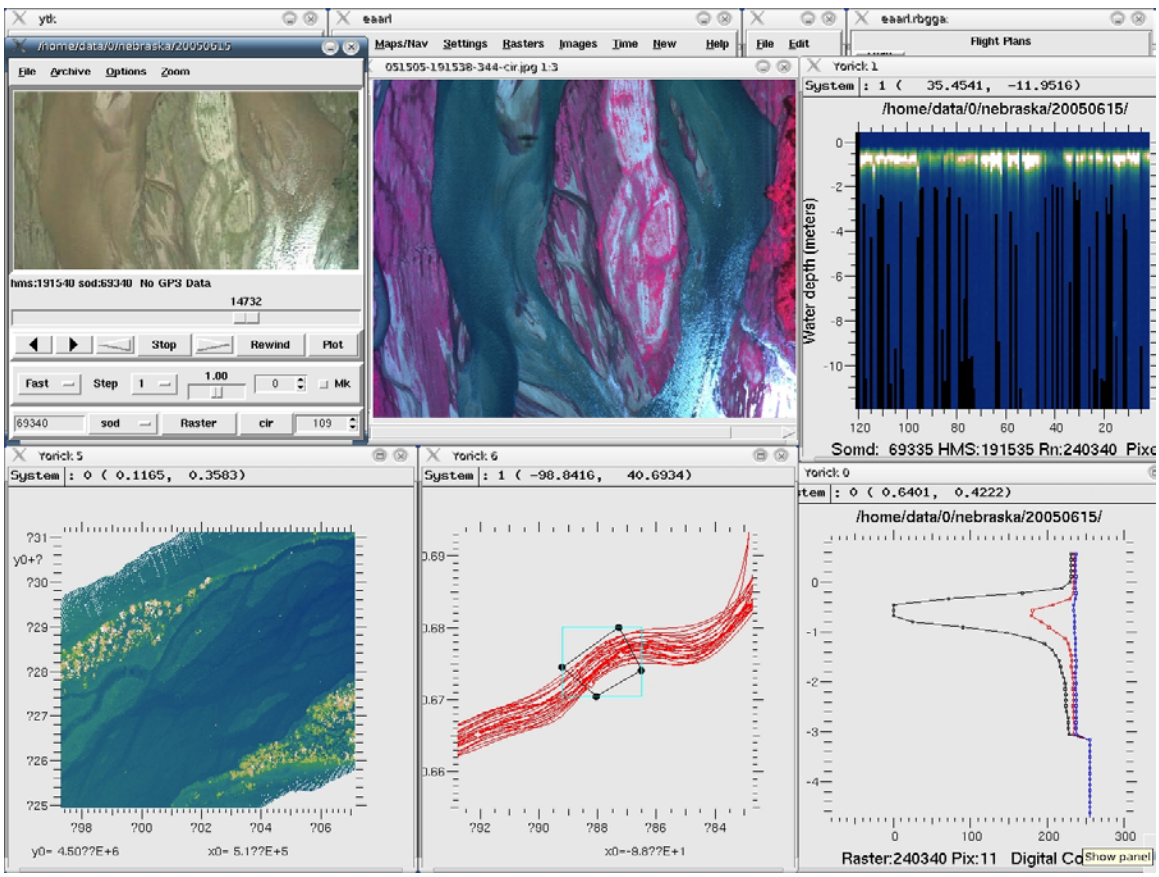


Figure 1. Screen capture of the ALPS software. Clockwise from upper left: RGB imagery, color-infrared imagery, laser raster, waveforms, flight line map, and first-surface elevation map.

Multi-Dimensional Surface-Water Modeling System

Over the last 10 years, the U.S. Geological Survey (USGS) has developed the Multi-Dimensional Surface-Water Modeling System, MD_SWMS, a graphical user interface for computational models of surface-water hydraulics and sediment transport in rivers (McDonald et al., 2001; McDonald et al., 2005). MD_SWMS runs on a PC operating system, is available at no cost to the user, and can be downloaded from: http://wwwbrr.cr.usgs.gov/gstl/2D-Download.php. The MD_SWMS software provides a framework for distributing surface-water models, developed by the USGS's National Research Program and other researchers, to scientists within the USGS, other government agencies, and the private sector. MD_SWMS is not a model but a software tool allowing users to interact with input data (channel topography) and generate numerical grids used by the surface-water models that are executed within it. Additionally MD_SWMS gives the user the means to visualize the output from the models and compare model predictions to verification data (water-surface elevations, velocities, and aerial images). In its preprocessing tools, MD_SWMS has the capability to filter raw input topography, useful for large LiDAR data sets, and the ability to delete data points, add data points, or interpolate between them.

Currently (2009), two hydraulic models can be run from MD_SWMS. Flow and Sediment Transport with Morphologic Evolution of CHannels (FaSTMECH) (Nelson et al., 2003) is a depth-averaged, quasi-three-dimensional flow model using a structured, curvilinear orthogonal coordinate system. A sediment-transport module in FaSTMECH allows users to examine sediment mobility in the channel for different grain sizes. The flow and sediment-transport routines can be used together in an iterative manner to predict spatial patterns of erosion and deposition (channel evolution). System for Transport and River Modeling (SToRM) is a two-dimensional flow model that uses an unstructured grid composed of irregular-triangular elements (Simões and McDonald, 2004).

Projects that have used MD_SWMS include: modeling hydraulics near bridges in cooperation with the Alaska Department of Transportation (Conaway and Moran, 2004), analysis of hazards due to radioactive mine tailings along the floodplain of the Colorado River in cooperation with the Utah Department of Environmental Quality (Kenney, 2005), and restoration of endangered white sturgeon habitat in the Kootenai River in cooperation with the Kootenai Tribe of Idaho (Barton et al., 2005). Each of these studies used MD_SWMS to answer a complex and spatially explicit problem. A critical component in each of these investigations was the detailed measurement of channel topography. The rivers in these investigations were of sufficient depth that conventional boat measurements with acoustic technology (echo sounding) could be used in submerged areas and combined with terrestrial topography to create maps of river channel topography used for hydraulic modeling.

Pilot Study – Platte River, Nebraska

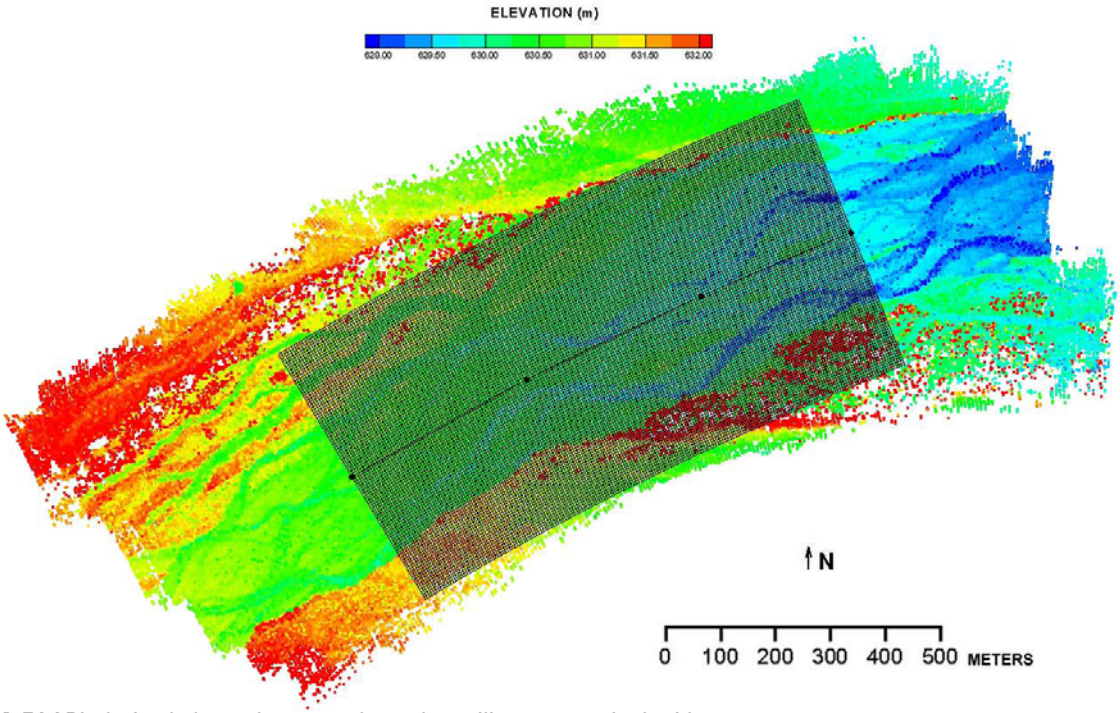
The Platte River in central Nebraska is a shallow, braided river channel. In 2006, a recovery program was signed by the States of Colorado, Nebraska, and Wyoming, and the U.S. Department of Interior to improve habitat for the four endangered and threatened species in the Platte River basin (Governance Committee, 2006). Over the first increment of the Platte River Recovery Implementation Program (13 years), monitoring will be conducted to evaluate program actions (flow and habitat enhancements) and guide the adaptive management process. The collection of topographic data will be an important component of monitoring for the recovery effort. Conventional ground surveys with total stations or real-time kinematic global positioning systems (RTK-GPS) have been used to collect elevations along channel cross sections in the Platte. However, the application of these technologies to collect topographic information over long reaches is neither practical nor efficient. Similarly, acoustic techniques used in the above-mentioned examples are not feasible because of the shallow depths. These difficulties prompted the USGS in 2001 to research the state of the art with regard to remote-sensing techniques. This research resulted in a formal proposal and eventual support from the USGS Venture Capital Fund to conduct field tests of the EAARL in a shallow river.

In 2002 and 2005, the EAARL was flown over the Platte River to evaluate the vertical accuracy of the system. Topographic measurements made on the ground with RTK-GPS equipment were compared with nearby topographic points collected with the EAARL sensor (Kinzel et al., 2007). In 2005, the vertical accuracy of topography collected with the EAARL system using a first-surface algorithm was determined to be ±18 cm in subaerial areas and ±24 cm for measurements in submerged areas. A bathymetric processing algorithm in ALPS was found to improve the ranging accuracy to the river bottom in submerged areas where convolved backscatter from the water column and bottom was encountered. However, EAARL measurements made in submerged areas were less precise than those made in areas above the water surface. Further, in deep (about >50 cm) and turbid areas, it was difficult to distinguish a weak bottom return, if present at all, from the stronger water-column backscatter.

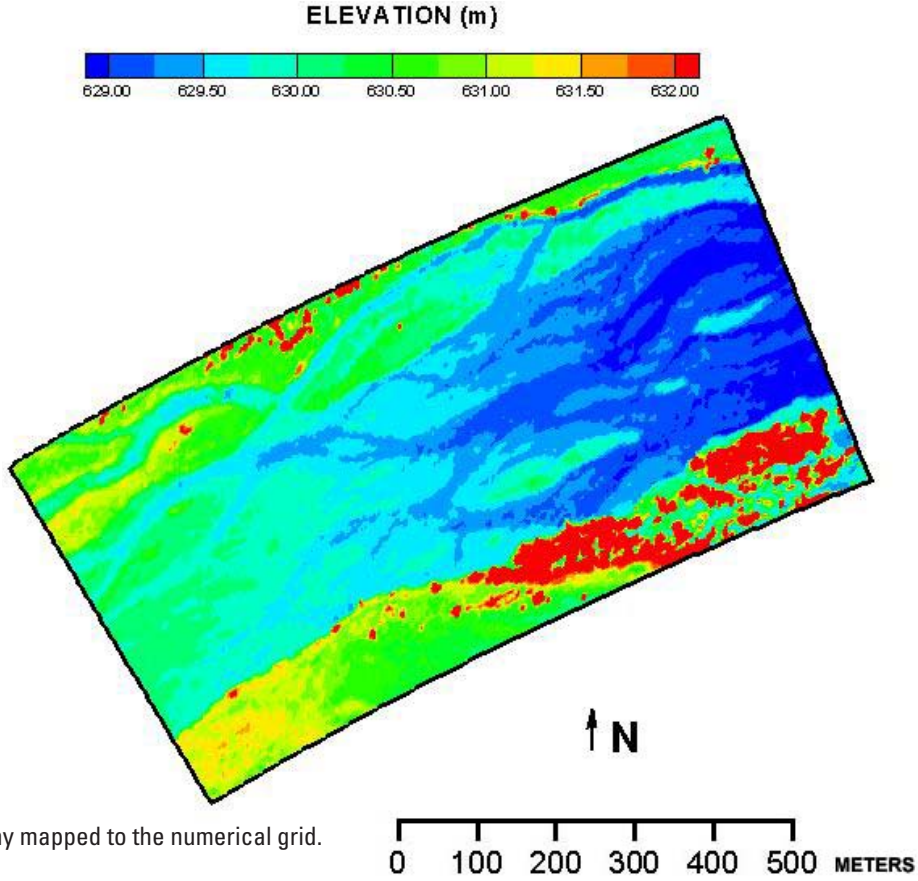
The application of the EAARL data in a hydraulic modeling context was explored by using the MD_SWMS interface and the FaSTMECH model to compute a flow solution through the EAARL channel topography collected in 2005 (fig. 2). Although a LiDAR-derived topographic data point is less precise than a point obtained from a ground survey, LiDAR point densities (number of points per square meter) have the advantage of being much greater than point densities that could be gathered from a ground survey. To avoid introducing bias in hydraulic model computations made from LiDAR-derived channel topography, the vertical errors in the LiDAR data need to be normally distributed about zero. This condition was met to a greater degree above the water surface than below it with the Platte River EAARL data. It should be noted that the process of creating a structured hydraulic modeling grid is itself an abstraction of the raw survey data. In models using structured grids, the raw topography is mapped to a regularly spaced series of grid nodes. The FaSTMECH model can determine the topographic elevation of each node by locating a point or points within a specified search radius of the node. If one point is located in the search radius, the node is given that elevation value. If more than one point is located, the node is assigned an elevation value that is the inverse distance weighted average of those points. If no point is located, the search radius is expanded until a point or points are found. It follows that if the search template is large relative to the density of the LiDAR data it could be equally likely for the elevation of a node to be mapped higher or lower than its true elevation, assuming the errors are randomly distributed through the reach.

The procedure for running a hydraulic model in MD_SWMS is relatively straightforward. The first step is to import the raw survey data and define a numerical grid. In figure 2*A*, a curvilinear numerical grid is overlain on the EAARL data. The grid was generated by digitizing the centerline of the channel and specifying the width of the grid across the centerline and the grid cell dimensions, in this case approximately 5×5 m. The raw topography was then mapped to the numerical grid (fig. 2*B*). The FaSTMECH model was run in MD_SWMS using the downstream water-surface elevation corresponding to a flow rate of 19 m^3/s). These boundary conditions were used to simulate the water-surface elevation and distribution of inundated area at the time of the EAARL survey. The predicted depths and velocities in the channel for this flow rate are shown in figures 2*C* and 2*D*. Water-surface elevation points determined by conventional survey were used as verification data in MD_SWMS (fig. 2*E*). A correspondence plot shows good agreement between predicted and measured values with a root mean square error of approximately 3 cm. Similarly, predictions of inundated and exposed area in the study reach compared favorably with manually registered color infrared imagery collected with the EAARL platform (figs. 2*F*–2*G*). Closer inspection of figure 2*F* indicates that the model, even with the relatively coarse grid resolution and the challenge of predicting wetting and drying of nodes in very shallow water (fig. 2*C*), reproduces the complex flow pattern around the vegetated sandbars in the study reach. In the future, automated georeferencing of EAARL imagery in ALPS will provide a raster data layer that could be used within MD_SWMS for model verification.

Previous hydraulic modeling with channel topography obtained from ground-survey data has shown the use of depth and velocity fields computed by FaSTMECH in MD_SWMS for habitat characterization (Kinzel et al., 2005). Additionally, EAARL topography acquired over multiple time periods has also been used to infer changes in riparian and in-channel areas (Kinzel et al., 2006). The example in this paper illustrates the use of both MD_SWMS and EAARL to make predictions of depth, velocity, and water-surface elevation. These predictions could be used to infer habitat quantity and quality in the reach for a range of hypothetical or real streamflows. Similarly, predictions of shear stress in the channel (not shown) could be used to compute sediment transport and movement of barforms in the reach during these flow events.

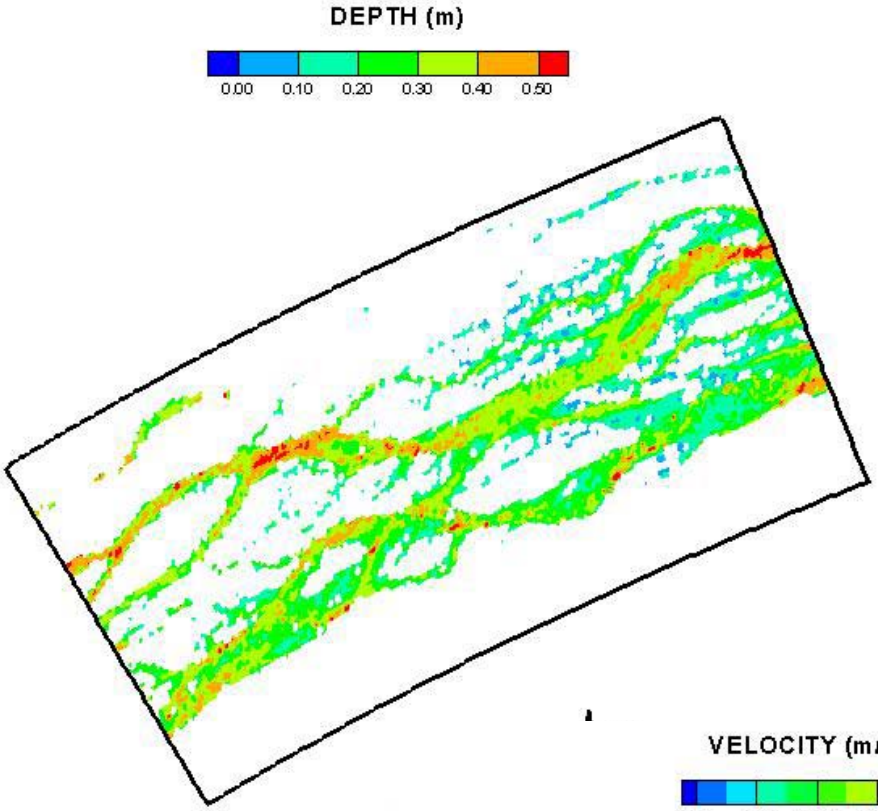


A. EAARL-derived channel topography and curvilinear numerical grid.

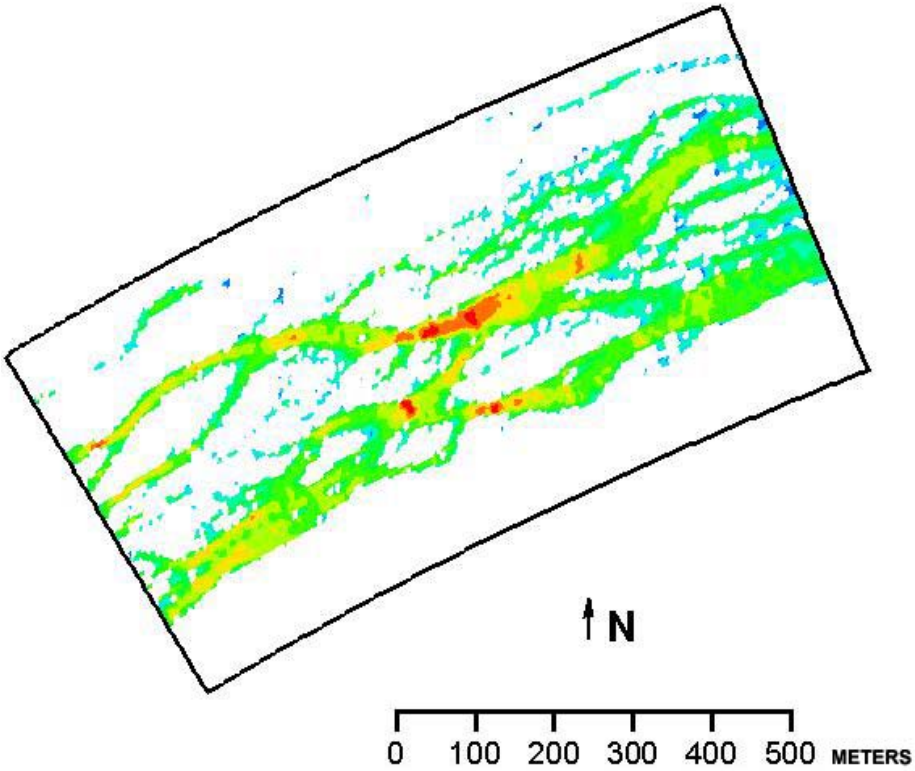


B. EAARL topography mapped to the numerical grid.

Figure 2. Output from MD_SWMS showing the use of EAARL data collected along a reach of the Platte River.

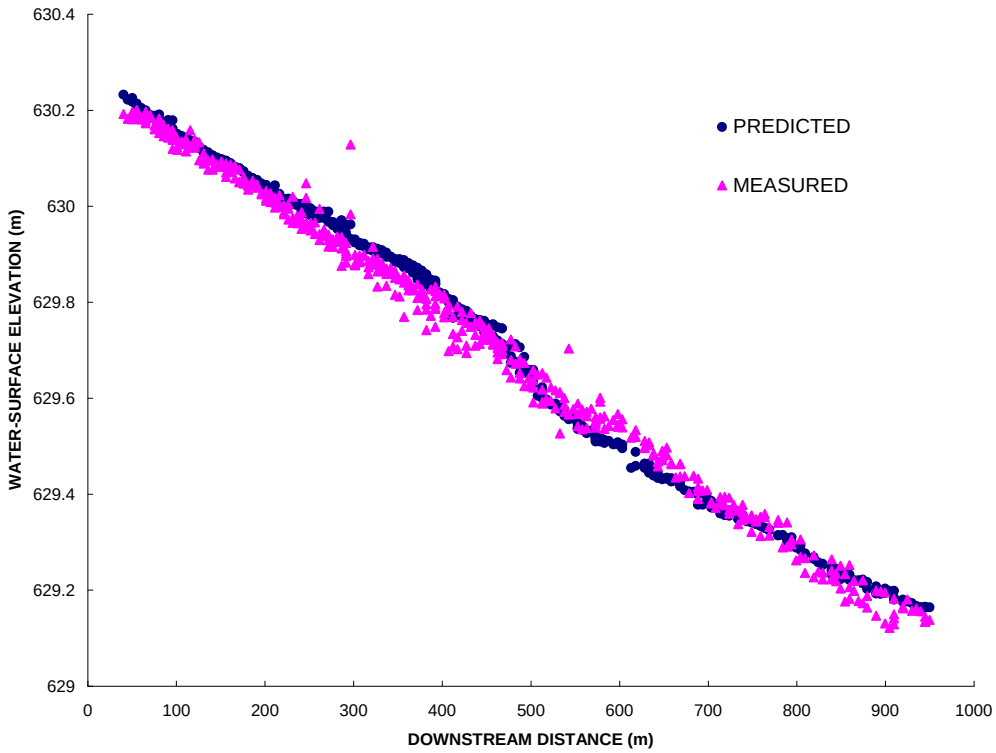


C. Predicted depth distribution using the FaSTMECH model.



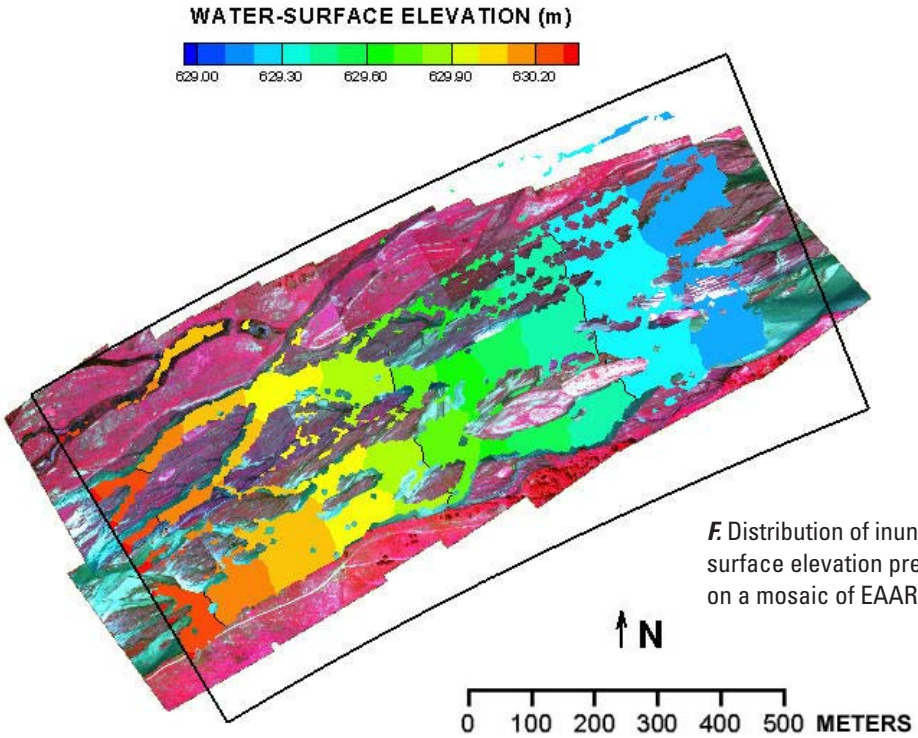
D. Predicted velocity distribution using the FaSTMECH model

Figure 2. Output from MD_SWMS showing the use of EAARL data collected along a reach of the Platte River.—Continued

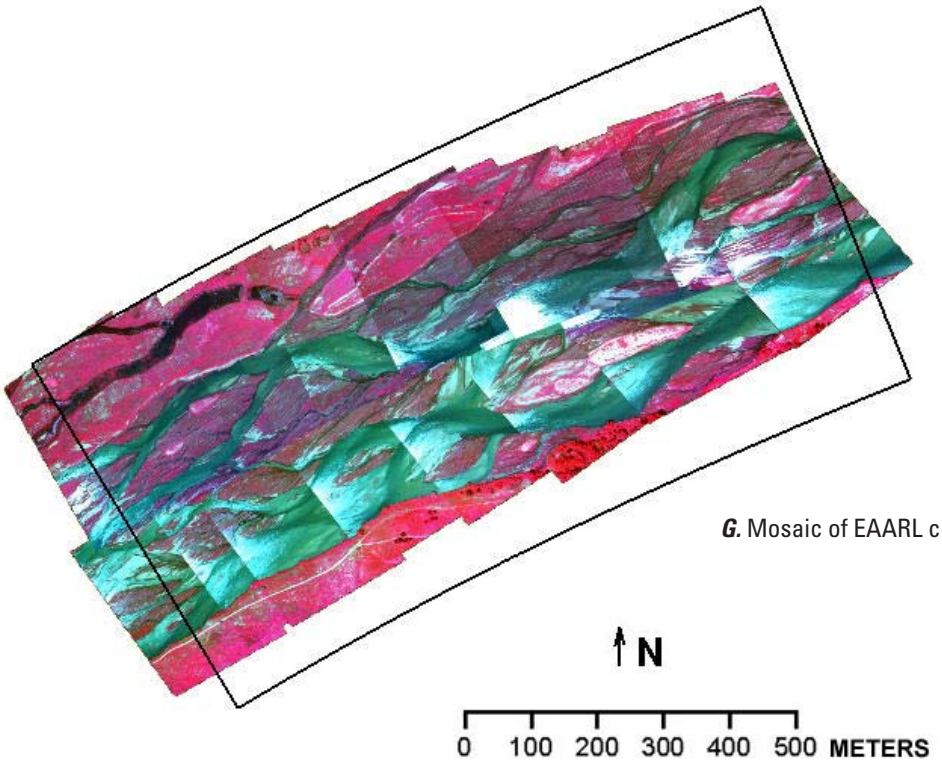


E. Comparison of measured water surface elevations with those predicted using the FaSTMECH model and EAARL collected topography.

Figure 2. Output from MD_SWMS showing the use of EAARL data collected along a reach of the Platte River.—Continued



F. Distribution of inundated area, as indicated by the water-surface elevation predicted by the FaSTMECH model, overlain on a mosaic of EAARL collected color-infrared imagery.



G. Mosaic of EAARL collected color-infrared imagery.

Figure 2. Output from MD_SWMS showing the use of EAARL data collected along a reach of the Platte River.—Continued

Conclusions

Advances in remote-sensing technology are improving the quality and quantity of topographic data gathered in and along rivers enabling unprecedented use in hydrodynamic modeling applications. In this paper, Experimental Advanced Airborne Research LiDAR (EAARL) data were used within the Multi-Dimensional Surface-Water Modeling System (MD_SWMS) to simulate flow in a reach of the Platte River. Water-surface elevations and inundated areas predicted by the model were similar to those measured and delineated with conventional ground surveys and aerial imagery. However, we plan on conducting a more detailed comparison of model results using channel topography collected with the EAARL to model results using channel topography collected from ground surveys. This will help quantify the effect of using EAARL surveys over ground surveys for flow computations. Hardware improvements in the EAARL platform are anticipated to occur that have the potential to improve its performance in shallow rivers. These improvements include increased laser power and point density in each laser swath or raster. Software improvements including processing algorithms able to accommodate the complex convolved waveforms returned from shallow areas also are envisioned. As additional EAARL surveys are conducted in rivers, ground-truth evaluations such as those conducted along the Platte River will be necessary to evaluate system performance in rivers with varying depths, turbidities, and substrates.

Future MD_SWMS enhancements include addition of an eddy-resolving, two-dimensional, structured, non-orthogonal, finite-difference model (H2KE), and a habitat suitability module. Continued collaboration between the USGS Geomorphology and Sediment Transport Laboratory and the USGS Center for Coastal and Watershed Studies is planned to further integrate the use of MD_SWMS and EAARL in river studies.

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