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Retro-modeling the Middle Mississippi River

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Summary A one-dimensional (1-D) unsteady-flow ''retro-model'' was developed using historic (c. 1900) hydrologic and geospatial data and implemented using HEC-RAS. The objective of this investigation was to create a 1-D unsteady-flow model for the Middle Mississippi River for the beginning of the 20th century in order to assess the magnitude and types of changes in flood stages associated with 20th century river engineering. The retro-model was constructed from survey data dating to 1888–1889 and hydrologic data from 1900 to 1904. The late 19th century survey data was supplemented by a modern high-resolution DEM used to fill gaps in the historic data. Land-cover data recorded during this historic survey was used to establish floodplain roughness values based on published Manning's *n* for the various land-cover types, and these roughness values were then adjusted to calibrate the model. Comparison of the retro-model results with the 2004 Upper Mississippi River System Flow Frequency Study (UMRSFFS) flood stages showed increases in flood stages of 2.3–4.7 m for large events (>50-year recurrence interval). These results confirm previous research results showing large-scale reductions in flood conveyance on the Middle Mississippi during the 20th century. Increased roughness of the floodway coupled with reduction in channel and floodplain area due to wing dike and levee construction are the likely explanation for the observed increases in flood stages. Between 1889 and 1998, channel widths through the study reach decreased ~40%, and floodplain area for the 100-year flood decreased by ~60%. In addition, Manning's *n* values in the retro-model were lower than the values used in the UMRSFSS, suggesting that (1) the modern floodway is rougher than the historic floodway, (2) this increased roughness is not a result of explicit changes in land cover, but rather (3) the increase is a result of implicit roughness changes such as wing dike construction. The retro-model developed in this investigation provides a framework for modeling hydrodynamic and ecological responses to altered hydrologic regimes during more than a hundred years of channel modification.

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Introduction

The assessment of physical and ecological change of river systems is hindered by a lack of reference conditions (Philippi, 1996; Frissell and Ralph, 1998). ''Retro-modeling'' can provide a surrogate for reference conditions. Retro-modeling is defined here as the use of archival hydrologic and geospatial data in state-of-the-art hydraulic models to assess historic conditions. Comparison between modeled historic and modern conditions can be used to assess change, which can provide valuable insight and guidance for future river management action.

An example of retro-modeling used as a surrogate for reference conditions, in addition to the research presented in this paper, is Jacobson and Galat's (2006) work on the Lower Missouri River. Jacobson and Galat's (2006) performed two-dimensional hydrodynamic modeling of the modern and historic channel system along selected reaches of the Lower Missouri River to evaluate the change in shallow-water habitat. They found the historical (1894) channel form provided 3–7 times more shallow surface water habitat than that modern channel, which has been optimized for navigation by river engineering. The information gained from this modeling can be useful for developing a rehabilitation plan from which a balance between the human demands on the river and the needs of river biota can potentially be reached.

A wealth of historical data exists from which to develop retro-models for the Mississippi River System. Maps, charts, surveys, structure-history databases, and other quantitative measurements stretch back 100 to as much as ~200 years. As part of a large system-wide project (Pinter et al., 2005), large numbers of archival geospatial data sources were located, digitized, and rectified and registered to a common coordinate system.

The objective of this investigation was to create a one-dimensional (1-D) unsteady-flow model for the MMR during the beginning of the 20th century in order to elucidate the magnitude and types of changes in flood stages that have resulted from 20th century river engineering. In particular we explore the contributors to changes in roughness.

1-D open-channel flow is described by the St. Venant equations. These equations are suitable for detecting flow response to changes in floodway (channel and floodplain) geometry and roughness. An unsteady-flow model was used for this investigation because it provided a more realistic simulation of river flow than a steady-flow model. Unsteady-flow models account for attenuation of flood peaks, backwater effects, and looped rating curves, which are commonly found conditions along complex river systems such as the Mississippi River.

The degree to which any model accurately depicts reality depends on numerous assumptions and data quality. While measurement techniques (geospatial and hydrologic) have improved since the late 19th and early 20th century, we show in this paper the data collected during this period are accurate enough to produce a realistic 1-D unsteady-flow model which can be calibrated to near modern standards (0.15–0.3 m; FEMA, 2003; Dyhouse et al., 2003). The ability to produce such an accurate representation of historic conditions allows for detailed comparison of historic and modern conditions from which the magnitude of change can be assessed.

Area of investigation

The Middle Mississippi River (MMR) is the portion of the Mississippi River between the confluences of the Missouri and Ohio Rivers (Fig. 1). The reach of the MMR modeled in this investigation extends from Jefferson Barracks to Grays Point, Missouri (MO). The selection of the study reach was based on the availability of hydrologic data and floodplain topographic data. The northern extent of the study reach, Jefferson Barracks, was chosen because high-resolution elevation data were not available for the St. Louis metropolitan area farther upstream. The southern extent was set at Grays Point because of gaps in the hydrologic record for the period of interest (1900–1905) at gaging stations farther downstream.

The study reach has undergone dramatic alteration in the past ~100 years. Levees within the study area at the beginning of the 20th century were small, local structures that provided little protection from large floods (Maher, 1964). In contrast, the modern Federal levees within the study area (Fig. 1) protect greater than half the floodplain area to the 50-year protection level or greater (USACE, 2004). In addition, the MMR has been extensively modified to facilitate river navigation, principally by construction of wing dikes (bank-perpendicular structures that concentrate flow; Parchure, 2005). Approximately, 63 km of wing dikes were installed prior to 1905 along the study reached. Another 231 km of wing dikes were added between 1905 and 1998. Prior to 1905, no bridges spanned the study reach, although construction on one bridge at Cape Girardeau, MO began in 1903. Six bridges are present today.

In 2004, the United States Army Corps of Engineers (USACE) published the Upper Mississippi River System Flow Frequency Study (UMRSFFS), which presents updated flood-frequency estimates for the Upper Mississippi, Missouri, and Illinois Rivers. This analysis involved the development of flow frequencies and hydraulic modeling. The flow frequencies were developed from 100 years of hydrologic data (1898–1997). This period was selected by the USACE (2004) to minimize the impact of shifts in land use. The construction of reservoirs since the 1930s in the Upper Mississippi River Basin has resulted in additional heterogeneity, which was addressed in the study by developing two UNET routing models: unregulated (i.e., without reservoir regulation) and current condition (i.e., with reservoirs). A statistical relationship was developed to translate unregulated flow frequencies to regulated flow frequencies (USACE, 2004).

For the hydraulic modeling, the USACE used HEC-GeoRAS (GIS tools) and Hydrologic Engineering Center-River Analysis System (HEC-RAS) to construct and manage the cross-sections. These data were then input into the Hydrologic Engineering Center-Unsteady Network Model (HEC-UNET) modeling tool to perform the 1-D unsteady-flow analysis. The HEC-UNET model was calibrated to reproduce the hydrograph for the high-flow year of 1993 and the low-flow year of 1988 at both stage and discharge measurement stations by adjusting roughness coefficients and estimated lateral