Application of Hydraulic Models for the Analysis of the Interaction of the Illinois River and Its Floodplain

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Abstract

The Illinois River is one of the major tributaries of the Mississippi River in the central United States with a drainage area of 75,156 square kilometers. The Illinois River connects the Great Lakes with the Mississippi River through the Illinois Waterway that consists of eight lock and dams along the Illinois River and its tributaries. Because of its central location in the state and being the receiving river downstream of the Greater Chicago metropolitan area, the Illinois River has experienced significant changes and pollution over the last 100 years. At present, however, the Illinois River has become the focus of state and federal restoration efforts.

One of the major restoration concepts is the reconnection of the Illinois River with its floodplain. Since much of the floodplain has been leveed off for agricultural uses, the reconnection issue is controversial and expensive. However, large floodplain areas that previously were agricultural lands have been purchased by governmental and non-governmental agencies for restoration purposes. It is anticipated that there will be more such purchases in the future.

This paper evaluates the interaction of the Illinois River with its floodplain using hydraulic models to better understand the influence of restoration efforts on river hydraulics. The models will be used to evaluate changes in water discharges, elevation, and velocities as different parts of the river and floodplain are reconnected. Different alternatives for reconnection are also to be evaluated.

Introduction

The Illinois River is one of the major tributaries of the Mississippi River. It has a drainage area of 75,156 square kilometers (28,906 square miles) that covers portions of the states of Illinois, Indiana, and Wisconsin. As one of the major navigation waterways, the Illinois River connects the Great lakes with the Mississippi River through the Illinois Waterway that is made navigable by a series of eight locks and dams along the Illinois River and its tributaries. The Illinois River watershed is generally flat and covered with fine soil, making it one of the best agricultural regions in the United States. Over 80 percent of the Illinois River basin is presently used for agricultural purposes.

The Illinois River has experienced significant changes in hydrology and water quality over the years, because of its downstream location from the Chicago metropolitan area and land use changes in the watershed. Over time these changes have resulted in environmental and ecological degradation along the river. With this realization, major restoration efforts are underway to improve the hydrology, water quality, and habitats along the river and its watershed. A major challenge in these restoration efforts is the proper understanding of the watershed hydrology and river hydraulics so that watersheds and rivers are managed in such a way to promote and sustain ecological restoration, while maintaining the economical functions of the river.

In support of this effort, the Illinois State Water Survey is developing hydrologic and hydraulic models to guide and evaluate the impacts of proposed or ongoing restoration efforts in the Illinois River basin. One of the major restoration concepts focuses on the management of the river/floodplain complex. The extensive Lower Illinois River floodplain is shown in Figure 1. In the Lower Illinois River over 30 levee and drainage districts have been established in the floodplain for agricultural production. Some levee and drainage districts have been purchased by state, federal, and non-governmental organizations for the purposes of "restoring" the floodplain. It is anticipated that there will be more such purchases in the future making large floodplain areas that were disconnected from the river available for restoration. However, there is no consensus on how to reconnect the floodplain to the river and if reconnected what would be the impact of flooding in newly restored floodplains. To assist in the understanding of these issues, the Water Survey has developed one- and two-dimensional hydraulic models for segments of the river. A discussion of the models and how they are being used for Illinois River floodplain restoration efforts is presented.

Application of One-Dimensional Unsteady Flow Model

The initial hydraulic model used for evaluating different floodplain management alternatives for the Illinois River is based on the UNET, a one-dimensional unsteady flow model supported by HEC (HEC, 1995). The output from the UNET model includes time-series stage and discharge values at selected locations and water surface profiles along the study reach. These values can then be used to evaluate changes in flood elevations and discharges for different floodplain management alternatives.

The UNET model solves the one-dimensional full dynamic wave Saint-Venant equations given in Equations 1 and 2.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+\frac{\partial S}{\partial t}=q_l \qquad (1)$$

and

$$\frac{\partial Q}{\partial t}+\frac{\partial \left(Q^2/A\right)}{\partial x}+gA\left(\frac{\partial h}{\partial x}+S_f\right)=q_l v_l \qquad (2)$$

where x is the distance along the channel, t is the time, Q is the flow, A is the cross-sectional area, h is the water depth, S is the storage volume per unit length in the direction

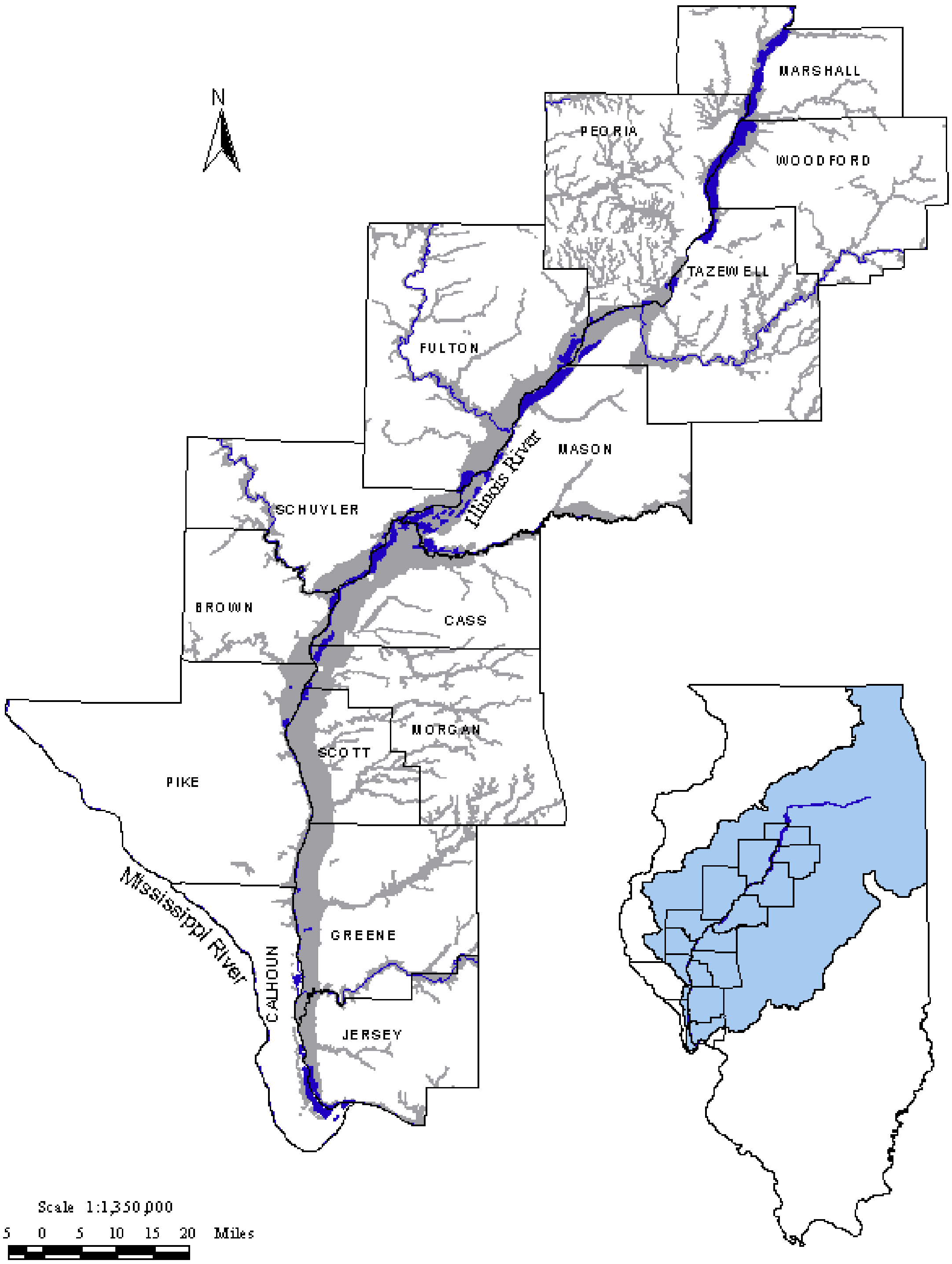

Figure 1. Lower Illinois River and its floodplain

of flow, S_f is the frictional slope, v_l is the lateral inflow velocity, g is the gravitational acceleration, and q_l is the lateral inflow per unit distance.

The flows in the river channel and floodplain are solved separately by using momentum exchange relationship. The mass and momentum equations for both the channel and floodplains are:

Channel

$$\frac{\partial A_c}{\partial t}+\frac{\partial Q_c}{\partial x_c}= \quad q_f \tag{3}$$

$$\frac{\partial Q_c}{\partial t}+\frac{\partial\left(Q_c^2/A_c\right)}{\partial x_c}+gA_c\left(\frac{\partial h}{\partial x_c}+S_{f_c}\right)=M_c \tag{4}$$

Floodplain

$$\frac{\partial A_f}{\partial t}+\frac{\partial Q_f}{\partial x_f}+\frac{\partial S}{\partial t}=q_c+q_l \tag{5}$$

$$\frac{\partial Q_f}{\partial t}+\frac{\partial\left(Q_f^2/A_f\right)}{\partial x_f}+gA_f\left(\frac{\partial h}{\partial x_f}+S_{f_f}\right)-\xi q_l v_l=M_f \tag{6}$$

M_c and M_f are the momentum flux exchanges per unit distance between the channel and floodplain, respectively; ξ is the fraction of the momentum entering the receiving stream; and the subscripts c and f represent the channel and floodplain. This momentum flux is the momentum of the flow passing through the channel section per unit time per unit distance along the channel. The water surface elevation is assumed to be the same for the channel and floodplain. Since the exchanges of mass between the channel and floodplain are equal, then $q_c\ \Delta x_c = q_f\ \Delta x_f$, where Δx_c and Δx_f are the lengths of the shoreline and bluff across which lateral inflow enters the channel and floodplain, respectively. Equations (3) and (5) can be used to yield:

$$\frac{\partial\left(A_f+\varphi A_c\right)}{\partial t}+\frac{\partial Q}{\partial x_f}+\frac{\partial S}{\partial t}-q_l=0 \tag{7}$$

where φ is equal to $\Delta x_c / \Delta x_f$ and $Q = Q_c + Q_f$.

Since the momentum exchanges between the channel and floodplain flows are also equal, i.e., $M_c\ \Delta x_c = -M_f\ \Delta x_f$, then equations (4) and (6) can be combined to yield the following expression:

$$\frac{\partial (Q_f + \varphi Q_c)}{\partial t} + \frac{\partial}{\partial x_f}\left(\frac{Q_c^2}{A_c} + \frac{Q_f^2}{A_f}\right) + g\left(A_c + A_f\right)\frac{\partial h}{\partial x_f} + \varphi\, g A_c S_{fc} \qquad (8)$$
$$+ g A_f S_{ff} - x q_l v_l = 0$$

If an equivalent frictional force is defined as:

$$g A S_f \Delta x_e = g A_c S_{fc} \Delta x_c + g A_f S_{ff} \Delta x_f \qquad (9)$$

and a velocity distribution factor, β, as:

$$\beta = \frac{Q_c^2 / A_c + Q_f^2 / A_f}{Q^2 / A} \qquad (10)$$

then equation (8) can be expressed in simplified form as:

$$\frac{\partial \left(Q_f + \varphi Q_c\right)}{\partial t} + \frac{\partial \left(\beta Q^2 / A\right)}{\partial x_f} + gA\left(\frac{\partial h}{\partial x_f} + S_f \frac{\Delta x_e}{\Delta x_f}\right) - x q_l v_l = 0 \qquad (11)$$

where Δx_e is the equivalent flow path, S_f is the frictional slope for the entire cross section, and $A = A_c + A_f$ is the total cross-sectional area.

The UNET model can simulate one-dimensional flow through single, dendritic, or looped systems of open channels. It can also simulate the interaction between channel and floodplain flows; channel and storage areas; levee failures; and flow through navigation dams, gated spillways, weir overflow structures, bridges and culverts, and pumped diversions. The UNET model allows either stage or flow hydrographs to be the boundary conditions.

The schematics for the UNET model for the Lower Illinois River is shown in Figure 2. The area is subdivided into three reaches. Reach 1 represents the segment of the river from the Peoria Lock & Dam to the junction of the Sangamon River. Reach 2 represents the Sangamon River from Oakland to the junction with the Illinois River. Reach 3 represents the Illinois River downstream of the junction with the Sangamon River to Grafton where the Illinois River joins the Mississippi river. The major tributaries to the Illinois River between Peoria and Grafton are shown as lateral inflows at their confluence with the Illinois River. Also shown in the figure are the discharge or stage gaging stations along the Lower Illinois River. The UNET model for the Illinois River was calibrated and verified using selected flood events from 1973 to 1993 (Akanbi, Lian, and Soong, 1999; Xia and Demissie, 1999).

The UNET model for the Illinois River has been used to evaluate the impacts of different floodplain management alternatives on flood elevations. One example is the utilization of a levee and drainage district as temporal flood storage to reduce flood peaks. The Thompson Levee and Drainage District in the LaGrange Pool, which has a

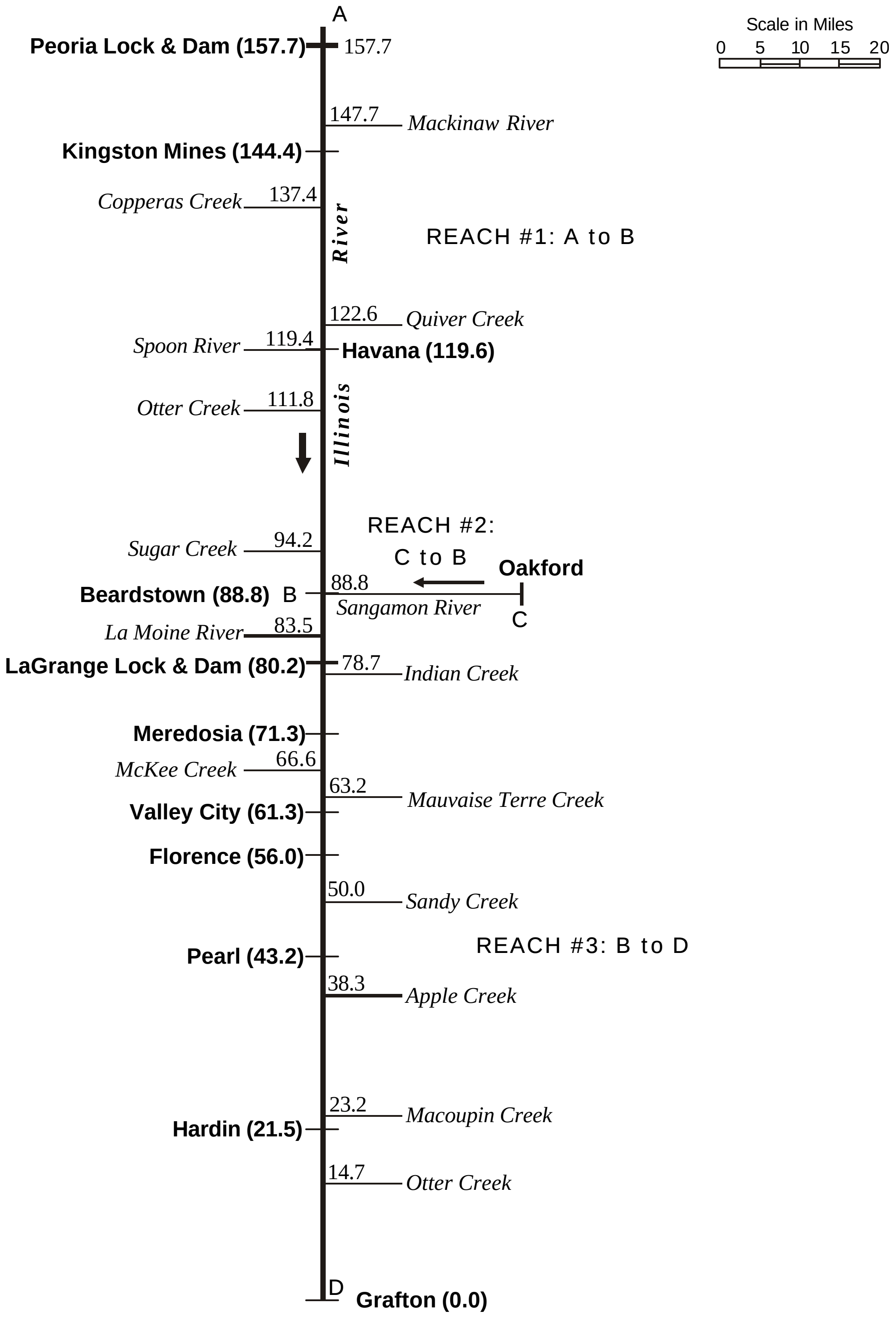

Figure 2. Schematics of the one-dimensional hydraulic model for the Lower Illinois River

surface area of 5,500 acres (2,226 hectares) was selected as one potential location for such an option. The impact of placing a 1,000-foot (305 meters) spillway at different elevations on the levee to allow flood waters to flow into the drainage district are shown in Figure 3 for a 50-year flood. Figure 3a shows the change in flood elevation at the levee district, while Figure 3b shows the change in flood elevations at Havana 7 miles (11.3 kilometers) downstream of the spillway. The reductions in the peak flood stages are given in Table 1 for two locations: at the drainage district and at Havana. As shown in Figure 3 and given in Table 1, placing the spillway 2-ft (0.61 meters) below the levee crest results in maximum reduction of the flood peak.

Table 1: Reduction of Peak Flood Stages at Thompson Lake Levee and Drainage District at Havana by Flood Storage Area (1 foot = 0.305m)

	Thompson Lake		*Havana*	
Depth of Opening	*Maximum stage*	*Peak stage reduction*	*Maximum stage*	*Peak stage reduction*
0-ft	452.00	0	450.79	0
2-ft	450.21	1.79	449.58	1.21
4-ft	451.69	0.31	450.43	0.36
6-ft	451.76	0.24	450.50	0.29

Application of Two-Dimensional Unsteady Flow Model

For a more detailed evaluation of floodplain restoration efforts, a two-dimensional hydrodynamic model was developed for selected segments of the Illinois River. The model selected was the RMA2 model developed by the U.S. Army Corps of Engineers (1996).

RMA2 solves the depth-integrated equations of continuity and momentum in two horizontal directions.

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{r}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right)$$
$$+\frac{gun^2}{\left(1.486h^{1/6}\right)^2}+\left(u^2+v^2\right)^{1/2}-xV_a^2\cos y-2hwV\sin f=0 \tag{12}$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{r}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)+gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right)$$
$$+\frac{gvn^2}{\left(1.486h^{1/6}\right)^2}+\left(u^2+v^2\right)^{1/2}-xV_a^2\sin y-2hwV\sin f=0 \tag{13}$$

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \tag{14}$$

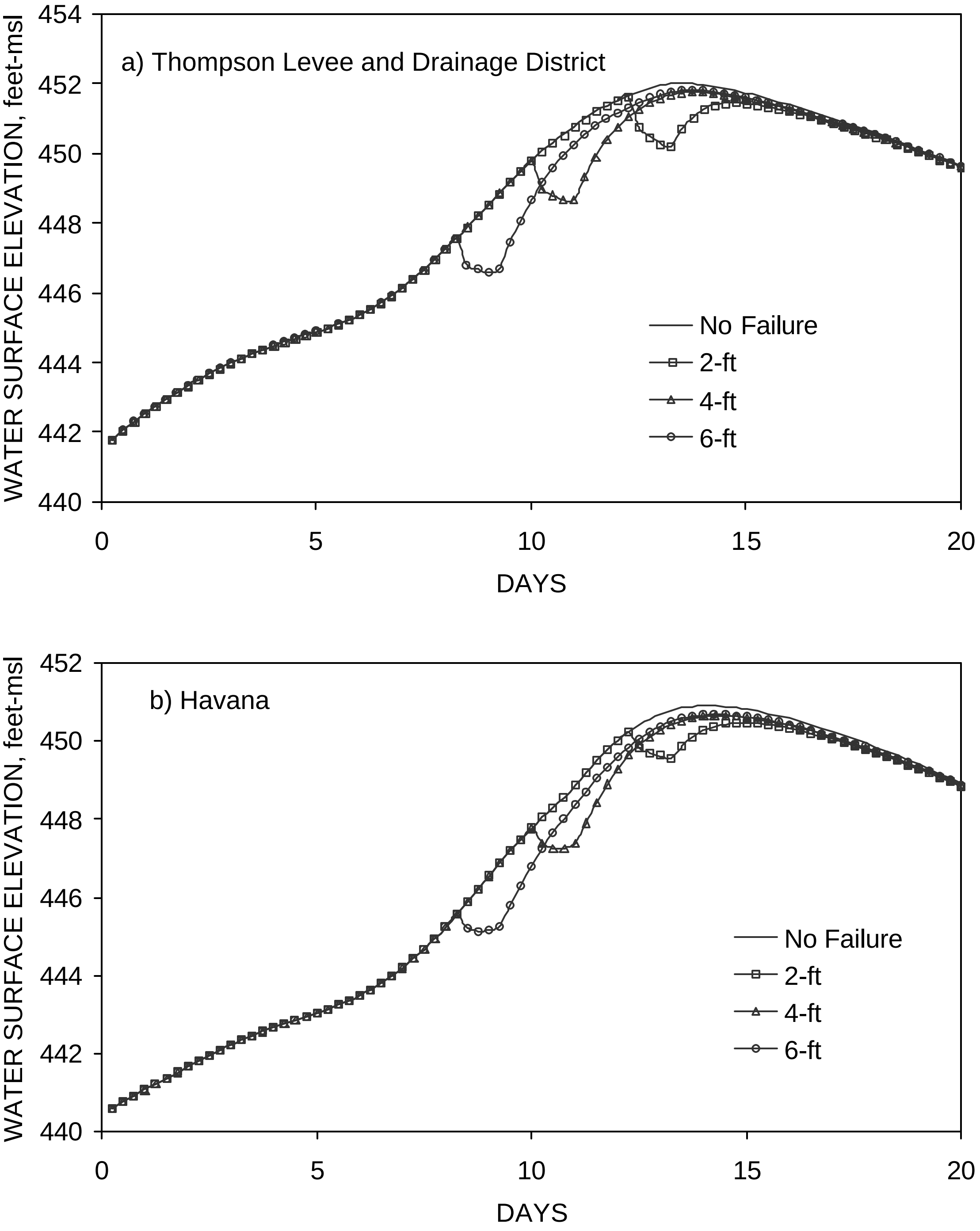

Figure 3. Impact of selected floodplain management options on flood elevations (1 foot = 0.305 meters)

where

h = Depth of water
u, v = Velocities in the Cartisian directions
r = Density of water
E = Eddy viscosity coefficient
a = Elevation of bottom
g = Gravitational acceleration
n = Manning's roughness n-value
x = Empirical wind shear coefficient
V_a = Wind speed
y =Wind direction
w = Rate of earth's angular rotation
f = Local latitude

Equations 12-13 are solved by the finite element method using the Galerkin Method of weighted residuals.

The two-dimensional hydrodynamic model was developed for the segment of the Illinois River that included the Thompson Levee and Drainage District and the Lake Chautauqua Fish and Wildlife Refuge. The model was used to evaluate changes in flow patterns under different management alternatives. Simulated flow patterns with different spillway locations along the levees are shown in Figure 4. Flow patterns for one spillway at a downstream location on the Thompson Levee and Drainage District are shown in Figure 4a. Figure 4b shows the flow patterns with two spillways along the levee. With two spillways along the levee, a flood conveyance through the drainage district is illustrated, while one spillway shows only floodwater inflow into the levee and drainage district.

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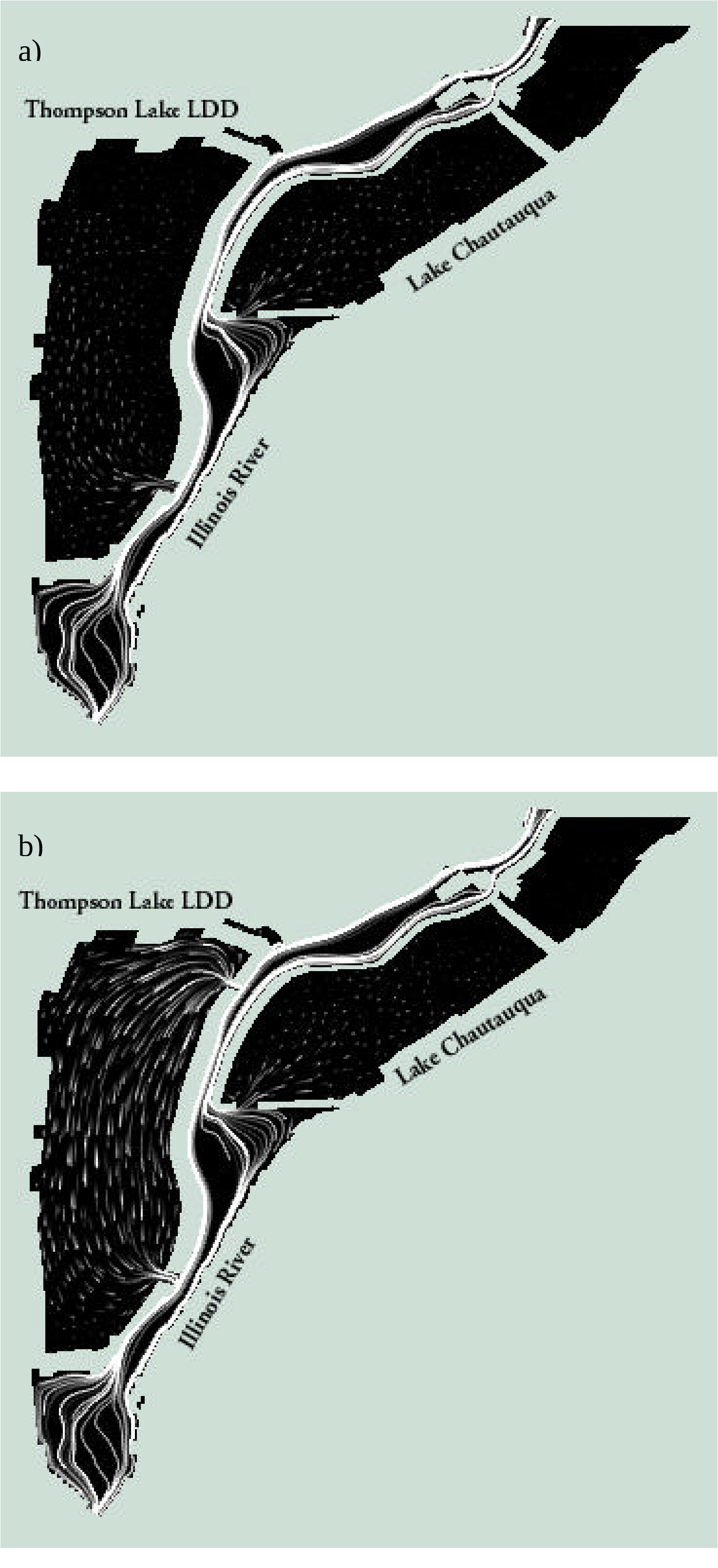

Figure 4. Simulated flow patterns along selected segments of the Illinois River floodplain under different restoration alternatives