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Evaluation of levee setbacks for flood-loss reduction, Middle Mississippi River, USA

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SUMMARY

One-dimensional hydraulic modeling and flood-loss modeling were used to test the effectiveness of levee setbacks for flood-loss reduction along the Middle Mississippi River (MMR). Four levee scenarios were assessed: (1) the present-day levee configuration, (2) a 1000 m levee setback, (3) a 1500 m levee setback, and (4) an optimized setback configuration. Flood losses were estimated using FEMA's Hazus-MH (Hazards US Multi-Hazard) loss-estimation software on a structure-by-structure basis for a range of floods from the 2- to the 500-year events. These flood-loss estimates were combined with a levee-reliability model to calculate probability-weighted damage estimates. In the simplest case, the levee setback scenarios tested here reduced flood losses compared to current conditions for large, infrequent flooding events but increased flood losses for smaller, more frequent flood events. These increases occurred because levee protection was removed for some of the existing structures. When combined with buyouts of unprotected structures, levee setbacks reduced flood losses for all recurrence intervals. The "optimized" levee setback scenario, involving a levee configuration manually planned to protect existing high-value infrastructure, reduced damages with or without buyouts. This research shows that levee setbacks in combination with buyouts are an economically viable approach for flood-risk reduction along the study reach and likely elsewhere where levees are widely employed for flood control. Designing a levee setback around existing high-value infrastructure can maximize the benefit of the setback while simultaneously minimizing the costs. The optimized levee setback scenario analyzed here produced payback periods (costs divided by benefits) of less than 12 years. With many aging levees failing current inspections across the US, and flood losses spiraling up over time, levee setbacks are a viable solution for reducing flood exposure and flood levels.

1. Introduction

Flood losses across the United States continue to rise despite decades of investment in flood control. Currently, the US employs a combination of both structural and non-structural methods for flood control. Most experts and formal reviews argue that the optimum strategy for reducing flood losses is to limit or reduce floodplain development (IFMRC, 1994; NWF, 1998), but the opposite is happening on many US floodplains as extensive development continues in areas with the greatest flood risk (Hipple et al., 2005; Pinter, 2005).

Along the Middle Mississippi River (MMR), federal levees raised or built mostly during the 1940s and 1950s protect >70% of the floodplain to the 50-year protection level or higher (Remo et al., 2009). As these levees age, repairs and/or replacements become necessary. Recent inspections authorized by the National Levee Safety Act of 2007 identified significant problems in the Mississippi River levees, protecting 25 communities in Madison, St. Clair, and Monroe counties in Illinois. Issues include under-seepage, slope instability, and subsidence (Hillig, 2009; Flinchpaugh, 2010; Flor et al., 2011). Because of under-seepage, the United States Army Corps of Engineers (USACE) currently will not guarantee that these levees can protect against 100-year flood levels (Hillig, 2009; Fitzgerald, 2010; Flinchpaugh, 2010).

As aging levees fail inspections, repair costs can be daunting. Repair costs of up to $500 million have been estimated for the Illinois levees mentioned above (Hillig, 2009; Ortbals, 2009; Desloge, 2010). Government entities face difficult decisions whether to repair these structures in place or, alternatively, to find flood mitigation strategies that satisfy both environmental and economic interests.

Several studies have attempted to determine optimal floodplain protection through static or dynamic hydraulic and economic models (Bozkurt et al., 2000; Zhu et al., 2007; Zhu and Lund, 2009). These studies use cost-benefit analysis and optimization techniques and include levee setbacks as one of the possible alternatives to raising existing levees. As research on levee setbacks continues and the

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benefits of levee setbacks become evident, more communities are choosing to implement levee setbacks as a way to increase protection levels.

The relocation of dikes (i.e., levee setbacks) is a primary strategy within the \$3 billion ''Room for the River'' program approved by the Dutch government in 2007. The goal of *Room for the River*, which will be completed in 2015, is to reduce high water levels in the Rhine, Meuse, Waal, and Ijssel Rivers while simultaneously improving the environmental quality of river areas. Projects are planned at more than 30 locations and, combined, will increase the Rhine's carrying capacity from 15,000 $m^3\ s^{-1}$ to 16,000 $m^3\ s^{-1}$ (Room for the River Program, 2012).

In the US, several small-scale levee setback projects have been completed, and more are in the design or construction phase. One of the larger levee setback projects within the US is located in Yuba County, CA and was completed in late 2010. The Three Rivers Levee Improvement Authority shifted 9.7 km (6 mi) of the Feather River levee farther from the channel, opening approximately 1600 acres to flood waters (Weiser, 2008). The setback area was designed to eliminate a choke point on the river that had repeatedly forced river levels higher for miles upstream during past flood events. This project was the final step in a larger four-phase project to upgrade all levees protecting Yuba County's Plumas Lake Basin (Weiser, 2008).

In this study, we tested flood-damage reductions in response to modeled levee setbacks along two MMR study reaches. For each floodplain-management scenario in this study, damages were assessed using a combination of one-dimensional (1D) hydraulic modeling and flood-loss modeling for a range of flood-recurrence intervals. While previous studies have combined hydraulic modeling and flood-loss assessments (NRC, 2000; Remo et al., 2012), this study is the first to calculate annualized damages using FEMA's Hazus-MH (Hazards US Multi-Hazard) flood-loss model results.

2. Methods

This study involved three methodological steps: (1) hydraulic modeling of water-surface elevations (WSELs), (2) flood-loss modeling, and (3) calculation of expected annual damages (EAD). These steps were used to test seven floodplain-management scenarios along two MMR study reaches (Table 1). The modeling tools used for this study included: (1) HEC-RAS (Hydrologic Engineering Center's River Analysis System) and (2) FEMA's Hazus-MH flood-loss modeling package.

The levee configurations analyzed here included: (1) modern levees, (2) a 1500 m levee setback, (3) a 1000 m levee setback, and (4) a levee setback designed to maintain protection for high-value infrastructure (i.e., an ''optimized'' levee setback). The modern-levees configuration (Scenario 1) was compared against the three levee-setback configurations (Scenarios 2, 3, and 4) to determine if the levee setbacks reduced flood losses. For each of the three levee setback configurations, buyouts of unprotected structures were also evaluated as an additional flood-mitigation strategy (total of seven scenarios).

Table 1
Scenarios used in this study.

Scenario	Levee configuration	Additional mitigation strategy
1	Modern levees	None
2A	1500 m levee setback	None
2B	1500 m levee setback	Buyouts
3A	1000 m levee setback	None
3B	1000 m levee setback	Buyouts
4A	Optimized levee setback	None
4B	Optimized levee setback	Buyouts

2.1. Study area

We chose two study reaches along the MMR in order to assess the effect of levee setbacks on flood losses on both a largely agricultural and a more urbanized floodplain. The Urban Study Reach encompasses 28.5 river km (17.7 river mi) of the MMR that includes the Mississippi River floodplain through St. Clair and northern Monroe counties, IL, and the Agricultural Study Reach encompasses 67.9 river km (42.2 river mi) of the MMR that includes the Mississippi River floodplain through Union and Jackson counties, IL (Fig. 1).

The Urban Study Reach includes two levee districts: the Metro East Sanitary District and the Prairie Du Pont-Fish Lake Drainage and Levee District. Together, these levee districts include 195 km^2 (75 mi^2) of leveed floodplain land. Levees of both districts are designed to protect against floods up to the 500-year level. The width of the floodplain in this study reach varies from 4240 m (13,900 ft) to 13,170 m (43,200 ft). The width of the MMR channel (bank to bank) varies from 480 m (1580 ft) to 880 m (2900 ft).

The Agricultural Study Reach includes the Degognia-Grand Tower Levee District, the Preston Drainage and Levee District, and the Clear Creek Drainage and Levee District. Together, these levee districts include 344 km^2 (133 mi^2) of leveed floodplain land. The levees in this area are designed to protect against floods up to the 50- to 100-year level. In this study reach, the width of the floodplain varies from 2130 m (7000 ft) to 9360 m (30,700 ft), and the MMR channel varies from 470 m (1550 ft) to 1130 m (3772 ft) wide.

2.2. Data sources

Hydrologic data used in this study included discharges and daily stage measurements. Discharges were collected for the upstream boundary and four hydrologic stations on major tributaries that feed into the Mississippi (Table 2). Discharges were acquired from the National Water Information System (USGS, 2010b). Stage measurements were collected for 17 stations along the MMR (Table 2) from the USACE's web-based database (USACE, 2010).

Roughness coefficients, levee locations, bridge designs and locations, in-stream structures, and cross sections were obtained from the Upper Mississippi River Floodway Computation (UMRFC; USACE, 2004a). The UMRFC is a steady-flow HEC-RAS model that was created in 2004 by the USACE and calibrated to the 100-year Upper Mississippi River System Flow Frequency Study (UMRSFFS) profile. Topography, in the form of a one-third arc-second digital elevation model (DEM), was obtained from the National Elevation Dataset (USGS, 2010a).

In order to complete the Level III Hazus-MH analysis for this study, assessor records were used to create building-inventory databases for each study reach. The assessor records were obtained from county assessor's offices in the form of parcel shapefiles (geo-referenced polygons of property lines) and building and parcel information, including the assessed values and occupancy classes.

2.3. Hydraulic modeling

All hydraulic modeling was completed using HEC-RAS (version 4.0), which implements one-dimensional steady and unsteady flow models of open-channel flow (Dyhouse et al., 2003). HEC-RAS was chosen for this study in order to maintain consistency with the UMRFC, and an unsteady-flow model was used here because it provided a more realistic simulation of flow than steady-flow modeling.

Instead of creating two separate hydraulic models, one for each study reach, we created one hydraulic model spanning 280 river km (174 river mi) from Grafton, IL to Thebes, IL. The initial hydraulic model corresponded to the modern levees configuration (Scenario 1), and hydraulic models for the other three levee config-

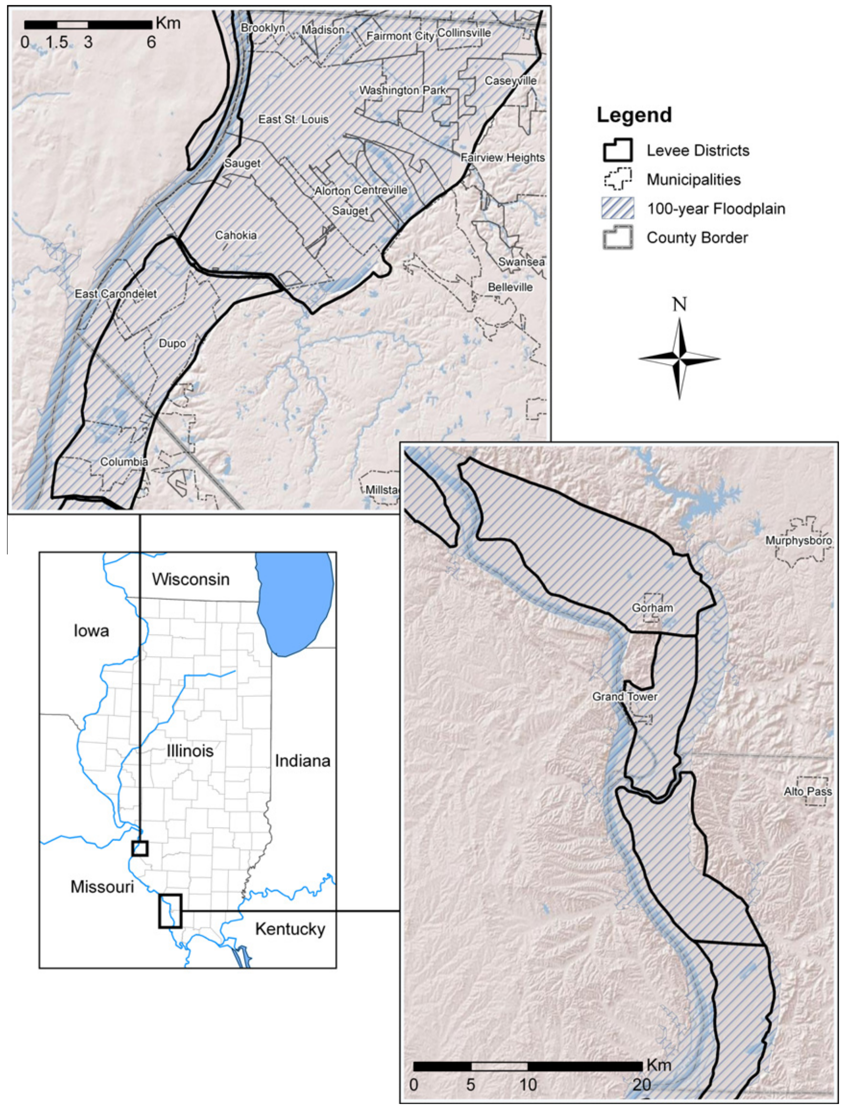

Fig. 1. Urban and agricultural study reaches, including floodplain extent, levee districts, and municipalities.

Table 2
Calibration and validation results for the hydraulic model of present-day conditions (Scenario 1).

Hydrologic station	Calibration 1995			Validation 1994		
	AD[a] (m)	RMSE[b] (m)	MAE[c] (m)	AD[a] (m)	RMSE[b] (m)	MAE[c] (m)
Alton	0.12	0.48	0.32	0.19	0.45	0.41
Hartford	−0.20	0.37	0.29	0.17	0.29	0.33
Chain of rocks	0.32	0.59	0.53	0.50	0.64	0.68
LD 27 Lower	−0.07	0.37	0.33	0.41	0.46	0.47
St. Louis	−0.29	0.45	0.36	0.09	0.22	0.21
Engineers depot	−0.24	0.41	0.32	0.10	0.24	0.22
Jefferson barracks	−0.26	0.43	0.34	0.07	0.28	0.23
Waters point	−0.27	0.48	0.37	−0.22	0.53	0.40
Selma	−0.15	0.40	0.31	−0.03	0.50	0.36
Little rock landing	−0.34	0.51	0.49	−0.40	0.60	0.47
Chester	−0.33	0.49	0.42	−0.24	0.52	0.37
Bishop landing	−0.06	0.41	0.32	0.22	0.51	0.40
Red rock landing	−0.18	0.48	0.36	−0.02	0.54	0.38
Grand tower	−0.04	0.33	0.26	0.04	0.47	0.36
Moccasin springs	−0.31	0.55	0.44	−0.30	0.52	0.40
Cape girardeau	−0.23	0.29	0.27	−0.23	0.24	0.17

[a] Average difference.
[b] Root mean square error.
[c] Mean absolute error

urations (Scenarios 2, 3, and 4) were created by adjusting the cross sections to reflect scenario conditions. While most of the UMRFC cross sections in the Scenario 1 model extended across the entire floodplain (from the Missouri-side bluff to the Illinois-side bluff), some cross sections within the Urban Study Reach extended only from levee to levee. Since floodplain topography was a necessary component for the creation of the scenario models, these cross sections were extended fully across the floodplain. The floodplain topography for these cross sections was extracted from the DEM using HEC-GeoRAS, which is an ArcGIS extension designed to process geospatial data for use within HEC-RAS.

Daily discharges were used for the upstream model boundary and for lateral inflows. Daily stage measurements were used as the downstream boundary. The upstream and downstream boundaries for this model coincide with gauging stations, and lateral inflows were added at the junctions of tributaries identified as "significant inflows" by the UMRSSFS (USACE, 2004b).

The Scenario 1 model was calibrated to the 1995 stage hydrographs by adjusting the channel's Manning's *n*, and the model was validated to the 1994 stage hydrographs at the stations identified in Table 2. The 1995 flood year was chosen for the calibration process because it represents the second-largest recent flood after 1993. The flood of 1993 was not used for calibration because flood-fighting efforts and levee failures are difficult to accurately model. Model calibration and validation were evaluated for degree of fit by calculating the average difference (AD), the root mean squared error (RMSE), and the mean absolute error (MAE) between the modeled and observed WSELs. Calibration results for this model had RMSE values ranging from 0.29 to 0.59 m, and the validation results had RMSE values ranging from 0.24 to 0.64 m (Table 2).

For Scenario 2, levees were moved to a minimum distance of 1500 m from the channel margin. Levees with an original location more than 1500 m from the bank were left in place, as were all levees on the opposite (Missouri) side of the river. Similarly, for Scenario 3, levees were moved a minimum of 1000 m from the channel margin, with levees on the Missouri bank again left in place. For Scenario 4, Illinois levees were left in place in areas with high-value infrastructure and set back or removed in areas with open land or only low-value infrastructure. Levees in Missouri were left in place for Scenario 4 as well.

In order to construct a continuous water-surface profile for each hydraulic model, rating curves were constructed from the modeled WSELs at 102 cross sections within the Urban Study Reach and 98 cross sections within the Agricultural Study Reach. On average, analyzed cross sections were spaced at 0.8 river km (0.5 river mi) intervals, with a maximum spacing of 2.3 river km (1.47 river mi) and minimum spacing of 0.32 river km (0.20 river mi). For each cross section, the log of the modeled discharge was plotted against the modeled WSEL, and a third-order polynomial regression equation was fitted to the points. These rating curves were then used to estimate WSELs for the 2-, 5-, 10-, 20-, 25-, 50-, 100-, 200-, and 500-year events at each cross section.

2.4. Flood-loss modeling

Flood losses for this study were modeled using FEMA's Hazus-MH package. Hazus-MH is a software program that estimates potential losses from floods, earthquakes, and hurricanes. Unlike the single hydraulic model created using HEC-RAS (which spanned 280 river km from Grafton, IL to Thebes, IL), two distinct flood-loss models were developed: one for the Urban Study Reach and one for the Agricultural Study Reach.

2.4.1. Flood-depth grids

A flood-depth grid is a geospatial array (2D raster grid) of water depth that will inundate the channel and floodplain for a specific discharge. While it is possible to create flood-depth grids using Hazus-MH, this study created flood-depth grids using rating curves created from HEC-RAS. For the four levee configurations in each study reach, a total of nine flood-depth grids were created: one each for the 2-, 5-, 10-, 20-, 25-, 50-, 100-, 200-, and 500-year floods.

To create the flood-depth grids, the cross sections used in HEC-RAS were exported to ArcGIS and converted from lines to points, with 50 points evenly spaced along each cross section. Each point was then associated with the WSELs from the rating curves for that cross section. Next, a raster (grid of cells, each with a unique value) was created from the cross-section points and their associated WSELs using the "topo to raster" function in ArcGIS. The topography raster was then subtracted from the water-surface raster, with the resulting raster of elevation differences being a flood-depth grid (water-surface elevation − ground elevation = water depth).

2.4.2. Building-inventory databases

To create the building-inventory databases here, county assessor records were compiled by study reach and organized into a format accepted by Hazus-MH. Illinois does not have a standard format for assessor records, and some data required by Hazus-MH were not available. Missing data were replaced with Hazus-MH default values from FEMA's Flood Model Technical Manual (FEMA, 2009) such as square footage, building material (default = wood), foundation type (default = concrete slab), and number of stories (default = 1).

The value of all assessed structures was calculated by multiplying the assessed value by 3.0 because the assessment rate in Illinois is 33.3% of fair-market value (IDR, 2010). Non-profit and government-owned structures are not assessed, so these values were estimated with Hazus-MH default replacement costs (FEMA, 2009). Building content values were estimated by multiplying each structure's value by Hazus-MH default percentages, which vary from 50% to 150% based on occupancy class (FEMA, 2009).

2.4.3. Calculation of expected annual damage (EAD)

In order to minimize computation time, a template flood-loss model containing the DEM and building-inventory database was created in Hazus-MH for each study reach. Using the templates, a flood-loss model was then constructed for the flood-recurrence intervals of each scenario by importing the respective flood-depth grid. The building-inventory module was executed, and structure-by-structure damage results were exported as point files. For each scenario, point files were created for all damaged buildings within each levee district and within the unprotected floodplain. Scenarios 2B, 3B, and 4B included additional flood mitigation in the form of buyouts of unprotected structures. For these buyout scenarios, the structure-specific damages for buildings located within the unprotected floodplain were removed to reflect buyouts of all unprotected structures. Buyout costs were calculated by summing the fair-market value of the unprotected structures.

Expected annual damage (EAD) is the average yearly flood damage that can be expected to occur, averaged over the full range of flood recurrence intervals over an extended period of time. EAD is often calculated in order to assess different floodplain-management plans because the damage risk from all magnitudes of floods must be integrated (NRC, 2000). Damage corresponding to each magnitude of flooding is weighted by the corresponding exceedence probability. The large damages during rare flooding events are thus weighted less, whereas small damages associated with frequent events are weighted proportional to their higher occurrence probabilities (NRC, 2000). For this study, the process used for calculating EAD involved two steps: (1) the incorporation of levee failure probabilities and (2) the numerical integration of damage-probability curves.

In addition to overtopping, levees may fail before stages reach the levee crests for geotechnical reasons such as erosion, under-seepage, or through-seepage (Bhowmik and Demissie, 1982; IFMRC, 1994). A stochastic levee-failure function was created and applied to each levee district within the two study reaches. The levee-failure function here was based on the model used by the USACE for planning studies (USACE, 1999), and consists of a function in which the probability of failure (P_f) varies smoothly between 0 when WSEL is at or below the levee toe ($h_{\min}$) and 1 when WSEL reaches the levee crest ($h_{\max}$) as follows:

$$P_f = 0.36 * \tan^{-1}(10.3 * ((\mathrm{WSEL} - h_{\min})/(\mathrm{h}_{\max} - h_{\min}) - 7.2)) \quad (1)$$

The arctan function most closely resembled the shape of the curve for a levee of "average reliability" (USACE, 1999, Appendix B). The upstream-overtopping locations and levee-crest elevations were taken directly from the UMRSFFS (USACE, 2004b, Table D-26). These locations and elevations represent low spots in the design elevations and included the assumption that minor depressions in the levee crests would be fixed during yearly maintenance or during flood-fighting activities (USACE, 2004b). Levee-toe elevations were extracted from the 1/9 arc-second DEM. For floods that did not overtop a given levee, the flood-damage estimates for structures within that levee district were multiplied by the corresponding levee-failure probability.

Damage-probability curves relate flood damages to exceedance probability (reciprocal of the return period). For this study, damage-probability curves were constructed from the Hazus-MH results for each flood recurrence interval modeled and for each scenario. A total of fourteen curves were constructed, each a unique combination of floodplain-management scenario and study reach.

With annual exceedance probability plotted on the x-axis and the estimated damage plotted on the y-axis, the area under each of the damage-probability curves represented the respective EAD. Since damage-probability curves are not defined by a continuous analytical function, the following numerical integration was performed:

$$\mathrm{EAD} = \sum D_i \Delta_p \quad (2)$$

where Δ_p is the exceedance-probability increment, and D_i is the midpoint damage for the increment. This numerical integration was used to approximate the EAD by calculating the area of a series of trapezoids representing the area under each damage-probability curve. The EAD for each scenario model was then compared to the EAD of Scenario 1 in order to determine how the modeled floodplain-management scenarios affected flood risk across the full spectrum of flood recurrence intervals.

Additionally, for each of the buyout scenarios (2B, 3B, and 4B), the costs (levee construction and buyouts) were divided by the benefits (reduction in EAD relative to Scenario 1) in order to calculate payback periods. Levee construction costs are difficult to predict accurately, but we estimated values here by first determining the volume of fill needed. This volume was based on a levee design with 3:1 side slopes, a 4 m crown width, and levee heights with a 500-year protection level with 1 m of freeboard. The total levee volume determined for each buyout scenario was then multiplied by a cost of $35.3/m^3, and a fixed cost of $3 million/km was added to account for additional setback costs (site acquisition, design and consulting, etc.). These construction costs ($35.3/m^3, $3 million/km) were estimated based on Zhu et al., 2007.

3. Results

Scenario 1 represents the current floodplain-management conditions and was used as the reference condition to compare water-surface profiles and damage estimates for each of the scenarios. Scenarios 2, 3, and 4 yielded lower flood levels for all recurrence intervals relative to Scenario 1. The levee-setback scenarios analyzed here reduced stages for all overbank flows ranging from the 2- to 500-year level. These stage reductions are the primary mechanism driving the decreased flood losses observed in this study. These reductions can be attributed to the expanded floodplain area proximal to the channel, allowing for increased floodwater storage and conveyance. Similar changes in flood levels have been documented both by modeling and following real-world levee construction and removal projects (Heine and Pinter, 2012). The largest stage reductions relative to Scenario 1 occurred in Scenario 4 because it opened up the largest amount of floodplain land (Table 3). For example, the average change in stage (relative to Scenario 1) for the 100-year flood ranged from −0.11 m for Scenario 3 to −1.58 m for Scenario 4 in the Agricultural Study Reach and from −0. 20 m for Scenario 3 to −0.81 m for Scenario 4 in the Urban Study Reach (Fig. 2).

The weighted damages calculated in the flood-loss modeling portion of this study were used to construct damage probability curves for the eight floodplain-management scenarios (Figs. 3 and 4). The damage probability curves for Scenarios 2B, 3B, and 4B (buyout scenarios) consistently plot below the curves for Scenario 1 in both study reaches.

In both study reaches, EAD was calculated for each scenario. EAD ranged from $13.9 million to $243.1 million in the Urban Study Reach and from $0.6 million to $27.3 million in the Agricultural Study Reach (Table 4). The highest EAD corresponded to Scenario 2A in the Urban Study Reach and Scenario 3A in the Agricultural Study Reach. The lowest EAD corresponded to Scenario 4B in the Urban Study Reach, and Scenarios 4B and 2B tied for the lowest EAD in the Agricultural Study Reach.

4. Discussion

Comparing EAD for the levee-setback scenarios to the EAD for Scenario 1 reveals whether the levee setback increased or decreased damages relative to the current floodplain conditions. Scenario 4 produced the largest reductions in EAD relative to Scenario 1, indicating that it was the most economically effective scenario tested here. Scenario 4A (optimized levee setback without buyouts) decreased EAD by 7% ($1.6 million) in the Urban Study Reach and 43% ($3.8 million) in the Agricultural Study Reach relative to Scenario 1. When combined with buyouts (Scenario 4B), the decrease in EAD was 55% in the Urban Study Reach and 93% in the Agricultural Study Reach (Table 5).

Scenario 4A is the only levee-setback scenario that decreased EAD without the implementation of buyouts. The two other levee-setback scenarios, which consisted of levee-setback distances of 1500 m (Scenario 2A) and 1000 m (Scenario 3A), resulted in significant increases in EAD without buyouts of unprotected structures. The increases in EAD for Scenarios 2A and 3A relative to Scenario 1 can be attributed to increased flood risk for structures no longer protected by levees. Scenario 2A eliminated levee protection for 603 structures worth $271.0 million in the Urban Study Reach and 267 structures worth $138.6 million in the Agricultural Study Reach. Similarly, Scenario 3A eliminated levee protection for 268 structures worth $192.9 million in the Urban Study Reach and 231 structures worth $127.7 million in the Agricultural Study Reach. In both study reaches, high-value commercial and industrial buildings are located within the modeled setback zones. Therefore, the levee setbacks in Scenarios 2A and 3A exposed areas with high-value structures, causing significant increases in EAD.

Scenario 4A also eliminated levee protection for some structures: 485 structures worth $47.6 million in the Urban Study Reach and 643 structures worth $18.9 million in the Agricultural Study Reach. However, unlike Scenarios 2A and 3A, the levees were only

Table 3
Differences in 100-year flood stage and floodplain area outside levees relative to Scenario 1.

	Urban Study Reach		Agricultural Study Reach	
	Increase in floodplain area (km^2)	Average stage decrease (m)	Increase in floodplain area (km^2)	Average stage decrease (m)
Scenario 2	23	0.32	38	0.34
Scenario 3	11	0.20	15	0.11
Scenario 4	43	0.81	333	1.58

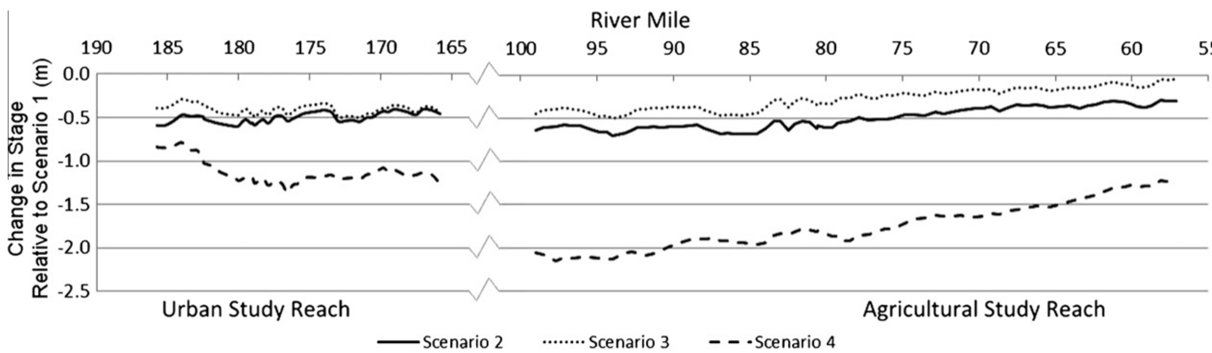

Fig. 2. Change in stage between Scenarios 2, 3, and 4 relative to Scenario 1. Negative numbers reflect a decrease in stage for the scenarios relative to Scenario 1.

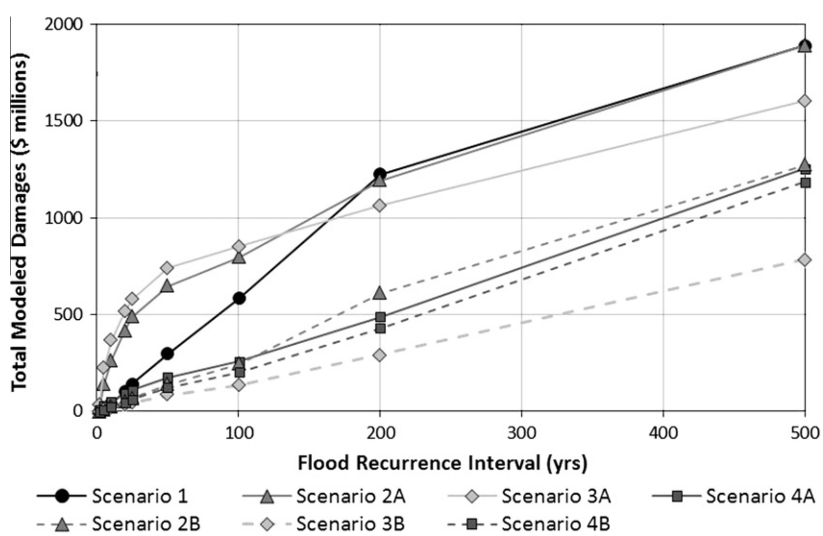

Fig. 3. Damage-probability curves for the Urban Study Reach.

set back in areas of relatively low-value infrastructure or open land. Designing the levee setback in this way minimized the total and average value of structures without levee protection. In the Urban Study Reach, the average fair-market value of unprotected structures was 78% ($350,900) less than in Scenario 2A and 86% ($621,700) less than in Scenario 3A. Similarly in the Agricultural Study Reach, the average fair-market value for unprotected structures was 94% ($489,700) less than in Scenario 2A and 95% ($523,400) less than in Scenario 3A.

A comparison of EAD for the three scenarios which used buyouts (2B, 3B, and 4B) to EAD for Scenario 1 shows that all three levee-setback configurations reduced flood risk when combined with buyouts of unprotected structures. Scenario 2B decreased EAD by $10.2 million (47%) in the Urban Study Reach and $8.3 million (93%) in the Agricultural Study Reach relative to Scenario 1. Similarly, Scenario 3B decreased EAD by $7.0 million (32%) in the Urban Study Reach and $8.0 million (90%) in the Agricultural Study Reach (Table 6).

The payback periods calculated for each of the buyout scenarios (2B, 3B, and 4B) demonstrate that while Scenarios 2B and 3B successfully reduce flood risk, they are less efficient than Scenario 4B (Table 6). The payback period for Scenario 4B is only 11 years in the Urban Study Reach and 8 years in the Agricultural Study Reach. Payback periods for the other two setback scenarios (2B and 3B) are >50 years in the Urban Study Reach and >60 years in the Agricultural Study Reach. Scenario 4B is the most effective floodplain-management scenario analyzed here and yields the largest reduction in EAD, the lowest buyout cost, lowest levee construction cost, and the shortest payback period.

The analysis above calculates only tangible economic benefits of levee setbacks. Many additional benefits of setbacks were not enumerated here, including reduction in levee maintenance costs (due to decreased total levee length) and habitat benefits from reconnecting large areas of floodplain. Furthermore, the presence of levees and floodwalls has been shown to create a false sense of security, causing increased development within the leveed flood-

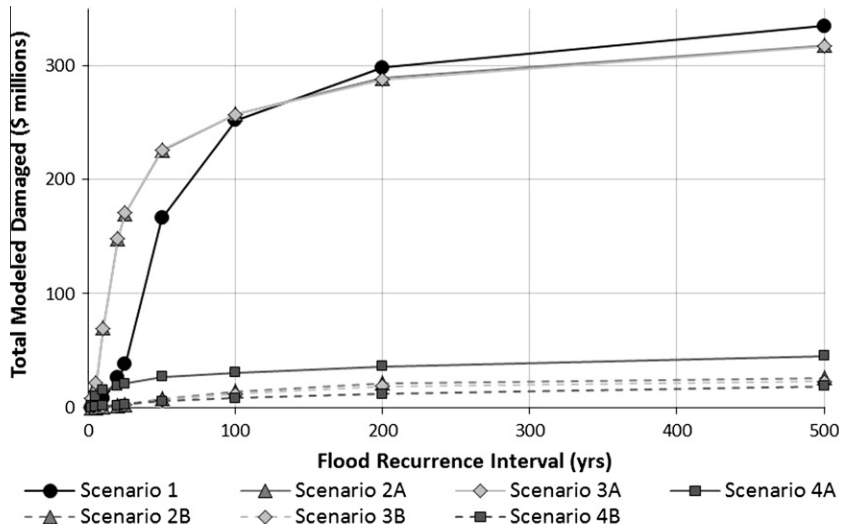

Fig. 4. Damage-probability curves for the agricultural Study Reach.

Table 4
Expected annual damages (EAD).

	EAD ($ millions)	
	Urban Study Reach	Agricultural Study Reach
Scenario 1	21.8	8.9
Scenario 2A	92.3	25.0
Scenario 2B	11.6	0.6
Scenario 3A	67.7	27.3
Scenario 3B	14.8	0.9
Scenario 4A	20.2	5.1
Scenario 4B	9.9	0.6

Table 5
Differences in EAD relative to Scenario 1.

	Urban Study Reach		Agricultural Study Reach	
	Difference (million)	% Difference	Difference (million)	% Difference
Scenario 2A	+$70.5	+323	+$16.1	+181
Scenario **2B**[a]	−$10.2	−47	−$8.3	−93
Scenario 3A	+$45.9	+211	+$18.4	+207
Scenario **3B**[a]	−$7.0	−32	−$8.0	−90
Scenario 4A	−$1.6	−7	−$3.8	−43
Scenario **4B**[a]	−$11.9	−55	−$8.3	−93

[a] Scenarios named with the letter "**B**" include buyouts of unprotected structures.

Table 6
Costs, benefits, and payback period for buyout scenarios.

Scenario	Decrease in EAD ($ millions)	Buyout cost ($ millions)	Levee construction cost ($ millions)	Payback period (yrs)
Urban Study Reach				
2B	$10.2	$271.0	$247.8	51
3B	$7.0	$192.9	$223.6	60
4B	$11.9	$47.6	$85.2	11
Agricultural Study Reach				
2B	$8.3	$138.6	$497.8	77
3B	$8.0	$127.7	$385.7	64
4B	$8.3	$18.9	$49.3	8

plain and contributing to long-term increases in flood damages (Tobin, 1995; Pielke, 1999; Pinter, 2005; Montz and Tobin, 2008). Levee setbacks decrease the amount of leveed floodplain land, decreasing future floodplain development and thereby limiting future flood damages.

5. Conclusions

Hydraulic modeling here confirms that levee setbacks can successfully reduce flood stages for all recurrence intervals. For the 100-year flood, these reductions ranged from 0.20 m for Scenario 3 (1000 m setback) to 1.61 m for Scenario 4 (optimized setback), averaged across the study area. Stage reductions increased with increasing discharge and increasing setback distance. The flood-level reductions result from increased floodwater storage and conveyance across the reconnected floodplain.

The flood-loss estimates here show that levee setbacks, without additional mitigation actions, reduce flood losses for large, infrequent flooding events but increase losses for smaller, more frequent flood events. When combined with buyouts of unprotected structures, levee setbacks reduce flood losses for all recurrence intervals. The 1000 m and 1500 m levee setbacks (Scenarios 3 and 2) must be combined with buyouts in order to reduce EAD relative to the present conditions. An optimized levee setback, manually designed to maintain protection around existing high-value structures (Scenario 4), can reduce damages with or without buyouts. The optimized levee setback configuration combined with buyouts (Scenario 4B) resulted in the largest decreases in EAD, including an $11.9 million (55%) decrease in the Urban Study Reach and an $8.3 million (93%) decrease in the Agricultural Study Reach.

The large reductions in damages for Scenario 4B relative to the current floodplain-management conditions demonstrate that, when used in conjunction with buyouts, carefully designed levee setbacks are an economically viable approach for flood-risk reduction along the two study reaches here and likely elsewhere where levees are widely employed for flood control. The payback periods calculated for Scenario 4B (8 years in the Agricultural Study Reach and 11 years in the Urban Study Reach) demonstrate that designing a levee setback around existing high-value infrastructure can maximize benefits while simultaneously minimizing costs. Potentially, Scenario 4 could be used as a template for the replacement of any aging or failing levee system. All of the net economic benefits above are achieved without adding the large potential additional benefits, tangible and intangible, of levee setbacks, such as habitat restoration, nutrient and carbon sequestration, as well as reduced maintenance costs for the setback levees themselves.

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