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Modeling residual flood risk behind levees, Upper Mississippi River, USA

Nicholas Pinter[a,*], Fredrik Huthoff[b], Jennifer Dierauer[c], Jonathan W.F. Remo[d], Amanda Damptz[c]

[a] Dept. of Earth and Planetary Sciences, University of California, Davis CA 93616, USA
[b] HKV Consultants, Botter 11-29, Lelystad, The Netherlands
[c] Department of Geology, Southern Illinois University, Carbondale, IL 62901, USA
[d] Dept. of Geography and Environmental Resources, Southern Illinois University, Carbondale, IL 62901, USA

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ABSTRACT

Flood protection from levees is a mixed blessing, excluding water from the floodplain but creating higher flood levels ("surcharges") and promoting "residual risk" of flood damages. This study completed 2D hydrodynamic modeling and flood-damage analyses for the 459 km^2 Sny Island levee system on the Upper Mississippi River. These levees provide large economic benefits, at least $51.1 million per year in prevented damages, the large majority provided to the agricultural sector and a small subset of low-elevation properties. However these benefits simultaneously translate into a large residual risk of flood damage should levees fail or be overtopped; this risk is not recognized either locally in the study area nor in national policy. In addition, the studied levees caused surcharges averaging 1.2–1.5 m and locally as high as 2.4 m, consistent with other sites and studies. The combined hydraulic and economic modeling here documented that levee-related surcharge + the residual risk of levee overtopping or failure can lead to negative benefits, meaning added long-term flood risk. Up to 31% of residential structures in the study area, 8% of agricultural structures, and 22% of commercial structures received negative benefits, totaling $562,500 per year. Although counterintuitive, structures at the margin of a leveed floodplain can incur negative benefits due to greater flood levels resulting from levees purportedly built to protect them. National levee policies and plans for local projects are unbalanced, crediting levee benefits but rarely fully planning for adverse impacts or considering alternatives.

1. Introduction

Recent floods in Europe have displaced half a million people and caused >€25 billion in insured economic losses (European Commission, 2014), and in the US flood damages have doubled (ASFPM, 2013). Such spiraling flood impacts are driven in part by increasing hydroclimatic extremes, but also by widespread reliance on structural flood-control measures, including urban floodwalls and levees (known regionally as "dikes", etc.). This research used (1) hydraulic modeling to precisely quantify and map surcharge and (2) economic flood-loss modeling using structure-by-structure assessor data to quantify levee benefits, costs, and residual risk. Analysis focused on the patterns and causes of economic 'negative benefits'—accrued by properties ostensibly protected by levees, but with higher long-term average flood risk than when modeled with no levees present. The purpose of this research was to map the hydraulic and economic impacts of levees in order to inform floodplain science, management, and policy.

US floodplains are lined by up to 161,000 km of levees (National Committee on Levee Safety, 2009), much of this in questionable states of repair. According to current US inspection data (National Levee Database as of 21 Dec., 2015), just 1.9% of levees by distance (by number, 103 of 2207 rated levees) were rated "Acceptable", with 53.7% of the nation's levees rated 'Minimally Acceptable' and 44.5% rated "Unacceptable". In the US, the benchmark for most levees is that they should protect for at least the 100-year recurrence interval flood, meaning the event that has a 1% chance of occurring or being exceeded in any given year. Under the US National Flood Insurance Program, floodplain land behind levees certified as providing ≥100-year protection (which should include 0.9 m [3 ft] of "freeboard", or safety margin) is removed from Special Flood Hazard Area on hazard maps (Federal Emergency Management Agency [FEMA] Flood Insurance Rate Maps). Other

* Corresponding author.
E-mail address: npinter@ucdavis.edu (N. Pinter).

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countries apply more stringent criteria for their levees, including The Netherlands, which requires at least 1250-year protection for river levees (Merz et al., 2010). Benchmarks such as the 100-year or even the 1250-year level are based on stationary flood statistics that may underestimate actual risk on rivers worldwide where both climate change and anthropogenic activities are increasing hydroclimatic extremes (e.g., Pinter et al., 2001; IPCC, 2014).

Levees function by confining flood discharges within the river channel and excluding overbank flows from some or all of the floodplain. This confinement causes higher water-surface elevations in the remaining portion of the channel (known as levee "surcharge"). These surcharges are caused by the loss of storage volume on the floodplain and loss of conveyance capacity (Yen, 1995; Bhowmik and Demissie, 1982; Heine and Pinter, 2011). A US Government Accountability Office study concluded "*[t]hat levees increase flood levels is subject to little disagreement*" (GAO, 1995), but the magnitudes of such surcharges are frequently disputed. Heine and Pinter (2011) surveyed long-term US Geological Survey river gages located close to levee construction projects. Surcharges were present at all sites, ranging from 42 cm up to 2.3 m. On the Mississippi and Missouri Rivers, a suite of large multivariate statistical models suggested up to 2.2 ± 0.2 cm of surcharge per 1% increase in floodplain area put behind levees (Pinter et al., 2008, 2010) —equivalent, for example, to an increase of 2.1 ± 0.2 m for a floodplain that went from 0% to 95% leveed.

Any levee is constructed to function up to a given maximum flood magnitude, above which flow will overtop the levee and flow into the levee-enclosed portion of the floodplain. In addition, some levee breaches occur before water reaches the levee crest for geotechnical reasons such as erosion, under-seepage, or through-seepage (Rogers et al., 2008; Flor et al., 2010; IFMRC, 1994). During widespread flooding in 1993 on the Mississippi River and its

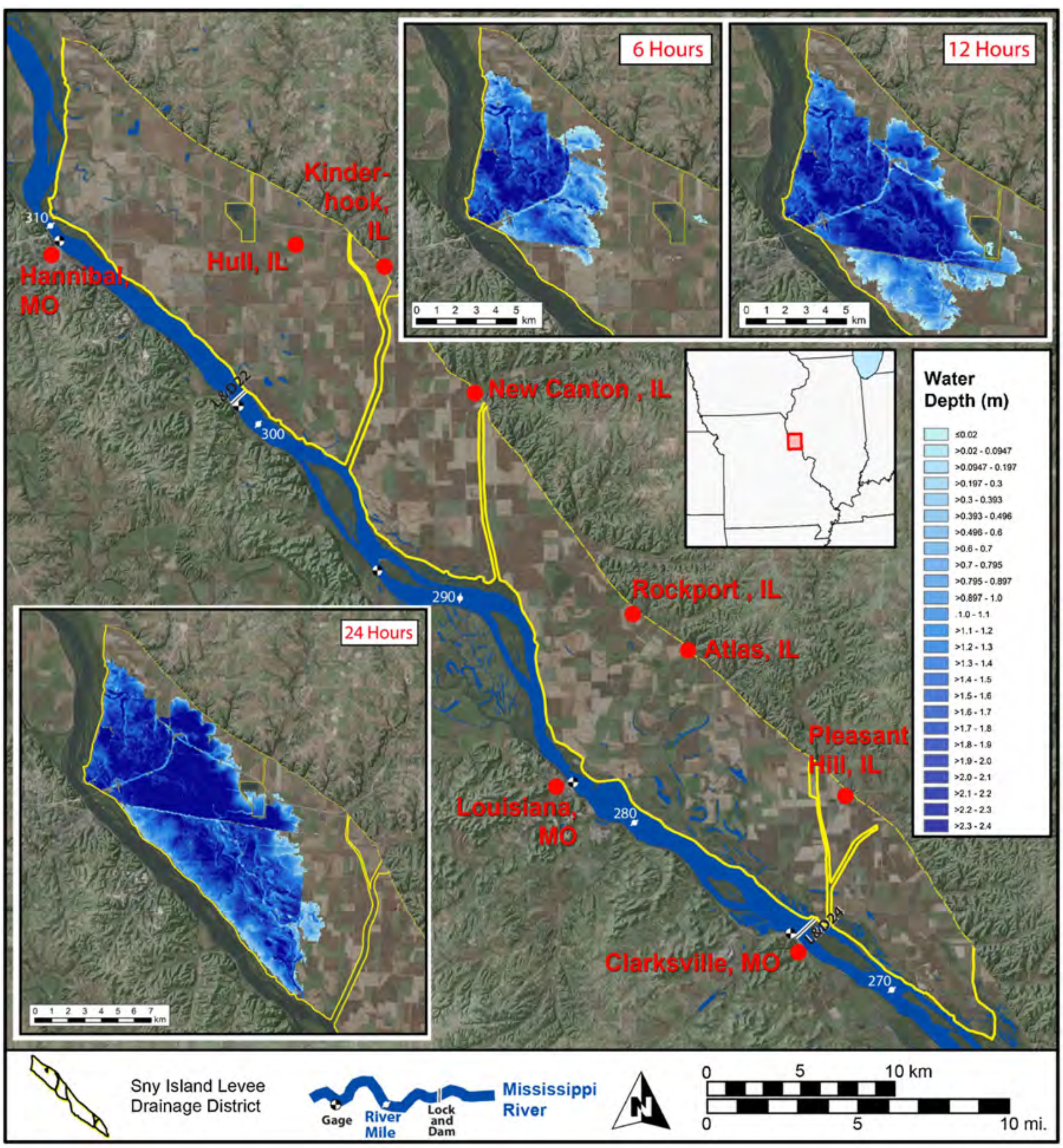

Fig. 1. The study area includes the natural floodplain circumscribed by the Sny Island levee system (yellow lines on map), along the east bank of the upper Mississippi River in Illinois, USA. Insets show water depths 6, 12, and 24 hours after a simulated breach in the upstream Sny levee cell.

tributaries, for example, 1043 of 1345 levees either failed or overtopped (Larsen, 1996; McConkey et al., 1993). Levee failures were also widespread along the Upper Mississippi River during the flood of 2008 (Rogers, 2009). "Residual risk" refers to the long-term potential for flood damages in areas protected by levees. A wide variety of researchers, agencies, and other groups have recognized that realistic assessment of long-term flood risk requires including the possibility of inundation behind levees, including levees that have received 100-year or higher levels of official recognition (USACE, 1996; Pinter, 2005; Bea et al., 2009; Bell and Tobin, 2007; ASFPM, 2007; ASCE, 2010; Ludy and Kondolf, 2012; National Research Council, 2013; Mazzoleni et al., 2014). "*Let no one believe that because you are behind a levee, you are safe*" (Galloway, 2005). Or put more bluntly, "*There are two kinds of levees . . . [t]hose that have failed and those that will fail*" (Martindale and Osman, 2010).

1.1. Study area: The Sny Island Levee District

The Sny Island levee district stretches 72 km from northwest to southeast (Fig. 1) along the east side of the Mississippi River. The Mississippi River channel flows through this reach along the western margin of its alluvial valley, creating a floodplain up to 13 km wide on the eastern (Illinois) bank. The Sny Island levees subdivide the floodplain into four separate levee cells, together circumscribing 459 km^2 of floodplain land. The earliest construction of levees in this area began in 1872, with the Sny Island Drainage and Levee District chartered in 1880 (Gard, 2002). Early levee construction was promoted as a mechanism to protect and drain floodplain land for agriculture. The late 19th and 20th centuries were characterized by cycles of incremental levee construction, punctuated by floods that overtopped or broke the existing levees, driving subsequent construction to increase levee heights. Levee breaks occurred in the Sny District during floods of 1876, 1880, 1881, 1882, 1888, 1903, 1922, 1926, 1927, 1942, 1947, 1955, 1965, and 1993 (Gard, 2002). During the flood of 1993 and despite aggressive flood-fighting efforts, the Sny levee failed on July 25th near RM 311.5. The breach was initially about 122 m wide (400 ft; Gomez et al., 1997), growing thereafter, and inundated the northern portion of the Sny district (Nakato et al., 1996; Magilligan et al., 1998).

As of 1993, the Sny levee system had been designated as protecting against the 50-year flood (≤2% annual exceedance probability), but levee repairs and enhancements after the 1993 flood led in 2004 to accreditation of the Sny levees as protecting to the 100-year level. This accreditation means that the Mississippi floodplain behind the Sny levees is no longer designated as a Special Flood Hazard Area on FEMA maps. The Sny Levee District pursued this map revision for the purpose of "*lessening of flood insurance premiums . . . ,an easing of restrictions on local landowners in further developing facilities . . . and the potential of increased economic development activity in the District*" (SILDD, 2002). Mississippi River floods in 2008 and 2013 did not breach the Sny levees. However, recently the Rock Island District of the Army Corps of Engineers (letter from Col. C.S. Baumgartner, dated 9/9/15) downgraded the Sny levees to an "Unacceptable" rating, primarily due to alleged levee-height increases without authorization or consideration of added surcharge.

2. Methods

For this study, we modeled long-term flood-damage potential that includes detailed hydrodynamic impacts of levees, probabilistic estimation of levee failure, and resulting economic losses using local assessment data. Thus (1) levee surcharges, (2) flood risk, and (3) the economic benefits of levees are all calculated with recognition of the residual possibility of levee failure. Four flood conditions were modeled in this study (Table 1), each with and without the presence of the SILDD levees.

The flood simulations here are hybrid 1D/2D model runs implemented with the SOBEK software package (see Supplementary materials). We coupled a 1D channel flow module for the Mississippi River with a 2D flow module for the floodplain. The study area was defined as the Mississippi River and its floodplain from "Lock and Dam 21 (lower)" gage to the "Lock and Dam 25 (pool)" gage. Flow magnitudes for the 2-yr, 5-yr and 100-yr flood events are from Upper Mississippi River Flow Frequency Study. The 1993 flood, the recurrence of which is estimated at approximately 400 years (annual exceedance probability of 0.0025), was modeled here using the observed hydrograph as an unsteady-flow simulation. The 2-yr, 5-yr, and 100-yr simulations were run using steady-flow conditions. For full methodological details, see Supplementary materials.

The 2D overland flow module was constructed based on floodplain topography, the locations and dimensions of bridges and culverts on the floodplain, and land cover for estimation of hydraulic roughness. Topographic data included LiDAR based (1 m)

Table 1
Modeling and analytical scenarios used in this study.

	No-Levee Scenarios (without levees)	Present conditions (without levees)	
2-year flood	2-yr flood w/o levees	2-yr w/levees	• No levee breach • Cell 1 breach • Cell 2 breach • Cell 3 breach • Cell 4 breach
5-year flood	5-yr flood w/o levees	5-yr w/levees	• No levee breach • Cell 1 breach • Cell 2 breach • Cell 3 breach • Cell 4 breach
100-year flood	100-yr flood w/o levees	100-yr w/ levees	• No levee breach • Cell 1 breach • Cell 2 breach • Cell 3 breach • Cell 4 breach
1993 flood (~400-year flood)	400-yr flood w/o levees	400-yr w/ levees	• No levee breach • Cell 1 breach • Cell 2 breach • Cell 3 breach • Cell 4 breach

and 1/9 arc-second (3 m) resolution Digital Elevation Models (DEMs). We added 1D hydraulic elements to simulate flow beneath bridges and through culverts (openings beneath elevated roadways) large enough to act as significant conduits for flow. We used US Geological Survey (UMESC, 2002) land-cover data to determine hydraulic roughnesses across the floodplain (see Supplementary materials).

The four flood conditions in this study (2-, 5-, 100-, and ~400-year [1993] floods) were each modeled with and without the presence of the Sny Island levees. For the flood scenarios without levees present, a modified floodplain DEM was constructed with all outer levees removed. Internal levees (around drainage canals and sedimentation reservoirs) were partly removed, such that they no longer created separate compartments in the levee cell. For each of the flood conditions, four additional simulations were run—each modeling the breach of one of the four different levee cells. The failure location was set with an initial breach of 122 m (400 ft; initial size of the 1993 breach) that enlarged over time using the Verheij-vdKnaap formula for growth of a sand-type levee breach. We assumed that failure of any one of the Sny levee cells would lower water levels on the Mississippi sufficiently that none of the other levee cells would breach in the same flood event. This assumption is realistic for the range of flood magnitudes spanned here, and is confirmed by the observed hydrograph of the 1993 flood.

2.1. Flood-damage modeling

FEMA's Hazus-MH flood model (see Supplementary material) was used to estimate structural flood damages and crops losses for each hydraulic modeling scenario using assessor records from the three Illinois counties (Pike, Calhoun, and Adams). Assessor records included 697 parcels with residential structures and 225 parcels with agricultural structures. The location of the primary structure on each parcel was identified using aerial orthophotos and moved to its correct location within each parcel. We also utilized Hazus-MH to estimate crop losses, and corresponding damage prevention by levees, using the Hazus agricultural loss module. Required inputs for determing crops losses include mapped or modeled flood area, date of flood occurrence, and estimated flood duration (3, 7, or 14 days; see Suppl. Mat. for full details). In addition, an inventory of commercial properties within the levee-protected portion of the study area was assembled based on county assessor records and field surveys.

2.2. Levee failure probabilities

Calculation of residual risk behind a levee incorporates the probabilities of a flood exceeding the design height of the structure or the levee failing before the design limit is reached. We used a levee-failure function derived from a US Army Corps of Engineers (USACE) model for planning studies for a levee of "average reliability" (USACE, 1999):

$$P_f = 0.36 * \tan^{-1}(10.3 * (\mathrm{WSEL} - h_{min})/(h_{max} - h_{min}) - 7.2) + 0.52 \quad (1)$$

Using this function, the probability of failure (P_f) varies smoothly from 0 when the water surface is at or below the levee toe (h_{min}) to 1.0 (100%) when water reaches the levee crest (h_{max}). Flood damages for each scenario were calculated as the probability of failure of each levee cell in the study area multiplied by the damages that would occur if such a breach occurred. We calculated damages and benefits using (1) the "average reliability" curve above; (2) levees with an additional 1.2 m (4.0 ft) of protection, for example due to extreme flood-fighting measures; and (3) indestructible levees that never fail under any condition.

All modeling in this study was designed to compare damages under present-day conditions (with levees) with damages for the same flood events if no levees were present. Thus:

$$\text{Levee benefit} = \text{No-levee damages} - \text{With-levee damages} \quad (2)$$

For each class of properties within the study area (residential, commercial, and agricultural), the benefit received from levees is the probability-weighted annualized flood damages that would exist if no levees existed minus the damages they face today with levees. This calculation includes only the flood-risk benefit of

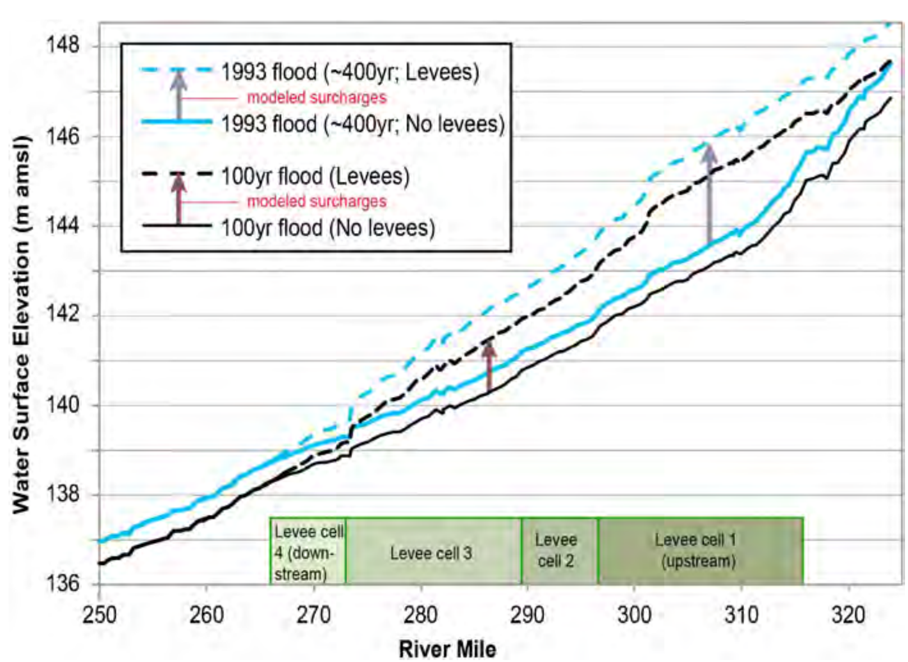

Fig. 2. Water-level profiles for the 100-yr and 1993 (~400-yr recurrence interval) flood events, with and without levees in the study area. The difference between each pair of line represents the surface at each location, meaning the additional flood stage caused by the presence of the levees.

levees (i.e., their primary purpose); it does not include other factors, including potential benefits such as pumping service provided to farmers by the levee district, nor adverse effects such as increased erosional scour if a levee breaks (vs. more gradual inundation if no levees were present).

3. Results and significance

3.1. Hydraulics: results

Hybrid 1D/2D modeling of flooding in the study area illustrates water depths and velocities over time both within the main Mississippi River channel and at floodplain locations across the study area, with and without the Sny levees present (Fig. 1 insets; Fig. 2). Assuming no breaches, the water levels for the 2-year flood (5918 cms at Hannibal) along the Mississippi River averaged 0.2 m higher when modeled with levees (present-day conditions) compared to the identical model with levees removed, 0.5 m higher for the 5-year flood, 1.3 m higher for the 100-year flood (steady-flow simulation) and the measured 2008 flood (unsteady flow simulation), and 1.5 m (4.9 ft) higher for the 1993 flood (Table 2; Fig. 2). The maximum values in Table 2 show the greatest computed differences at any point in the modeled study reach between with-levee and no-levee water levels, ranging from 0.4 m for the 2-year flood up to 2.4 m (7.9 ft) higher water levels for the 1993 flood.

3.2. Hydraulics: significance

Detailed 2D floodplain flow modeling helps to parse out the relative effects of storage vs. conveyance on water levels during floods. Some previous studies have asserted that most or all of water-level increase associated with levees is due to the loss of storage volume on the floodplain (Dyhouse, 1985; Helms et al., 2002). In contrast, other studies have shown that up to 70–90% of total flood flux can be conveyed on the floodplain (Bhowmik and Demissie, 1982; Silva et al., 2001; Heine and Pinter, 2011). The 2D modeling here illustrates the significance of floodplain conveyance, in particular by the 16 levee-breach simulations. Although each levee failure was simulated near the flood peak—i.e., optimum timing for floodplain storage benefits (Helms et al., 2002)—flood levels in the breach simulations were still up to 0.6 m higher than in the no-levee scenarios. These residual surcharges, even when the levees failed or were overtopped, were driven by loss of conveyance due to the remaining, unbreached lengths of levee.

3.3. Flood-loss modeling: results

Although this study area is rural, its levees protect significant infrastructure: $39.3 million in residential structures, $3.2 million commercial, and $6.5 million in agricultural structures. We compared annualized flood losses with and without levees, modeling identical flow magnitudes, and found that the large majority of levee benefits were accrued by the agricultural sector (Table 3). Average annual reductions in crop losses were estimated between ~$47.5 and $52.2 million. An additional $2.7–3.1 million

Table 3
Annualized damages for each property class in the study, including damages with no Sny levees present and with all present-day levees in place. Annualized levee benefits are the difference between damages with levees and damages without levees. Results from the use of three different levee-failure probability (P_f) functions are shown.

	Commercial		
	USACE P_f	Flood-fighting P_f	No-fail levees
No levees	$1,805,044	$1,805,044	$1,805,044
With levees	$1,923,665	$1,812,693	$0
Levee benefit ($/yr)	−$118,621	−$7,649	$1,805,044
	Crop losses		
	USACE P_f	**Flood-fighting P_f**	**No-fail levees**
No levees	$56,082,073	$56,082,073	$56,082,073
With levees	$8,595,544	$3,856,563	$0
Levee benefit ($/yr)	$47,486,526	$52,225,509	$56,082,073
	Agricultural structures		
	USACE P_f	**Flood-fighting P_f**	**No-fail levees**
No levees	$3,483,911	$3,483,911	$3,483,911
With levees	$813,983	$384,155	$0
Levee benefit ($/yr)	$2,669,928	$3,099,756	$3,483,911
	Residential		
	USACE P_f	**Flood-fighting P_f**	**No-fail levees**
No levees	$2,088,917	$2,088,917	$2,088,917
With levees	$1,029,015	$469,923	$0
Levee benefit ($/yr)	$1,059,902	$1,618,994	$2,088,917

per year of flood-prevention benefits was accrued to agricultural structures in the study area. These agricultural benefits substantially exceeded benefits to other sectors. Levees in the study area provide $1.1–1.6 million in annualized flood-damage prevention to residential structures. Our inventory of 32 commercial structures in the study area included three located outside the levees; excluding those three, the Sny system provided up to $120,000 per year in net flood prevention to the remaining commercial properties. Including those three structures, however, commercial properties in the study area received −$118,600 in flood prevention benefits (Table 3)—meaning a net increase (not decrease) in flood hazard (see Section 3.3.1 below).

3.3.1. Positive versus negative levee benefits

Whereas many floodplain occupants accrue positive economic benefits due to the prevention of flood damages, structure-by-structure loss modeling here identifies a significant subset of floodplain structures for which long-term flood risk was, on the contrary, increased by the presence of the same levees. Up to 309 residential structures (31% of total), 19 agricultural structures (8%) and 10 commercial structures (32%) in the study area were estimated to have negative levee benefits (Fig. 3). Negative benefits result from the combination of (1) levee surcharge and (2) residual risk – higher water levels caused by levees combined with the long-term possibility of levee overtopping or failure. Looking at the 1010 residential parcels in the study area, 360 received a net positive benefit, 309 a negative benefit, and 341 a zero benefit (outside the flood-depth grid for all modeled floods), using the USACE levee-failure probability function. Negative levee benefits for residential structures ranged up to 5.87% per year of their value. Using the more conservative flood-fighting levee-failure function,

Table 2
Water-level surcharges in the Mississippi River attributable to levees in the study area.

Flood scenarios	Av. difference in water level (m)	Max. difference in water level (m)
2-yr	0.2	0.4
5-yr	0.5	0.9
100-yr	1.3	2.1
2008 flood (max H)	1.3	2.1
1993 flood (max H)	1.5	2.4

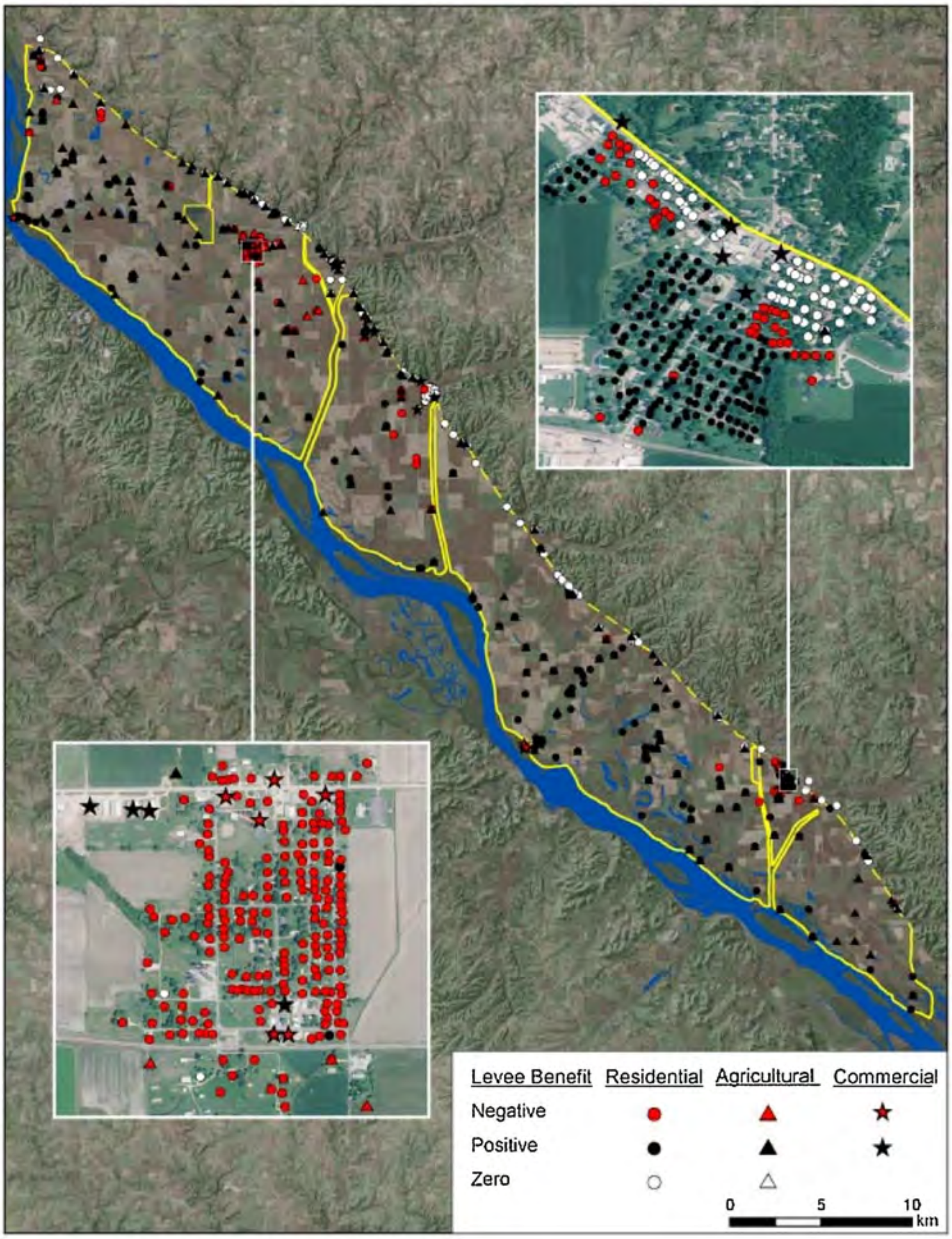

Fig. 3. Levee benefit equals average annualized flood damages without levees present minus damages with the levees present. Some residential, agricultural, and commercial structures in the study area accrue net positive benefits, whereas many structures accrue negative benefits, meaning increased flood risk as a result of the levees. Values shown here were calculated using the preferred (USACE) levee-failure probability function, and more conservative functions shift benefits towards more positive values.

the balance shifted somewhat—to 424 residential structures with positive benefits and 245 with negative benefits. Most negative-benefit structures were concentrated near the inland margin of the floodplain, where most of the study area's towns are located, whereas most of the positive-benefit structures are located across the floodplain closer to the river and at lower elevations.

We modeled flood damages and levee benefits for the 32 commercial properties in our inventory for the study area, which included 29 structures within the levees and three structures located on the river side of the levees (a marina, a restaurant, and a grain storage facility). Together, these commercial properties include about \$6.3 million in assessed structure value and another ~\$6.3 million in estimated content value. The commercial properties included some structures located in the towns, generally at the margin of the floodplain, as well as other structures at lower elevations and closer to the river. The flood damage and levee-benefit results varied with elevation, ranging from relatively large positive benefits at low elevations on the floodplain to negative values for properties at higher elevations. When analysis was limited to only the 29 structures within the levees, the total benefit for all of those commercial properties was \$13,500 per year using the USACE levee-failure function and about \$120,000 per year in benefits using the flood-fighting levee function. However, the three additional commercial properties, being located outside of the levees, received significant water-level surcharges from the Sny levees without any benefits in terms of reduced flood frequency. Therefore the cumulative commercial levee benefit for all 32 structures was negative: −\$118,600 per year using the USACE levee-failure function and −\$7,600 per year using the flood-fighting function. Looking at individual commercial properties, 10 of the 32 had negative benefits (7 inside the levees and 3 outside) using the USACE levee-failure function and 7 of the 32 using the flood-fighting function (4 inside; 3 outside).

Most agricultural structures in the study area are located in the lower-lying and more distal areas of the floodplain. The 227 parcels with taxable agricultural structures had a cumulative assessed structural value of $6,531,990 (+100% default content value applied by Hazus-MH to agricultural structures). Using the USACE levee-failure probability function, 206 agricultural structures derived a positive levee benefit, 19 structures (8.4%) derived a negative benefit, and 2 had zero benefits (located outside of the flood-depth grids). Among the relatively small number of negative-benefit properties—generally farms located near the inland margin of the floodplain—negative benefits ranged up to 5.03% per year of assessed structural value. Using the flood-fighting levee-failure function, the cumulative agricultural-structure benefit increased to $3,100,000, and only one of the 227 agricultural structures received a negative benefit.

3.4. Flood-loss modeling: significance

Although the cumulative totals of benefits in the study areas were mostly positive, the large majority of these totals were concentrated in a small subset of structures. For example, the 100 residential structures (~10%) with the greatest annualized benefits comprised fully 124% of the total cumulative benefit (Fig. 4), meaning that the remaining 910 structures (~90%) had a net negative benefit as a group. Using the more conservative levee-failure probability function, this balance shifted—to 424 structures with positive benefits and 245 with negative benefits. Similarly, the commercial properties in the study area spanned a broad range of benefit values, from large positive benefits (up to 13% per year of their assessed structural value) to large negative benefits (down to −12% per year of their assessed structural value). The total sum of benefits for all commercial properties was positive when the three properties outside of the levee were excluded, but commercial benefits were negative as a group when those three properties were included (for both levee-failure functions tested).

4. Discussion

4.1. Levee-related surcharges

Levees protect by excluding flood flows from the floodplain, which increases flood stages in surrounding areas and on that levee itself. In our study area, modeled water-level profiles in the Mississippi channel show that, while the Sny Island levees do protect the floodplain against small to moderate flood events, this protection results in water levels much higher than if the levees were not present at all (Fig. 2). The maximum values ranged up to 2.4 m (7.9 ft) higher water levels attributable to the Sny levee system for a flood of the magnitude of the 1993 event. These results are consistent with the surcharges empirically documented in Heine and Pinter (2011) and Pinter et al. (2008, 2010). The largest surcharge modeled for the Sny levees (2.4 m) is similar to the 2.3 m surcharge documented following levee construction on the Wabash River at Mt. Carmel (Heine and Pinter, 2011); in both cases, the levee systems are large and extensive, spanning >90% of the available floodplain area. Such surcharges associated with progressive construction of the Sny levee system help to explain, in part, the large increases in flood magnitudes and frequencies documented by Criss and Winston (2008) across the river at Hannibal Missouri.

4.1.1. Policy implications of levee surcharges and residual risk

Levee surcharges drive a “hydrologic spiral” in which new and higher levees result in higher floods, which in turn drive demand for more and higher levees. Recognition and rejection of this hydrologic spiral in The Netherlands was the impetus for their new “Room for the River” flood-management strategy (e.g., Silva et al., 2001; Klijn et al., 2012). However political pressure for new and larger levees remains strong in the US. The Upper Mississippi River Comprehensive Plan calls for $4–6 billion in enlarged levees along most of the Upper Mississippi River despite a maximum benefit-to-cost (B/C) ratio of only 0.05 ($0.05 of benefit per $1.00 invested; (USACE, 2008)). The plan received endorsements from the Mississippi River Commission and the Governors of Missouri,

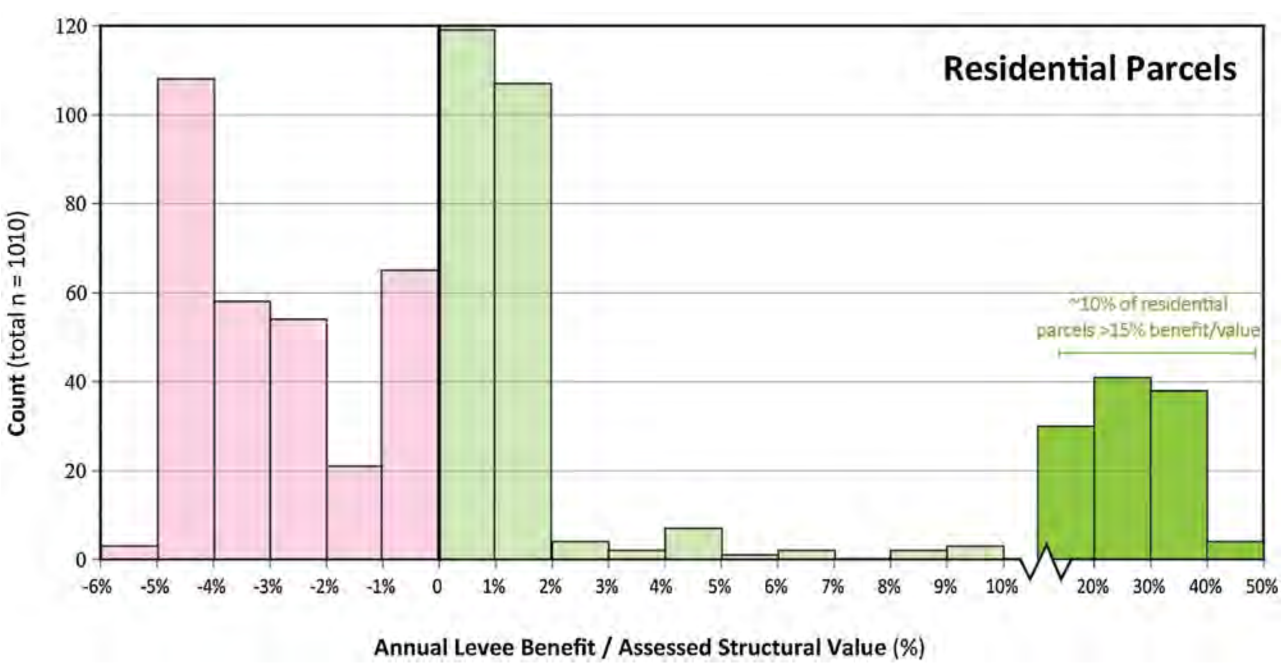

Fig. 4. For residential parcels in the study area, annualized levee benefit (damages without levees minus damages with levees present) as a percent of assessed value of each structure. Parcels with zero benefits (outside of modeled flood-depth grids) are not included. Values here are using the USACE levee-failure probability function.

Illinois, and Iowa and continues to enjoy considerable support. Such plans eschew lessons from the catastrophic 1993 flood that flood defenses should be strengthened in areas of concentrated infrastructure like cities, but levees in rural and undeveloped areas should be assessed for alternatives such as setbacks (SAST, 1994). And, importantly, that residual risk should be recognized and reflected in public outreach and insurance requirements (SAST, 1994).

The result is that, despite many billions invested in flood-control infrastructure across the US, flood damages have doubled in the past two decades (ASFPM, 2013). These increases have been driven, in large part, by the failure to recognize the residual risk of flooding. In Illinois, for example, less than 3% of the people living behind levees carry flood insurance (Martindale and Osman, 2010).

4.1.2. FEMA Levee Analysis and Mapping Procedure

In February of 2011, several US Senators and Representatives asked FEMA to reassess its all-or-nothing approach to levee accreditation and sought partial credit for levees that fell short of the 100-year protection threshold. In response, FEMA developed an alternative Levee Analysis and Mapping Procedure (LAMP). In 2013, the US National Research Council completed an assessment of LAMP and recommended that FEMA abandon LAMP because the effort represents a "*diversion of NFIP [National Flood Insurance Program] effort away from the long-recognized need to move the NFIP to risk-based analysis*" (NRC, 2013). Our study documents the tangible flood-prevention benefits of levees, which apply even to levee systems that do not meet the 100-year threshold. However, this study also illustrates rigorous calculation of flood risk for levee-protected structures, as advocated by the NRC (2013) and many others. The political pressure for LAMP is one-sided, seeking reduced flood-hazard mapped area and insurance rate reductions for floodplain residents behind non-accredited levees, but with no corresponding recognition of the residual risk behind accredited ≥100-year levees. A comprehensive, risk-based approach to levee-protected areas would address both issues.

4.2. Negative levee benefits

Negative-benefit structures in the Sny Island study area were concentrated at higher elevations, generally near the inland margin of the floodplain. Hydraulic modeling with the levees removed suggests that many of these structures would remain dry (zero damage) even for the largest discharges modeled without levees. Increased flood risk resulted from greater flood occurrence and inundation depths with Sny levees present. When the Sny Island levees were accredited as protecting at the 100-year level, all structures on that portion of the floodplain were removed from the Special Flood Hazard Area designated on FEMA maps, and restrictions on development and requirements placed on insurance and mortgage lending were removed. Residents and property owners behind levees or considering new or enlarged levees should be made aware that, in some cases, this structural protection may counterintuitively increase their long-term exposure to flooding, not eliminate it.

4.3. Other Levee-related costs and benefits

The calculations of levee-related benefits and costs here include only a subset of the broad range of real-world levee impacts. For example, without the Sny levees, modeled flood velocities in the Mississippi River were lower, for example up to 20% lower near the railroad bridges that span the river at the towns of Hannibal and Louisiana. Higher velocities, especially at the bridges and bridge approaches, resulted in scour damage in both 1993 and 2008. Similarly, the 2D modeling here replicated the high flow velocities at levee breaches, which historically cause significant flood-related damage (Rogers, 2009; Gard, 2002; Izenberg et al., 1996; Mazzoleni et al., 2014). Inundation of un-leveed floodplains is gradual and typically does not cause extensive scour. Finally, the modeling here documented levee-driven surcharges on the opposite bank of the Mississippi River. Portions of Hannibal, MO are protected by a floodwall, but this study shows that the town receives up to 2.4 m of additional flood stage due to the presence of the Sny levees.

Lastly and importantly, levee protection is a tangible economic benefit, but one that comes with substantial additional costs to the floodway ecosystem. Natural floodplains are some of the richest and most diverse habitats on earth and owe this diversity primarily to their hydrological connectivity to the river channel (Tockner and Stanford, 2002). Large levee systems sever this connectivity and thus significantly degrade floodplain and channel habitats and reduce the ecosystem services provided by river corridors (Tockner et al., 1999; Opperman et al., 2009). Along with other processes, levees have contributed to the loss of roughly 57% of the original wetlands that existed across the Midwestern US (SAST, 1994; Hey and Philippi, 1995; Gergel et al., 2002).

5. Conclusions

A wide range of previous research has shown that levee protection is a mixed blessing. By excluding flood waters from the floodplain, levees create a surcharge—higher water levels than would be experienced were the levees not present. For the 459 km^2 Sny Island levee system, Mississippi River water levels would be lower by an average of 1.2–1.5 m (4–5 ft) without the levees present; local water-level reductions were up to 2.4 m (8 ft; e.g., at the town of Hannibal, Missouri). We compared average annualized flood damages, calculated using structure-by-structure assessed property values, for with-levee and no-levee model scenarios with identical flow magnitudes, and found that levees in the study area do prevent net damage when floodplain areas behind these levees are considered as a whole. The large majority of these levee benefits were accrued by the agricultural sector, including reductions in average crop losses and prevention of damage to agricultural structures. Among all classes of beneficiaries, flood-damage benefits were geographically stratified, with the greatest benefits to those properties and structures at the lowest elevations and generally closest to the river channel. An unexpected result, however, was the identification of a significant subset of floodplain occupants for whom long-term average flood risk was, on the contrary, increased by the presence of the same levees. Up to 31% of residential structures (309 of 1010), 8% of agricultural structures (19 of 227), and 32% of commercial structures (10 of 32) in the study area were estimated to have negative levee benefits, ranging up to 5.87% per year of those structure's assessed value.

Residual risk refers to the potential for flood damages on a natural floodplain, even behind a levee or other flood-control structure. When the Sny Island levees were accredited in 2008 as protecting at the 100-year level, all structures on that portion of the floodplain were removed from the Special Flood Hazard Area designated on FEMA maps, and restrictions on development and requirements placed on insurance and mortgage lending were removed. This national policy runs contrary to sage advice to the contrary—"*Let no one believe that because you are behind a levee, you are safe*" (Galloway [Brig. Gen., USACE, Ret.], 2005).

Residual risk, surcharges, and negative benefits represent negative impacts of levees but, conversely, the prevalence of levees across the US represents a broad opportunity for flood-risk reduction. Any large surcharge represents a targeted opportunity to reduce flood levels for neighboring areas – for example, for population and/or high-value commercial centers—through measures such as levee setbacks, bypass channels, floodplain storage, levee removal or notching, or other floodplain reconnection measures (e.g., Opperman et al., 2009). The Netherlands has invested more than €13 billion in such levee alternatives as the guiding principle of its national "Room for the River" approach to managing flood hazard (Wolsink, 2006; Klijn et al., 2012). In the US, research has shown that such measures can be both hydraulically effective as well cost-beneficial (e.g., Dierauer et al., 2012) and would yield large additional benefits to habitat, floodplain biodiversity, and provision of ecosystem services.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.`01.003.

References

American Society of Civil Engineers (ASCE), 2010. So You Live Behind a Levee. American Society of Civil Engineers, Washington DC.

Association of State Floodplain Managers (ASFPM), 2013. Flood Mapping for the Nation: A Cost Analysis for the Nation's Flood Map Inventory. Available online at: http://www.floods.org/ace-files/documentlibrary/2012_NFIP_Reform/Flood_Mapping_for_the_Nation_ASFPM_Report_3-1-2013.pdf.

Bea, R., Mitroff, I., Farber, D., Foster, H., Roberts, K.H., 2009. A new approach to risk: the implications of E3. Rick Manage. 11, 30–43.

Bell, H., Tobin, M., 2007. Efficient and effective? The 100-year flood in the communication and perception of flood risk. Environ. Hazards 7, 302–311.

Bhowmik, N.G., Demissie, M., 1982. Carrying capacity of flood plains. J. Hydraul. Div., ASCE 108, 443–452.

Criss, R.E., Winston, W.E., 2008. Public safety and faulty flood statistics. Environ. Health Perspect. 116, A2.

Dierauer, J., Pinter, N., Remo, J.W.F., 2012. Evaluation of levee setbacks for flood-loss reduction, Middle Mississippi River, USA. J. Hydrol. 450, 1–8.

Dyhouse, G.R., 1985. Levees at St. Louis–More harm than good? in W.R. Waldrop (ed.), Hydraulics and Hydrology in the Small Computer Age: Proceedings of the Specialty Conference. American Society of Civil Engineers Hydraulics Division, p. 390–395.

European Commission, 2014. A European Flood Action Programme. http://ec.europa.eu/environment/water/flood_risk/impacts.htm Last updated: 27/08/2014.

Flor, A.D., Pinter, N., Remo, J.W.F., 2010. Evaluating levee failure susceptibility on the Mississippi River using logistic regression analysis. Eng. Geol. 116, 139–148.

Galloway, G., 2005, cited in Armah, J., H. Ayan, C., Bernard, A., Blumenhal, L., Fortmann, L.R., Garretson, C., Goodwin, W.D., Runolfson, T.B., Davis, J. Vano, and R.O. Zerbe Jr, 2009. Principles and guidelines for evaluating federal water projects: U.S. Army Corps of Engineers planning and the use of benefit cost analysis: A report fort he Congressional Research Service. Evans School of Public Affairs, University of Washington, Accessed 10/31/14 at http://fas.org/irp/agency/dhs/fema/evans.pdf.

Gard, W.T., 2002. The Sny Story: The Sny Island Levee Drainage District and Sny Basin. North Richland Hills. Smithfield Press, Texas.

General Accounting Office (GAO), 1995. Midwest Flood: Information on the Performance, Effects, and Control of Levees. U.S. Government Document, GAO/RCED-95-125, 75 pp.

Gergel, S.E., Dixon, M.D., Turner, M.G., 2002. Consequences of human-altered floods: Levees, floods, and floodplain forests along the Wisconsin River. Ecol. Appl. 12, 1755–1770.

Gomez, B., Phillips, J.D., Magilligan, F.J., James, L.A., 1997. Floodplain sedimentation and sensitivity: summer 1993 flood, Upper Mississippi River valley. Earth Surfaces Process Landforms 22, 923–936.

Heine, R.A., Pinter, N., 2011. Levee effects upon flood levels: an empirical assessment. Hydrol. Process. doi:http://dx.doi.org/10.1002/hyp.8261.

Helms, M., Büchele, B., Merkel, U., Ihringer, J., 2002. Statistical analysis of the flood situation and assessment of the impact of diking measures along the Elbe (Labe) river. J. Hydrol. 267, 94–114.

Hey, D.L., Philippi, N.S., 1995. Flood reduction through wetland restoration: the Upper Mississippi River Basin as a case history. Restor. Ecol. 3 (1), 4–17.

Interagency Floodplain Management Review Committee [IFMRC], 1994. Sharing the challenge: Floodplain management into the 21st Century. US Government Printing Office, Washington, DC, pp. 191.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA.

Izenberg, N.R., Arvidson, R.E., Saatchi, S.S., Osburn, G.R., Dohrenwend, J., 1996. Erosional and depositional patterns associated with the 1993 Missouri River floods inferred from SIR-C and TOPSAR radar data. J. Geophys. Res. 101 23,1`49-23,167.

Klijn, F., Knoop, J.M., Ligtvoet, W., Mens, M.J.P., 2012. In search of robust flood risk management alternatives for the Netherlands. Nat. Hazards Earth Syst. Sci. 12, 1469–1479.

Larsen, L.W., 1996. The Great USA Flood of 1993. Presented at IAHS Conference, Anaheim, CA, June 24-28, 1996. (Last accessed 11/18/2014 at http://www.nwrfc.noaa.gov/floods/papers/oh_2/great.htm).

Ludy, J., G.M., Kondolf, 2012. Flood risk perception in lands protected by 100-year levees. Natural Hazards, doi10.1007/s11069-011-0072-6.

Magilligan, F.J., Phillips, J.D., James, L.A., Gomez, B., 1998. Geomorphic and sedimentological controls on the effectiveness of an extreme flood. J. Geol. 106, 87–95.

Martindale, B., and P. Osman, 2010. Why the concerns with levees; They're safe, right? Illinois Association for Floodplain and Stormwater Management, (accessed 10.31.14) at http://www.illinoisfloods.org/documents/IAFSM_Levee%20Article.pdf.

Mazzoleni, M., Bacchi, B., Barontini, S., Di Baldassarre, G., Pilotti, M., Ranzi, R., 2014. Flooding hazard mapping in floodplain areas affected by piping breaches in the Po River, Italy. J. Hydraul. Eng. 19, 717–731.

Merz, B., Hall, J., Disse, M., Schumann, A., 2010. Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci. 10, 509–527.

McConkey, S., Allan, K., Pollock, B., 1993. 1993 Mississippi River record stages and levee failures along the Illinois border. Illinois State Water Survey, 163. Miscellaneous Publication, pp. 41.

Nakato, T., Johnson, S., Johnson, D., Jones, D., 1996. Levee System along the Upper Mississippi River. Proceedings of the International Workshop on Floodplain Risk Management, 11-13 November 1996, Hiroshima, Japan, 107-120.

National Committee on Levee Safety 2009. Report to Congress on Recommendations for a National Levee Safety Program. http://www.iwr.usace.army.mil/ncls/.

National Research Council (NRC), 2013. Levees and the National Flood Insurance Program: Improving Policies and Practices. National Academies Press, Washington, DC.

Opperman, J.J., Galloway, G.E., Fargione, J., Mount, J.F., Richter, B.D., Secchi, S., 2009. Sustainable floodplains through large-scale reconnection to rivers. Science 326, 1487–1488.

Pinter, N., 2005. Policy Forum: one step forward: two steps back on U.S. floodplains. Science 308, 207–208.

Pinter, N., Thomas, R., Wlosinski, J.H., 2001. Flood-hazard assessment on dynamic rivers. Eos: Trans. Am. Geophys. Union 82 (31), 333–339.

Pinter, N., Jemberie, A.A., Remo, J.W.F., Heine, R.A., Ickes, B.S., 2008. Flood trends and river engineering on the Mississippi River system. Geophys. Res. Lett. 35, L035987. doi:http://dx.doi.org/10.1029/2008GL035987.

Pinter, N., Jemberie, A.A., Remo, J.W.F., Heine, R.A., Ickes, B.A., 2010. Empirical modeling of hydrologic response to river engineering, Mississippi and Lower Missouri Rivers. River Res. Appl. 26, 546–571.

Rogers, J.D., 2009. Overview of post-flood surveys of the Upper Mississippi River valley in the summer of 2008. In: Criss, R.E., Kusky, T.M. (Eds.), Finding the balance between floods, flood protection, and river navigation, Proceedings of a conference held November 11, 2008 at St. Louis University: St. Louis, MO, St. Louis University Center for Environmental Sciences, pp. 41–46.

Rogers, J.D., Boutwell, G.P., Schmitz, D.W., Karadeniz, D., Watkins, C.M., Athanasopoulos, A.G., Cobos-Roa, D., 2008. Geologic conditions underlying the 2005 failure of the 17th street canal levee failure in New Orleans. ASCE J. Geotech. Geoenviron. Eng. 134, 583–601.

Scientific Assessment and Strategy Team (SAST), Interagency Floodplain Management Review Committee, 1994. Science for Floodplain Management into the 21st Century: Preliminary Report. Washington, DC.

Silva, W., F. Klijn, J. Dijkman, 2001. Room for the Rhine Branches in the Netherlands. Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling: Lelystad, The Netherlands

Sny Island Levee Drainage District (SILDD), Board of Commissioners, 2002. 2002 Annual Newsletter, Accessed 10/30/2014 at http://www.snyisland.org/newsletter.htm.

Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. Environ. Conserv. 3, 308–330.

Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F., Ward, J., 1999. Hydrological connectivity and the exchange of organic matter and nutrients in a dynamic river floodplain system (Danube, Austria). Freshwater Biol. 41, 521–535.

U.S. Army Corps of Engineers (USACE), 1996. Engineering and design risk-based analysis for flood damage reduction studies. Report EM1110-2-1619, Washington, DC.

U.S. Army Corps of Engineers [USACE], 1999. Risk Analysis in Geotechnical Engineering for Support of Planning Studies. ETL 1110-2-556, Washington, D.C.

U.S. Army Corps of Engineers [USACE], 2008. Upper Mississippi River Comprehensive Plan: Main Report. Rock Island District. USACE: Final Report, dated June, 2008, 133 pp.

Upper Midwest Environmental Sciences Center (UMSEC) 2002. 2000 LCU Data for the Upper Mississippi River System. http://www.umesc.usgs.gov/data_library/land_cover_use/2000_lcu_umesc.html.

Wolsink, M., 2006. River basin approach and integrated water management: Governance pitfalls for the Dutch Space-Water-Adjustment Management Principle. GEOFORUM 37, 473–487.

Yen, B. C., 1995. Hydraulics and Effectiveness of Levees for Flood Control. Paper presented at: U.S.- Italy Research Workshop on the Hydrometeorology, Impacts, and Management of Extreme Floods, November 1995.