Title: Modeling the effects of levee setbacks on flood hydraulics

Running title: Levee setback hydraulics

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Modeling the effects of levee setbacks on flood hydraulics

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Abstract

Relocating levees further back from river channels to increase river-floodplain connection can reduce flood stages and provide a host of co-benefits. Modeling case studies show the significant potential of large levee setbacks for reducing flood stages; however, the difficulty of comparing between these case studies limits our understanding of how the hydraulic effects of setbacks vary in different settings. We filled this research gap by systematically modeling the hydraulic effects of setbacks across a range of river and flood conditions. We used unsteady, 1-D HEC-RAS models to quantify changes in flood stage, channel velocity, and sediment transport capacity for various setback sizes with different river slopes, widths, floodplain roughness, and flood sizes (peak flows) and durations. Setbacks reduce flood stages within the setback, as well as up- and downstream. Channel velocity and sediment transport capacity both increased upstream and decreased within the setback. Channel slope, flood size, and flood duration had the largest influence on hydraulic changes. There are diminishing returns in hydraulic effects with increasing setback size. These results can help guide the design and prioritization of levee setback projects and help set reasonable expectations for the scale of changes to flood hydraulics relative to the size of the reconnected floodplain.

Keywords: levee setbacks; HEC-RAS; natural infrastructure; flood hydraulics

1. Introduction

Levees are one of the most common flood control structures, having been used for millennia to protect low-lying land from inundation (e.g., Chen et al., 2012). While levees can be successful in achieving this goal, they constrict water into the channel, increasing flood stages at the levee and upstream (Heine & Pinter, 2012; Tobin, 1995). Levee setbacks — relocating a levee further from the river channel — are a natural infrastructure approach for reconnecting rivers and their floodplains to provide hydrologic, water quality, habitat, and recreation benefits. Setbacks can reduce flood risks by increasing floodplain storage, reducing water elevations, and attenuating flood peaks while still providing local flood protection.

Restoring river-floodplain connectivity can relieve pressure on the river system during floods, reducing the risk of flood mitigation system failure and providing environmental and societal co-benefits (Knox, Wohl, et al., 2022; Opperman et al., 2009; Serra-Llobet et al., 2021). Levee setbacks reduce flood stages through several processes (throughout this article we use flood stage and water surface elevation [WSE] interchangeably). First, the cross-sectional flow area is increased at the levee setback, which reduces WSE for a given discharge. This lower WSE increases water surface slope, causing the reduced WSE to propagate upstream (Smith et al., 2017). Additionally, the restored floodplain slows the flow, potentially reducing peak discharges and flood stages downstream. These benefits can be significant. For example, a levee setback along the Missouri River is estimated reduce flood stages for the 1% annual chance (100-yr)
event by 0.1 – 0.5 m (0.4 – 1.5 ft) (Smith et al., 2017). New setback levees may also be located on more stable ground, be less susceptible to failure in future floods, and could improve the effectiveness of other levees in the system (Dahl et al., 2017).

Most studies on the hydraulic benefits of levee setbacks model the effects of hypothetical projects and show variable results depending on location, setback size, and flood magnitude. For example, modeling various levee removal scenarios on the middle Mississippi River showed anywhere from 1.4 – 2.5 m (4.6 – 8.2 ft) reductions in flood stage for the 1% and 0.2% annual chance (100 and 500-yr) events (Remo et al., 2012). Another study in this area showed smaller, but still significant, benefits of various levee setback scenarios: 0.1 – 1.6 m (0.3 – 5.2 ft) stage reductions for the 1% annual chance (100-year) flood (Dierauer et al., 2012). Modeling levee setbacks on the Illinois and Sangamon Rivers showed similarly large ranges of flood stage reductions (Guida et al., 2016; Remo et al., 2017; Theiling et al., 2018). These studies are large scale, showing that multiple levee setbacks on a long stretch of river can significantly reduce flood stage. In reality, however, individual levee setback projects may be small (Smith et al., 2017) and the benefits may be restricted to the area of the setback itself (Echevarria-Doyle & Dahl, 2018; Jacobson et al., 2015). Stage reductions extend upstream of the setback, but it is unclear how far (Guida et al., 2016; Remo et al., 2017).

While these studies show the significant potential of levee setbacks to reduce flood stages, they are specific to their individual study areas and make it difficult to generalize about the potential of levee setbacks as a flood management tool. Flood stage reductions are highly variable, depending on the size of the setback, flood magnitude, and the location of measurement. Furthermore, levee setbacks induce other hydraulic changes, to velocity and sediment transport capacity for example, that have not been quantified. Perhaps most importantly, there is a large disconnect between the sizes of the setbacks modeled and the size of projects being implemented in practice.

The goal of this paper was to better understand how the hydraulic effects of levee setbacks scale with setback size, and how these relationships are affected by river and flood characteristics. We modeled a large set of idealized levee setback scenarios to systematically explore these questions. This paper has the following objectives:

1. Determine how changes in hydraulic characteristics within, upstream, and downstream of levee setbacks scale with the size of the reconnected floodplain
2. Explore how river size, slope, and roughness and flood size (peak flow) and duration affect hydraulic characteristics

2. Methods
We modeled the hydraulic effects of various levee setback scenarios using the one-dimensional, unsteady, Hydrologic Engineering Center – River Analysis System (HEC-RAS) v. 6.1.0, developed by the U.S. Army Corps of Engineers (USACE, 2021). We ran a series of simulations for “idealized” river geometries (i.e., channel geometries representative of typical systems, but not corresponding to actual rivers). We compared these results to a series of modeled levee setback scenarios for a ~375 km reach of the Wabash River in Indiana, USA. The methods for each are described below.
2.1. Idealized Models

We modeled 18 unique river geometries (3 bed slopes, 3 widths, and 2 floodplain roughnesses; see Table 1). The range of channel widths modeled (100 – 1000 m) correspond to drainage areas of roughly 1,400 to 1.8 million km², based on a relationship from a study on channel geometry globally (Frasson et al., 2019), although the authors note the considerable uncertainty in this relationship. Each river had a trapezoidal cross section with the same basic geometry – only channel width was varied. Nine unique flood hydrographs (3 different peak flow rates and 3 different durations) were routed through each river geometry. Hydrograph peaks were scaled as 2.5x, 3.5x, and 4.5x the calculated bankfull discharge for each geometry (representative of moderate, major, and extreme flood events, see Knighton (1998) p. 296). Synthetic hydrographs were assumed to have the shape of a Log-Pearson Type III probability density function, which approximates typical hydrograph shapes (Wolff & Burges, 1994). Baseline scenarios for each river geometry and flood combination included levees on both sides of the channel at a fixed distance from the banks (equal to the river top width). A total of 18 setback scenarios were run for each river geometry and flood hydrograph. Setback lengths ranged from 2.5 to 30 km and widths were set as 1/12, 1/8, or 1/4 times the setback length. Setback width was set relative to setback length to allow for consistent 2:1 (downstream:cross-stream) expansion and contraction ratios at the upstream and downstream ends. All setbacks were on one side of the channel only. This yielded a total of 3,078 simulations.

All simulations had a cross section spacing of 250 m. Time steps were 10, 30, and 60 minutes for the 10-, 30-, and 60-day hydrographs, respectively. We used a normal depth downstream boundary condition, with the friction slope set equal to the river bed slope. All other model parameters were left at the default value.

Table 1. Summary of river geometry and hydrograph characteristics for the idealized scenarios.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
<th>Justification</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel top width (TW)</td>
<td>100, 300, 1000 m</td>
<td>Moderate to large rivers</td>
<td>Knighton (1988) p. 172</td>
</tr>
<tr>
<td>Channel bed slope (S)</td>
<td>1e-4, 3e-4, 1e-3</td>
<td>Range of typical bed slopes for large meandering streams</td>
<td>Knighton (1998) p. 209</td>
</tr>
<tr>
<td>Bank height</td>
<td>5 m</td>
<td>Fixed bankfull depth</td>
<td>Assumed</td>
</tr>
<tr>
<td>Bank side slope</td>
<td>4:1 (H:V)</td>
<td>Typical bank angle</td>
<td>Assumed</td>
</tr>
<tr>
<td>Floodplain slope</td>
<td>100,000:1 (H:V)</td>
<td>Create essentially flat floodplain</td>
<td>Assumed</td>
</tr>
<tr>
<td>Channel roughness (Manning n)</td>
<td>0.03 s/m⁺¹⁄³</td>
<td>Typical channel roughness of large rivers</td>
<td>Chow (1959)</td>
</tr>
<tr>
<td>Floodplain roughness (Manning n)</td>
<td>0.05, 0.15 s/m⁺¹⁄³</td>
<td>Captures a range of typical floodplain roughness values in Mississippi Basin</td>
<td>Remo &amp; Pinter (2007)</td>
</tr>
<tr>
<td>Channel length</td>
<td>150 km</td>
<td>Sufficiently long channel to observe upstream and downstream effects</td>
<td>Assumed</td>
</tr>
<tr>
<td>Bankfull discharge (Qbf)</td>
<td>~300 – 15,000 m³/s</td>
<td>--</td>
<td>Calculated based on geometry, assuming uniform flow</td>
</tr>
<tr>
<td>Hydrograph peak (Qp)</td>
<td>2.5x, 3.5x, 4.5x Qbf</td>
<td>Representative of moderate (~20-40 yr), major (~100 yr), and extreme (~200 yr) flood events</td>
<td>Knighton (1998) p. 296. Ratios of Qx/Q2.33 for eastern U.S.</td>
</tr>
<tr>
<td>Hydrograph duration (Qd)</td>
<td>10, 30, 60 days</td>
<td>Representative of common flood durations for medium to large rivers</td>
<td>Assumed</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------</td>
<td>---------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Setback length</td>
<td>2.5, 5, 10, 15, 22.5, 30 km</td>
<td>Range of setback sizes</td>
<td>Assumed</td>
</tr>
<tr>
<td>Setback width</td>
<td>1/12, 1/8, 1/4 x setback length</td>
<td>Range of setback sizes</td>
<td>Assumed</td>
</tr>
<tr>
<td>Setback Area</td>
<td>0.43 – 113 km²</td>
<td>--</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

We quantified hydraulic effects of levee setbacks for each scenario by comparing the setback scenario results with the baseline, fully leveed scenario. At each cross section, we calculated changes in peak water surface elevation (WSE), maximum channel velocity, and an estimate of cumulative channel sediment transport capacity. We focused primarily on changes in peak WSE—specifically spatially averaged (mean) changes in peak WSE within the setback area, change in peak WSE at the downstream end of the model domain, and the distance upstream with at least a 10 cm (4 in) reduction in WSE. We selected this fixed value to better compare between scenarios and to avoid variation due to model errors for small WSE changes. We also quantified maximum and minimum changes in both channel velocity and sediment transport capacity (Figure 1).

Sediment transport capacity in the channel (not including the floodplain) was estimated using the Engelund and Hansen total load formula (Engelund & Hansen, 1967). We used the ratio of cumulative sediment transport capacity in the setback scenario over the baseline scenario:

$$Q_s \text{ ratio} = \frac{\sum Q_{s,s}}{\sum Q_{s,b}}$$

Where $Q_s$ is the channel sediment transport capacity and the subscripts $s$ and $b$ refer to setback and baseline conditions, respectively. Ratios greater than one indicate the setback increased cumulative sediment transport capacity at that cross section. See the Supplementary Materials for more details on sediment transport methods.

We also explored the effects of different levee setback configurations (i.e., setback levee shapes, aspect ratios, etc.) on flood hydraulics. For one river geometry ($S = 1e-4$, top width $= 100$ m, floodplain $n = 0.05$) and one flood hydrograph (hydrograph peak ($Q_p$) = 3.5x bankfull flow, hydrograph duration ($Q_d$) = 10 days), we ran six different levee setback configurations—all with the same total area of restored floodplain (15 km²). Finally, we compared 1-D and 2-D modeling results for a single setback on two river geometries. The purpose of this comparison was to show that our 1-D modeling results are valid, and more complex 2-D simulations are not needed for our simple idealized river geometries.

Creation of HEC-RAS input files and results post-processing were done in R version 4.1.1 (R Core Team, 2021). We used the following packages: *colorspace* (Zeileis et al., 2020), *dataRetrieval* (De Cicco et al., 2022), *dplyr* (Wickham et al., 2020), *hdf5r* (Hoefling & Annau, 2021), *RColorBrewer* (Neuwirth, 2014), *readr* (Wickham & Hester, 2021), *stringr* (Wickham, 2019), *vioplot* (Adler & Kelly, 2019), and *viridis* (Garnier et al., 2021).

### 2.2. Wabash River Model
We modeled the hydraulic effects of levee setbacks using a 1-D, unsteady HEC-RAS model from the lower 375 km of the Wabash River (from Montezuma, IN to the confluence with the Ohio River). The goal of this modeling was to compare idealized model results with hypothetical setback performance in a real river and levee system with variable channel and floodplain geometry, variable roughness, and a more realistic flood hydrograph. The Wabash River drains ~85,000 km² of Indiana, Illinois, and Ohio in the Midwest U.S. Significant portions of the study reach have been leveed to protect agricultural and urban areas in the floodplain. We modified an existing, calibrated HEC-RAS model developed for flood hazard studies on the lower Wabash. Sixteen setback scenarios were modeled with variable lengths and widths meant to represent the range of potential setbacks that could be implemented in practice: 1, 5, 10, and 15 km long and 2x, 4x, 8x, and 16x local bankfull width. We modeled these same setbacks at two locations: upstream (narrower channel and floodplain) and downstream (wider channel and floodplain). Setback performance was modeled for a ~4% annual chance exceedance (~25 year) flood event from April 2013 (peak flow rate ~3,600 m³/s, ~50 day duration). Flow data for the Wabash (03340500) and two tributaries, the White (03374100) and Patoka (03376500) Rivers were obtained from U.S. Geological Survey (USGS) stream gages. The study reach had the following characteristics: average bed slope ~1x10⁻⁴ m/m, typical bankfull width of 175 – 325 m, channel roughness of 0.035, floodplain roughness of 0.05 – 0.12. More details on this modeling, including determining bankfull discharge for the Wabash (Figure S4, after Sholtes and Bledsoe, 2016), can be found in the Supplementary Materials.

Comparison to Implemented Levee Setbacks

We compared the scale of our modeled levee setbacks to representative projects that have been implemented in the U.S. We identified completed projects based on literature and web search (e.g., Behm, 2021). For each project, we delineated the reconnected floodplain area based on available planning documents, aerial imagery, and the USACE National Levee Database (USACE, 2016). We also estimated pre-setback river confinement as the average distance between levees on opposite sides of the river, or a levee and bluff that naturally limits the floodplain extent. A summary of projects is shown in Table 2 and Figure S2. This list is not meant to be exhaustive, but instead to allow comparison between the characteristics of setbacks in this paper to those implemented in practice.
<table>
<thead>
<tr>
<th>Project/River</th>
<th>Location</th>
<th>Reconnected Area [km²]</th>
<th>Reconnected area [km²] / Levee top width [km]</th>
<th>Setback Length [km]</th>
<th>Setback Width [km]</th>
<th>L:W</th>
<th>River Slope* [m/m]</th>
<th>Map ID</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Tolt R.</td>
<td>King County, WA (47.641° N, 121.922° W)</td>
<td>0.2</td>
<td>2.9</td>
<td>0.9</td>
<td>0.3</td>
<td>3:1</td>
<td>4e-3</td>
<td>D</td>
<td>Behm, (2021)</td>
</tr>
<tr>
<td>Lower White R.</td>
<td>King County, WA (47.259° N, 122.237° W)</td>
<td>0.4</td>
<td>4.9</td>
<td>1.9</td>
<td>0.3</td>
<td>6:1</td>
<td>3.7e-3</td>
<td>E</td>
<td>Jones et al. (2018)</td>
</tr>
<tr>
<td>Bear R</td>
<td>Yuba County, CA (38.952° N, 121.565° W)</td>
<td>1.5</td>
<td>3.6</td>
<td>5.3</td>
<td>0.4</td>
<td>13:1</td>
<td>8.1e-4</td>
<td>G</td>
<td>Serra-Llobet et al. (2022)</td>
</tr>
<tr>
<td>Hamilton City,</td>
<td>Glenn County, CA (39.759° N, 122.018° W)</td>
<td>US: 1.2</td>
<td>US: 4.5</td>
<td>US: 3.1</td>
<td>US: 0.4</td>
<td>US: 8:1</td>
<td>4e-4</td>
<td>C</td>
<td>Golet et al. (2006)</td>
</tr>
<tr>
<td>Sacramento R.</td>
<td></td>
<td>DS: 2.2</td>
<td>DS: 1.6</td>
<td>DS: 4.6</td>
<td>DS: 0.7</td>
<td>DS: 7:1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L536, Missouri R.</td>
<td>Atchison County, MO (40.270° N, -95.542° W)</td>
<td>4.6</td>
<td>3.9</td>
<td>7.9</td>
<td>0.7</td>
<td>11:1</td>
<td>2e-4</td>
<td>B</td>
<td>TNC (2021)</td>
</tr>
<tr>
<td>Feather R.</td>
<td>Yuba County, CA (39.051° N, 121.601° W)</td>
<td>5.9</td>
<td>5.8</td>
<td>10</td>
<td>0.7</td>
<td>14:1</td>
<td>1.2e-4</td>
<td>F</td>
<td>Serra-Llobet et al. (2022)</td>
</tr>
<tr>
<td>New Madrid Floodway,</td>
<td>Mississippi County, MO (36.715° N, 89.275° W)</td>
<td>541.7</td>
<td>111.4</td>
<td>91.4</td>
<td>8.1</td>
<td>11:1</td>
<td>7e-5</td>
<td>H</td>
<td>Luke et al. (2015)</td>
</tr>
</tbody>
</table>

Table 2. Characteristics of implemented levee setback projects in the U.S. *Estimates of river slope based on digital elevation models. †Not a levee setback but functions similarly when activated. US = upstream. DS = downstream.
3. Results

We found that levee setbacks alter hydraulic characteristics of floods within the setback zone and up- and downstream. Changes in peak WSE along the river follow a characteristic curve, regardless of river geometry and flood characteristics (Figure 1). The largest reductions in WSE are within the setback itself, with a maximum reduction at or near the upstream end. These drops are due to the newly reconnected floodplain increasing cross sectional area. Downstream from the setback there is also a reduction in WSE, which was generally of a consistent value and persisted to the end of the model domain. Increased floodplain attenuation in the setback reduced peak flow rates – resulting in a reduction in WSE that should propagate indefinitely downstream, assuming no tributary or groundwater inflows. WSE reductions upstream of the setback followed a somewhat logarithmic curve shape, from a maximum drop at the start of the setback and decreasing to zero moving upstream. These reductions are caused by lower stages within the setback zone, which increase water surface slope upstream (Smith et al., 2017).

While the specific shape and magnitude of these ΔWSE curves varied, the characteristic structure and physical processes remained the same between all simulations (Figures S13-15). The following sections describe the changes within each of the three zones (in setback, downstream, and upstream) in more detail. In all cases, we have plotted changes in WSE versus relative setback area (area of reconnected floodplain divided by the pre-setback distance between levees). This relative setback area controls for differences in river and levee top width and collapses the data onto a single curve.

Our modeled changes in peak channel velocity and cumulative sediment transport capacity also showed characteristic curves, which were largely similar. Both values were increased upstream of the setback, decreased within the setback, and showed little change downstream (although in a few cases there were slight reductions in velocity if flood attenuation was large). The maximum increase in velocity and transport capacity occurred at the upstream end of the setback, coinciding with the largest drop in WSE. The largest decrease in velocity and transport capacity occurs near the downstream end, where the setback begins constricting back to the fully leveed downstream channel. At this point, friction slope is at a minimum, the flow is decelerating, and floodplain conveyance is at a maximum. These factors all contribute to low channel velocity and therefore low sediment transport capacity.
Figure 1. Conceptual figure outlining hydraulic effects of levee setbacks in different zones. Curves show representative changes in maximum water surface elevation (WSE), maximum channel velocity (V), and cumulative sediment transport capacity (Qs) based on our simulations. For each curve, we show the metrics analyzed in this paper (e.g., mean ΔWSE within the setback).

3.1. Changes in Water Surface Elevation

3.1.1. Within Setback

WSE was reduced the most within the setback. The average drop in WSE was higher for larger setback areas, steeper rivers, and larger and shorter floods (Figure 2).
Larger setbacks provide more available flow area, reducing WSE. Generally, there were diminishing returns with setback area. The smallest setback (2.5 km long, 208 m wide, 0.43 km\(^2\) area), resulted in 0 – 0.14 m (~0 - 0.5 ft) average drop in WSE within the setback, depending on river and flood characteristics. The largest setback (30 km long, 7.5 km wide, 112.5 km\(^2\) area) resulted in 0.26 – 2.6 m (~0.8 – 8.6 ft) average reductions. Despite a ~260x increase in floodplain area, there was ~18x difference in WSE reductions, demonstrating the non-linear scaling between reconnected floodplain area and flood stage reductions.

There may be a minimum threshold of reconnected floodplain area before measurable benefits are observed (Figure 2 inset plots). This threshold ranges from ~0.2 – 1 km\(^2\)/km of relative floodplain area (0.06 – 3 km\(^2\) total area depending on river confinement), with lower gradient rivers requiring larger areas before WSE reductions were observed.

Steeper rivers had larger reductions in WSE within the setback, all else being equal. River slope is also a dominant control on the importance of flood characteristics. For the steepest river (S = 0.001), flood duration had no impact on mean WSE change. On the other hand, shorter floods resulted in larger reductions in WSE for the two shallower slopes we examined. Larger floods also resulted in larger reductions in WSE – an intuitive result given that bigger flows are accessing more of the reconnected floodplain area.

**Figure 2.** Mean change in peak WSE (relative to the baseline) within the setback versus relative area of reconnected floodplain for all scenarios where floodplain n = 0.05. Panels a-c show results for the three modeled channel slopes. Curves are LOESS fits to point data to show general trends. Inset plots show detail for smaller reconnected areas, with log scale on the x-axes. Points for different flood durations are overlapping in panel (c). Flood peak is shown as a multiple of bankfull discharge (xQ\(_{bf}\)).
3.1.2. **Downstream of Setback**

Reductions in WSE downstream of the setback (caused by hydrograph attenuation on the floodplain) were smaller than changes within the setback. Furthermore, river and flood characteristics affected these downstream changes in different ways compared to within-setback changes. While reductions were still larger with larger setback area and larger and shorter floods, channel slope showed the opposite effect (Figure 3). Lower gradient rivers had the biggest reductions in WSE, with the steepest river (S = 0.001) showing essentially no downstream change. The short, 10-day floods showed some evidence of diminishing returns with increasing setback size, while the longer floods did not. However, these diminishing returns could emerge for setbacks larger than we examined here.

Again, there appears to be a strong threshold effect, with a minimum relative setback area needed for observable downstream WSE changes (Figure 3 inset plots). Unlike for within-setback results, however, these thresholds are dependent on both river slope and flood length (but not flood magnitude). For the lowest gradient river (S = 1e-4), minimum relative setback areas of ~1, 5, and 10 km²/km are needed for short, medium, and long floods, respectively. Thresholds for the moderate slope river (S = 3e-4) are larger, with at least 3-4 km²/km relative setback area needed for reductions for the shortest flood. No amount of floodplain reconnection appeared to reduce downstream WSE for the steepest river.

![Figure 3](image.png)

**Figure 3.** Change in maximum WSE (relative to the baseline) at the downstream end of the model domain versus relative area of reconnected floodplain for all scenarios where floodplain n = 0.05. Panels a-c show results for the three modeled channel slopes. Curves are LOESS fits to point data to show general trends. Inset plots show detail for smaller reconnected areas, with a log scale on the x-axes. Flood peak is shown as a multiple of bankfull discharge (xQ<sub>bf</sub>).

3.1.3. **Upstream of Setback**

Lowered WSEs extended up to ~50 km upstream from the start of the setback (Figure 4). There were large differences due to river slopes, with low gradient rivers showing the largest upstream impact and the steepest river showing impacts extending no more than ~5 km upstream. Upstream distances exhibited strong diminishing returns – setbacks greater than ~50 km$^2$/km showed little additional benefit. On the other hand, even small setbacks showed extensive benefits. Reduced WSEs extended further upstream for larger, longer floods. These flood characteristics, however, had much less influence on upstream WSE reductions for the medium and high gradient rivers.

The minimum setback areas needed for measurable upstream changes again varied based on river slope (Figure 4 inset plots). For the low gradient river, there were essentially no upstream benefits below ~2 km$^2$/km. For the moderate gradient river, this threshold was lower (~0.5 km$^2$/km), while the steepest river showed changes for even the smallest setbacks.

![Figure 4](image-url). Distance upstream (US) with a lowered WSE due to the setback (defined as ≥ 10 cm reduction in WSE) versus relative area of reconnected floodplain for all scenarios where floodplain n = 0.05. Panels a-c show results for the three modeled channel slopes. Curves are LOESS fits to point data to show general trends. Inset plots show detail for smaller reconnected areas, with log scale on the x-axes. Flood peak is shown as a multiple of bankfull discharge ($xQ_{bf}$).

3.1.4. **Floodplain Roughness Effects**

Floodplain roughness also controls hydraulic behavior. Higher roughness in the setback resulted in larger reductions in WSE downstream, but smaller changes within the setback and upstream (Figure 5). Like before, there is a large dependence on channel slope, with more pronounced differences within the setback for steeper rivers, but the opposite for downstream and upstream effects. Downstream changes were relatively small (< 0.2 m difference between
the two sets of scenarios), but within setback and upstream differences were much larger, with lower roughness floodplains showing considerably larger changes.

**Figure 5.** Effects of floodplain roughness (FP n) on changing peak WSE. Violin plots show differences in (a-b) ΔWSE or (c) distance upstream (US) with lowered WSE between high and low floodplain roughness scenarios. Values >0 indicate floodplains with higher roughness show larger changes, while values <0 indicate floodplains with lower roughness show larger changes. Individual violins show the probability distribution function overlain by a traditional boxplot (white dot is median, boxes show first and third quartiles, lines show non-outlier range).

### 3.1.5. 1-D-2-D Model Comparison

We compared simulated changes in WSE using both 1-D and 2-D modeling for a single setback (15 km long and 3.75 km wide) for two different river geometries (100 m TW, 0.05 floodplain roughness, 0.001 and 0.0001 river bed slopes). Our results show the mean differences in WSE were both ≤ 5 cm (Figure S1), suggesting more complex 2D simulations do not yield significantly different results for our idealized rivers. This is not surprising given the simple prismatic channels we simulated. Two dimensional modeling is more important for understanding flow paths on floodplains with complex topography (Jacobson et al., 2015) and for simulating sinuous river channels (Echevarria-Doyle & Dahl, 2018).

### 3.1.6. Wabash River Comparison

We compared results from the Wabash River modeling to idealized simulation results that most closely matched the river geometry and flood characteristics of the Wabash (S = 1e-4 and 3e-4, floodplain n = 0.05, Qp = 3.5x bankfull, Qd = 60 days). The Wabash simulations showed the same general trends in reducing WSE within the setback as the idealized simulations (Figure 6), with higher reductions at the upstream setback because this location had a higher slope (Figures S5). Relationships are also similar for the upstream distance with lowered WSE, although the apparent maximum upstream distance is about 20 km for both setbacks on the
Wabash, between the maximum extent for our idealized scenarios. For both the upstream and
downstream setbacks, the 20 km limit corresponds to areas where the bed and water surface
slope steepen (Figure S5), suggesting local variability in channel morphology can limit the
hydraulic effects of setbacks.

Downstream results do not match our idealized results. Wabash simulations show slight
increases in WSE and discharge downstream. This suggests that the reconnected floodplains
are reducing the amount of flood attenuation, contrary to our expectations and results from the
idealized scenarios. On the Wabash, there are sections of river that have no levees or levees
only on one side, allowing for significant floodplain inundation and therefore flood peak
attenuation even in the baseline scenario. Adding a setback reduces upstream WSE,
concentrating more flow in the channel, therefore reducing this upstream attenuation, resulting
in a higher discharge at the setback compared to the baseline. Within the setback and
downstream, there is some flood attenuation but this may not counteract the increased
discharge from upstream. In the idealized models, the full river is leveed and there is therefore
little or no floodplain attenuation in the baseline scenario that could be affected by reducing
WSE. Still, changes in WSE for the Wabash and idealized results are small (± 2 cm), reinforcing
that downstream effects are likely minor for smaller setbacks.

![Figure 6](image-url)

**Figure 6.** Comparing changes in WSE (a) downstream and (b) within the setback and (c)
distance upstream (US) with lowered WSE for Wabash River scenarios compared to the
idealized scenarios that most closely correspond (S = 1e-4 and 3e-4, floodplain n = 0.05, Qp =
3.5x bankfull, Qd = 60 days). Idealized results are shown with fitted LOESS curves to show
general trends. Results are shown for Wabash setbacks at two locations: upstream (confined)
and downstream (unconfined). See Figures S3 and S5 for locations. Note that the x-axis scales
are different than previous figures.
3.2. Velocity and Sediment Transport Effects

Peak channel velocities decreased within the setback and increased upstream, relative to the baseline, fully leveed scenario. The largest reduction in velocity within the setback was ~1.5 m/s, although reductions <0.5 m/s were more typical, especially for low gradient rivers and smaller floods (Figure 7). Upstream velocity increases were slightly smaller, showing the same trends with river slope and flood size. Both increases and decreases in velocity showed similar relationships with relative setback size as WSE, with especially pronounced diminishing effects for very large setbacks (Figures S7-S8). Downstream changes in velocity were negligible, and are therefore not analyzed.

Cumulative sediment transport capacity was similarly reduced within the setback and increased upstream (with negligible changes downstream), with larger relative changes in the setback (Figure 9). Transport capacity was generally reduced by 1.3 – 3x within the setback, although reductions of up to 12x were observed. Upstream, transport capacity increases were generally 1.1 – 2x, with a maximum of 9x. Changes in transport capacity were more pronounced for larger floods on low gradient rivers. The exception is that steep rivers showed bigger upstream increases in sediment transport capacity for small setbacks (Figures S9-S10). Steeper rivers showed reach-wide net deposition (e.g., erosion upstream was more than compensated for by deposition in the setback; Figure 8b), while low gradient rivers showed a mix of net erosion and deposition potential. However, overall changes tended to be small, with 95% of simulations showing less than ±5% change in reach-wide transport capacity. All sediment results are changes in cumulative transport capacity over a single flood event. More detailed analysis would include longer-term modeling to assess potential aggradation and degradation risk over multiple flood events and more frequent sub-bankfull flows, which are not affected by a setback.

Lower floodplain roughness caused bigger changes in both velocity and sediment transport capacity, both within the setback (decreases) and upstream (increases) (Figures S11-S12). Floodplain roughness had the largest effect on velocity in steep rivers, but the largest effect on sediment transport capacity in low gradient rivers. Median velocity differences were ~0.06 – 0.3 m/s, depending on slope. Median transport capacity differences were ~1.1 – 1.6x.
Figure 7. Violin plots summarizing maximum changes in peak channel velocity (V) within and upstream of the setback for all simulations where floodplain n = 0.05, grouped by river slope and colored by flood peak (shown as a multiple of bankfull discharge (xQ_{bf})). Increases in velocity (positive values) occurred upstream of the setback, while decreases in velocity (negative values) occurred within the setback. There were negligible changes in velocity downstream.

Figure 8. Violin plots showing (a) distributions of minimum and maximum sediment transport (Qs) ratios (see Eq. 1), with increases in transport capacity (>1) occurring upstream of the
setback and decreases in transport capacity (<1) occurring within the setback. There were negligible changes in Qs downstream. Panel (b) shows cumulative change in transport capacity across the entire modeled reach. Values >1 indicate net deposition and values <1 indicate net erosion. Data for simulations where floodplain n = 0.05. Flood peak is shown as a multiple of bankfull discharge (xQbf).

4. Discussion

Our simulations generally show that larger setbacks yield larger changes in WSE, velocity, and sediment transport capacity and that river slope and flood size and duration significantly affect these hydraulic characteristics. These observations may be intuitive and align with our understanding of basic hydraulic process, but this work systematically quantifies these relationships. There are no existing design guidance or standards for levee setbacks (Smith et al., 2017), which may partly explain the few projects implemented in practice (Table 2). While there is uncertainty in transferring our idealized results to real rivers, our findings can still help guide the planning and design of levee setback projects. The sections below discuss the impacts of setback size and river and flood characteristics on levee setback performance, as well as the lessons we can apply to project prioritization and design.

4.1. Effect of levee setback size on flood stage reductions

Levee setbacks can significantly reduce peak water surface elevations during floods. Smaller reductions extend downstream and upstream, showing setbacks can have wide ranging effects outside their immediate location. However, these large benefits require large setbacks – much larger than what have been implemented in practice. Most levee setback projects are relatively small, reconnecting less than 6 km² of floodplain (Table 2). Floodplain area relative to channelized river widths ranged from 1.6 – 5.8 km²/km, on the low end of what we simulated. For these small sizes, we saw generally minor reductions in WSE (see inset plots in Figures 2-4), although this was highly dependent on river slope (e.g., up to 0.5 m reductions for the steepest slope). The exception to this small scale of levee setback is large, managed floodways, such as the Birds Point-New Madrid Floodway on the Mississippi River. This floodway is not a levee setback, but functions similarly when the levees are intentionally breached (which last occurred in 2011; Luke et al., 2015). This breaching floods ~540 km² of floodplain, or a relative area of 111 km²/km, putting it well within the range of considerable WSE reductions shown in our modeling.

Table 3 summarizes prior levee setback studies (primarily using 1-D modeling) and their main findings. These papers also show that large scale floodplain reconnection is needed to see meaningful flood reduction benefits. For example, modeled stage reductions on the Middle Mississippi River ranged from 0.11 – 1.58 m for hypothetical setbacks of 11 – 333 km² (~10 – 222 km²/km) (Dierauer et al., 2012). A similar study on the Lower Tisza River in Hungary showed stage reductions for the 5- to 500-year floods of 0.14 – 1.49 m for setbacks of ~80 – 320 km² (~57 – 229 km²/km) (Guida et al., 2015). On the Lower Sangamon River, Illinois, stage reductions of ~0.6 – 1.0 m were found for setbacks of ~12.7 – 34.6 km² (~25 – 69 km²/km) (Theiling et al., 2018). Two-dimensional modeling of levee setbacks on a hypothetical river showed maximum stage reductions of 0.4 – 0.5 m for 3.5 – 4.2 km² setbacks (~8 – 9.5 km²/km) (Echevarria-Doyle & Dahl, 2018). These magnitudes of WSE reductions are all within the ranges we found in our modeling for the corresponding bed slope and relative size of
reconnected floodplain. While these previous case studies show the same general trends as our work, we are the first to systematically explore the effects of setback size and river and flood characteristics (see next section) on setback performance.

This literature and our results suggest that there may be a minimum setback size for meaningful stage reductions. For example, we showed setbacks of at least ~5 km²/km (steep slopes, 1.5 – 15 km² depending on river confinement) to 25 km²/km (low slopes, 7.5 – 75 km² depending on river confinement) are required to see a mean WSE reduction of 0.5 m (1.6 ft) within a setback (Figure 2). While these values may not transfer from our idealized models to a specific river, the presence of these thresholds and variability with confinement and river slope are significant. However, smaller reductions in WSE could still be beneficial in reducing inundation and failure probability for nearby levees (Smith et al., 2017). Additionally, while individual setbacks may be small, the cumulative effect of many setbacks in a confined river system could provide important, system-level benefits.
Table 3. Summary of prior levee setback studies. Note inconsistent information on setback sizes and river and flood characteristics are available for different studies. Qp = flood peak, Qd = flood duration, Qbf = bankfull flow, TW = top width, FP = floodplain.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Setback Details</th>
<th>River Characteristics</th>
<th>Flood Characteristics</th>
<th>Summary Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echevarria-Doyle and Dahl (2018)</td>
<td>Hypothetical River – 2D modeling</td>
<td>Various setback scenarios, straight and sinuous channels (3.5-4.2 km²)</td>
<td>S = 4e-4 TW = 137 m Channel n = 0.025 s/m¹/³ FP n = 0.035-0.05 s/m¹/³</td>
<td>Qp = 1.7xQbf Qd = 10 days</td>
<td>Highest reductions upstream of setback (~0.4-0.5 m drop), moderate at setback (0.1-0.2 m drop), no benefits downstream. Velocity increased upstream and decreased within the setback. Sinuous channel simulations show similar trends.</td>
</tr>
<tr>
<td>Dierauer et al. (2012)</td>
<td>Middle Mississippi River (Grafton, IL to Thebes, IL)</td>
<td>1500 m, 1000 m, and “optimized” levee setbacks (11-333 km²)</td>
<td>TW = 470-1,130 m</td>
<td>100-yr flood</td>
<td>Mean WSE reduction 0.11-1.58 m. Benefits proportional to restored floodplain area.</td>
</tr>
<tr>
<td>Guida et al. (2014)</td>
<td>Tisza River, Hungary</td>
<td>500 - 2000 m setbacks (80-320 km²)</td>
<td>TW = 150 m</td>
<td>5-yr to 500-yr flood</td>
<td>WSE reductions 0.24-1.49 m (500-yr) and 0.14-0.91 m (5-year).</td>
</tr>
<tr>
<td>Guida et al. (2016)</td>
<td>Illinois River (Peoria, IL to La Grange Lock and Dam)</td>
<td>500 and 1000 m setbacks, full levee removal</td>
<td>TW = 250 m</td>
<td>1.25-yr to 500-yr flood</td>
<td>Max WSE reduction 0.45-1.1 m for 100-yr flood. Benefits extend ~70 km upstream.</td>
</tr>
<tr>
<td>Jacobson et al. (2015)</td>
<td>85 km reach of Missouri River (Boonville, MO to Jefferson City, MO)</td>
<td>Levee setbacks (up to 305 m) and/or channel widening</td>
<td>TW = 348 m Channel n = 0.022 s/m¹/³ FP n = 0.04-0.09 s/m¹/³</td>
<td>10-yr flood Qd = 20 days</td>
<td>Mean WSE reductions 0.12-0.66 m. &lt;0.13% peak flow attenuation. 2-D modeling showed similar results, but very complex floodplain flows.</td>
</tr>
<tr>
<td>Remo et al. (2012)</td>
<td>Middle Mississippi River (St. Louis, MO to Cairo, IL)</td>
<td>Full levee removal, just ag levee removal (up to 1,900 km²)</td>
<td>TW = 430-1,160 m</td>
<td>100-yr and 500-yr flood</td>
<td>Mean WSE reduction 2.3-2.5 m (full removal) or 1.4 m reduction (just ag levees removed). Max WSE reduction 2.1-3.5 m.</td>
</tr>
<tr>
<td>Remo et al. (2017)</td>
<td>Illinois River (Peoria, IL to La Grange Lock and Dam)</td>
<td>Various scenarios (up to ~750 km²)</td>
<td>TW = 250 m</td>
<td>5-yr to 500-yr flood</td>
<td>Max WSE reduction 0.8 m (5-yr) to 1.3 m (500-yr). Stage reductions can extend &gt;70 km upstream from setback location.</td>
</tr>
<tr>
<td>Smith et al. (2017)</td>
<td>L-575 on Missouri River near IA/ MO border</td>
<td>Real project (2.6-3.9 km², see Table 2)</td>
<td>S = 2e-4 TW = 250 m</td>
<td>100-yr flood</td>
<td>Max WSE reduction 0.12-0.46 m. Mean velocity reduced 0.58 m/s.</td>
</tr>
<tr>
<td>Theiling et al. (2018)</td>
<td>Sangamon River (IL)</td>
<td>Various setback scenarios (13-35 km²)</td>
<td>TW = 100 m</td>
<td>Largest flood on record</td>
<td>Max WSE reduction 0.6-1.0 m, benefits reach ~10 km upstream.</td>
</tr>
<tr>
<td>This study</td>
<td>Hypothetical Rivers</td>
<td>Range of setbacks (0.43 – 113 km²)</td>
<td>TW = 100, 300, 1000 m S = 1e-4, 3e-4, 1e-3 Channel n = 0.03 s/m¹/³ FP n = 0.05, 0.15 s/m¹/³</td>
<td>Qp = 2.5x, 3.5x, 4.5x Qbf Qd = 10, 30, 60 days</td>
<td>Mean WSE reductions 0.2-2.6 m. Benefits extend up to 50 km upstream. Non-linear relationships between WSE reductions and setback area. Max changes in velocity ~±1.5 m/s.</td>
</tr>
</tbody>
</table>
4.2. Effects of river and flood characteristics on levee setback benefits

River characteristics, including bed slope and floodplain roughness, and flood characteristics, including size and duration, have potentially significant effects on the hydraulics of levee setbacks, with slope and flood magnitude being the most important. For a given setback area, steeper channels have larger WSE reductions in the setback, but smaller changes up and downstream. Steeper slopes also resulted in bigger velocity changes. Changes in sediment transport capacity, however, were largest for low gradient rivers. Other studies modeling levee setbacks simulated a single river reach of fixed slope, and therefore did not examine the role of slope in controlling hydraulic response.

Differences in slope effects depending on location (within the setback versus up or downstream) can be attributed to differences in hydraulic processes. Reductions in WSE, velocity, and transport capacity within the setback are attributed to increased cross sectional area decelerating the flow. Steeper rivers have higher velocities, greater potential for deceleration, and therefore larger reductions in WSE and velocity. Changes upstream of the setback are caused by these WSE reductions increasing the upstream water surface slope, thereby reducing WSE but increasing velocity and transport capacity. Steeper bed slopes limit how far upstream these impacts can propagate, explaining why these simulations showed smaller upstream effects than low gradient rivers. Downstream reductions in water surface elevation are due to flood wave attenuation on the reconnected floodplain. Flood attenuation is greater for lower gradient rivers (Ponce, 2014), and slope is often the most important geomorphic or hydrologic variable describing the potential for flood attenuation (Sholtes & Doyle, 2011; Woltemade & Potter, 1994). On steeper rivers (including the steepest we modeled) the gravity force dominates flood wave propagation, resulting in minimal attenuation (Ponce, 2014).

Larger floods resulted in larger hydraulic changes at all locations. This is intuitive since larger floods will have deeper and faster flow, and greater potential for reduction. The effects of flood size on downstream attenuation are mixed. A restored floodplain on a small Oregon stream resulted in 16-27% reductions in peak flow rates, with the highest reduction for the largest floods (Ahilan et al., 2016). Others have found largest relative reductions for intermediate floods (e.g. 10-yr (Sholtes & Doyle, 2011) or 5-50 yr (Woltemade & Potter, 1994)). We saw little difference in relative (percent) flood peak attenuation for different flood sizes for a given river slope (Figure S6a), although we did show substantially larger downstream WSE reductions for larger floods (Figure 3). Flood duration has the largest effect upstream of the setback (Figure 4), followed by downstream (Figure 3), and within the setback (Figure 2). Flood duration had the largest effect for low gradient rivers, but essentially no effect for the steepest river. Longer floods had lowered WSE ~10-15 km further upstream compared to shorter floods for the low gradient river (Figure 4a). Longer floods had lower water surface slopes throughout the model reach, in part because upstream and downstream depths were more similar than for shorter floods where peak flow rate was more variable along the channel at any given time. This causes setbacks with longer floods to see impacts further upstream because the same change in stage can propagate further upstream. On the other hand, longer floods showed up to 0.8 m less change in downstream WSE for large setbacks on the same rivers (Figure 3a) because of greater peak flow attenuation (Figure S6b). Shorter floods have been shown to attenuate more on floodplains because a higher percentage of the flood volume can access the floodplain (Rak et al., 2016; Woltemade & Potter, 1994).
Floodplain roughness has variable effects in different parts of the system. Higher roughness leads to greater flood wave attenuation and greater WSE reduction downstream (Figure 5a; Anderson et al., 2006; Rak et al., 2016; Woltemade and Potter, 1994). Within the setback, higher floodplain roughness resulted in smaller changes in WSE than the low roughness scenarios. Rougher floodplains have lower velocities, which force a larger proportion of discharge to flow through the less resistive river channel (Rak et al., 2016). This also explains why both channel velocity and sediment transport capacity showed larger changes with low roughness floodplains. Upstream effects were also larger for low roughness floodplains, induced by the larger WSE reductions in the setbacks for these scenarios.

4.3. Prioritizing and designing levee setback projects

These results can be used to guide watershed-scale prioritization of levee setbacks and the design of individual projects. Setbacks will likely have the most upstream and downstream benefits when located on low gradient rivers; however, stage reductions within the setback are larger for steeper rivers. Furthermore, we show that setbacks have the greatest potential on very confined sections of river. This is relatively intuitive, but we demonstrate that the same size of reconnected floodplain will have larger hydraulic effects on confined sections of river – and that this persists across river types and flood characteristics.

Floodplain restoration is pursued for a variety of reasons, only one of which is usually flood mitigation. Existing floodplain prioritization tools, such as The Nature Conservancy Floodplain Prioritization Tool (TNC, 2019) and smaller, regional scale efforts (Reynolds, 2014) account for the ecological and social benefits of floodplain reconnection in addition to flood reduction benefits. However, these approaches use proxies for flood mitigation potential that do not account for the hydraulic effects of levees. Our idealized results may be useful for comparing relative potential for different levee setback options for flood stage reduction and add more mechanistic rigor to existing prioritization approaches.

At a more local level, we have demonstrated that design decisions can affect the relative efficacy of a setback for reducing flood stages. For example, setback configuration is important. Short and wide setbacks generally reduce WSE more than longer, narrow setbacks (Supplementary Materials, Figures S16 – S17). Setback configurations also change the magnitude and location of changes in WSE, velocity, and sediment transport capacity – all important considerations when designing setback projects to simultaneously reduce flood stages while not increasing erosion or sedimentation risk. A major cost in setback projects is land acquisition (Guida et al., 2016), and prioritizing the land that could provide the most benefit is therefore an important design consideration. Local constraints such as infrastructure (e.g., an existing bridge crossing) or landowner support, however, may limit flexibility in setback configuration.

Vegetation management within reconnected floodplains can alter roughness. Generally, rougher floodplains resulted in less hydraulic changes – which may be a benefit (smaller changes in velocity and transport capacity) or a detriment (smaller reductions in flood stage). It is important to balance these perhaps conflicting hydraulic objectives with the ecological benefits of reconnected floodplains, especially as these ecosystems are managed for multiple benefits (Opperman et al., 2009; Serra-Llobet et al., 2022).

Comparing the idealized results with the Wabash modeling suggest that even under more realistic conditions (varying river and floodplain geometry, effects of bridges), the basic trends
observed in the idealized modeling scenarios hold true. However, local variability in bed slope and floodplain connectivity has important implications for the effectiveness of setbacks. For example, setbacks on the Wabash slightly reduced flood attenuation on upstream floodplains, leading to minor increases in peak discharge. Similarly, locally steep bed slopes limited the upstream extent of WSE reductions. Comparing our results to other studies (Table 3) also shows these variations. For example, the general shape of changing WSE along the river from prior work matches our results (Figure 1), but with more variability introduced by changing channel geometry and infrastructure (e.g., Guida et al., 2016; Jacobson et al., 2015; Remo et al., 2012). This emphasizes the need to tailor setback projects to account for these unique local features.

4.4. Additional work should explore co-benefits of floodplain reconnection

While this research focused on identifying trends in the hydraulic effects of levee setbacks, this is only one potential benefit of these projects. Reconnected floodplains can provide essential habitat (Erwin et al., 2017; Jeffres et al., 2008; Konrad et al., 2008), retain pollutants (McMillan & Noe, 2017), allow for more natural river migration (Larsen et al., 2006), and restore coarse sediment dynamics (Florsheim & Mount, 2002). We found generally diminishing returns with larger setbacks, but this trend may not apply to all the environmental and societal benefits of these projects. Additional modeling of the socio-ecological and geomorphic effects of setbacks could provide valuable relationships, analogous to the ones we outline here, that may be used to guide the prioritization and design of these projects. This would require coupling hydraulic, geomorphic, and ecological modeling. This has been already done in some cases (e.g. Larsen et al., 2006). However, some benefits may require detailed two-dimensional approaches (Black et al., 2016; Jones et al., 2018) which may be difficult to apply at the same scale we used here.

5. Conclusions

We used idealized modeling scenarios to explore the hydraulic effects of levee setbacks during floods to help guide design and planning of these projects. Larger setbacks reduce flood stages more than smaller setbacks, although there are diminishing returns. Stage reductions can be large (over 2 m), but would require much larger reconnected floodplains than have been implemented in practice. The hydraulic benefits of setbacks can extend many kilometers up- and downstream, especially for low gradient rivers. River slope and hydrograph characteristics (peak flow and duration) were the primary controls on hydraulic behavior and should be considered in design and planning.

Levees are ubiquitous flood control structures in the U.S., with estimates of 160,000 – 180,000 km (100,000 – 112,000 miles) of documented and undocumented structures (Heine & Pinter, 2012; Knox, Morrison, et al., 2022; National Committee on Levee Safety, 2009). There is clearly great potential for levee setbacks, especially as levees age, degrade, and fail (Tobin, 1995). This work improves our understanding of the hydraulic effects of reconnecting rivers and floodplains, which is critical for effectively siting and designing these projects. This is especially timely as we increasingly recognize and value the benefits that functioning river-floodplain systems can provide (Serra-Llobet et al., 2022; Wohl, 2021; Wohl et al., 2021).

Data Availability Statement

The data that support these findings, including the code to run the hydraulic models and analyze results, are openly available on Zenodo at https://doi.org/10.5281/zenodo.8325554.
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