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Utilizing Graceful Failure As An Opportunity for Flood Mitigation Downstream to Protect Communities and Infrastructure

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16. Abstract

In 2011, we observed how “graceful failure” through planned destruction of portions of the Birds Point Levee by the US Army Corps of Engineers (USACE) was enacted to alleviate extreme flooding on the Mississippi River. This action, while flooding thousands of acres of croplands as intended, reduced flooding and potential damage to waterway infrastructure and populated communities downstream. Recent trends and future climatic projections indicate that we will have more of these “extreme” flooding situations in our future. Therefore, this project focused on exploring the potential feasibility to utilize other locations along the inland waterway system where “graceful failure” or planned breach of levees may be used as a means of flood protection for downstream communities and infrastructure. Spatial analysis techniques were used with development of specific criteria and screen national-level data sets to identify probable locations for such mitigative approaches. The criteria was primarily focused on identifying non-urbanized, non-developed land where intentional flooding for storage of flood waters would minimize impacts. Each location that was identified as a potential candidate was further evaluated for capacity for flood water detention. A consolidated set of areas were identified that could provide some storage capacity for flood mitigation. Additional engineering and localized analysis would be necessary to vet the areas for actual storage implementation. However, this study provides and example of an unconventional approach to flood mitigation on inland waterways which could reduce the need for disaster response and assist in transportation planning during extreme flood conditions.

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flood, levee, risk, resiliency, waterway, mitigation, capacity

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Introduction

In 2011, the Birds Point Levee was intentionally breached at three points south of Cairo, Missouri, diverting flood waters from the Mississippi and Ohio rivers to the New Madrid floodway (Husted, 2015; USACE, 2017). This action, planned and executed by the U.S. Army Corps of Engineers (USACE), is thought to have saved the city of Cairo. Each year, floods pose risks to communities throughout the United States (Vinukollu, 2018), and with increasingly intense weather systems coupled with increasing population and infrastructure, the associated human and economic cost of floods is likely to grow more severe (National Climate Assessment, 2014).

With this anticipated increased risk, it is necessary to rethink and expand the planning and systems in place to mitigate that risk, and to expand the understanding and implementation of proven strategies. One such flood risk mitigation approach in need of further study is the intentional, planned rupture/breech of levees by controlling agencies to divert potentially harmful flood waters to less vulnerable land use zones (USACE, 2017). This approach falls under the principal of "graceful failure", which encourages the consideration of how a system may fail in the planning and design phase such that failure can become a positive and controlled feature. The idea of "graceful failure" has been attributed to Zolli and Healy (2012) in *Resilience: Why Things Bounce Back*, where they stated that "Resilient systems fail gracefully."

The objective of this study was to perform a data-driven, comprehensive analysis of the national system of floodplains and levees to understand the capacity of the system overall and at specific sites for temporary or intermittent floodwater storage using a modified graceful failure consideration. The levees under consideration are already constructed, but perhaps modifications may be made to them to enable a future, intentional failure to reduce impacts or stress on the system later. The goal of this initial, screening-level analysis was to evaluate potential and demonstrate an approach to identify opportunities for graceful failure to be employed for flood mitigation along a portion of the U.S. inland waterway system. The idea behind the approach was that there may exist sufficient areas of non-urbanized, minorly developed land behind levees on navigable waterways that could serve as flood water detention/temporary storage areas without creating significant adverse impacts to people or infrastructure. Once identified, these sites could then be further evaluated for the efficacy of expanding graceful failure techniques to provide flood mitigation benefits.

Background

According to the US Department of Homeland Security, floods are the most common disaster (DHS, 2019). Flood impacts nationwide can be on the order of about eight billion dollars each year (Nunez, 2019). In fact, since 2010, in the US alone, flood-related billion-dollar disaster events amount to approximately $60.5 billion (NOAA, 2020). This does not account for the many smaller flood events that result in damages less than $1 billion. Unfortunately, despite such statistics, often people do not perceive floods as real risks to them (Bubeck et al., 2012; Adeola, 2009).

Historically, government agencies and communities have predominantly utilized 'hard' flood prevention in the form of infrastructure like levees that are meant to prevent any flooding from occurring (Cuny, 1991). However, recent research indicates that hard flood prevention tactics are much less effective than 'soft' flood prevention strategies that aim to harness natural flood events rather than actively fight them like hard flood prevention infrastructure (Cuny, 1991). Not only do hard flood prevention strategies require significant capital investments, they can actually cause more harm than good by disrupting natural ecosystems and providing residents with a false sense of security that can actually worsen the consequences of a flood (Dixit, 2009). This false sense of security is often referred to as the “levee effect” – a phenomenon known as the “levee effect” and those who live behind levees often minimize localized flood prevention or mitigation strategies soon after the levee is built (Dixit, 2009). The decreased sense of risk that a levee provides can be extremely destructive if the levee fails because there are no other safeguards in place to reduce the impacts of a flood that exceeds the levee design. Further, because ‘hard’ infrastructure solutions to floods require a large initial investment, have reoccurring maintenance costs, and significant damage and recovery/repair costs when they fail, these solutions are simply not viable for developing countries or areas that are economically depressed (Cuny, 1991).

As noted, floods can cause large amounts of damage to communities and as such, they have been identified as a threat rather than as an opportunity. Yet, floods can provide significant economic benefits to communities that can harness them. Beyond the economic implications of flooding, floods are essential to the health of natural ecosystems, and the construction of levees has had severe negative impacts upon the ecosystems outside of the levees (Cuny, 1991). However, these ecosystems have been shown to recover rapidly in the event that floods are once again allowed to run their natural course. By directing and seeking to control flooding through graceful failure, the consequences of floods would be minimized while the full benefits of floods would be realized.

In 1937, the concept of soft flood prevention methods was tested for the first time in the intentional breach of the levee slightly downriver from Cairo, IL. Although the breaching of the levee did not exactly go as planned, the breach of the levee reduced the flood height at Cairo by an estimated 3.5 feet and demonstrated that the graceful failure of a levee could work to reduce the impacts of floods (USACE, 2017). By breaching the levee at a selected point, the damages of the flood were restricted to the Birds Point-New Madrid floodway and the amount of uncertainty in what areas would be impacted by the flood was greatly decreased. Instead of having to react to a levee failure at a random location, the intentional levee breach allowed preparations to be made ahead of time to decrease the impact on human life and infrastructure. Following the levee breach in January of 1937, farmers were able to grow a successful crop in the 1937 growing season, and by 1938 the levee was fully restored (USACE, 2017). In 2011, an even larger flood than before occurred, and the Birds Point-New Madrid Floodway was utilized for the second time. This time, there had been much more previous planning prior to the breach, but the actual breaching of the levee was delayed due to legal action. Following the breach, there were no deaths in the floodway, but approximately 1/3 of the farmland was unable to be used for at least a year due to the damages caused by the flood (Olson and Morton, 2012). Part of these damages were caused by the delay in the breach which caused the river level to be higher than had been planned for (Olson and Morton, 2012). Although the levee breach did cause damages to the land affected, it successfully prevented the failure of nearby levees, potentially reduced impacts to communities and infrastructure downstream, and provided useful knowledge about the impacts of a controlled levee breach on the affected area. Despite the two levee breaches of the levee downstream of Cairo, IL not going precisely according to plan, the breach proved that graceful failure is a viable method to decrease the negative consequences of a flood event.

Methodological Approach

In an attempt to identify lands to serve as potential flood water detention areas along the inland waterway system, an approach for selecting and screening the areas using spatial data analysis was developed. Since the primary goal of this project was to determine how to decrease flood damages in developed areas, the level of development was chosen as a key metric to find sites with high potential to undergo graceful failure. Therefore, initial criteria were developed of the potential detention area lands as the following:

- Land that was within five miles of one of the major rivers of the Mississippi River Basin,
- Land that was behind a levee, and
- Land use or land cover categorization that indicated that it was not developed to minimize potential impacts to individuals, infrastructure or communities due to intentional flooding by levee breach.

Using a similar approach as Patterson and Doyle (2009) used in their analysis of national flood policy's effect on socio-economic exposure to floods, study sites were selected based on the level of development as indicated by the National Land Cover Database (NLCD). Khorram et al., 2000 indicated that the NLCD is reasonably accurate justifying our use of it to identify areas where communities would not be negatively impacted if flooded.

Spatial data was gathered for use in the analysis from publicly available sources such as the USGS[1] (National Land Cover Database), the US Army Corps of Engineers[2] (navigable waterways and levees), and US Census Bureau[3] (populated places). Using ESRI's ArcGIS Desktop software (ArcMap version 10.5.1), spatial analysis was performed to exclude land areas that did not meet the criteria above.

The analysis consisted of four parts: 1) the initial analysis of land adjacent to levees along rivers in the Mississippi River Basin using development data in ArcMap to find areas with low levels of development, 2) compiling all of the separate development analyses and selection of potential sites, 3) verifying the viability of each site using population density and urban development data, and 4) using digital elevation model (DEM) files and river gauge data in ESRI's ArcGIS Desktop ArcScene software to determine the volume of water that each site could hold given various flood levels and outer levee heights.

Spatial Analysis Using ArcGIS

The initial selection of potential 'graceful failure' sites was based purely off of proximity to levees along rivers in the Mississippi River Basin. First, a shapefile of major rivers in the contiguous U.S. was utilized in ArcMap. A buffer of 5 miles was then created around these rivers using the buffer tool in

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[1] USGS. 2019. National Land Cover Database (NLCD) 2016. US Geological Survey and the Multi-Resolution Land Characteristics (MRLC) consortium. Available for download at https://www.mrlc.gov/

[2] USACE. 2018. National Waterway Network. US Army Corps of Engineers Digital Library. Available at https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/1472/

[3] USCB. 2019. TIGER/Line Shapefiles and Geodatabases. Available at https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-geodatabase-file.html

ArcMap. Shapefiles of levees in states that contained the rivers being studied were added and merged into one large Mississippi River Basin levees shapefile (Figure 1).

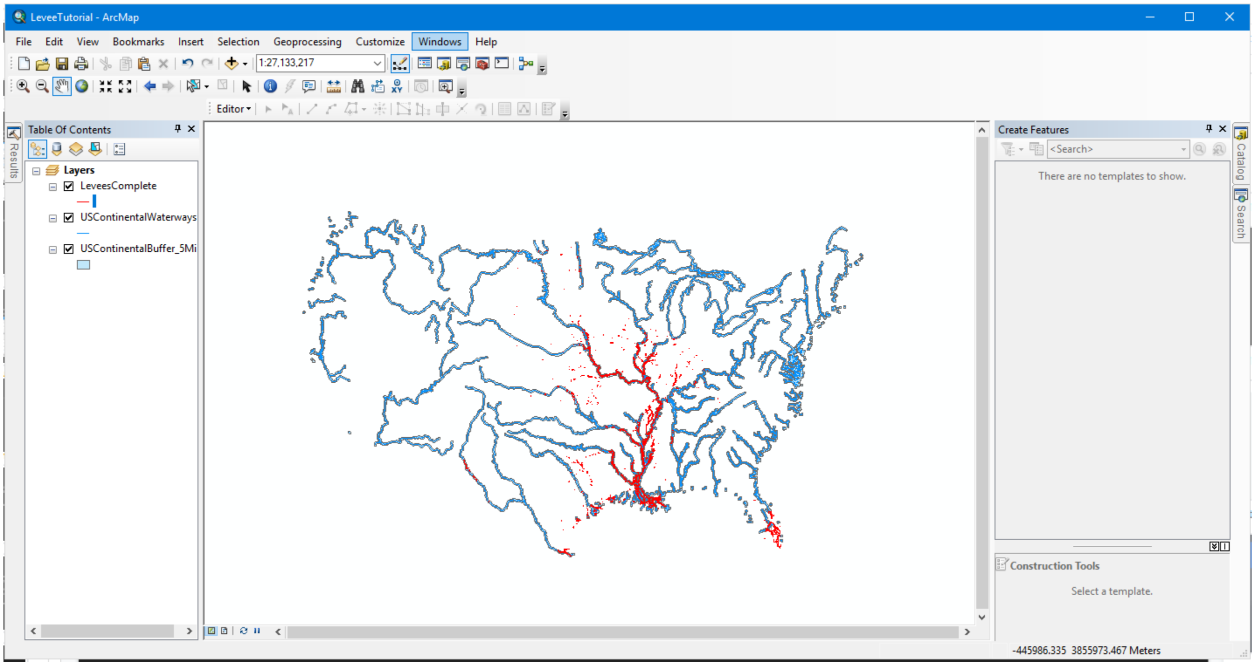
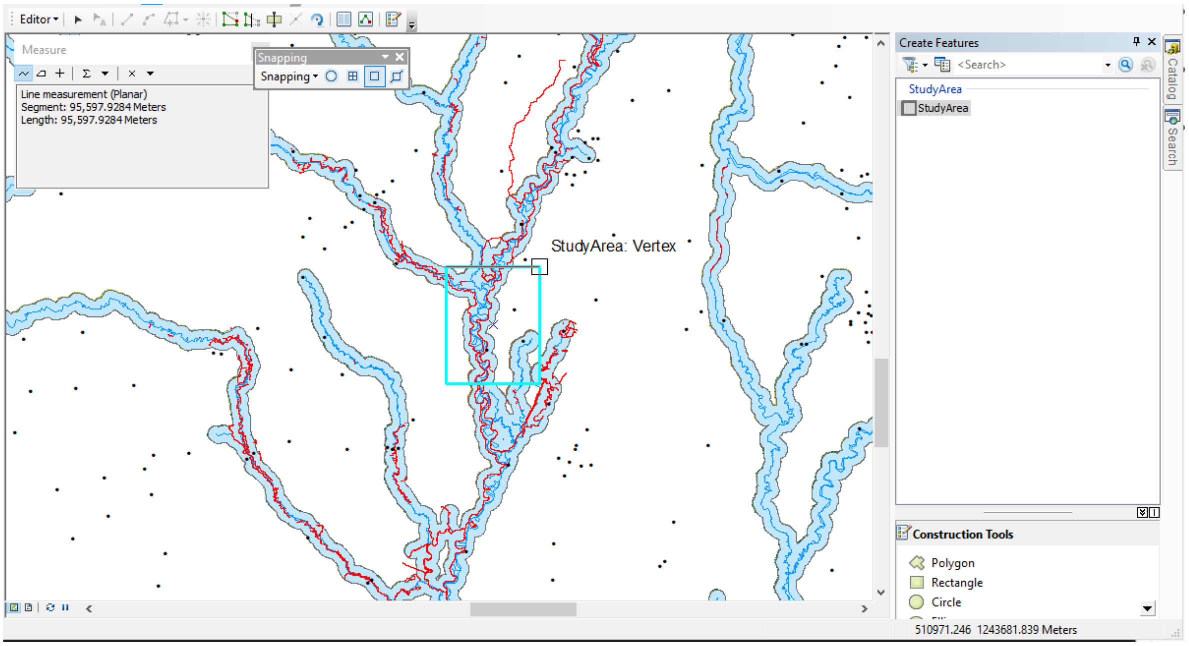


Figure 1: Major rivers with the 5-mile buffer (blue) and levees in the Mississippi River Basin (red)

Due to the extent of the area being considered, rectangular areas with an area less than or equal to 13,500 km^2 were created covering all areas of the buffer by levees in the Mississippi Basin (Figure 2). Restricting the area of these rectangles to 13,500 km^2 was necessary to prevent data overload in the following steps. For each rectangle, a fishnet of 30 m x 30 m squares with points at the center of each square was created using ArcMap's Create Fishnet tool. The points were then clipped so that only the points lying within the 5-mile river buffer remained (Figure 3).



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Line measurement (Planar)
Segment: 95,597.9284 Meters
Length: 95,597.9284 Meters
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510971.246  1243681.839 Meters
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Figure 2: Example rectangular study areas

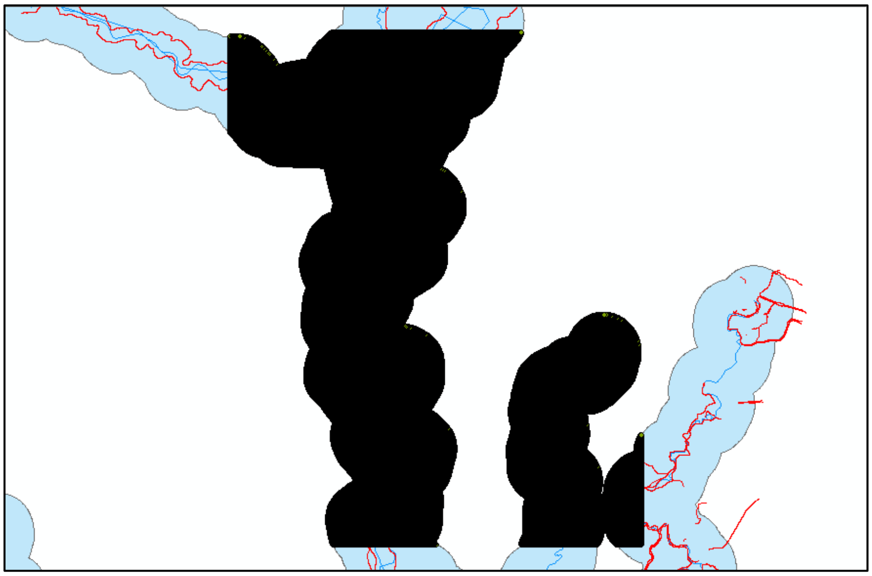
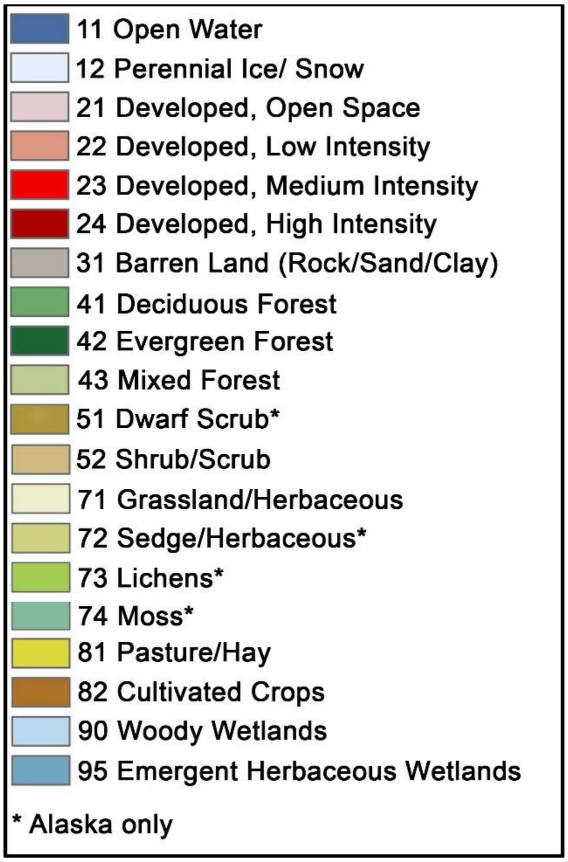


Figure 3: Study area covered in fishnet points

From the United States Geological Survey (USGS) National Land Cover Database (NLCD), the 2016 land cover data for the contiguous U.S. was downloaded and added to the ArcMap document. To increase processing speed the NLCD data was clipped to the geometry of the 5 mile river buffer. Using the Extract Values to Points tool in ArcMap, the land cover value was connected/assigned to the point at the center of each square of the fishnet previously created. The land cover values from the NLCD data are given for 30 m x 30 m squares so they aligned with the fishnet squares and points.

Hot Spot Analysis

Hot spot analysis was utilized as a spatial statistics tool to identify conglomerate areas with similar values/attributes to help in identifying potential areas for flood water detention that would meet our criteria. A value of 1 was assigned to all the points with a land cover value representing urban developed land (i.e., land classification values of 11, 31, 41, 42, 43, 51, 52, 71, 72, 73, 74, 81, 82, 90, and 95), and a value of 100 was assigned to all the points with a land cover value representing land that was not classified as any kind of urban development. The listing of land cover classification values in the NCLD is provided in Figure 4. Using these assigned values, a hot spot analysis was conducted using ArcMap's Optimized Hot Spot Analysis tool to create a map of areas with low development and areas of high development. To increase processing speed, the hotspot maps (created as a series of points) were aggregated into a polygon layer using the Aggregate Points tool in ArcMap. For each study area (rectangle), hot spot analysis provided clustering of both highly developed and low development areas (Figure 5).



🟦 11 Open Water
⬜ 12 Perennial Ice/ Snow
⬜ 21 Developed, Open Space
🟧 22 Developed, Low Intensity
🟥 23 Developed, Medium Intensity
🟥 24 Developed, High Intensity
⬜ 31 Barren Land (Rock/Sand/Clay)
🟩 41 Deciduous Forest
🟩 42 Evergreen Forest
🟩 43 Mixed Forest
🟫 51 Dwarf Scrub*
🟫 52 Shrub/Scrub
⬜ 71 Grassland/Herbaceous
🟨 72 Sedge/Herbaceous*
🟩 73 Lichens*
🟩 74 Moss*
🟨 81 Pasture/Hay
🟫 82 Cultivated Crops
🟦 90 Woody Wetlands
🟦 95 Emergent Herbaceous Wetlands

* Alaska only

Figure 4: NLCD Land Cover Classifications[4]

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[4] USGS. NLCD Land Cover Classifications. Available at https://www.mrlc.gov/data/legends/national-land-cover-database-2011-nlcd2011-legend

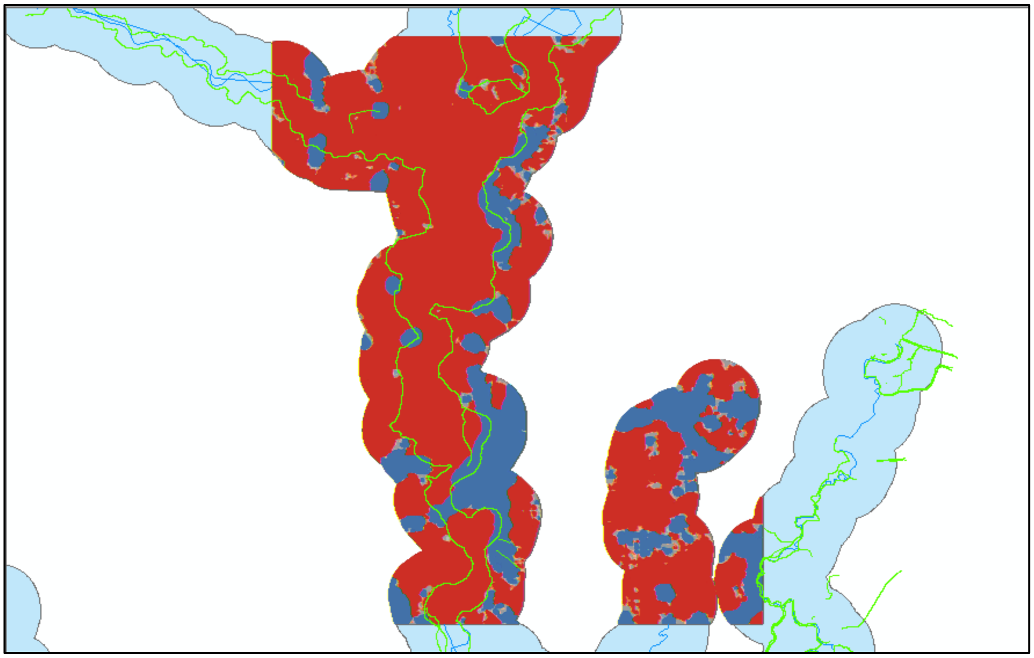

Figure 5: Hot spot map with areas of high development shown in blue and areas of low development shown in red. Levees are portrayed by the green lines.

Once hot spot maps had been created for each study area, the maps were merged together to create a single polygon layer representing all areas of high and low development along levees in the Mississippi River Basin (Figure 6). From this Mississippi River development map, potential sites were selected based off of large areas of undeveloped land behind levees (Figure 7). These potential sites were clipped to the area behind the levee to the edge of the 5-mile river buffer. A total of 20 sites were selected for further study. Each site was assigned a number from 1-20 for tracking purposes only.

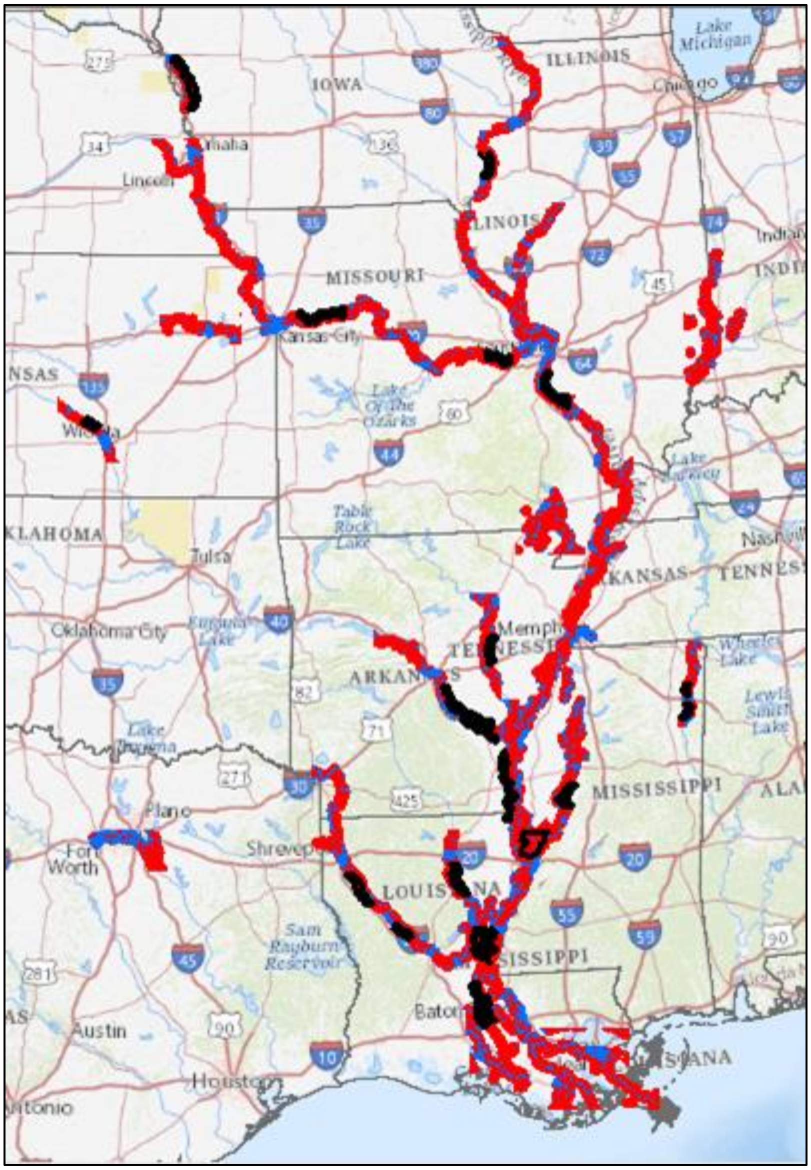

Figure 6: Compilation of hot spot areas with selected potential sites shown in black.

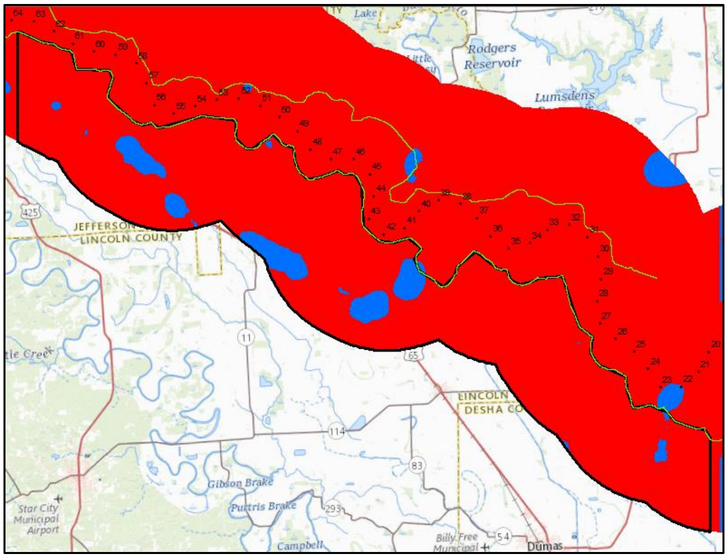

Figure 7: A closer look at one of the potential flood water detention sites identified along the Arkansas River.

Screening for Development and Population Density

Urban development data from the US Census Bureau in the form of a shapefile was added to the ArcMap document and each of the sites were checked with this data to ensure that the hot spot analysis had yielded accurate results. No sites were eliminated by this check.

Following the urban development check, population density data in the form of a color-coded shapefile was added to the ArcMap document. The potential sites were cross checked with the population density data and none of the sites were eliminated because the area within all the potential sites consisted of a vast majority of the lowest population density (less than 100 people per square mile). Following all the checks of the potential sites, all 20 sites remained as candidates for the volume analysis.

Flood Detention Volume Analysis

To conduct the volume analysis, 1 arc second x 1 arc second Digital Elevation Models (DEM) covering the areas of each potential site were downloaded from USGS's The National Map[5]. These DEM raster files were added to an ArcScene document and elevated to show a 3D image of the land within and around the potential sites. When more than one 1 arc second x 1 arc second DEM was necessary to cover the area of the potential site, the multiple DEMs were stitched together into one DEM with the ArcScene Mosaic to New Raster tool (Figure 8).

Using the National Weather Service's map of U.S. river gauges[6], two gauges were located along the stretch of river next to each potential site and flood stage elevation was obtained for each gage. This elevation represented a minimal elevation where levee breach might be enacted. Levee

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[5] USGS. 2019. The National Map. Available at https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map

[6] NOAA. 2019. River Observations. National Oceanic and Atmospheric Association. National Weather Service. Available at https://water.weather.gov/ahps/

overtopping represented a worst-case scenario or maximum volume that the site might hold during a flood water detention scenario. The height of the levee was estimated by sampling of the DEM along the levee at multiple points in the area of interest and in the area of the gauges.

River flood stage elevation and the height of overtopping the levee from the gauge stations was estimated by employing the center of the site and estimating levee heights from the DEM at each gauge location and at the center. A weighted-average approach was applied using the distance of each gauge station to the center of the potential site to obtain the "slope" of the levee, the river surface at flood stage, etc.

Using the calculated flood stage height at the center of the potential site, the amount of water that could be contained at that level behind the levee was calculated employing the Surface Volume tool in ArcScene. This involved creating a "surface" at the flood stage elevation under consideration and "slicing" the DEM. The maximum inundation area of the potential site (i.e., that corresponding to the flooding of the site at the top of levee elevation) was obtained from the site layer's attribute table where the area of the polygon is automatically calculated and recorded. This provided a representative flood detention surface area and allowed for consideration of the extent of flooding. The volume of water that could be stored during a levee overtopping) was also considered, allowing floodwaters to fill to that elevation from the lowest point in that vicinity, similar to a bathtub filling. The volume is calculated as a composite volume of the smaller columns of water between the surface and the bottom of the DEM surface for the area encompassed by the surface. This process was repeated for top of levee (representing the maximum volume that could be contained) and mid-way between flood elevation and top of levee using the center of the site along the river as the point of reference.

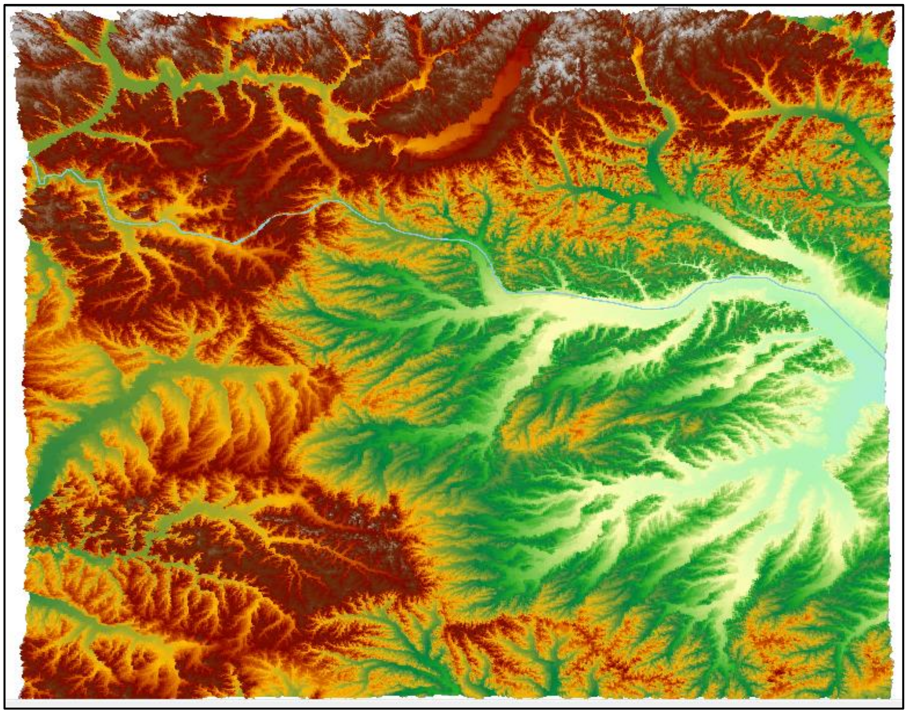

Figure 8: Elevated and stitched together DEMs in ArcScene. The river is shown as a light blue line. Different colors are associated with different elevations where the lighter colors are associated with lower elevations.

Throughout this process, two sites were eliminated as they were found to contain a lock and dam. A third site was eliminated due to the lack of gauge station data near the site, making the volume analysis very difficult and almost certainly inaccurate. In the end, volume data was obtained for 17 potential sites.

Results

Initial screening based upon location along the Mississippi River Basin, levee proximity, and land cover classification resulted in 20 potential sites that could be used for flood water detention and graceful failure option. Additional screening and analysis were conducted to determine preliminary feasibility of the sites to store enough flood waters to potentially be beneficial. From this evaluation, 17 potential sites were identified. For each of the 17 resulting sites, the volume of flood waters that could be contained at each of three elevations (flood stage, top of levee, and mid-way between flood stage and top of levee) were calculated. The resulting sites with associated potential storage volumes based upon river and levee elevation are presented in Table 1.

Table 1: Summary of Viable Site Characteristics

Site Number	Nearby City	Flood Height Volume (acre-feet)	Top of Levee Height Volume (acre-feet)	Midpoint Height Volume (acre-feet)	Site Total Surface Area (acres)
1	Waverly, MO and Napolean, MO	785,867.84	1,790,055.58	1,250,190.69	137,393.39
2	Washington, MO and Hermann, MO	36,480.96	96,816.08	61,610.94	76,475.56
3	Hornick, IA	563,520.97	899,905.21	721,305.62	166,408.30
4	Arnold, MO and Chester, IL	118,024.23	535,421.88	286,822.63	117,946.68
6	Keithsburg, IL and Gladstone, IL	197,645.44	462,967.65	320,609.58	60,057.71
7	Georgetown, AR and Des Arc, AR	459,001.37	851,110.35	640,887.22	69,279.36
8	Fulton, MS	84,598.90	117,701.70	100,907.88	24,960.53
9	Fulton, MS and Bigbee, MS	83,925.62	111,188.71	96,873.75	43,622.10
10	Pine Bluff, AR	1,978,326.92	3,165,285.40	2,525,347.32	158,554.27
11	Pine Bluff, AR and Pendleton, AR	1,067,979.58	1,871,206.03	1,440,464.67	99,752.00

12	Greenville, MS	1,125,677.31	1,851,811.20	1,469,930.06	174,422.61
13	Belzoni, MS	187,436.50	652,730.15	397,517.65	84,825.76
14	Vicksburg, MS and Yazoo City, MS	706,272.40	1,748,136.69	1,176,862.73	207,411.35
17	Coushatta, LA and Shreveport, LA	255,599.34	856,010.00	510,153.12	98,744.66
18	Grand Ecore, LA and Alexandria, LA	100,608.89	597,058.40	310,269.54	55,536.31
19	Melville, LA and Krotz Springs, LA	1,048,010.95	3,276,938.14	2,118,307.11	122,567.51
20	Krotz Springs, LA	564,821.99	1,631,042.80	1,096,454.90	67,252.03

From this, we see many sites that fall under low development and meet the criteria are on the lower Mississippi and some are in the vicinity of the Birds Point-New Madrid Floodway. Therefore, these sites may offer little to no additional benefits for flood detention and mitigation using intentional levee breach beyond that of the New Madrid Floodway. However, the sites farther upstream in Iowa, Illinois, and Missouri may have some promise for additional consideration.

Conclusions

The intent of this research project was to develop an approach to screen and identify potential areas where graceful failure through intentional levee breach could be used as a flood hazard mitigation effort along the Mississippi River Basin area. Publicly available data sets were utilized along with ESRI's ArcGIS software tools to perform a high-level screening analysis employing spatial analysis techniques in the approach. Criteria was identified and applied along the Mississippi River and tributaries to identify potential flood detention areas as those clustered areas (as identified by hot spot analysis) within 5 miles of the waterway center line, behind levees, and with low developed land cover types. The initial screening resulted in 20 potential sites. Three of these were removed due to basic feasibility considerations leaving 17 potential sites.

Digital elevation model (DEM) data was used to estimate levee heights along the river and also in calculating volume of flood waters that could potentially be stored/diverted. Locations along the river near the center point of the possible inundation area was used in combination with river gage stations to estimate flood stage and elevations of the river. The volume of floodwaters that each site could hold was computed for three different flood elevations (flood stage, top of levee, and mid-way between flood stage and top of levee) using gage data and DEM data.

Many of the resulting sites from the screening analysis were along the lower Mississippi and would likely not offer significant flood detention in comparison to the New Madrid Floodway. However, a few sites in Iowa, Illinois, and Missouri show potential because of their location, the number of downstream communities, and their potential to store a large volume of water to reduce damages downstream due to their location in the watershed and the number of communities downstream and the large volume of water that they could store. Additional analysis at the local level including investigation of the levee (e.g., potential breach points, condition, materials, etc.), land ownership, and other potential risks to humans and infrastructure must be taken into consideration.

This screening level analysis of the potential of graceful failure techniques for flood mitigation through intentional levee breach on the US inland waterway system is a first of its kind. The approach could be applied to smaller tributaries and other river systems to help reduce flooding downstream, assuming levees are present on the waterbodies. Additional research including hydrodynamic modeling and additional analysis to determine to what extent this amount of storage could actually make an impact on the river flood levels is needed.

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