



US Army Corps
of Engineers ®

Tulsa District

APPENDIX B: Hydrologic and Hydraulic Analysis
Tulsa and West-Tulsa Levee Feasibility Study

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ATTACHMENT 1: SQRA HYDROLOGY /	See Table of Contents NOTE 1 - Pursuant to
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EG-1105-2-112 and EG-1110-2-0074

1 APPENDIX B – HYDRAULICS AND HYDROLOGY

1.1 Introduction

The Tulsa/West Tulsa (TWT) Levee System is comprised of two left-bank segments (Levees A and B), and a right-bank segment (Levee C). All segments have tiebacks along tributaries. The main stem levee segments protect residential, commercial, and industrial areas from large flows along the Arkansas River. The Arkansas River flows from west to east, approximately 15 miles into Tulsa County. It then flows southeast through Tulsa County for approximately 25 miles. It has a drainage area of roughly 74,500 square miles above Keystone Dam, of which about 23,000 square miles are considered to contribute to flood flows.

Keystone and Kaw Dams regulate flows along the Arkansas River through Tulsa County. Other flood-control dams are in the watershed but have minimal impact on the levee system. The minimum level of protection along the main stem levee segments is about 360,000 cubic feet per second (cfs), which is approximately a 0.4 percent annual chance exceedance (ACE) flood. Overtopping would initially occur along the lower end of Levee B near Newblock Park.

Bigheart, Harlow, and Parkview Creeks are left bank tributaries of the Arkansas River that drain areas above Levees A and B. The lower reaches of these streams have gentle slopes within the flat Arkansas River floodplain. West Bigheart Creek, a tributary of Bigheart Creek, is separated from the protected area by the Levee A tieback and is largely regulated by Sand Springs Lake. Harlow Creek is separated from the protected area by the Levee B tieback. Bigheart Creek and Harlow Creek both originate in Osage County, and the confluence of both of these streams occurs just upstream from the Charles Page Floodway Structure. Parkview Creek drains from the interior of Levee B and exits to the Arkansas River in Newblock Park. None of the tieback levees protect to the 1 percent ACE flood from these tributaries. Significant interior ponding can also occur during intense local storms that also affect the tributaries. There are a total of seven pump stations and interior ponding areas to address these issues (P.S. 1 through 3 are behind Levee A, P.S. 4 and 5 are behind Levee B, and P.S. 6 and 7 are behind Levee C).

Several significant floods have occurred along the Arkansas River in Tulsa County. Prior to the construction of Keystone Dam, the flood of record occurred in October 1959, with an estimated peak flow of 246,000 cfs. The second largest pre-regulation flood was 244,000 cfs in June 1923. Since the construction of Keystone Dam, significant flood-control releases occurred in 1974, 1986, 1993, 1998, 2007, and 2019. The two most significant releases occurred in October 1986, with a peak flow of 307,000 cfs, and May 2019, with a peak flow of 277,000 cfs.

Large floods on the tributaries, including Bigheart, Harlow, and Parkview Creeks, occurred in June 1974 and May 1984. No stream gages are located in the watershed; however, the June 1974 flood was estimated to have a 2 percent ACE based on high water marks. The 1984 Memorial Day Flood was the worst flood event in the Tulsa's history. It affected most of the Tulsa metropolitan area, and was estimated to have a 1 percent ACE. Harlow Creek overtopped

the Levee B tieback, affecting residential areas; most of the flooding resulted from rainfall occurring over the interior area.

HYDROLOGIC AND HYDRAULIC MODELING

The hydrologic analysis that was used in this study originated from two primary sources: 1) available gage data for the Arkansas River and 2) the development of synthetic hydrographs for the ungaged tributaries (including Harlow Creek) using the application of NOAA Atlas 14 frequency rainfall to the respective watersheds in HEC-HMS. This analysis occurred during the development of the 2015 Semi-Quantitative Risk Assessment (SQRA) and was adopted for this study. Detailed information about the hydrologic analysis can be found in the SQRA report, which has been appended to this document.

Hydraulic modeling was also developed for the 2015 SQRA, and was subsequently used for the 2019 modified SQRA. The HEC-RAS model, which incorporated a combination of unsteady one-dimensional channel flow with a two-dimensional grid in the areas protected by the levee segments, incorporated the observed 1986 Arkansas River flood hydrograph, which was subsequently scaled to different magnitudes. Tributary hydrographs were derived from HEC-HMS. The HEC-RAS model was used to evaluate the alternatives and ultimate selection of the Tentatively Selected Plan (TSP) during the feasibility study. Detailed information about the development of the hydraulic model can be found in the SQRA report, which has been appended to this document.

Several feasibility study alternatives were modeled, including Alternative 1 (filtered berms w/ toe drains), Alternative 2 (filtered berms w/ cutoff walls), and Alternative 3 (full cutoff wall). The final array of alternatives selected for analysis were 1E (filtered berms w/ local cutoff wall, Harlow Creek detention ponds), 3B (full cutoff wall w/ no increase in level of protection), 5 (non-structural buyout), and 6 (no action). Alternative 1E was subsequently recommended as the TSP.

EXISTING CONDITIONS

As they currently exist, the main stem levee segments offer a 0.4 percent ACE minimum level of protection (Levee B will overtop with an estimated flow of 360,000 cfs). Loading begins at approximately 150,000 cfs. Therefore, only the 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE scenarios were analyzed for life loss and economic damages. For existing conditions, the levee was assumed to fail when loaded at these frequency flows along the Arkansas River. Past performance has shown that local failures can occur within this range of flow frequencies, which happened near LCL 2 (Levee A) during the 1986 flood. The corresponding flow frequency was approximately 0.2 percent ACE.

Performance during the historic 2019 flood must also be considered as part of an analysis of existing conditions. According to preliminary data from the Oklahoma Mesonet, the statewide average rainfall total in May was 10.48 inches. The National Weather Service (NWS) cooperative observer site at Pawnee, within the Keystone watershed, led the state with 22.52 inches. At least 24 NWS sites in the region broke their all-time May rainfall mark. Nineteen of

those sites broke their all-time wettest calendar month marks as well, including seven sites whose records date back over 100 years. Record rainfall was also observed within the Arkansas River watershed in Kansas. Twenty Kansas Mesonet stations reported rainfall amounts over 20 inches for the month, with a Butler County station reporting over 30 inches. The average rainfall for the entire state of Kansas was 10.26 inches, which was the highest total in 125 years of record keeping.

Eight U.S. Army Corps of Engineers (USACE) reservoirs in Oklahoma reached new pools of record, including Keystone Lake. The historic rainfall observed in May produced widespread flooding along the Arkansas River and its tributaries. A release of 277,000 cfs resulted in the highest release from Keystone Dam into the Arkansas River since 1986. Although riverine flooding within the City of Tulsa and its suburbs was largely confined to open public spaces (with the notable exception of the River Spirit Casino, which was closed for several weeks), neighborhoods in unincorporated Tulsa County to the west of Sand Springs did experience significant flooding.

The TWT Levee System was loaded for an extended duration during the 2019 flood, with a peak release of 277,000 cfs from Keystone Dam occurred over a duration of 30 hours. The duration of releases exceeding 200,000 cfs occurred over 10 consecutive days. This duration of loading was significant because it had not previously been loaded for this long at these observed flow rates.

Scenarios with the probabilities and corresponding flow rates were developed for the Arkansas River and Harlow Creek (Levee B Tieback), respectively are listed in Table B-1.

Table B-1: ACE flow rates for the Arkansas River and Harlow Creek.

ACE	Flow (cfs)	
	Arkansas River	Harlow Creek
0.20 percent	490,000	No Scenario
0.50 percent	310,000	No Scenario
1 percent	205,000	4,170
2 percent	155,000	3,630
5 percent	125,000	3,000
10 percent	105,000	2,360
20 percent	100,000	1,850
50 percent	85,000	1,220

No scenarios were developed for Bigheart Creek (Levee A Tieback) or Cherry Creek (Levee C Tieback).

Along the main stem levee segments, loading was assumed to begin at a flow rate of approximately 150,000 cfs. Therefore, only the 1 percent, 0.5 percent, and 0.2 percent ACE Arkansas River events resulted in inundation behind Levees A, B, and C. For existing conditions, these scenarios were modeled with a breached levee. It should be noted that although this is how existing conditions were modeled, it does not imply that any of the levee segments would be expected to fail at the 1 percent ACE or even the 0.5 percent ACE loading events. In fact, historical performance shows that the 1 percent ACE event only minimally loads the main stem levee segments, and 0.5 percent ACE events have a mixed performance history, with a local failure near P.S. No. 2 during the 1986 flood, but no failures were observed during the 2019 flood. Failure would be expected during the 0.2 percent ACE event, as the main stem levee segments overtop, and would then be at high risk for head cutting and subsequent failure, although the failure and non-failure inundation areas would effectively be the same. Actual probabilities of breach at these loading frequencies were determined from the development of fragility curves (see [Appendix A](#)).

A representative location was selected for breach along each of the main stem levee segments (Figure B- 1). Along Levee A, [See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074](#) was the modeled location of failure. This location was selected because of past performance issues. More specifically, it experienced a localized failure during the October 1986 flood. Along Levee B, [See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074](#)

[See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074](#) Along Levee C, [See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074](#) represents the site of initial overtopping along the segment.

In addition to the three main stem breach locations [See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074](#) This site is located on the upper end of the Levee B Tieback. It is located at a location that overtops at a 1.2 percent ACE with performance history of doing so during the May 1984 flood.

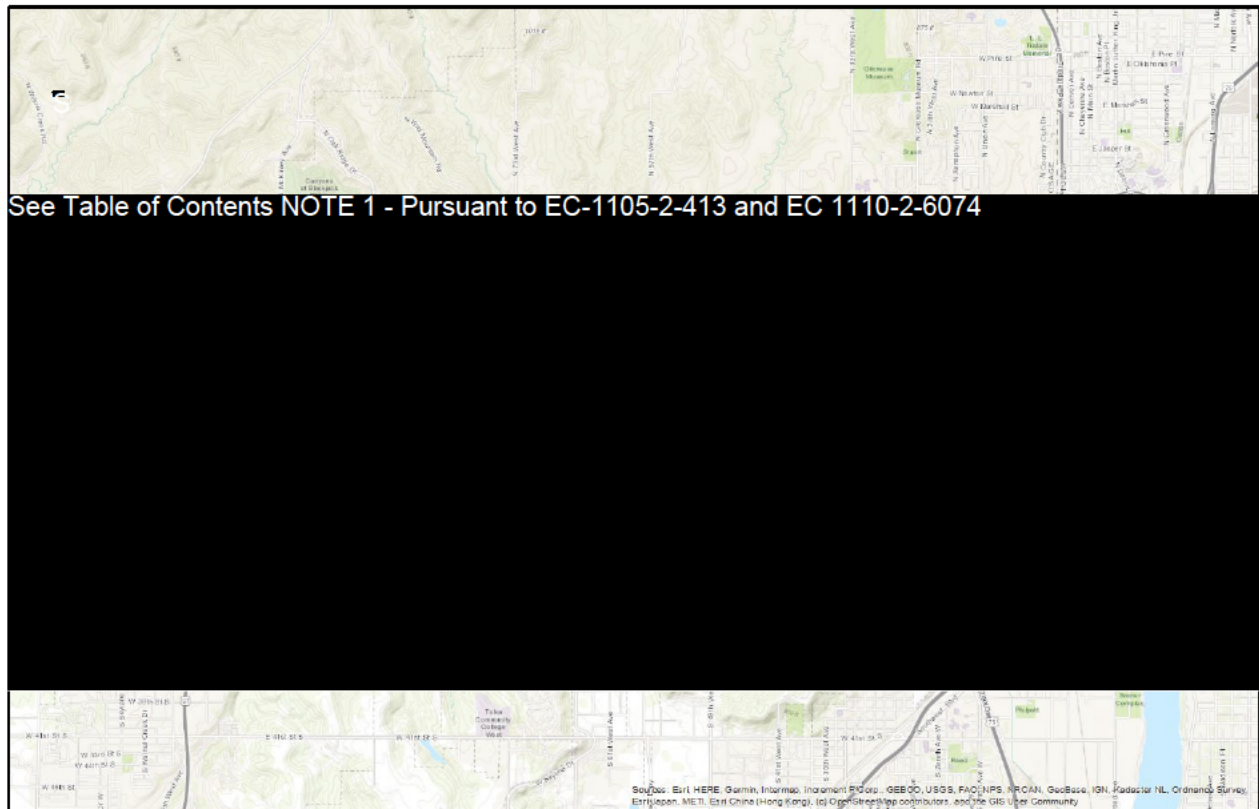


Figure B- 1: See Table of Contents NOTE 1 - breach analysis.

Existing conditions were evaluated by modeling the 1 percent, 0.5 percent, and 0.2 percent ACE Arkansas River events along the main stem Levee A, B, and C segments. See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074 Each breach location was analyzed separately. The Levee B Tieback was evaluated by modeling the 50 percent, 20 percent, 10 percent, 5 percent, 2 percent, and 1 percent ACE. See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074 In order to better inform the life loss and damages at this location, two additional (and non-standard) scenarios were added: 1.4 percent ACE and 1.2 percent ACE.

Water surface profiles and inundation maps for the existing conditions scenarios are presented at the end of this report.

ALTERNATIVE 1: FILTERED BERMS W/ TOE DRAINS

Alternative 1A - This alternative would address all potential failure modes for the entire system primarily with filtered exits. Throughout the entire levee system (A, B and C), conduits would be abandoned and/or replaced and filtered exits constructed.

- Levee A: Construct full Cutoff Walls at Charles Page Blvd (North and South) for approximately 600 feet and seal joints where needed and full Cutoff Wall at the Superfund Site for a combined total of approximately 15,000 feet within Levee A.

- Levee B: Permanently Raise Levee B back to original design flow at Pump Station No. 5 for approximately 3,000 feet; construct a stability berm with a filtered exit and relief wells at Pump Station No. 4; and a detention pond(s) for approximately 30 acres behind Levee B; and filter along the tieback.
- Levee C: Permanently Raise Levee C back to original design flow at I-244 Corridor for approximately 1,000 feet; construct a landside berm with relief wells for approximately 6,800 feet; and construct a flood wall structure with flap gate.
- Non-Structural measures include: Update the City of Tulsa Hazard Mitigation Plan; update Temporary Evacuation Plan; Update Warning System; buy-out; and raise structures.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EPC 1105.2.112 and EPC 1110.2.6074](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, B, and C. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table](#) although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with [See Table of Contents NOTE 1 - Pursuant to EPC 1105.2.112 and EPC 1110.2.6074](#) (Levee B), the low point along the main stem of the Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 1A that involved raising Levees B and C back to the original design flow became a moot point and were not investigated any further. The modeled scenarios for Alternative 1A were identical to the existing conditions scenarios, except that none of the levee segments were assumed to breach.

Alternative 1B – This alternative would address all PFMs for only Levee A and B, primarily with filtered exits. Throughout Levee A and B, conduits would be abandoned and/or replaced and filtered exits constructed. The same as Alternative 1A, but without Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EPC 1105.2.112 and EPC 1110.2.6074](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table](#) although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table](#) (Levee B), the low point along the main stem of the

Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 1B that involved raising Levee B back to the original design flow became a moot point and were not investigated any further. The modeled scenarios for Alternative 1B were identical to Alternative 1A, except that Levee C was omitted from the analysis.

Alternative 1C – This alternative would address PFMs except no overtopping failure modes for the entire levee system (A, B and C) primarily with filtered exits. Throughout the entire levee system (A, B and C), conduits would be abandoned and/or replaced and filtered exits constructed. Same as Alternative 1A but with no levee raise in Levee B or Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to E.O. 11659 and E.O. 11734](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, B, and C. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table](#) although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table](#) (Levee B), the low point along the main stem of the Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 1C that involved raising Levees B and C back to the original design flow became a moot point and were not investigated any further. The modeled scenarios for Alternative 1C were identical to Alternative 1A (and subsequent alternatives).

Alternative 1D – This alternative would address penetration failure modes except no overtopping failure modes for Levee A and B only. Throughout Levee A and B, conduits would be abandoned and/or replaced and filtered exits constructed. Same as Alternative 1C but with no issues addressed within Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to E.O. 11659 and E.O. 11734](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table](#), although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table](#) (Levee B), the low point along the main stem of the

Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 1D that involved raising Levee B back to the original design flow became a moot point and were not investigated any further. With the assumptions that were made concerning overtopping, the modeled scenarios were identical to Alternative 1A (and subsequent alternatives).

Alternative 1E – As the team formulated through the process, this alternative was refined to address seepage and erosion throughout Levee A and B to include construction of a filtered berm with toe drain except for a cutoff wall to rock at the Superfund Site for approximately 2,000 feet within Levee A. Construct a robust filter at Charles Page Floodway Structure. Buyout within landside toe where required and other properties as needed. Armor landside slope at P.S. No. 5 for approximately 3,000 feet. Construct a detention pond for 100 year storm above Levee B tieback. Levee A and B conduits deemed unnecessary will be abandoned and all required for continued operation of the system will be replaced. Reconstruction Measures – Update Pump Stations 1-7.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur. [See Table of Contents NOTE 1 - Pursuant to E.O. 11652 and E.O. 11654](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur. [See Table of Contents NOTE 1 - Pursuant to E.O. 11652 and E.O. 11654](#) although overtopping did occur with the 1 percent ACE scenario. The modeling for this alternative was identical to Alternative 1A (and subsequent alternatives) for Arkansas River events, and Harlow Creek events were added to address the Levee B tieback.

The detention pond option was proposed as a way to reduce the peak flow along Harlow Creek during a local storm. Specifically, two detention ponds would be constructed along the upper end of Harlow Creek in the immediate vicinity of US-412. Rough sizing of the detention pond was estimated by determining incremental volume between the 10 percent ACE and 1 percent ACE Harlow Creek hydrographs. The reduction in volume was accounted for in the HEC-RAS model by using the 10 percent ACE Harlow Creek hydrograph for life loss and damages estimation, which removed loading from the Levee B Tieback.

Water surface profiles and inundation maps for Alternative 1E are presented at the end of this report.

ALTERNATIVE 2: FILTERED BERMS AND CUTOFF WALLS

Alternative 2A - This alternative would address all PFMs for the entire system primarily with cutoff walls. Throughout the entire levee system (A, B and C), a cutoff wall would be constructed at each penetration for approximately 6,800 total feet and replace approximately 90 conduits.

- **Levee A:** Construct full Cutoff Walls at Charles Page Blvd (North and South) for approximately 600 feet and seal joints where needed; full Cutoff Wall at the

Superfund Site for approximately 15,000 feet; and construct a detention pond for tieback.

- **Levee B:** Permanently Raise Levee B back to original design flow and armor landside slope at Pump Station No. 5 for approximately 3,000 feet; construct a cutoff wall for approximately 3,000 feet at Pump Station No. 4; and raise levee to original design flow and construct cutoff wall for approximately 9,000 feet along the tieback.
- **Levee C:** Armor landside slope at I-244 Corridor for approximately 1,000 feet; construct a cutoff wall for approximately 6,800 feet; and construct a flood wall structure with flap gate.
- **Non-Structural measures** in this alternative include updating the City of Tulsa Hazard Mitigation Plan; Evacuation Plan; Warning System; and potential buy-out of homes.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 4405-2-412 and EOG 4410-2-6074](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, B, and C. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 4405-2-412 and EOG 4410-2-6074](#) although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table of Contents NOTE 1 - Pursuant to EOG 4405-2-412 and EOG 4410-2-6074](#) (Levee B), the low point along the main stem of the Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 2A that involved raising Levees B and C back to the original design flow became a moot point and were not investigated any further. The modeled scenarios for Alternative 2A were identical to Alternative 1A (and subsequent alternatives).

Alternative 2B – This alternative would address all PFMs for only Levee A and B, primarily with cutoff walls. Throughout Levee A and B, a cutoff wall would be constructed at each penetration for approximately 3,600 total feet and replace approximately 65 conduits. The remainder areas throughout Levee A and B would be addressed with filtered berm with toe drains. This alternative is the same as Alternative 2A but with no issues addressed within Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 4405-2-412 and EOG 4410-2-6074](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 4405-2-412 and EOG 4410-2-6074](#) although overtopping did occur with the

1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) (Levee B), the low point along the main stem of the Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 1B that involved raising Levee B back to the original design flow became a moot point and was not investigated any further. The modeled scenarios for Alternative 2B were identical to Alternative 1A (and subsequent alternatives).

Alternative 2C – This alternative would address penetration failure modes (no overtopping failure modes) for the entire levee system primarily with cutoff walls. Throughout the entire levee system (A, B and C), cutoff walls would be constructed at each penetration and conduits replace. Same as Alternative 2A with no levee raise in Levee B or Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, B, and C. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) although overtopping did occur with the 1 percent ACE scenario. The flow associated with overtopping along the main stem segments was investigated using a modified HEC-RAS geometry with adjusted Manning's roughness coefficients for the Arkansas River channel. These values were adjusted in order to calibrate the model to observed stages and flows during the May 2019 flood. The minimum modeled flow associated with overtopping [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) (Levee B), the low point along the main stem of the Arkansas River for all three levee segments, was estimated to be 360,000 cfs. Since the design flow of the project is 350,000 cfs, the parts of Alternative 2C that involved raising Levees B and C back to the original design flow became a moot point and were not investigated any further. The modeled scenarios for Alternative 2C were identical to Alternative 1A (and subsequent alternatives) since they ultimately did not incorporate an increase in the crest elevations of Levees B or C.

Alternative 2D – This alternative would address penetration failure modes (no overtopping failure modes) for only Levee A and B. Same as Alternative 2C but with no issues addressed within Levee C.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to EOG 1105-0-110 and EOG 1110-0-0071](#) although overtopping did occur with the

1 percent ACE scenario. The modeled scenarios for Alternative 2D were identical to Alternative 1A (and subsequent alternatives).

ALTERNATIVE 3: FULL CUTOFF WALL **See Table of Contents NOTE 1 -**

Alternative 3A - This alternative would address all potential failure modes for the entire system primarily with a permanent levee raise to 1/500 ACE and permanent levee raise of 1/100 ACE for the tiebacks. A cutoff wall would be constructed along the entire levee system (A, B and C) (approximately 20 miles) and approximately 90 conduits replaced. Non-structural measures would include updating the City of Tulsa Hazard Mitigation Plan; Evacuation Plan; Update Warning System; and potential buyouts.

See Table of Contents NOTE 1 - originally included an increase in the level of protection along the main stem levee segments to a 0.2 percent ACE flood along the Arkansas River. This level of protection corresponded to a discharge of 490,000 cfs (cfs). A scenario was developed in the HEC-RAS model that took the October 1986 release hydrograph from Keystone Dam and scaled all of the ordinates so that the peak discharge matched the 0.2 percent ACE flood. The geometry of the HEC-RAS model was modified so that the “bump outs” constructed within the Arkansas River as part of the development of The Gathering Place were accounted for. The Gathering Place is a public open space centered on the east bank of the Arkansas River along Riverside Drive approximately two miles south of downtown Tulsa and adjacent to the Maple Ridge historic district, an upscale residential area. This public-private partnership covers approximately 100 acres of land and cost about \$465 million to construct.

The HEC-RAS model was set up with two different geometries for the 0.2 percent ACE flood scenario. The original geometry file included Levees A, B, and C with existing crest profiles. As they currently exist, the levees offer a 0.4 percent ACE minimum level of protection (Levee B will overtop with an estimated flow of 360,000 cfs). A second geometry file was then created with all levee crests raised so that they contained the 0.2 percent ACE flood. The 0.2 percent ACE scenario was then run with both of the geometry files so that the incremental differences in the water surface profiles along the Arkansas River could be determined.

Once the HEC-RAS modeling was completed for the 0.2 percent ACE **See** it was obvious that any increase in the crest heights of Levees A, B and C would increase the water surface profiles in the vicinity of the TWT Levee system. This effect was most pronounced immediately upstream and across from Levee A (on the right bank of the Arkansas River), and also across from Levee C on the left bank of the Arkansas River. In both areas, the increased depths as a result of the implementation of the 0.2 percent ACE **See** would affect residential structures. The impacts opposite Levee A on the right bank of the Arkansas River would increase 0.2 percent ACE depths in the Town and Country subdivision in unincorporated Tulsa County by 2-5 feet. The impacts opposite Levee C on the left bank of the Arkansas River would increase 0.2 percent ACE depths in low-lying areas within the Maple Ridge historic district adjacent to the Gathering Place. In this area, including the Gathering Place, flood inundation depths would increase by 2-5 feet over existing 0.2 percent ACE conditions. This effect was less pronounced

in the HEC-RAS model downstream [redacted] See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC-1110-2-6074 in Tulsa.

Since the 0.2 percent ACE [redacted] increased flood inundation depths both opposite Levee A on the right bank of the Arkansas River and opposite Levee C on the left bank of the Arkansas River, it represented a transfer of risk. This transfer of risk was not trivial (with increases in flood inundation depths of 2-5 feet), and it affects both residential areas and public use areas with significant levels of financial investment. Therefore, the transfer of risk posed by the adoption of the 0.2 percent ACE [redacted] was deemed unacceptable by the PDT, and after consultation with the local sponsor [redacted] See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC-1110-2-6074

See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [redacted] See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC-1110-2-6074 although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, B, and C. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [redacted] See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC-1110-2-6074 although overtopping did occur with the 1 percent ACE scenario. The modeled scenarios for Alternative 3A were identical to Alternative 1A (and subsequent alternatives) with the exception of the modified geometry that was used to assess loading for the modified 0.2 percent ACE scenario.

Alternative 3B – The same as Alternative 3A, except without raising the main-stem and/or tie backs within the levee system and no issues addressed within Levee C. This alternative would also include construction of a robust filter at Charles Page Floodway Structure. Buyout within

landside toe where required and other properties as needed. Armor landside slope at P.S. No. 5 for approximately 3,000 feet. Construct a detention pond for 100 year storm above Levee B tieback. Levee A and B conduits deemed unnecessary will be abandoned and all required for continued operation of the system will be replaced. Reconstruction Measures – Update Pump Stations 1-7.

The 1 percent ACE, 0.5 percent ACE, and 0.2 percent ACE Arkansas River scenarios were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to E.O. 11659 and E.O. 11140](#) although the 0.2 percent ACE scenario did completely inundate the protected areas behind Levees A, and B. Levee C was not modeled. The 50 percent ACE, 20 percent ACE, 10 percent ACE, 5 percent ACE, 2 percent ACE, and 1 percent ACE Harlow Creek events were modeled with the assumption that failure did not occur [See Table of Contents NOTE 1 - Pursuant to E.O. 11659 and E.O. 11140](#) although overtopping did occur with the 1 percent ACE scenario. The modeled scenarios for Alternative 3B were identical to Alternative 1A (and subsequent alternatives).

Water surface profiles and inundation maps for Alternative 3B are presented at the end of this report.

ALTERNATIVE 4: DIVERSION OF WATER AROUND TULSA

Construct gravity flow pipelines to reduce flow around Tulsa area.

This alternative was evaluated very early during the feasibility study using open-channel flow equations to estimate the volume of water that would be required for diversion, which was then used to estimate the size and total number of conduits. No HEC-RAS modeling was performed for Alternative 4 since it had been screened out prior to the detailed modeling analysis of the other alternatives.

ALTERNATIVE 5: NON-STRUCTURAL BUYOUT

Buyout all residential structures behind Levees A and B and relocate.

No HEC-RAS modeling was performed for Alternative 5 since it was the non-structural option. All scenarios would be identical to the existing conditions scenarios since no action would be taken with respect to the structural integrity of Levees A or B.

ALTERNATIVE 6: NO ACTION (FWOP CONDITION)

Ongoing and potential for other local or State sponsored projects that could be undertaken without Federal participation. It is expected that current FRM structures would be maintained and residual risk of flood damages would remain.

No HEC-RAS modeling was performed for Alternative 6 since it was the no action option. All scenarios would be identical to the existing conditions scenarios since no action would be taken with respect to the structural integrity of Levees A, B, or C.

RISK ANALYSIS

As described in EM 1110-2-1619, flood damage reduction studies incorporate a risk-based approach in the determination of benefits. This approach includes the evaluation of uncertainty in the stage-probability function. Uncertainty arises from two primary sources: 1) natural uncertainty, which is a statistical parameter associated with the hydrologic record, and 2) numerical model uncertainty, which is associated with the quality of topographic data that were used. For gaged streams, natural uncertainty can be estimated by performing a statistical analysis, and this estimate will improve as the period of record length increases. For ungaged streams, [Figure 5-3 \(EM 1110-2-1619\)](#) can be used to estimate natural uncertainty. The total uncertainty for a reach, expressed as standard deviation, can be estimated using the following equation:

$$S_t = \sqrt{S_{natural}^2 + S_{model}^2}$$

Since the Arkansas River has a long hydrologic period of record, the statistically-derived natural standard deviation, 0.332, was used in the computation. Model calibration was considered to be “good” with the Light Detection and Ranging (LiDAR) dataset that was used to develop the hydraulic model and available stream gage data, so the model standard deviation that was selected was 0.3 ([see Table 5-2, EM 1110-2-1619](#)). The total standard deviation that was estimated for the Arkansas River was 0.447.

Harlow Creek is ungaged. Therefore, a statistically-derived natural standard deviation cannot be computed. Instead, [Figure 5-3 \(EM 1110-2-1619\)](#) was used, and the slope of the channel was estimated to be 0.001. The natural standard deviation was therefore estimated as 1.5. Model calibration was considered to be “fair” since the LiDAR dataset that was used to develop the hydraulic model was used, but verification was limited to high water marks in the absence of a gage, so the model standard deviation that was selected was 0.7 ([see Table 5-2, EM 1110-2-1619](#)). The total standard deviation that was estimated for Harlow Creek was 1.655.

The estimates for total standard deviation were used in conjunction with the computation of economic benefits. Please see [Appendix C](#) for additional information.

CLIMATE CHANGE

Consideration of potential climate impacts to civil works projects is required, as described in ECB 2018-14. As part of a climate change adaptation pilot program, The USACE Institute for Water Resources (IWR) funded a study of the Oologah Lake watershed, located on the Verdigris River in southeastern Kansas and northeastern Oklahoma. The study was titled “Reservoir and Watershed Risk-Based Assessments – Oologah Lake and Watershed Responses to Climate Change Pilot Study.”

A set of 112 hydrographs was developed by colleagues at the University of Oklahoma by simulating runoff from bias-corrected, spatially-disaggregated (BCSD) statistically downscaled climate projections with the Variable Infiltration Capacity (VIC) model ([see Qiao et al. 2014](#)). Numerical routing was then used to transform these hydrographs into a long-term simulation of

pool elevations so that droughts could be identified and the critical period for each could then be determined as well.

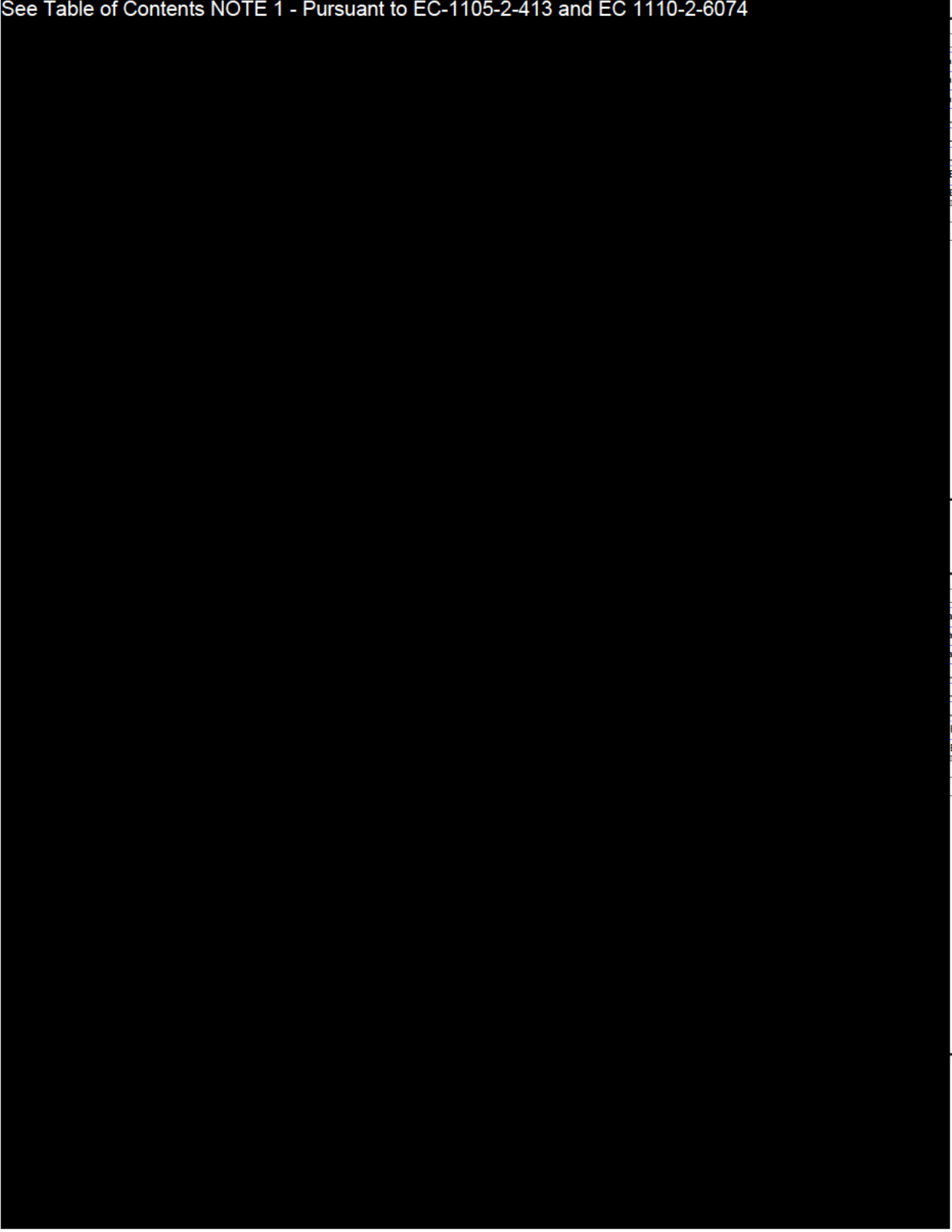
Although this study focused on drought, important conclusions can be drawn about future precipitation. The model projections show no major changes to average precipitation. Hydrologic runoff stresses resulting from climate change at Oologah Lake are not expected to significantly increase over time. Since the Oologah Lake watershed is part of the Arkansas River watershed and is adjacent to the Keystone Lake watershed, conclusions drawn from this study are applicable to the Tulsa / West Tulsa Feasibility Study.

REFERENCES

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- USACE (2014). Utilization of Regional Climate Science Programs in Reservoir and Watershed Risk-Based Assessments.
- USACE (1996). Risk-based analysis for flood damage reduction studies. EM 1110-2-1619.
- USACE (2018). Guidance for incorporating climate change impacts to inland hydrology in civil works studies, designs, and projects. ECB 2018-14.

WATER SURFACE PROFILES (EXISTING CONDITIONS)

See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074




See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074



See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074



See Table of Contents NOTE 1 - Pursuant to EC-1105-2-413 and EC 1110-2-6074



WATER SURFACE PROFILES (ALTERNATIVES ANALYSIS)

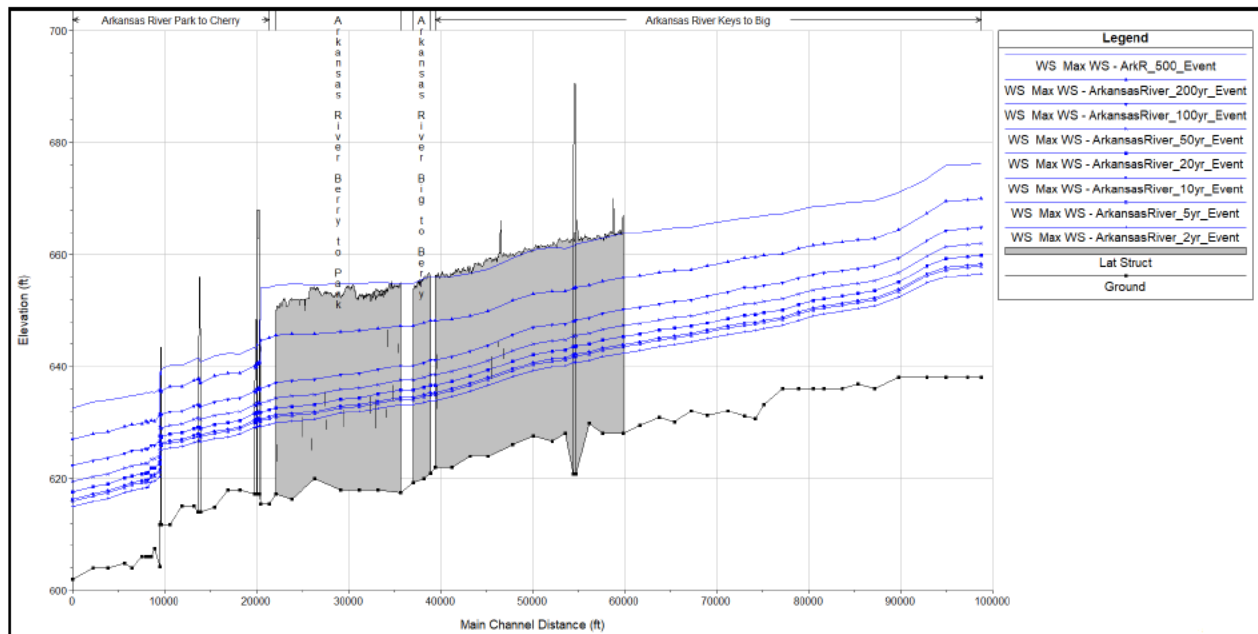


Figure B-10: Levees A and B No Fail Condition (Alternatives 1E and 3B)

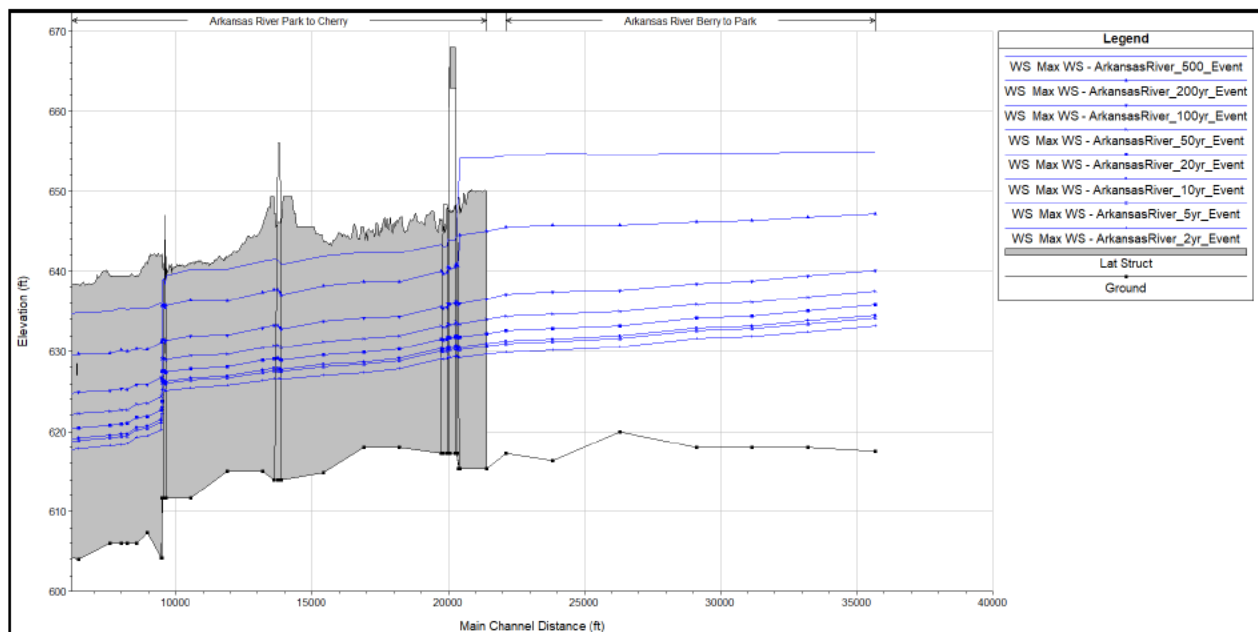


Figure B-11: Levee C No Fail Condition (Alternatives 1E and 3B)

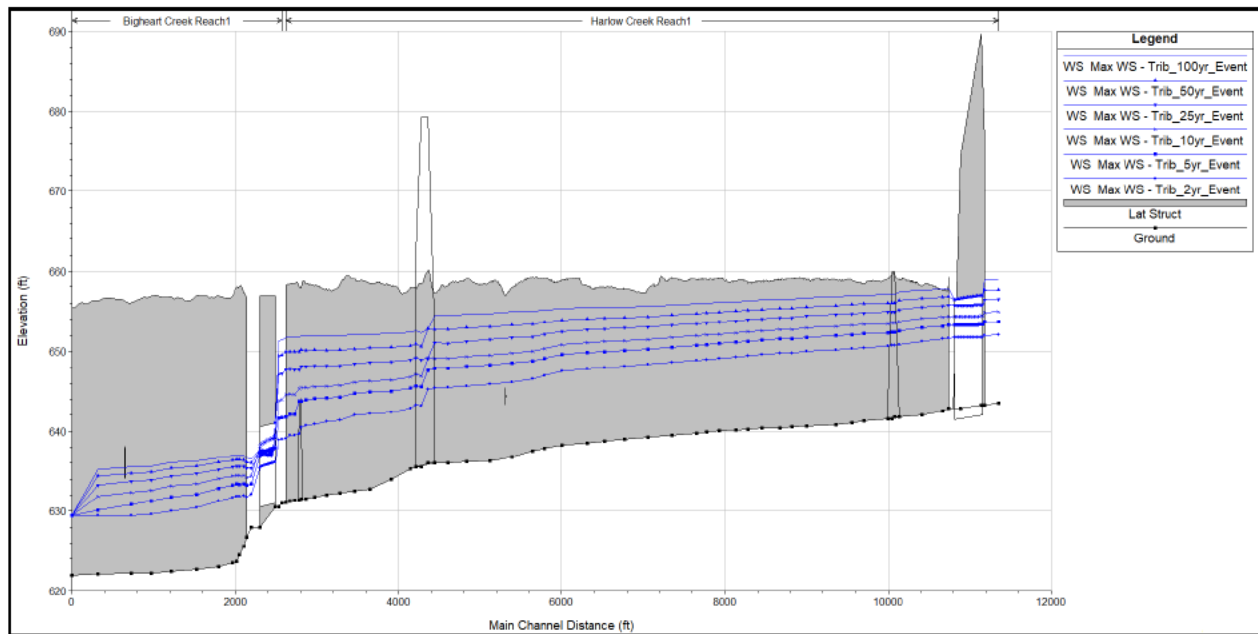


Figure B-12: Levee B Tieback, No Fail Condition (Alternative 1E)

INUNDATION MAPS (EXISTING CONDITIONS)

