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SEGMENTATION AND STABILITY APPROACH REPORT

Levee Breach Analysis Mapping and Risk Assessment

LOWER RAGING RIVER, KING COUNTY, WASHINGTON

April 7, 2022

Shannon & Wilson No: 103692-304

SHANNON & WILSON

Submitted To: King County Department of Natural Resources and Parks Water and Land Resources Division
201 South Jackson Street
Seattle, WA 98104
Attn: Ms. Judi Radloff

Subject: SEGMENTATION AND STABILITY APPROACH REPORT, LEVEE BREACH ANALYSIS MAPPING AND RISK ASSESSMENT, LOWER RAGING RIVER, KING COUNTY, WASHINGTON

We prepared this report to present our levee segmentation and stability analysis approach for the Lower Raging River component of the King County Levee Breach Analysis Mapping and Risk Assessment project. Our scope of services was specified in our Personal Services Agreement with King County, Number E00670E20, dated February 2, 2021.

We appreciate the opportunity to be of service to you on this project. If you have questions concerning this report, or we may be of further service, please contact us.

Sincerely,

SHANNON & WILSON

4/7/2022

Oliver Hoopes, PE
Associate

KDK:OTH:SRB/oth

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1 INTRODUCTION

1.1 Project Understanding

The King County Levee Breach Analysis Mapping and Risk Assessment (Project) is intended to identify the areas along portions of several river corridors within King County where containment levee systems may be vulnerable to breaching and place people, property, and infrastructure at risk.

King County initiated the Project with a data gaps compilation in 2018 that consisted of gathering information and assessing existing data, including assessing data suitability to the mapping and risk assessment analysis. This initial effort provided recommendations for additional work needed to execute the levee breach analysis, which are presented in a report titled Levee Breach Analysis for King County Rivers, final 2019 (Watershed Science and Engineering, Inc., 2019). The results and recommendations presented in the 2019 report form the basis for the current work scope.

This report is focused on the Lower Raging River, which runs through the unincorporated town of Fall City, Washington (Figure 1).

1.2 Project Scope

The current scope of services includes activities to complete the levee breach analysis by collecting additional data to address data gaps identified in the 2019 report and then developing breach progression maps and conducting risk analyses for three levee containment systems. Development of these products for the three levee containment systems includes:

- Geotechnical data collection to physically characterize the flood facilities that comprise the levee containment systems:
  - Compile and review existing geologic and geotechnical subsurface data.
  - Perform subsurface explorations (borings and test pits) and laboratory testing.
- Levee Segmentation:
  - Perform geologic evaluation.
  - Develop light detection and ranging (lidar) geometric inventory of levees.
  - Divide the levee system into segments (levee segmentation).
- Geotechnical reliability analysis efforts:
  - Perform scour analysis.

- Perform seepage analysis.
- Perform global slope stability analysis.
- Perform seismic analysis (liquefaction, pseudo-static loading).

- Perform hydrologic and hydraulic modeling.
- Develop inundation maps.
- Perform economic risk modeling and analysis.

1.3 Report Purpose

This report presents our approach for performing the geotechnical analysis effort for the Lower Raging River corridor portion of the Project. The focus of the geotechnical analysis effort is levee segmentation and geotechnical reliability analysis.

This report presents proposed levee segmentation for the Lower Raging River and the proposed approach and methods for the geotechnical reliability analysis efforts. This report will be submitted to King County for review and comment prior to our completion of the geotechnical analyses. We note that our geotechnical analysis results may trigger the need to modify our segmentation selections.

1.4 Report Organization

The main text of this report focuses on our levee segmentation approach and provides an overview of our geotechnical approach. Specific details for our geotechnical approach are included in the appendices.

2 LEVEE SEGMENTATION APPROACH

2.1 Segmentation Overview

A levee segment is a basic unit that will be used to the inform risk analysis and plan and manage this scope of work. The intent of levee segmentation is to identify river reaches with similar physical characteristics (e.g., geometry, levee materials, stability, condition, hydraulics, maintenance and repair history, river gradient). A levee system also can be segmented based upon its hydrologic, hydraulic, and geotechnical failure characteristics; location of damage reaches; and different probabilities of levee failure along the river.

A primary premise of levee segmentation is that conditions within a selected segment are similar and can be adequately represented by a single transverse analysis cross section with one set of associated analysis input parameters. Where variations in conditions become significant enough that they are not adequately represented by a selected analysis cross section, additional segments would be required and would need to be represented by new analysis cross sections.

Our approach for selecting reaches is based on a balance of the following considerations:

- Segments should be selected such that analyses results will apply over the entire segment.
- The number of segments analyzed should be limited to a value that can be sufficiently analyzed and evaluated given available resources and budget.
- Refining, splitting, or creating additional segments or sub-segments may not be supported by the amount of data available.
- Reducing the number of segments analyzed may lead to conservatism when characterizing some analysis cross sections where conditions are better than at the selected cross section.

2.2 Geologic Evaluation

Our Geotechnical Data Report for the Lower Raging River (Shannon & Wilson, 2021) presents a summary of the regional geologic setting and site subsurface conditions encountered based on subsurface explorations completed for both the Project and historic projects with explorations.

2.2.1 Site Subsurface Conditions

Based on our historical information review and the soils we sampled in our subsurface explorations, the following groups of materials are present in the upper 50 feet along the Lower Raging River system:

- **Levee Fill** – Levee fill represents the material primarily used to construct the levees. Levee fill generally consists of poorly graded gravel with silt, sand, and cobbles. Explorations encountered levee fill to a depth of 5 to 6 feet bgs in all four Lower Raging River Project borings.
- **Native Gravel** – Gravel is present below the levee fill. The thickness of the native gravel ranges from 14 to 24 feet, with the layers ending 20 to 30 feet bgs in each boring. Native gravel primarily consists of poorly to well-graded gravel with silt, sand, and/or cobbles. In most borings, the contact between levee fill and native gravel is difficult to distinguish.
- **Native Sand** – Native sand consists of silty sand to poorly graded sand with silt, with the sand particles being primarily fine- to medium-grained. Native sand underlies the native gravel in B-RR-1 and B-RR-3. In B-RR-1, the native sand layer encountered was 5

feet thick; in B-RR-3 the layer was 18 feet thick. Native sand ranged from brown to gray with iron oxide staining locally.

- **Native Silt** – Silt was encountered in B-RR-1, B-RR-2, and B-RR-4, with the layer beginning between 22 and 30 feet bgs and extending to the bottom of each boring, to a depth of 51.5 feet bgs. In B-RR-2, the silt layer was directly beneath the native gravel layer. In B-RR-1, silt was encountered below the native sand layer, and in B-RR-4 silt was encountered beneath very soft silt. Native silt is primarily nonplastic to low plasticity silt or silt with sand ranging in color from brown to gray. Cohesionless native silt ranged from very loose to medium dense and cohesive native silt ranged from stiff to very stiff.
- **Native Very Soft Silt** – Native very soft silt was encountered in B-RR-4 between 22 and 30 feet bgs, and in B-RR-3 from 25 to 26 feet bgs. This silt is brown and low to medium plasticity. In B-RR-3, some wood fragments and other organic materials were encountered in this unit.

The historic borings completed for the Raging River Bridge Replacement Project (Shannon & Wilson, 1997) indicate denser soil layers are present below 50 feet bgs at the historic boring locations. Because the levees along the Lower Raging River are typically less than 8 feet high, these deep, dense soil layers do not contribute to the stability or seepage characteristics of the levees. Therefore, we will not include these layers in our seepage and stability analysis models.

2.2.2 Geologic Variability

Based on our review, we consider the geologic variability along the Lower Raging River system to be low. In our opinion, dividing the Lower Raging River into multiple segments based on geologic variability is not warranted for the purposes of the Project.

2.3 Geometric Inventory of Levees

Topographic and bathymetric geometries of levees play a significant role in their performance and reliability. Geometry can also be highly variable within levee systems. Therefore, geometry is a primary factor in levee segmentation and will be incorporated into our geotechnical risk and reliability analyses as uncertainty variables.

To accomplish this, we developed a geometric inventory of the Lower Raging River levee system using geographic information system (GIS) spatial analyses.

2.3.1 Spatial Analysis Approach

We developed the geometric inventory of the Lower Raging River levee system by performing the following steps:

- Step 1 – Cut transverse cross sections along the levee at 50-foot increments.
- Step 2 – Delineated key features along the levee system for each cross section. The features we delineated are defined in Exhibit 2-1. We performed the initial delineations by hand by drawing alignments along the levees for each feature on the map in ArcGIS Pro.

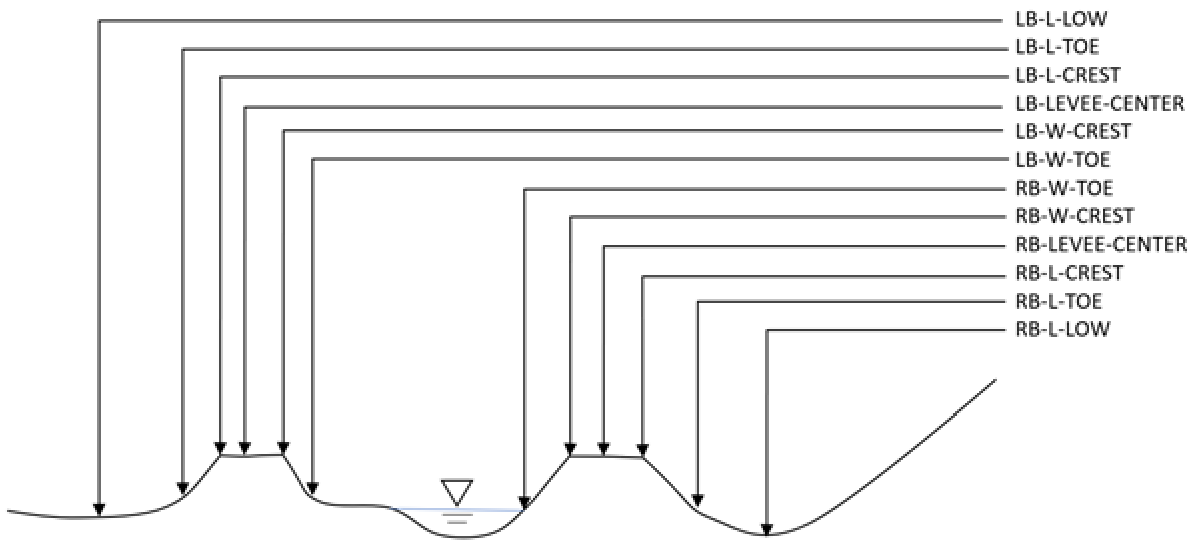

Exhibit 2-1: Levee Geometric Delineation Nomenclature

NOTES:

1 TOE = Bottom of Levee Side Slope; CREST = Top of Levee Side Slope; LEVEE-CENTER = Levee Center Line; LOW = Landward Lowest Elevation Outside of Levee Footprint.

L = Landward; LB = Left Bank = River-Left Levee; RB = Right Bank = River-Right Levee; W = Waterward

- Step 3 – The plan view delineations were a good initial draft of the levee crests, toes, and landward low points. However, this plan view delineation method proved to be inaccurate in some areas due to the difficulty of identifying slope breaks based on relatively coarse lidar and relative elevation raster image pixels. These difficulties typically arose near sharp bends in the levee alignments and where topographic relief is small and difficult to distinguish. Therefore, we improved the accuracy of the feature delineations using a computer algorithm. This algorithm extracts a subset of the ground surface curve near the hand-delineated feature and then finds the "breakpoint" in the curve. This is accomplished by rotating the ground surface curve such that the end points are level and then identifying either the highest or lowest point of the curve, depending on whether the point is a crest or a toe, respectively. Exhibit 2-2 demonstrates this approach.
- For our geometric analyses, we used the crest and toe locations derived from this technique primarily to calculate representative levee slope angles. To calculate heights,

we took the minimum and maximum ground surface points within 5 feet of these locations. These additional points are also indicated in Exhibit 2-2.

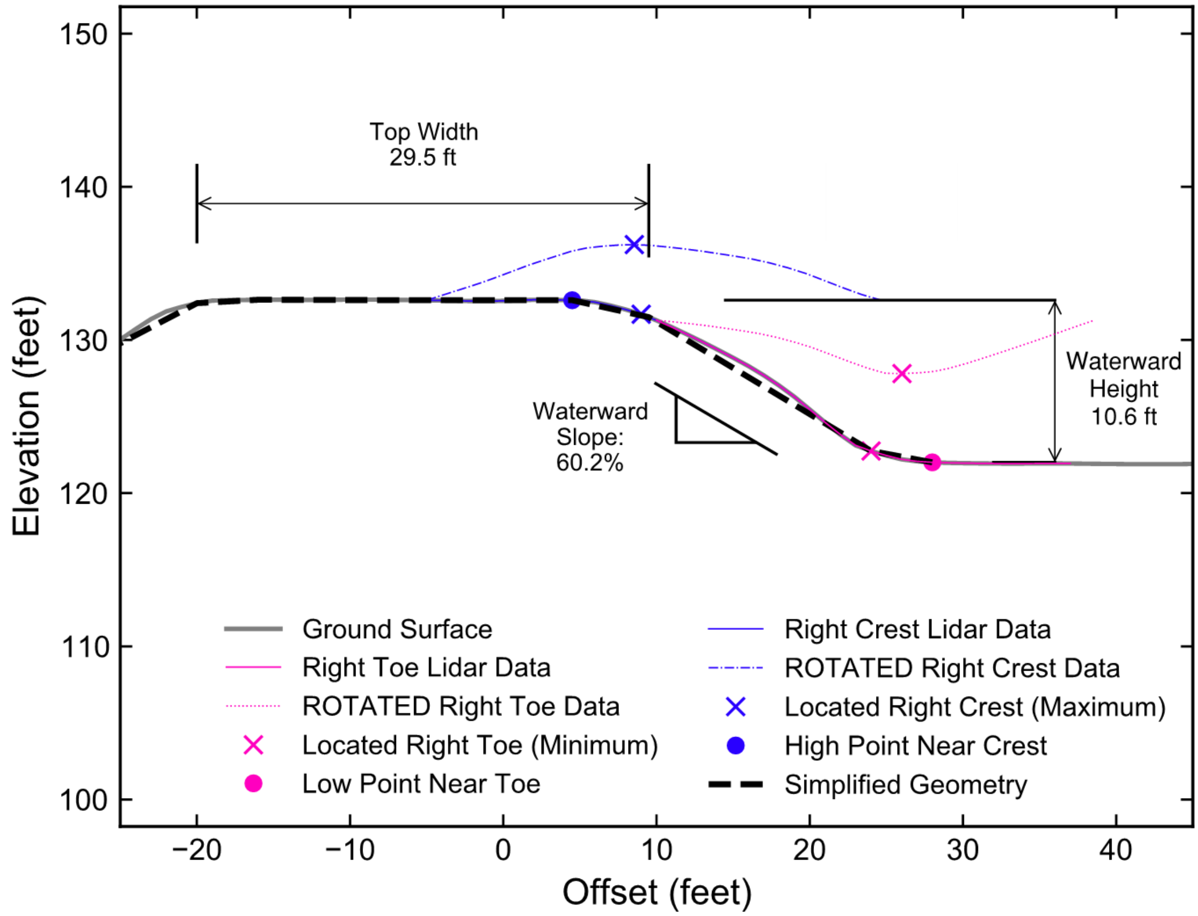

Exhibit 2-2: Lidar Crest and Toe Identification Algorithm Demonstration

- Step 4 – Categorized the flood facilities on both sides of the river as either levees or revetments. We distinguished between these two types because failures of revetments do not constitute a levee breach and therefore do not contribute to the type of flood risk considered for this study.
  Exhibit 2-3 provides definitions of the facility types. In our evaluations, we use the landward vertical relief rather than the height of the levee fill prism for this classification. As indicated in Exhibit 2-3, we define the landward vertical relief as the vertical distance between the top of the levee and the lowest landward point within a distance defined by 10 Horizontal to 1 Vertical line from the crest.
- Step 5 – Calculated the following representative geometric parameters for each cross section based on the delineated points:
  - Representative waterward slope
  - Waterward height
  - Representative landward slope

- Landward height
- Landward total vertical relief

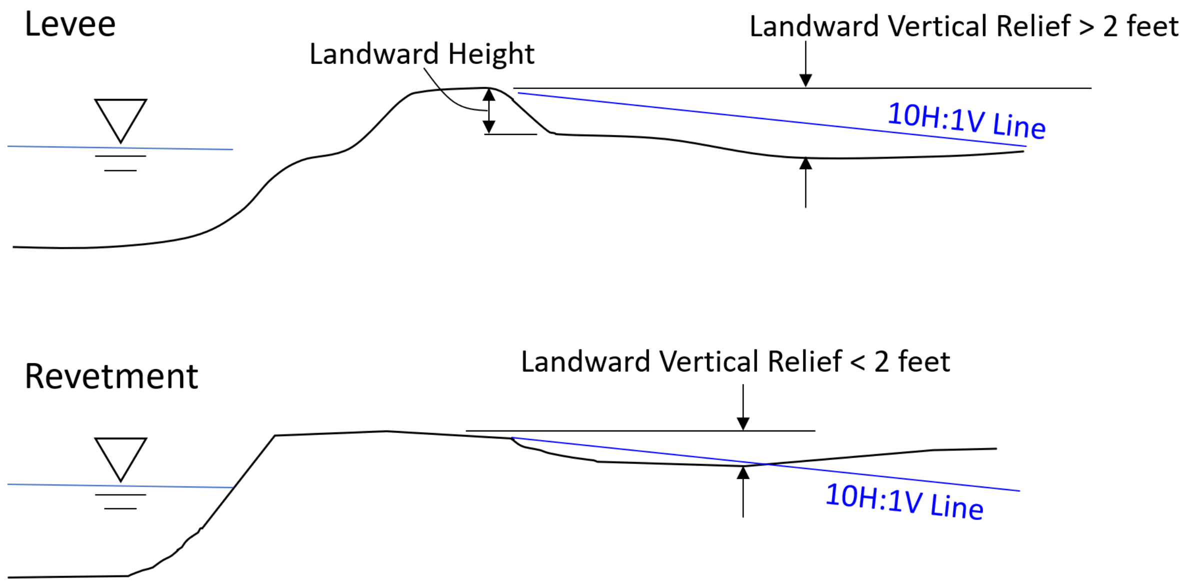

Exhibit 2-3: Levee and Revetment Definitions

2.3.2 Spatial Analysis Results

The results of our GIS spatial analyses are included as cross section figures in Appendix A. Landward height and waterward slopes, which are critical to steady-state seepage stability and rapid drawdown stability failure modes, are summarized in Figures 2 and 3. These figures also show preliminary water levels for the 500-year flood event with and without climate change effects included.

Figure 4 summarizes the flood facility types along the Lower Raging River system. Figures 2 through 4 also indicate the approximate locations of levee repair and improvement projects King County has performed in the past 25 years. As indicated in the figures, we have divided these improvements into three categories:

- Unreinforced levee raise
- Gabion wall levee raise
- Scour repair

The unreinforced levee raise improvements were completed in 1996 and consisted of increasing levee facility heights using compacted fill material. We noted these improvements for reference but did not distinguish between these raised levee segments and other levee segments along the river.

The other two improvement categories, gabion wall levee raise and scour repair, were different because they included geosynthetic reinforcements. The two scour repair segments (one in 1998 and one in 2018) also included heavy riprap scour protection in addition to geogrid reinforcement. The gabion wall levee raise was completed in 1996 and consisted of relatively short (less than 5 feet) vertical gabion walls with steel wire mesh reinforcements extending between gabion baskets on both sides of the levee. Because these are engineered sections constructed in the relatively recent past and include reinforcements, we have categorized them separately from the original levees.

Figures 5 through 12 present statistical summaries of the geometric inventory parameters landward height, waterward slope, and waterward height. Each figure presents scatter plots with each point representing one cross section. The figures are arranged in pairs where the first of the pair (e.g., Figure 5) presents facility types and the data in the second figure of the pair (e.g., Figure 6) is filtered to only show levees that have not been repaired.

Exhibit 2-4 presents a statistical summary of the geometric parameters presented in Figures 5 through 12. Exhibit 2-3 only includes levee data and excludes repaired sections.

Exhibit 2-4: Levee Geometric Parameters Statistical Summary (Excludes Revetments and Repairs)

Location	Geometric Parameter	Data Count	Minimum Value	Maximum Value	Mean	Median	Standard Deviation	Relevant Figures
Left Bank	Landward Height (feet)	84	0.0	9.9	3.7	3.0	2.0	5, 6
	Total Landward Relief (feet)	84	1.5	10.9	4.5	4.2	1.9	--
	Waterward Slope (%)	84	18	72	45	45	14	5 to 8
	Waterward Height (feet)	84	2.1	17.4	8.2	8.9	3.5	7, 8
Right Bank	Landward Height (feet)	115	1.3	10.2	5.4	5.3	2.2	9, 10
	Total Landward Relief (feet)	115	2.1	10.7	6.3	6.1	2.1	--
	Waterward Slope (%)	115	21	69	50	52	10	9 to 12
	Waterward Height (feet)	115	3.3	15.7	9.1	8.8	3.0	11, 12

2.3.3 Spatial Analysis Observations

Review of the spatial analysis results yielded the following observations of the Lower Raging River System:

- Repaired levee sections typically have higher landward heights.
- Waterward heights for repaired sections versus unrepaired sections do not appear to differ substantially.

- Waterward heights along the Right Bank are typically higher than the Left Bank.
- High degree of variability in the left bank waterward slope, as evidenced by the relatively high standard deviation.

2.4 Levee Segmentation and Representative Section

Based on our geologic evaluation, geometric inventory analyses, and the limits of our scope and authorized budget, we have selected to evaluate the Lower Raging River system as a single segment with one representative section.

We selected Left Bank Station 45+50 as the representative section. This location is indicated in Figures 2 through 4 and shown in cross sectional view in Figure 13. Geometric parameters for this section are included in Figures 5 through 12 for reference. We selected this location for the following reasons:

- A breach at this location could impact a large number of people and structures in the Fall City area.
- The landward height value of 7.9 feet is in the 89th percentile of all the levee cross sections we evaluated.
- The waterward slope value of 60.2% is in the 89th percentile of all the levee cross sections we evaluated.
- The waterward height value of 10.6 feet is in the 73rd percentile of all the levee cross sections we evaluated.

The hydraulic breach analyses are yet to be completed. Our assessment that a breach at Left Bank Station 45+50 could flood a large area of Fall City is based on the preliminary water depth map for the 500-year flood with climate change effects shown in Figure 3. The modeled flood depths for this flood are high enough to highlight the flow paths through relatively low areas of Fall City. In other words, we used the 500-year flood water levels as a visualization tool to subjectively assess the inundation area of potential breaches ahead of the actual hydraulic breach modeling analyses. Figure 3 shows that the flooded areas at Left Bank Station 45+50 are connected to several other areas that extend northward into the Fall City neighborhoods. We therefore conclude floodwater from a breach at Station 45+50 could flow northward along these low-lying flow paths, thus putting structures and people along these flow paths at risk.

We also considered other sections east of (downstream of) Station 23+00. This area has a high density of homes, a narrow crest width, and steep landward and waterward slopes. However, based on the preliminary floodwater maps we reviewed (see Figure 2), the flood risk in this area is dominated by flooding of the Snoqualmie River regardless of the integrity of the Lower Raging River Left Bank levee. Therefore, because this area is at risk of flooding regardless of whether a levee breach occurs there, we consider performing a detailed geotechnical analysis here to be unnecessary for this study.

In addition, the Left Bank levee between Station 17+00 and 21+00 was reconstructed in 1996. This reconstruction included steel gabion basket walls and steel mesh geosynthetic reinforcement. This means that the geometry and the included reinforcement in the embankment along this section are completely different than anywhere else in the Lower Raging River system. Therefore, risk and reliability analysis results from this location would not be applicable to other portions of the levee system.

3 GEOTECHNICAL APPROACH

Geotechnical reliability assessment for levees is a process of geotechnical investigation and analysis to estimate the level of protection provided by the levee. Levee reliability is a measure of the ability of a levee to provide a specified level of protection against flooding, typically stated in terms of a flood return period. For example, a levee may be designed to provide protection against a 100-year flood. Immediately after construction, one would expect the levee to have a high degree of reliability up to the design flood protection level. But over its design life span, the reliability of the levee may decrease due to scour, erosion, settlement, and other factors that can reduce the ability of the levee to provide the intended level of protection.

Geotechnical investigation and analysis have a significant role in the assessment of levee reliability as levees are soil embankments typically built on natural ground. A thorough understanding of the geotechnical characteristics of the embankment and foundation soils provides the basis for estimating the likely performance of a levee under design flood conditions.

The primary goal of our geotechnical reliability analyses is to develop fragility curves. Fragility curves are graphical representations that relate the magnitude of a hazard to the conditional probability of levee failure should that hazard occur. A levee risk assessment requires the integration of the probability of losses (economic, injuries, loss of life, etc.) given levee failure and the probability of levee failure occurring. The latter probability is based on the fragility curve.

Development of fragility curves for the Lower Raging River requires assessment of several potential failure modes. Each failure mode requires identification and quantification of uncertainty variables and analytical methods. These are described in the following sections.

3.1 Potential Failure Modes

We will assess the following potential failure modes:

1. **Underseepage** - Underseepage can occur in situations in which one or more highly permeable soil layers extend beneath a levee from the river to the landward levee slope.
2. **Rapid Drawdown** - Slope failure due to rapid drawdown can occur when the river stage drops more quickly than the groundwater level in the embankment can respond.
3. **Landward and Waterward Static** - Static slope failure occurs when the steepness of a slope and the mass of the soil on the slope exceed the strength of the slope soils. The static stability of a levee is also affected by the river stage, soils, soil layering, and the assumption of steady-state seepage (i.e., the flood stage is in effect for an infinite amount of time).
4. **Waterward Post-Seismic/Liquefied (where applicable)** - Liquefaction or partial liquefaction is the loss of shear strength in a saturated, granular soil immediately following an earthquake. Liquefaction in the soils in or beneath the levees could result in lateral displacement and settlement of the levee or levee foundation soils. Post-seismic stability will be evaluated for one river stage.
5. **Landward and Waterward Seismic** - Seismic slope failure is similar to static slope failure but with an added, potentially destabilizing, seismic inertial force. Seismic stability will be evaluated for one river stage.
6. **Transient Drawdown** - This scenario is equivalent to the Rapid Drawdown scenario above except the groundwater pressures are evaluated using a transient seepage finite element analysis of the levee subjected to the selected flood hydrograph. Transient drawdown stability will be evaluated as the lowest factor of safety during the drawdown portion of the flood hydrograph.
7. **Transient Landside Static** - This scenario is equivalent to the Landward Static scenario above, except the groundwater pressures are evaluated using a transient seepage finite element analysis of the levee subjected to the selected flood hydrograph.

3.2 Uncertainty Variables

We will use several variables to incorporate the uncertainty of geometry, groundwater, and soil parameter aspects into the levee system. Specific parameters we will evaluate and the appendix within this report that covers our approach to developing them are as follows:

- Scour potential (see Appendix B),
- Hydraulic conductivity (see Appendix C),
- Soil shear strength (see Appendices D and E),
- Soil unit weight (see Appendix D),

- Waterward slopes (see Appendices A and F), and
- Landward levee height (see Appendices A and F).

We note that confining soil layer (also known as landward blanket) thickness is typically an important and relatively uncertain parameter for levee analyses. However, as described in Section 2.2.1, the near-surface material encountered in the Lower Raging River explorations consists of cohesionless sands and gravels. Therefore, we are not including this variable in our Lower Raving River analyses.

3.3 Analytical Methods

3.3.1 Seepage Analyses

Seepage through a levee embankment that emerges on, or near, the landward slope can weaken fine-grained fill in the vicinity of the landward toe, cause sloughing of the landward slope, or lead to piping (i.e., internal erosion) of fine sand or silt materials. Seepage exiting from the landward slope can also result in seepage forces and piping that decrease the stability of the slope.

Appendix C presents further discussion regarding our seepage analyses, including: underseepage evaluations performed in general accordance with USACE guidelines; steady-state seepage analyses for seven river stages; and transient seepage analyses for a flood hydrograph associated with one river stage.

3.3.2 Stability Analyses

Slope stability analyses will be completed in general accordance with USACE guidelines. Appendix D presents a detailed discussion regarding our slope stability analyses. Key points related to our levee approach are highlighted below:

- The failure surfaces will be restricted to entry points at the levee crest and exit points near the levee toe such that the failure surface envelopes at least one-third of the levee top width. In our experience, a levee stability failure that involves at least one-third of the levee top width results in enough deformation to where a breach is likely.
- Estimated porewater pressures from transient and steady-state finite element seepage analyses will be imported for use in the slope stability analyses.
- Seismic (i.e., pseudo-static) slope stability analyses will be performed in the same manner as static analyses except with an additional horizontal force applied to represent the inertial forces of an earthquake.

- Post-seismic/liquefied slope stability analyses will be performed in the same manner as static analyses except that residual shear strength parameters will be used for soil layers susceptible to liquefaction.

3.3.3 Seismic Analyses

Seismic analyses will be performed in general accordance with USACE guidelines, and will include determination of site class, moment magnitude, and spectral accelerations to perform liquefaction and deformation analyses. Liquefaction or partial liquefaction is the loss of shear strength in a saturated, granular soil during an earthquake. Liquefaction in the soils in or beneath the Lower Raging River levees could result in lateral displacement and settlement of the levee or levee foundation soils.

Appendices D and E present further discussion regarding our seismic analyses.

3.4 Probability of Failure and Fragility Curves

Levee fragility curves are functions that describe the probability of failure, conditioned on the flood stage, over the range of flood stages to which a levee might be exposed. For this study, we define the probability of failure (***Pf***) for the levee as the probability that the factor of safety of a given failure mode will drop below 1.0.

Evaluation of ***Pf*** requires estimation of the distribution of factor of safety given the uncertainty of the input variables and the degree of influence they have on factor of safety. We will likely perform over 150 seepage and stability analyses on the representative section, each with different combination of uncertainty parameters. Utilizing the methods outlined in Appendix F, we will aggregate these results into *Pf* point values for each flood stage and use them to compile the fragility curves.

As described in Appendix F, we will likely produce multiple fragility curves within the levee segment that each cover a range of levee geometric variables. We decided to do this for the following reasons:

- It may allow for evaluation of geotechnical reliability estimates for different geometries (and associated locations) within the Lower Raging River system.
- Statistical evaluation of geometry may produce geometric combinations that do not exist along the levee system.

4 CLOSURE

Shannon & Wilson has prepared the enclosed "Important Information About Your Geotechnical/Environmental Report" to assist you and others in understanding the use and limitations of our reports.

5 REFERENCES

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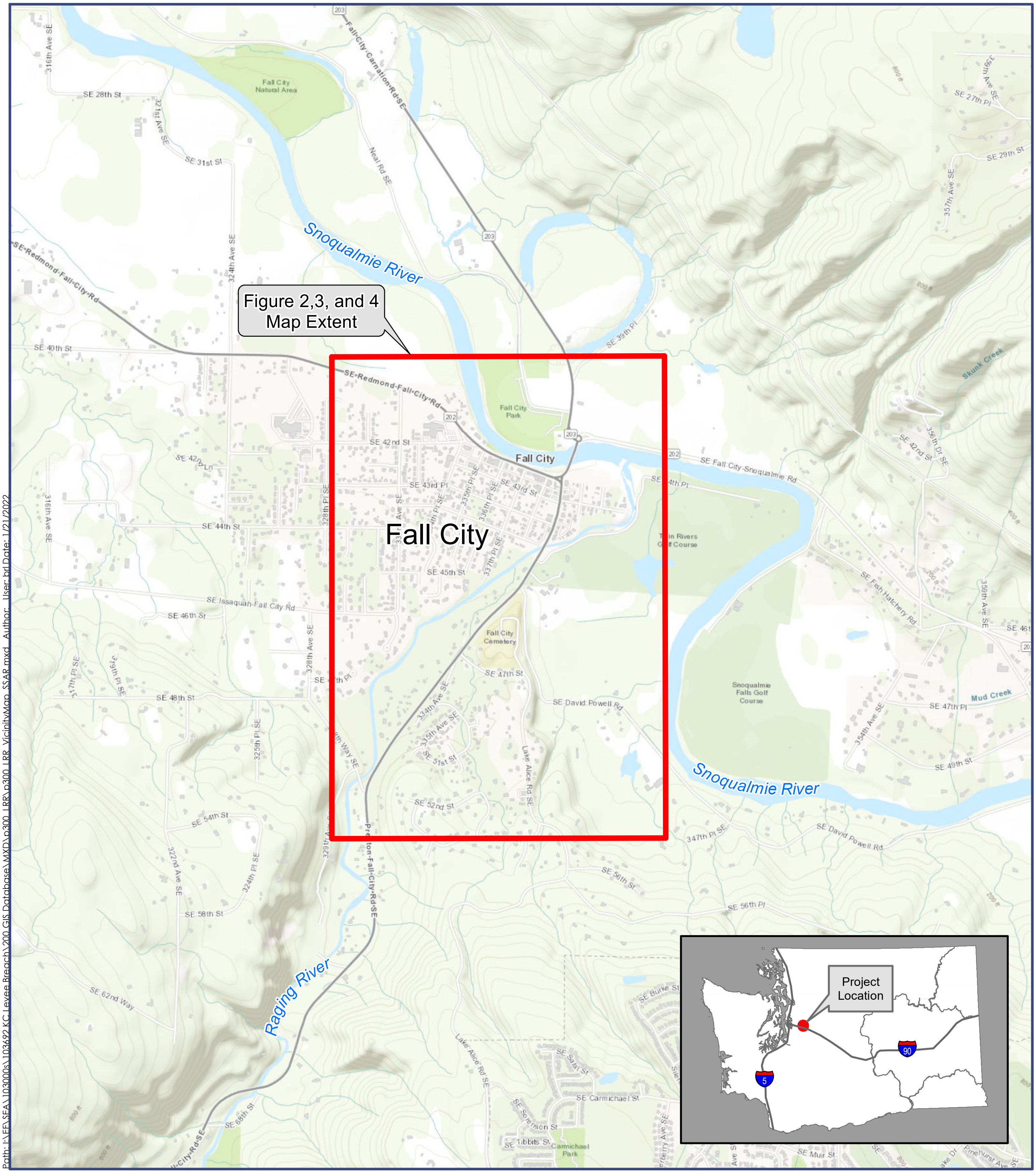

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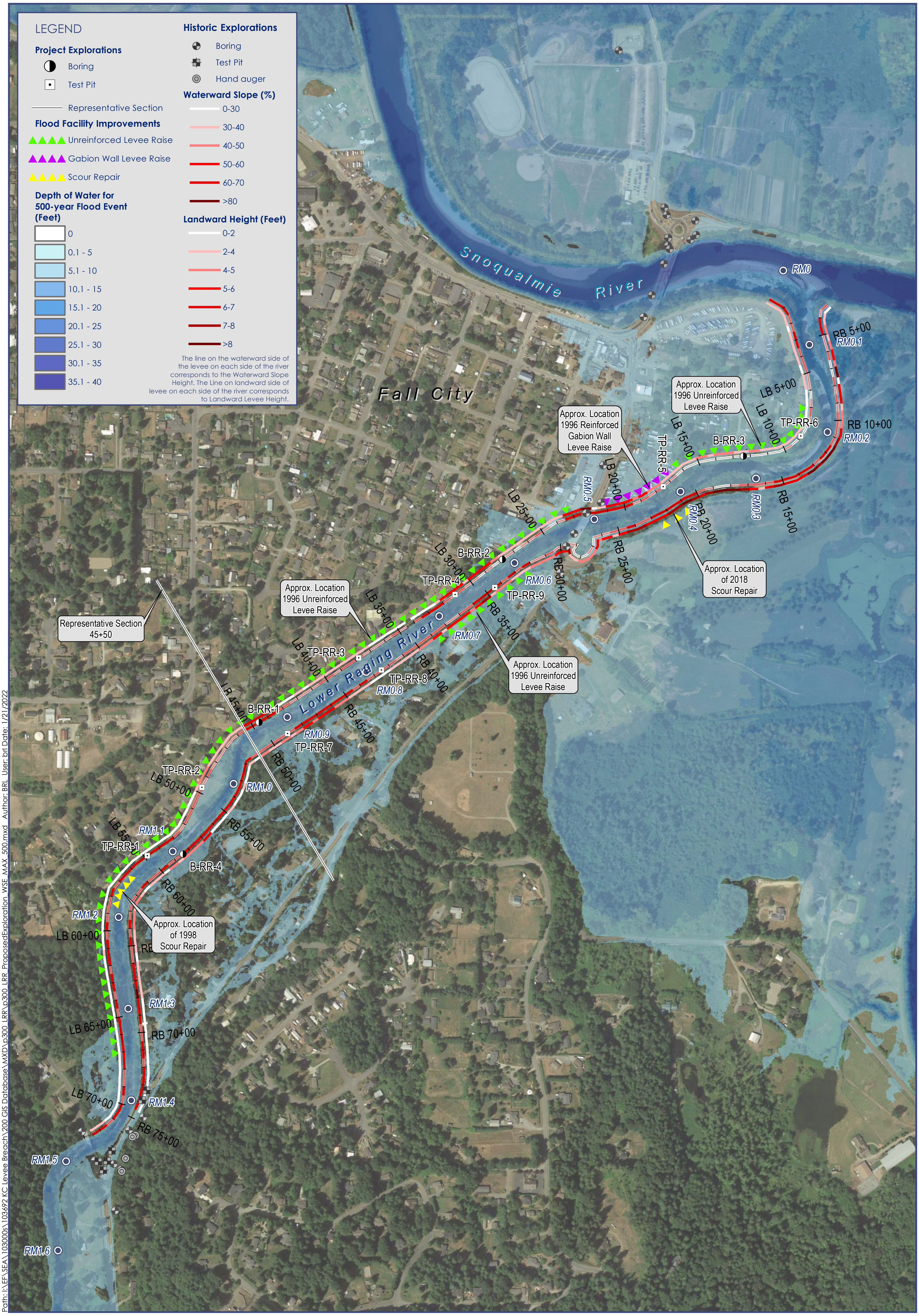
April 2022

Lower Raging River
Vicinity Map

Figure 1



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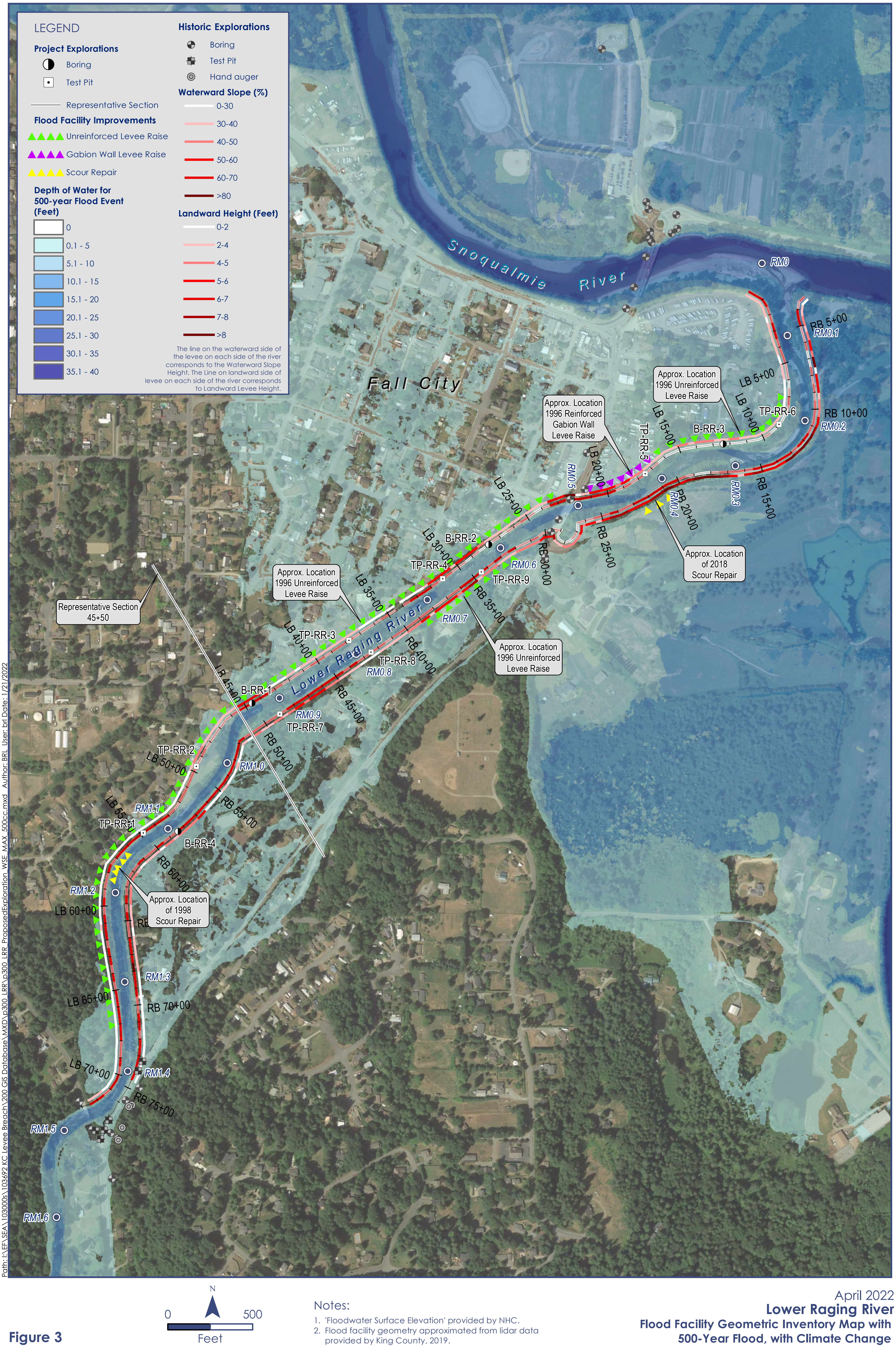
Notes:
1. 'Floodwater Surface Elevation' provided by NHC.
2. Flood facility geometry approximated from lidar data provided by King County, 2019.

April 2022
Lower Raging River
Flood Facility Geometric Inventory Map with 500-Year Flood

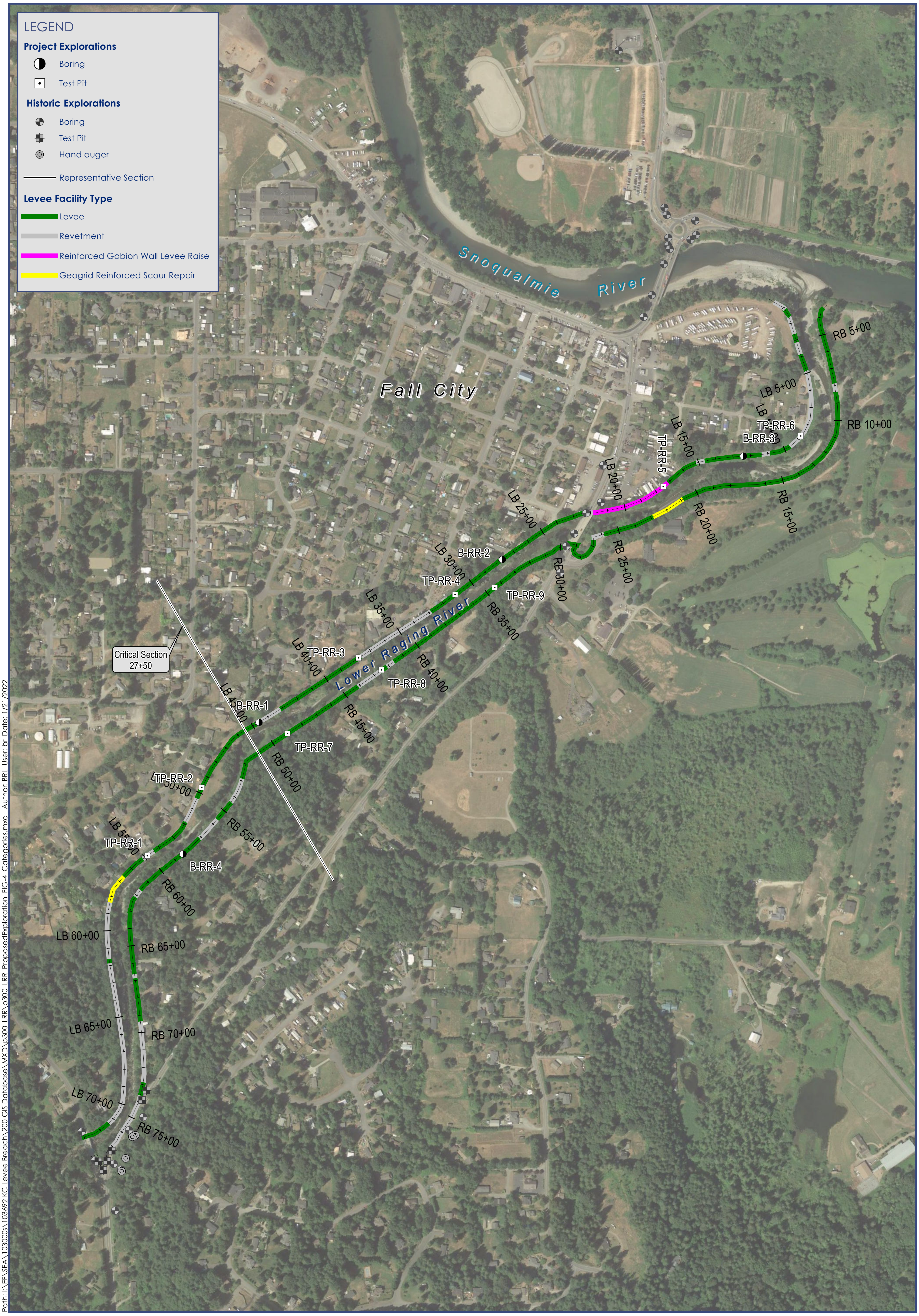
Figure 2



Notes:
1. 'Floodwater Surface Elevation' provided by NHC.
2. Flood facility geometry approximated from lidar data provided by King County, 2019.

Figure 3

April 2022
Lower Raging River
Flood Facility Geometric Inventory Map with 500-Year Flood, with Climate Change



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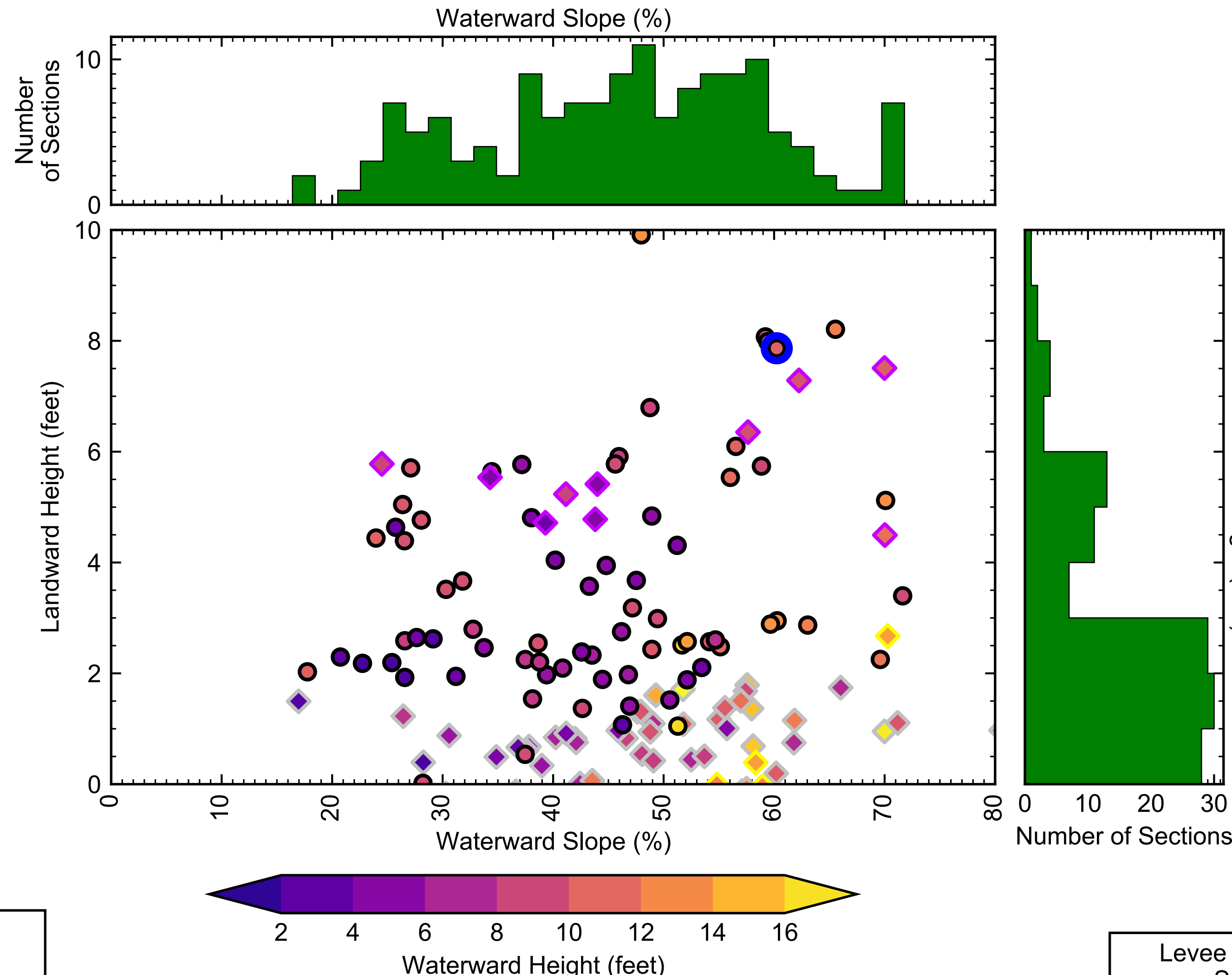
Notes:
1. 'Floodwater Surface Elevation' provided by NHC.
2. Flood facility geometry approximated from lidar data provided by King County, 2019.

Figure 4

April 2022
Lower Raging River
Facility Type Summary

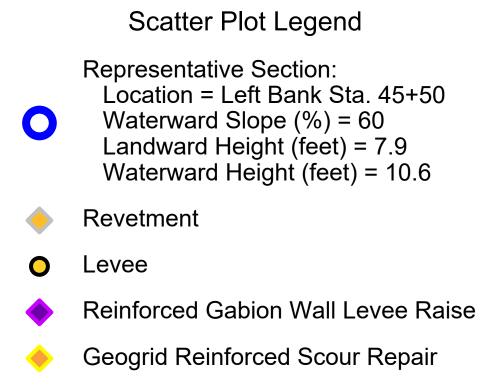


Statistical Summary:

Waterward Slope (%)
mean = 47
median = 48
std = 13
min = 17
max = 81

Landward Height (feet)
mean = 2.4
median = 1.9
std = 2.3
min = -1.9
max = 9.9

Waterward Height (feet)
mean = 8.7
median = 9.1
std = 3.6
min = 2.1
max = 19



Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LOWER RAGING RIVER LEFT BANK
WATERWARD SLOPE & LANDWARD HEIGHT

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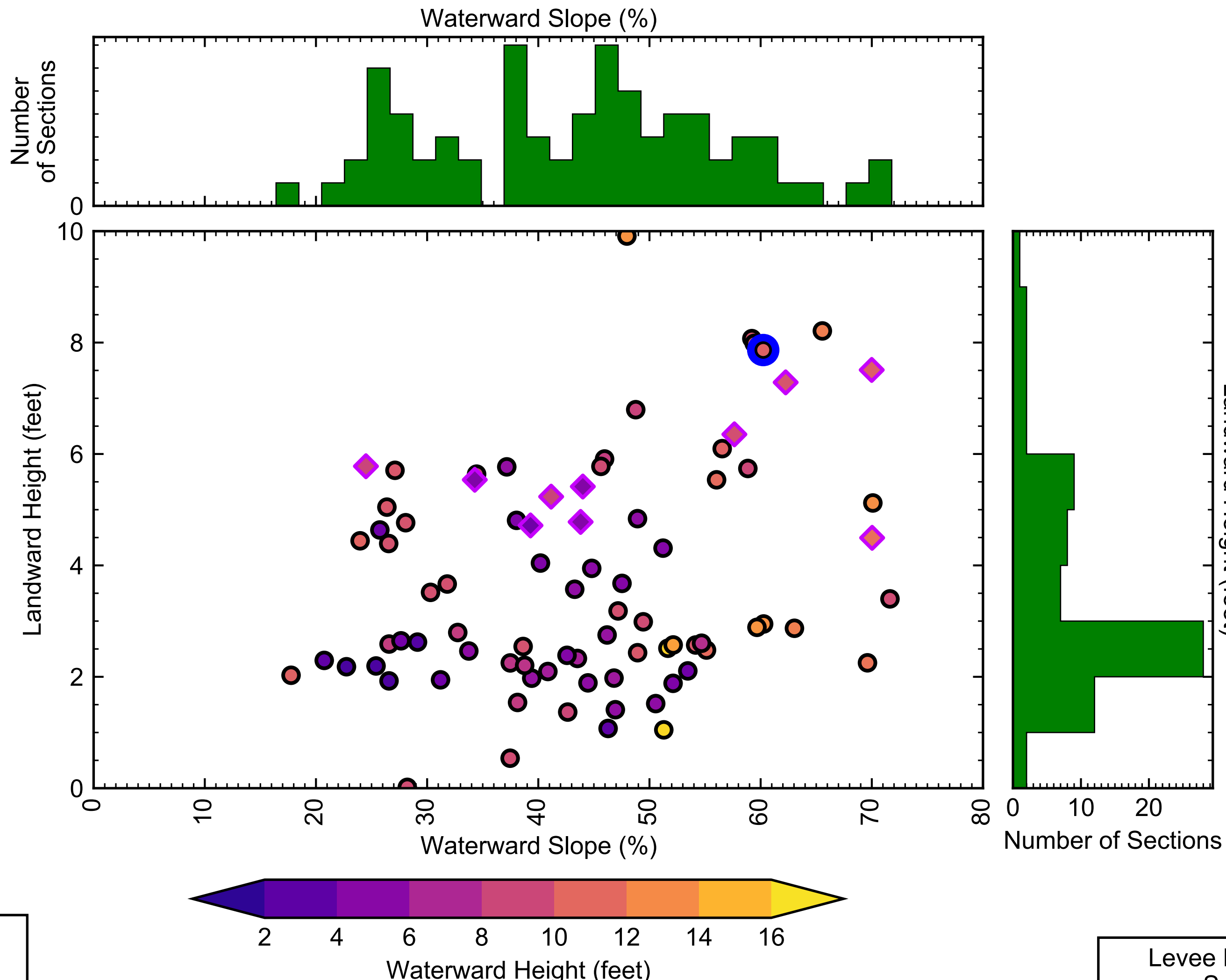
FIG. 5

FIG. 5



Statistical Summary:

Waterward Slope (%)
mean = 44
median = 45
std = 13
min = 18
max = 72

Landward Height (feet)
mean = 3.5
median = 2.8
std = 2.0
min = 0.0
max = 9.9

Waterward Height (feet)
mean = 8.1
median = 8.7
std = 3.4
min = 2.1
max = 17

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Landward Height (feet) = 7.9
Waterward Height (feet) = 10.6

Levee

Reinforced Gabion Wall Levee Raise

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LRR LEFT BANK, LEVEE ONLY DATA
WATERWARD SLOPE & LANDWARD HEIGHT

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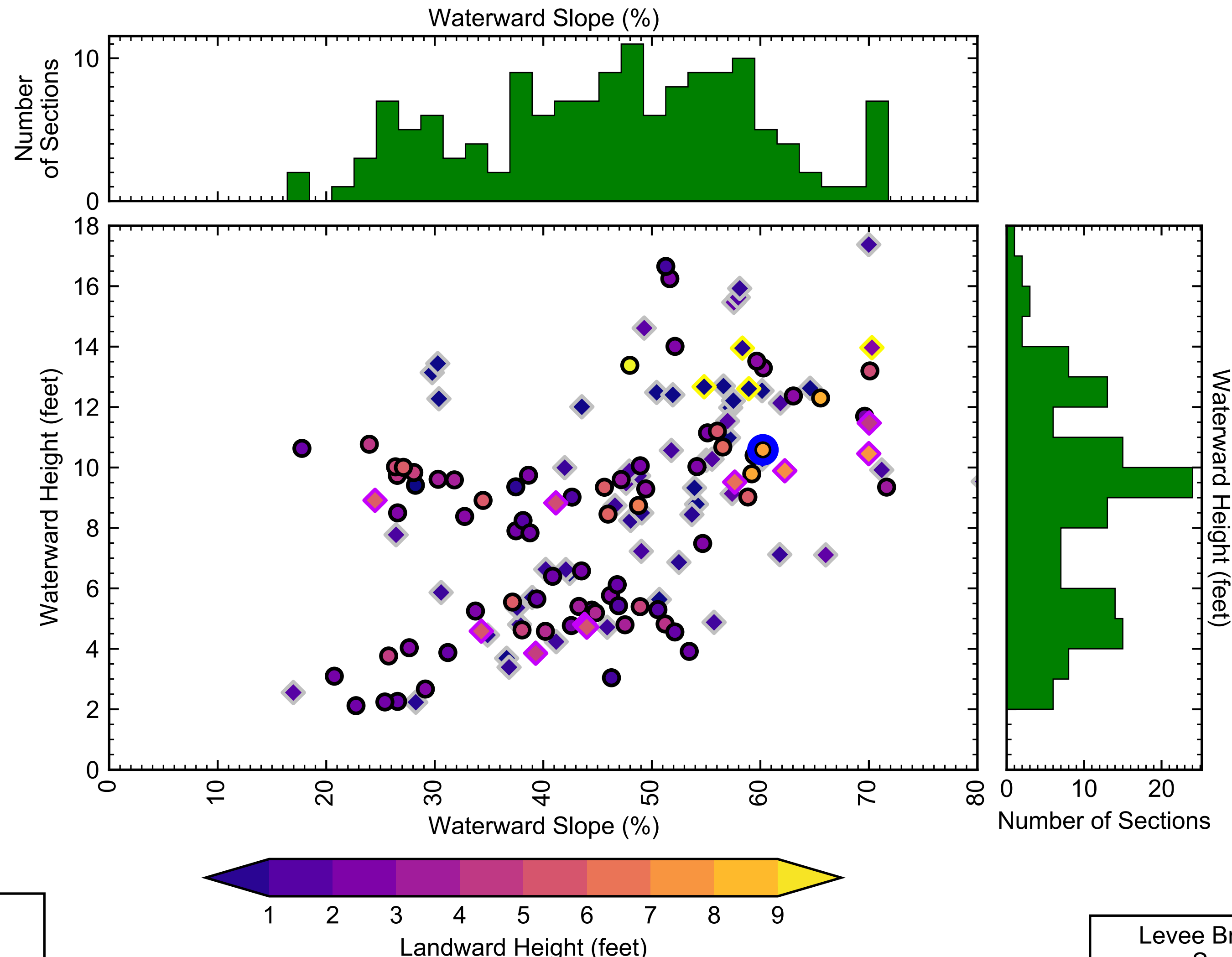
FIG. 6



Statistical Summary:

Waterward Slope (%)
mean = 47
median = 48
std = 13
min = 17
max = 81

Waterward Height (feet)
mean = 8.7
median = 9.1
std = 3.6
min = 2.1
max = 19

Landward Height (feet)
mean = 2.4
median = 1.9
std = 2.3
min = -1.9
max = 9.9

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Waterward Height (feet) = 10.6
Waterward Height (feet) = 7.9

Revetment

Levee

Reinforced Gabion Wall Levee Raise

Geogrid Reinforced Scour Repair

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LOWER RAGING RIVER LEFT BANK
WATERWARD SLOPE & WATERWARD HEIGHT

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FIG. 7

FIG. 7

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04. Levee Stability Assess\Levee Geometric Data

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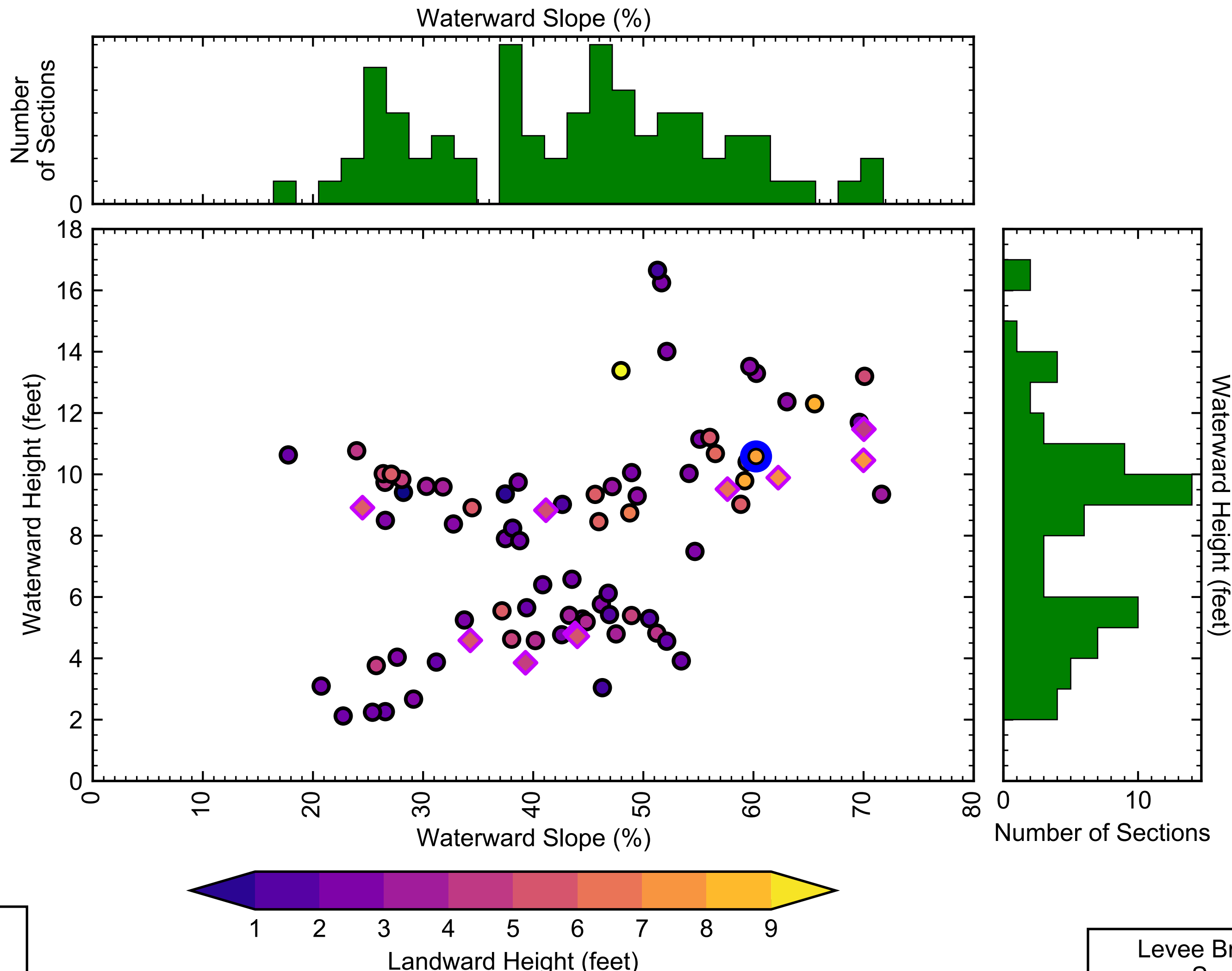
FIG. 8



Statistical Summary:

Waterward Slope (%)
mean = 44
median = 45
std = 13
min = 18
max = 72

Waterward Height (feet)
mean = 8.1
median = 8.7
std = 3.4
min = 2.1
max = 17

Landward Height (feet)
mean = 3.5
median = 2.8
std = 2.0
min = 0.0
max = 9.9

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Waterward Height (feet) = 10.6
Waterward Height (feet) = 7.9

Levee

Reinforced Gabion Wall Levee Raise

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LRR LEFT BANK, LEVEE ONLY DATA
WATERWARD SLOPE & WATERWARD HEIGHT

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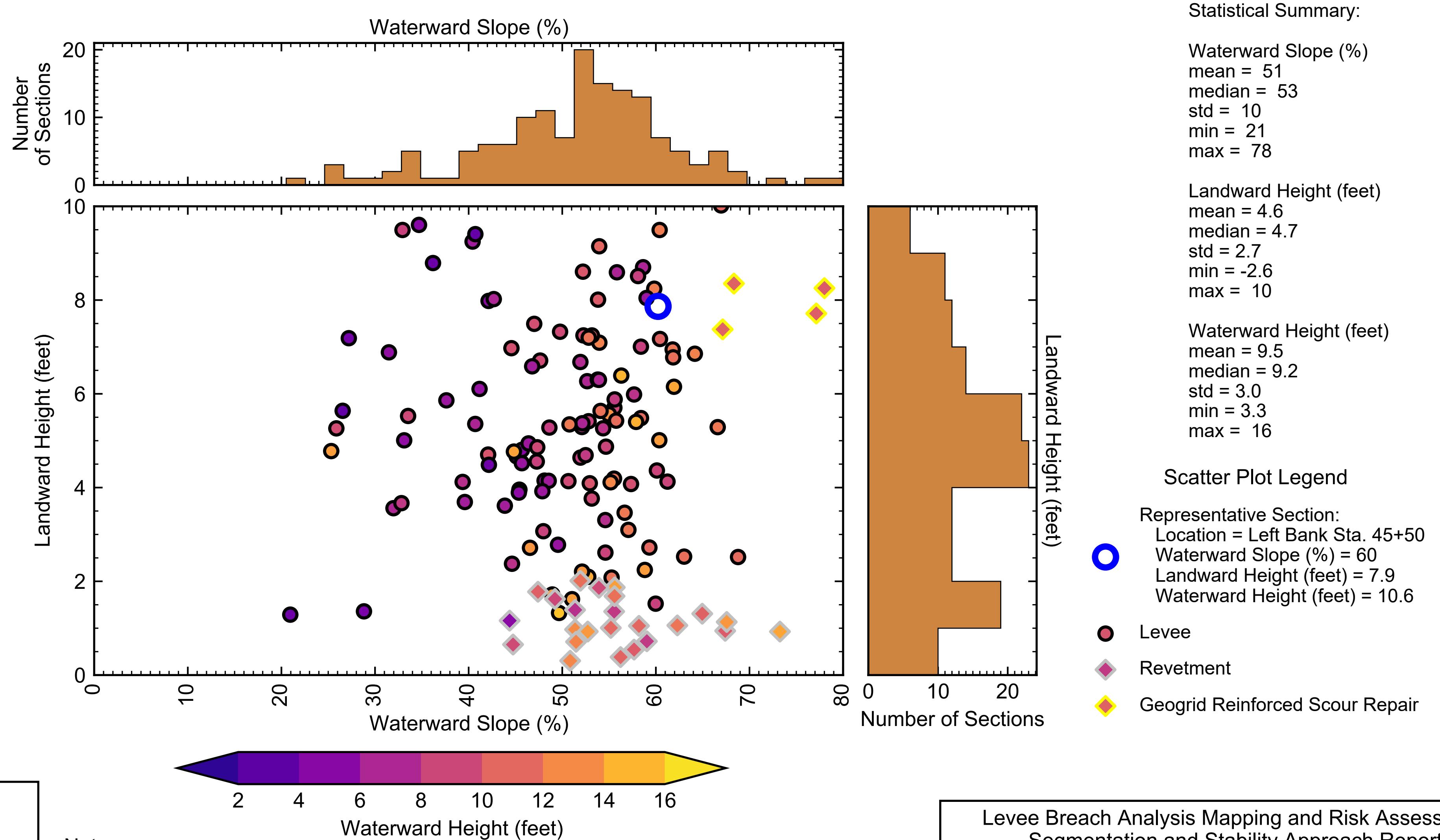
FIG. 8



Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LOWER RAGING RIVER RIGHT BANK
WATERWARD SLOPE & LANDWARD HEIGHT

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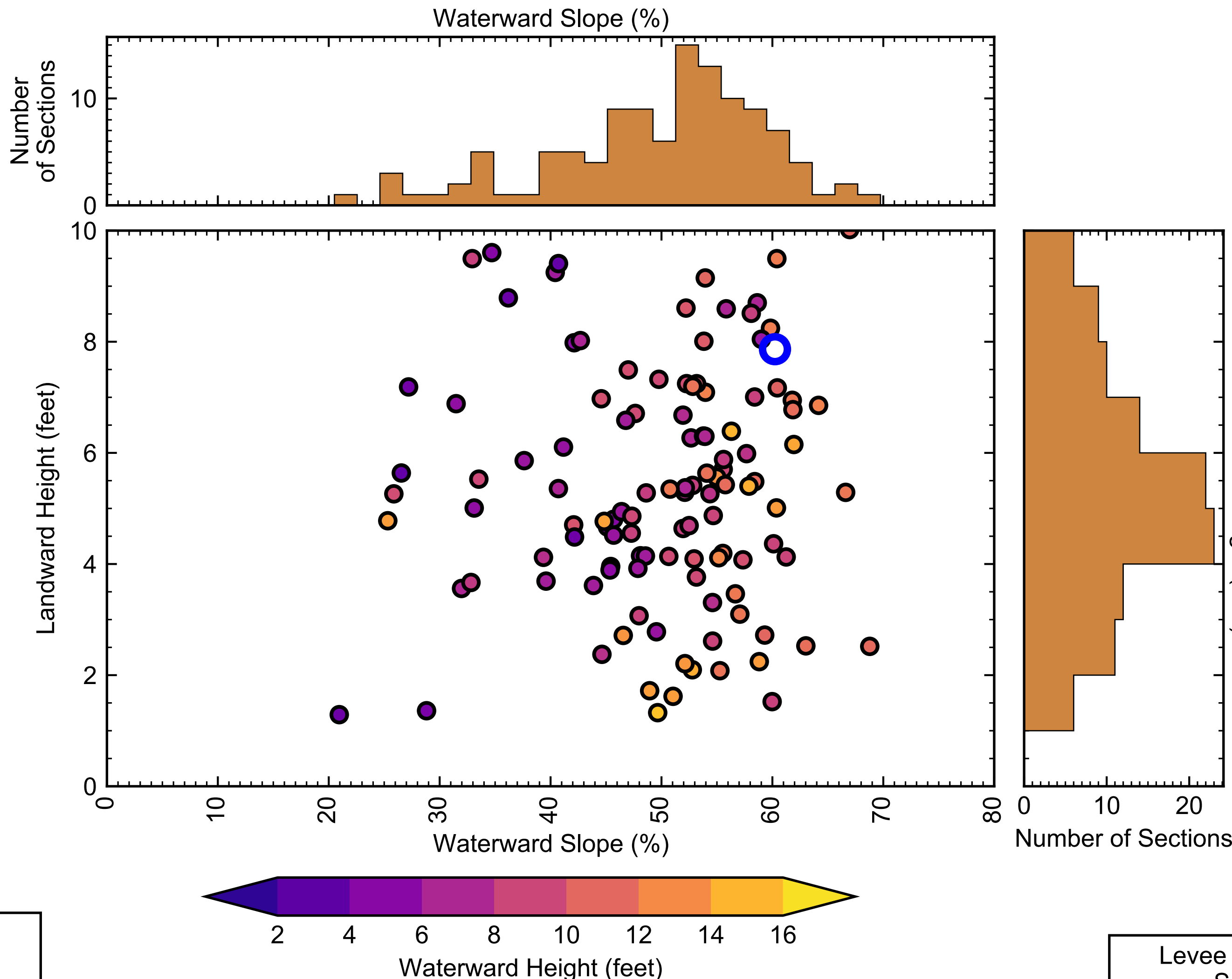
FIG. 9

FIG. 9



Statistical Summary:

Waterward Slope (%)
mean = 50
median = 52
std = 9.8
min = 21
max = 69

Landward Height (feet)
mean = 5.4
median = 5.3
std = 2.2
min = 1.3
max = 10

Waterward Height (feet)
mean = 9.1
median = 8.8
std = 3.0
min = 3.3
max = 16

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Landward Height (feet) = 7.9
Waterward Height (feet) = 10.6

Levee

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LRR RIGHT BANK, LEVEE ONLY DATA
WATERWARD SLOPE & LANDWARD HEIGHT

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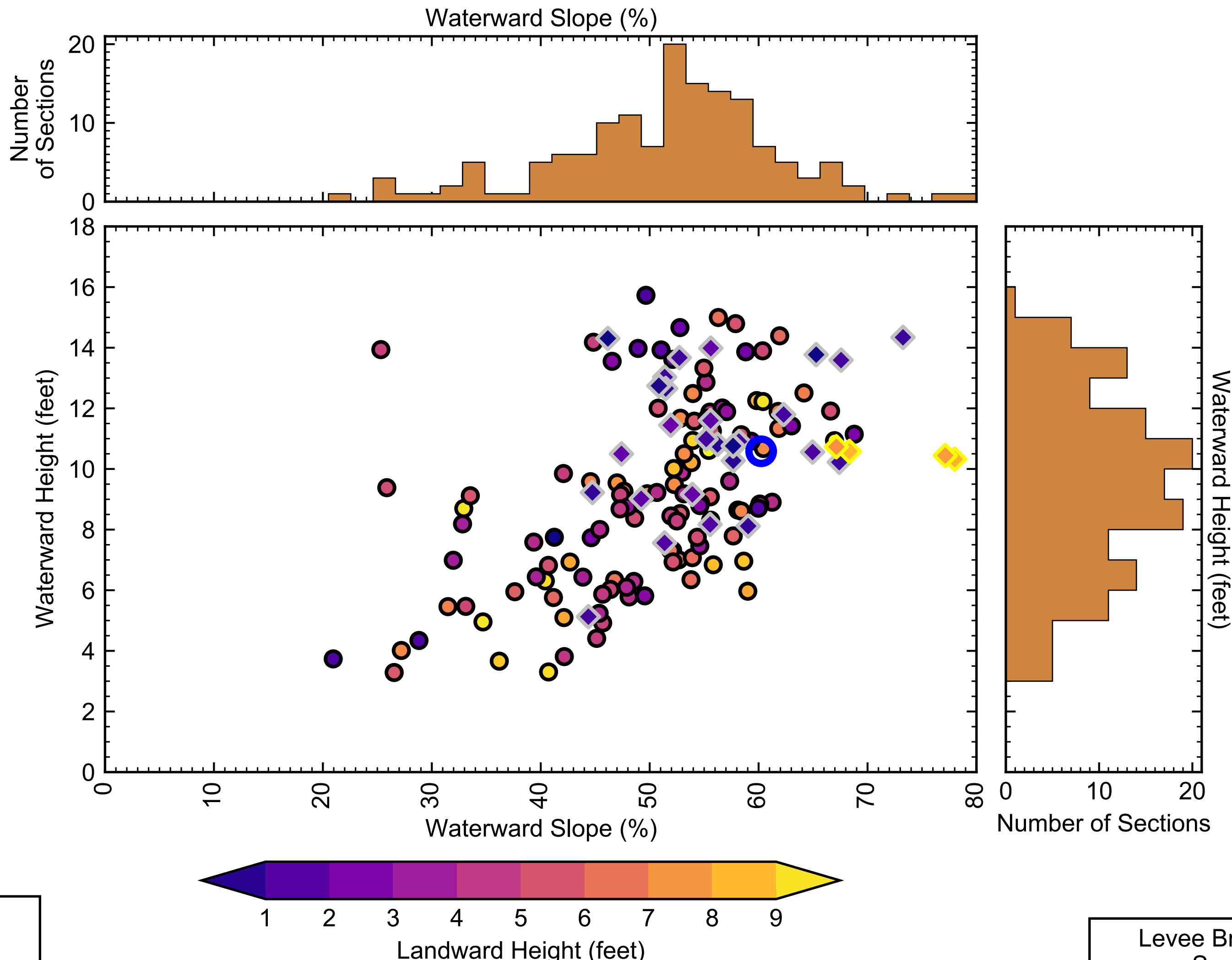
FIG. 10

FIG. 10



Statistical Summary:

Waterward Slope (%)
mean = 51
median = 53
std = 10
min = 21
max = 78

Waterward Height (feet)
mean = 9.5
median = 9.2
std = 3.0
min = 3.3
max = 16

Landward Height (feet)
mean = 4.6
median = 4.7
std = 2.7
min = -2.6
max = 10

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Waterward Height (feet) = 10.6
Waterward Height (feet) = 7.9

Levee

Revetment

Geogrid Reinforced Scour Repair

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LOWER RAGING RIVER RIGHT BANK
WATERWARD SLOPE & WATERWARD HEIGHT

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FIG. 11

FIG. 11

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04. Levee Stability Assess\Levee Geometric Data

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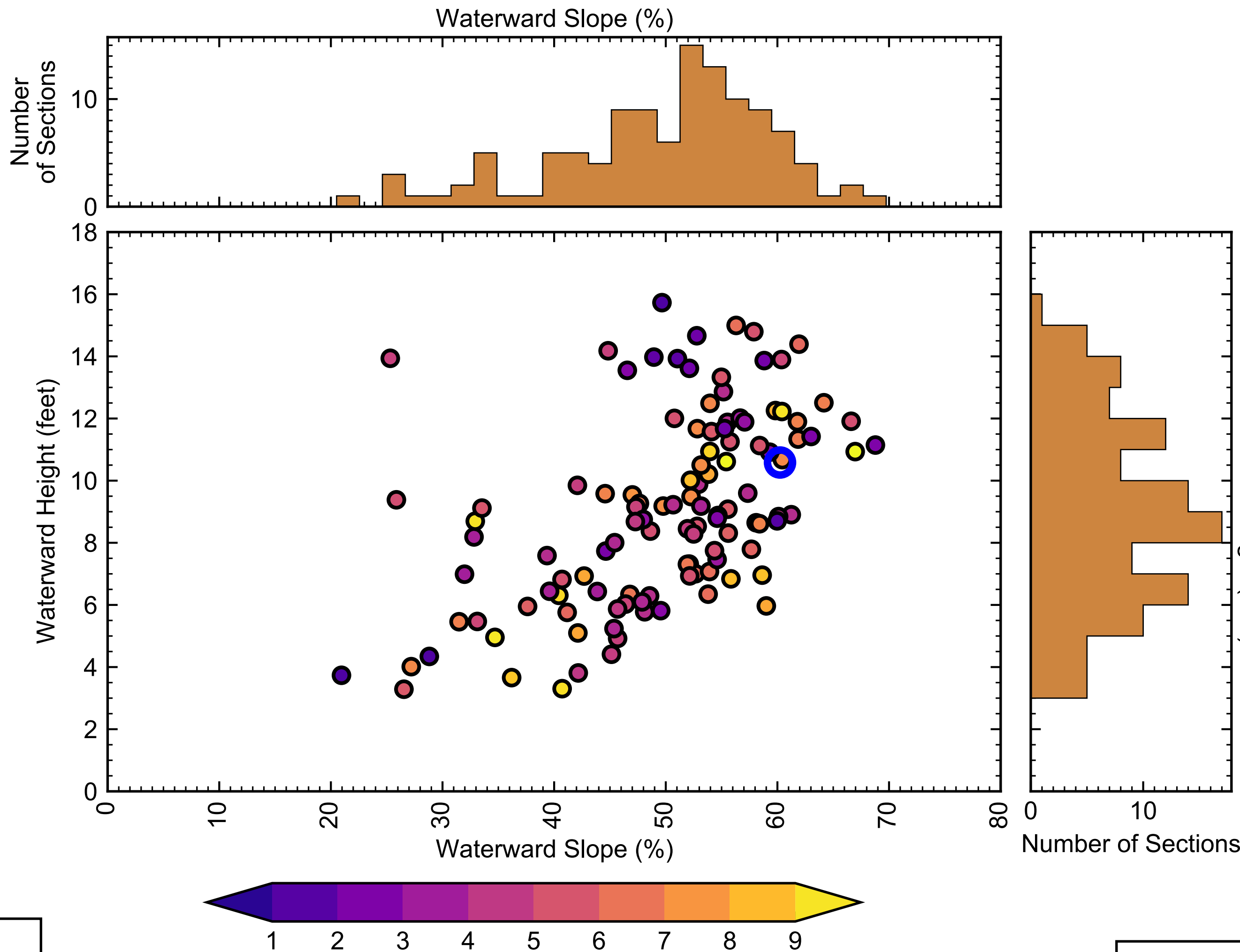

Statistical Summary:

Waterward Slope (%)
mean = 50
median = 52
std = 9.8
min = 21
max = 69

Waterward Height (feet)
mean = 9.1
median = 8.8
std = 3.0
min = 3.3
max = 16

Landward Height (feet)
mean = 5.4
median = 5.3
std = 2.2
min = 1.3
max = 10

Scatter Plot Legend

Representative Section:
Location = Left Bank Sta. 45+50
Waterward Slope (%) = 60
Waterward Height (feet) = 10.6
Waterward Height (feet) = 7.9

Levee

Notes:
1. std = Standard Deviation; min = Minimum; max = Maximum, LRR = Lower Raging River
2. Histograms and statistical summary parameters include levee geometric data and exclude revetments. We categorized the flood protection facilities on both banks as a revetment if the total vertical relief between the top of the levee and the low point on the landward side is 2 feet or less.
3. Negative heights indicate the ground surface on the landward side is higher than the levee. Points for stations with negative levee heights are not shown.

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LIDAR GEOMETRIC SUMMARY
LRR RIGHT BANK, LEVEE ONLY DATA
WATERWARD SLOPE & WATERWARD HEIGHT

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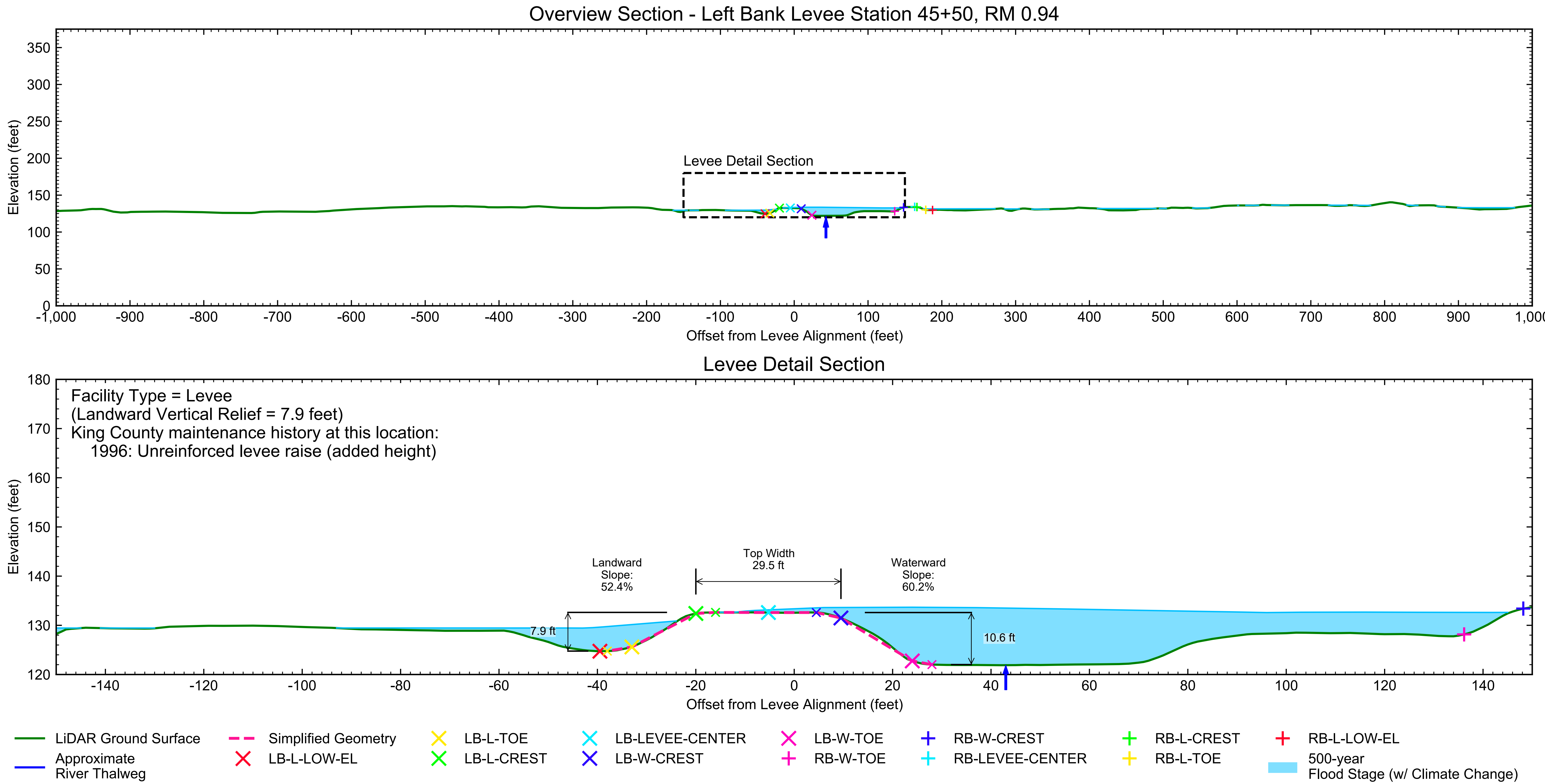
FIG. 12

FIG. 12



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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REPRESENTATIVE SECTION
LOWER RAGING RIVER
LEFT BANK STA 45+50, RM 0.94

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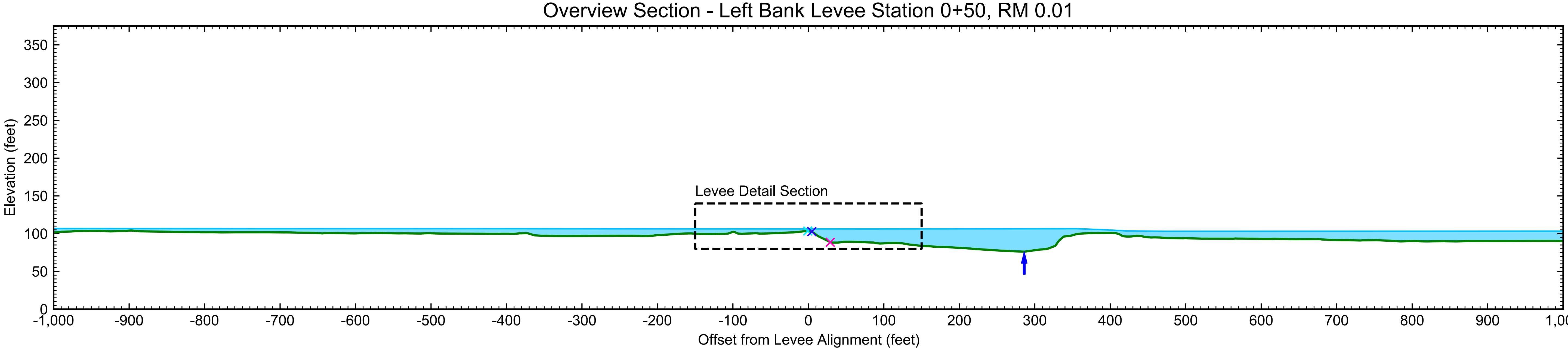
FIG. 13

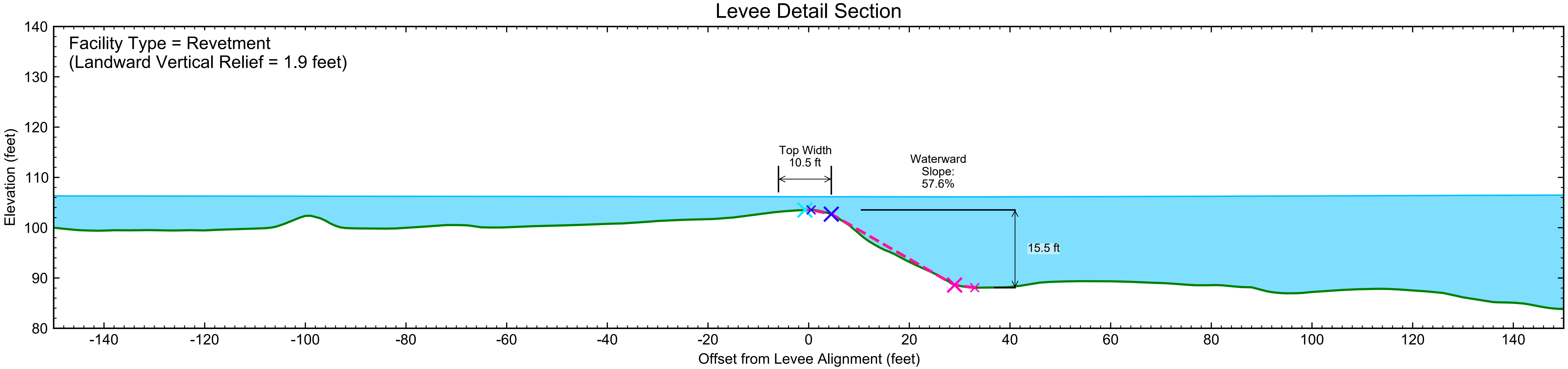
APPENDIX A: LIDAR-BASED GEOMETRIC INVENTORY FIGURES

Appendix A

Lidar-Based Geometric Inventory Figures

CONTENTS





LiDAR Ground Surface; Approximate River Thalweg; Simplified Geometry; LB-L-LOW-EL; LB-L-TOE; LB-L-CREST; LB-LEVEE-CENTER; LB-W-CREST; LB-W-TOE; RB-W-TOE; RB-W-CREST; RB-LEVEE-CENTER; RB-L-CREST; RB-L-TOE; RB-L-LOW-EL; 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 0+50, RM 0.01

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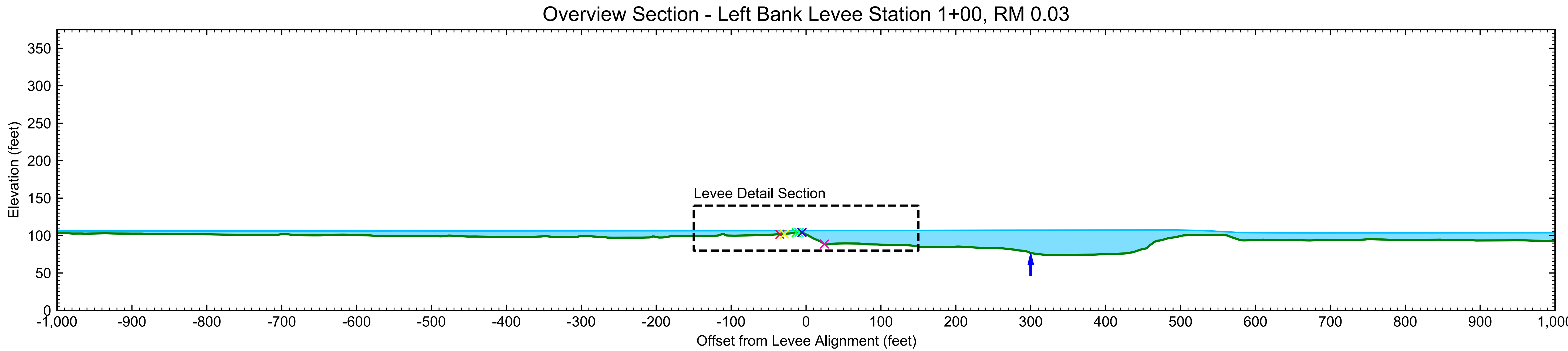
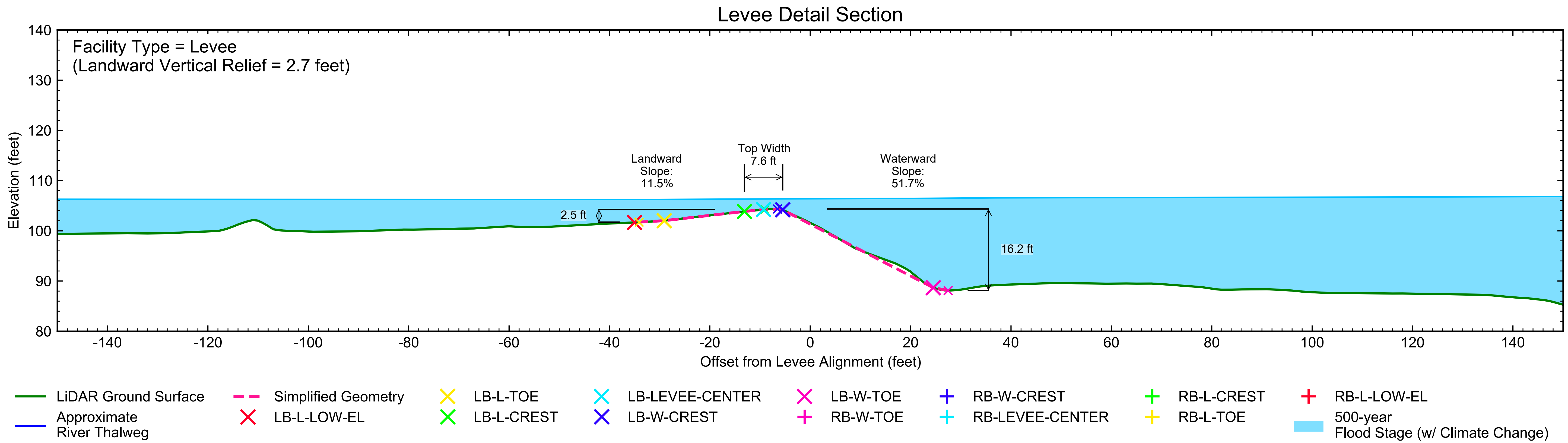
FIG. A-1





Notes:

1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 1+00, RM 0.03

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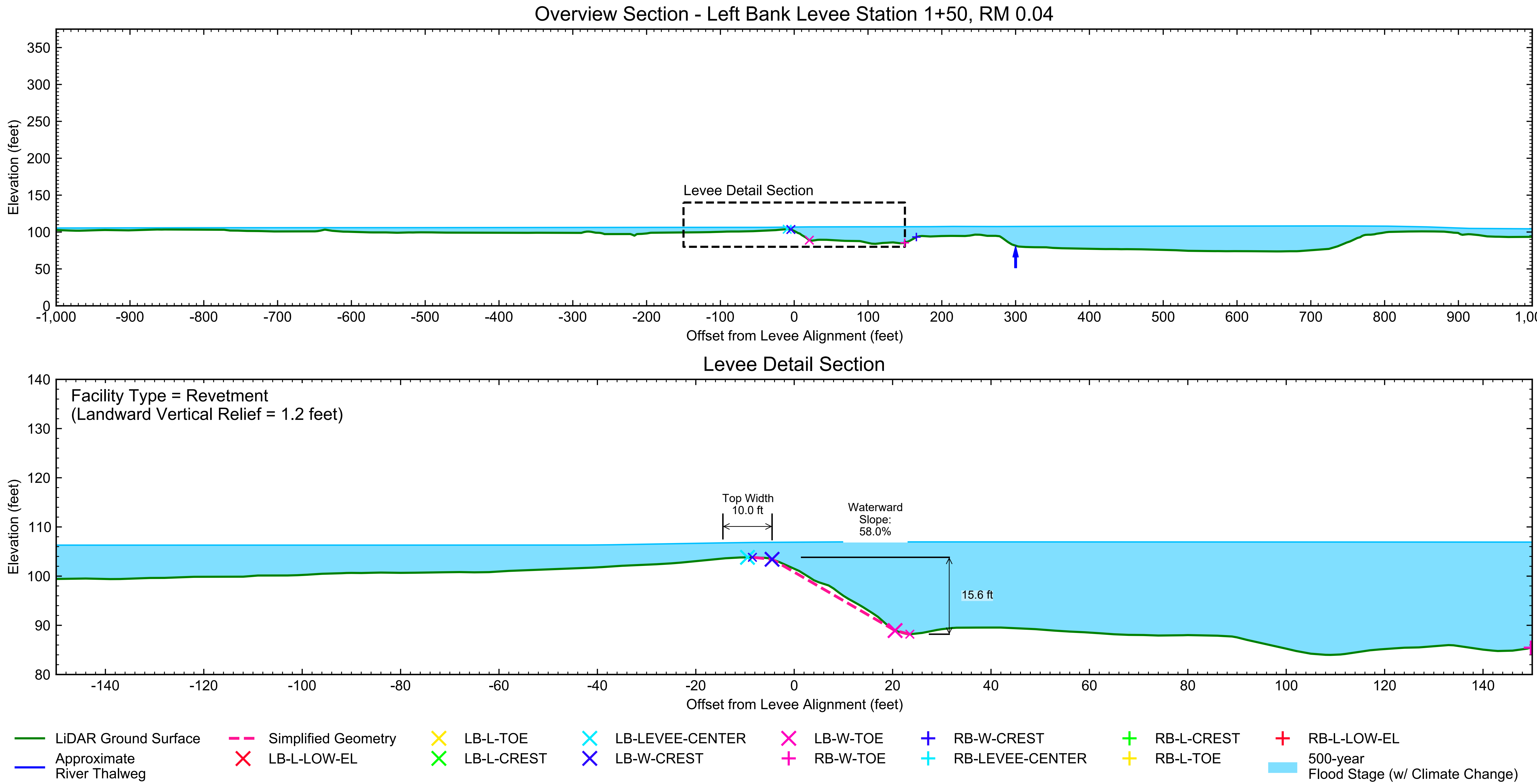
FIG. A-2



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
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6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 1+50, RM 0.04

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FIG. A-3

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04. Levee Stability Assess\Levee Geometric Data
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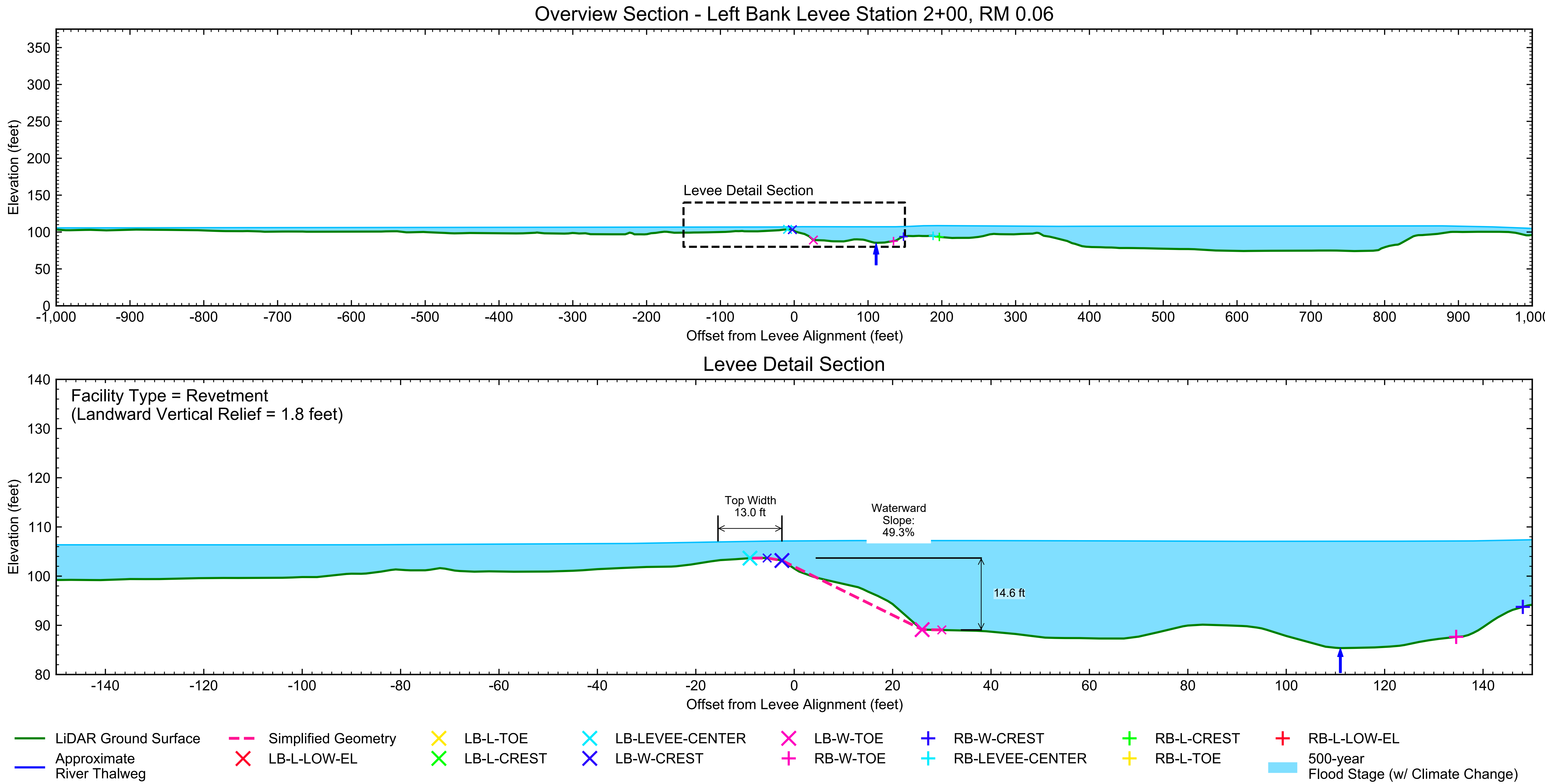

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 2+00, RM 0.06

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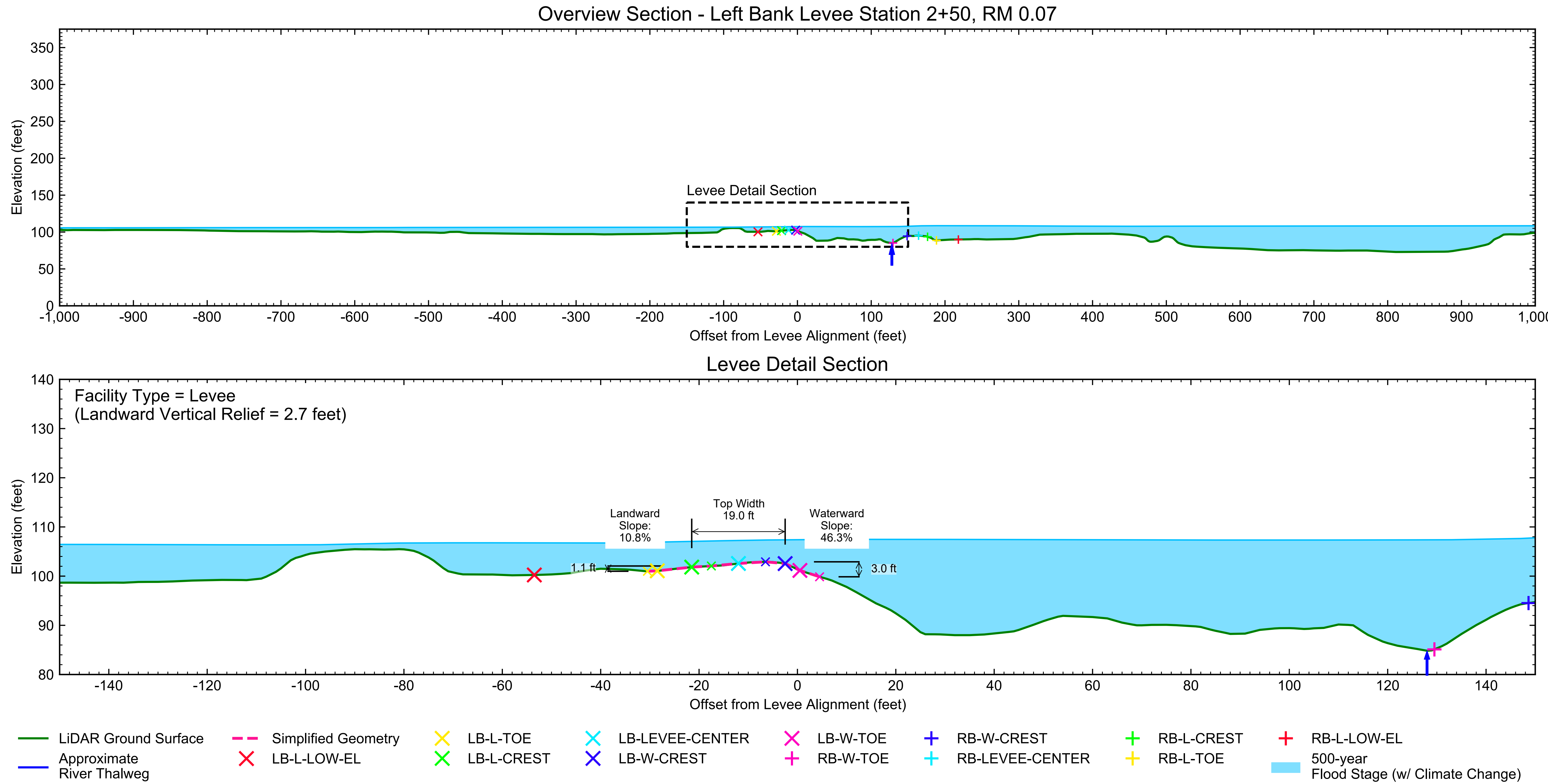
FIG. A-4



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
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Levee Breach Analysis Mapping and Risk Assessment
Segmentation and Stability Approach Report
King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 2+50, RM 0.07

April 2022 | 103692-304

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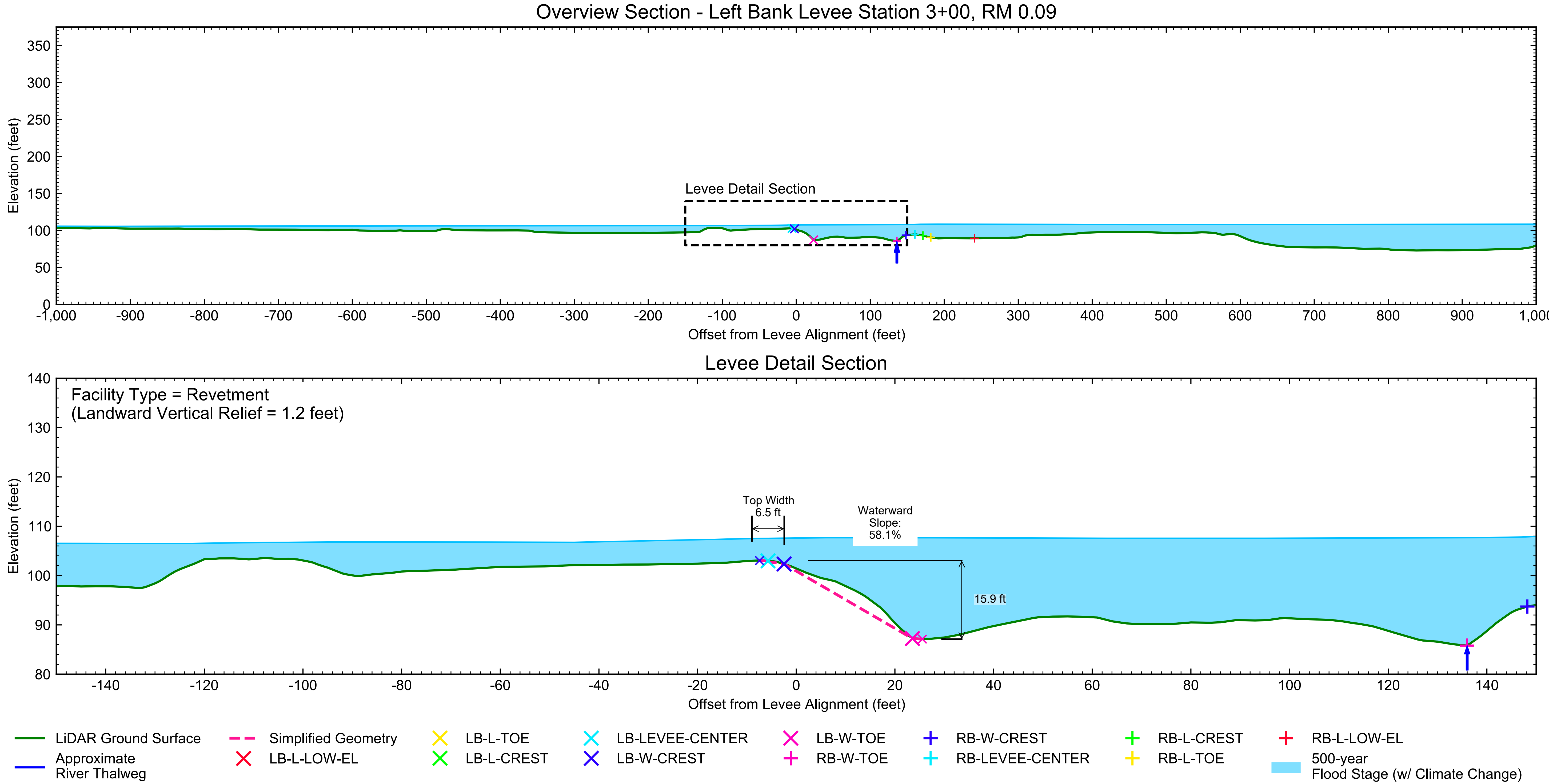
FIG. A-5



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 3+00, RM 0.09

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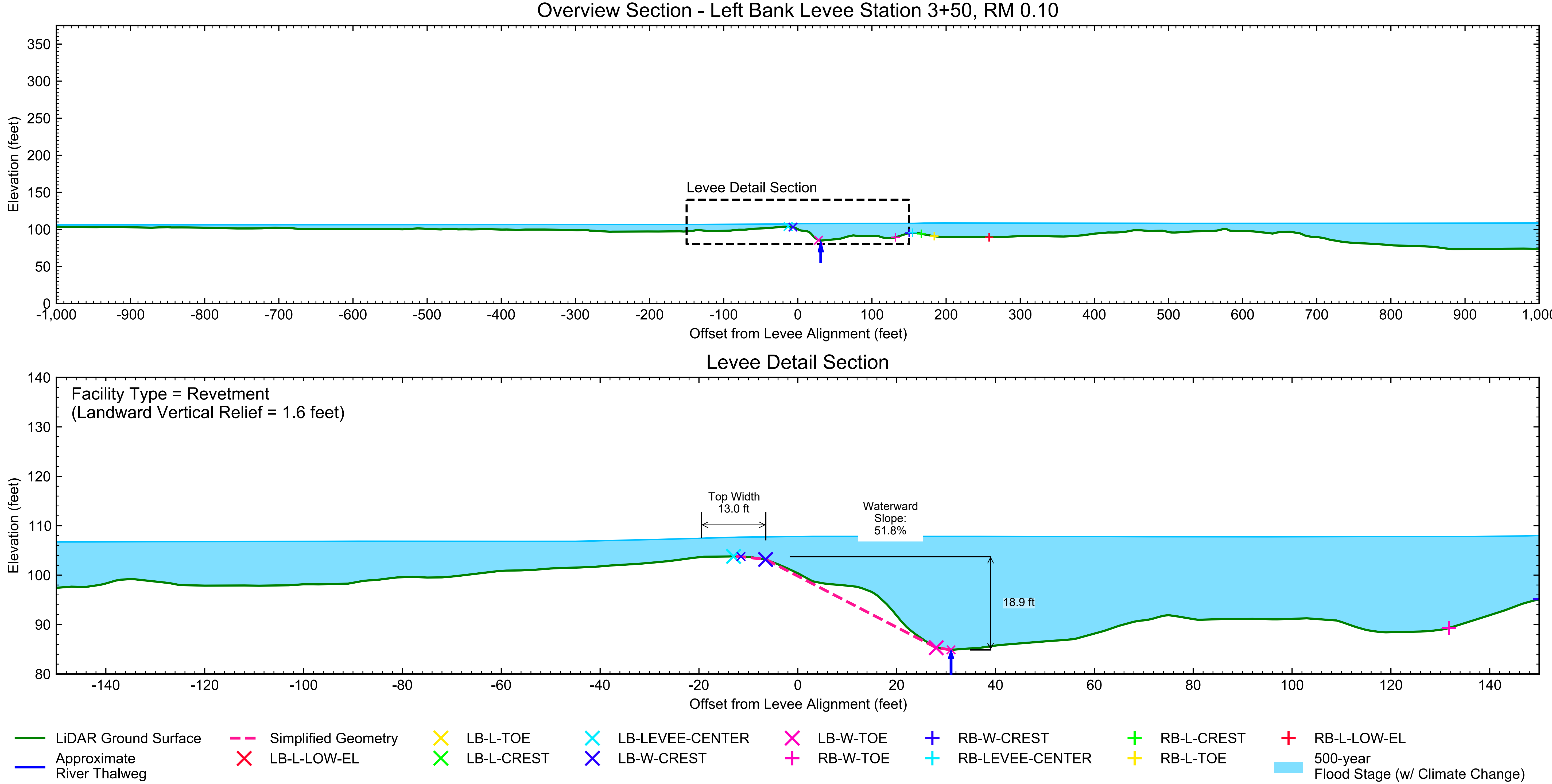
FIG. A-6



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LOWER RAGING RIVER
LEFT BANK STA 3+50, RM 0.10

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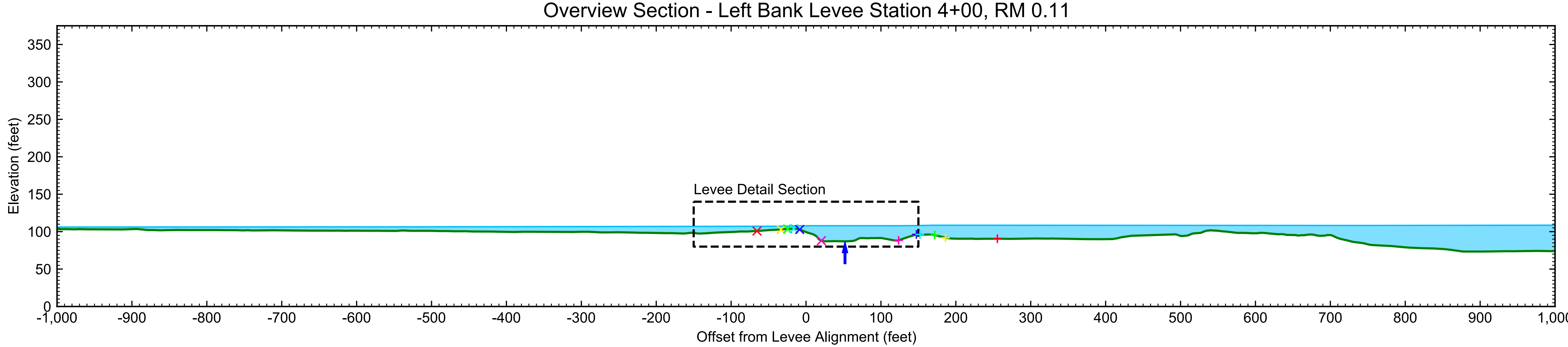
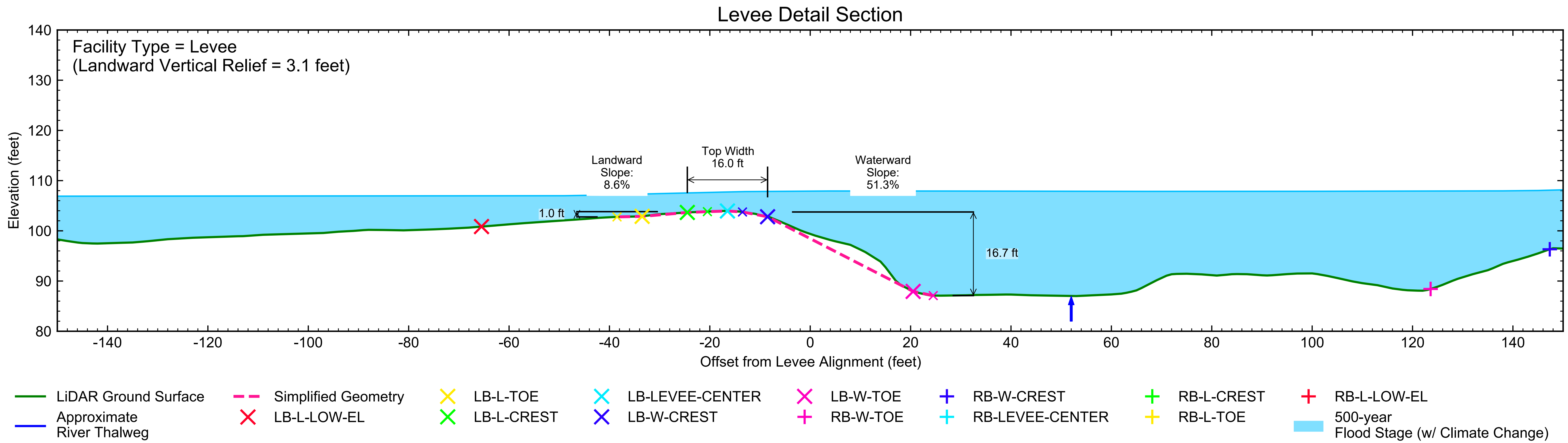
FIG. A-7





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LOWER RAGING RIVER
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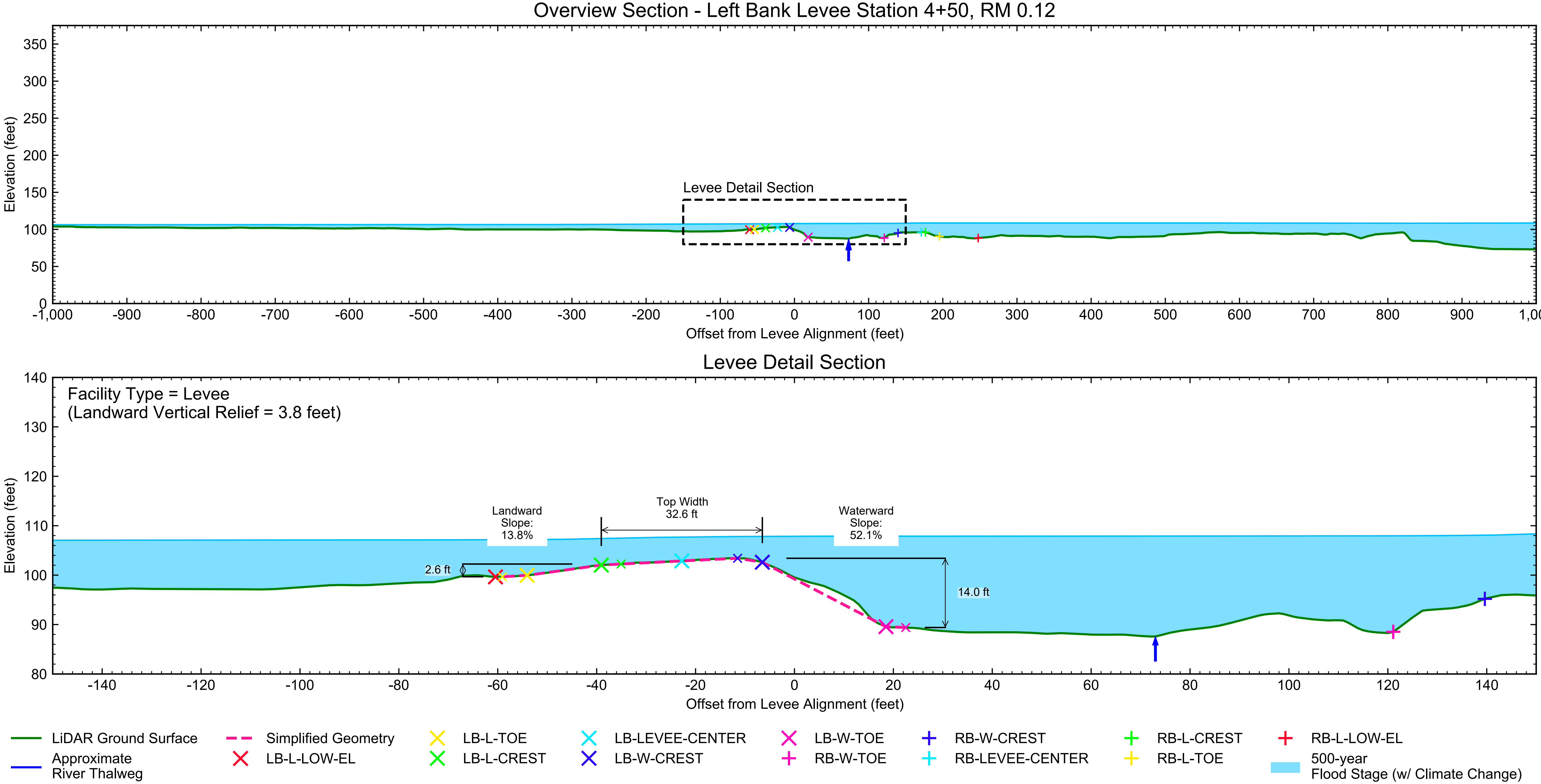
FIG. A-8



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LEFT BANK STA 4+50, RM 0.12

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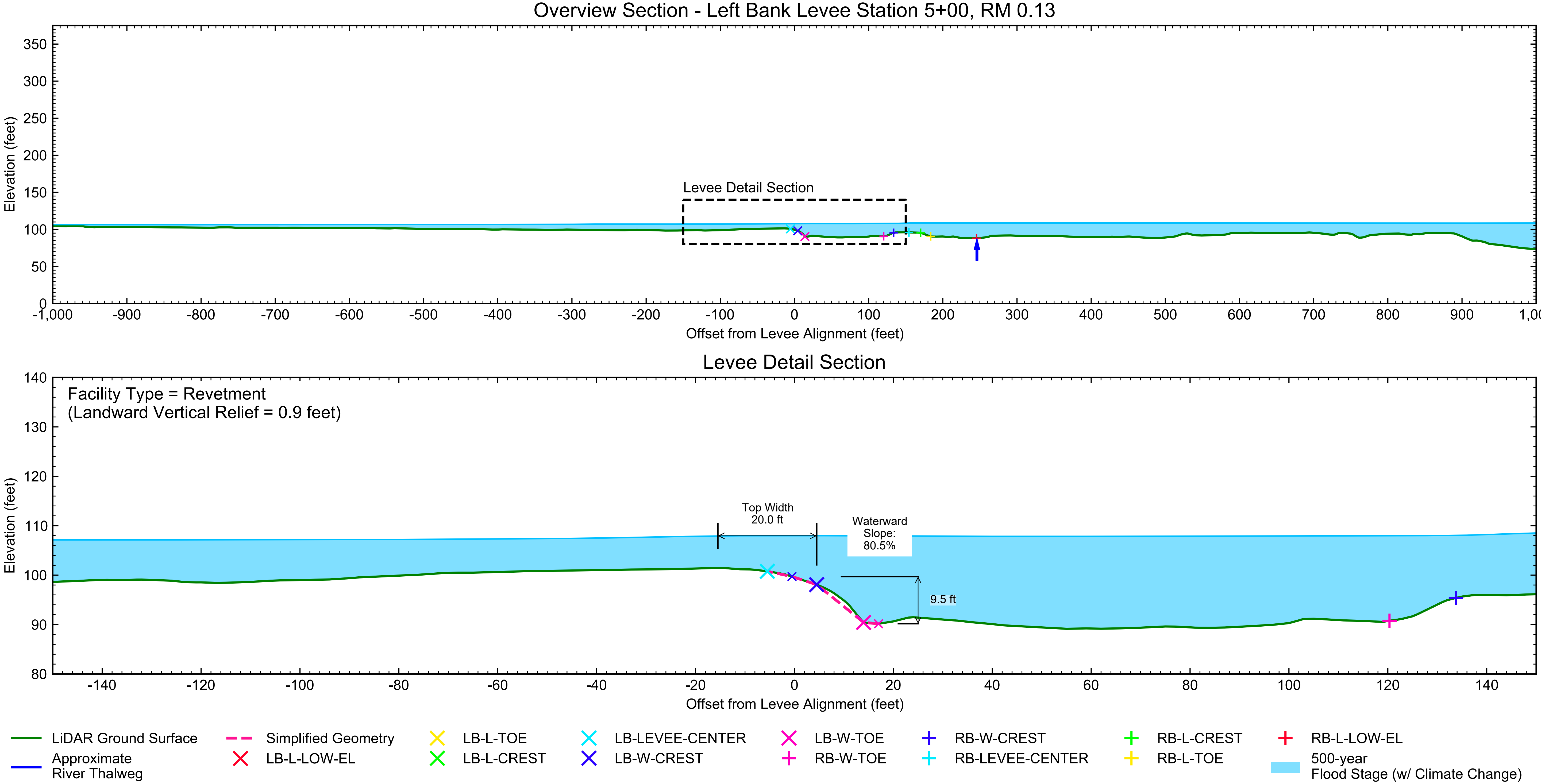
FIG. A-9



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 5+00, RM 0.13

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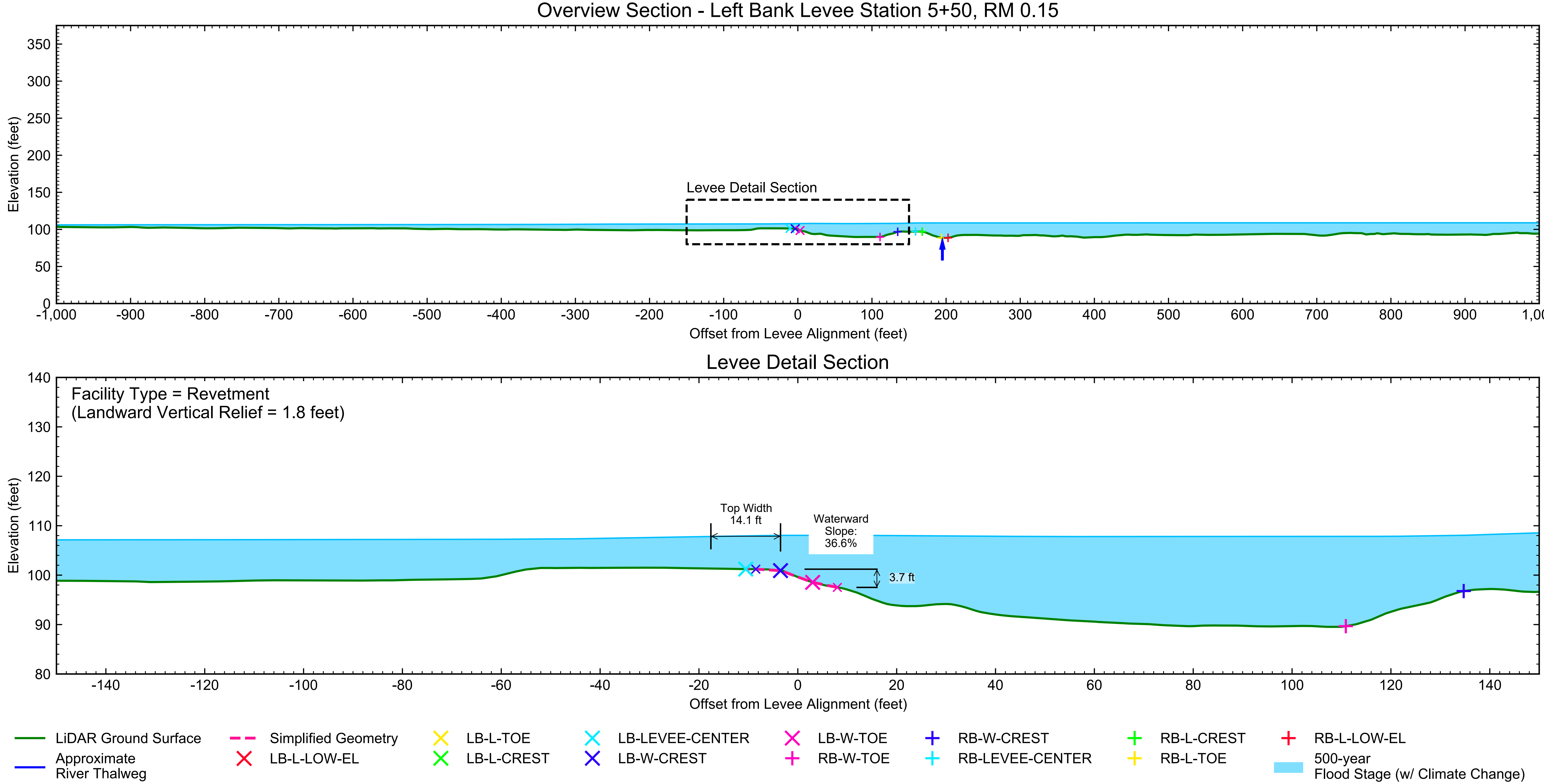
FIG. A-10



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 5+50, RM 0.15

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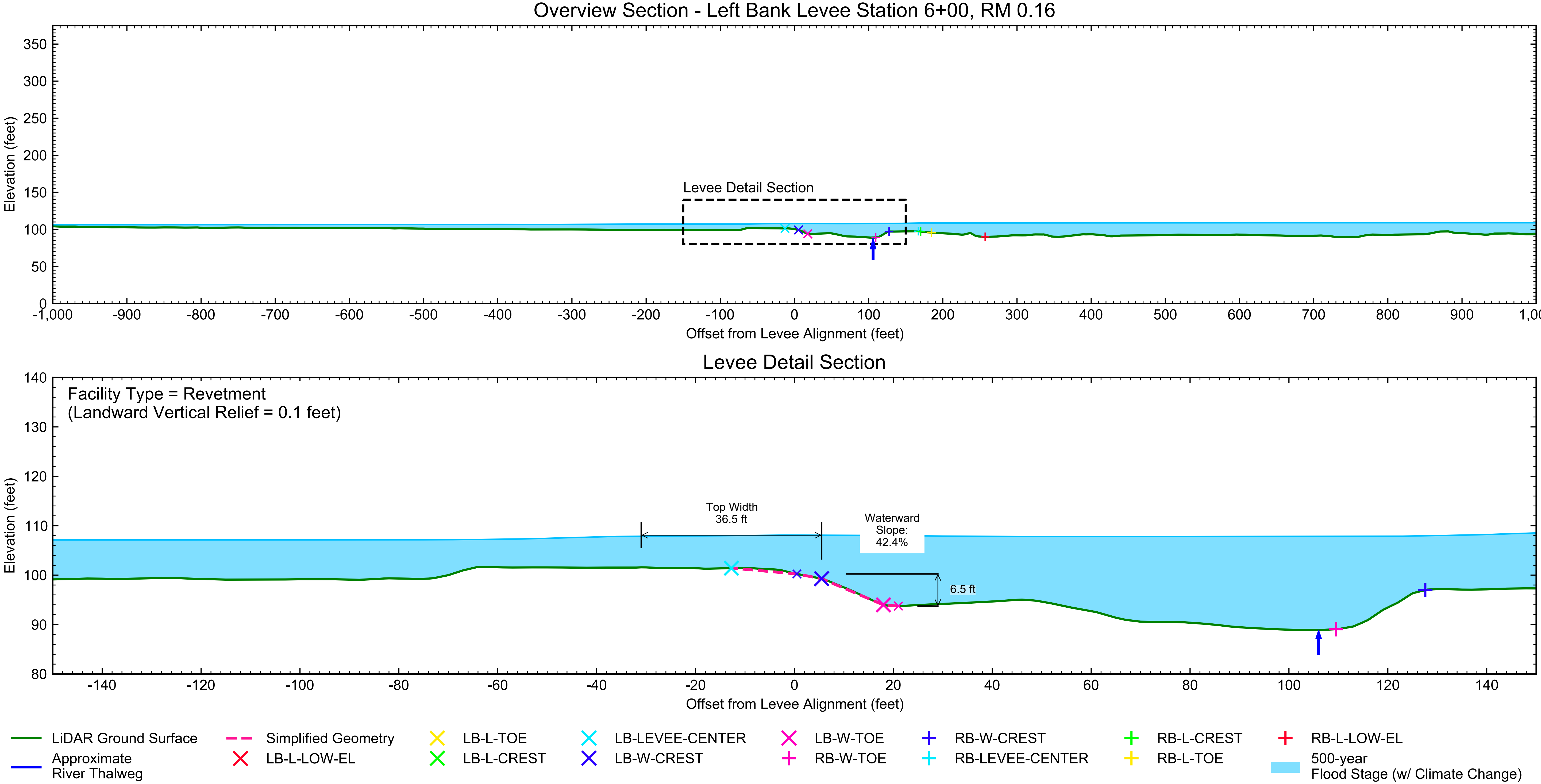
FIG. A-11



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 6+00, RM 0.16

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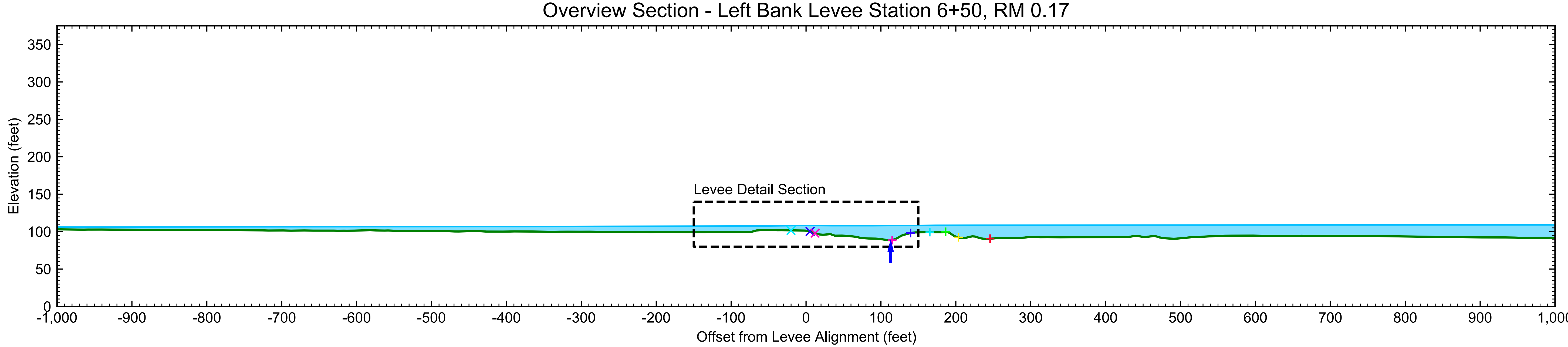
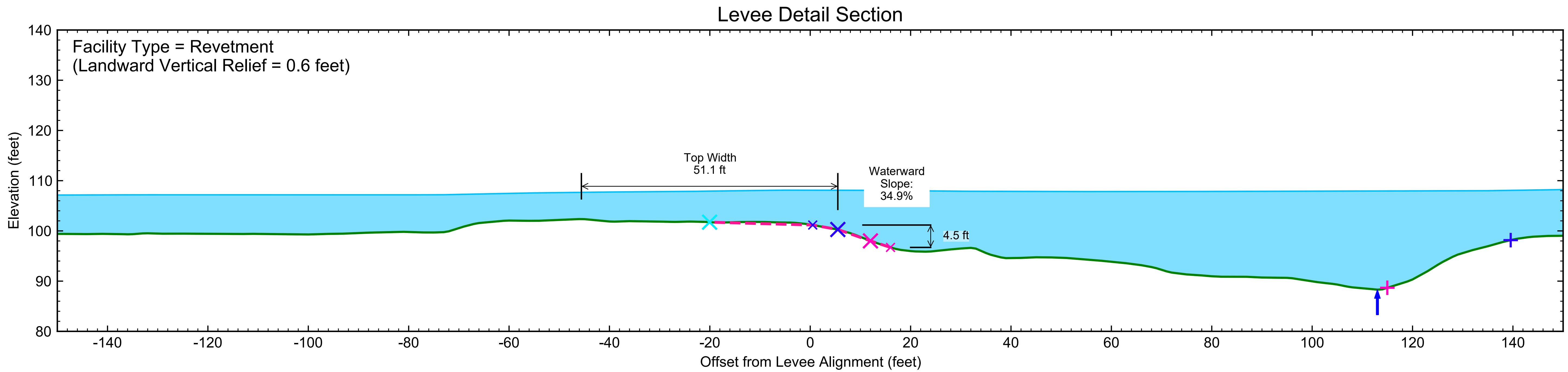
FIG. A-12





LiDAR Ground Surface — Approximate River Thalweg — Simplified Geometry — LB-L-LOW-EL — LB-L-TOE — LB-L-CREST — LB-LEVEE-CENTER — LB-W-CREST — LB-W-TOE — RB-W-TOE — RB-W-CREST — RB-LEVEE-CENTER — RB-L-CREST — RB-L-TOE — RB-L-LOW-EL — 500-year Flood Stage (w/ Climate Change)

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 6+50, RM 0.17

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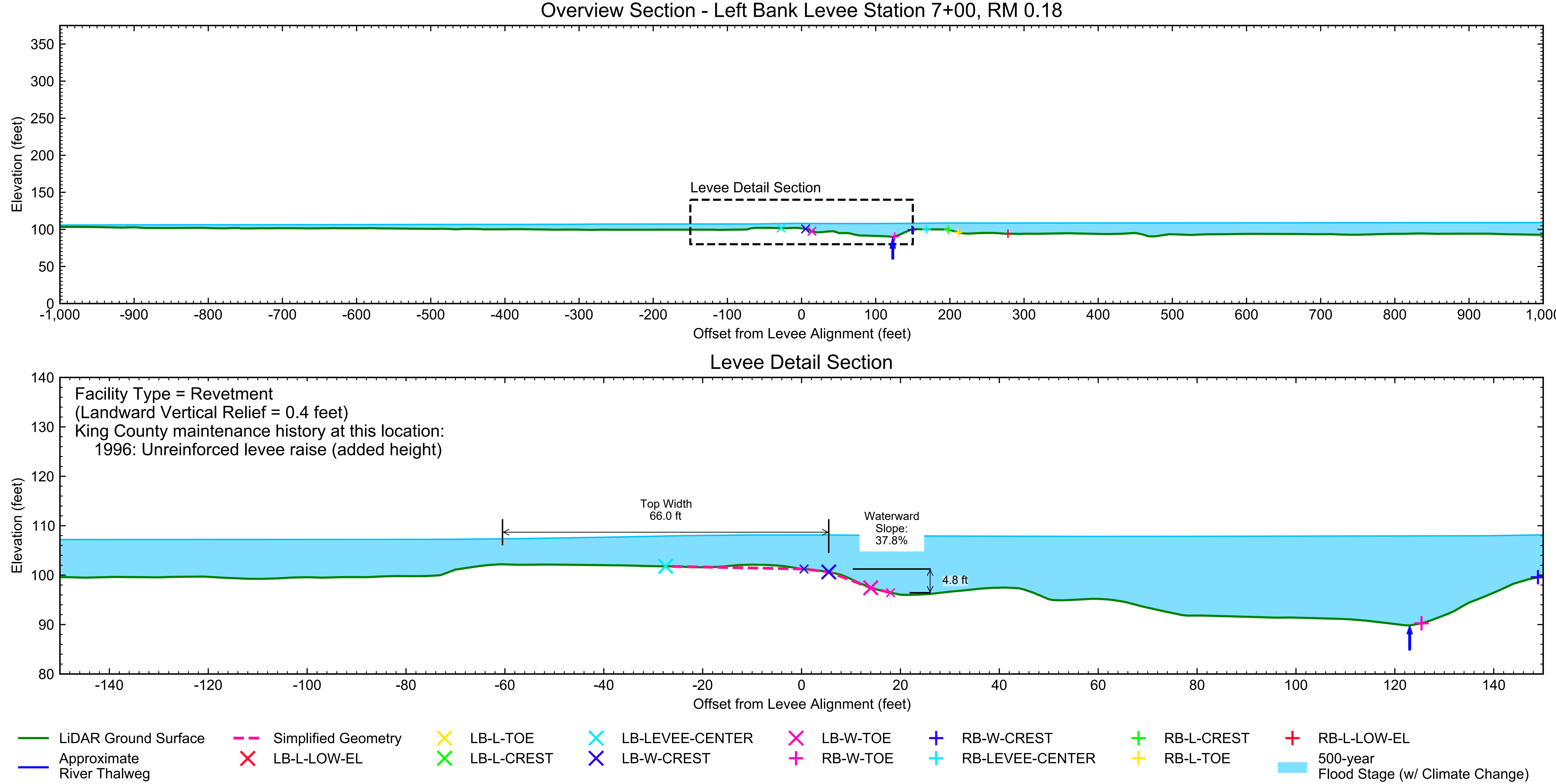
FIG. A-13

ver:0.14.0.post1+gf81b80b, by:OTH
\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data



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LIDAR CROSS SECTION
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FIG. A-14

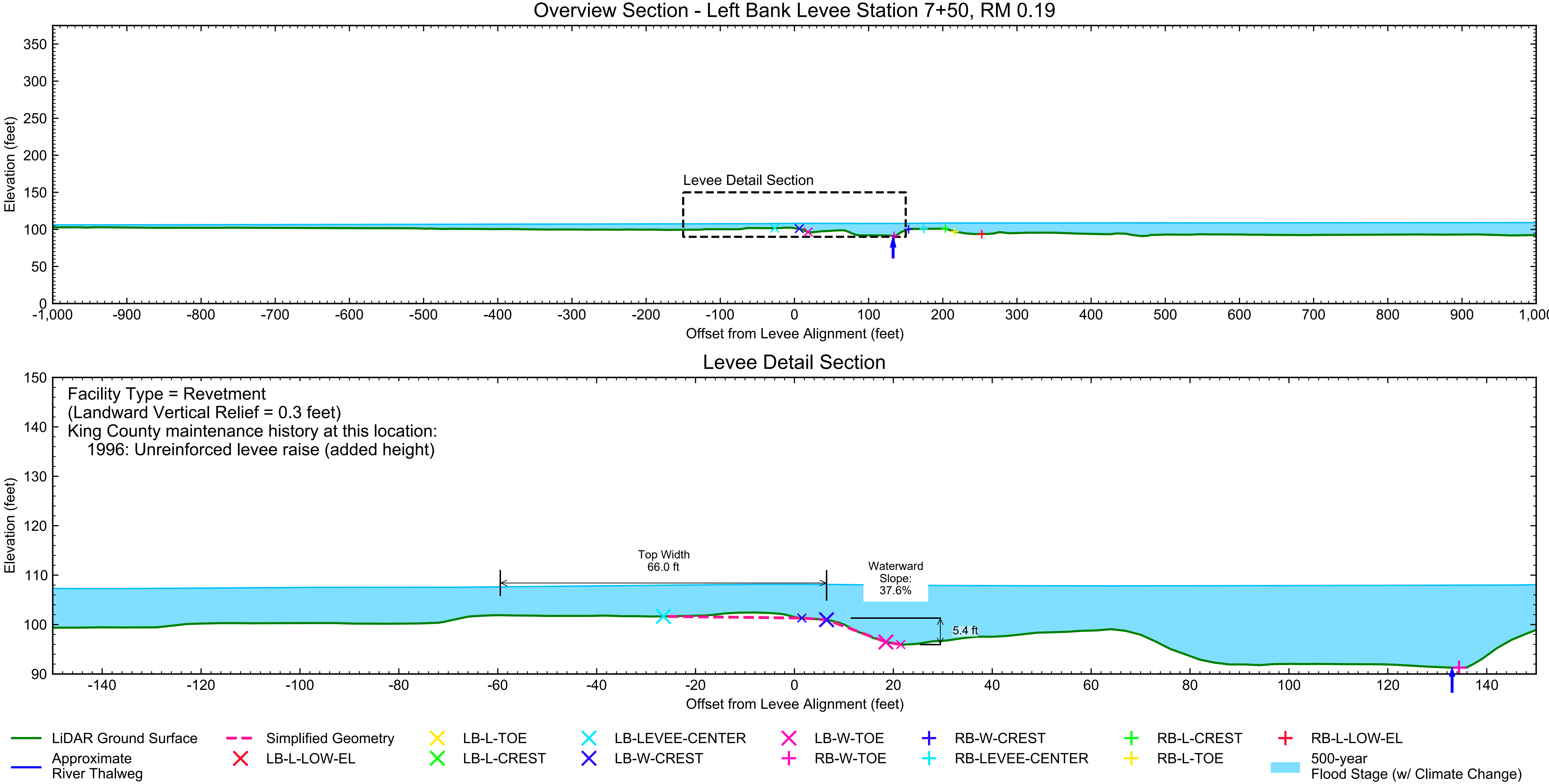

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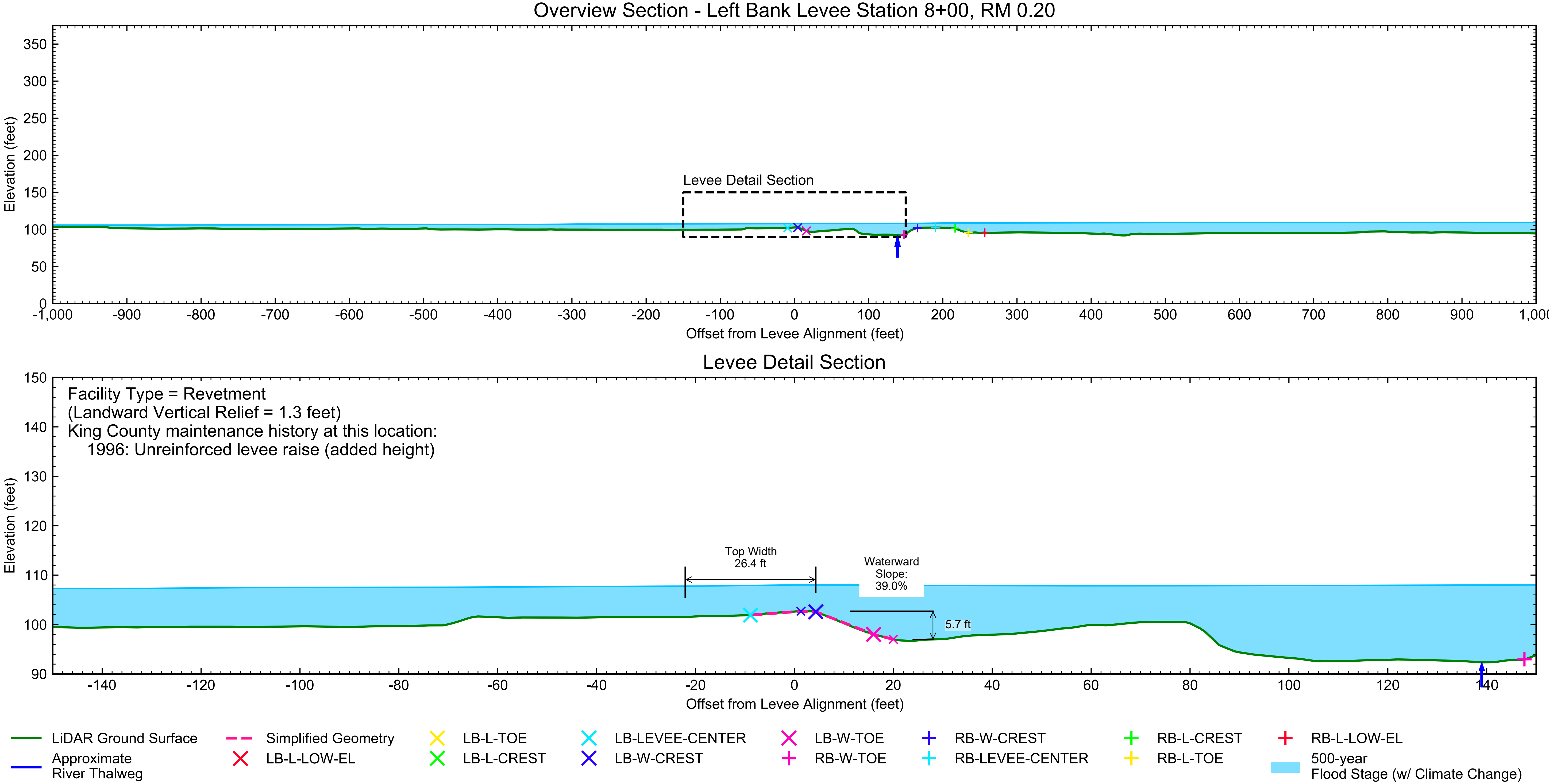
FIG. A-15



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LIDAR CROSS SECTION
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LEFT BANK STA 8+00, RM 0.20

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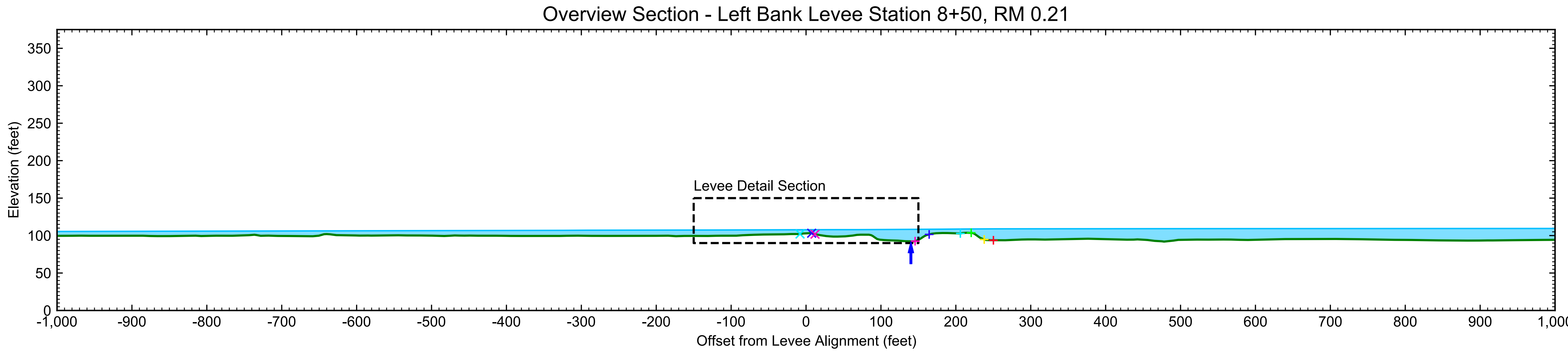
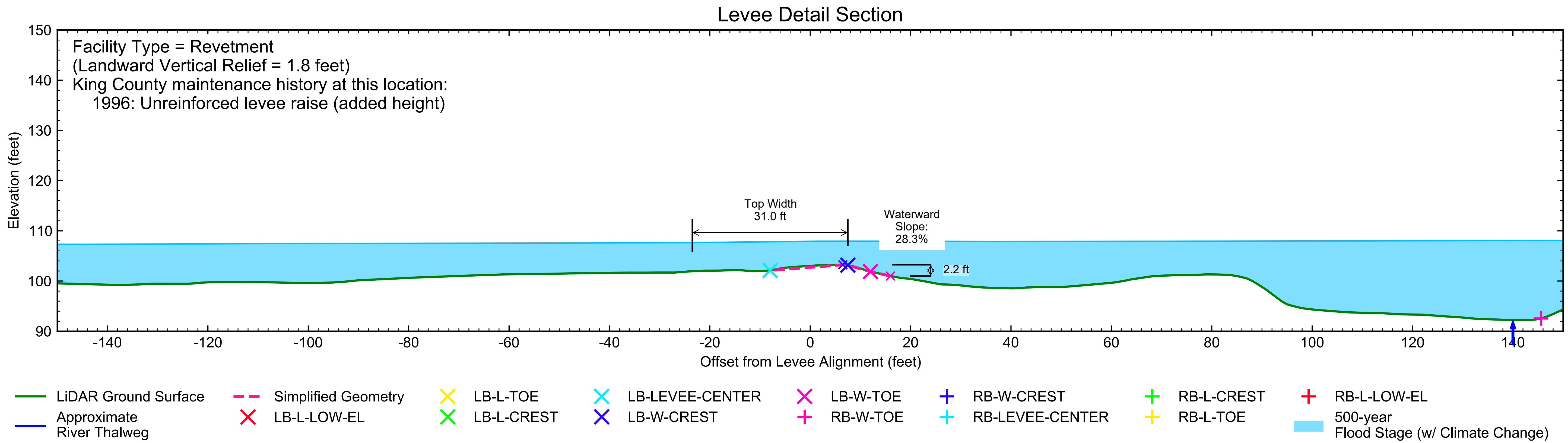
FIG. A-16





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LIDAR CROSS SECTION
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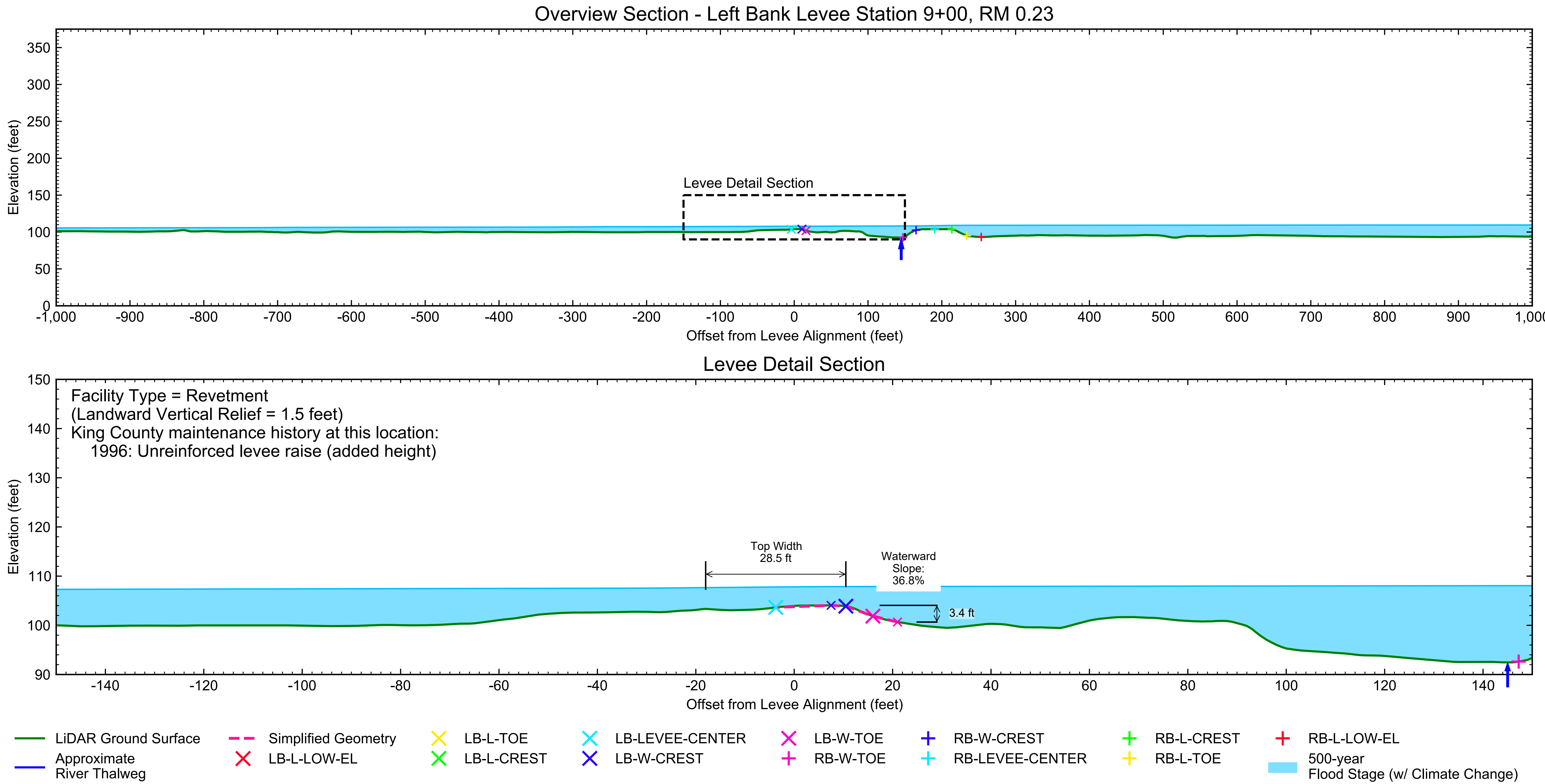
FIG. A-17



Notes:
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

Levee Breach Analysis Mapping and Risk Assessment
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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 9+00, RM 0.23

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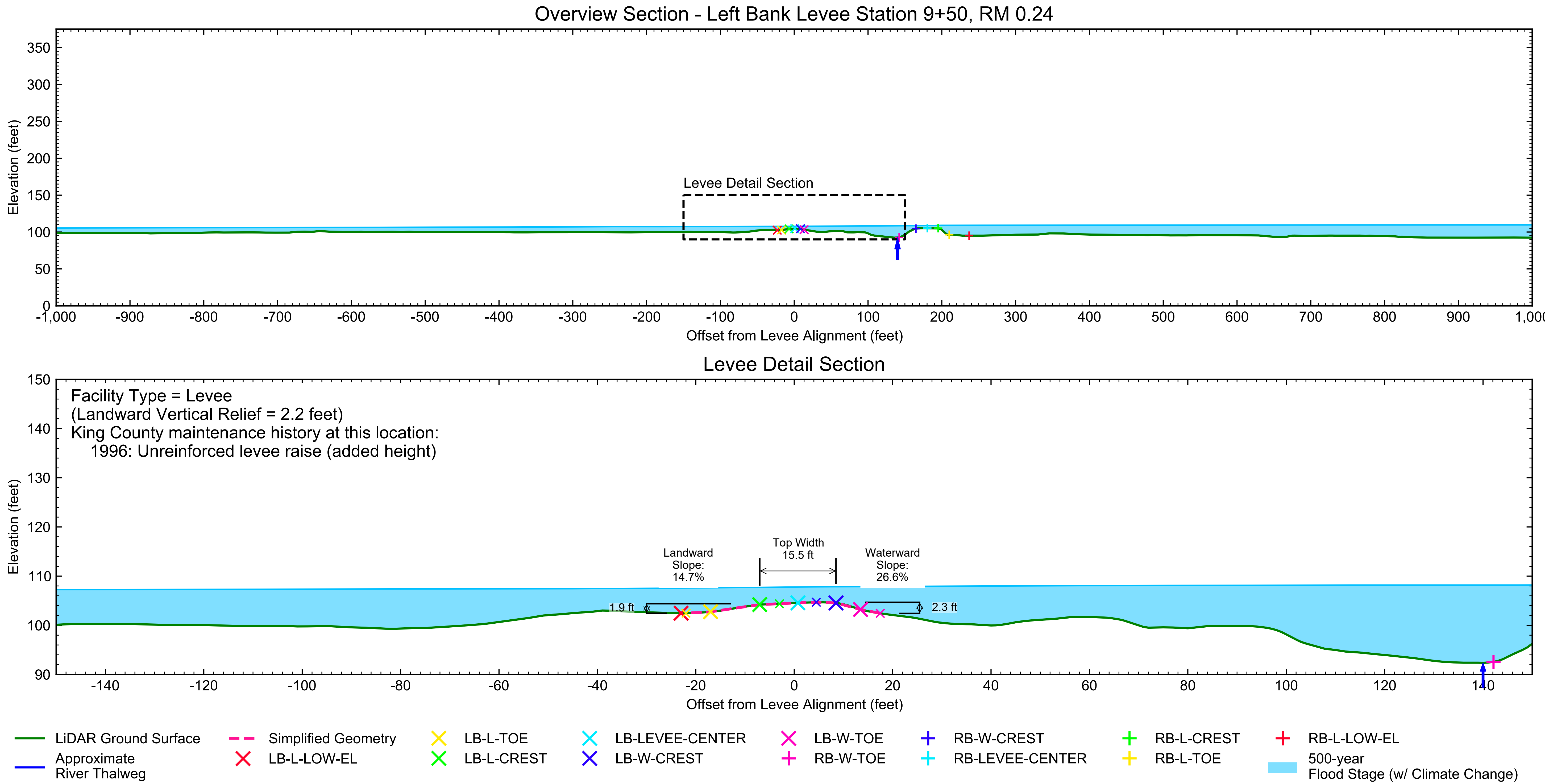
FIG. A-18



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 9+50, RM 0.24

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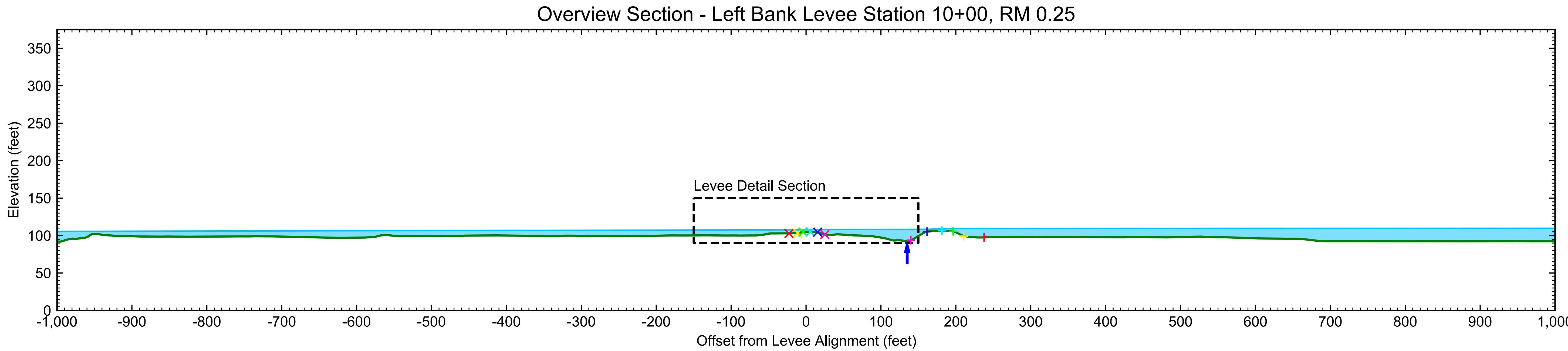
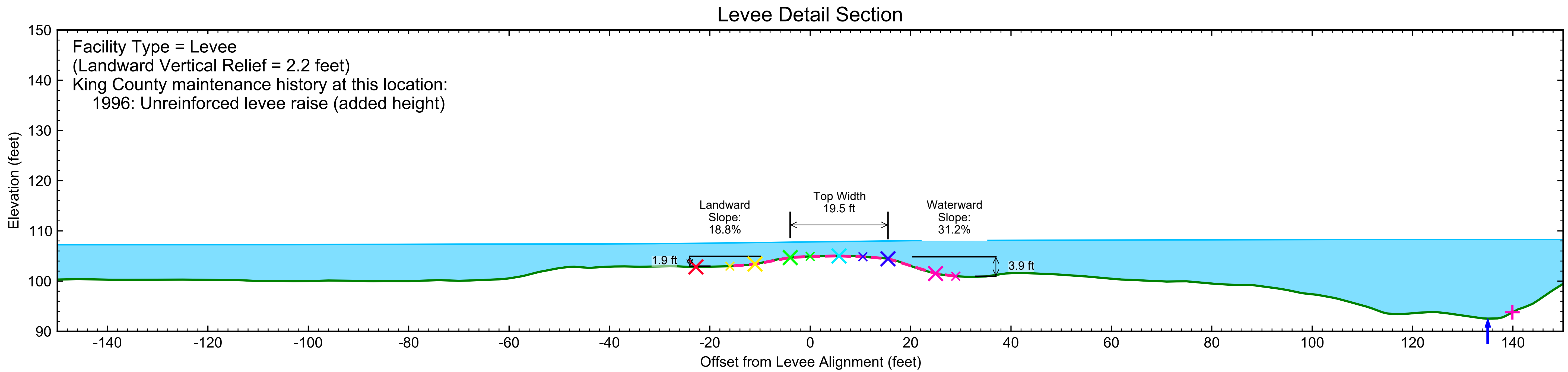
FIG. A-19





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL

Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
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LEFT BANK STA 10+00, RM 0.25

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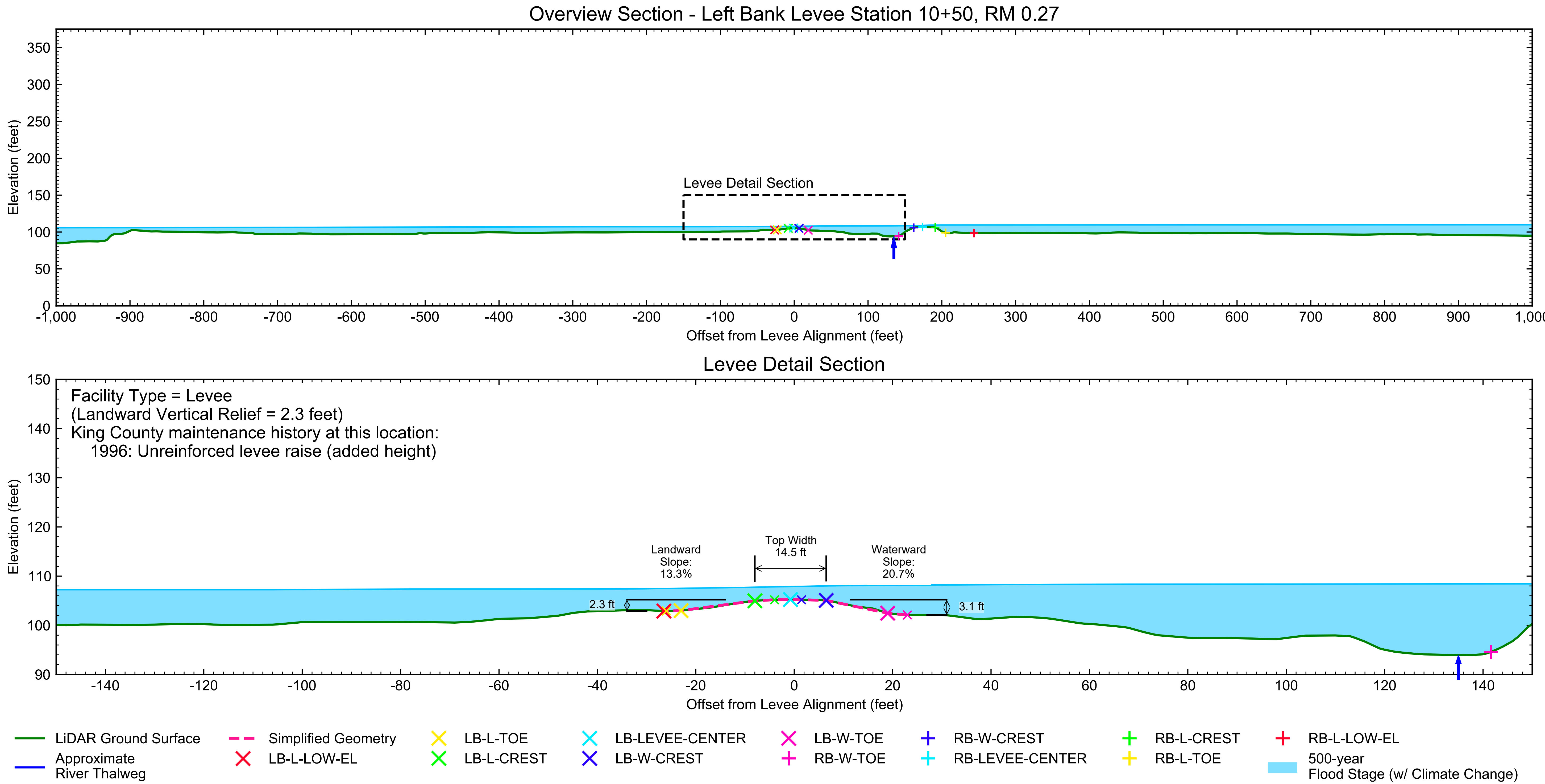
FIG. A-20



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 10+50, RM 0.27

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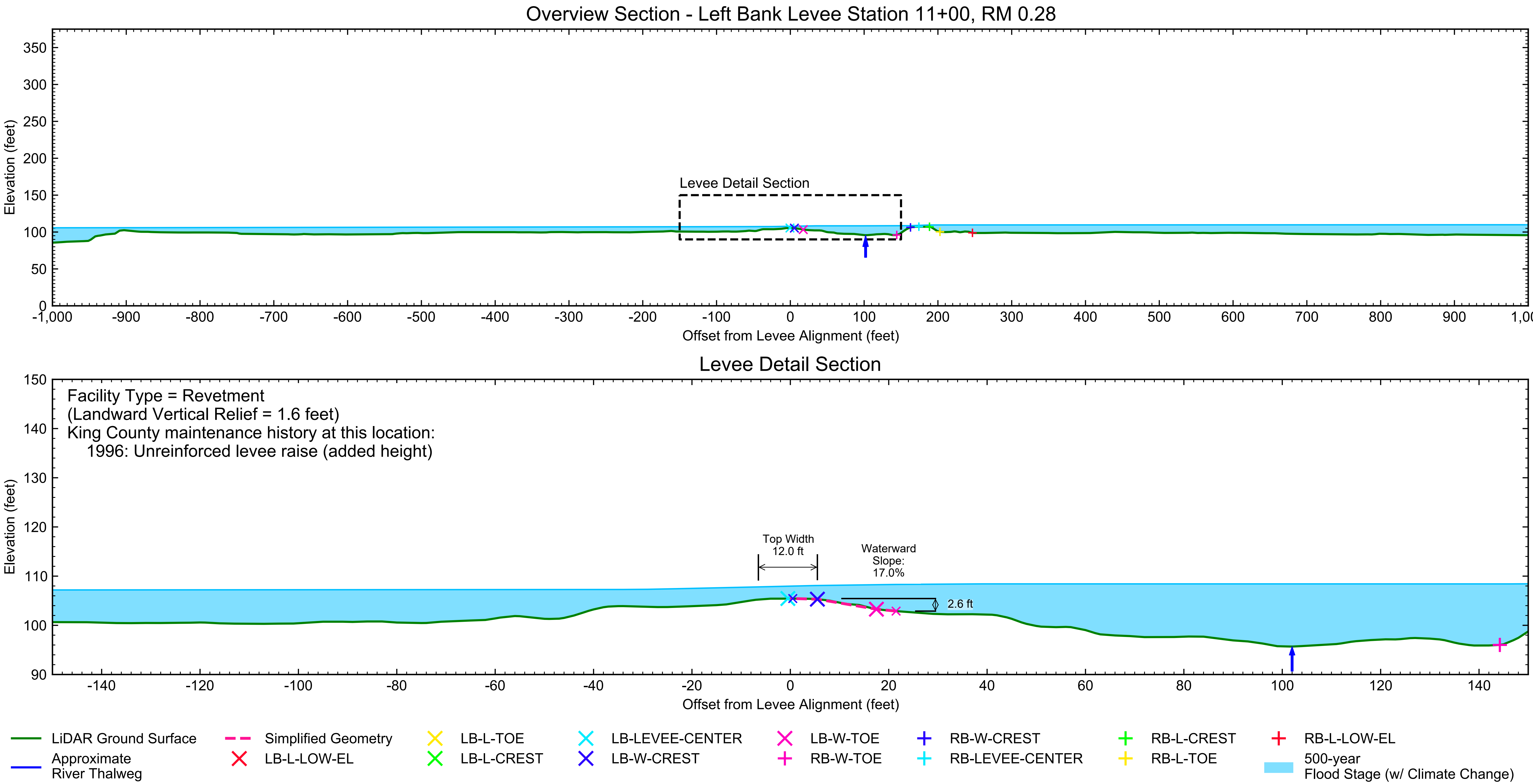
FIG. A-21



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 11+00, RM 0.28

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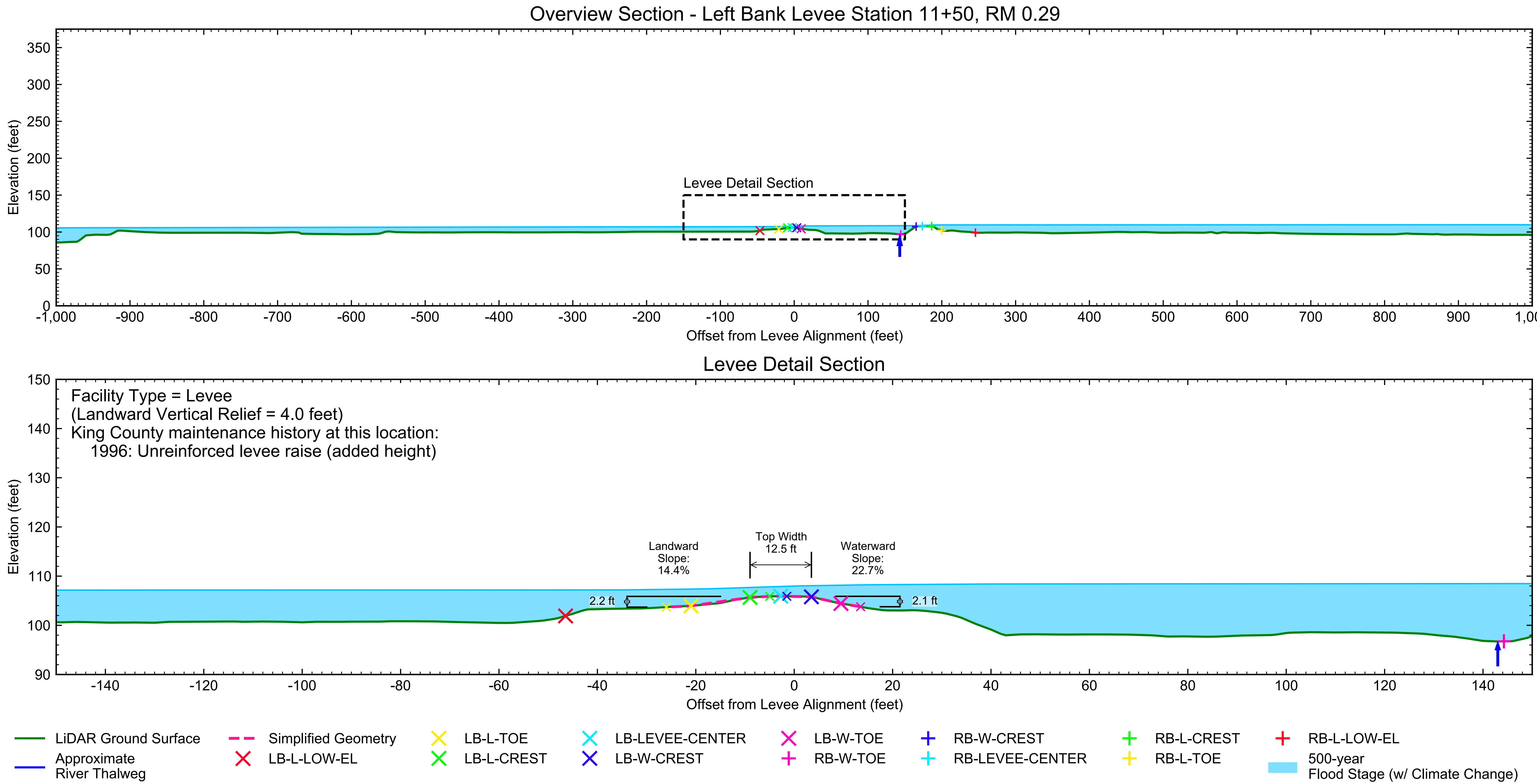
FIG. A-22



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 11+50, RM 0.29

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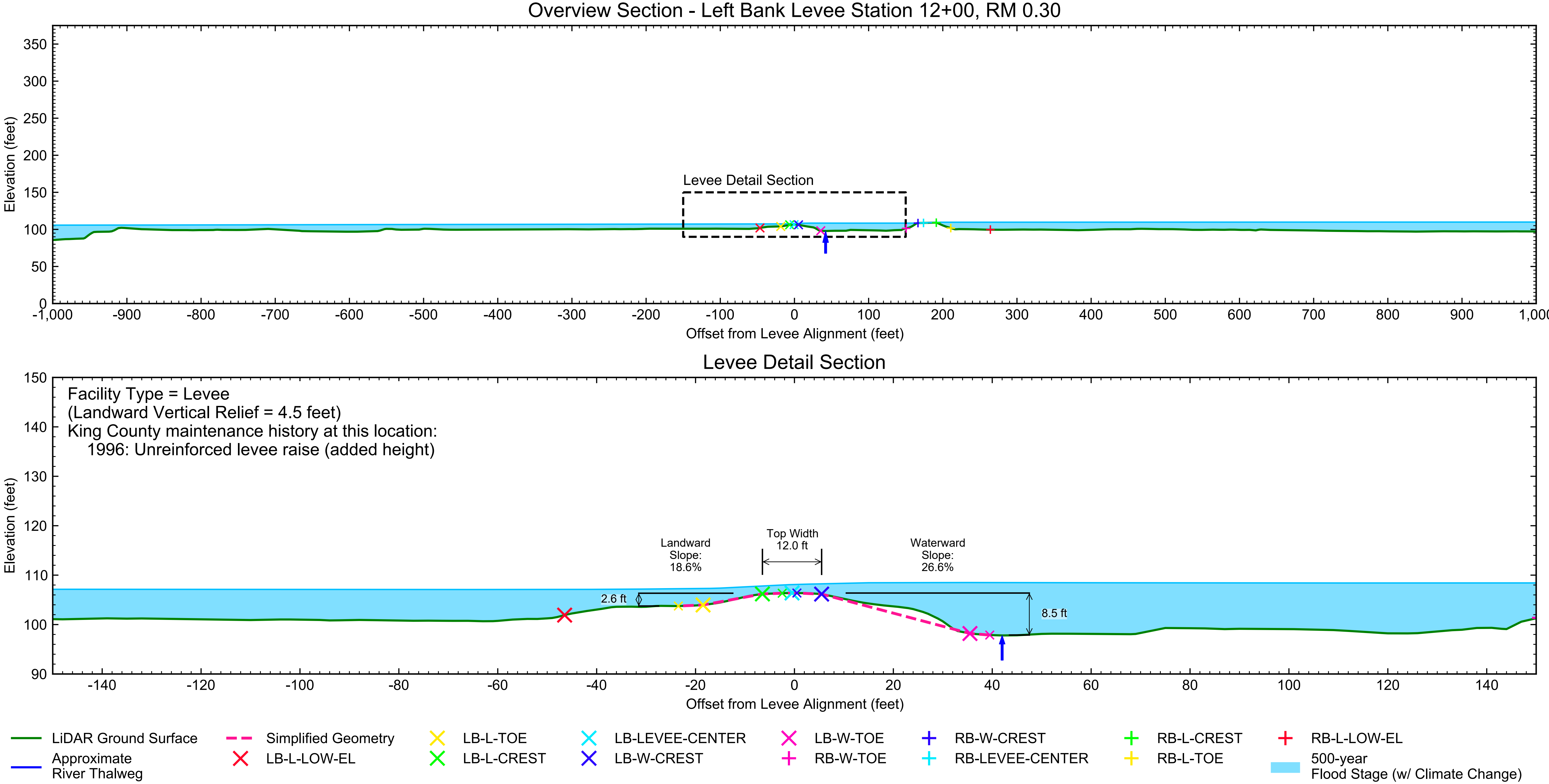
FIG. A-23



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 12+00, RM 0.30

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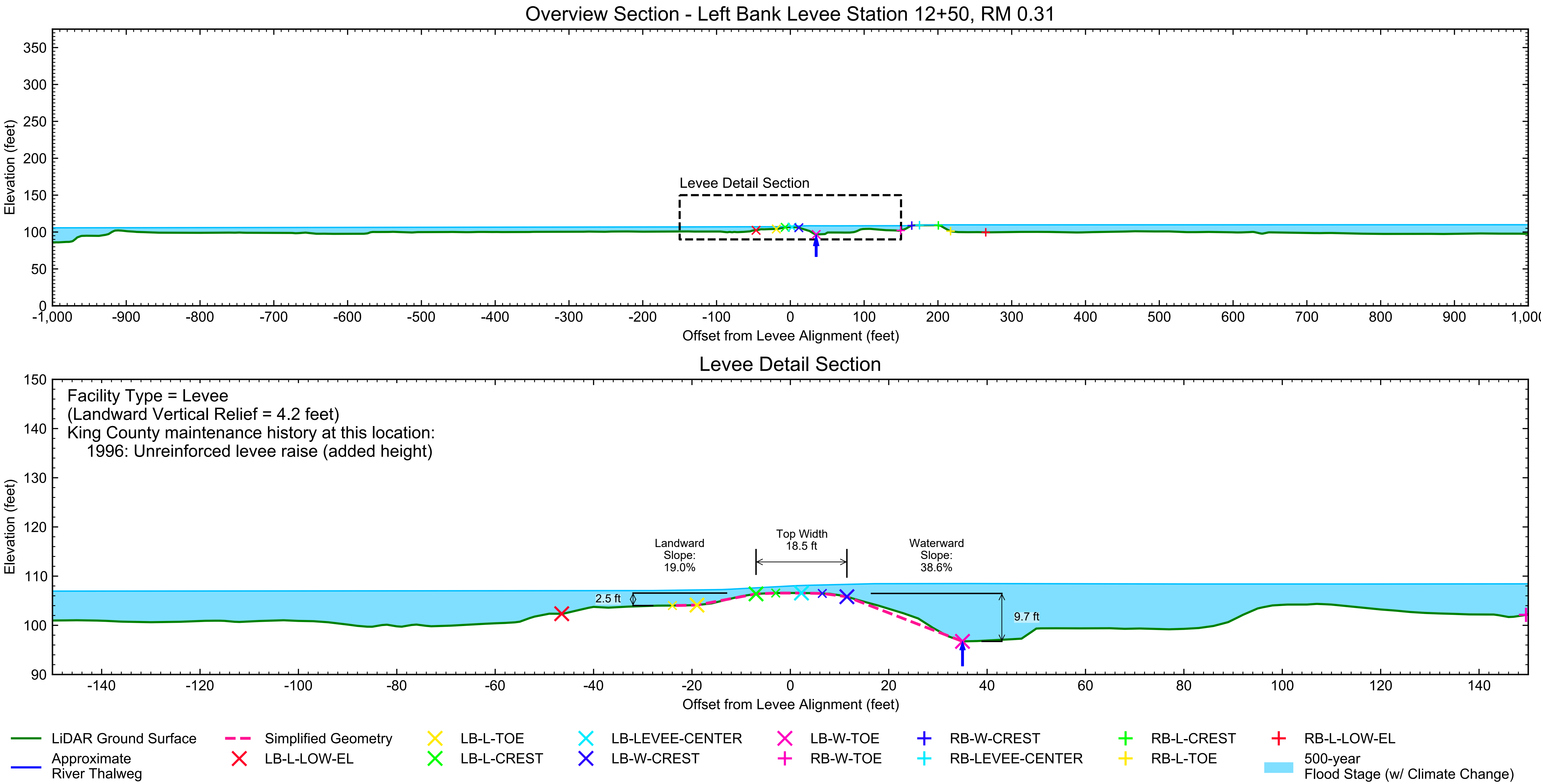
FIG. A-24



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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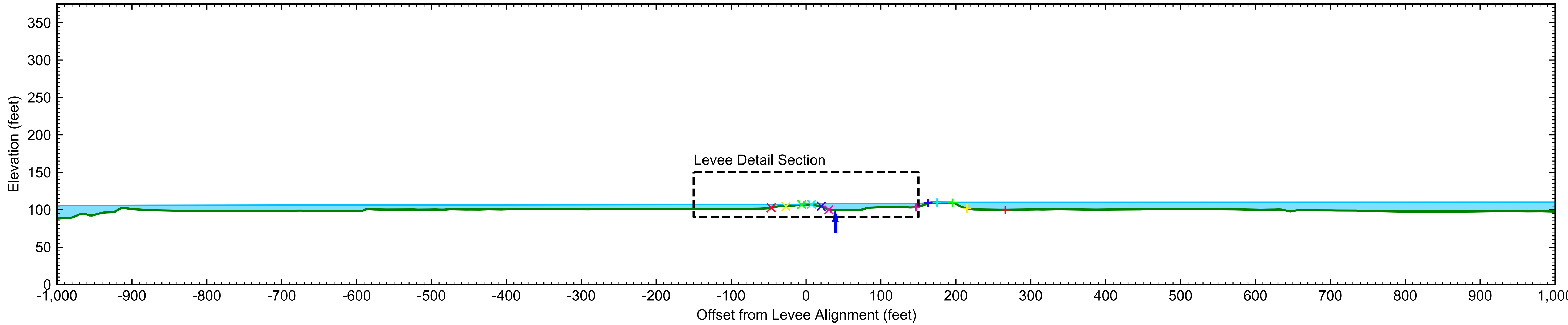
FIG. A-25

Overview Section - Left Bank Levee Station 13+00, RM 0.32



Levee Detail Section

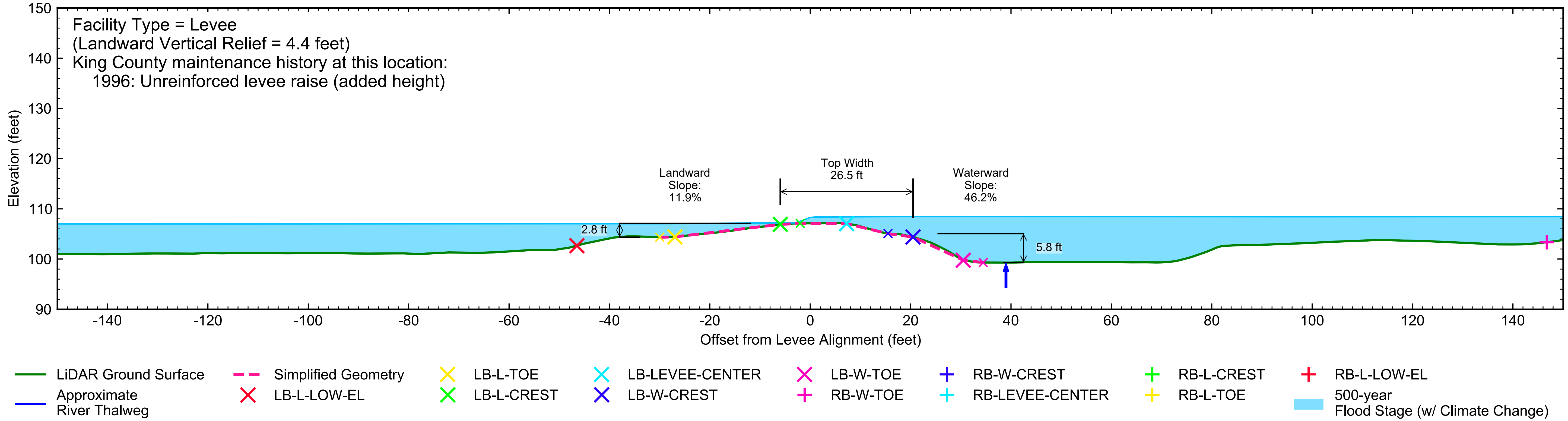


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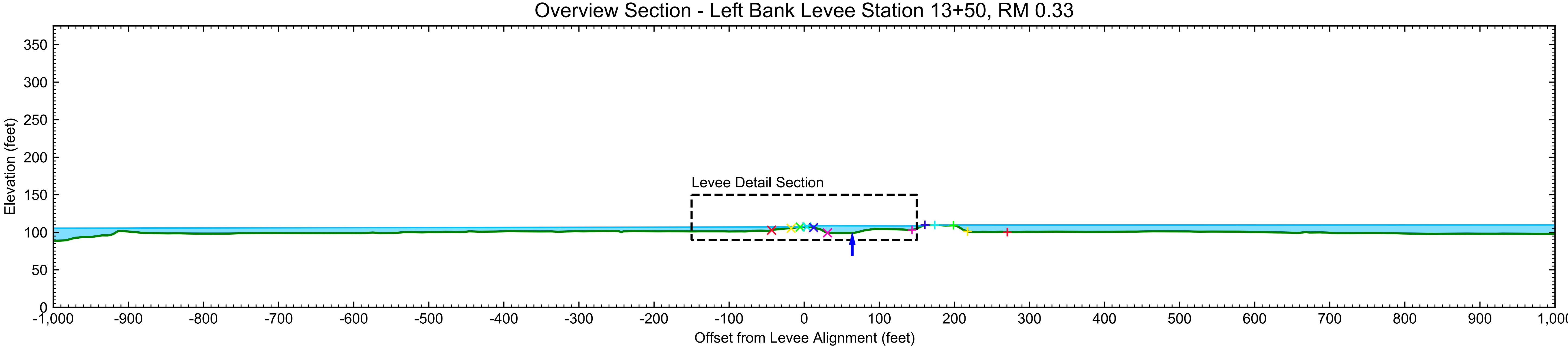
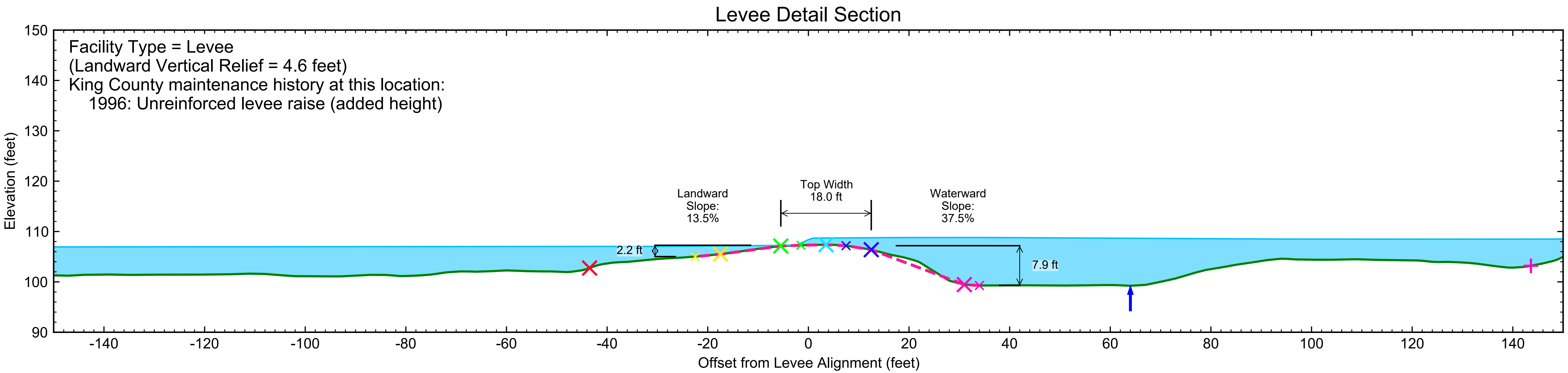
FIG. A-26





LiDAR Ground Surface
Approximate River Thalweg
Simplified Geometry
LB-L-LOW-EL
LB-L-TOE
LB-L-CREST
LB-LEVEE-CENTER
LB-W-CREST
LB-W-TOE
RB-W-TOE
RB-W-CREST
RB-LEVEE-CENTER
RB-L-CREST
RB-L-TOE
RB-L-LOW-EL
500-year Flood Stage (w/ Climate Change)

Notes:
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FIG. A-27

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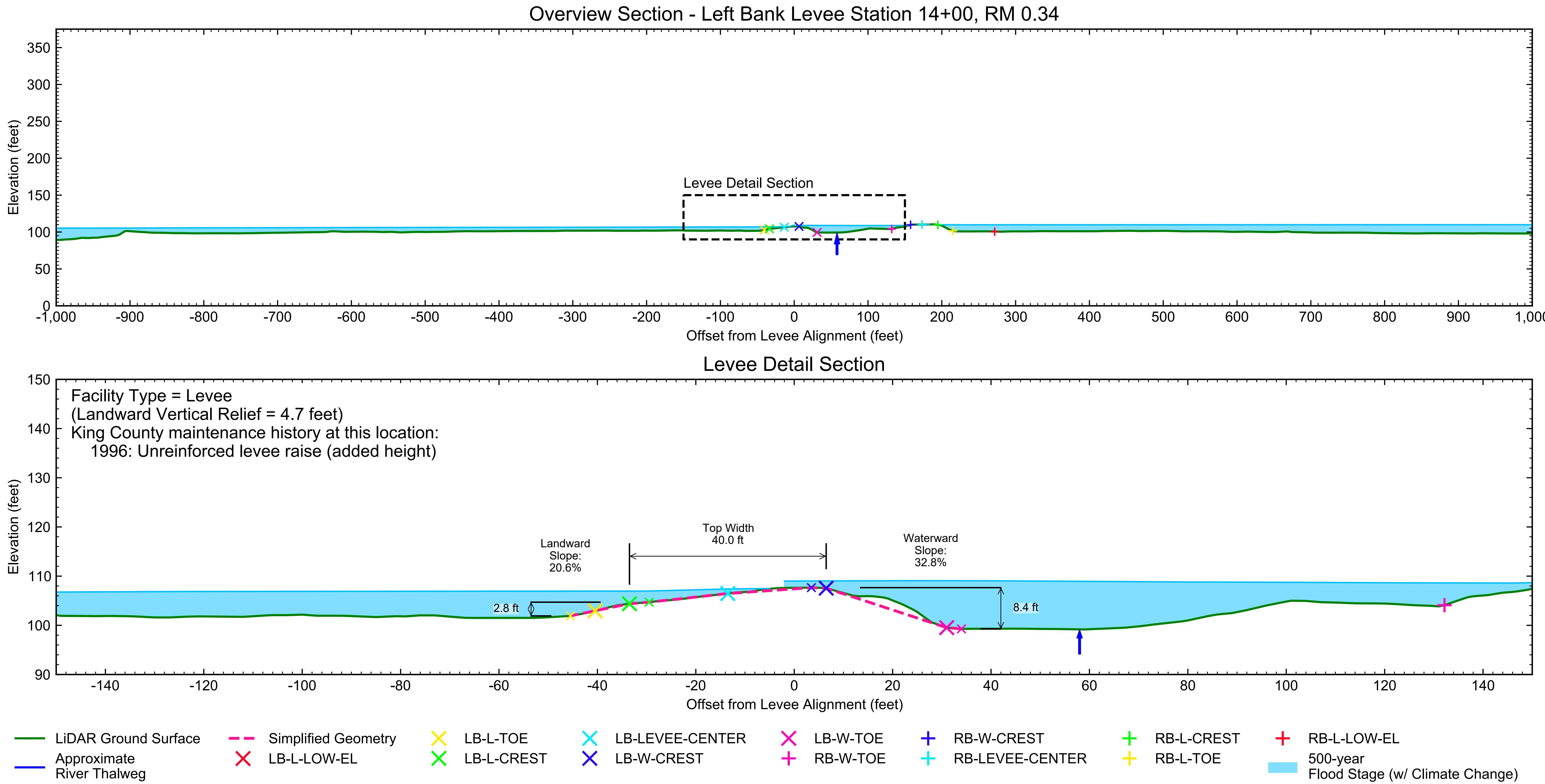

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FIG. A-28

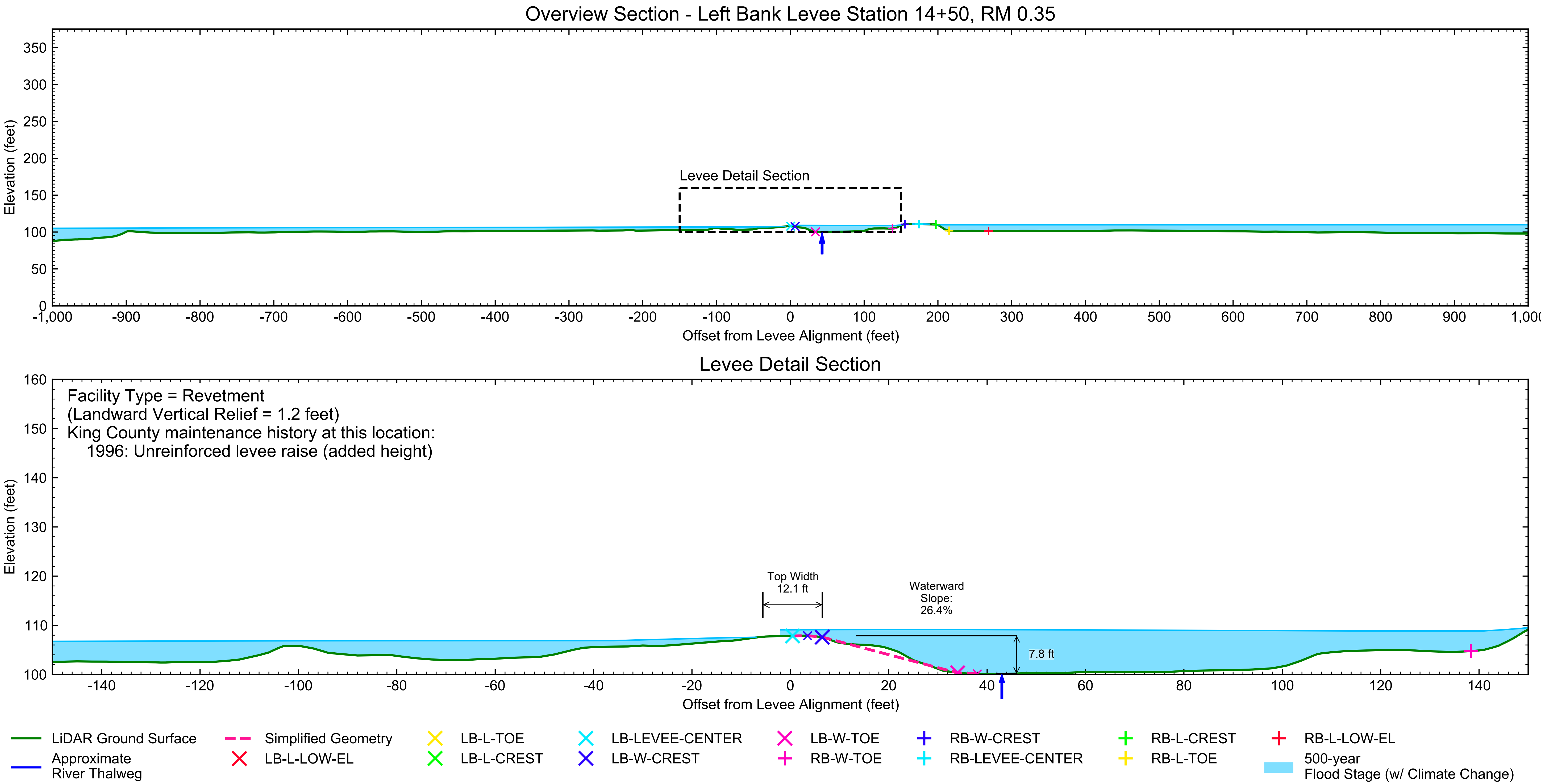

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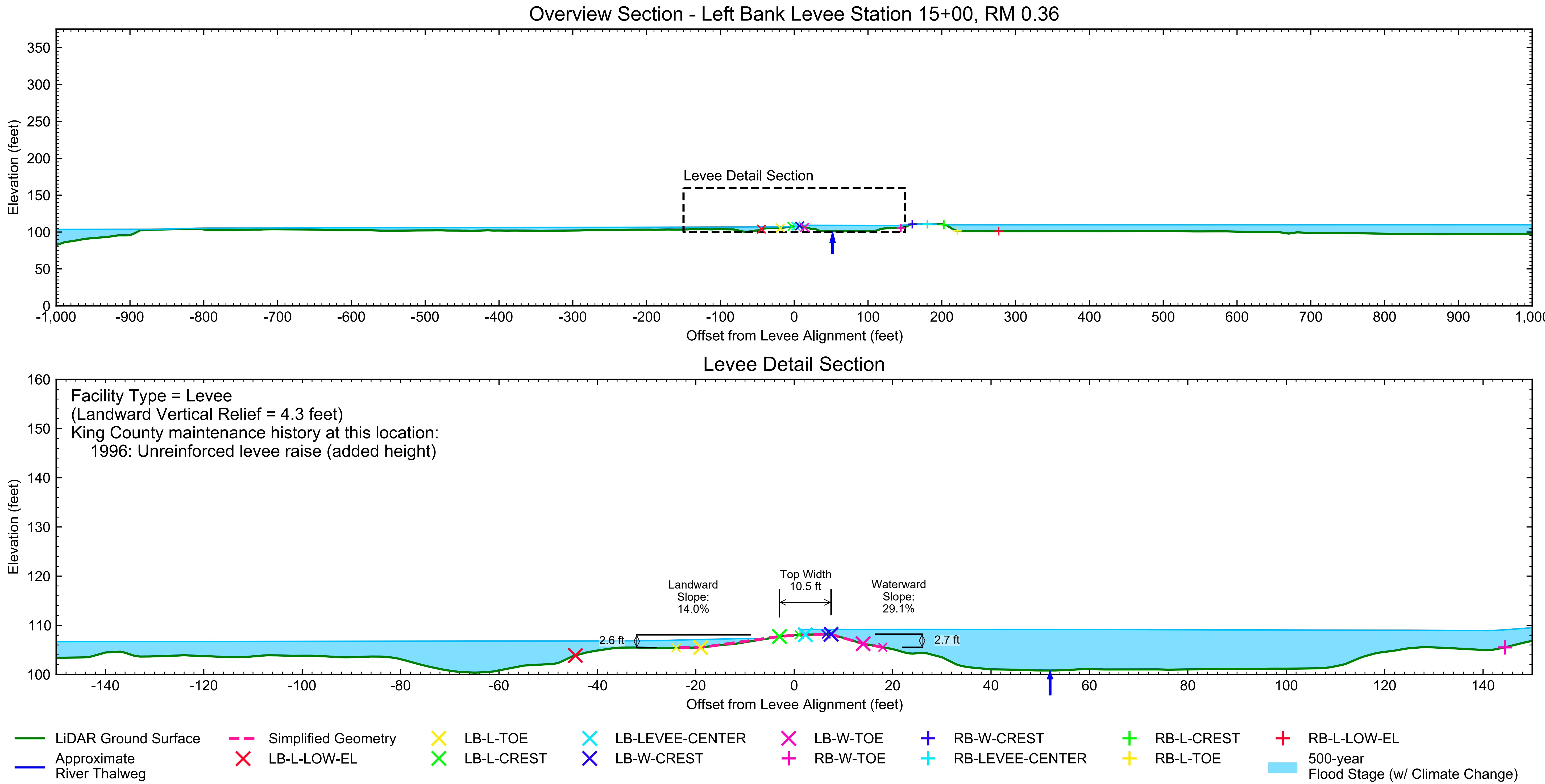
FIG. A-29



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 15+00, RM 0.36

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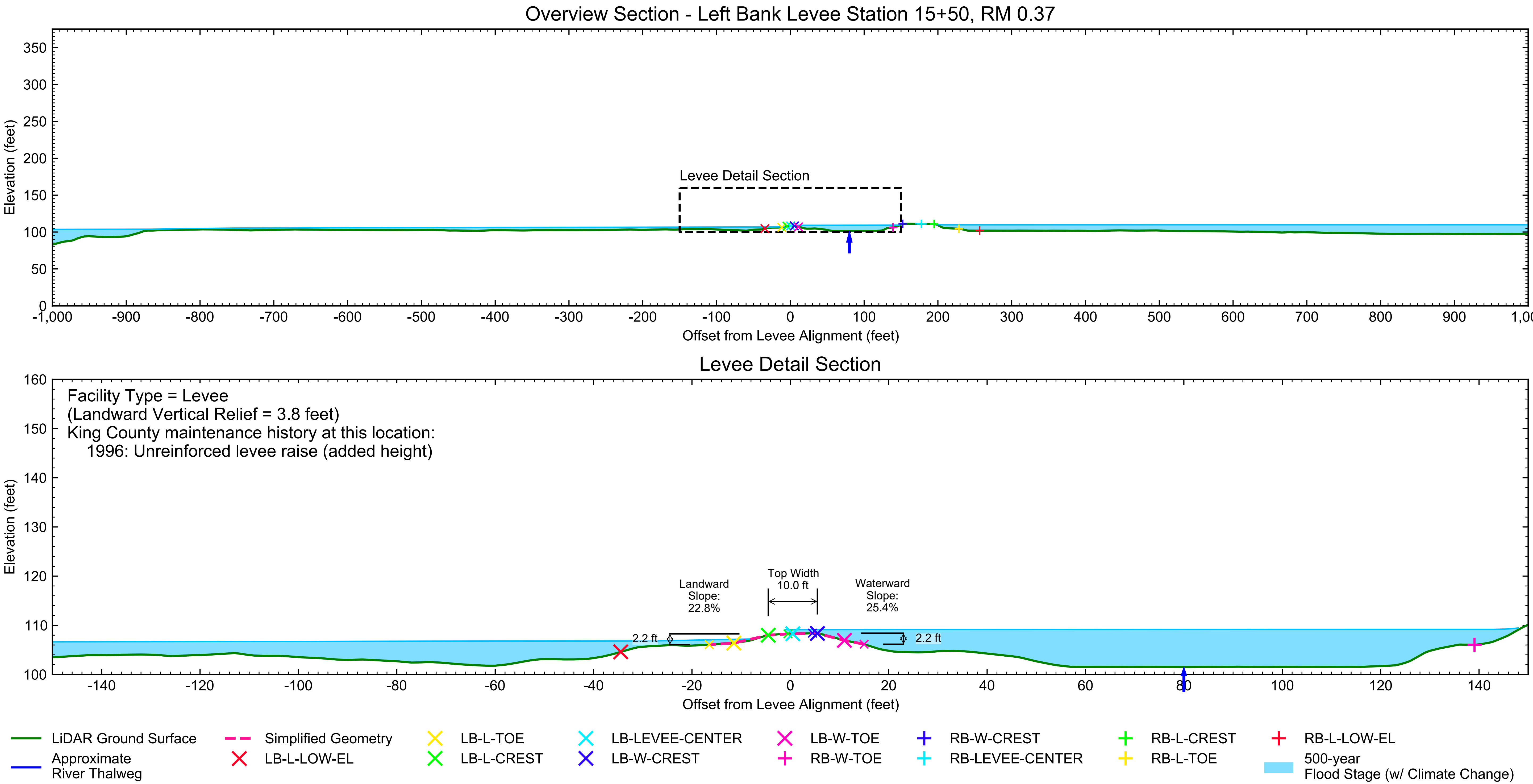
FIG. A-30



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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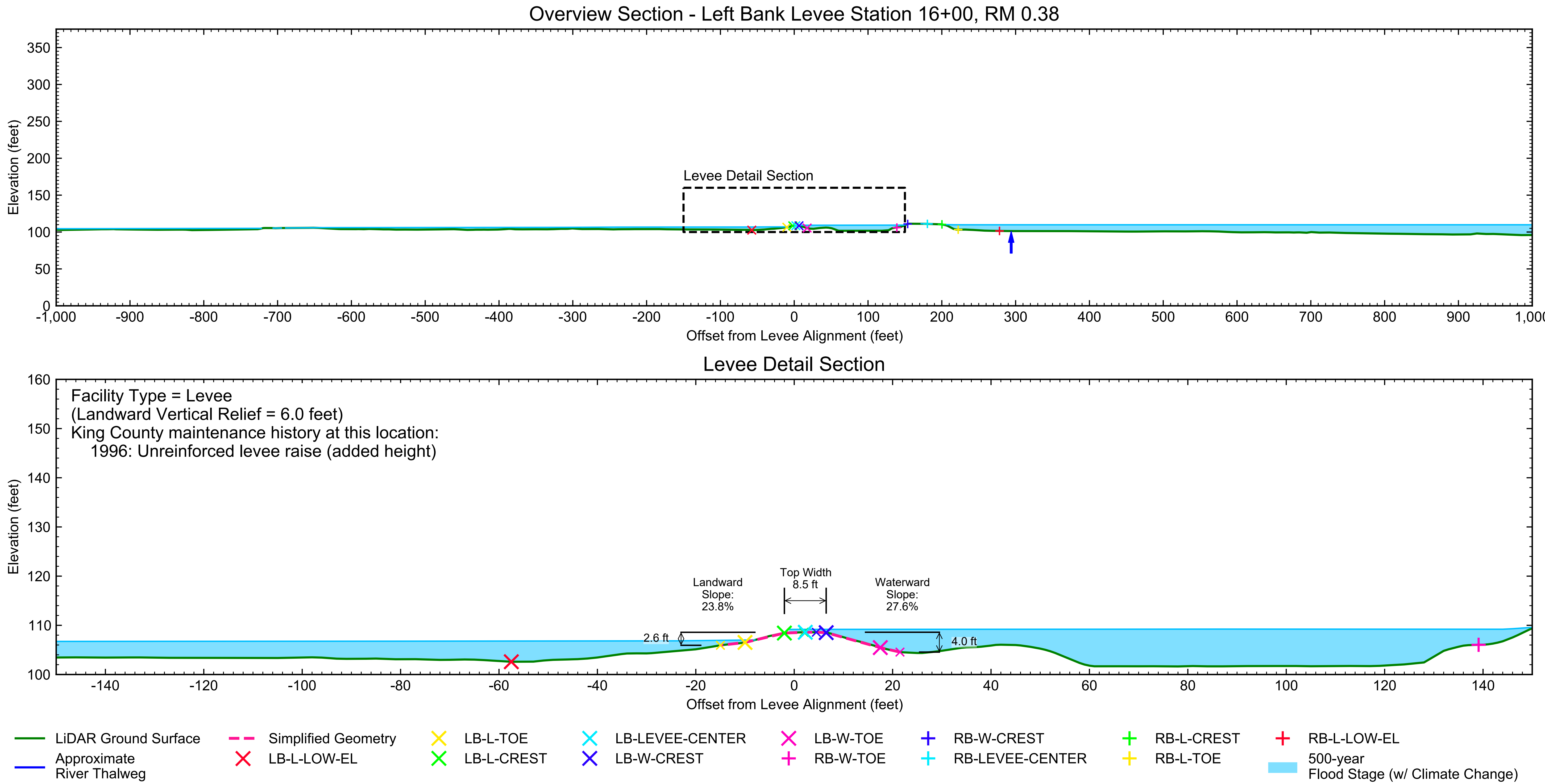
FIG. A-31



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 16+00, RM 0.38

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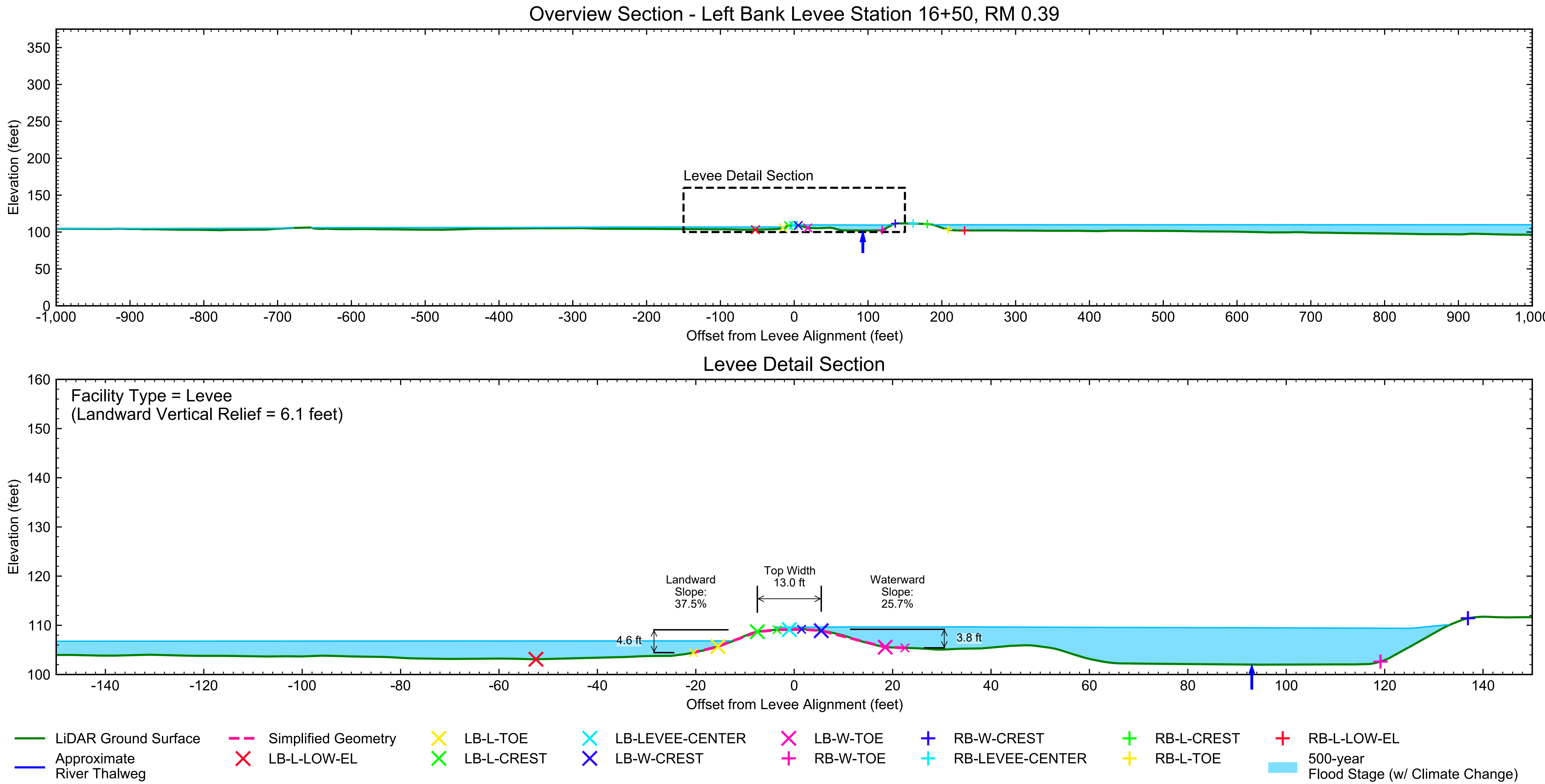
FIG. A-32



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 16+50, RM 0.39

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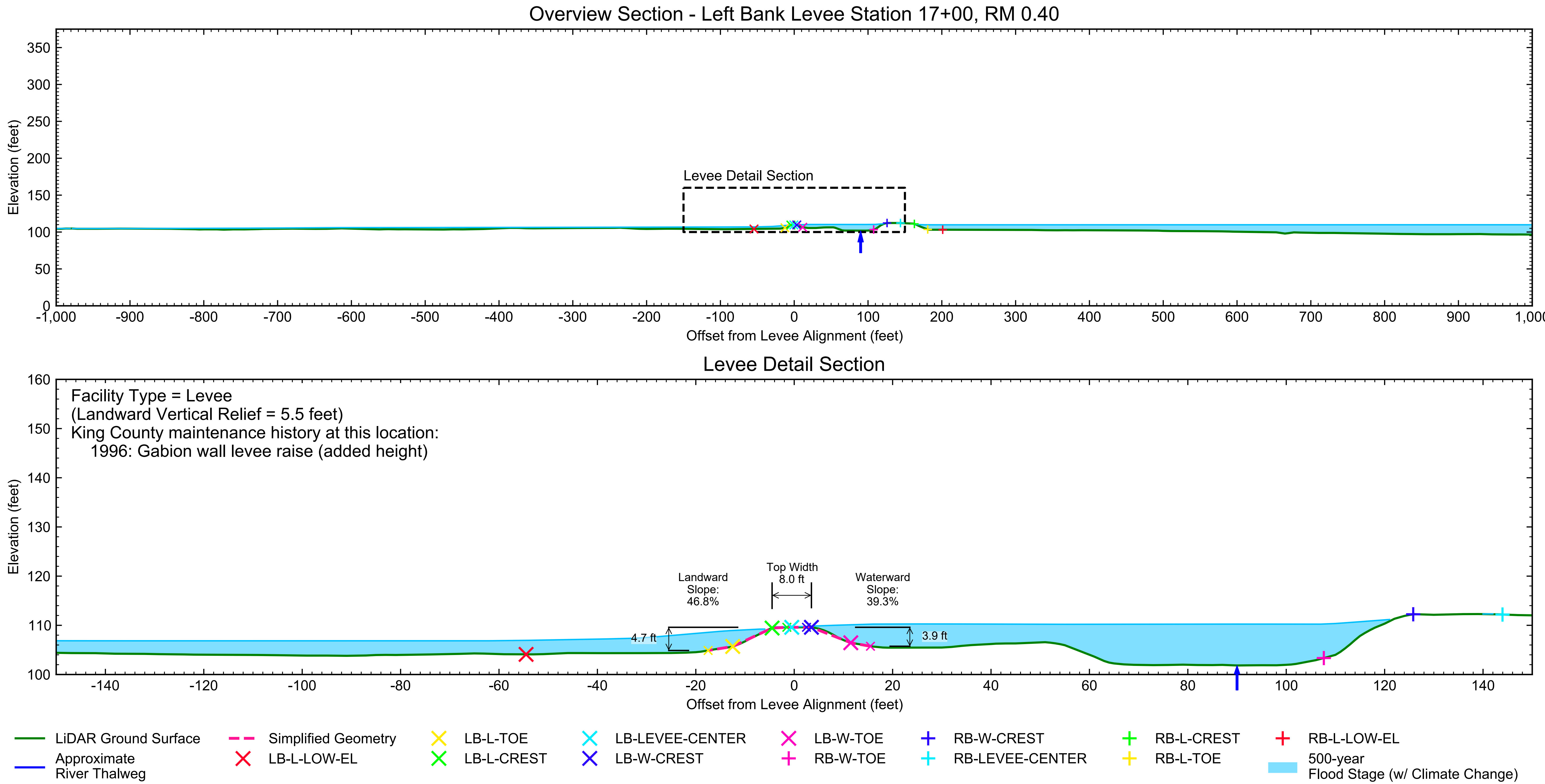
FIG. A-33



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 17+00, RM 0.40

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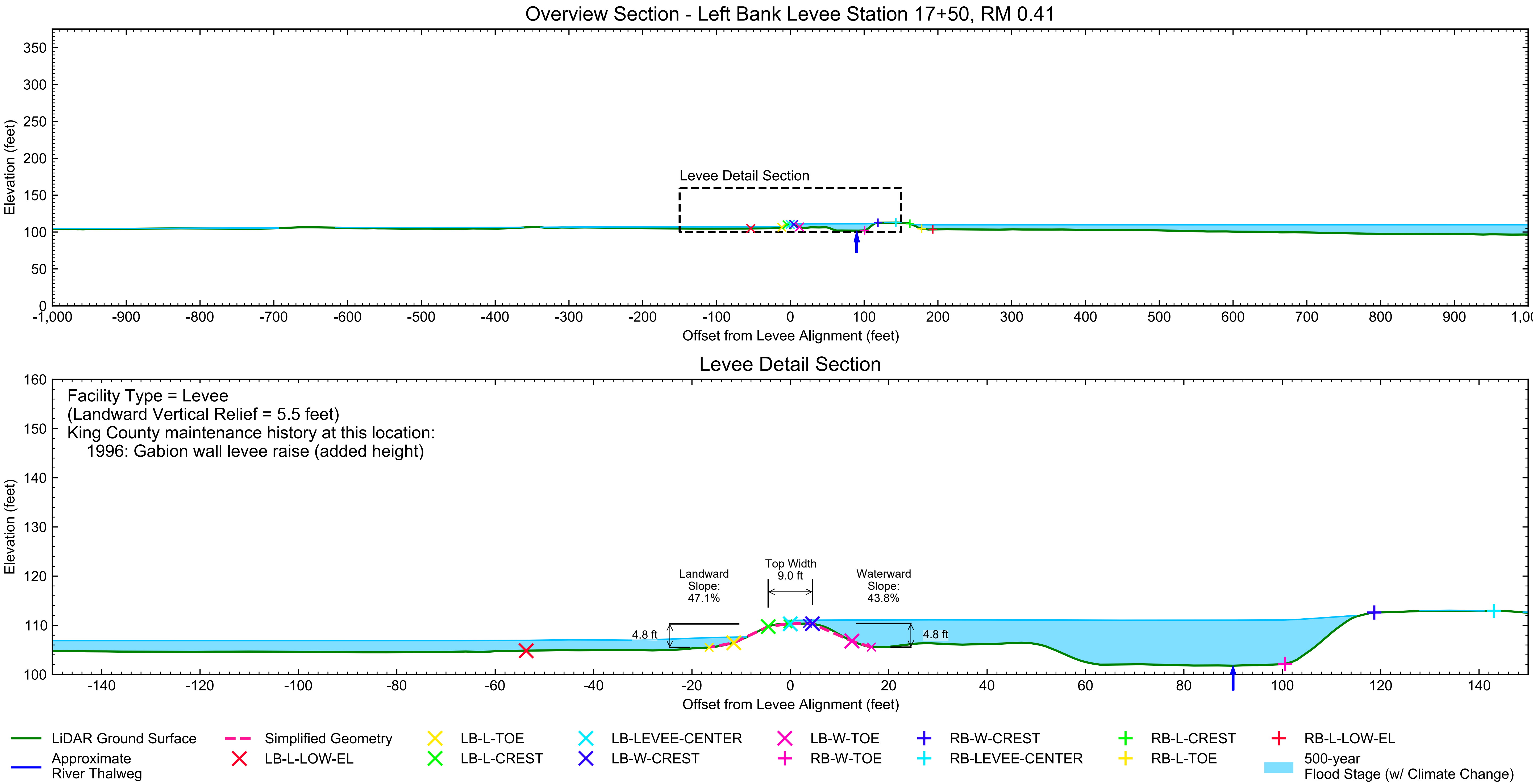
FIG. A-34



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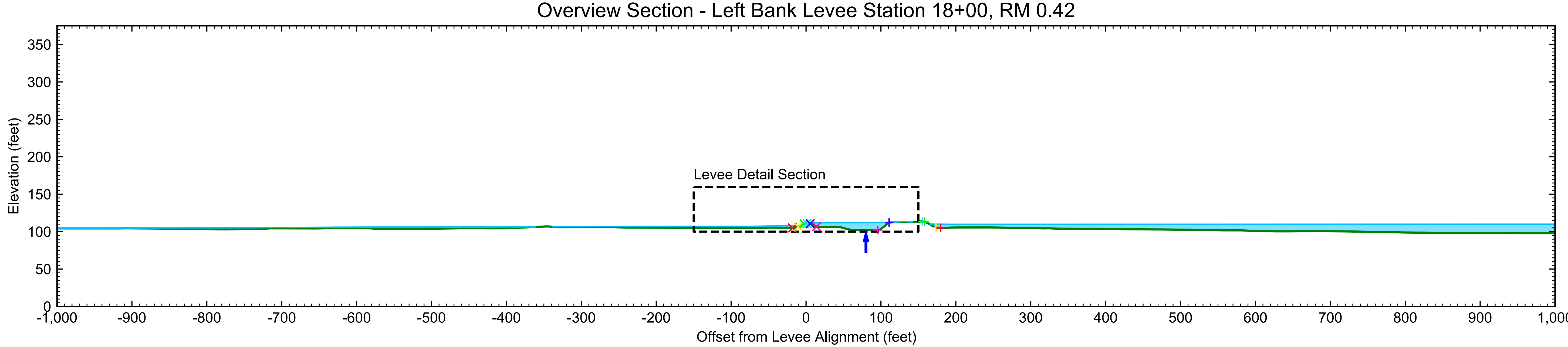
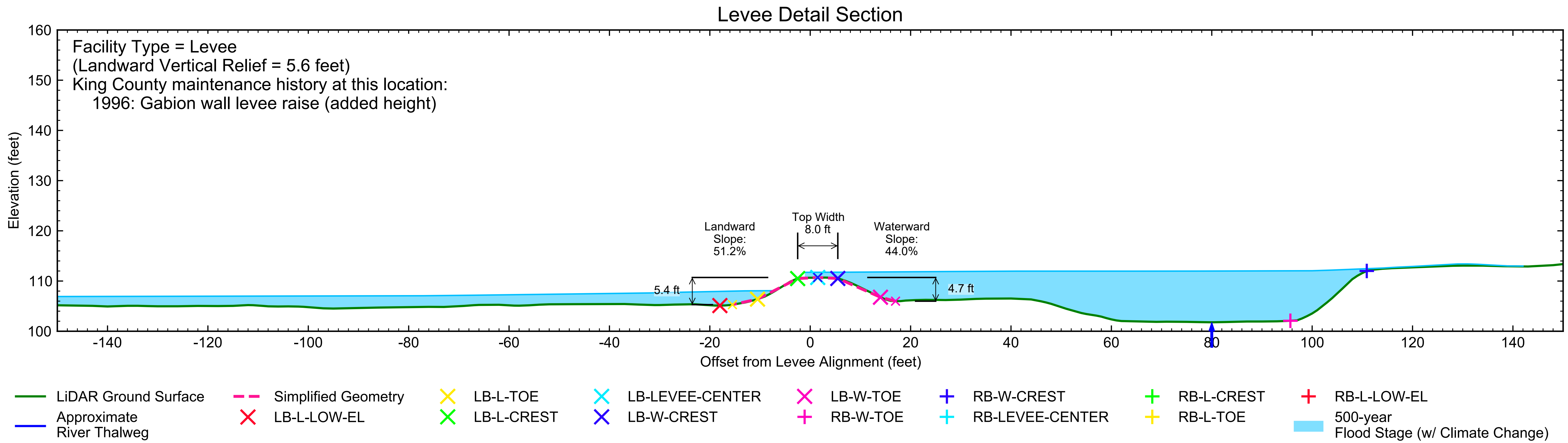
Levee Breach Analysis Mapping and Risk Assessment Segmentation and Stability Approach Report King County, Washington	
LIDAR CROSS SECTION LOWER RAGING RIVER LEFT BANK STA 17+50, RM 0.41	
April 2022	103692-304
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-35





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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 18+00, RM 0.42

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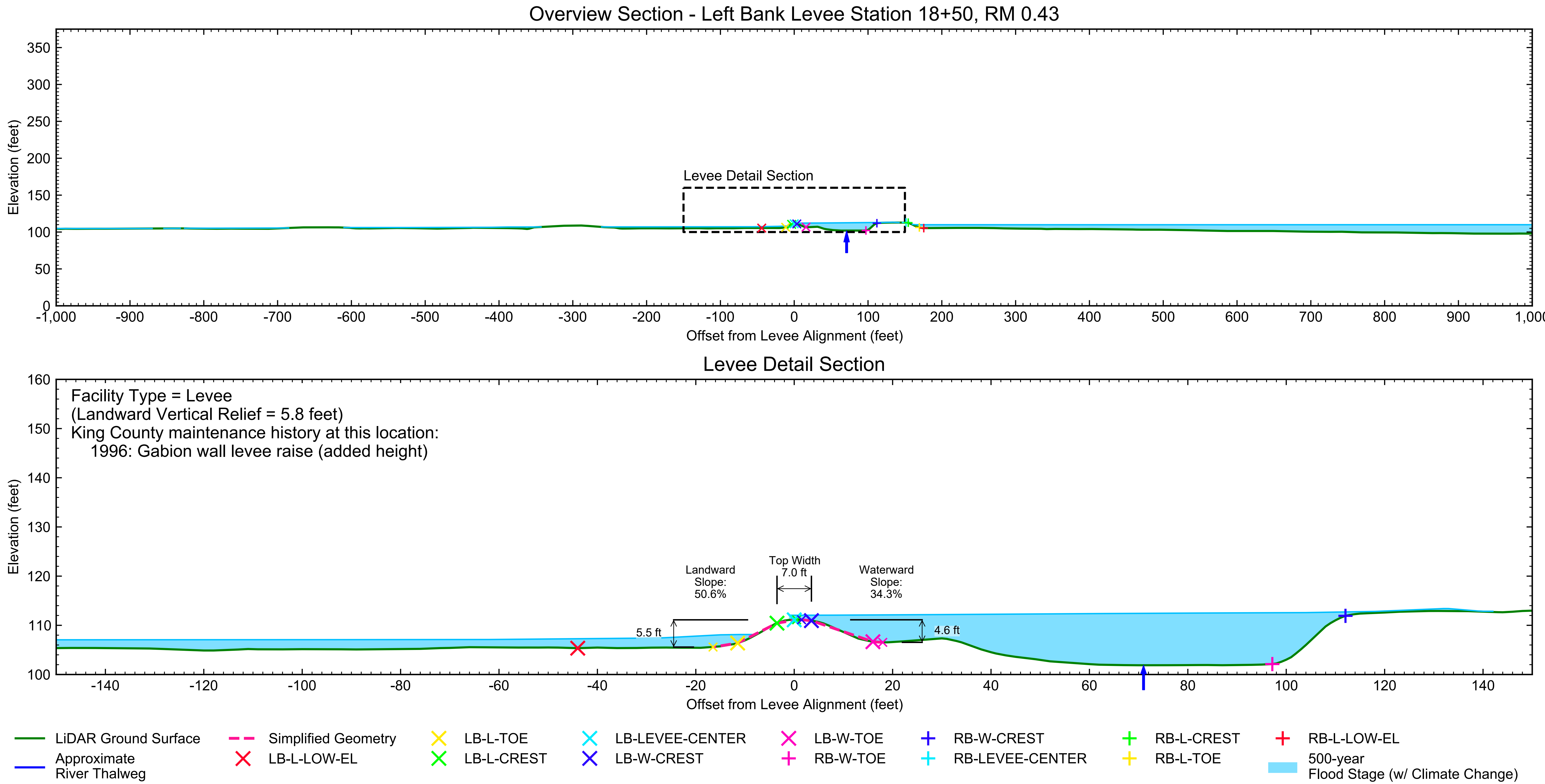
FIG. A-36



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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 18+50, RM 0.43

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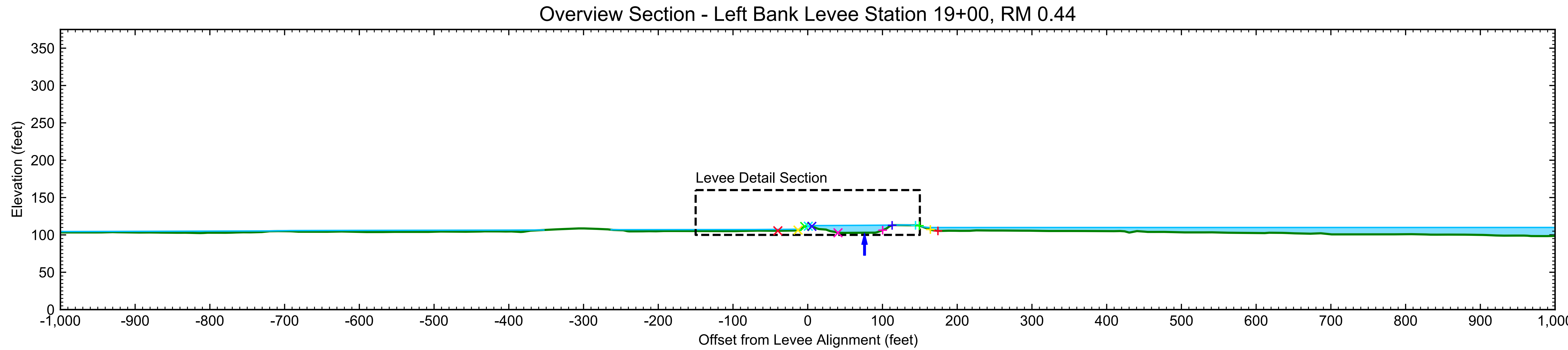
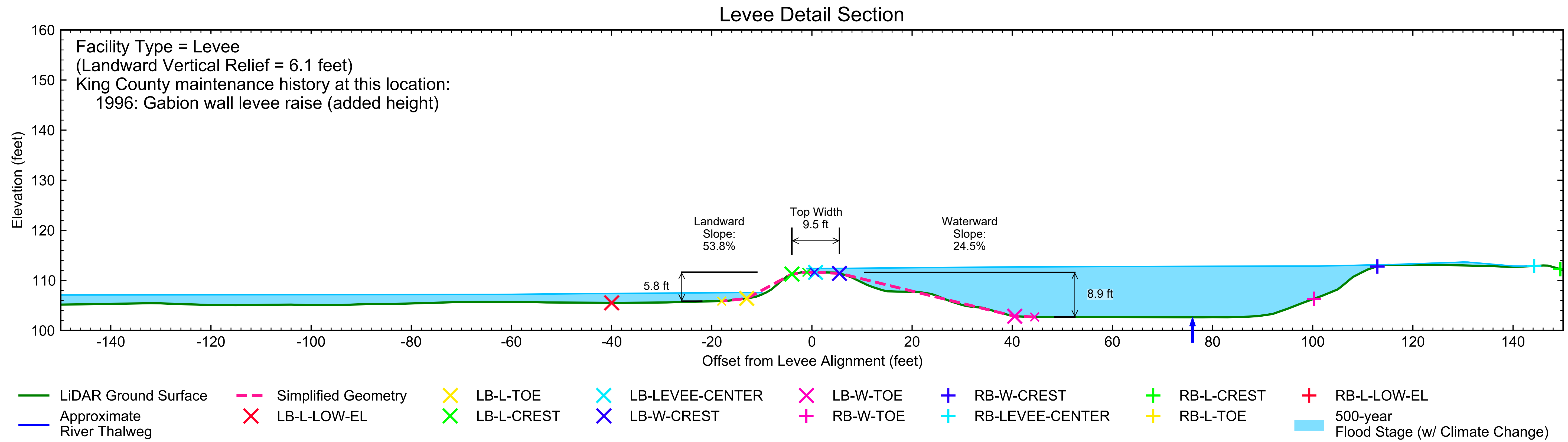
FIG. A-37





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 19+00, RM 0.44

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FIG. A-38

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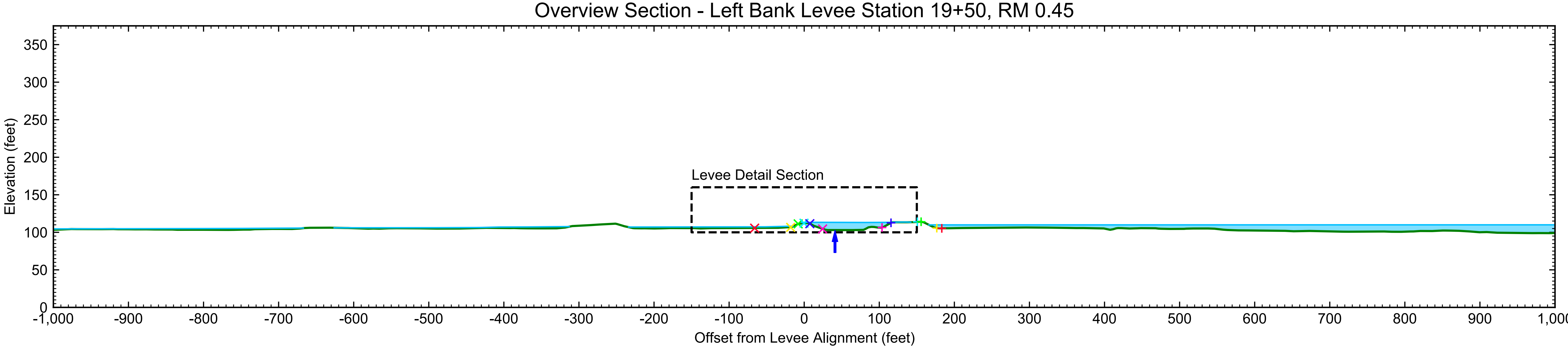
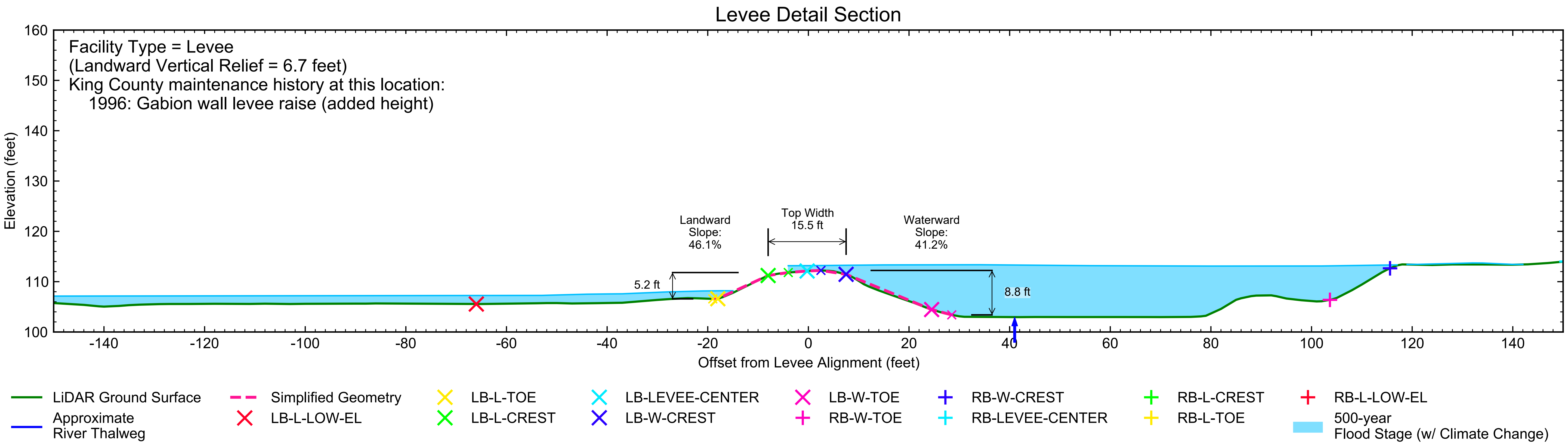
\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 19+50, RM 0.45

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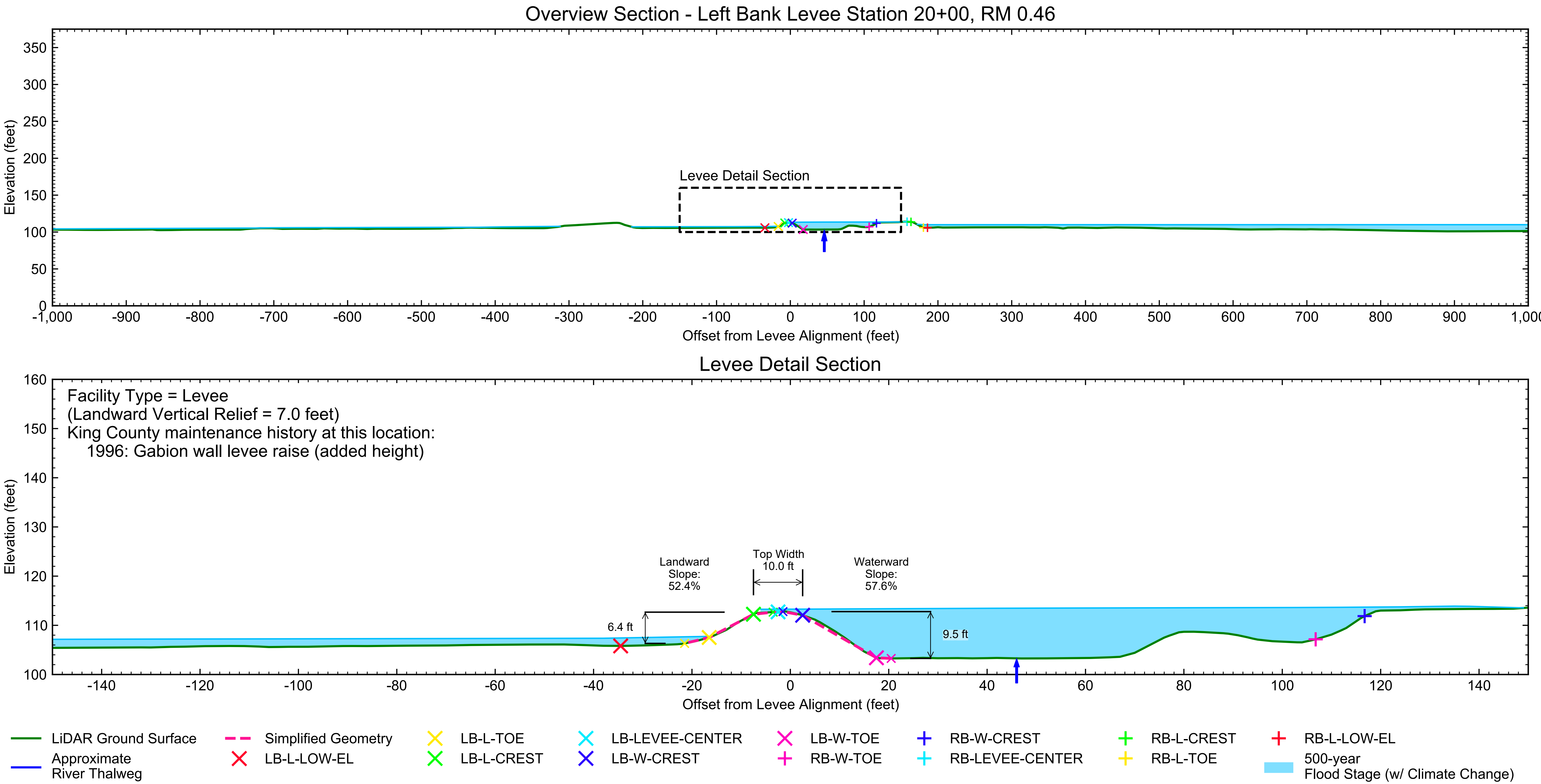
FIG. A-39



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LIDAR CROSS SECTION
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LEFT BANK STA 20+00, RM 0.46

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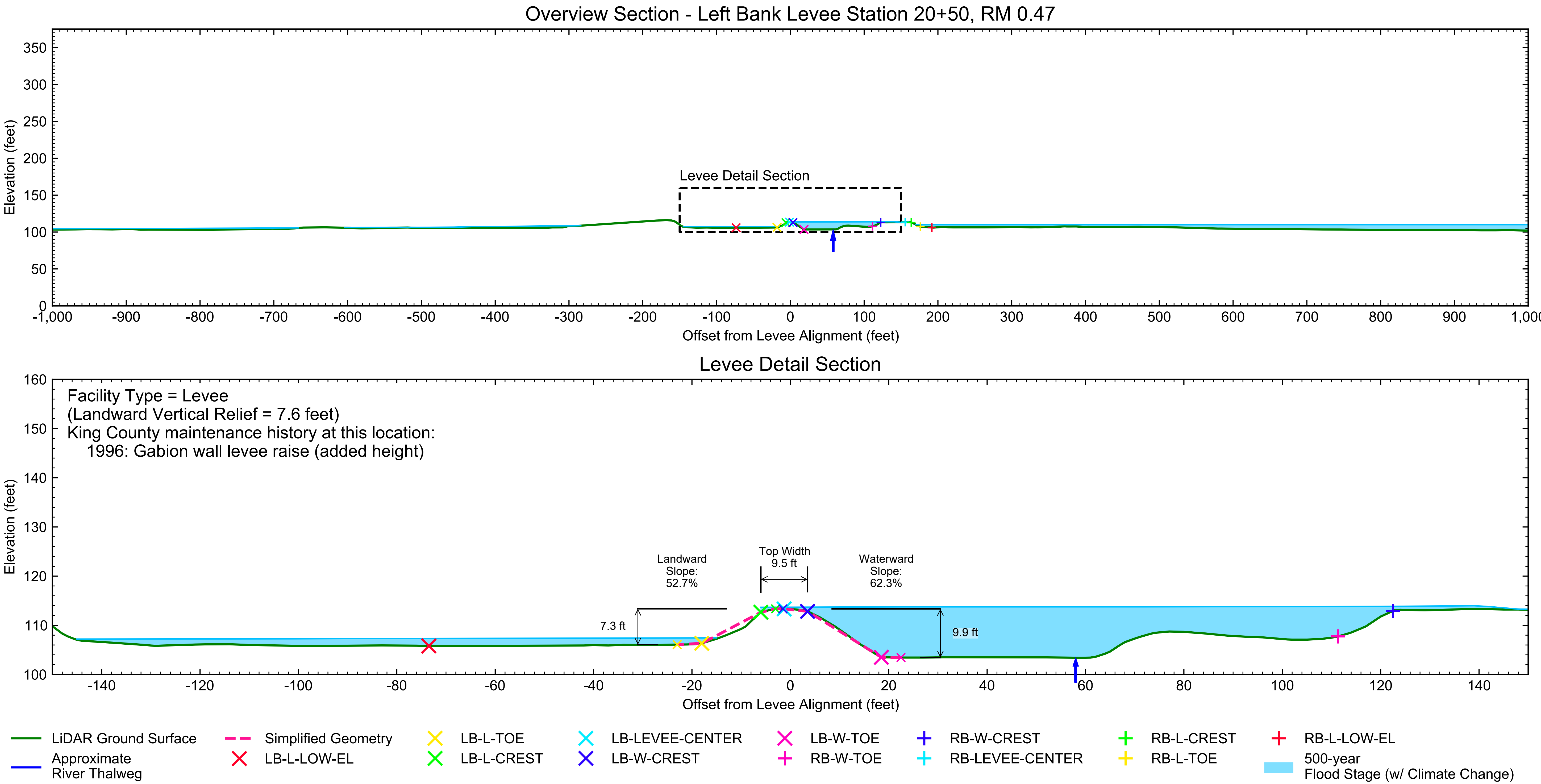
FIG. A-40



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 20+50, RM 0.47

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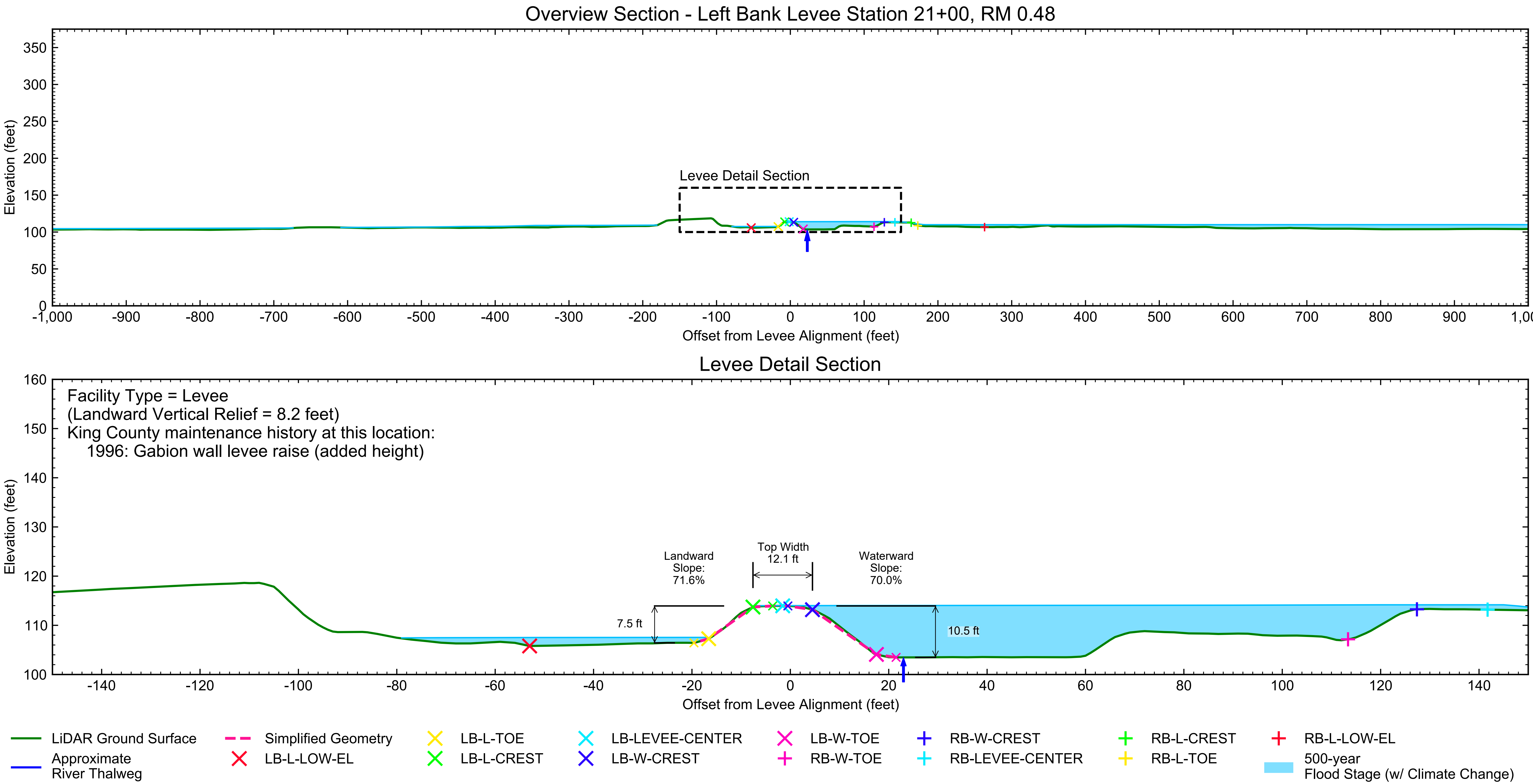
Geotechnical and Environmental Consultants

FIG. A-41



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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 21+00, RM 0.48

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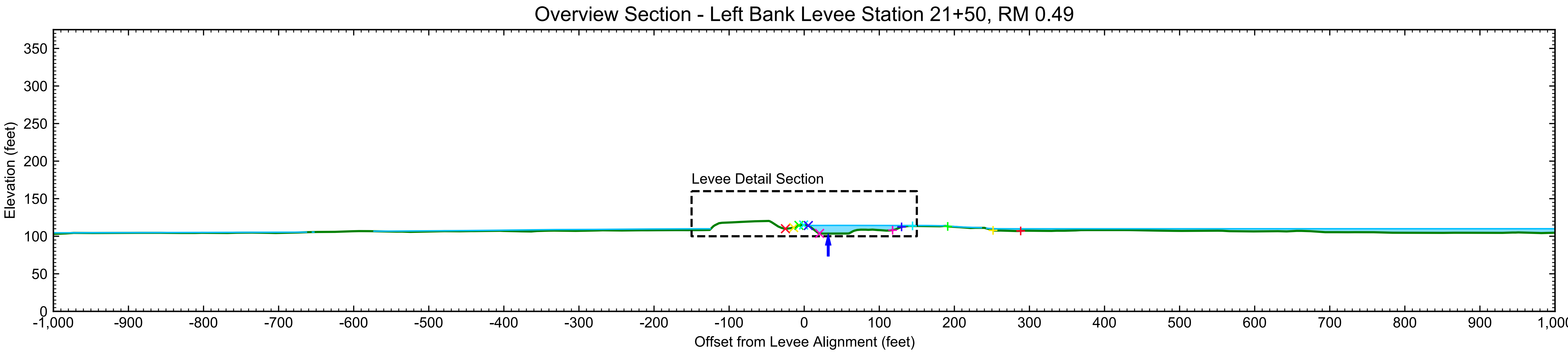
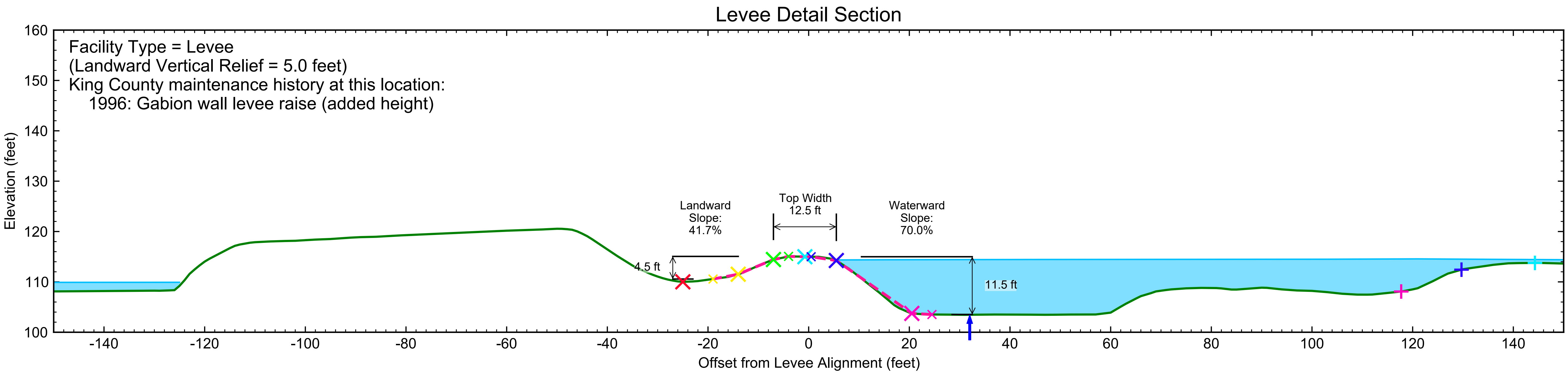
FIG. A-42





LiDAR Ground Surface
Approximate River Thalweg
Simplified Geometry
LB-L-LOW-EL
LB-L-TOE
LB-L-CREST
LB-LEVEE-CENTER
LB-W-CREST
LB-W-TOE
RB-W-TOE
RB-W-CREST
RB-LEVEE-CENTER
RB-L-CREST
RB-L-TOE
RB-L-LOW-EL
500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
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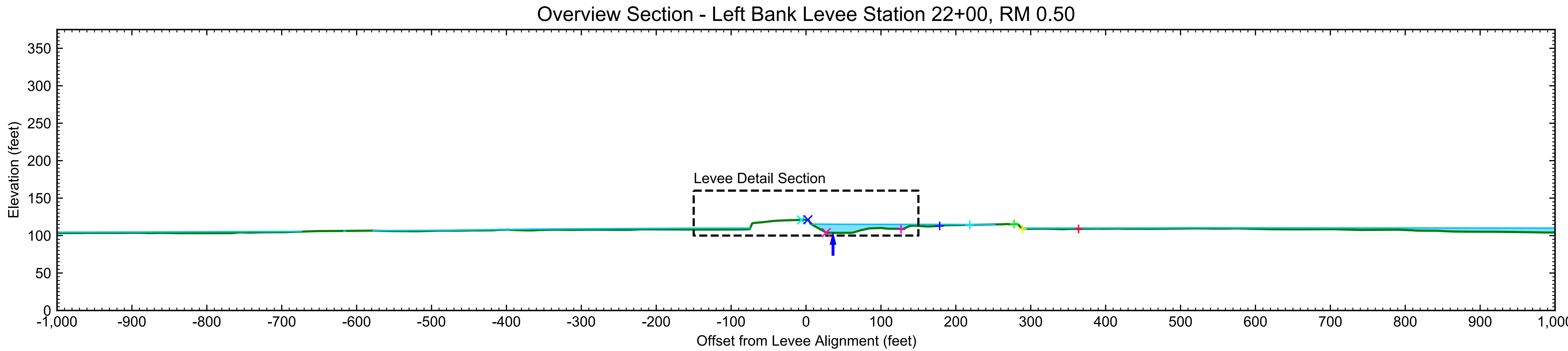
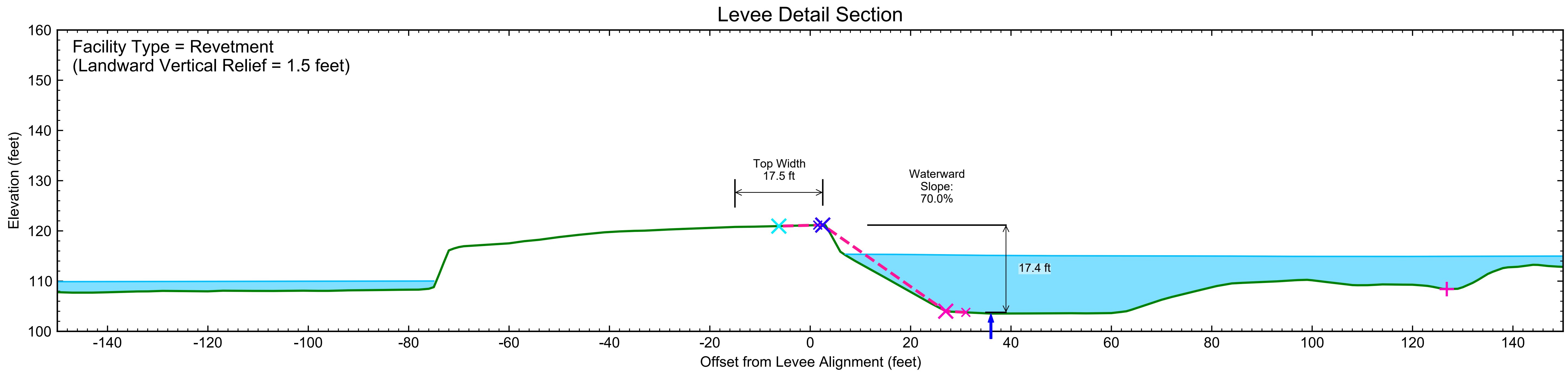
FIG. A-43





LiDAR Ground Surface | Approximate River Thalweg | Simplified Geometry | LB-L-LOW-EL | LB-L-TOE | LB-L-CREST | LB-LEVEE-CENTER | LB-W-CREST | LB-W-TOE | RB-W-TOE | RB-W-CREST | RB-LEVEE-CENTER | RB-L-CREST | RB-L-TOE | RB-L-LOW-EL | 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
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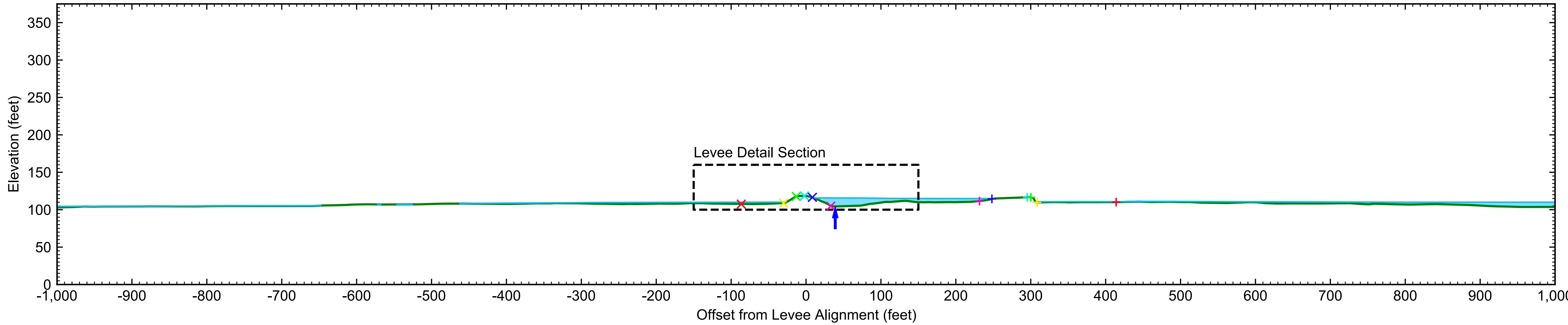
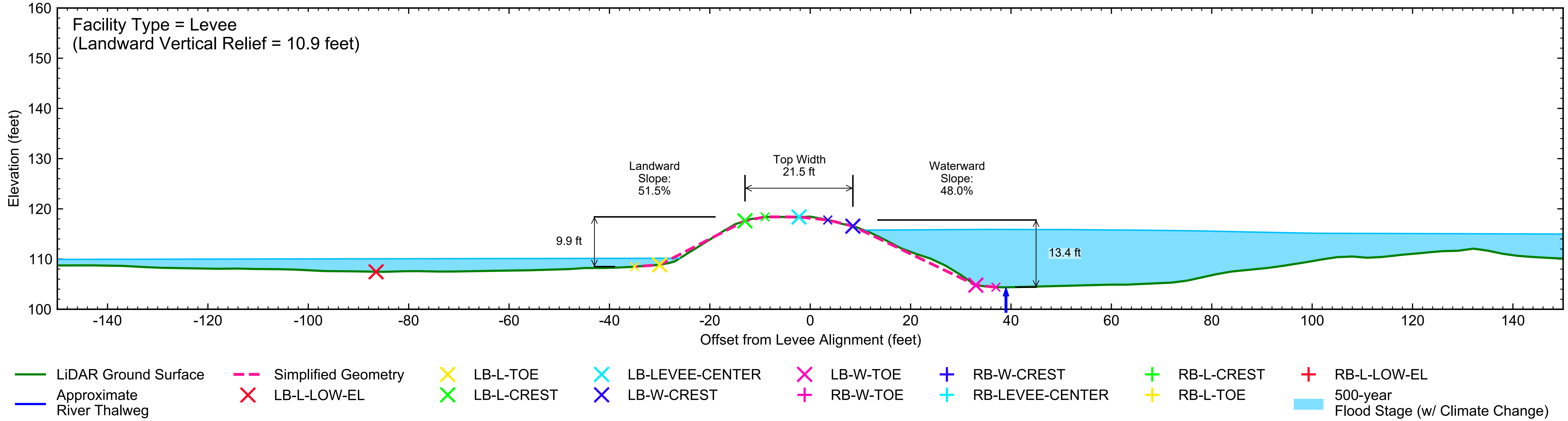
FIG. A-44

Overview Section - Left Bank Levee Station 22+50, RM 0.51



Levee Detail Section



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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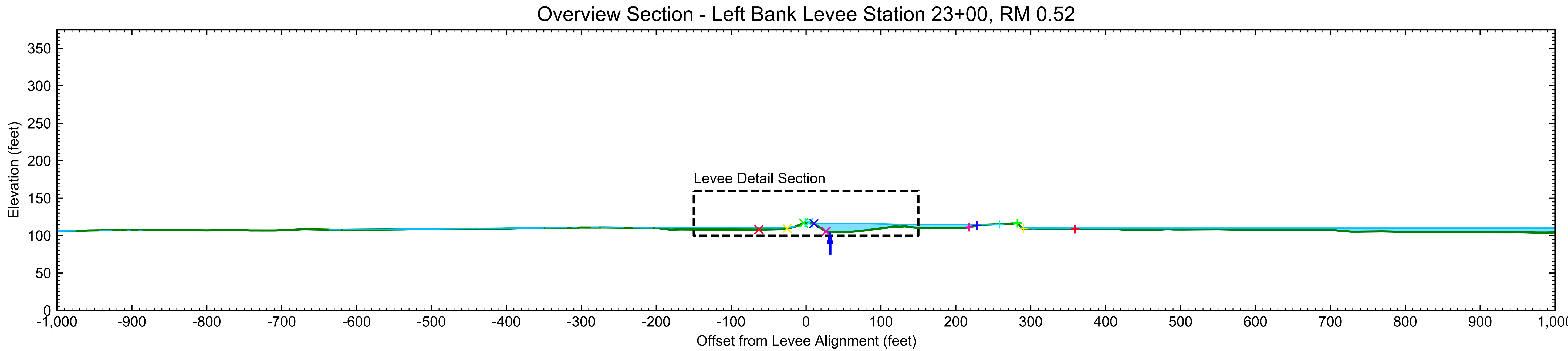
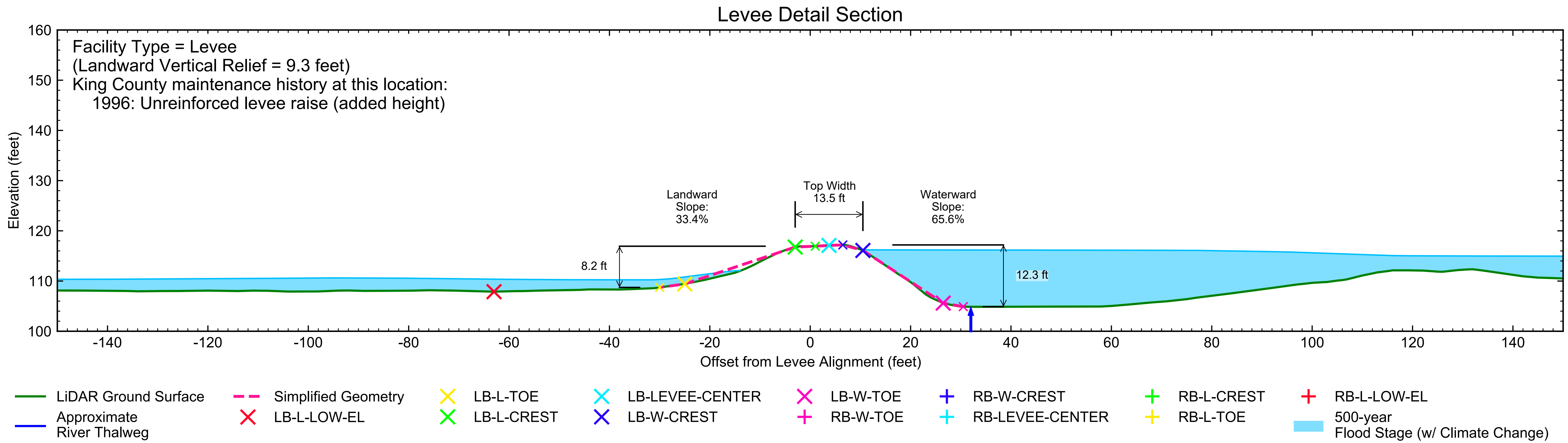
LIDAR CROSS SECTION **LOWER RAGING RIVER** **LEFT BANK STA 22+50, RM 0.51**	
April 2022	103692-304
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-45





Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 23+00, RM 0.52

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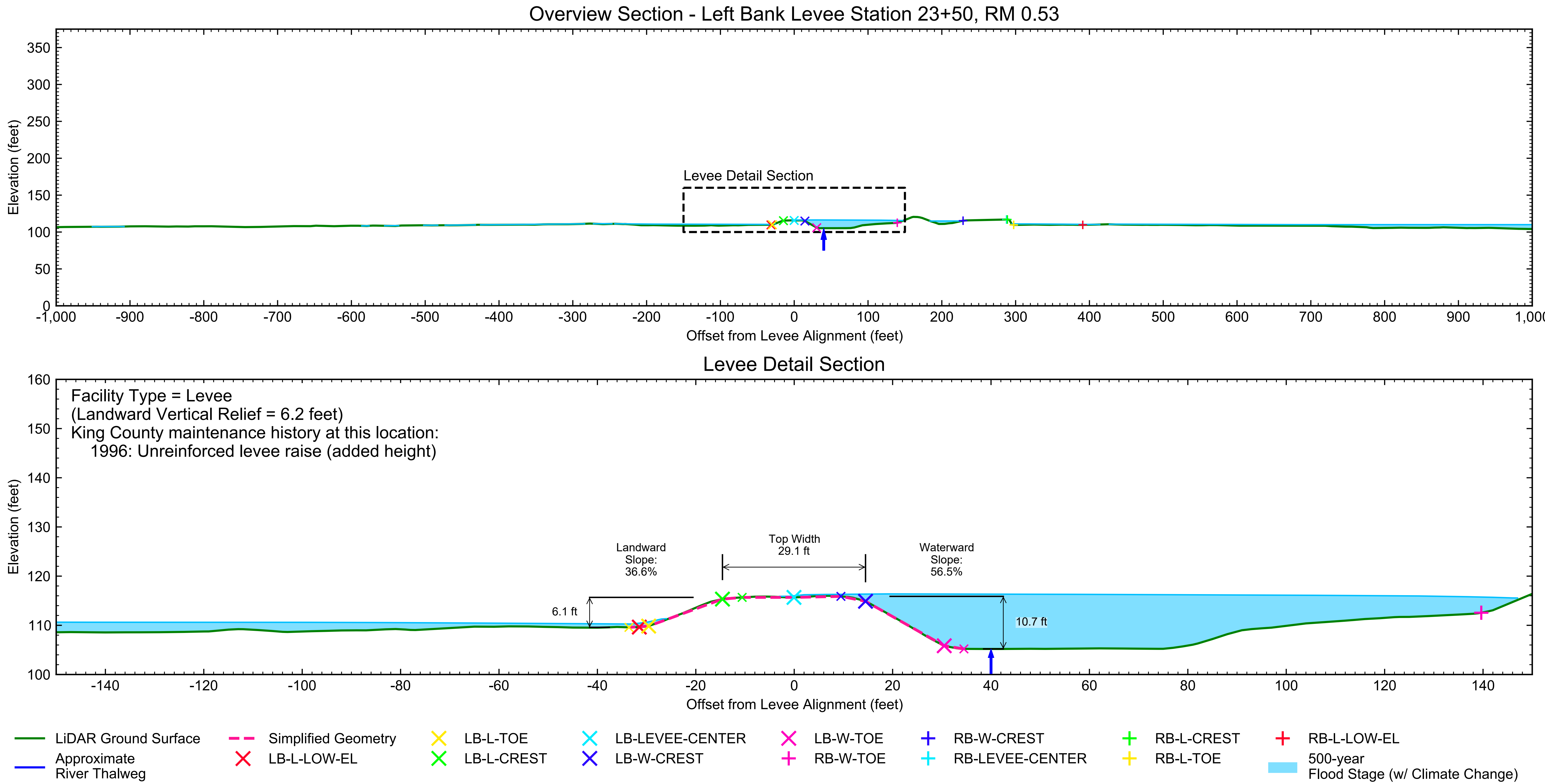
FIG. A-46



Notes:
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LOWER RAGING RIVER
LEFT BANK STA 23+50, RM 0.53

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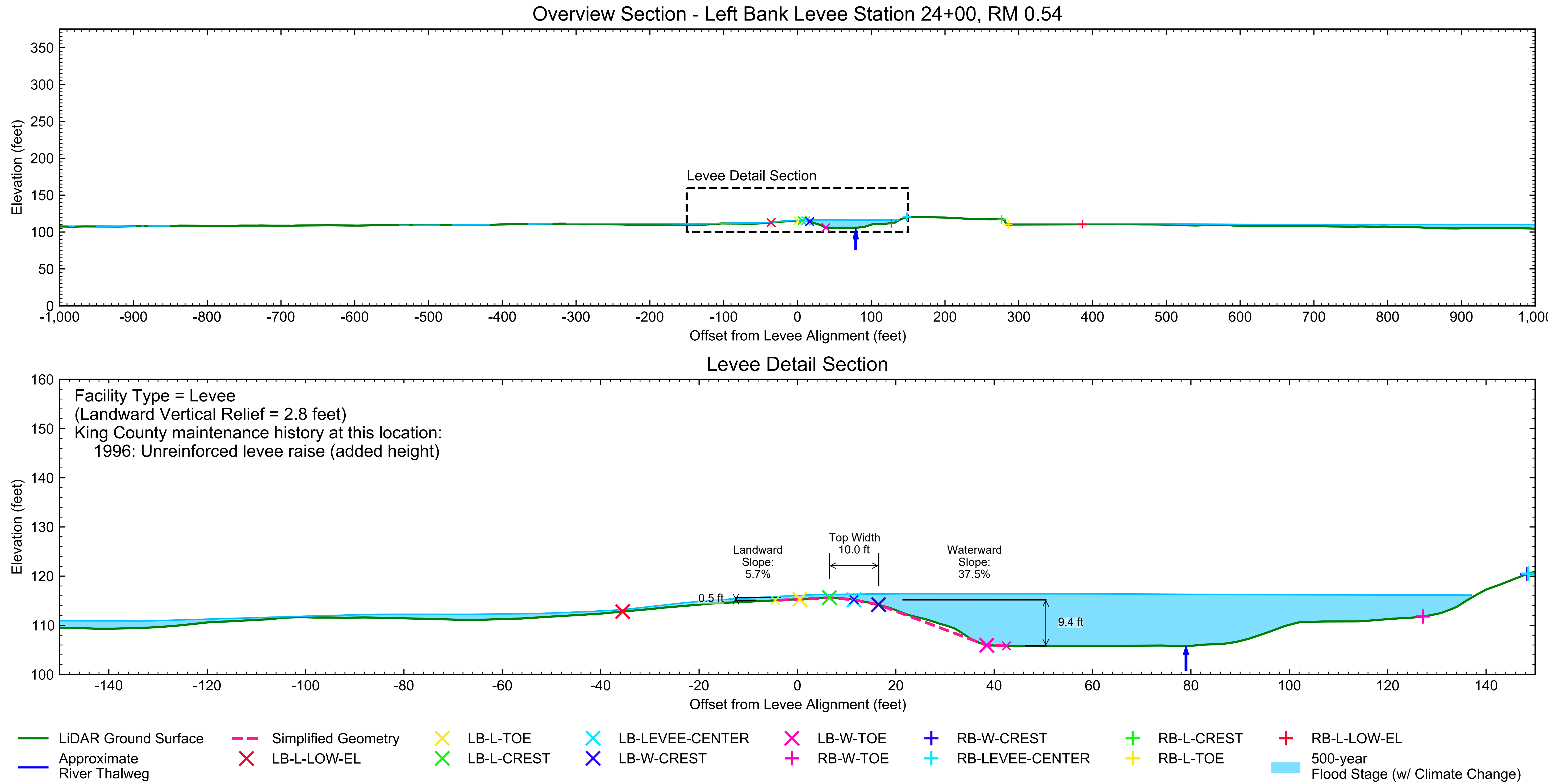
FIG. A-47



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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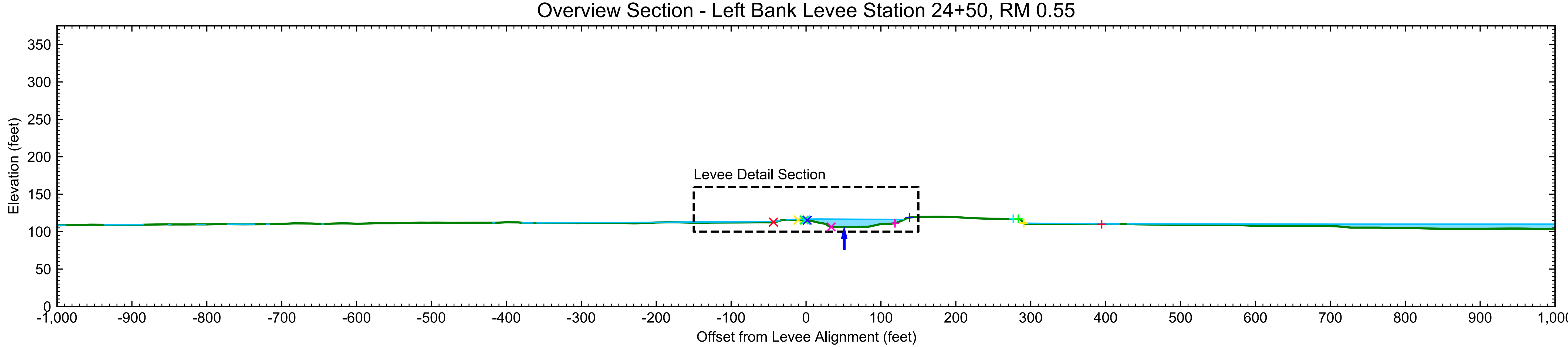
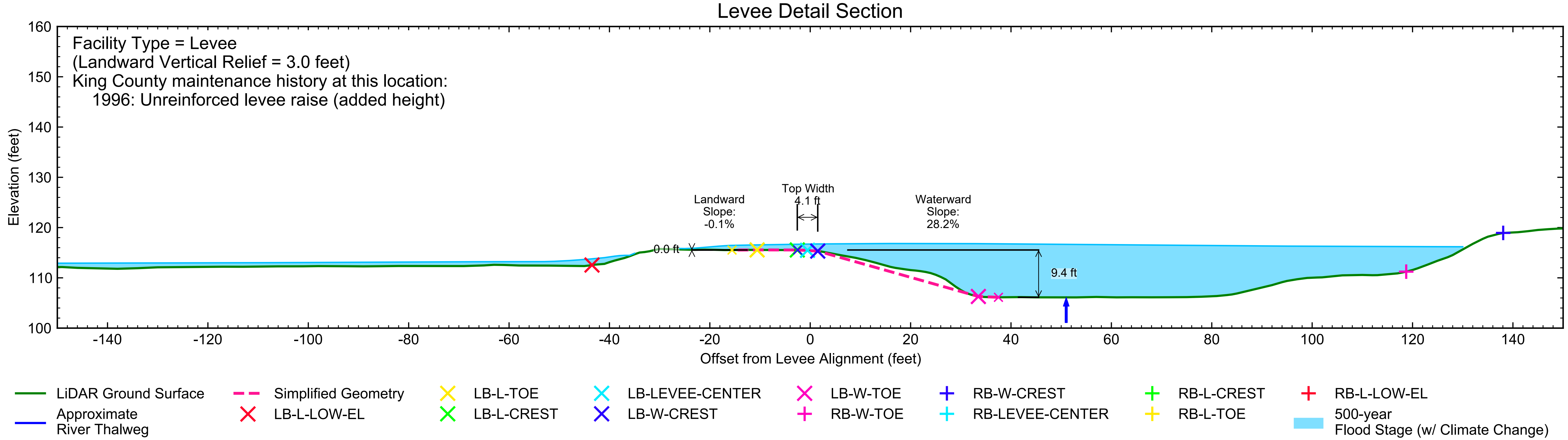
FIG. A-48





Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
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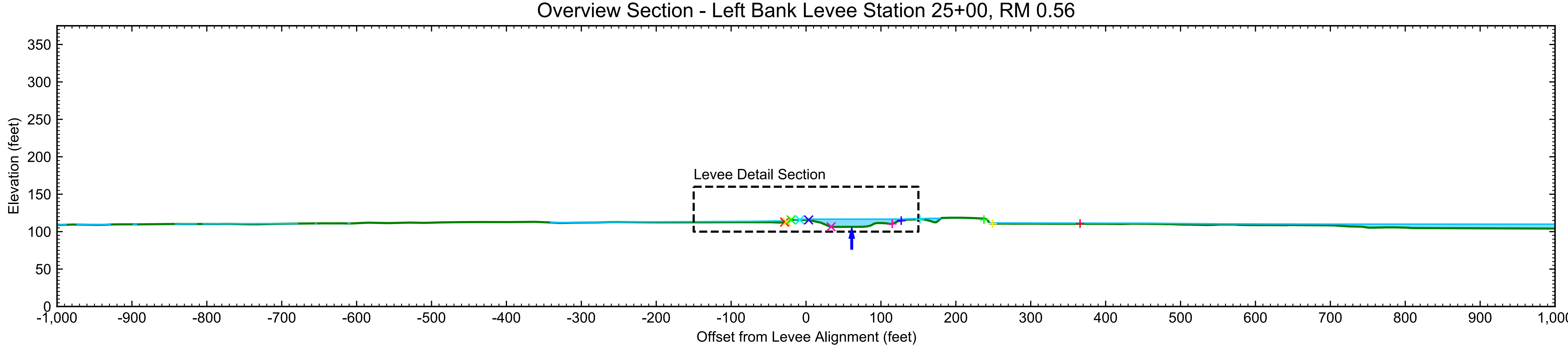
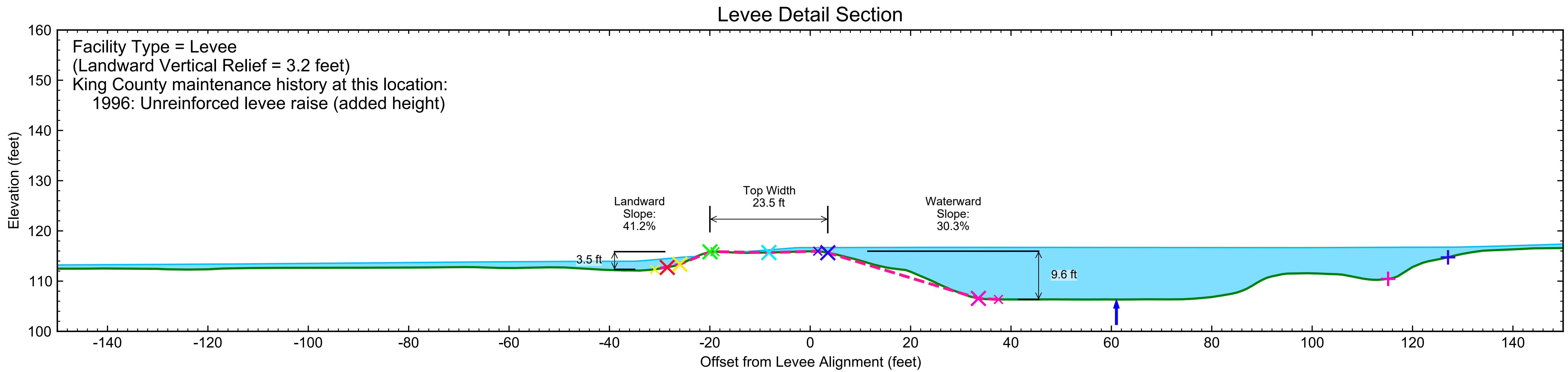
FIG. A-49





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL
Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
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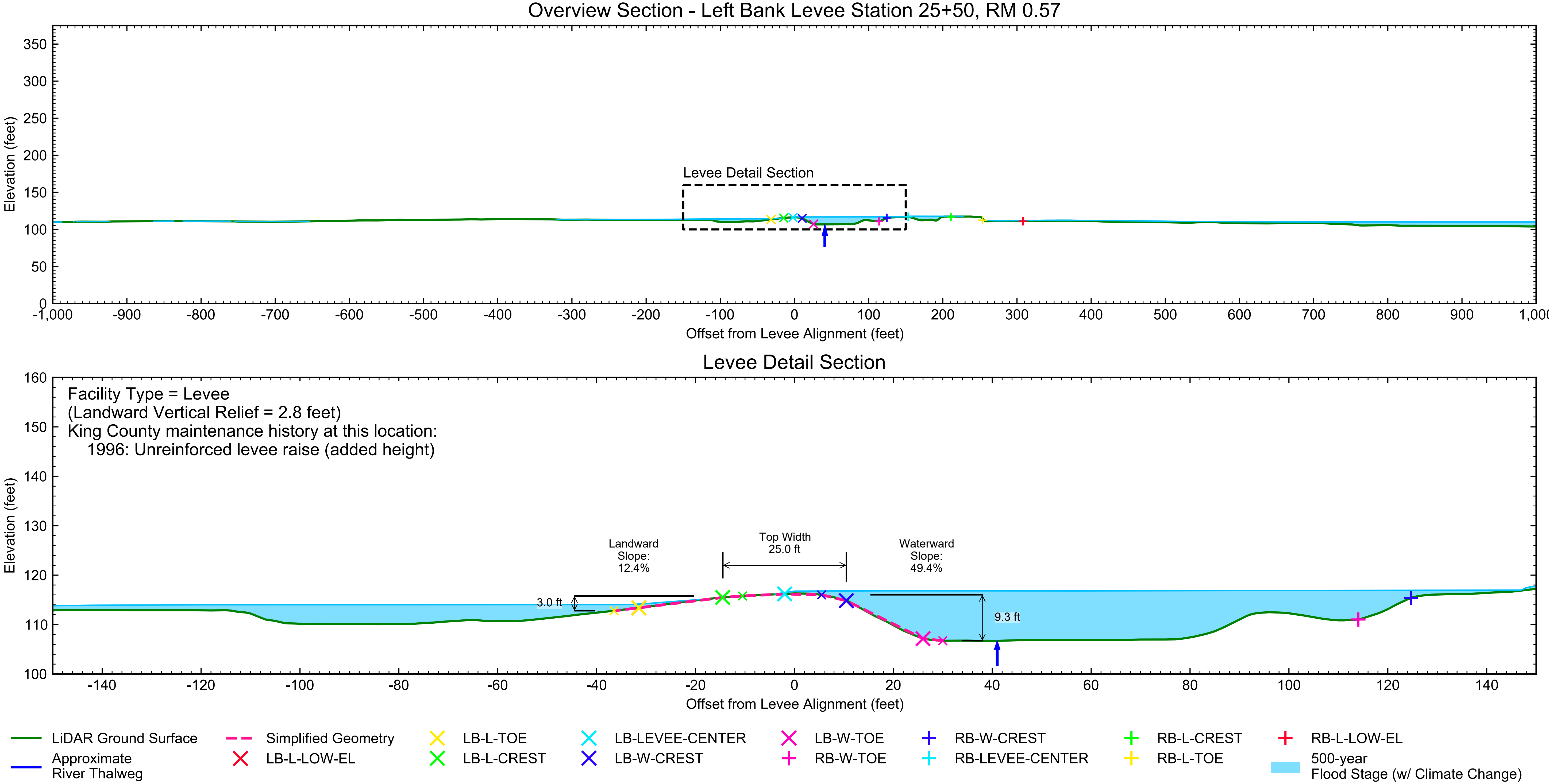
FIG. A-50



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
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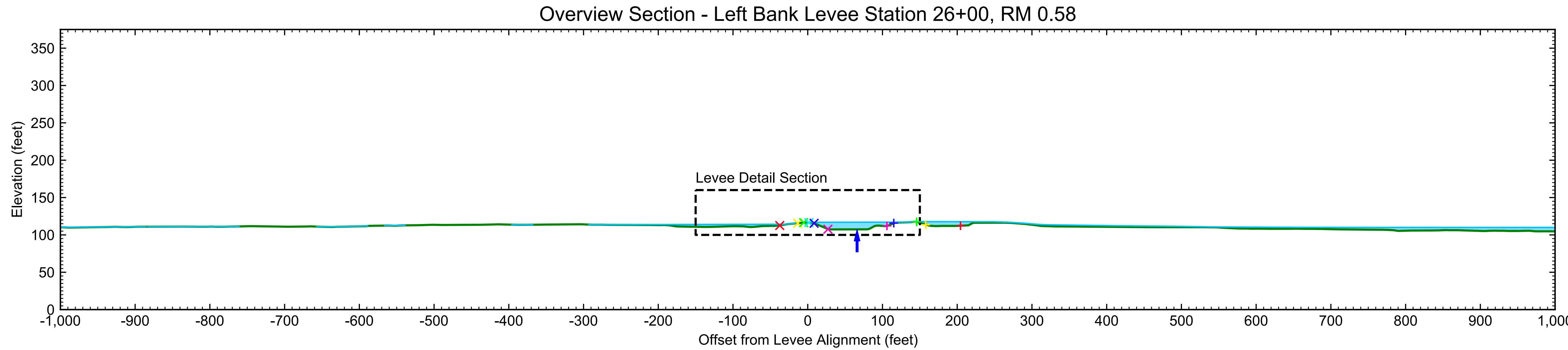
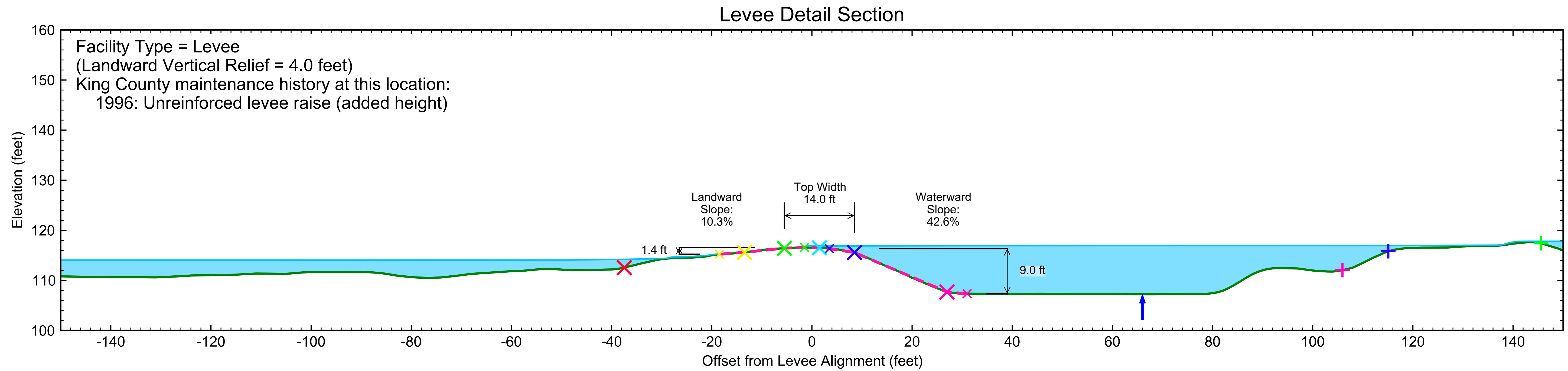
FIG. A-51





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL

Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION
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LEFT BANK STA 26+00, RM 0.58

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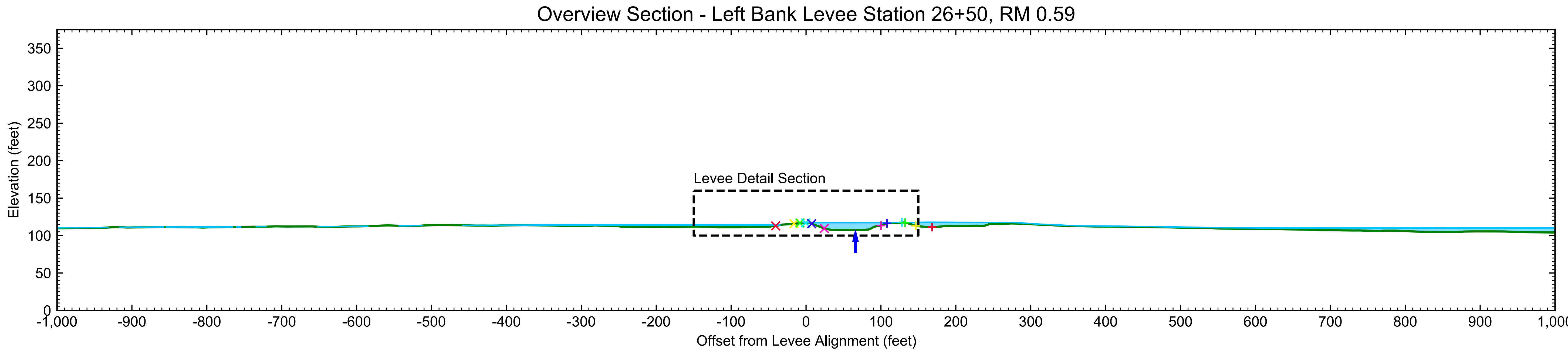
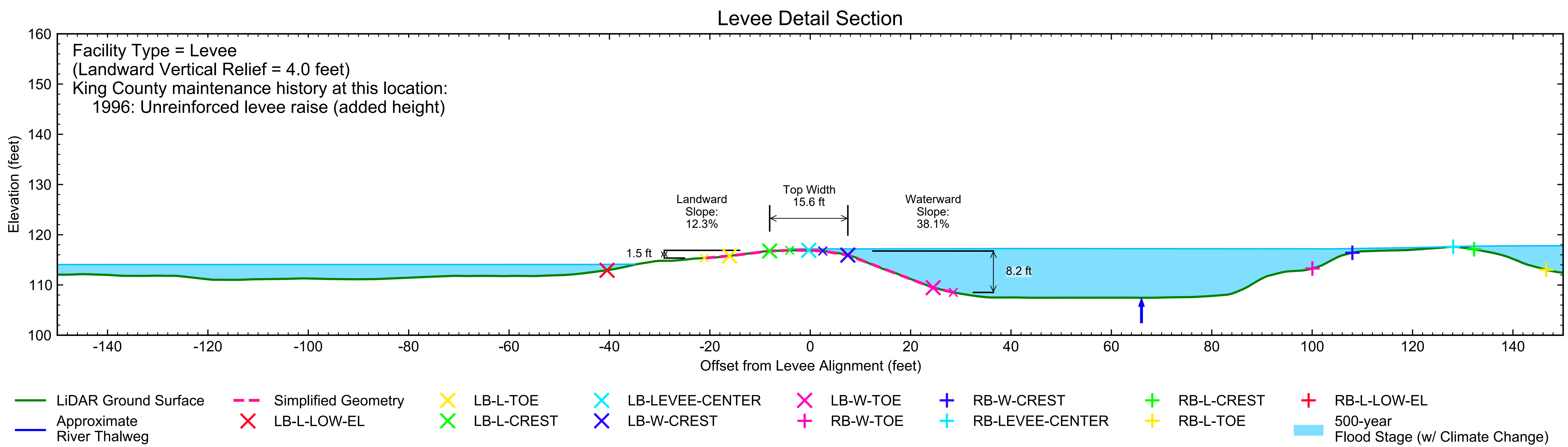
FIG. A-52





Notes:
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6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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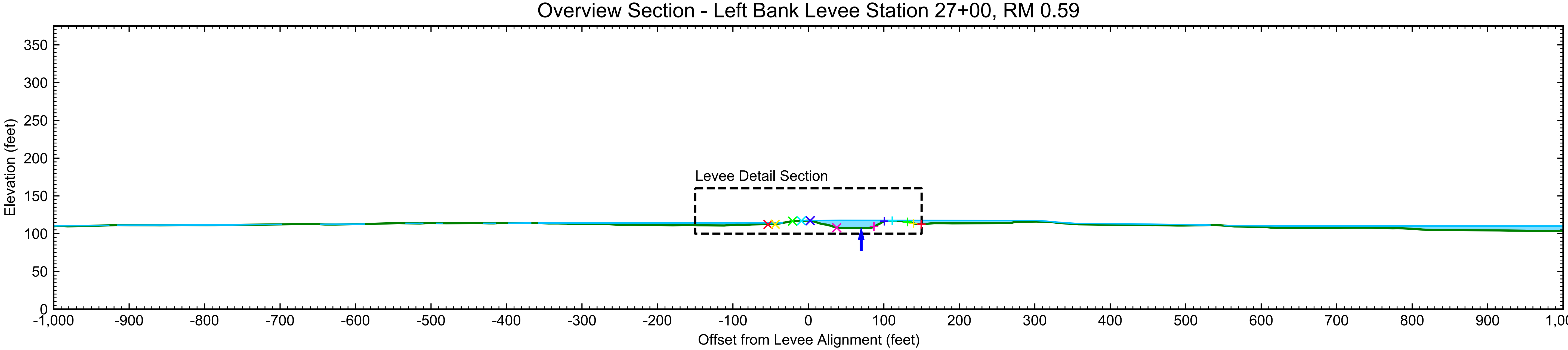
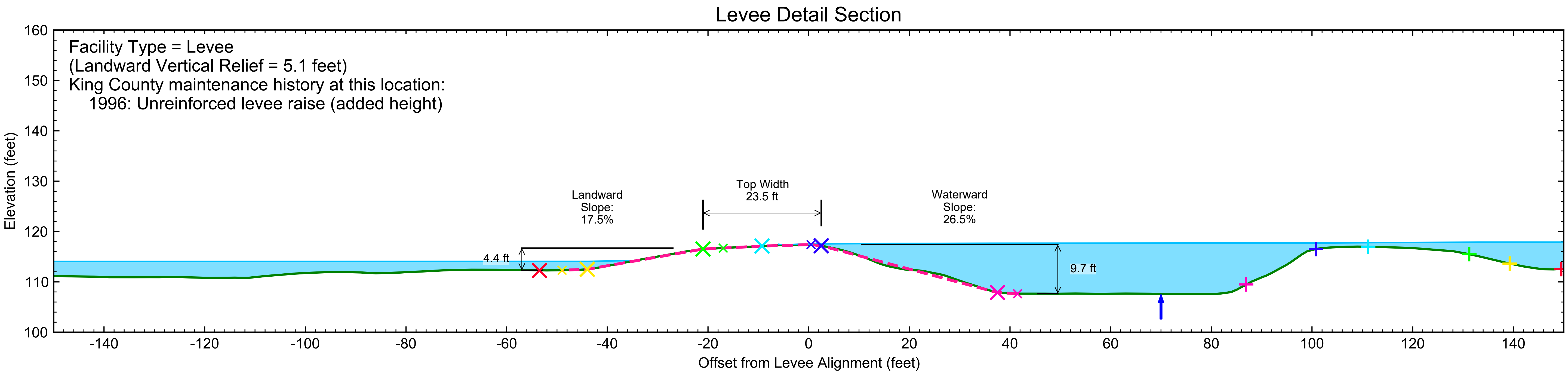
FIG. A-53

Overview Section - Left Bank Levee Station 27+00, RM 0.59



Levee Detail Section



- LiDAR Ground Surface
- Approximate River Thalweg
- Simplified Geometry
- LB-L-LOW-EL
- LB-L-TOE
- LB-L-CREST
- LB-LEVEE-CENTER
- LB-W-CREST
- LB-W-TOE
- RB-W-TOE
- RB-W-CREST
- RB-LEVEE-CENTER
- RB-L-CREST
- RB-L-TOE
- RB-L-LOW-EL
- 500-year Flood Stage (w/ Climate Change)

Notes:
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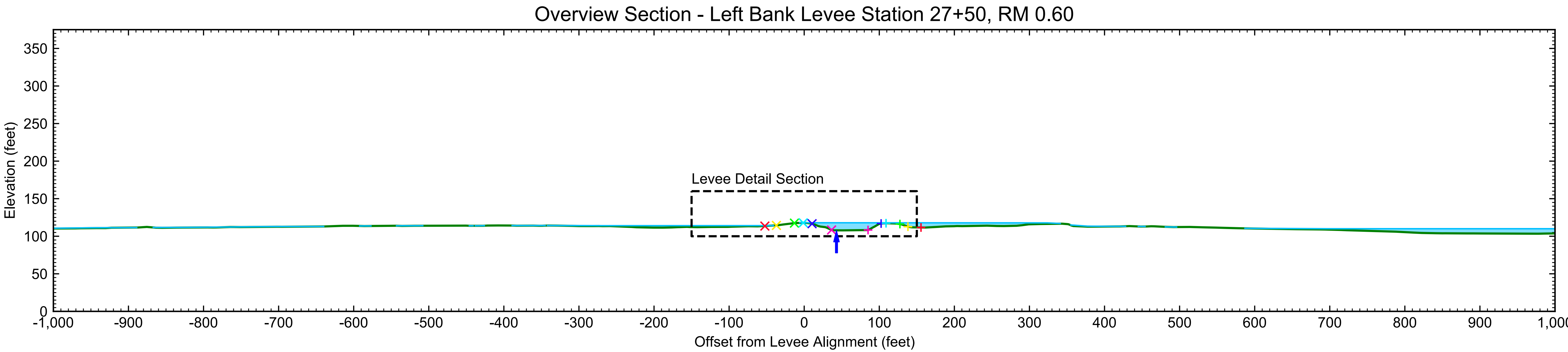
FIG. A-54



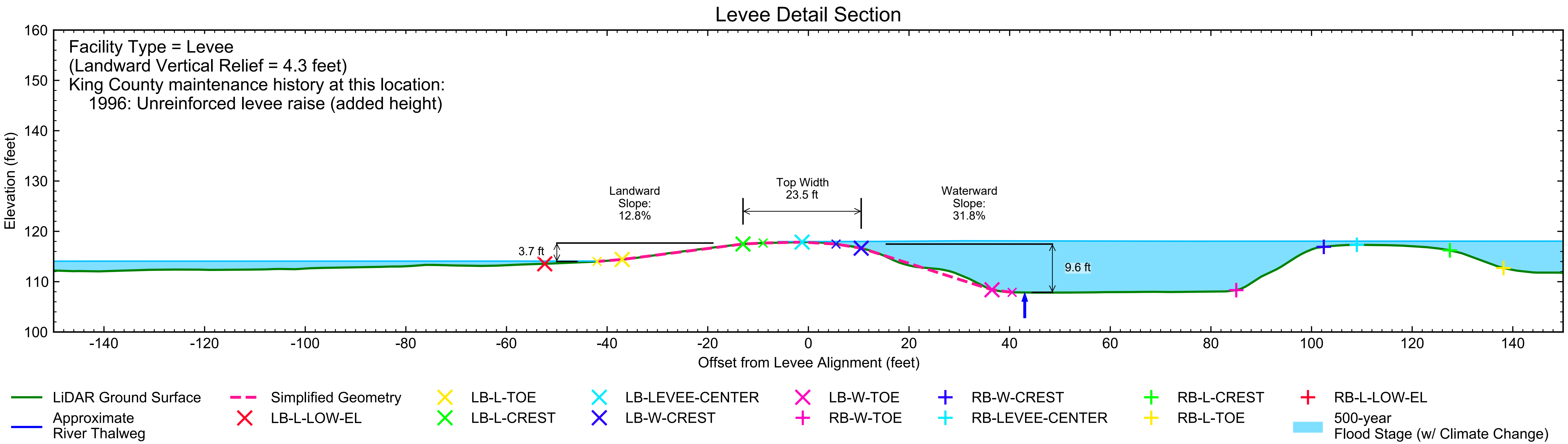


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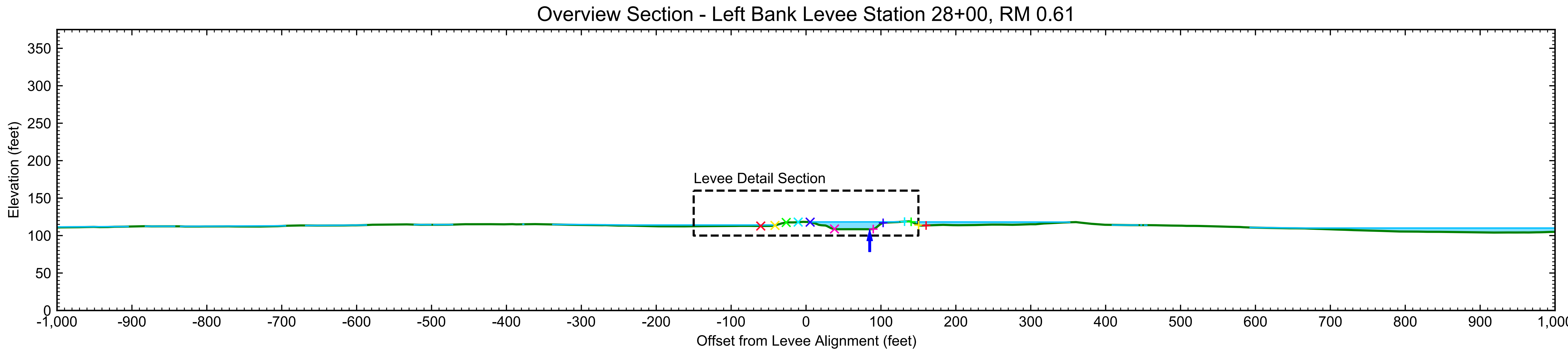
FIG. A-55



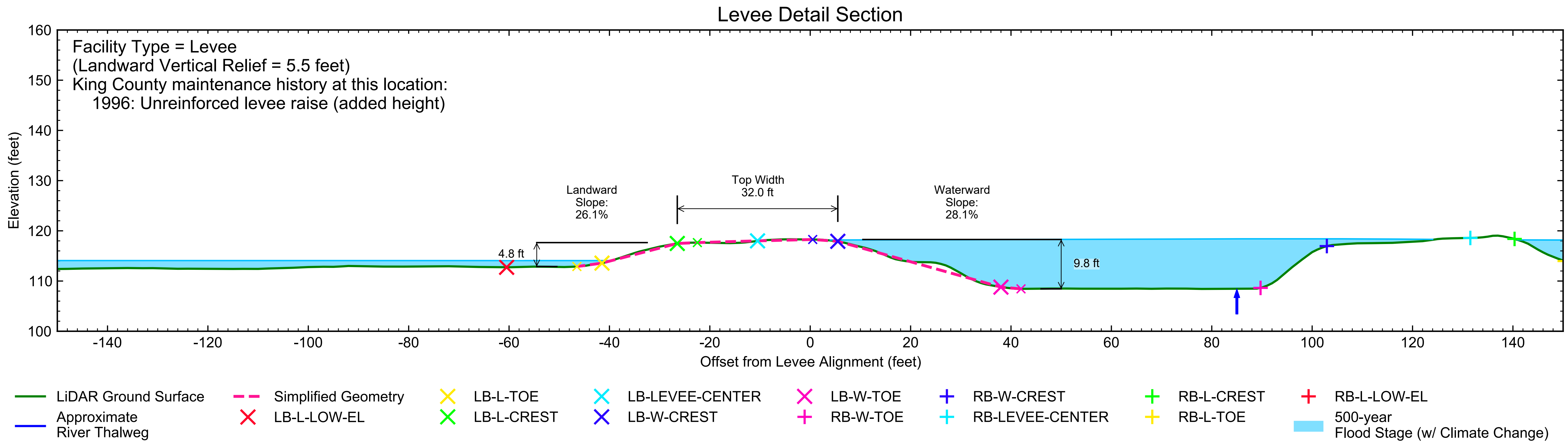


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FIG. A-56

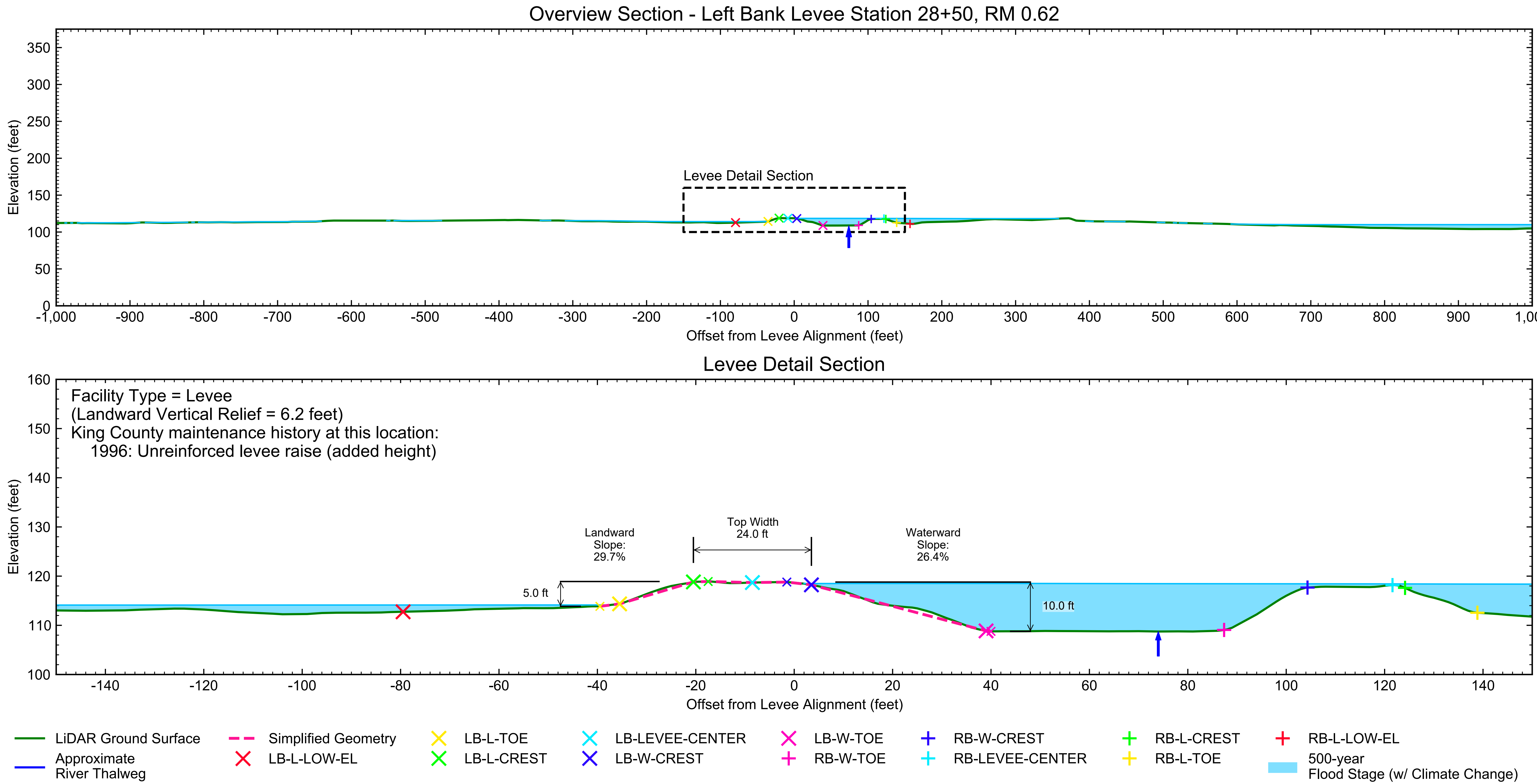

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FIG. A-57

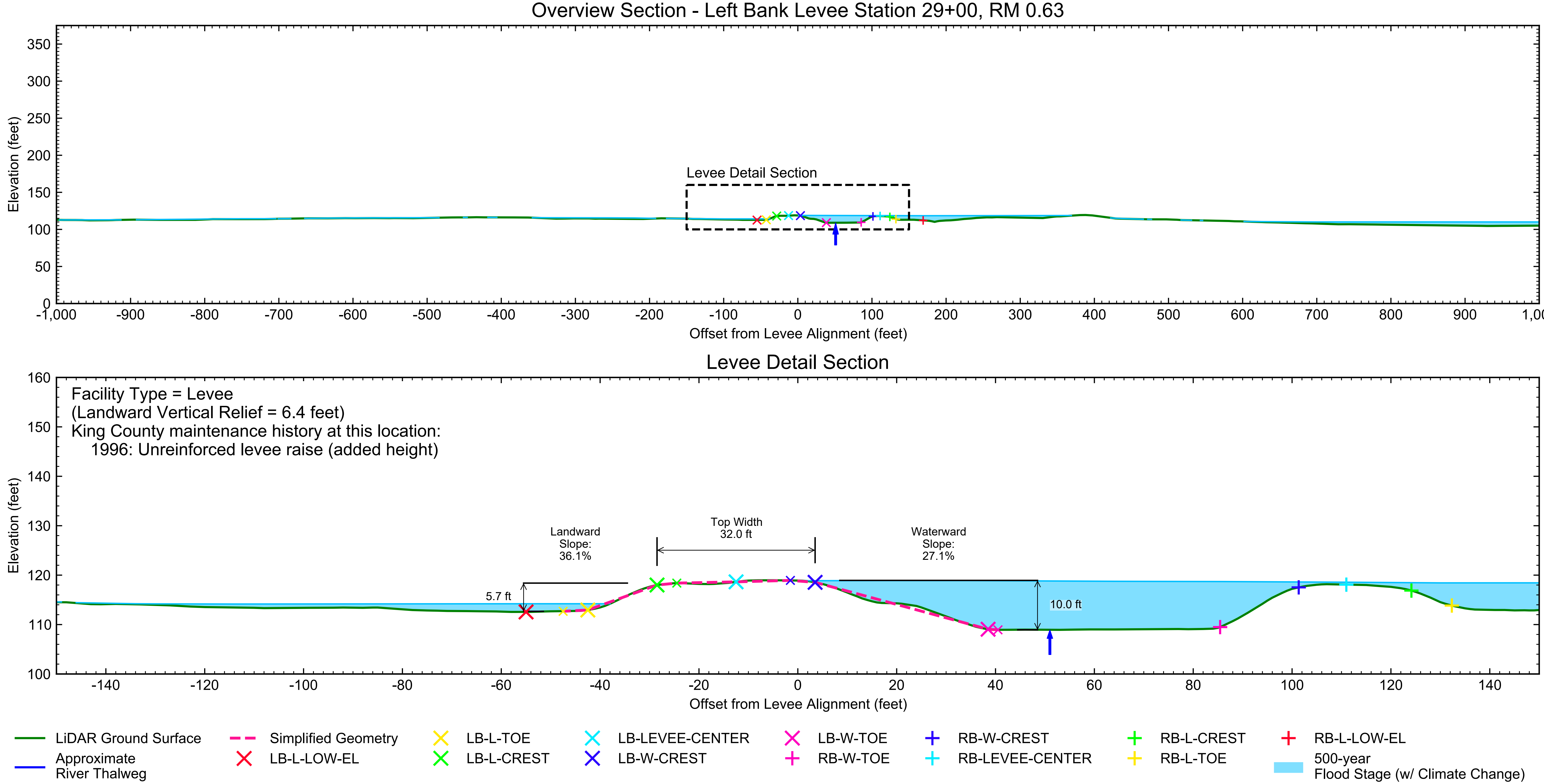

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FIG. A-58

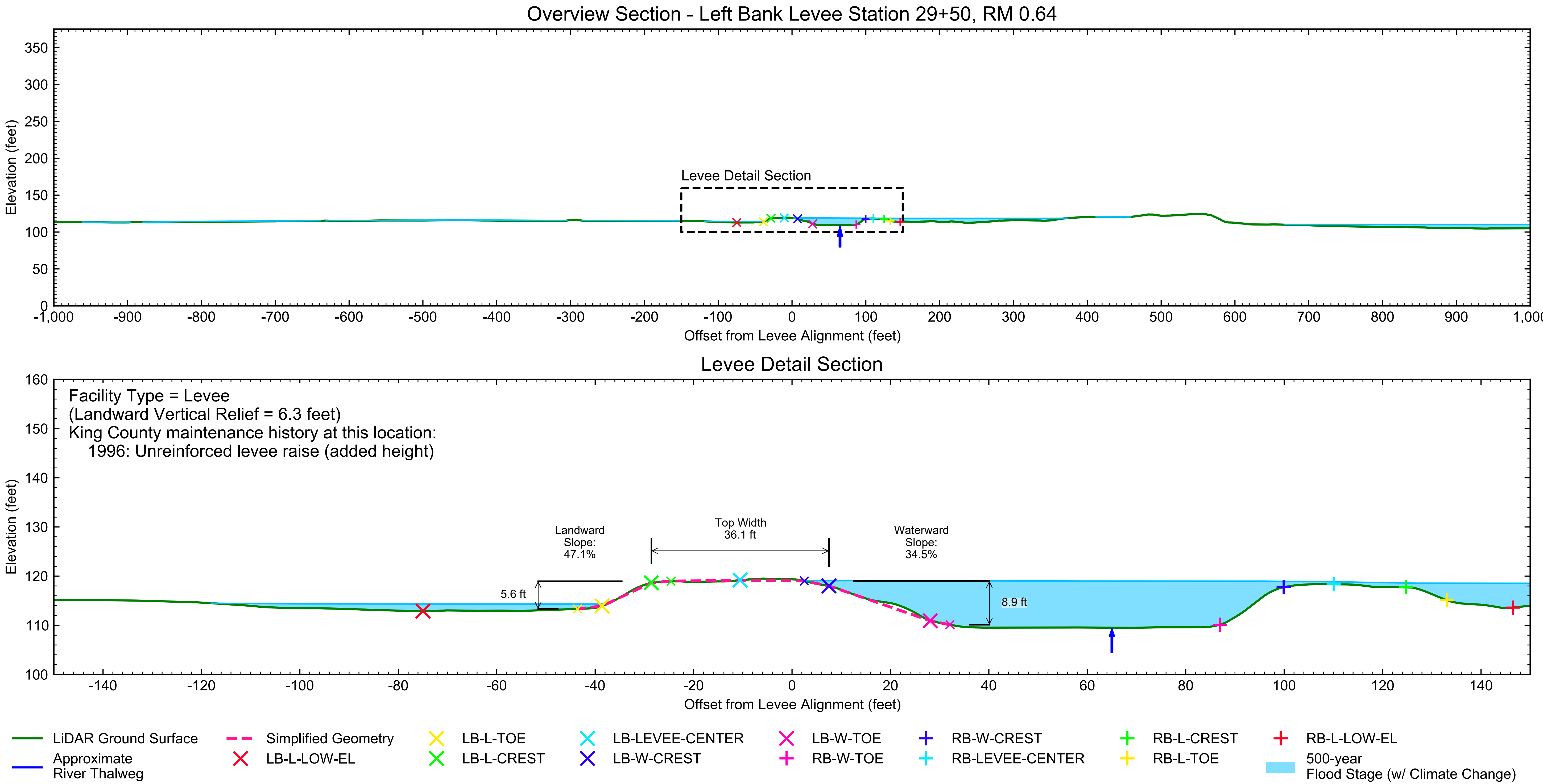

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FIG. A-59

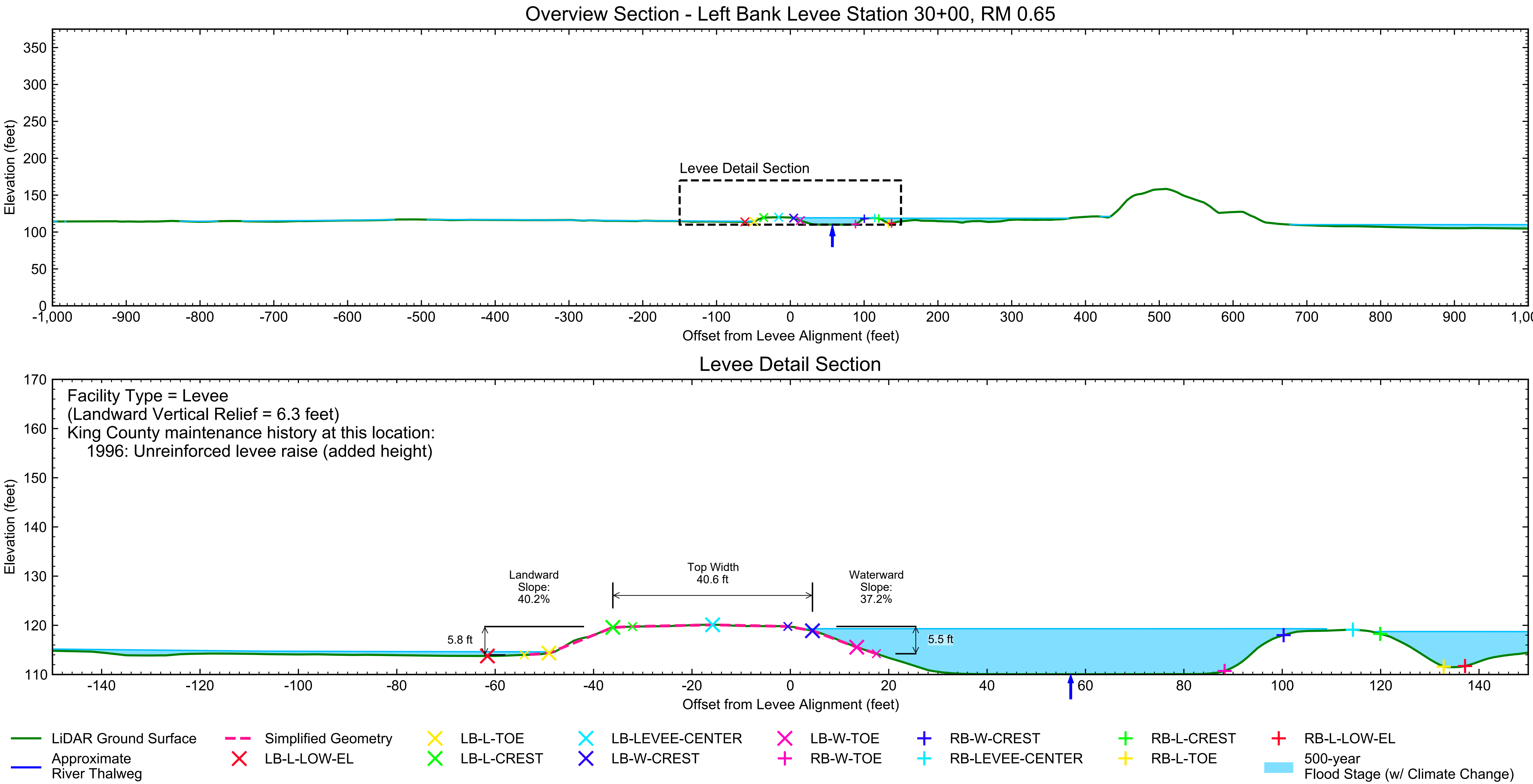

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FIG. A-60

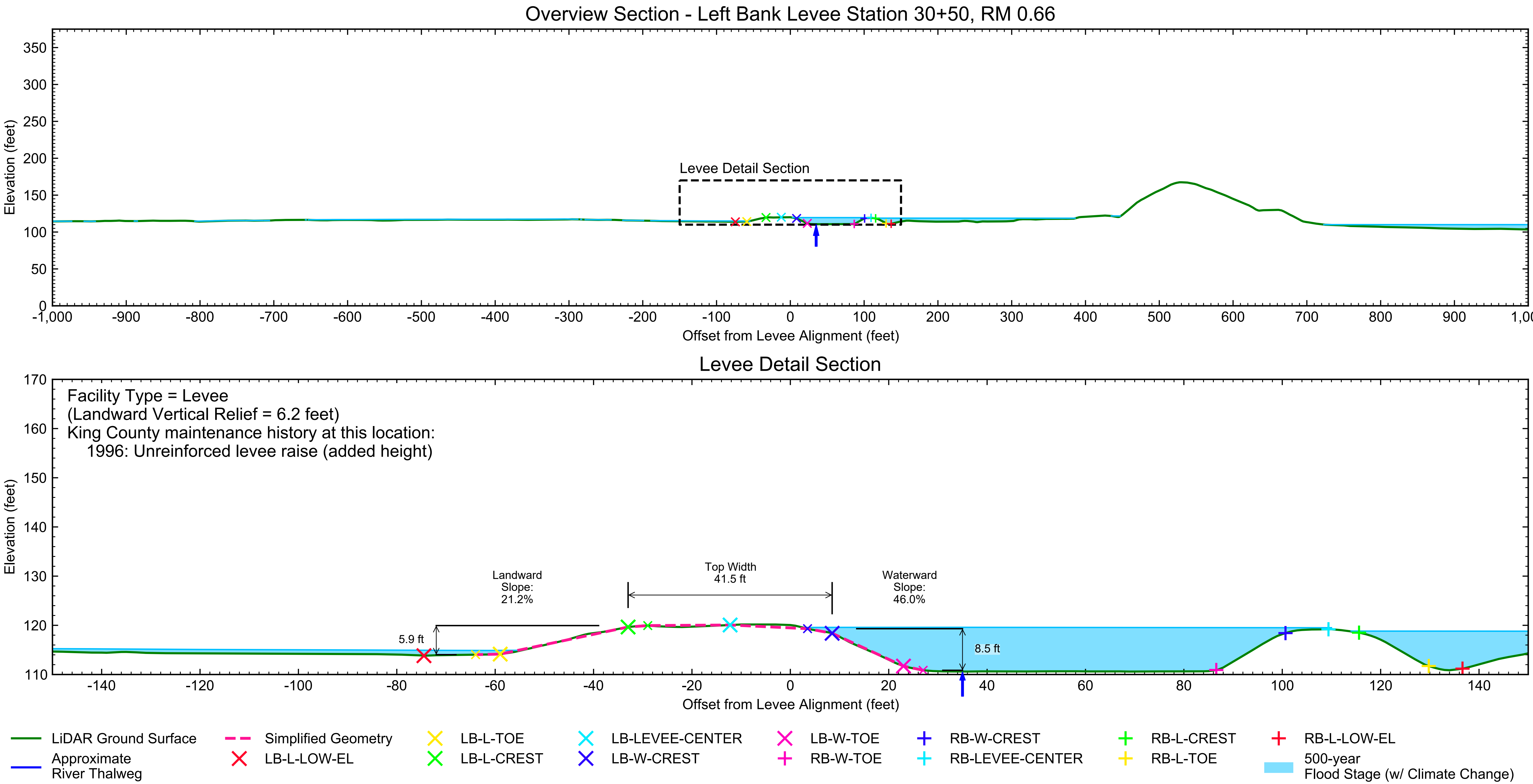

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FIG. A-61

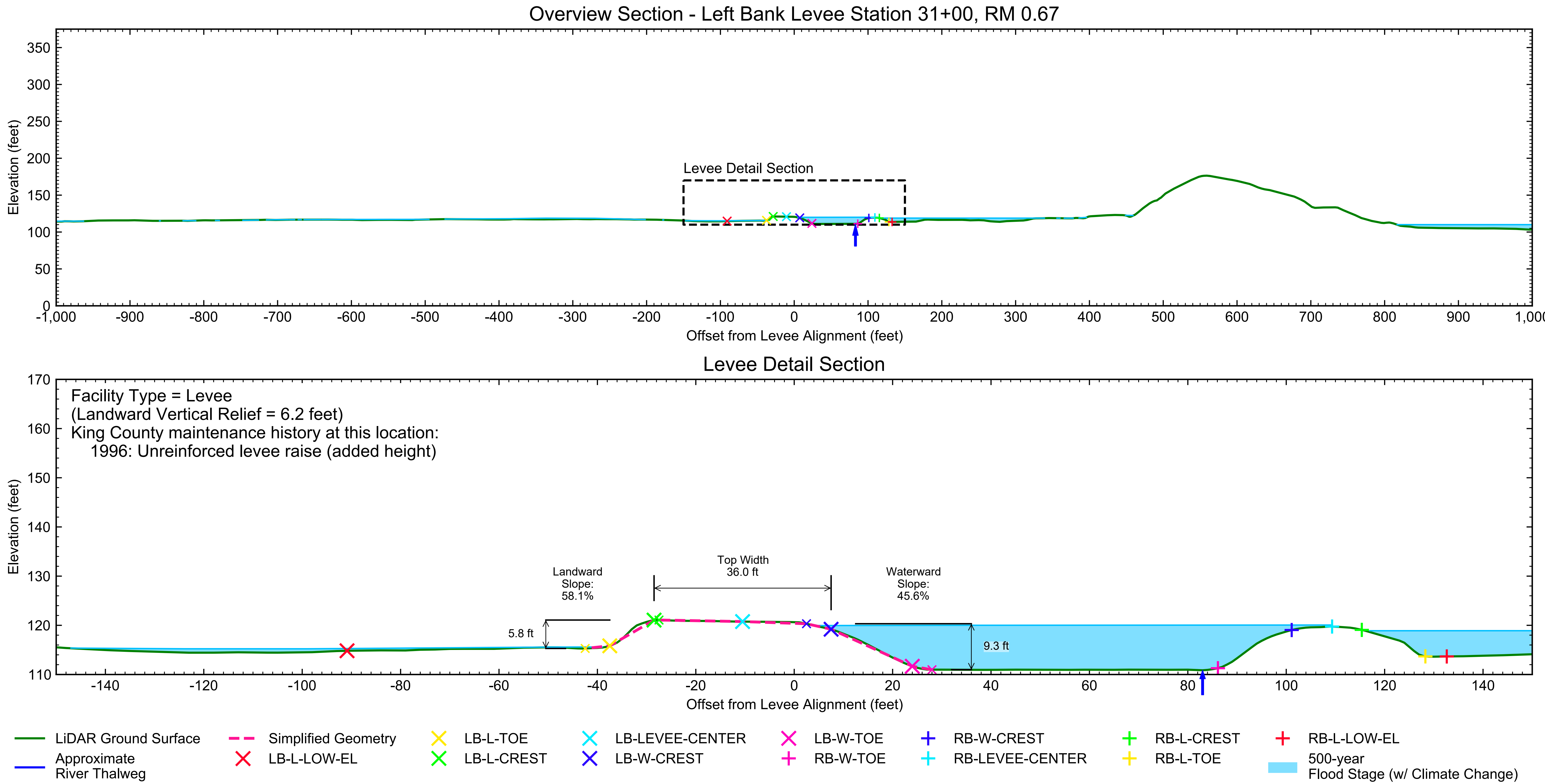

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FIG. A-62

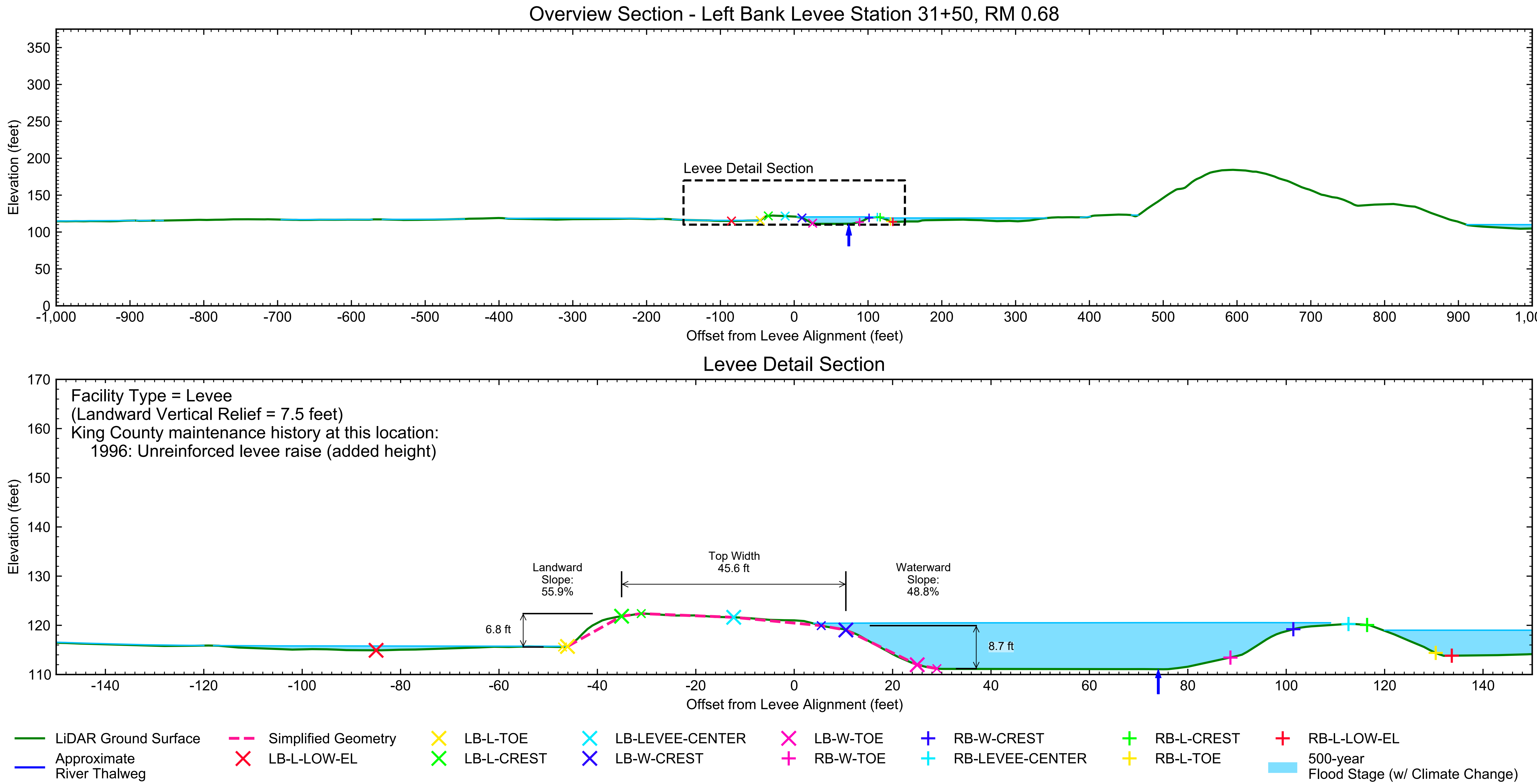

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FIG. A-63

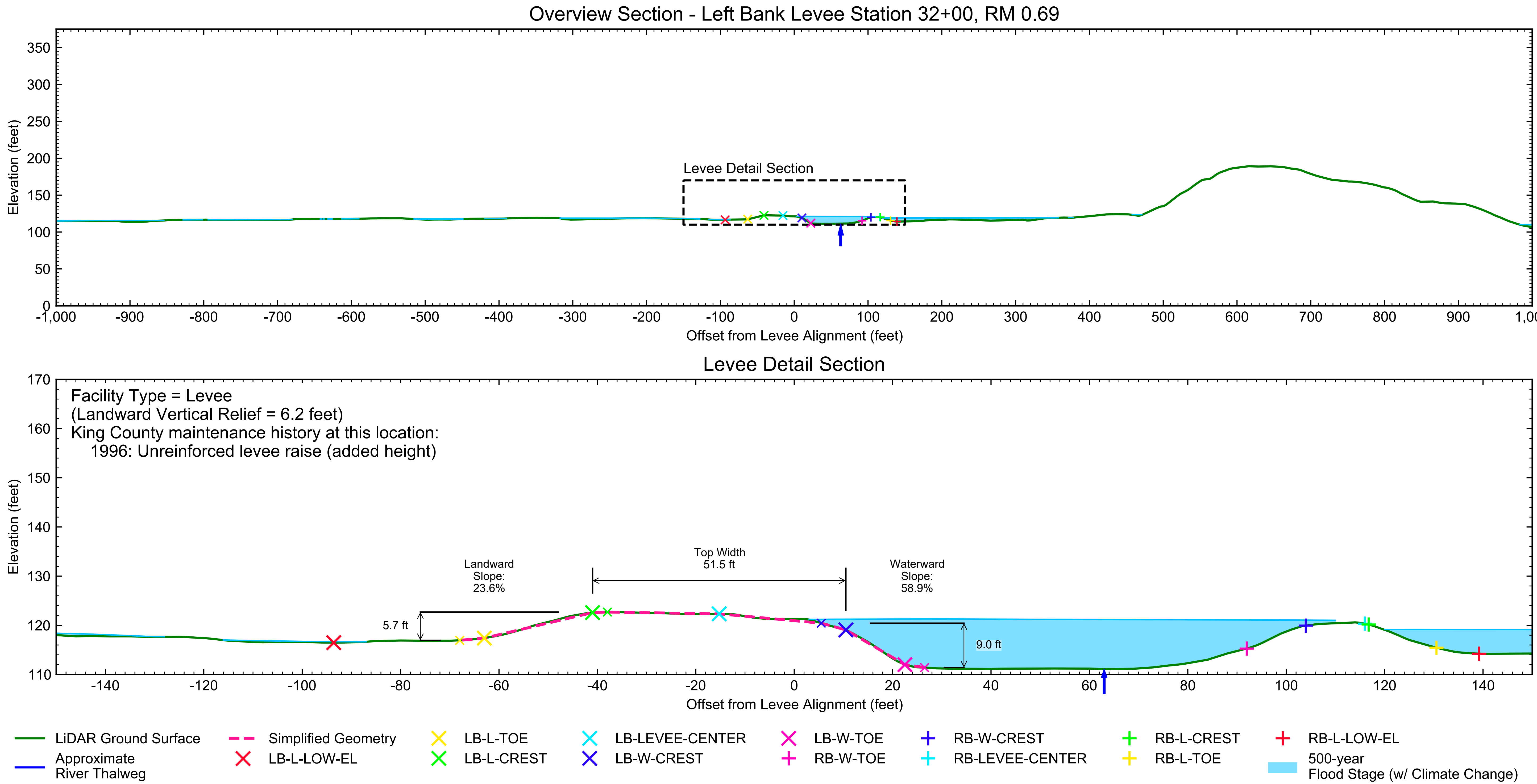

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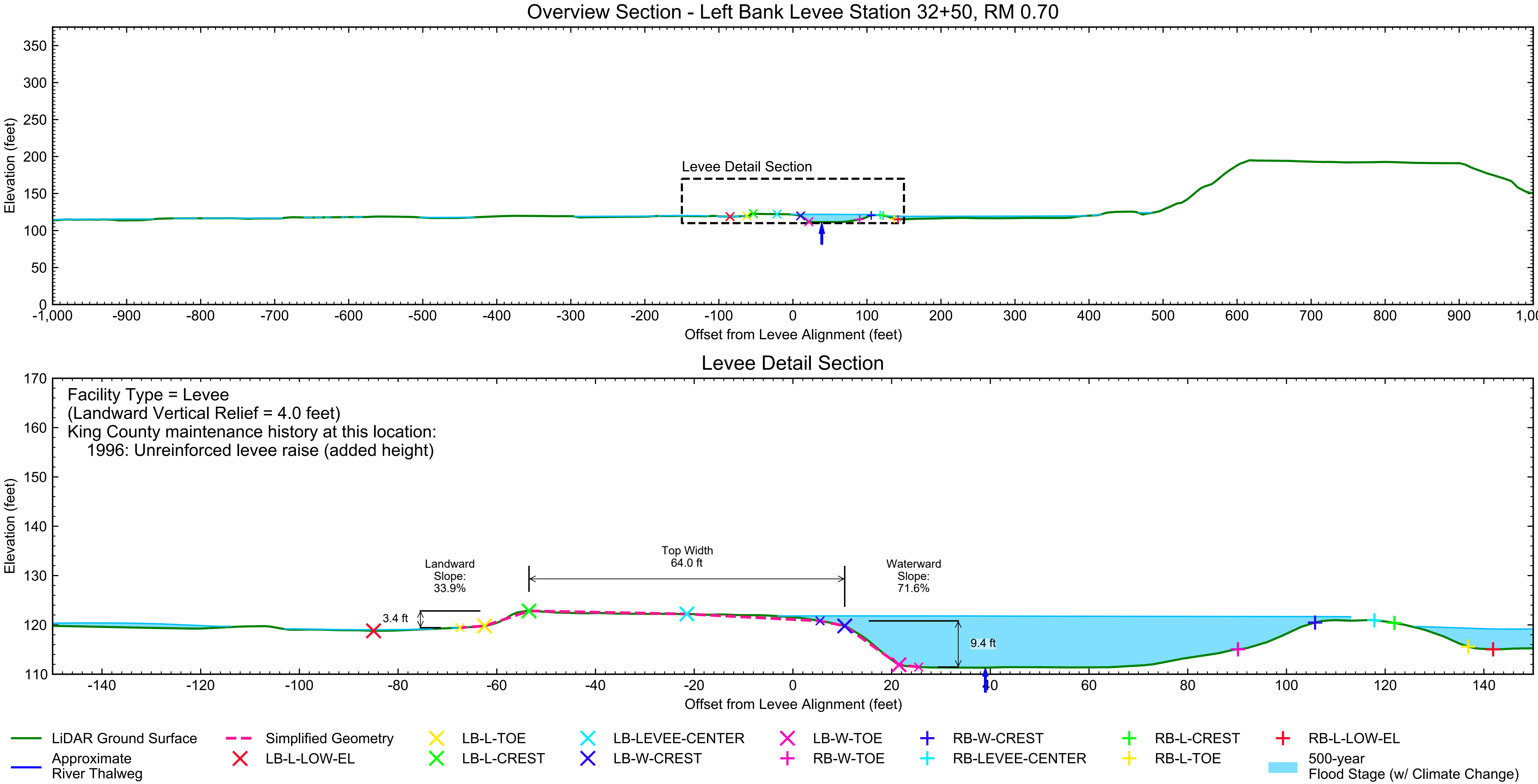
FIG. A-64



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 32+50, RM 0.70

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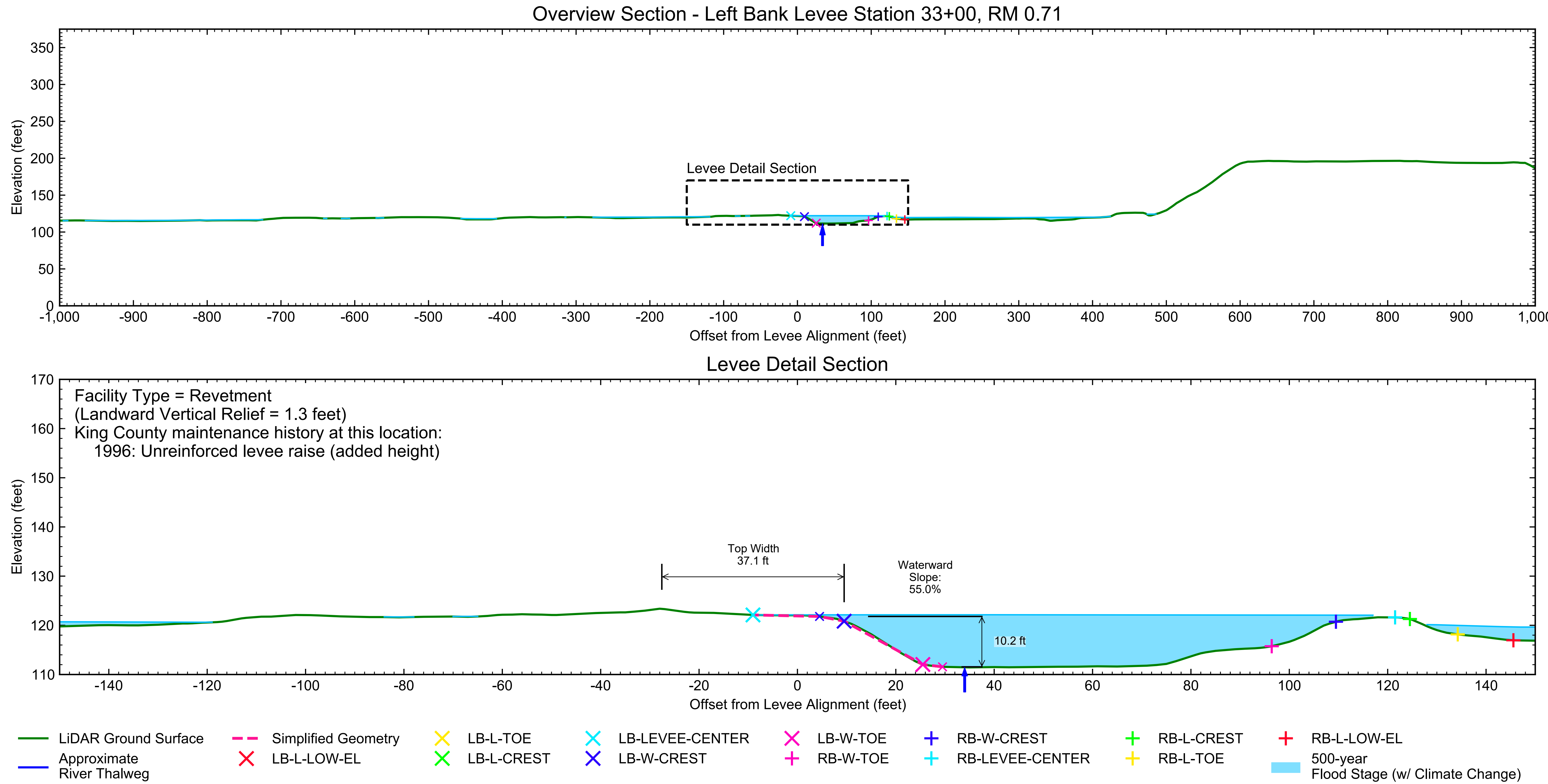
FIG. A-65



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LIDAR CROSS SECTION
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LEFT BANK STA 33+00, RM 0.71

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FIG. A-66

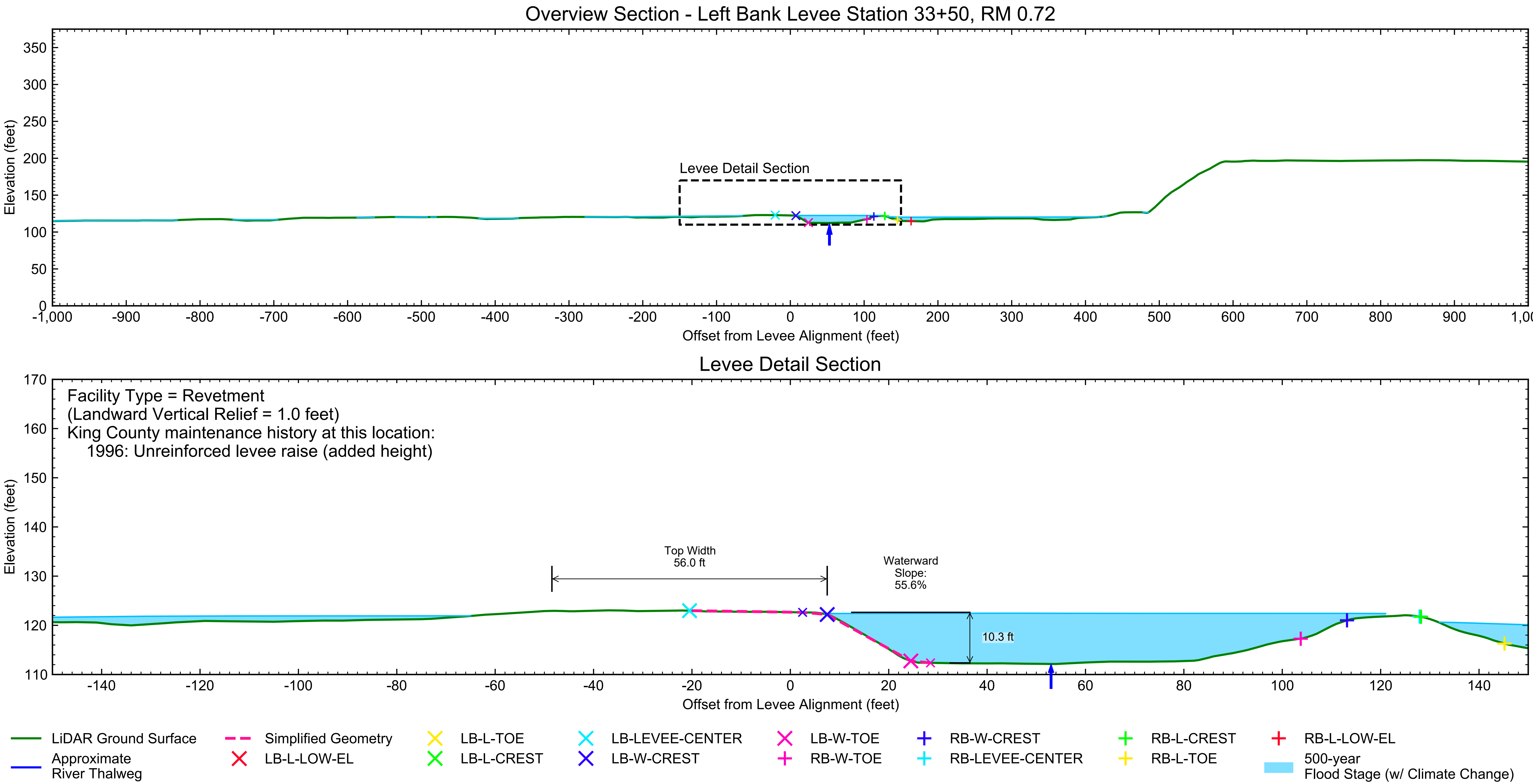

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FIG. A-67

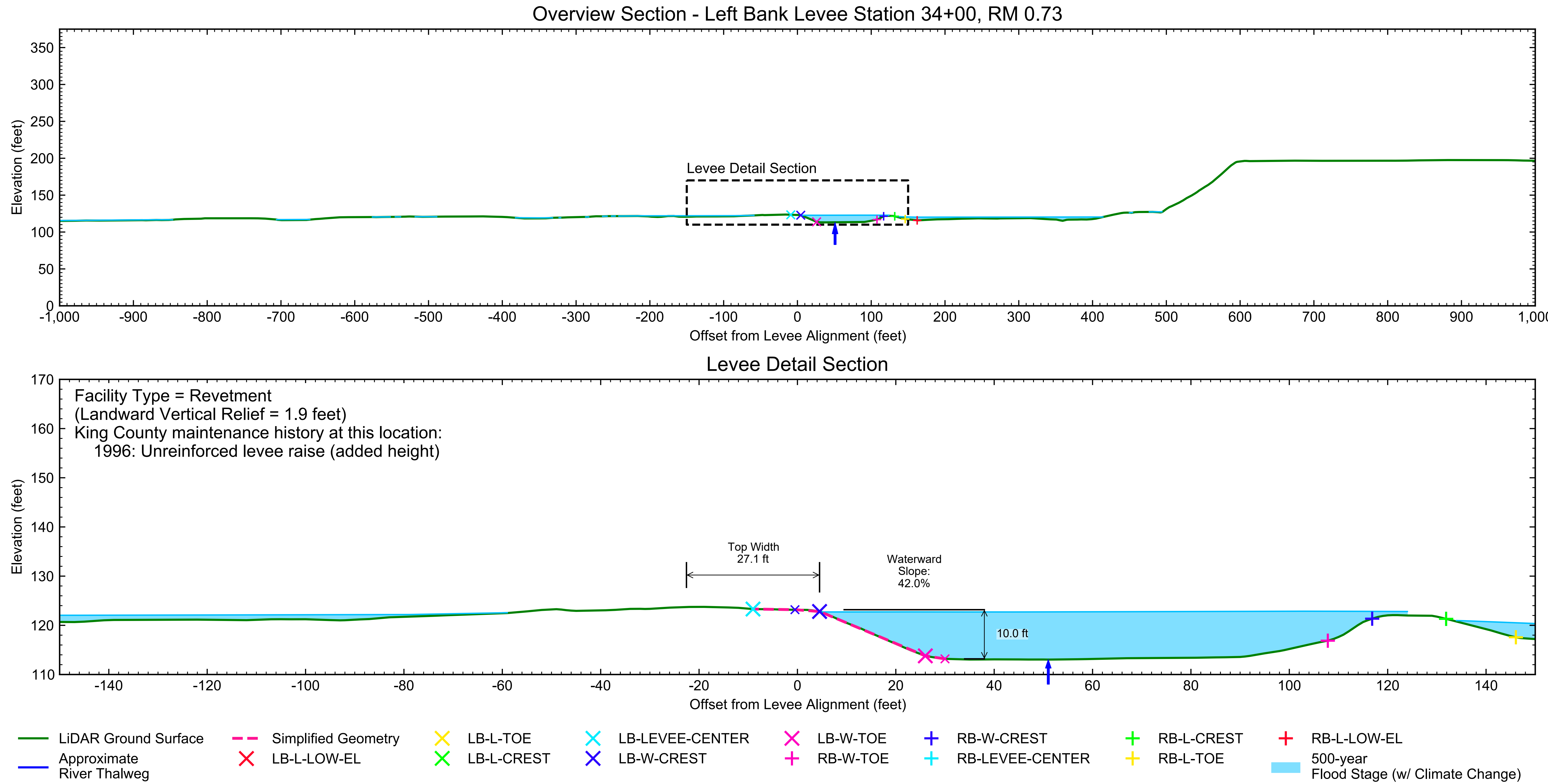

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FIG. A-68

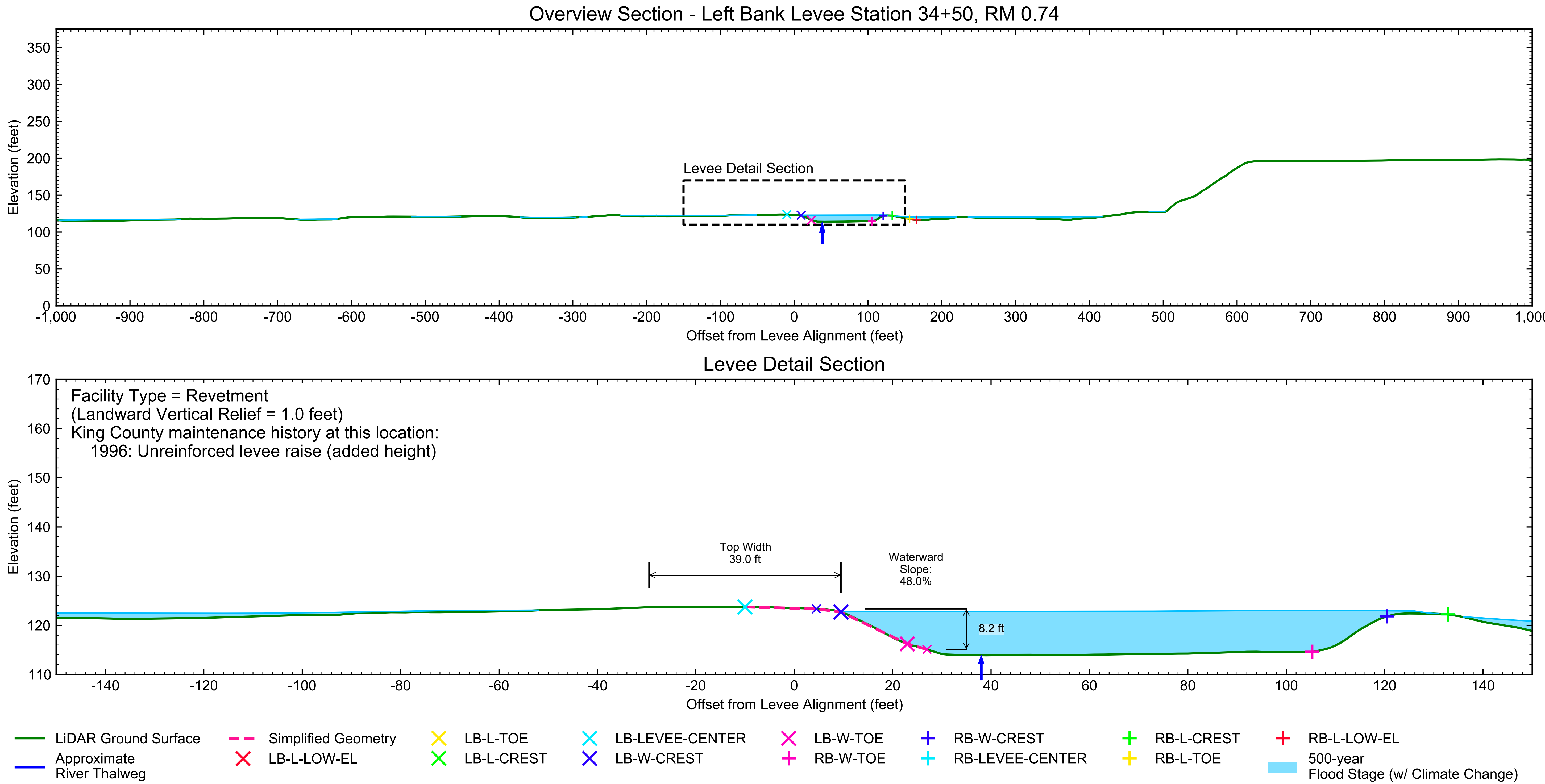

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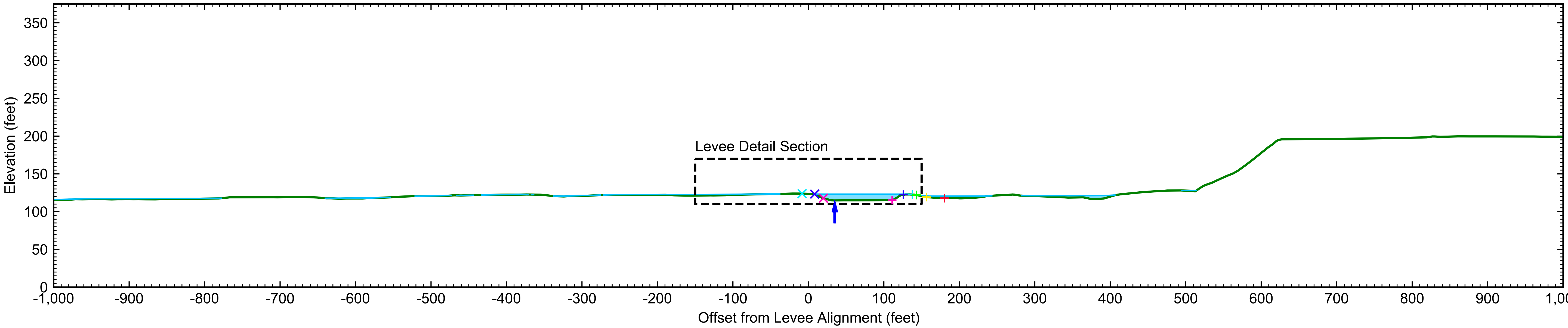
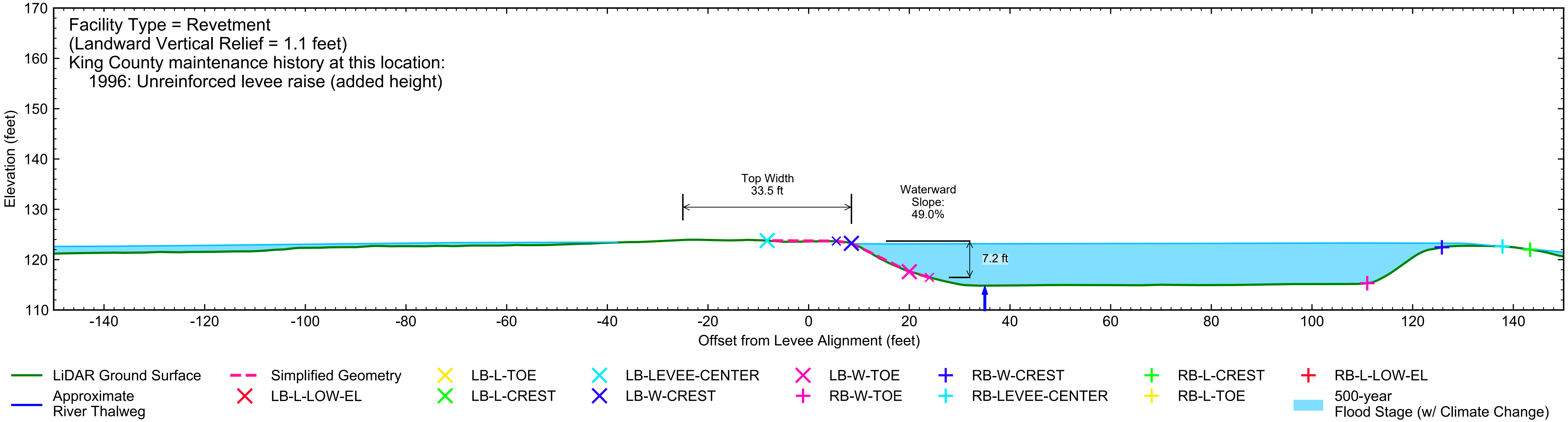
FIG. A-69

Overview Section - Left Bank Levee Station 35+00, RM 0.75



Levee Detail Section



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LEFT BANK STA 35+00, RM 0.75

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FIG. A-70

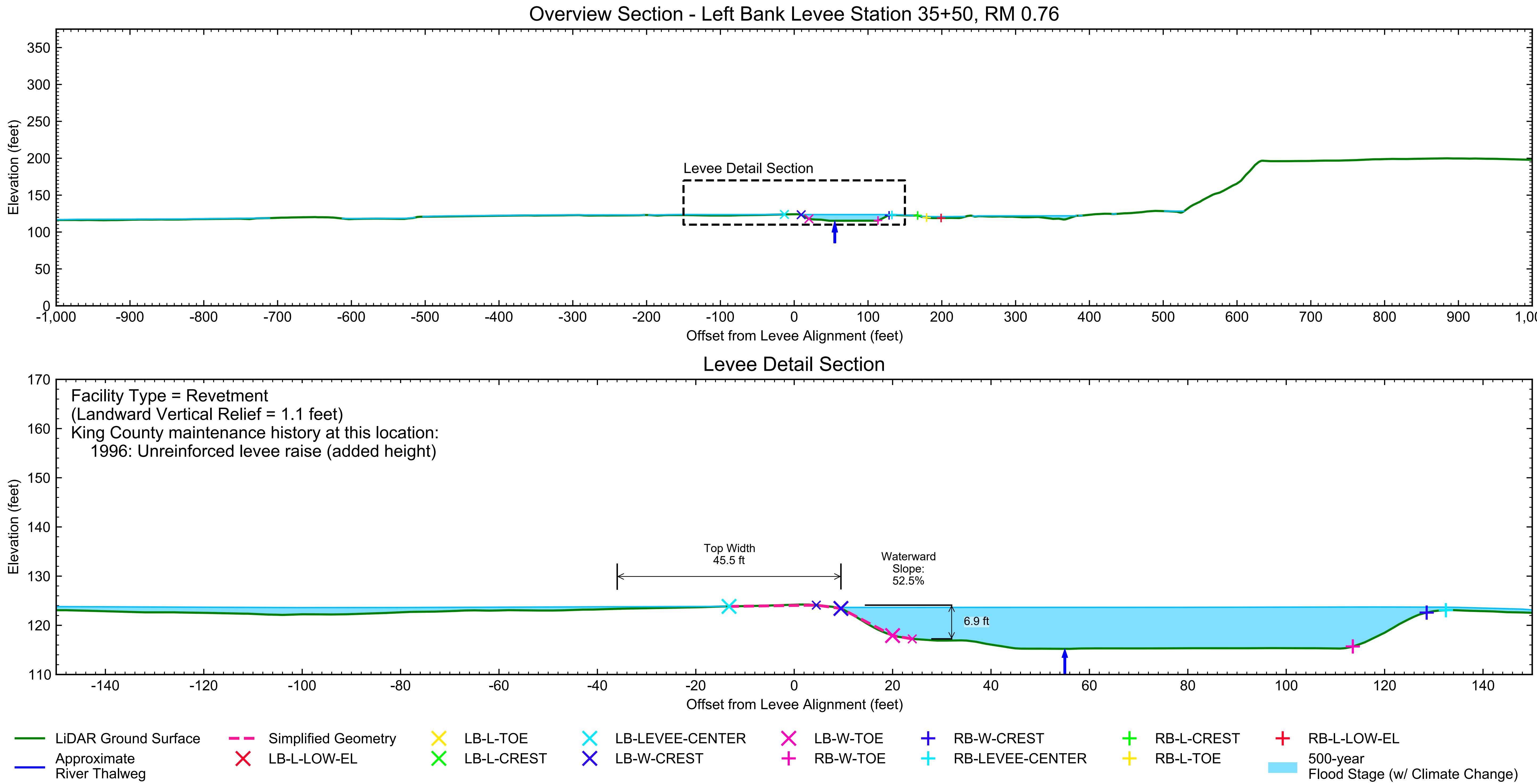

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FIG. A-71

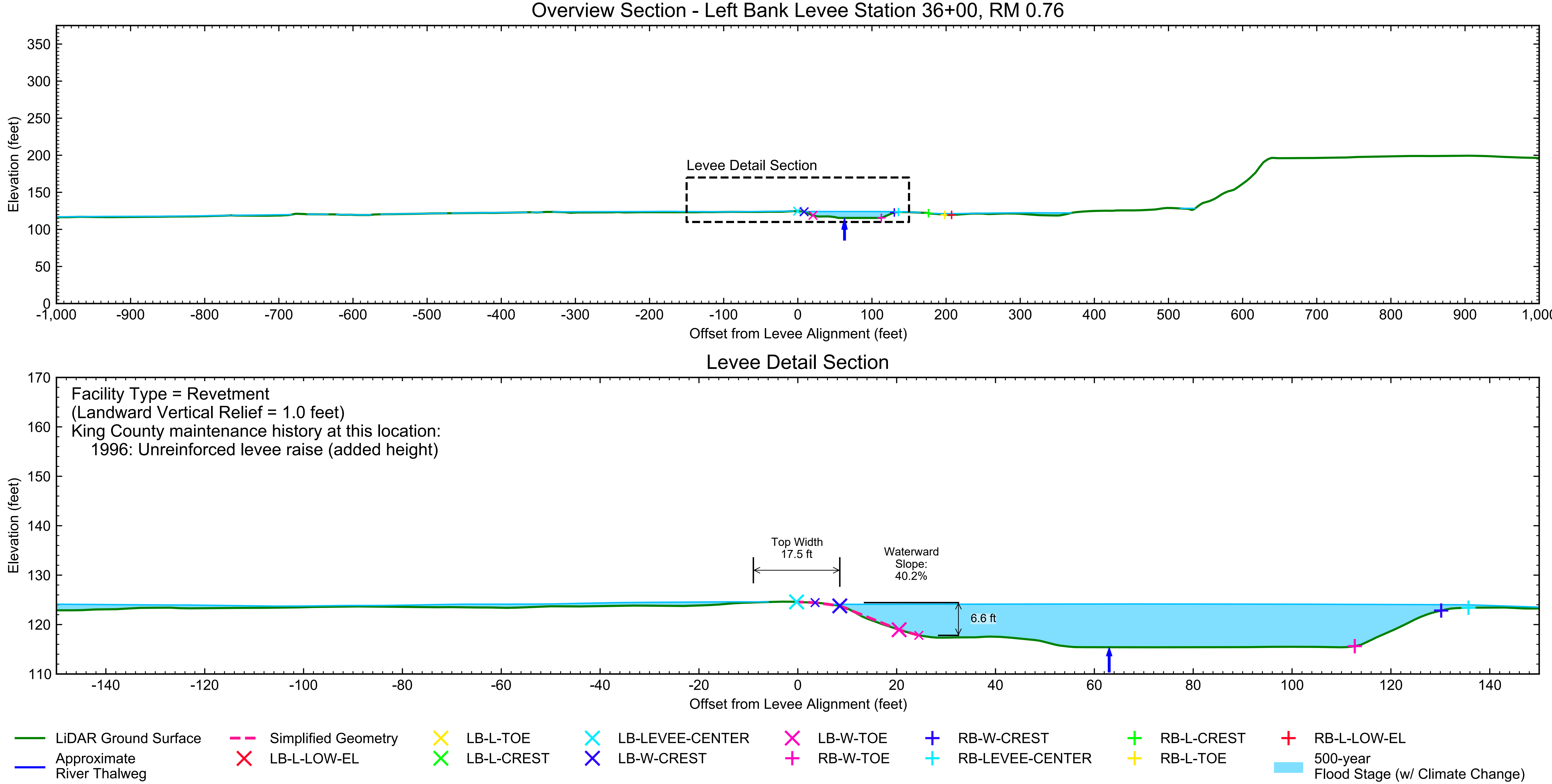

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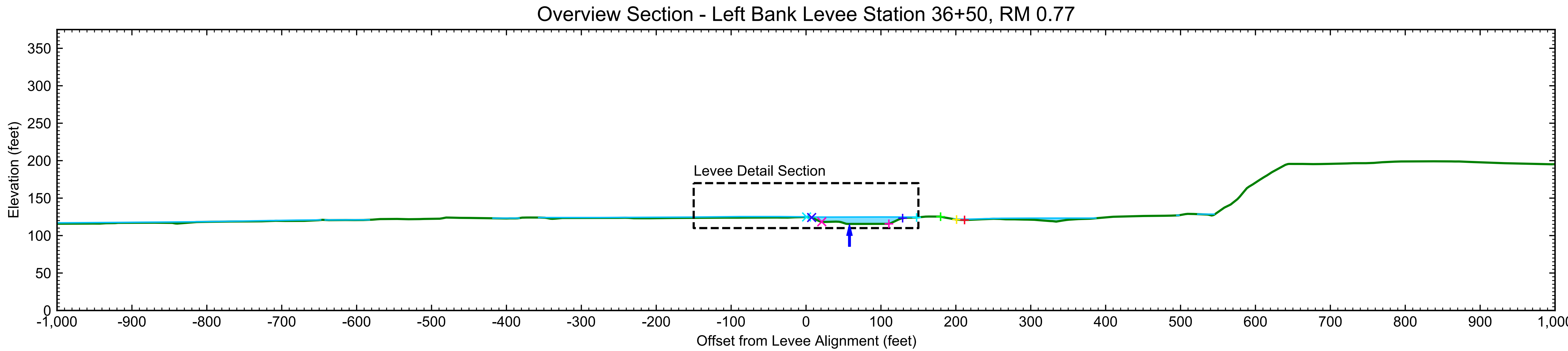
FIG. A-72



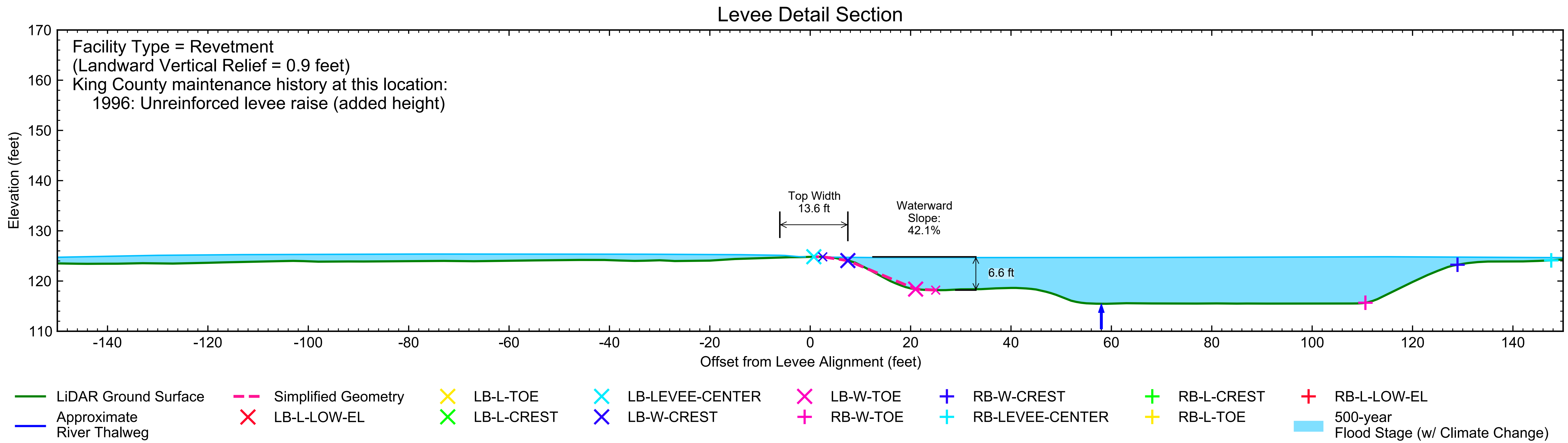


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FIG. A-73

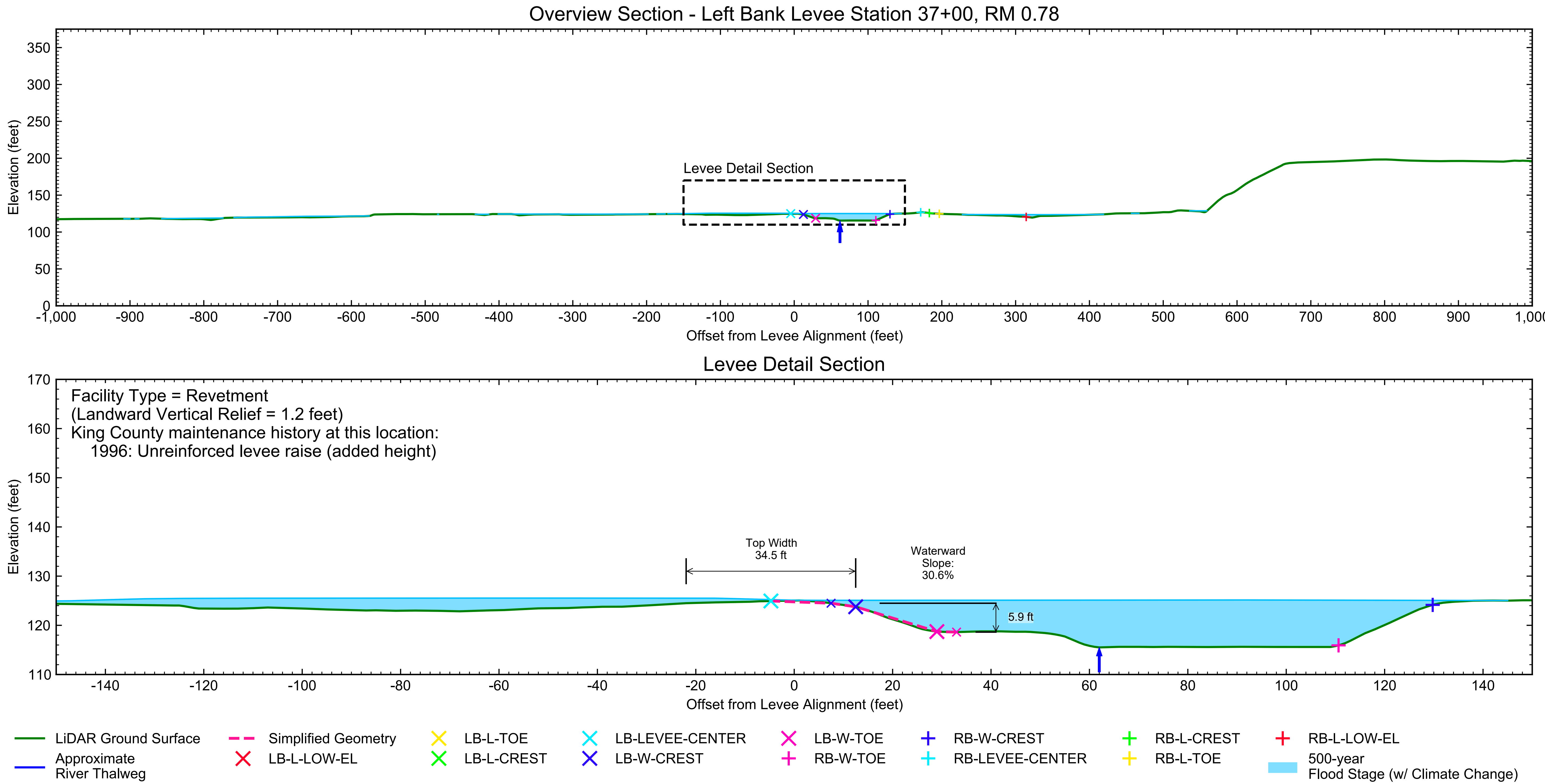

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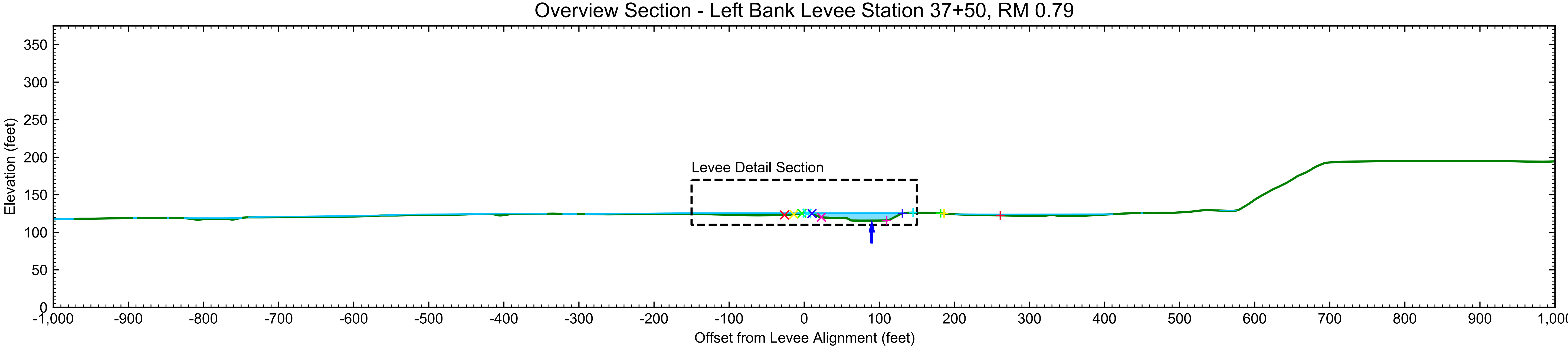
FIG. A-74



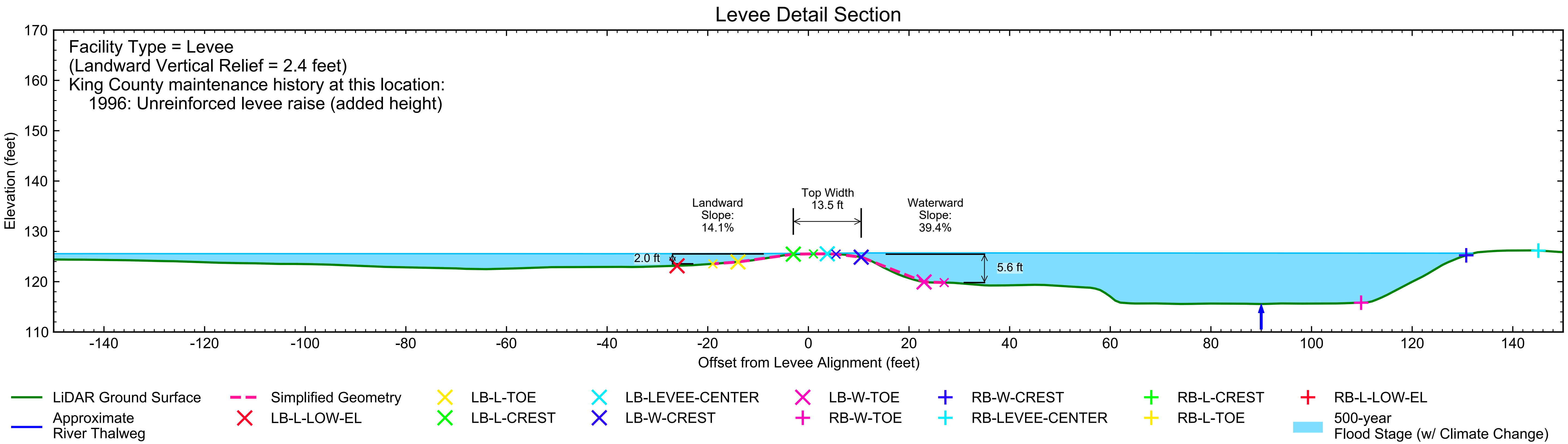


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FIG. A-75

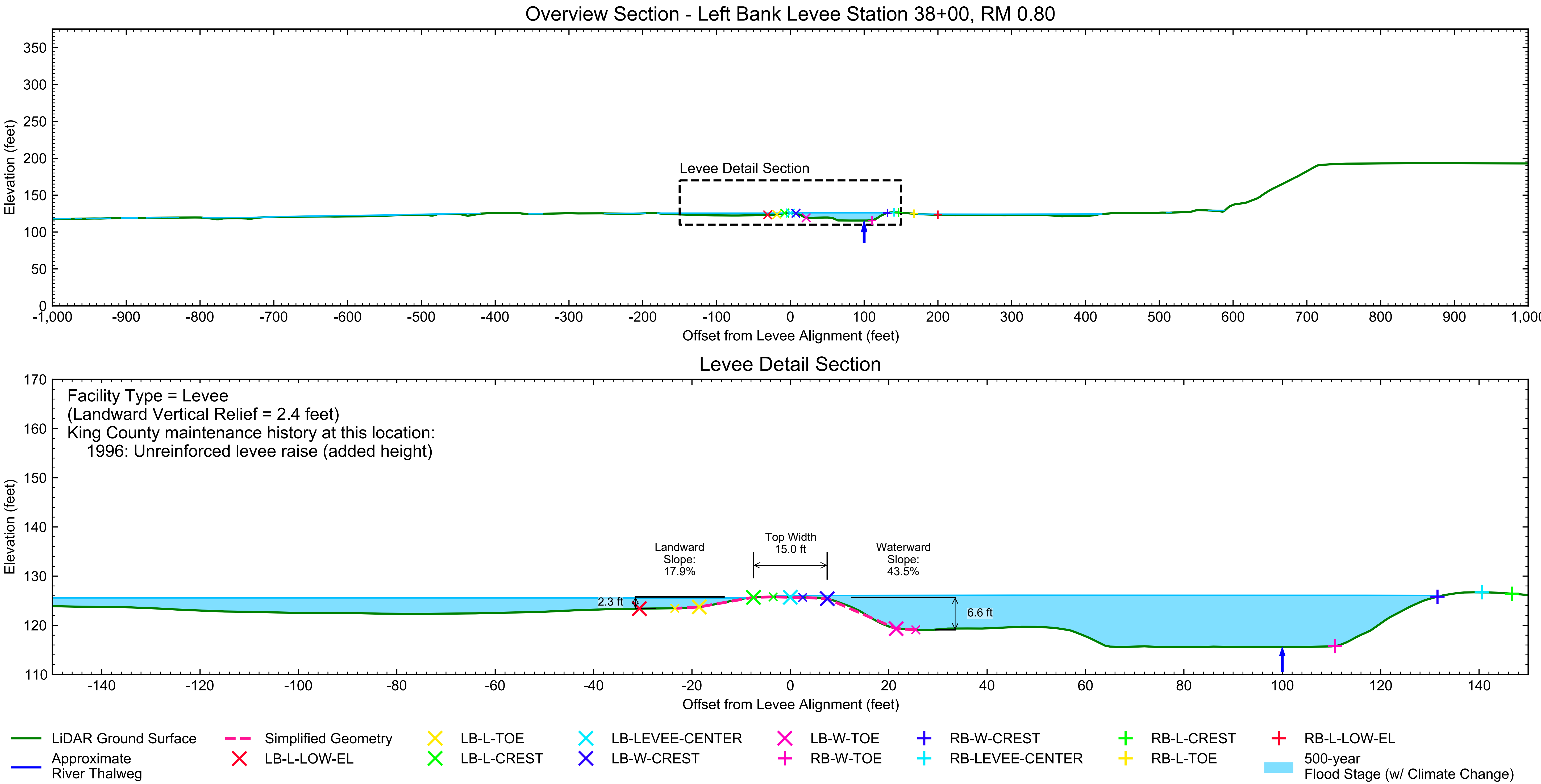

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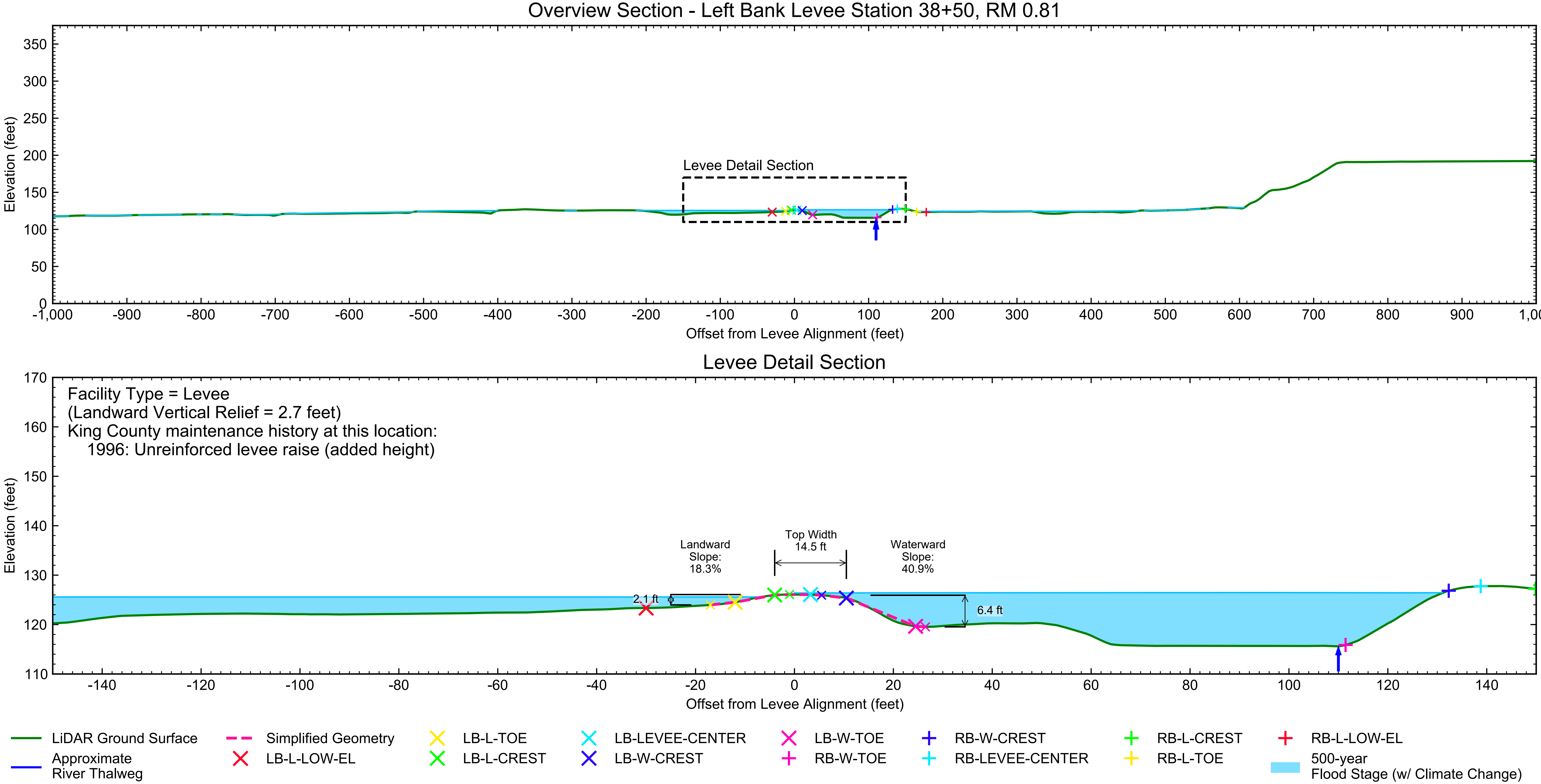
FIG. A-76



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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 38+50, RM 0.81

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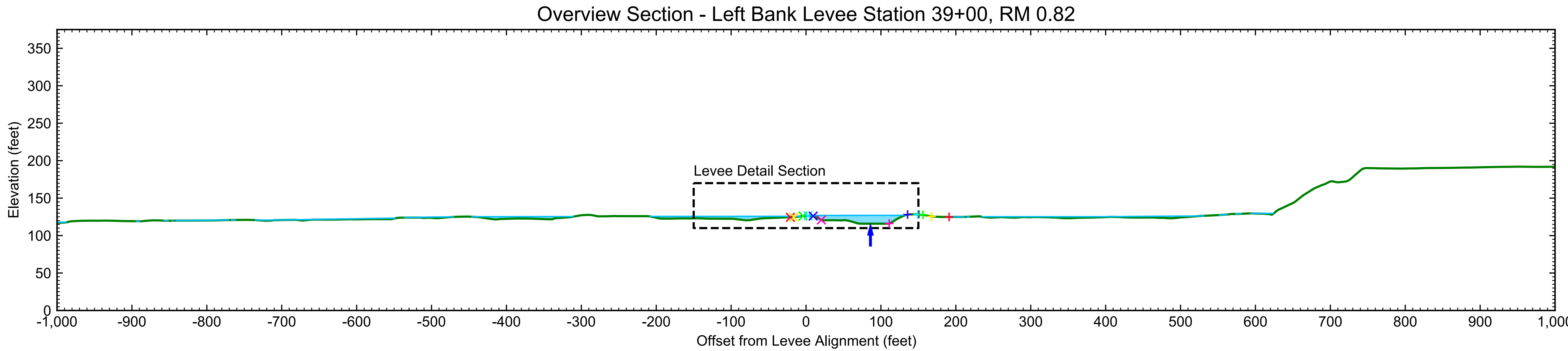
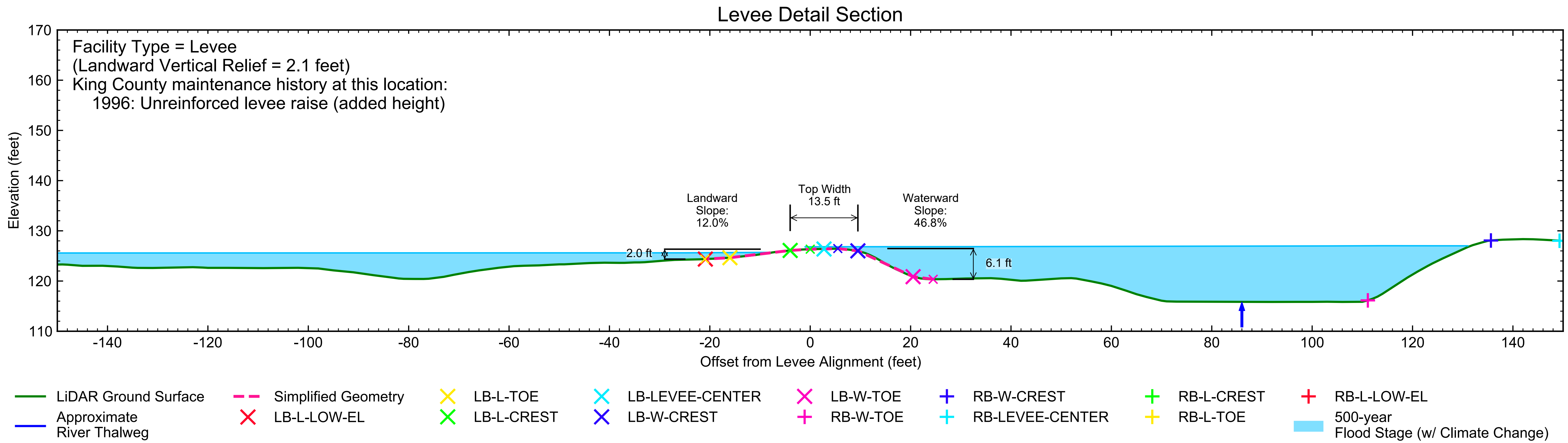
Geotechnical and Environmental Consultants

FIG. A-77





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 39+00, RM 0.82

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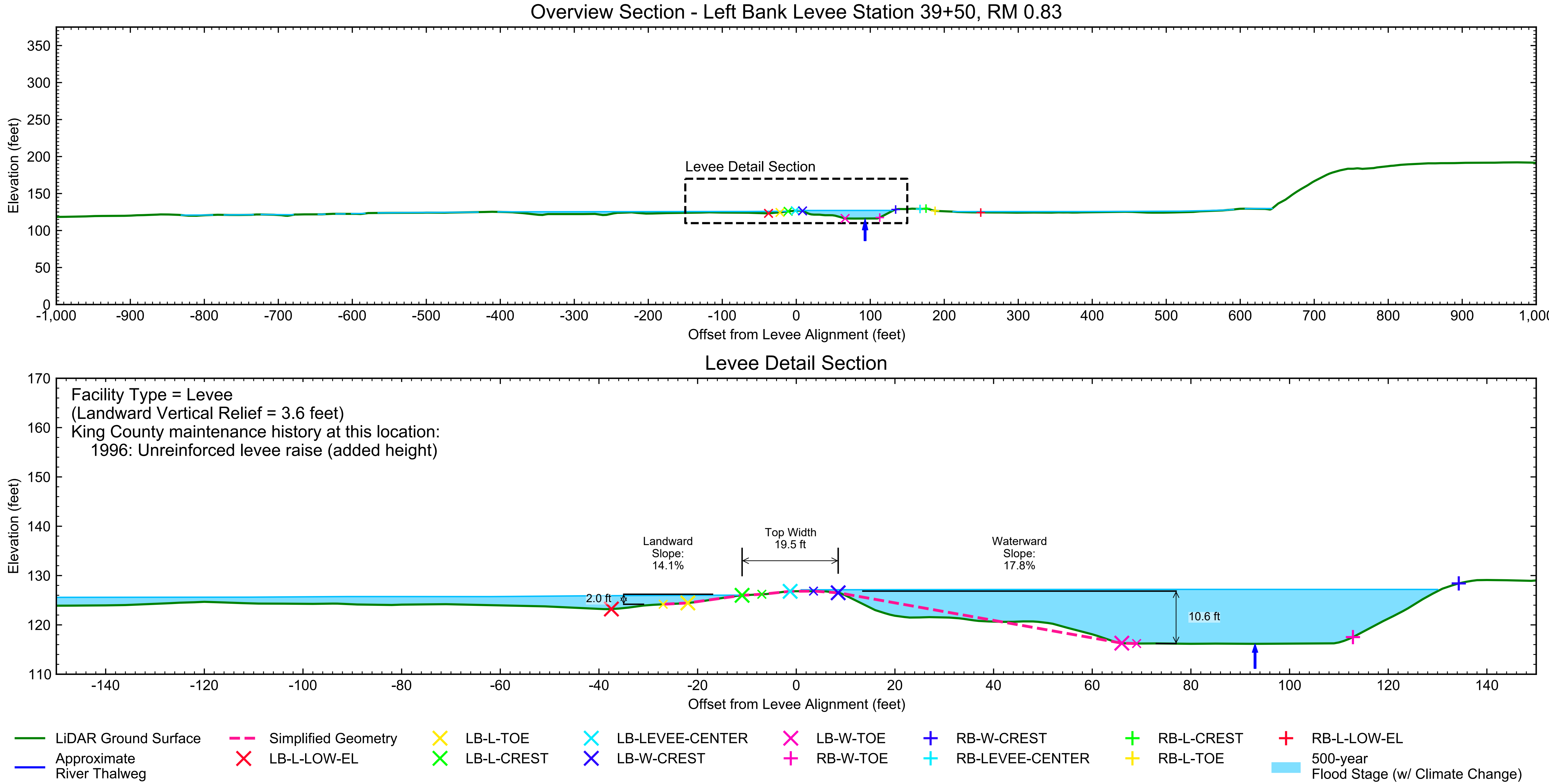
FIG. A-78



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 39+50, RM 0.83

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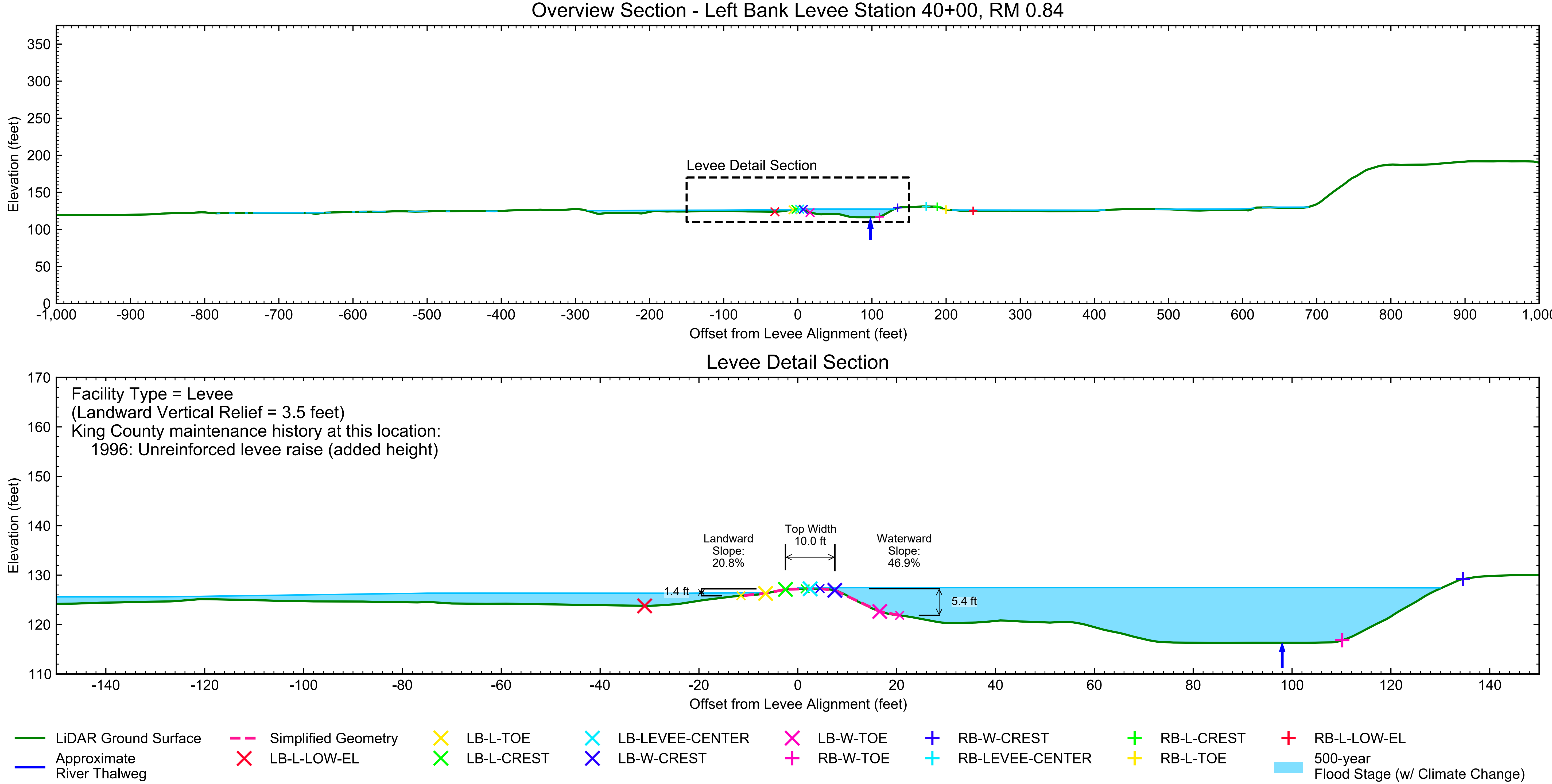
FIG. A-79



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 40+00, RM 0.84

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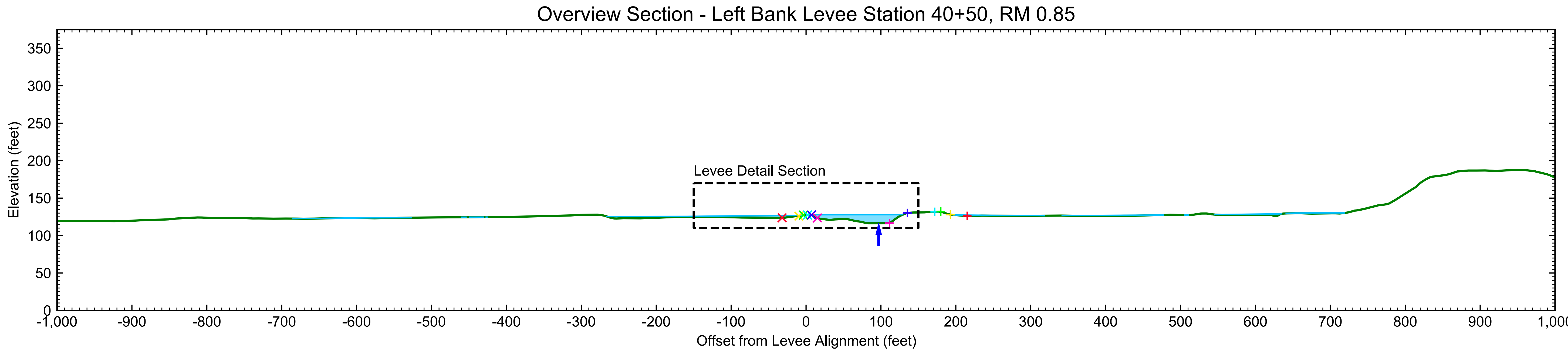
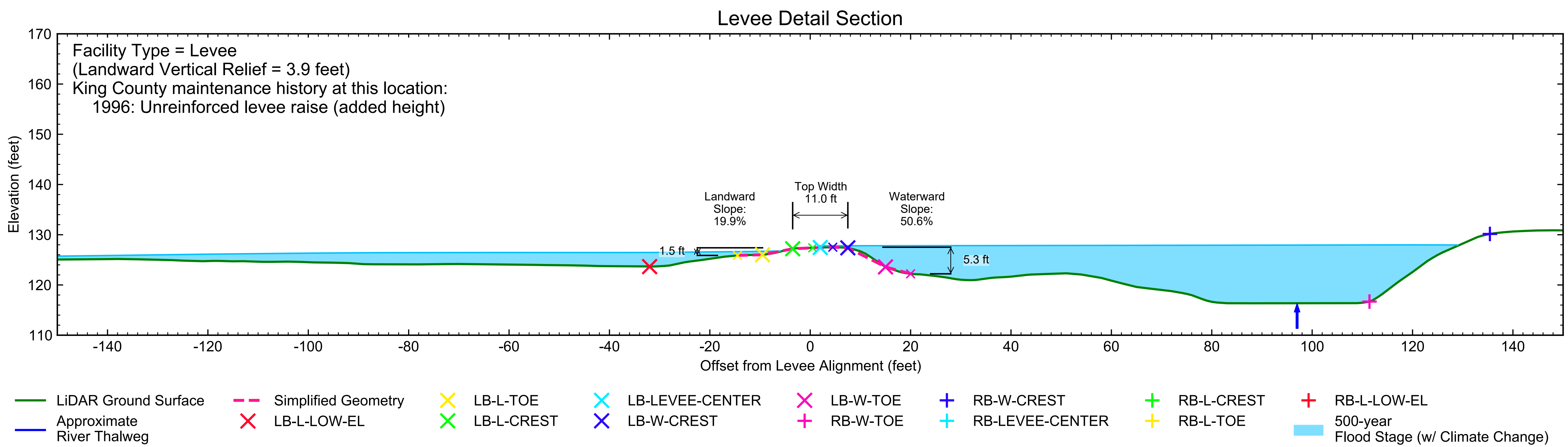
FIG. A-80





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 40+50, RM 0.85

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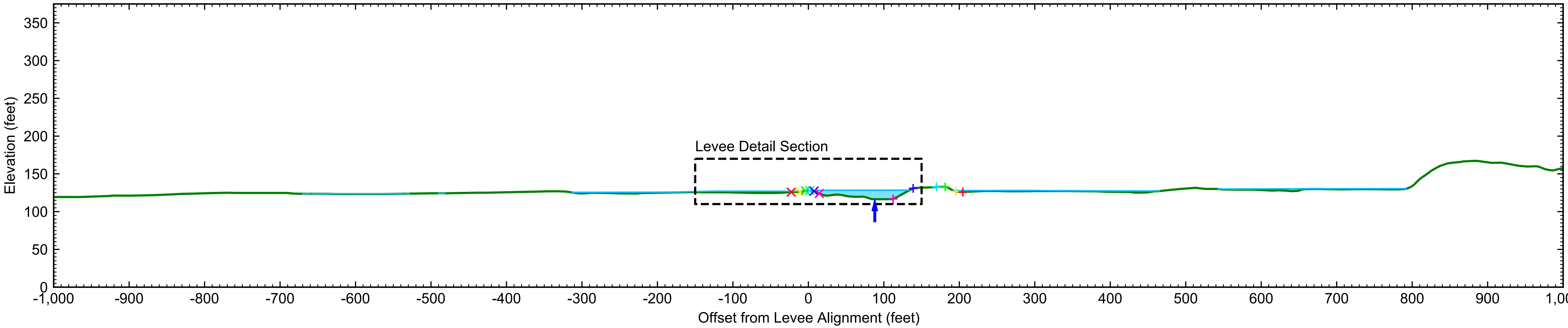
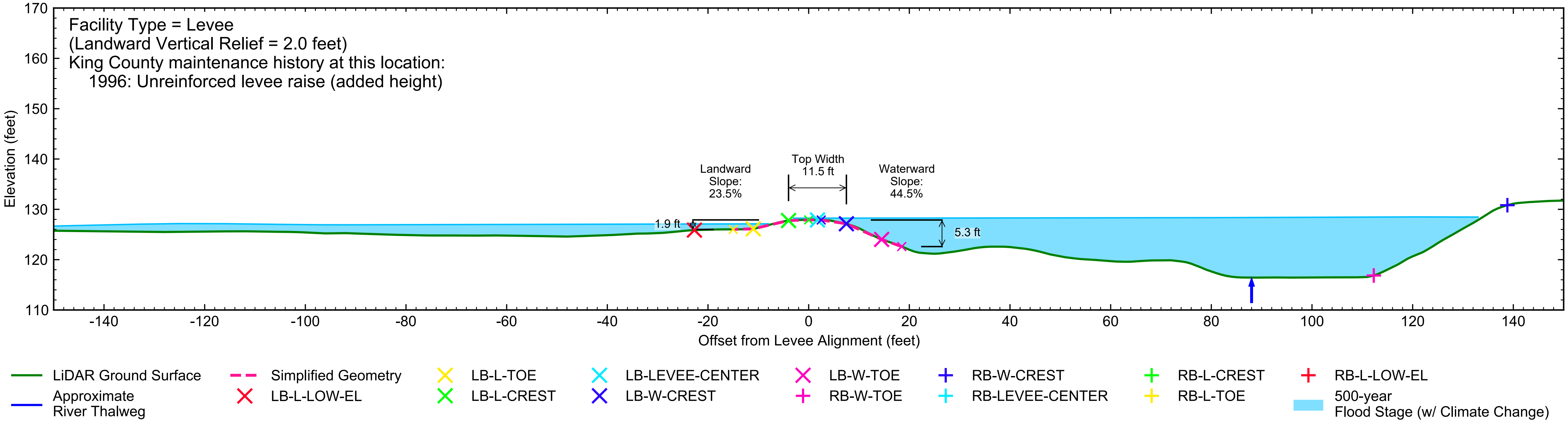
FIG. A-81

Overview Section - Left Bank Levee Station 41+00, RM 0.86



Levee Detail Section



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 41+00, RM 0.86

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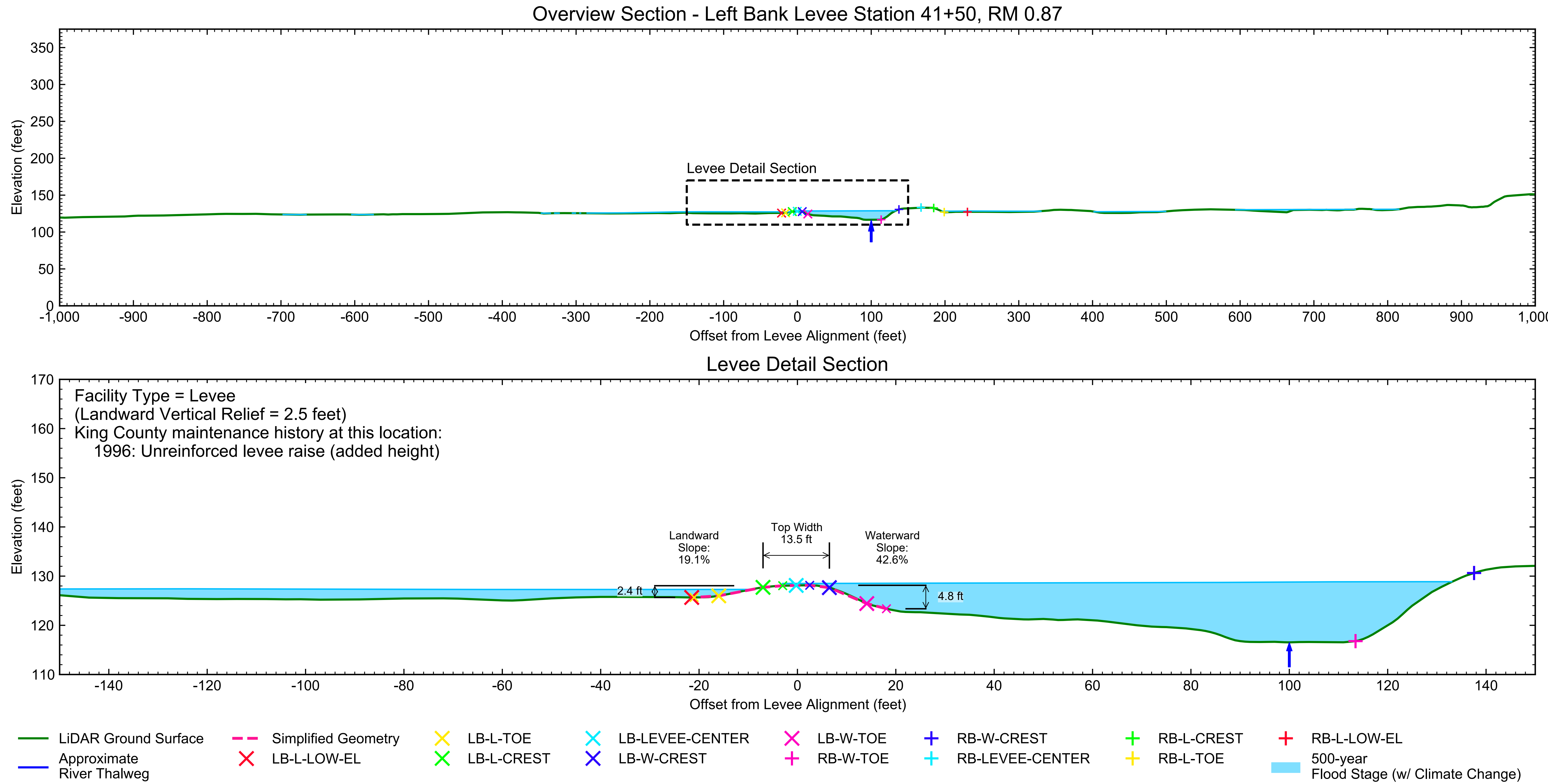
FIG. A-82

ver:0.14.0.post1+gf81b80b, by:OTH

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04. Levee Stability Assess\Levee Geometric Data



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 41+50, RM 0.87

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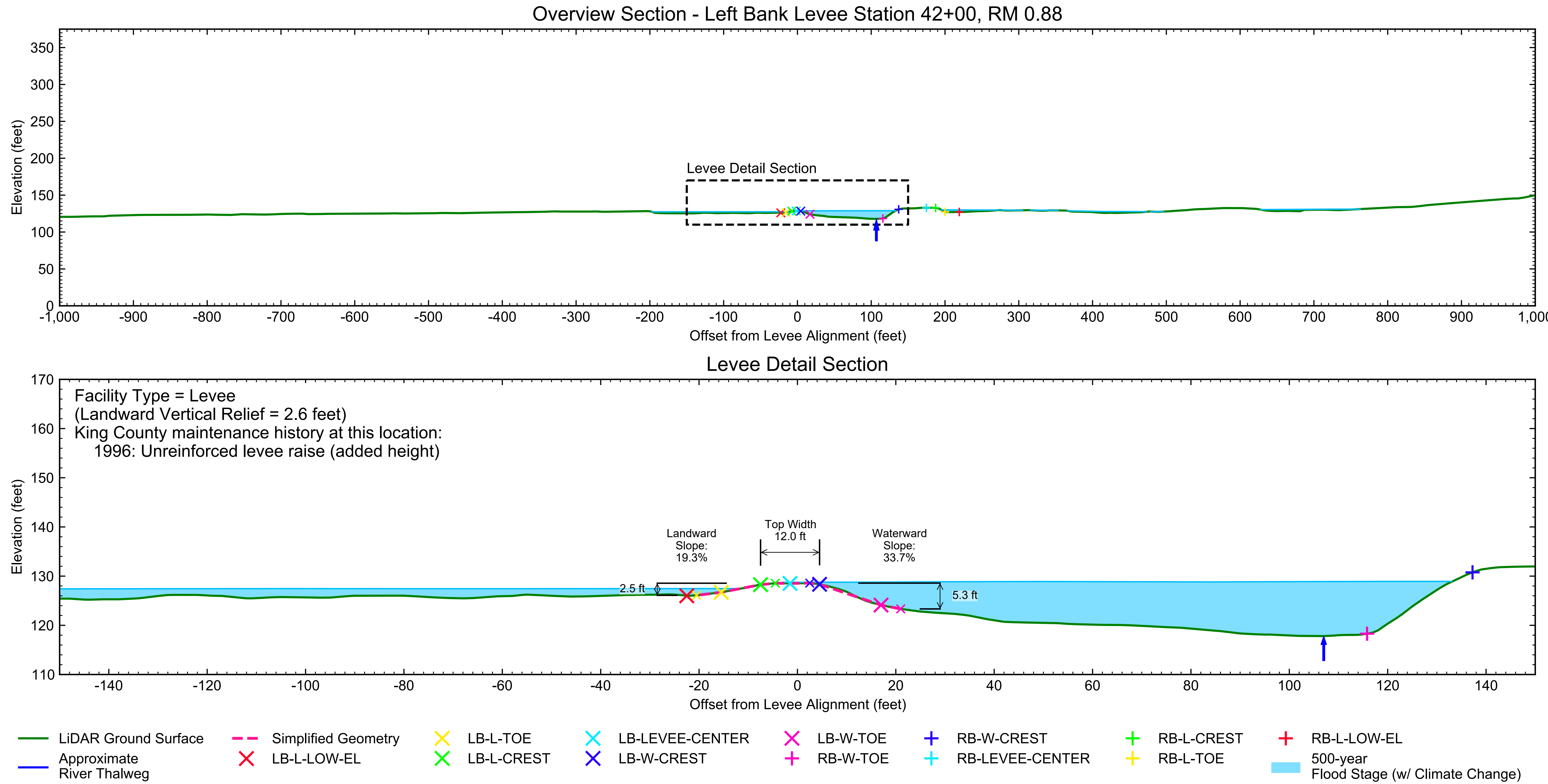
FIG. A-83



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 42+00, RM 0.88

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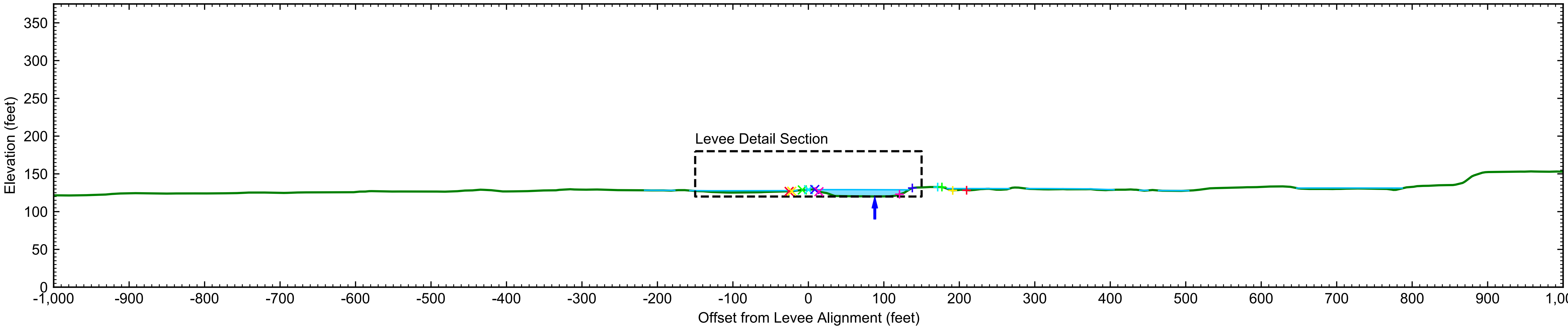
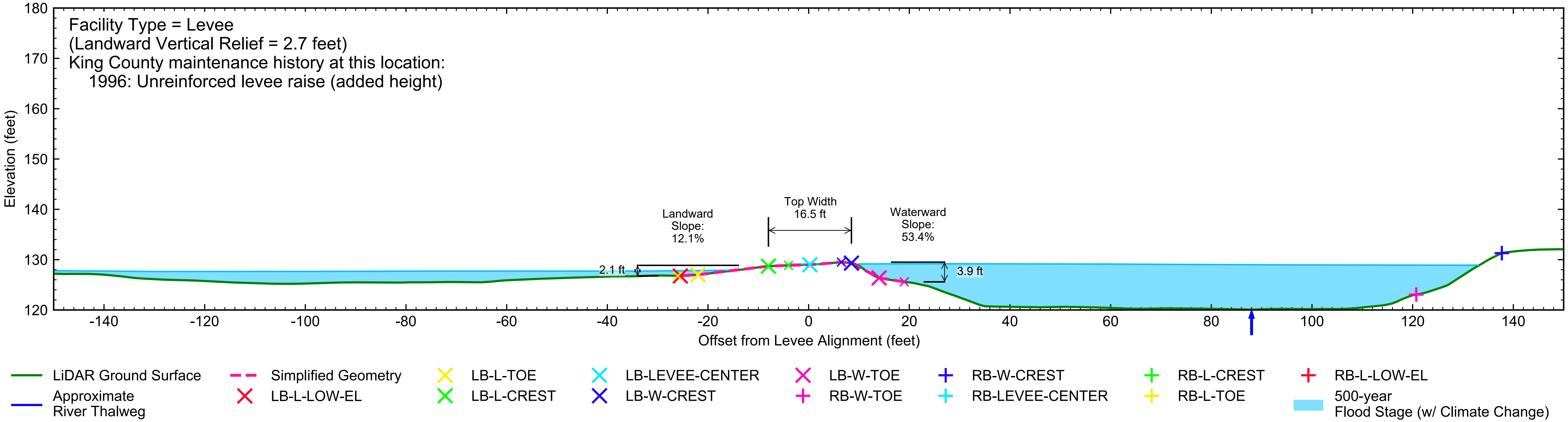
FIG. A-84

Overview Section - Left Bank Levee Station 42+50, RM 0.89



Levee Detail Section



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 42+50, RM 0.89

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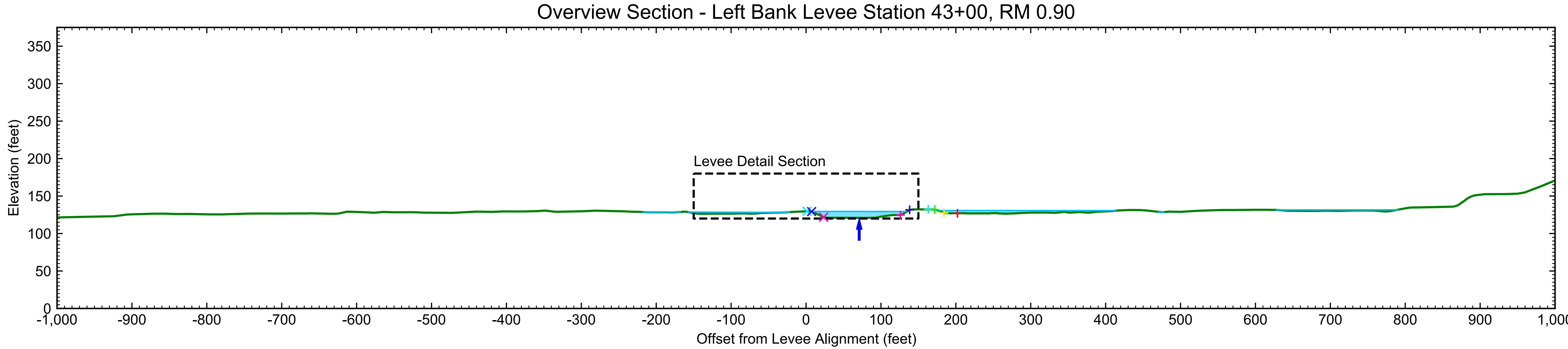
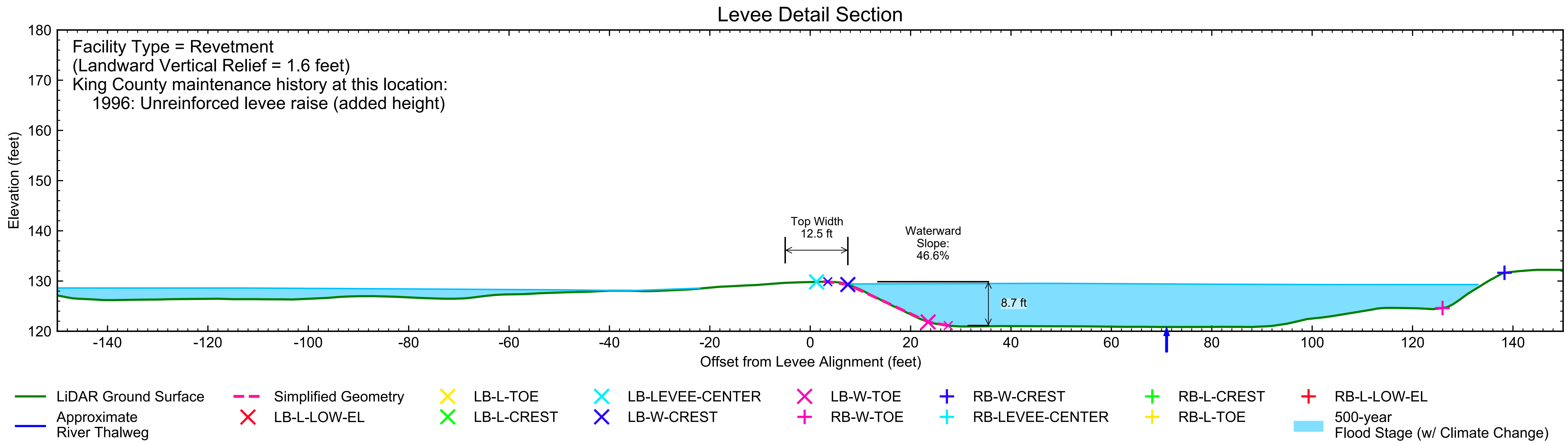
FIG. A-85





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 43+00, RM 0.90

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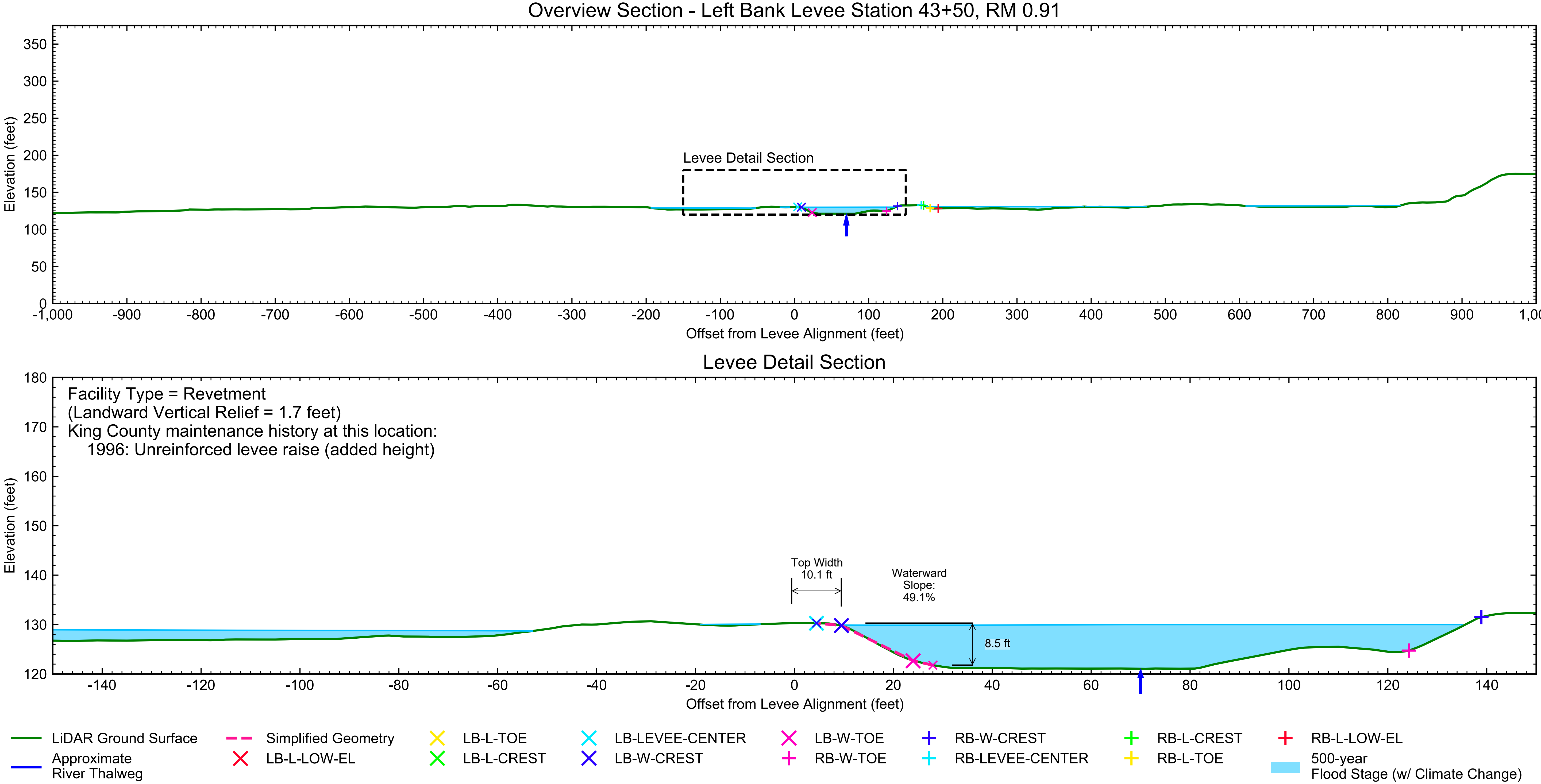
FIG. A-86



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 43+50, RM 0.91

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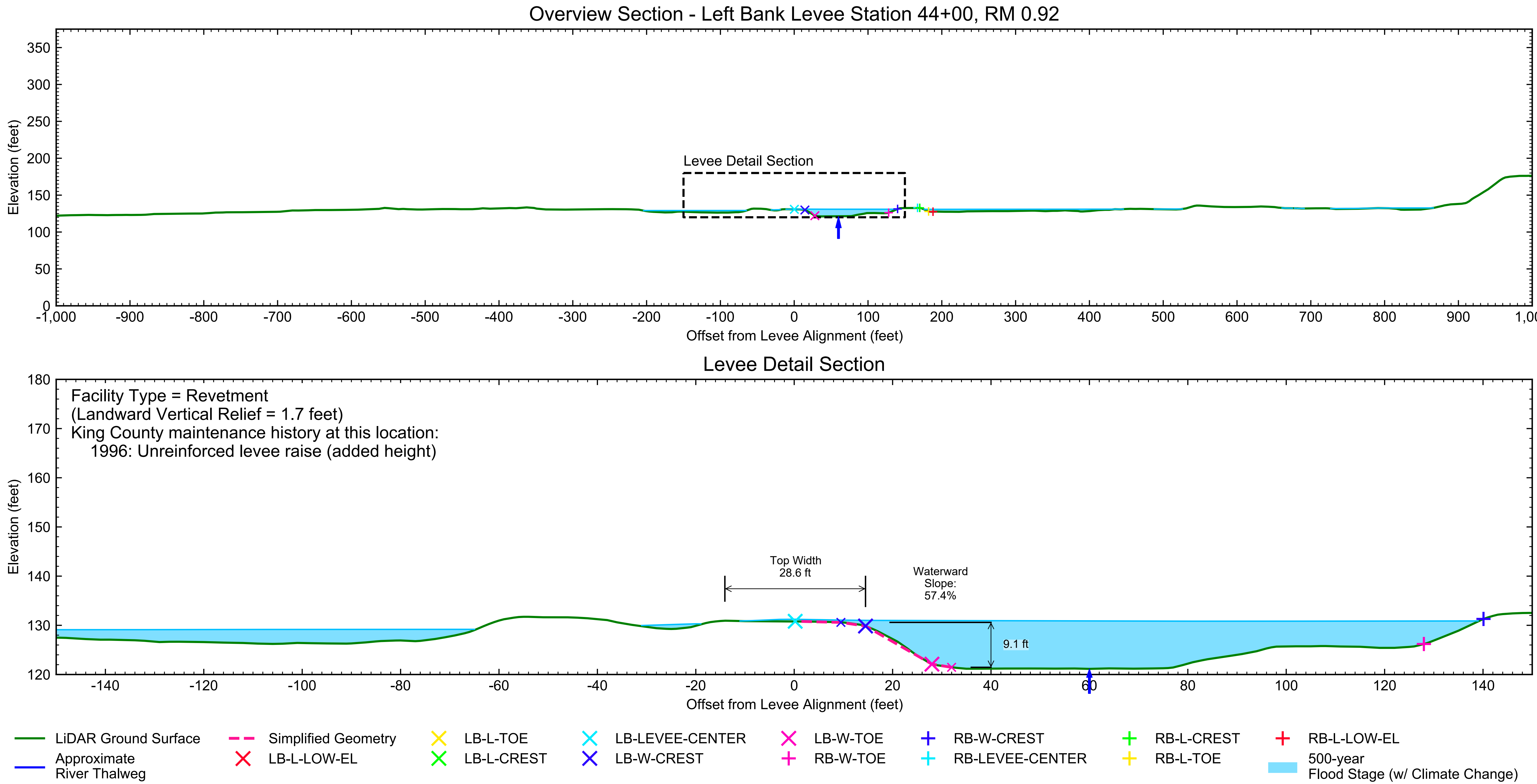
FIG. A-87



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 44+00, RM 0.92

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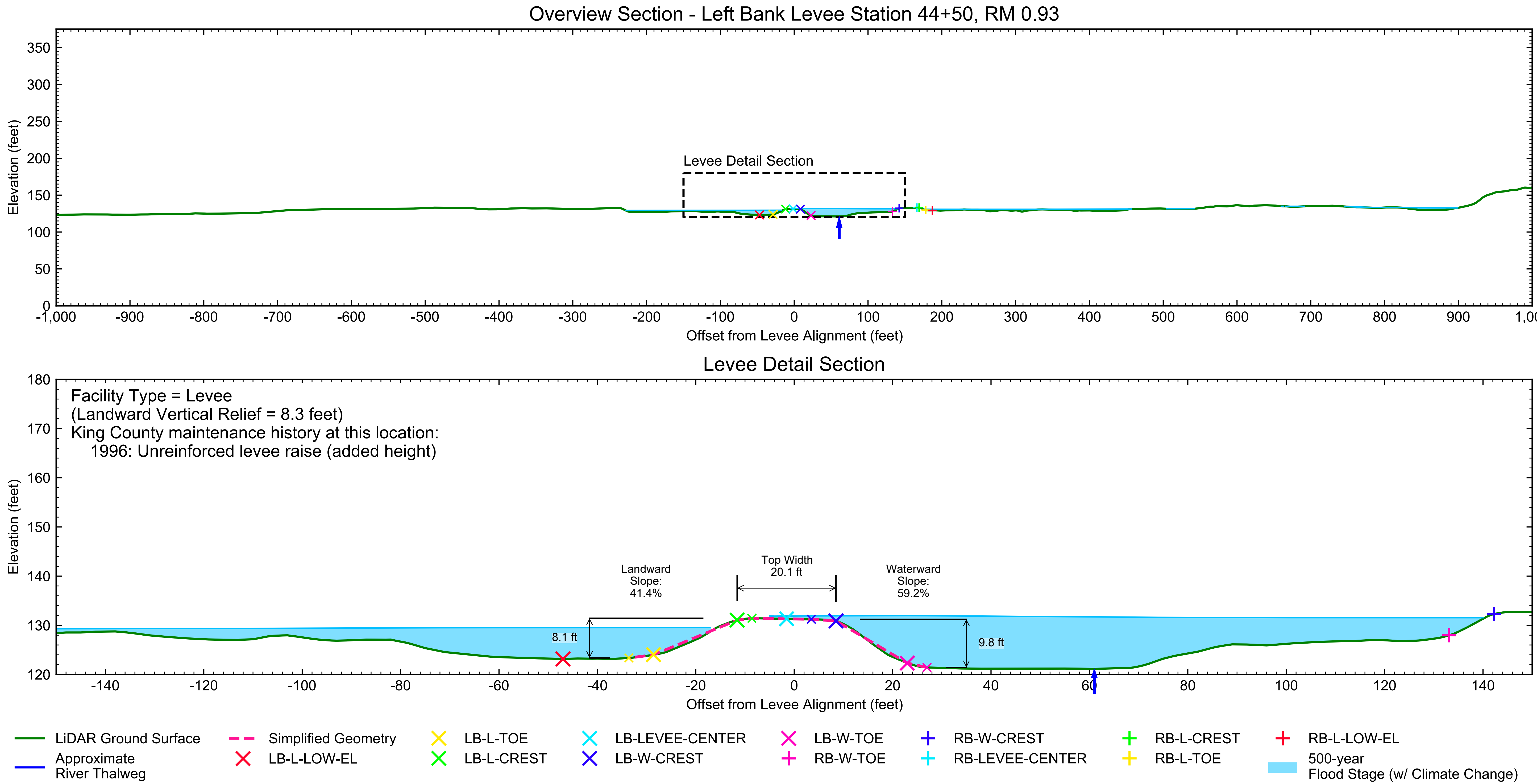
FIG. A-88



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 44+50, RM 0.93

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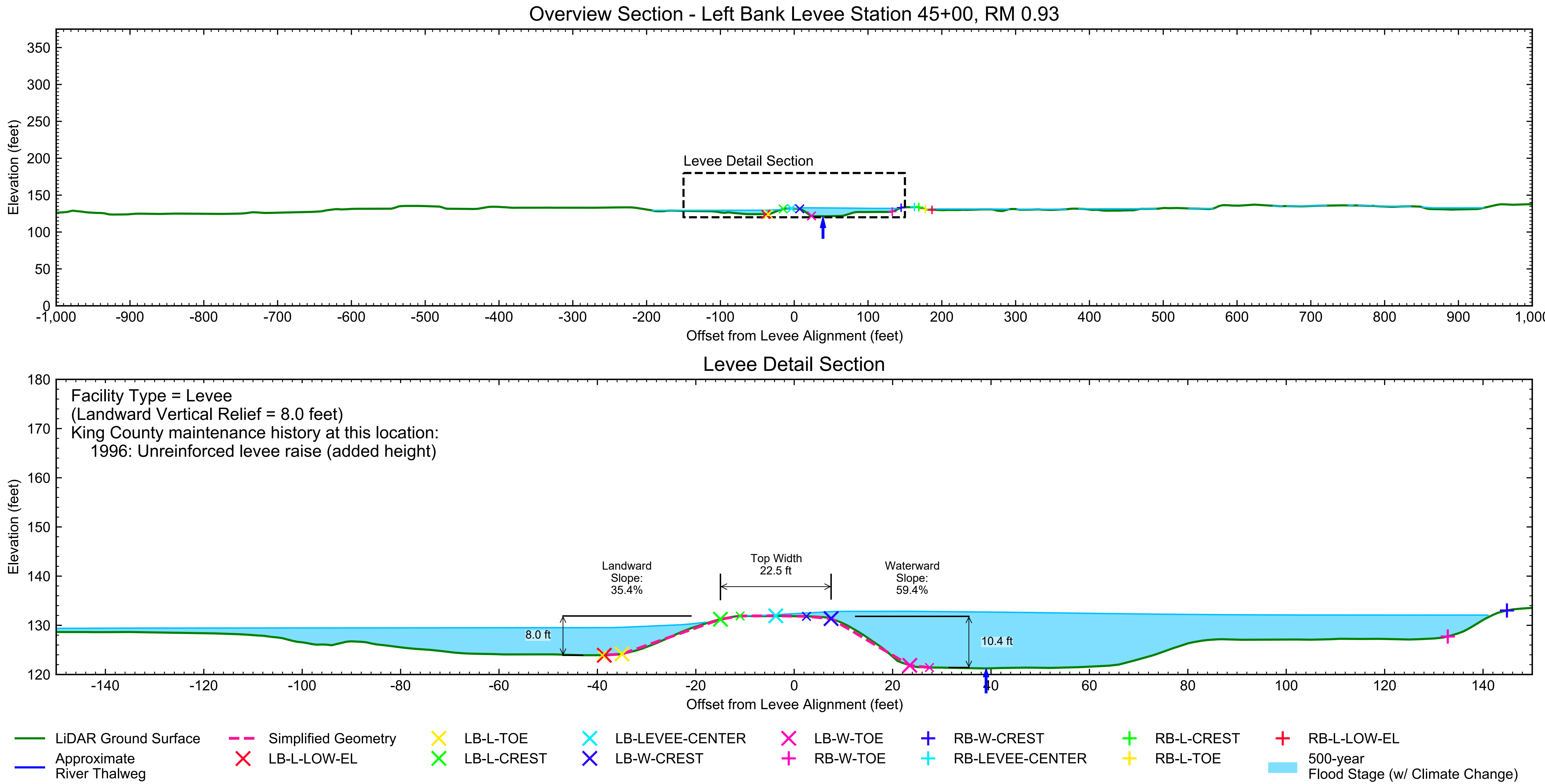
FIG. A-89



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LIDAR CROSS SECTION
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LEFT BANK STA 45+00, RM 0.93

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FIG. A-90

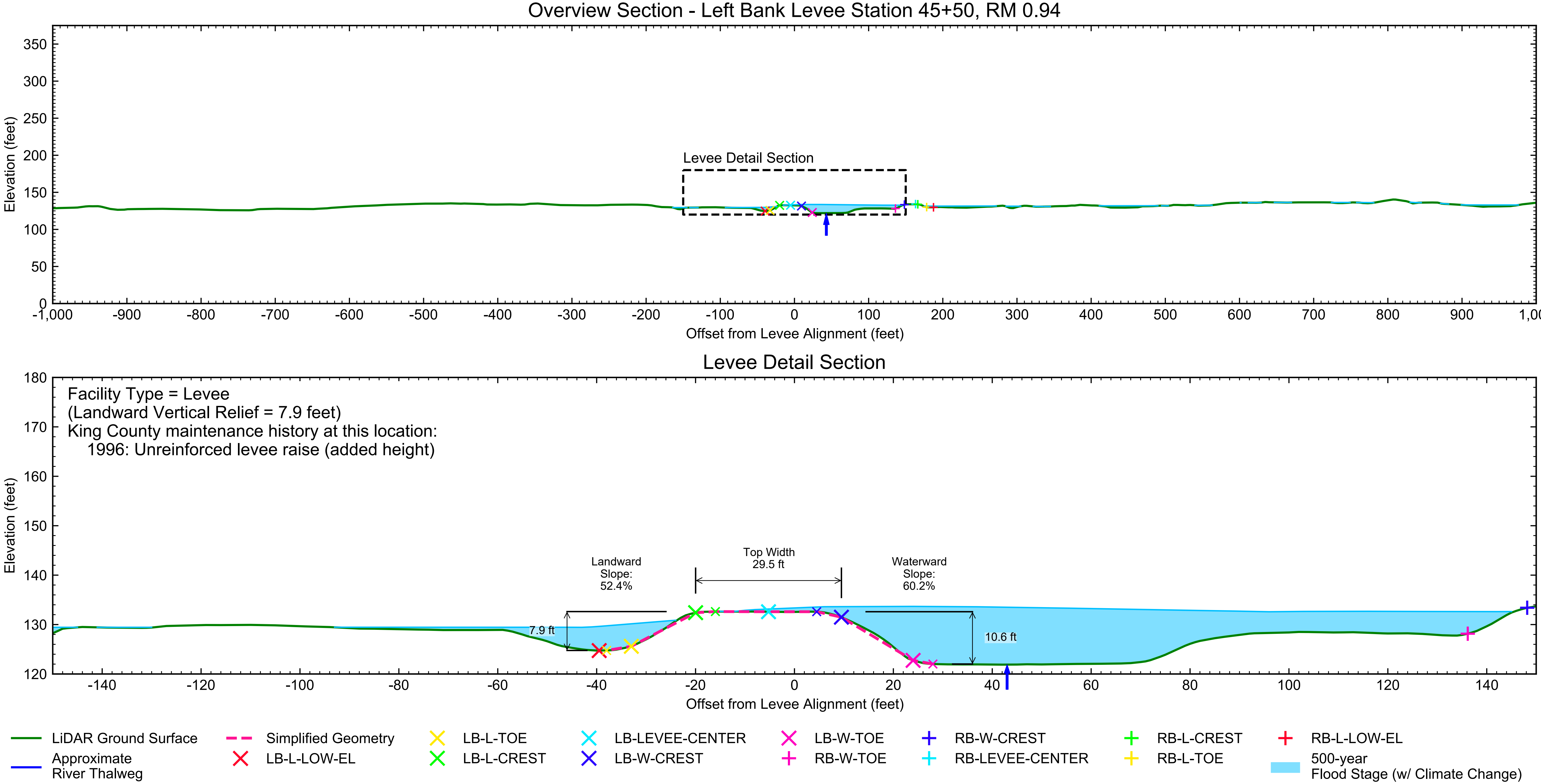

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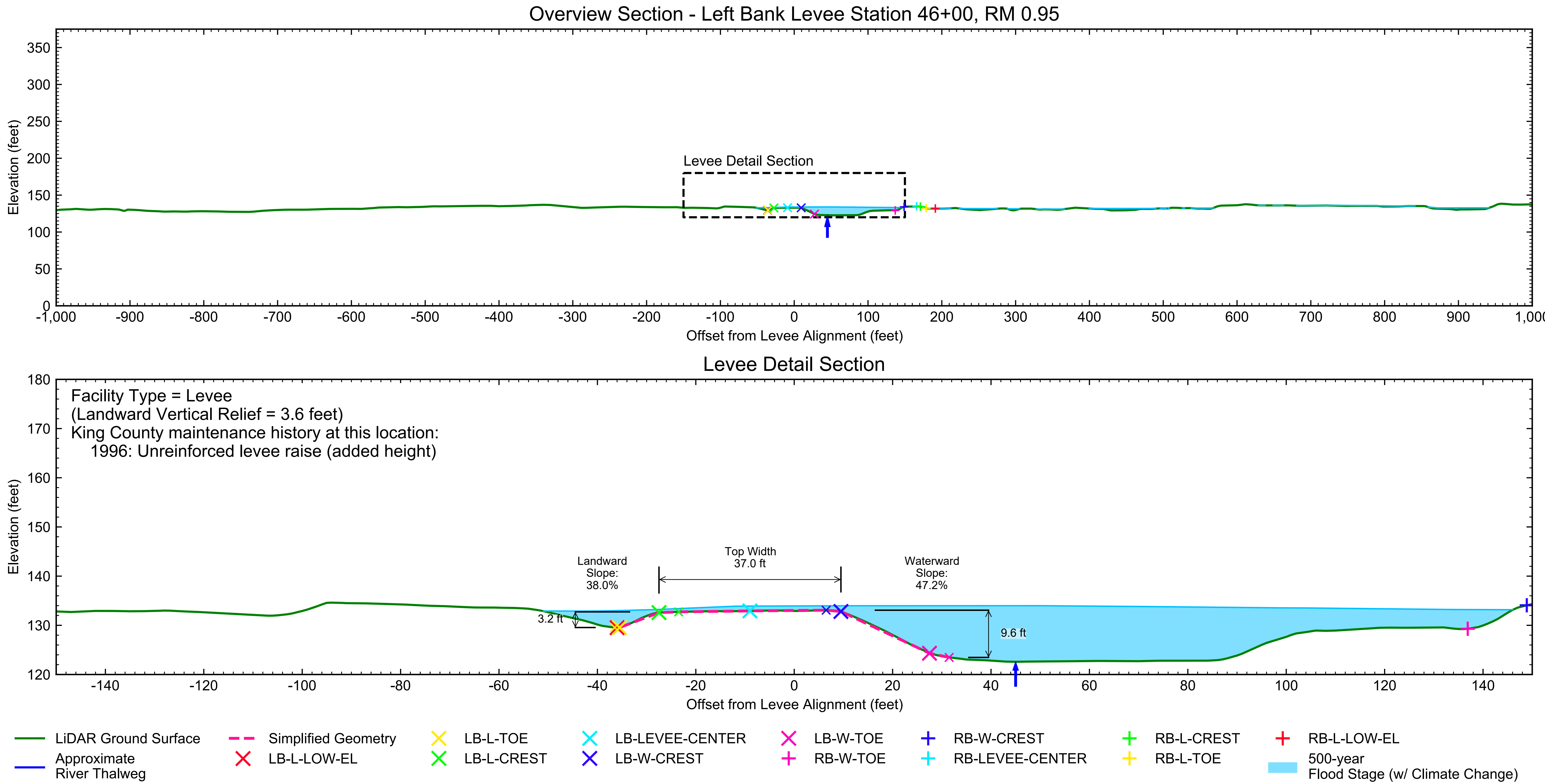
FIG. A-91



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LIDAR CROSS SECTION
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LEFT BANK STA 46+00, RM 0.95

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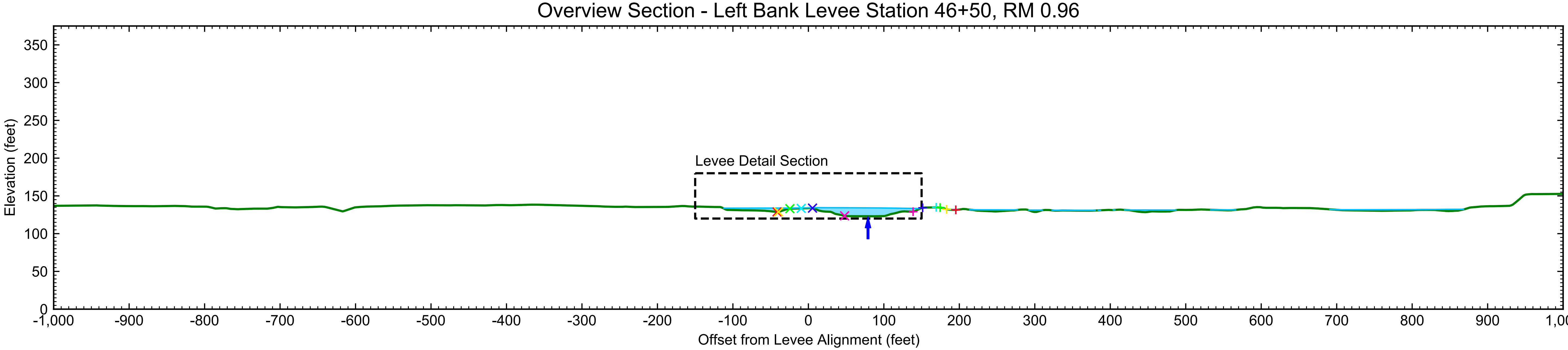
FIG. A-92



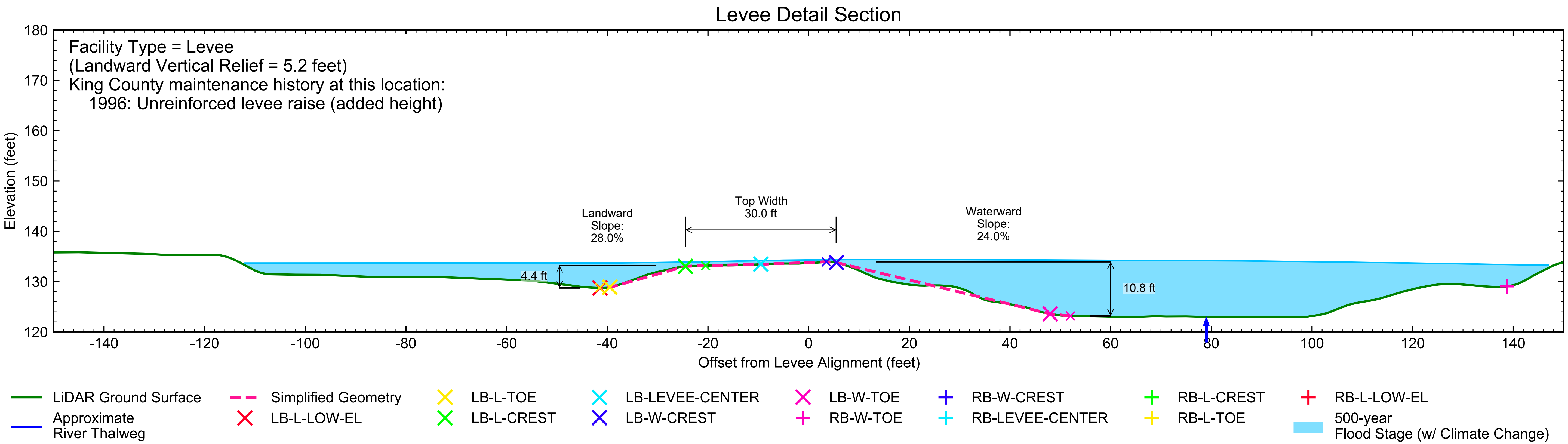


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FIG. A-93

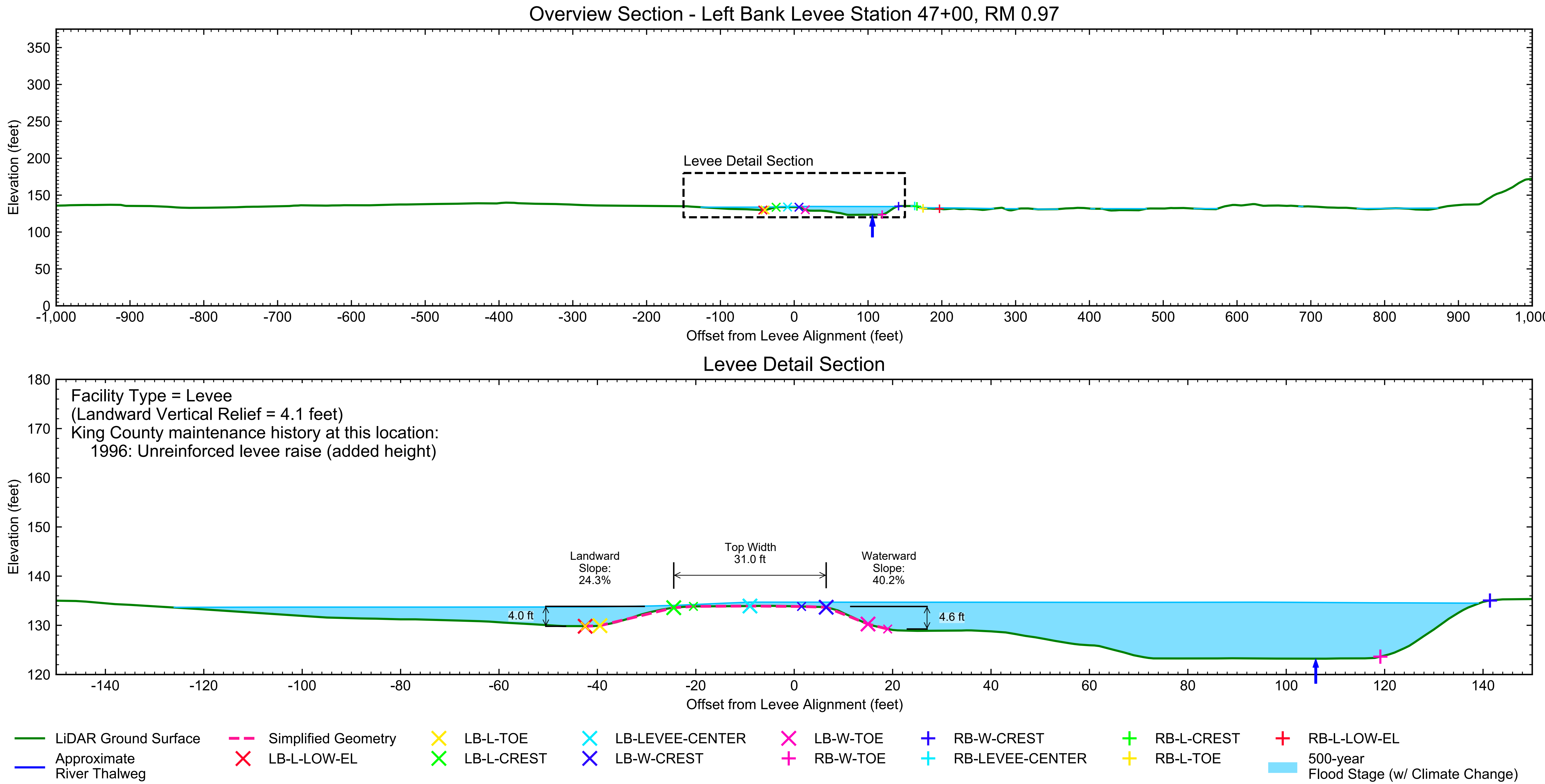

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FIG. A-94

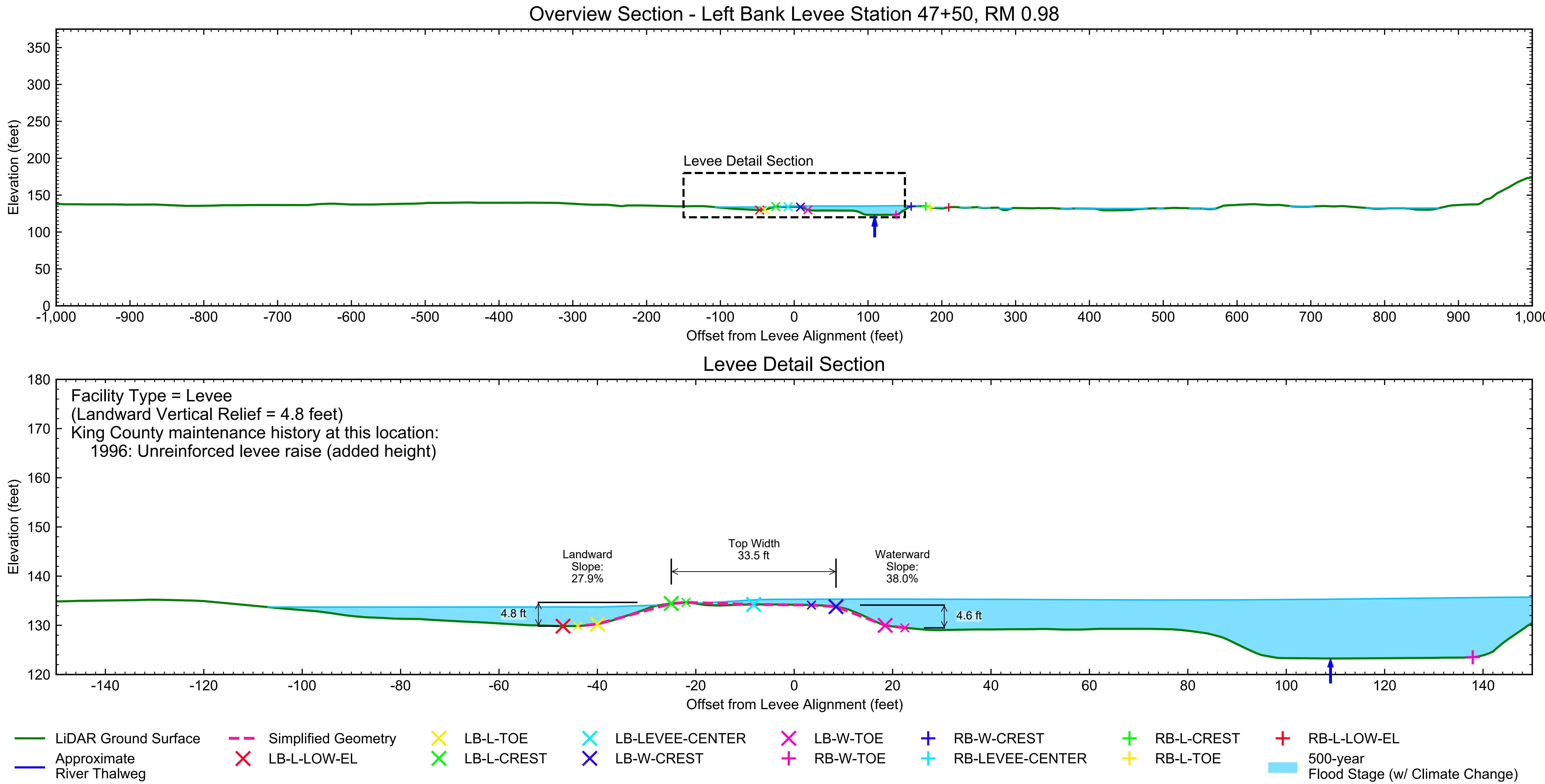

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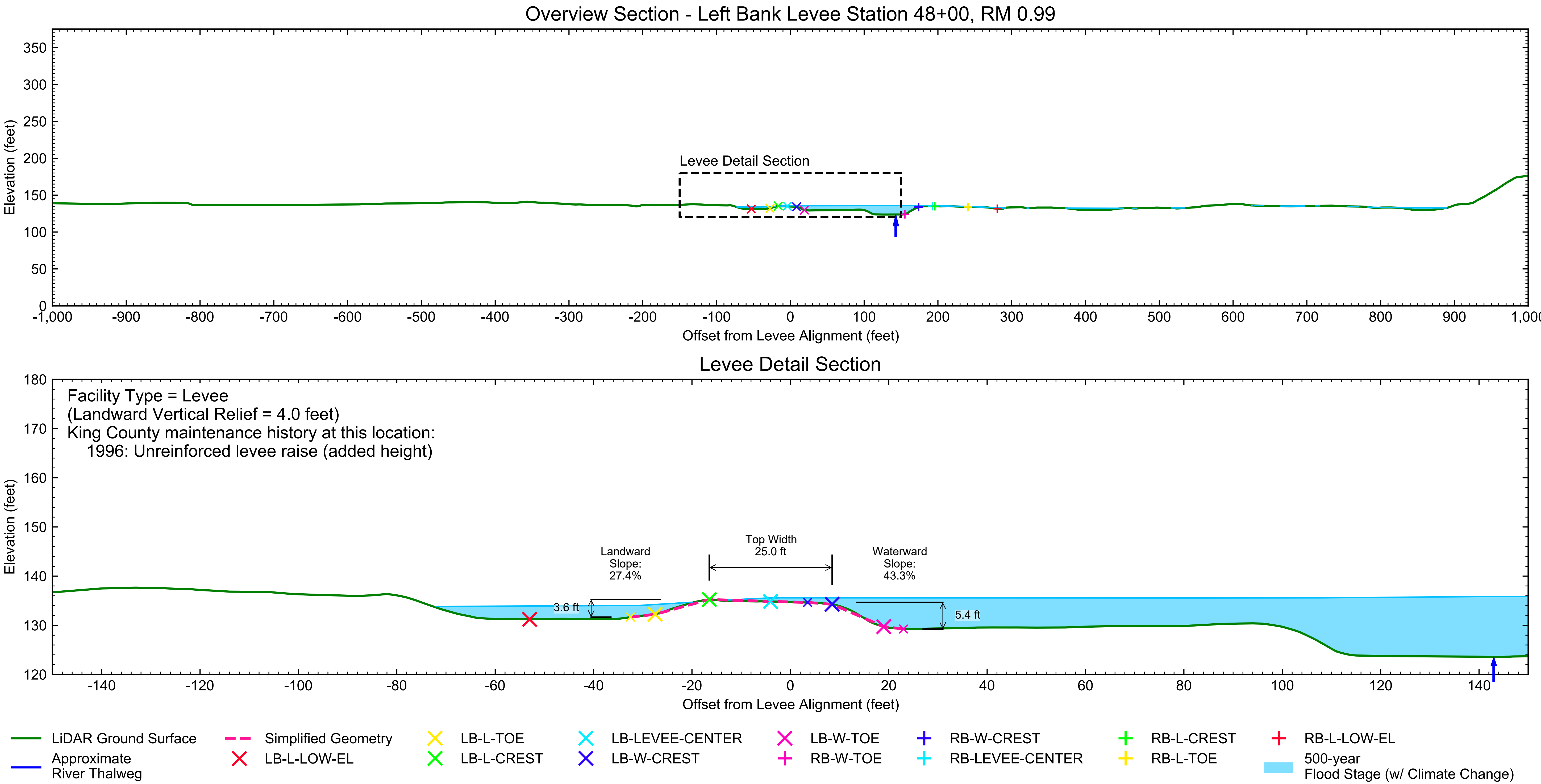
FIG. A-95



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LIDAR CROSS SECTION
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FIG. A-96

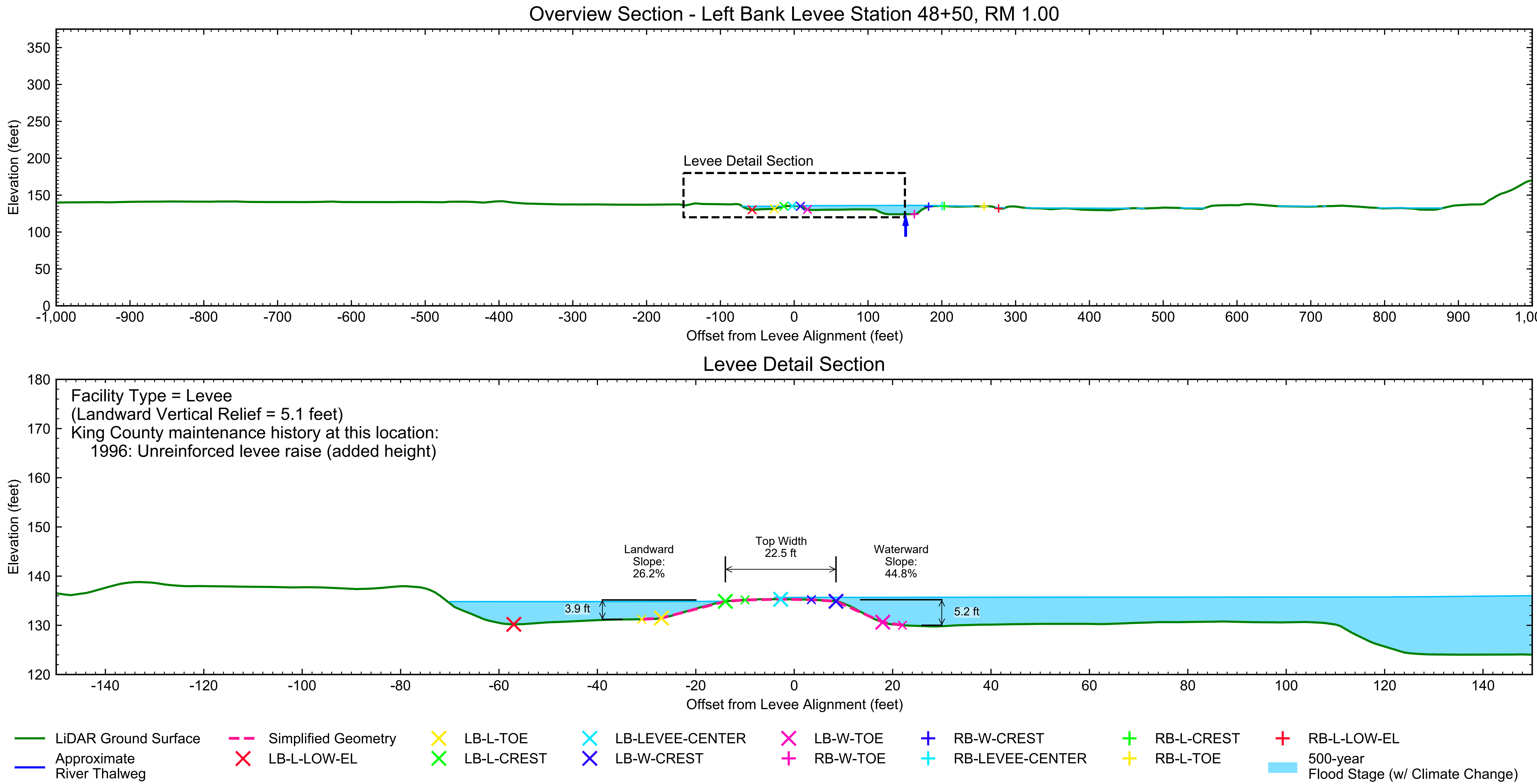

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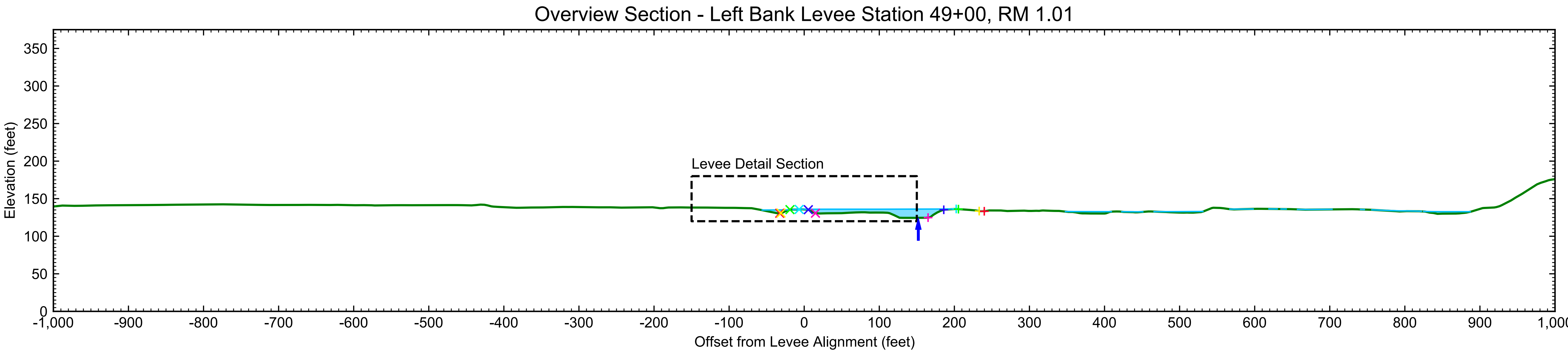
FIG. A-97



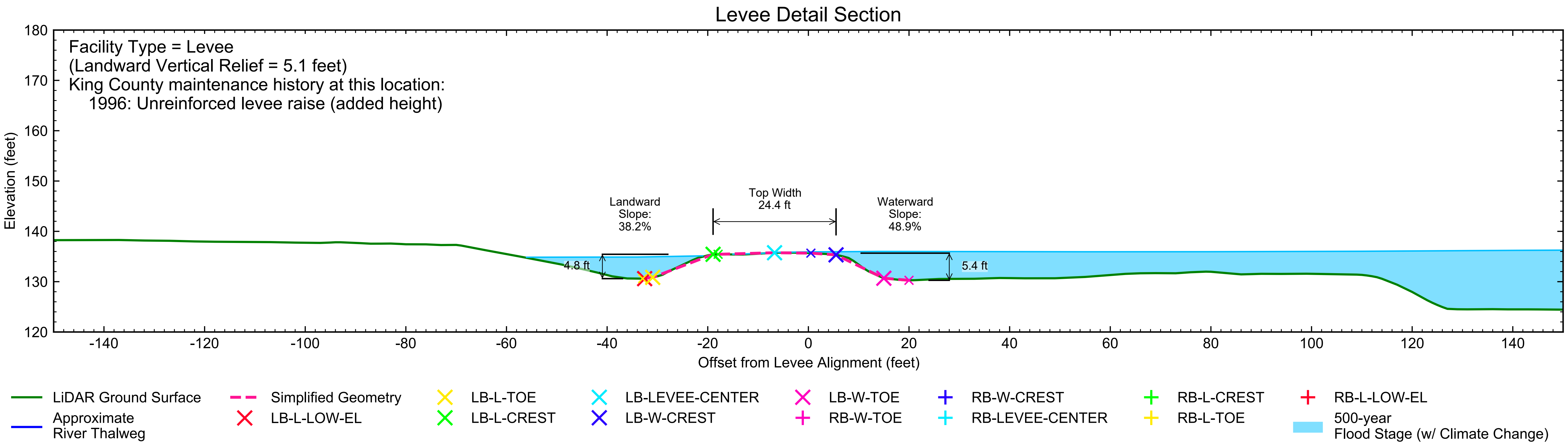


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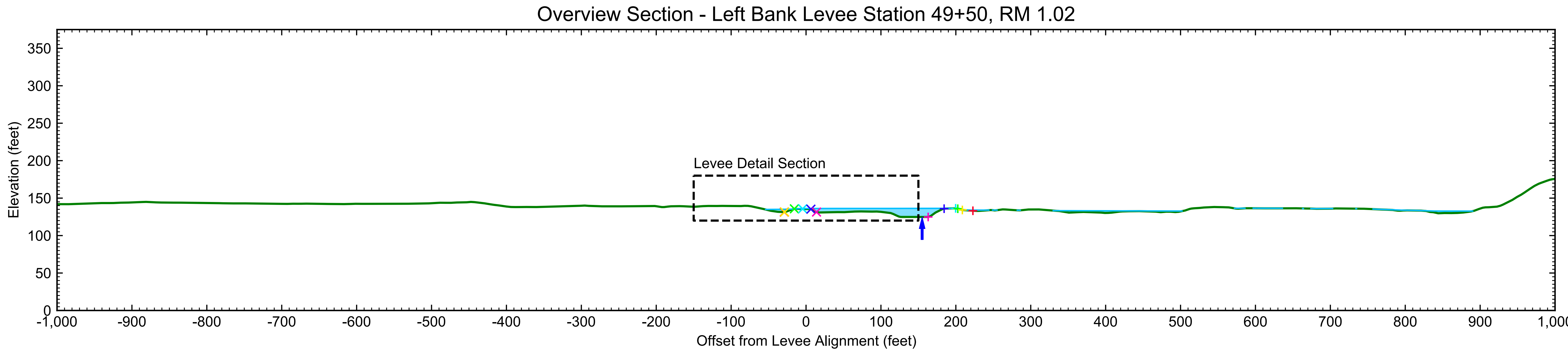
FIG. A-98



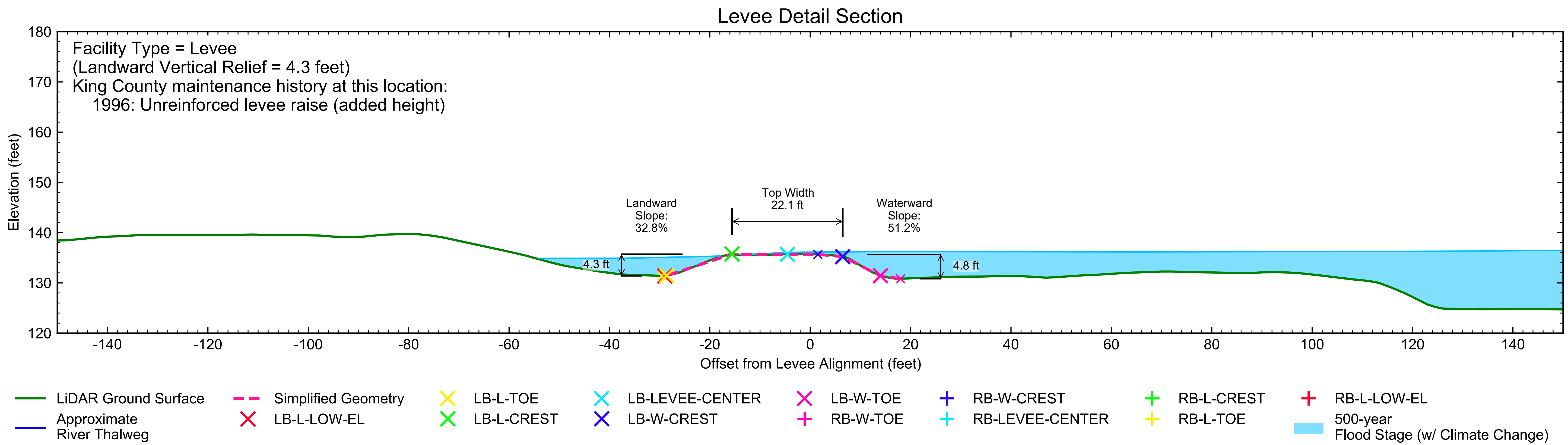


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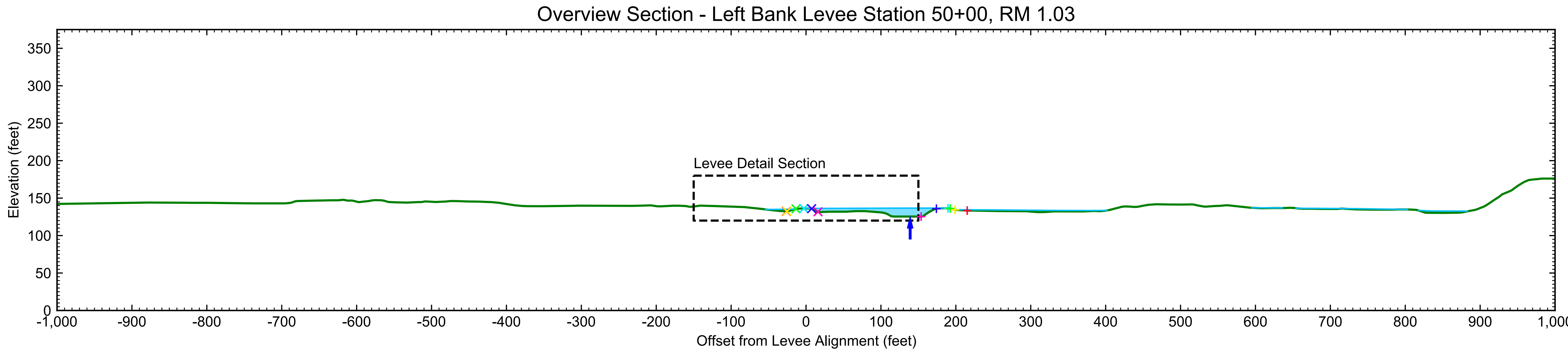
FIG. A-99



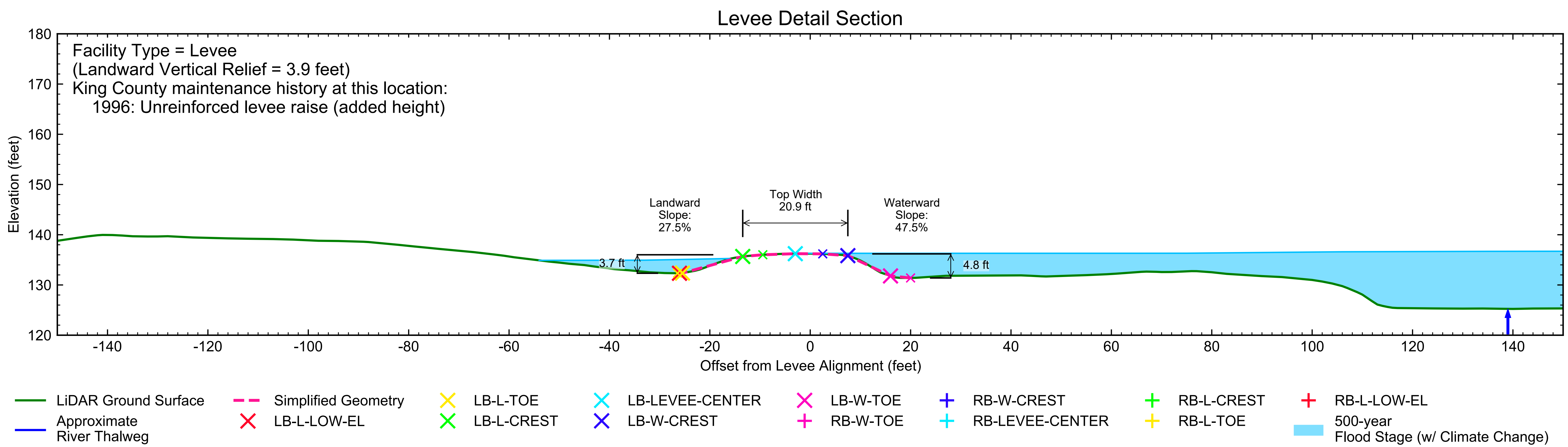


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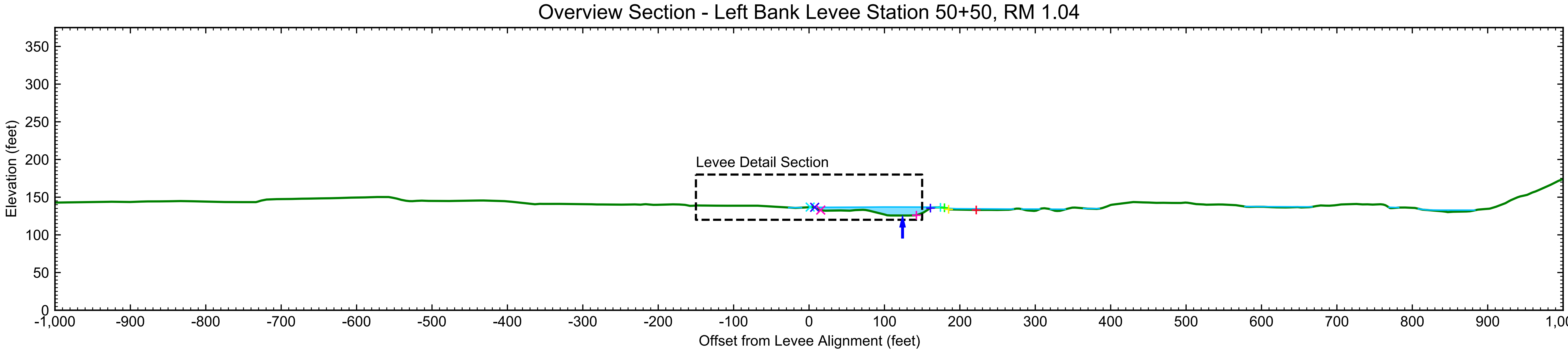
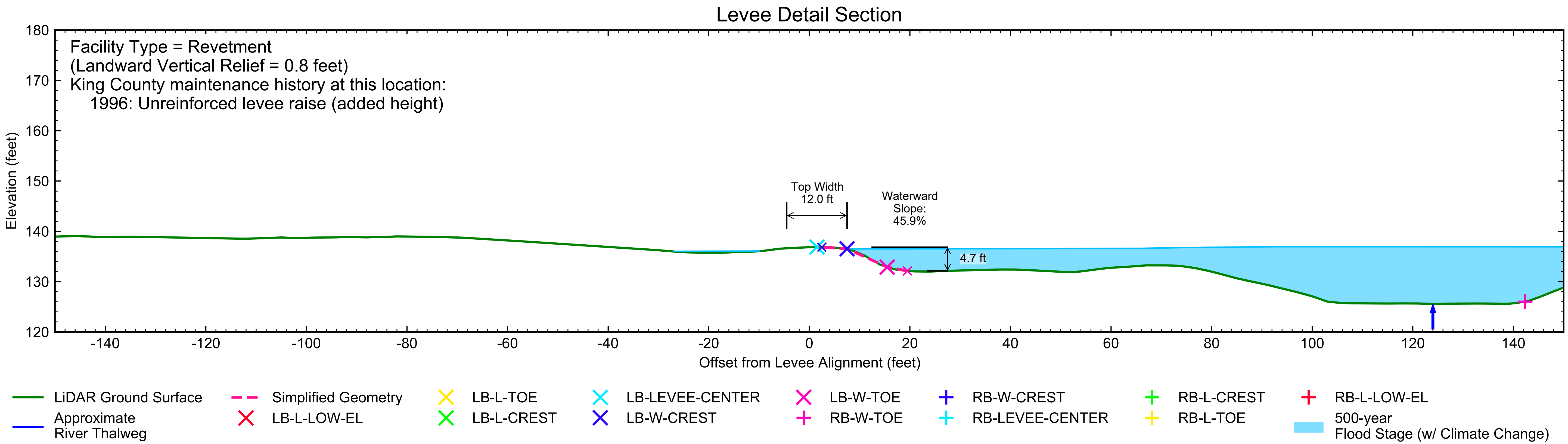
FIG. A-100





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4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 50+50, RM 1.04

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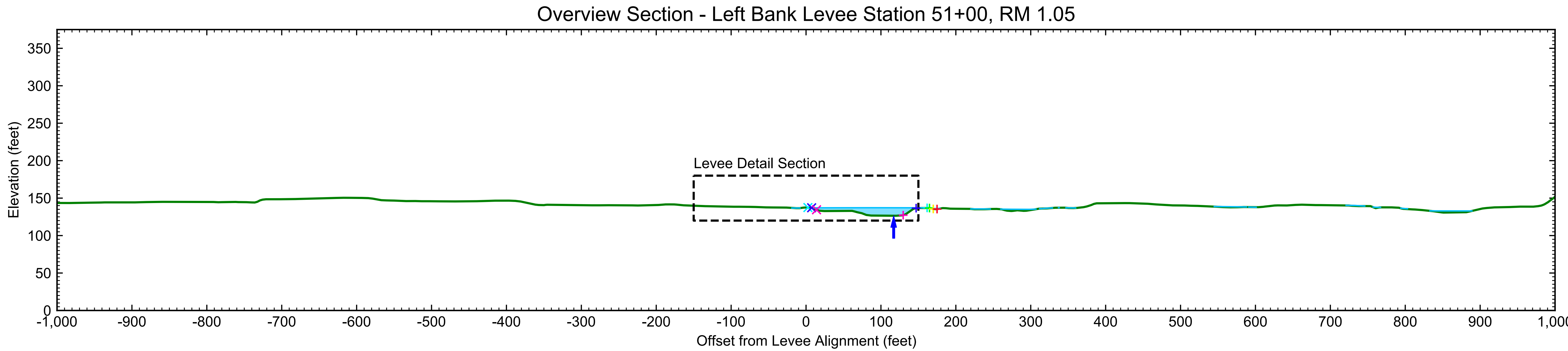
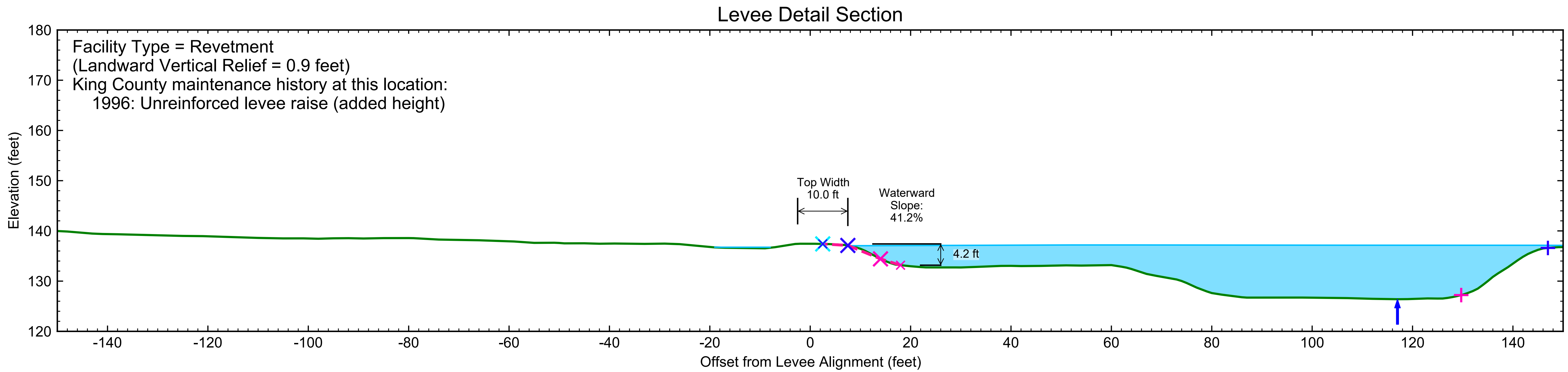
FIG. A-101





- LiDAR Ground Surface
- Approximate River Thalweg
- Simplified Geometry
- LB-L-LOW-EL
- LB-L-TOE
- LB-L-CREST
- LB-LEVEE-CENTER
- LB-W-CREST
- LB-W-TOE
- RB-W-TOE
- RB-W-CREST
- RB-LEVEE-CENTER
- RB-L-CREST
- RB-L-TOE
- RB-L-LOW-EL
- 500-year Flood Stage (w/ Climate Change)

Notes:
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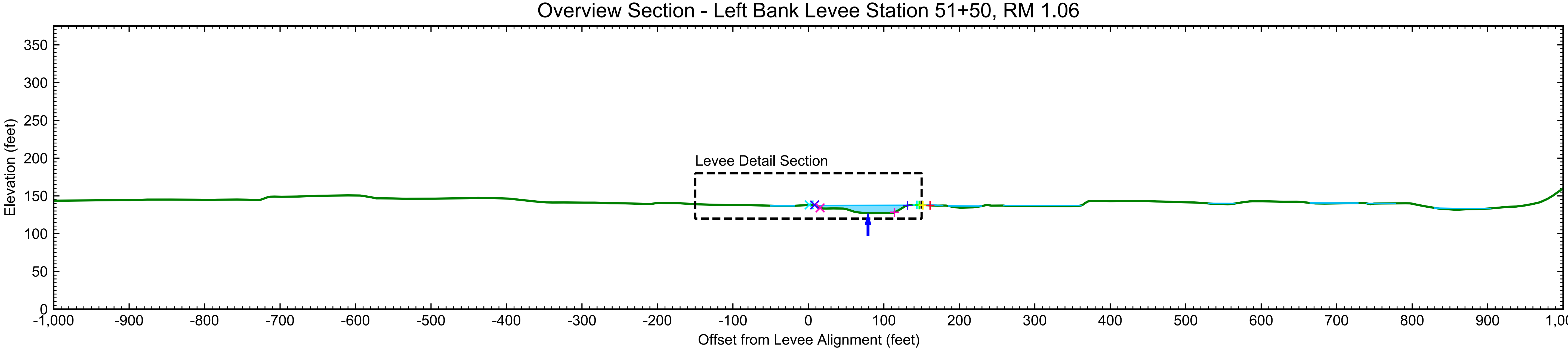
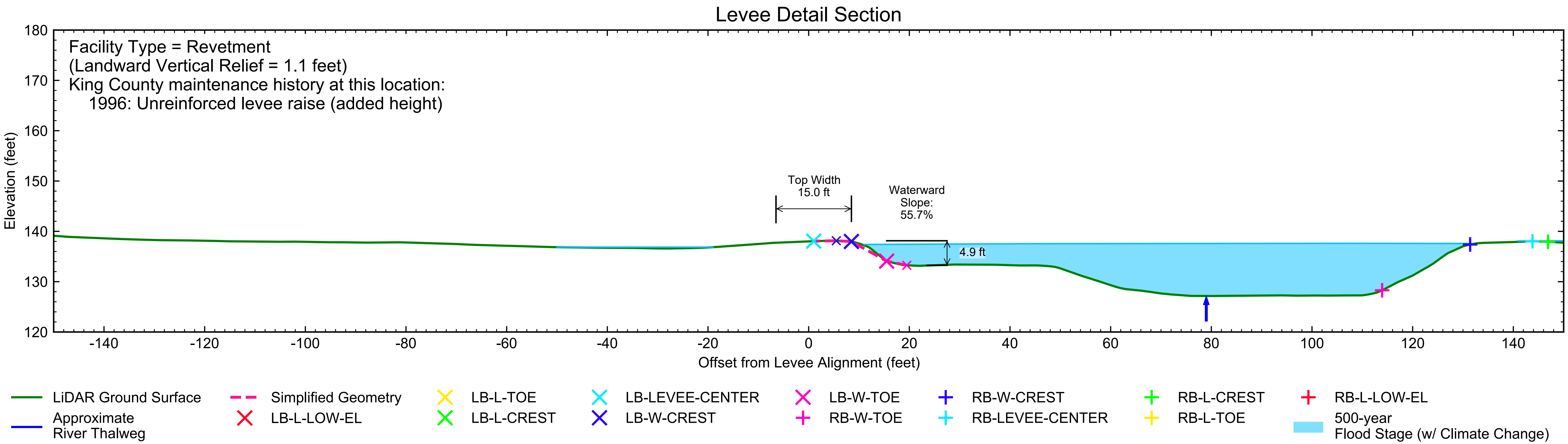
FIG. A-102





Notes:
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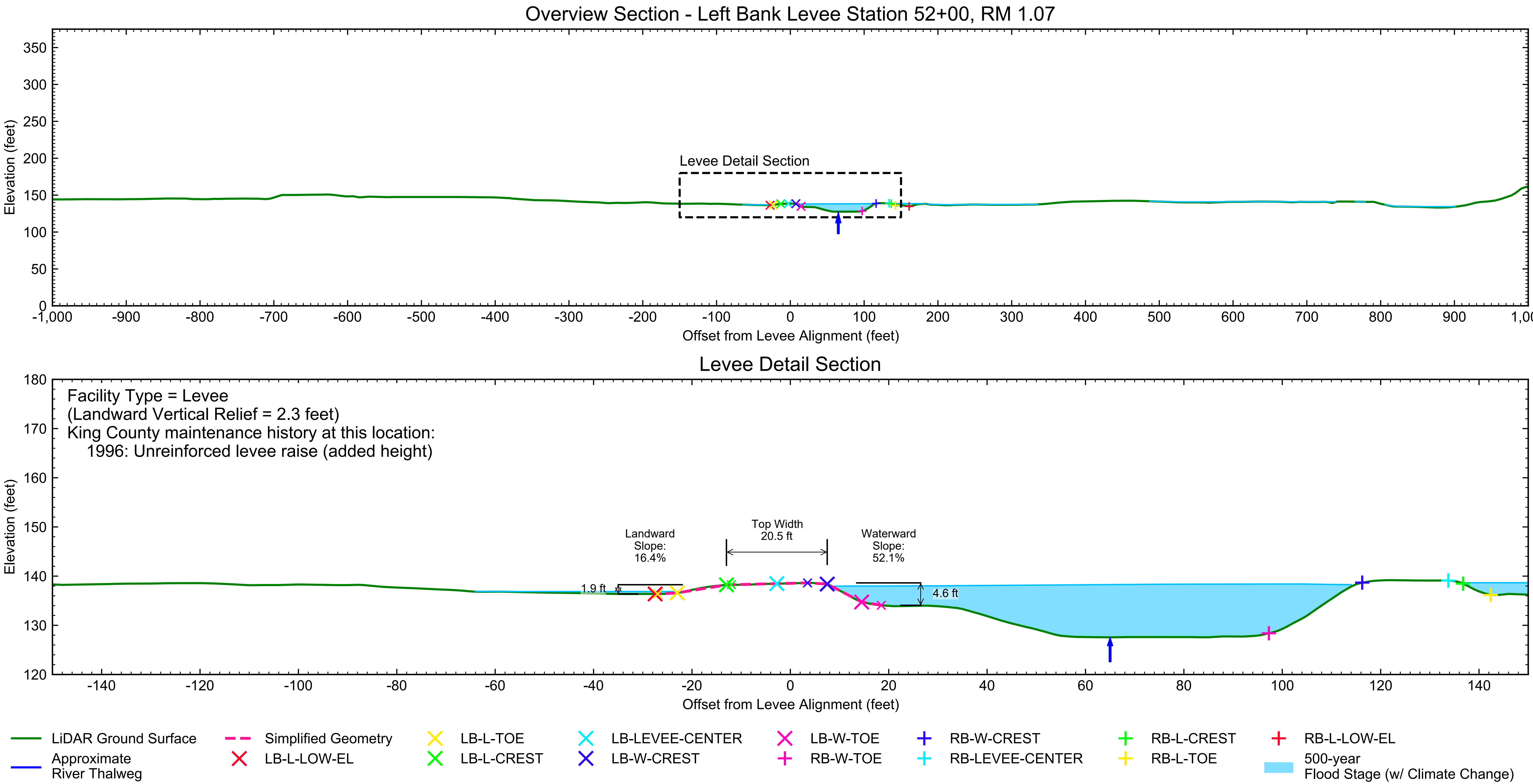
FIG. A-103



Notes:
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LIDAR CROSS SECTION
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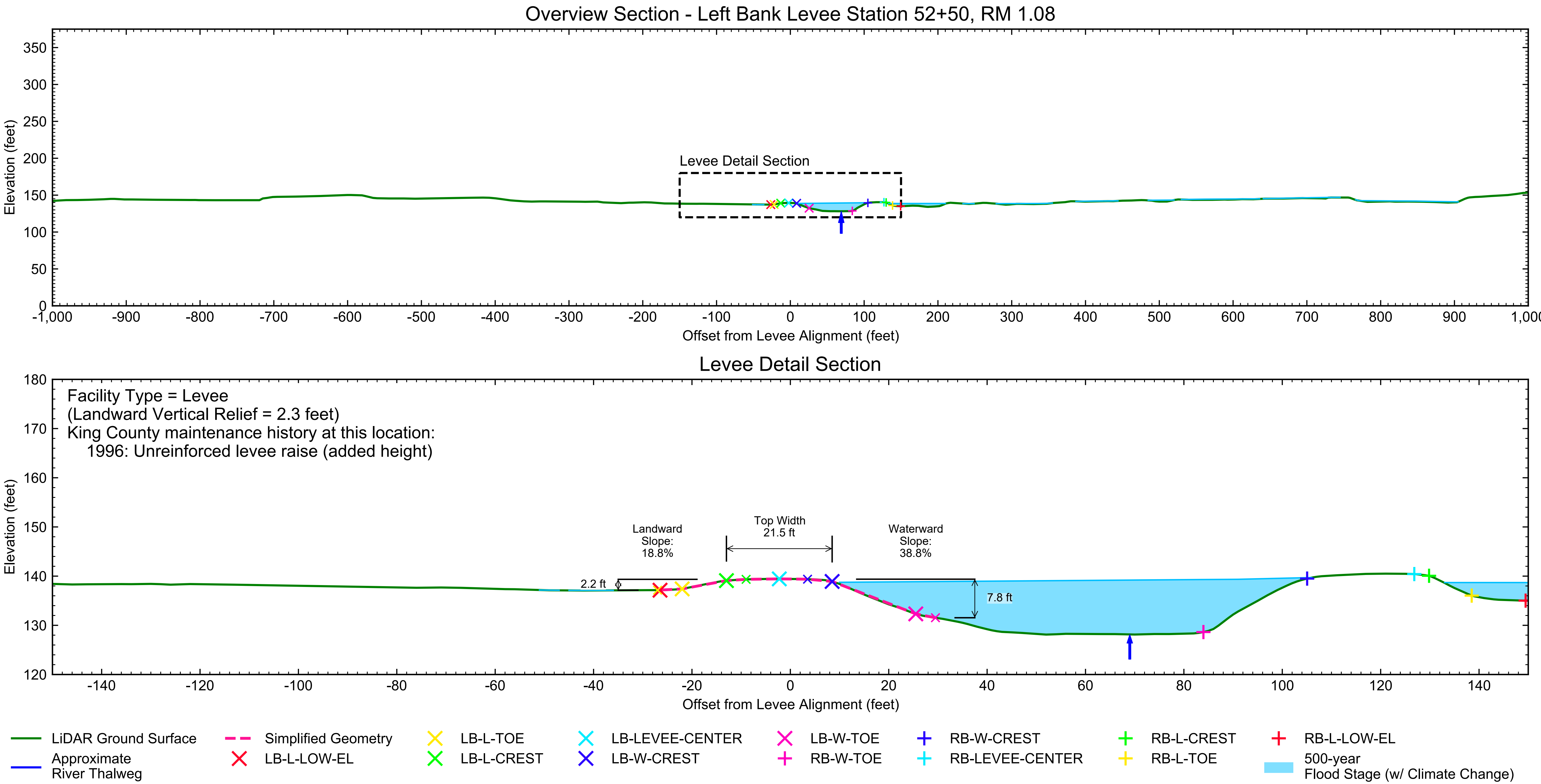
FIG. A-104



Notes:
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LIDAR CROSS SECTION
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FIG. A-105

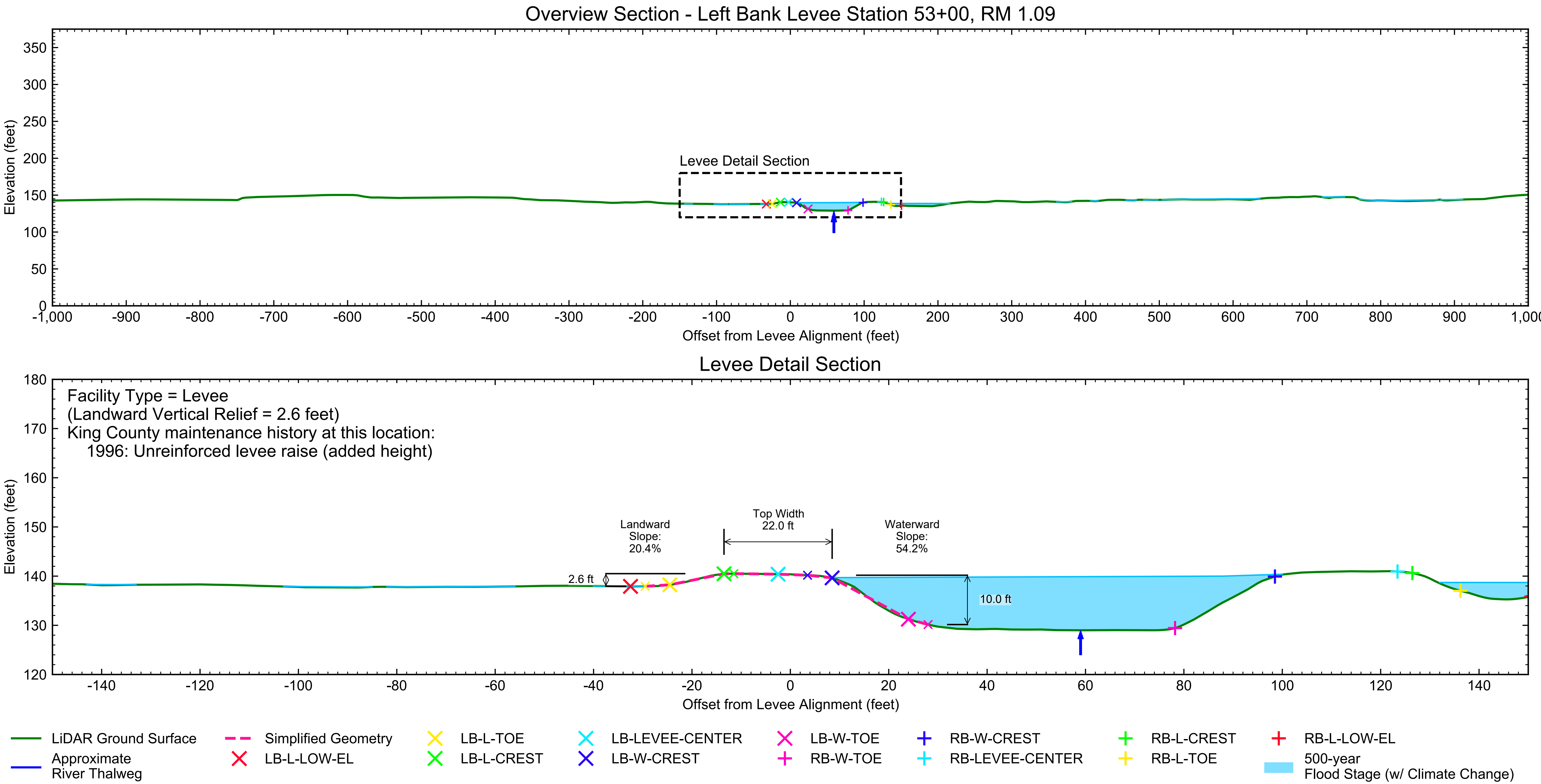

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FIG. A-106

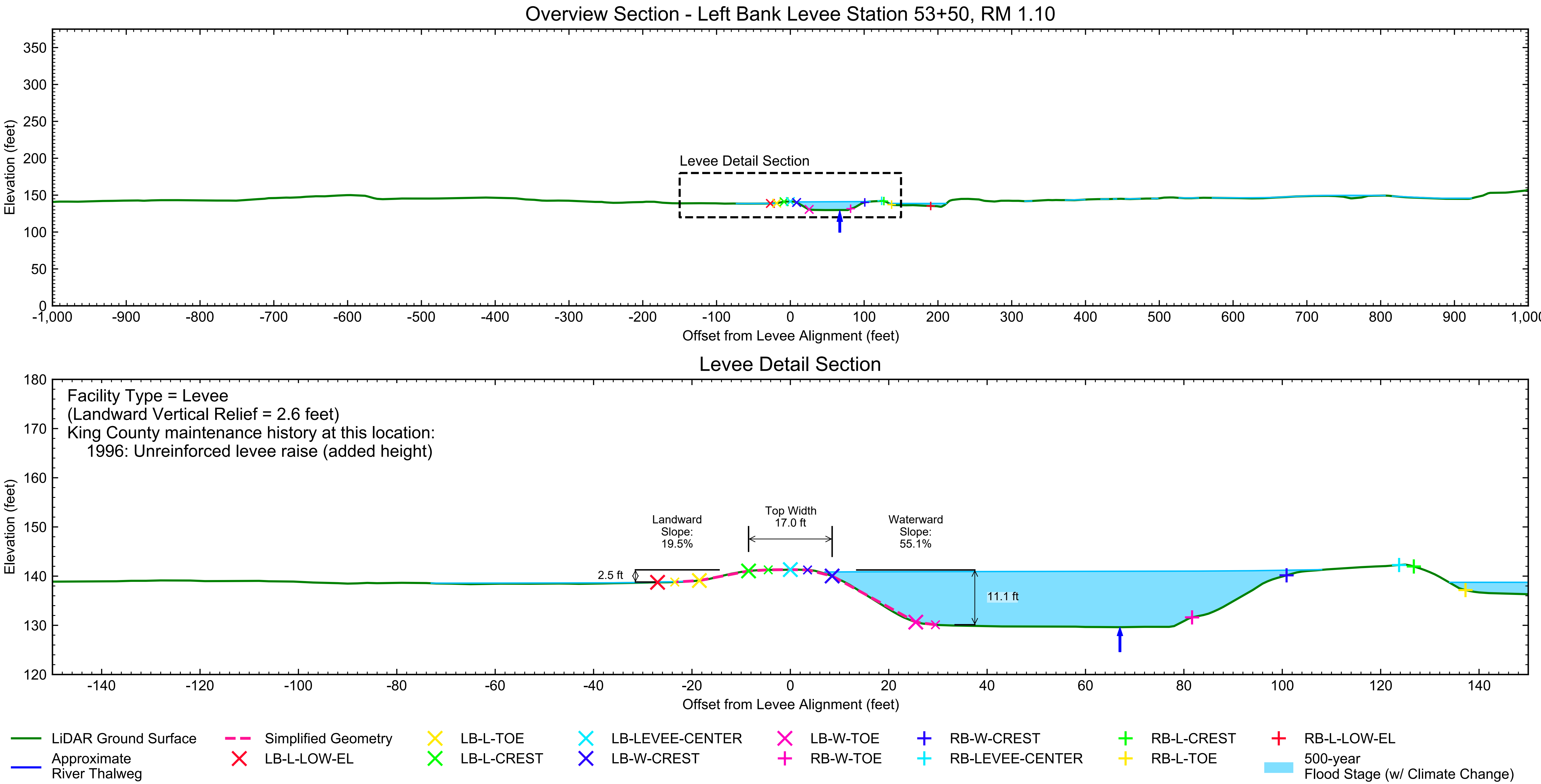

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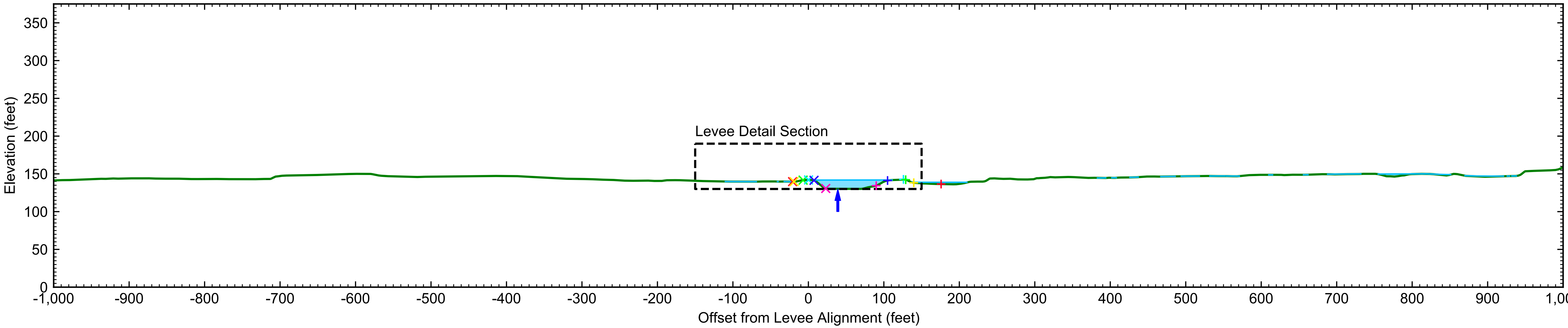
FIG. A-107

Overview Section - Left Bank Levee Station 54+00, RM 1.11



Levee Detail Section

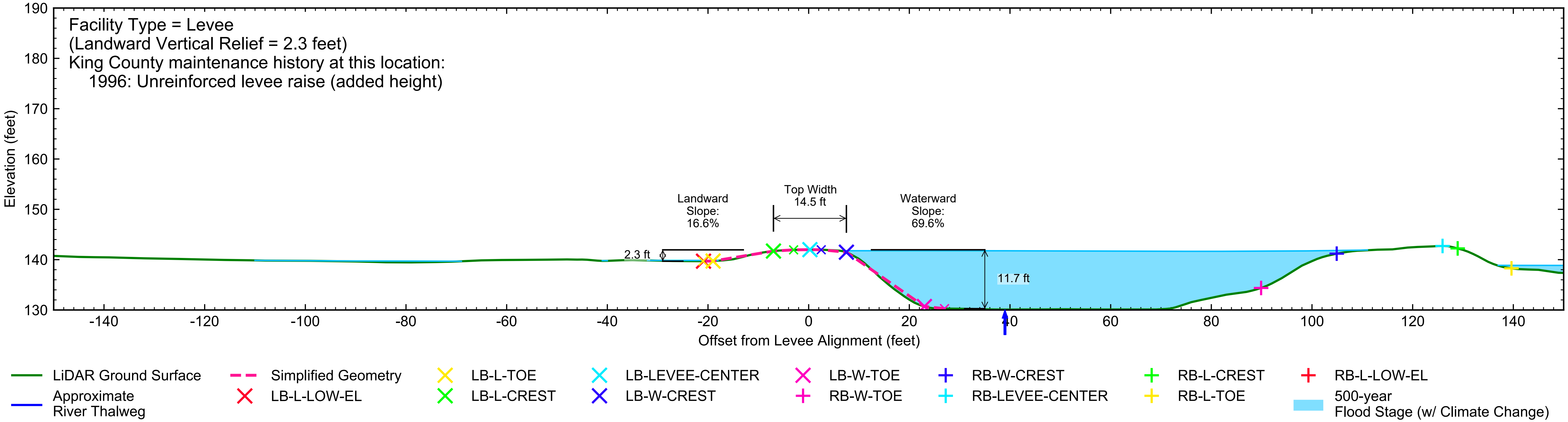


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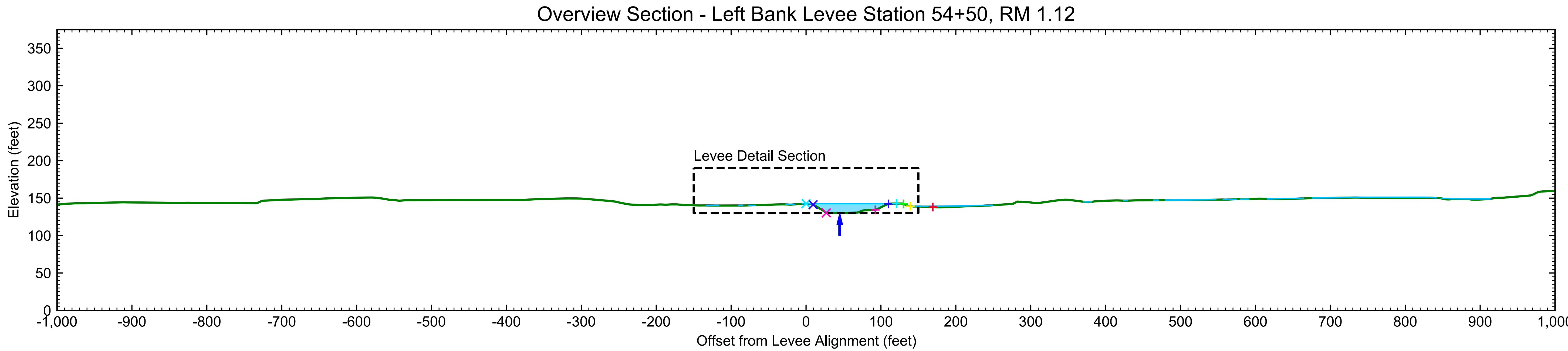
FIG. A-108



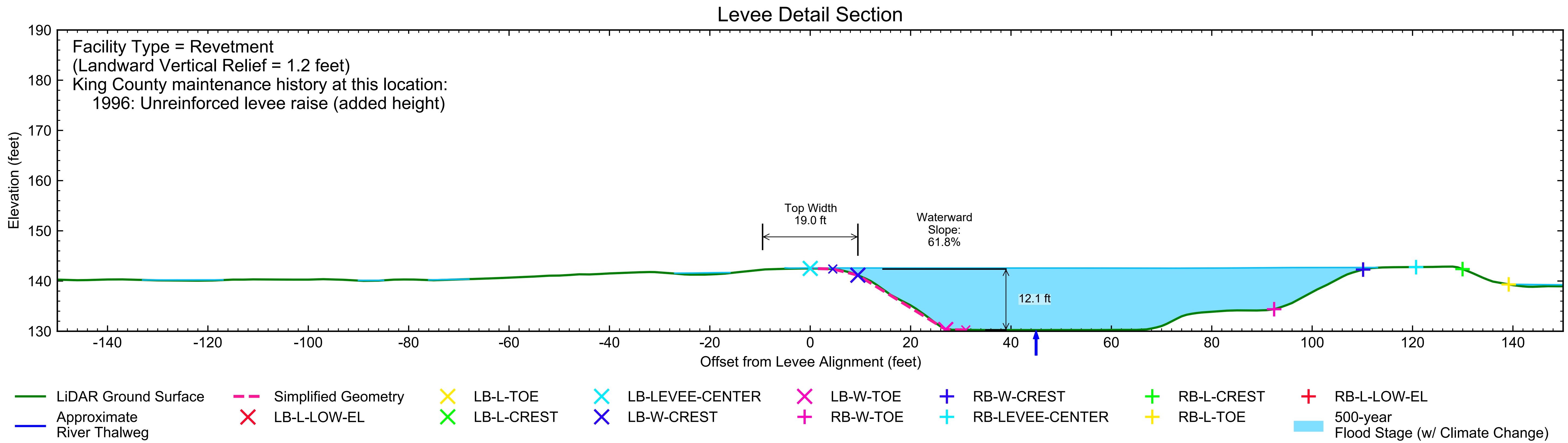


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FIG. A-109

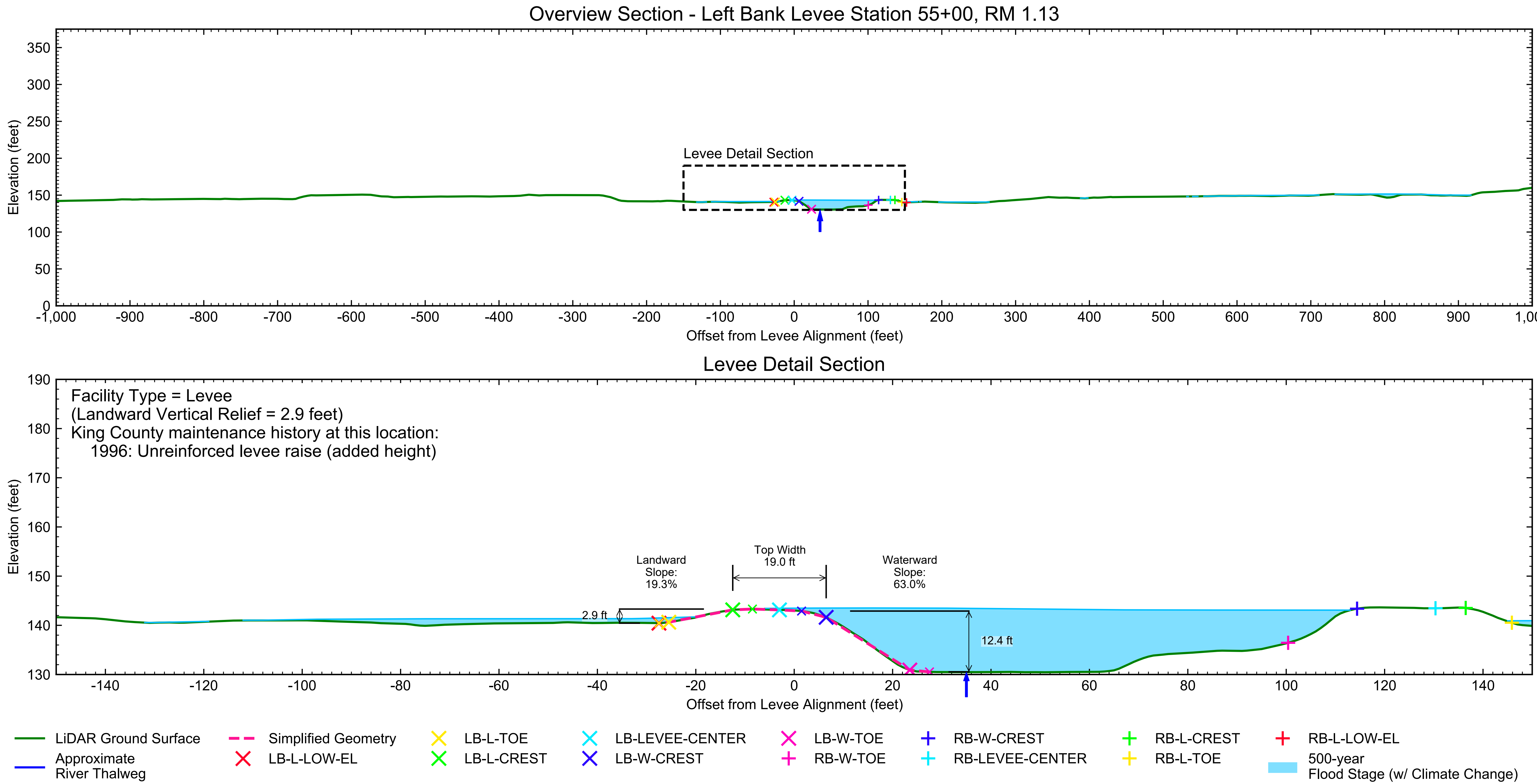

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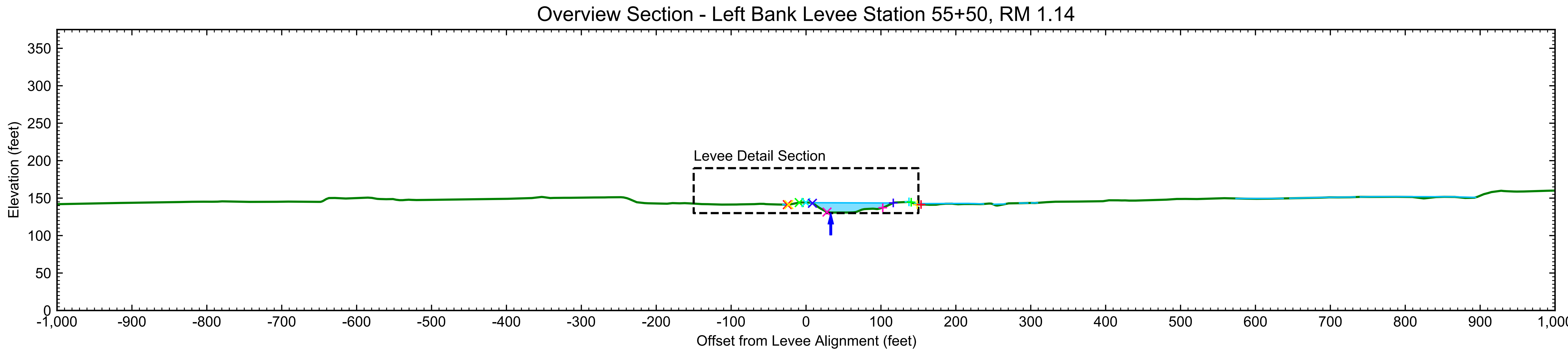
FIG. A-110



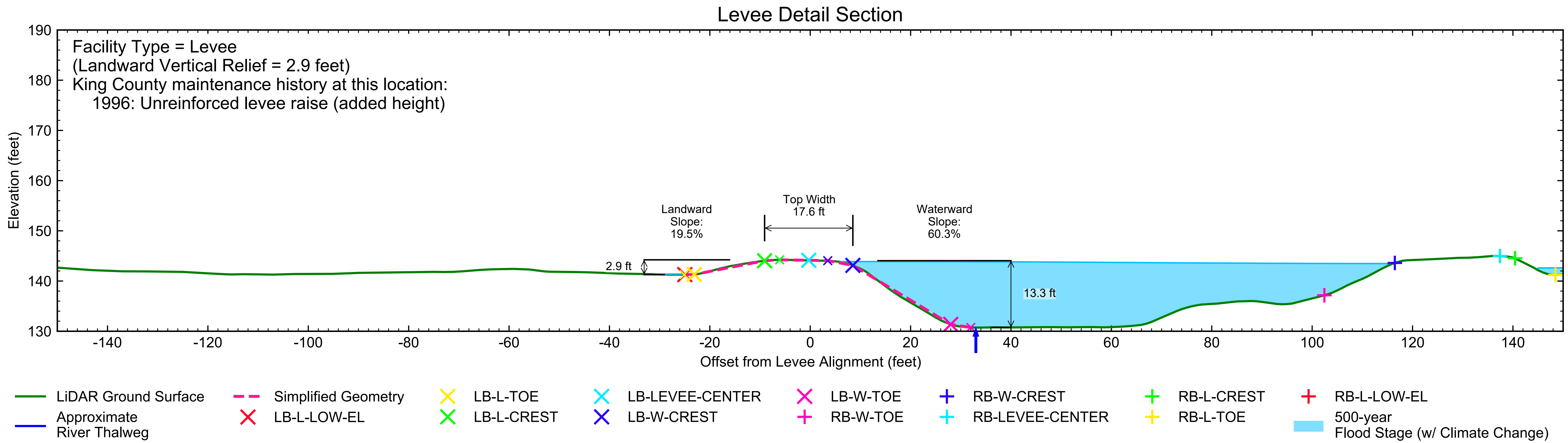


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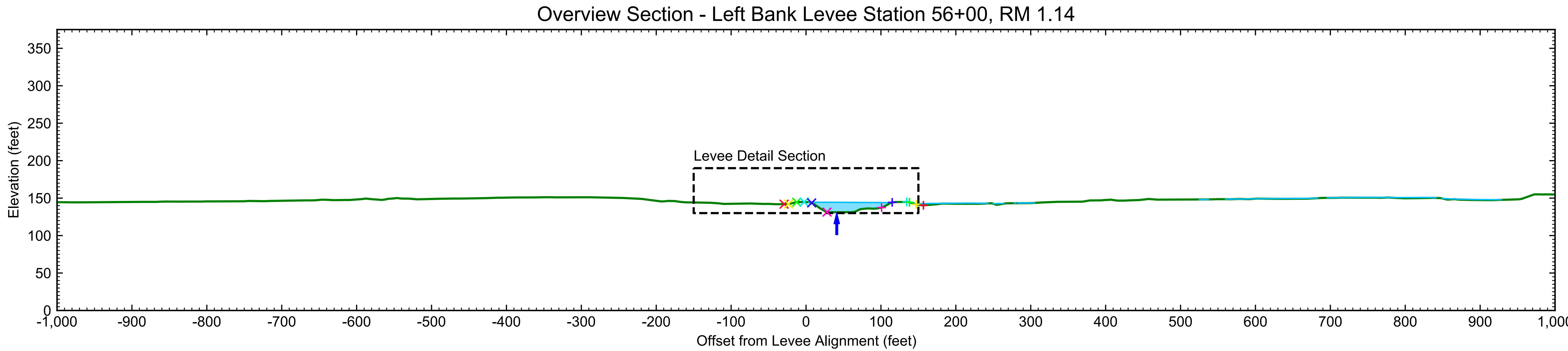
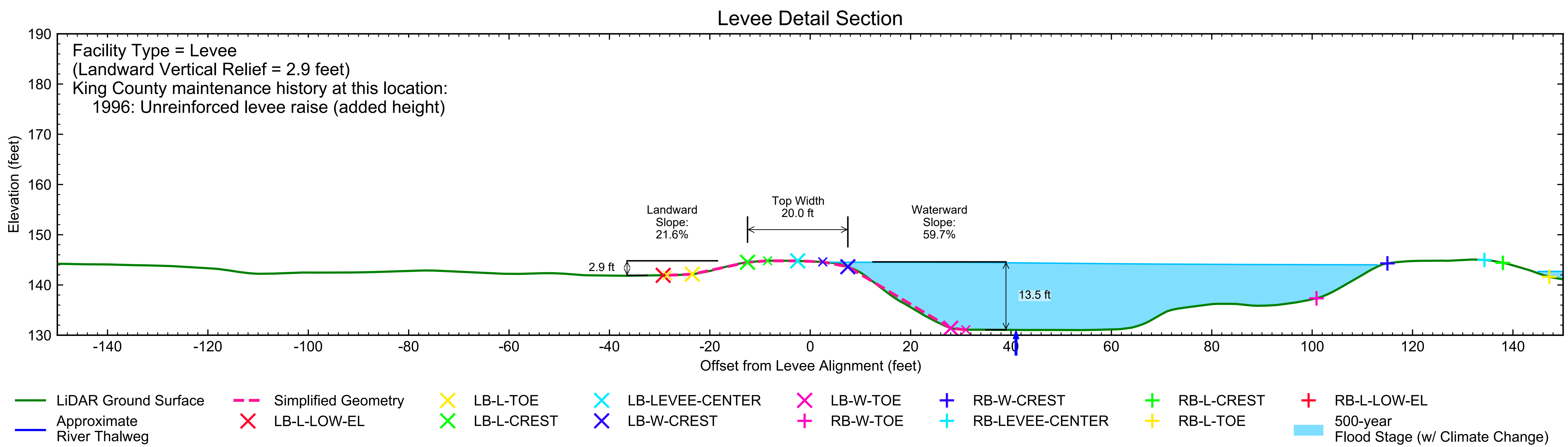
FIG. A-111





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 56+00, RM 1.14

April 2022 | 103692-304

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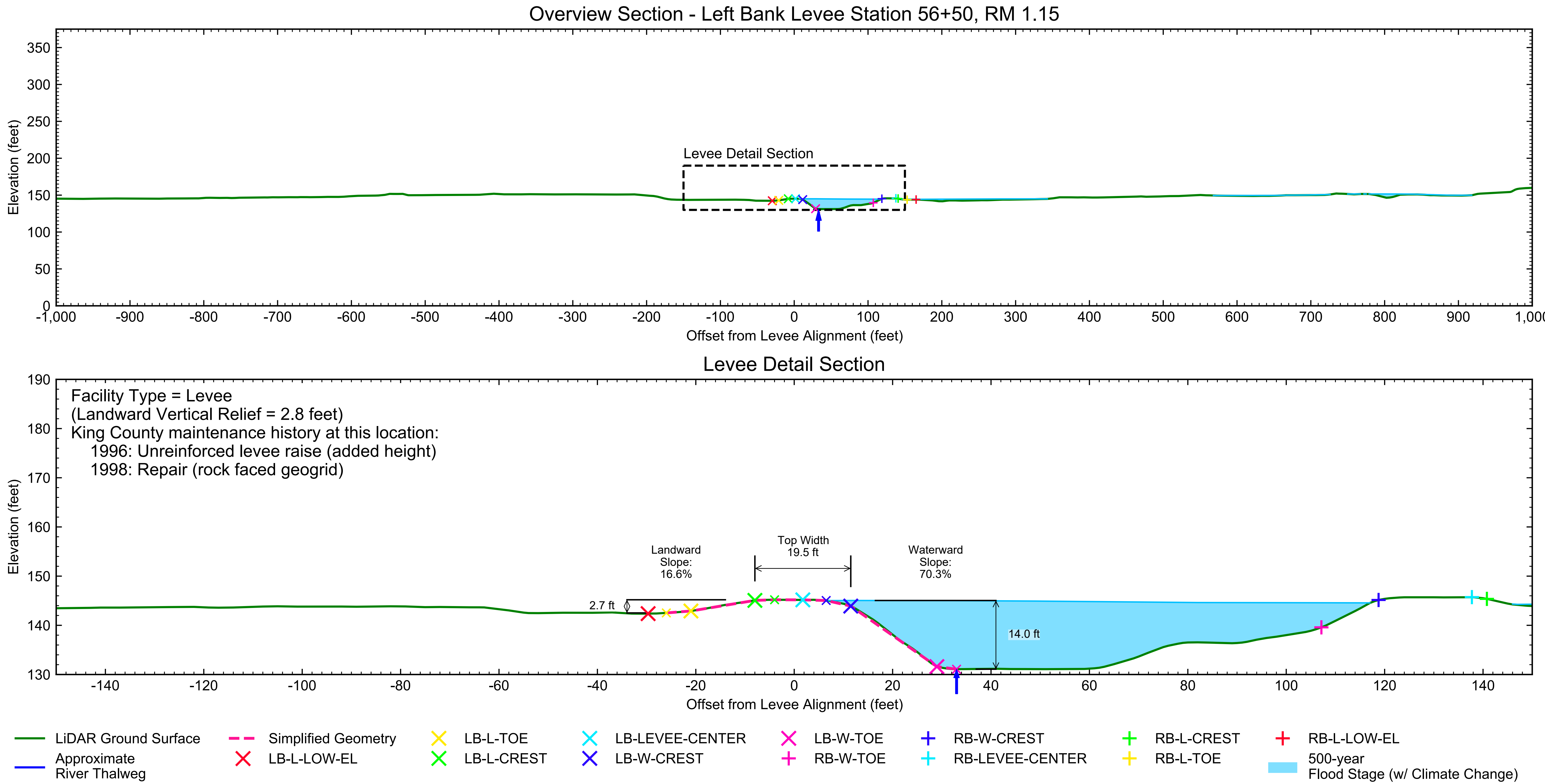
FIG. A-112



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 56+50, RM 1.15

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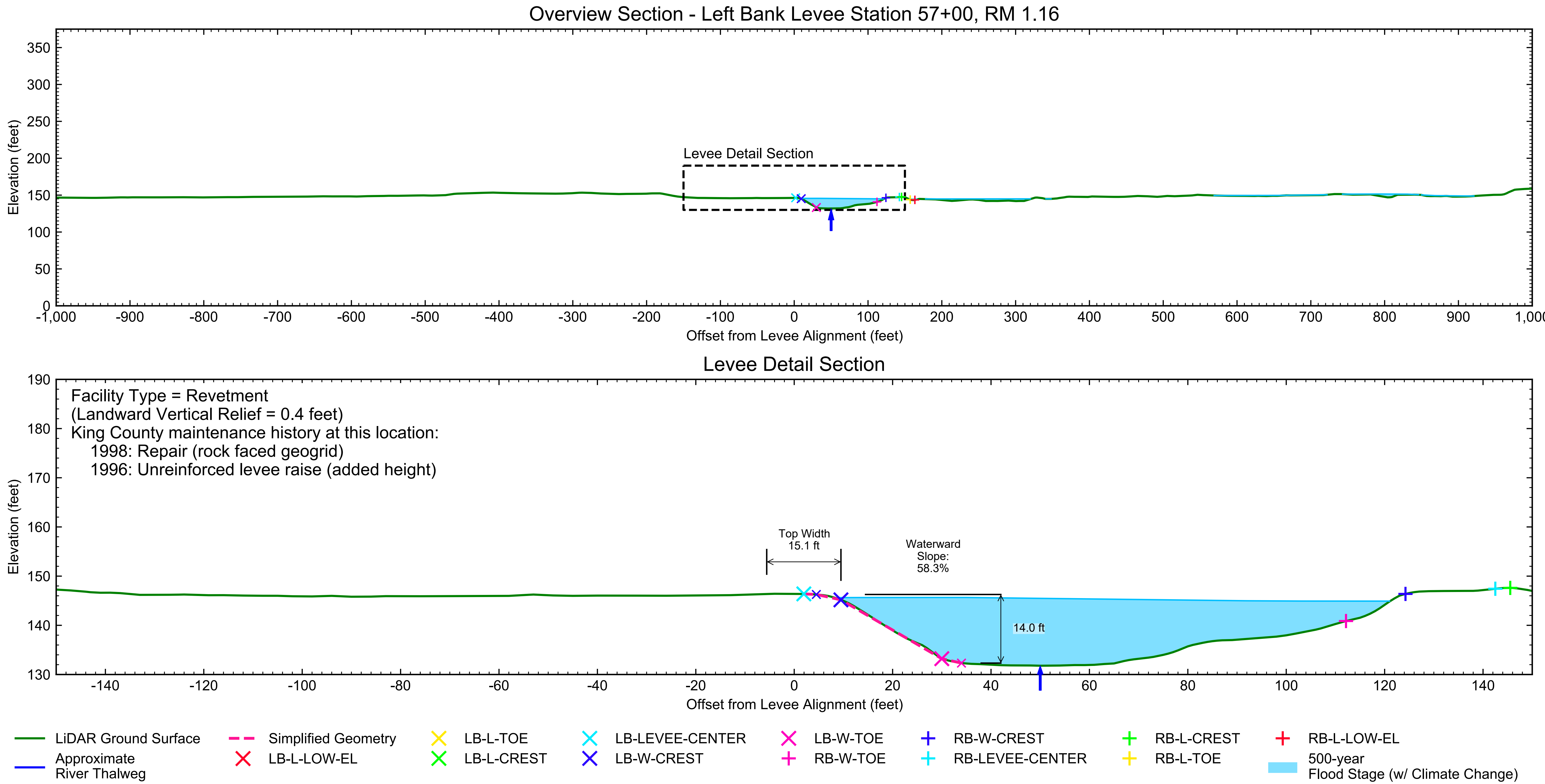
FIG. A-113



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 57+00, RM 1.16

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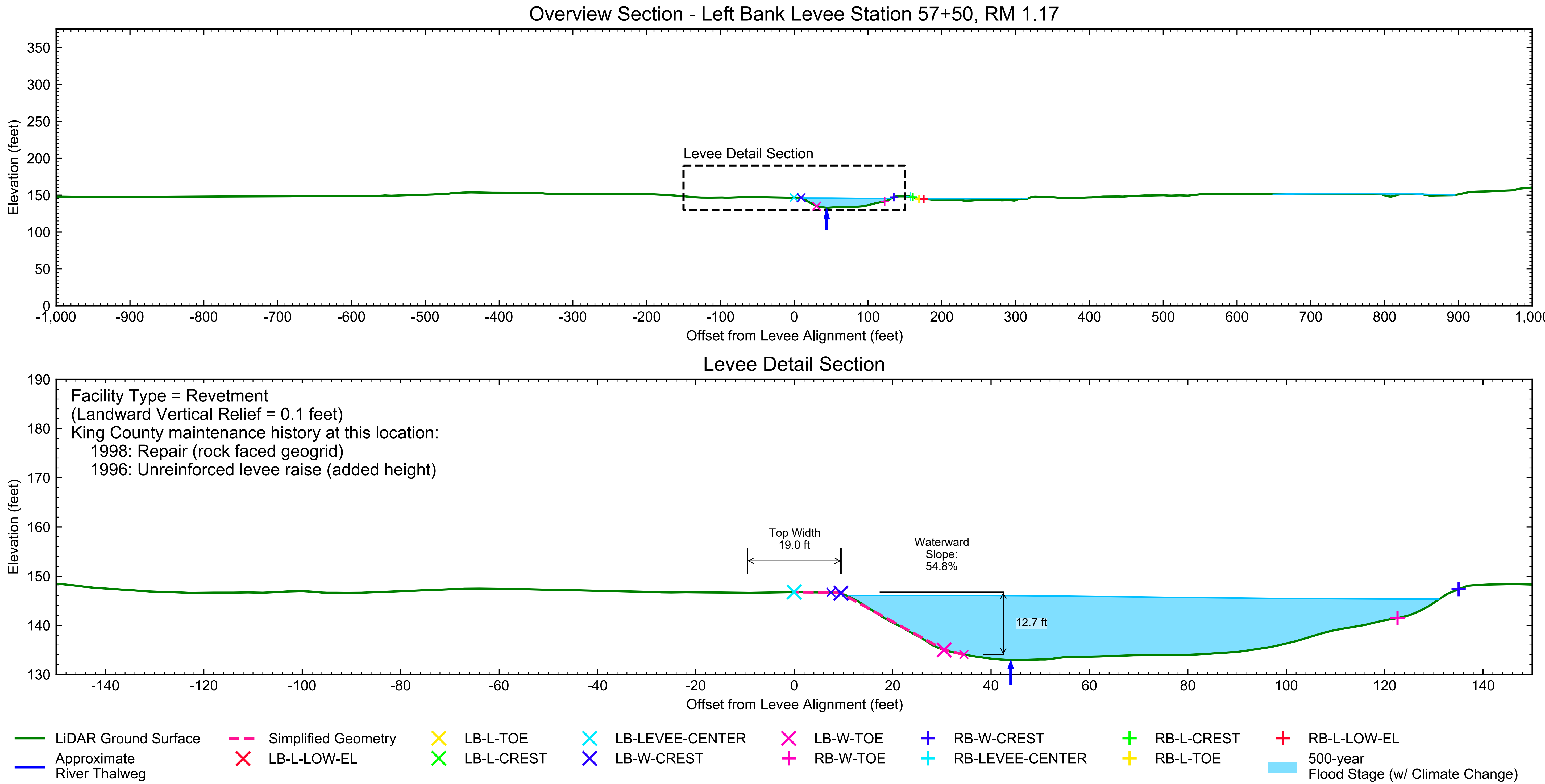
FIG. A-114



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 57+50, RM 1.17

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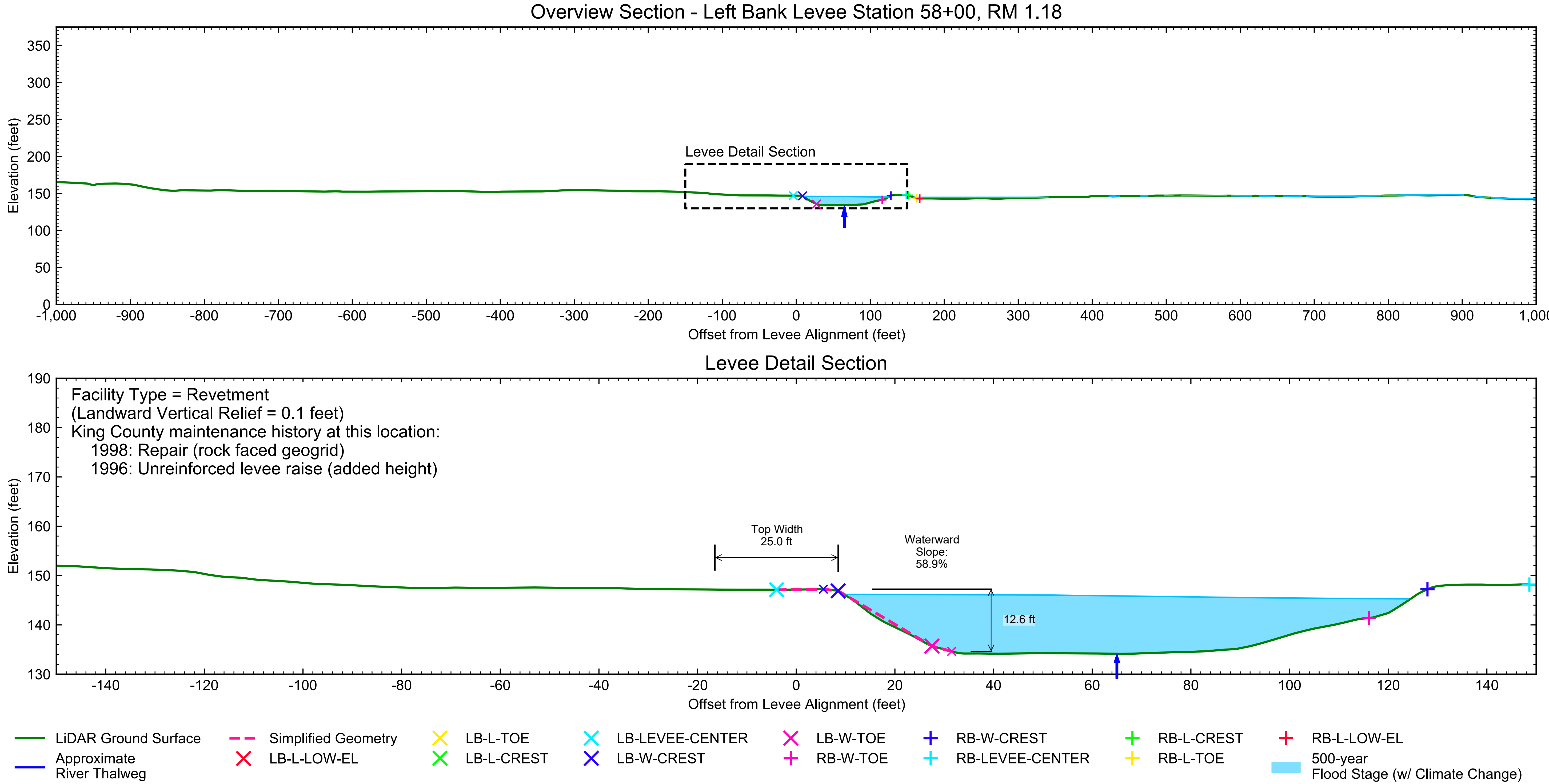
FIG. A-115



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 58+00, RM 1.18

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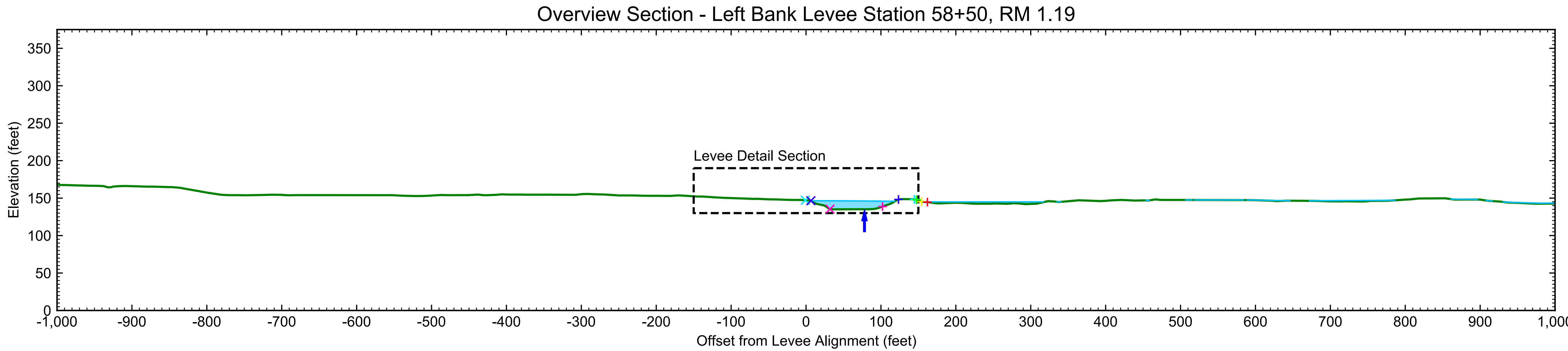
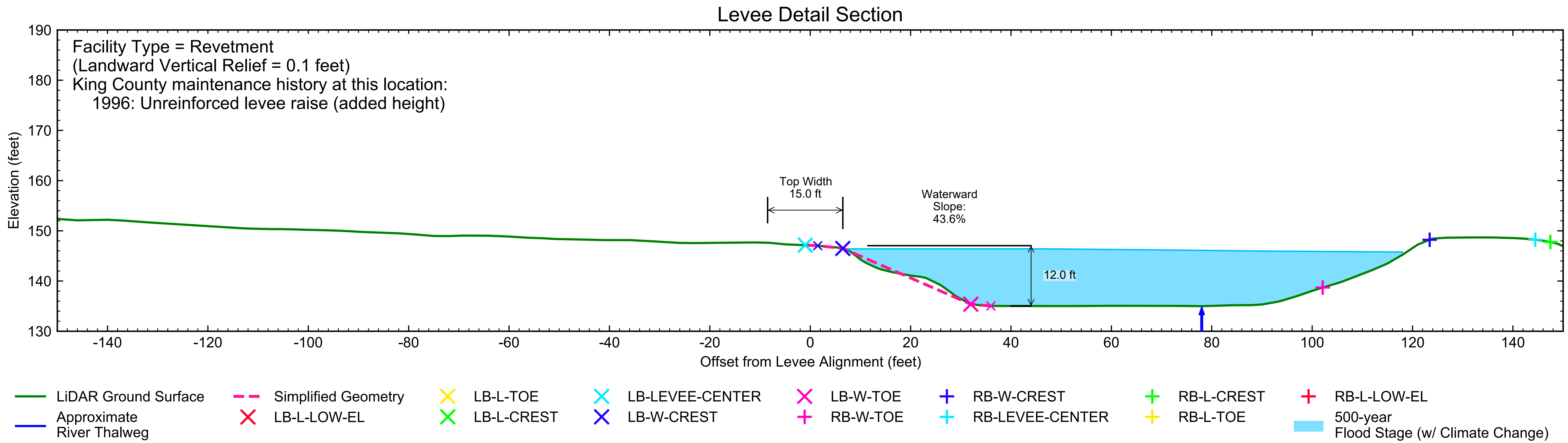
FIG. A-116





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 58+50, RM 1.19

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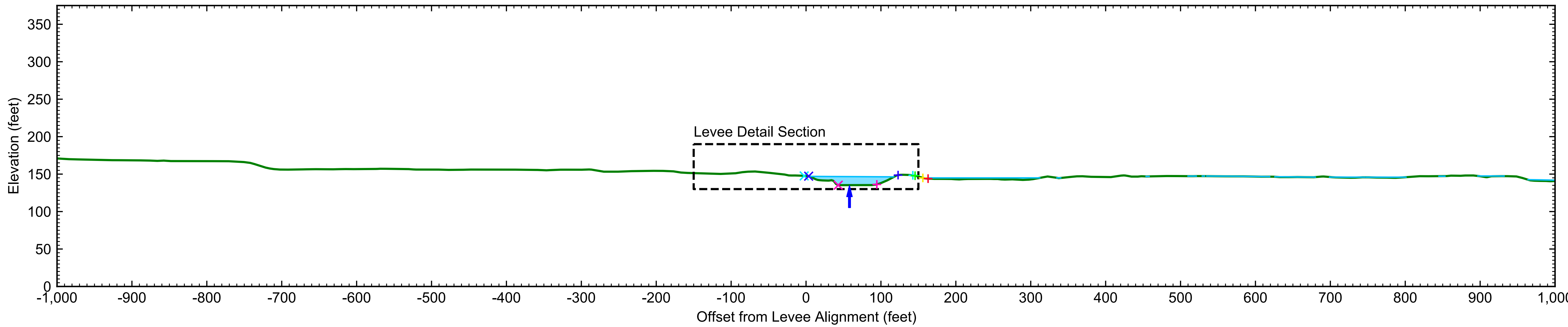
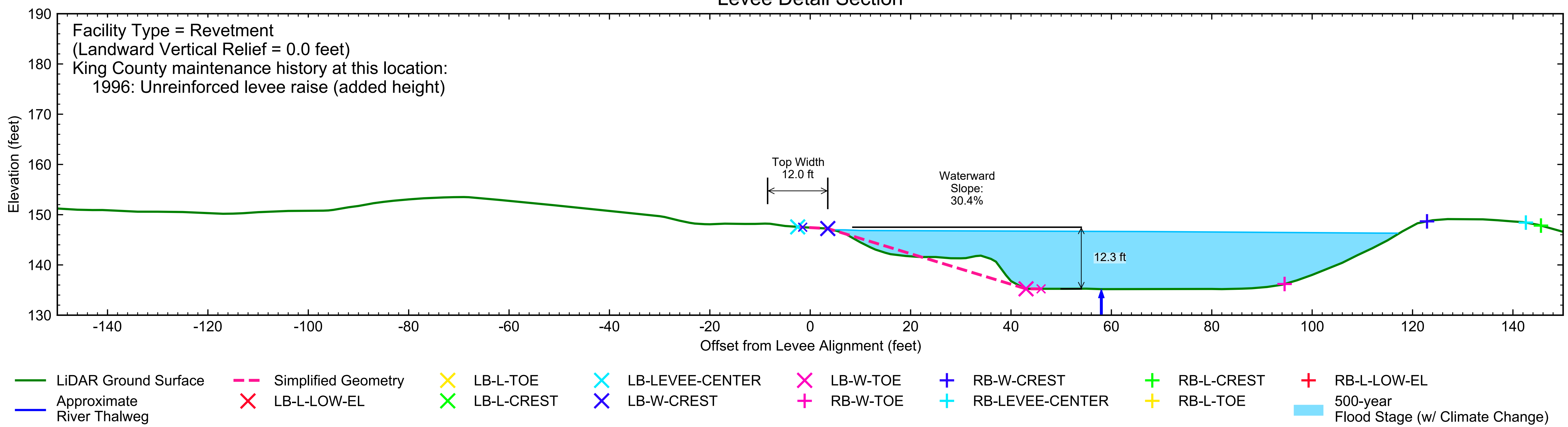
FIG. A-117

Overview Section - Left Bank Levee Station 59+00, RM 1.20



Levee Detail Section



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 59+00, RM 1.20

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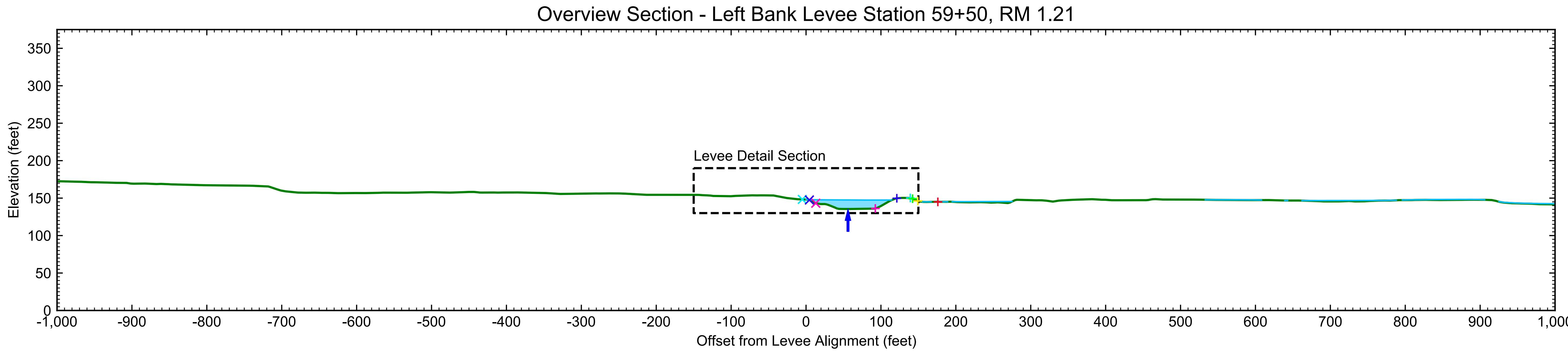
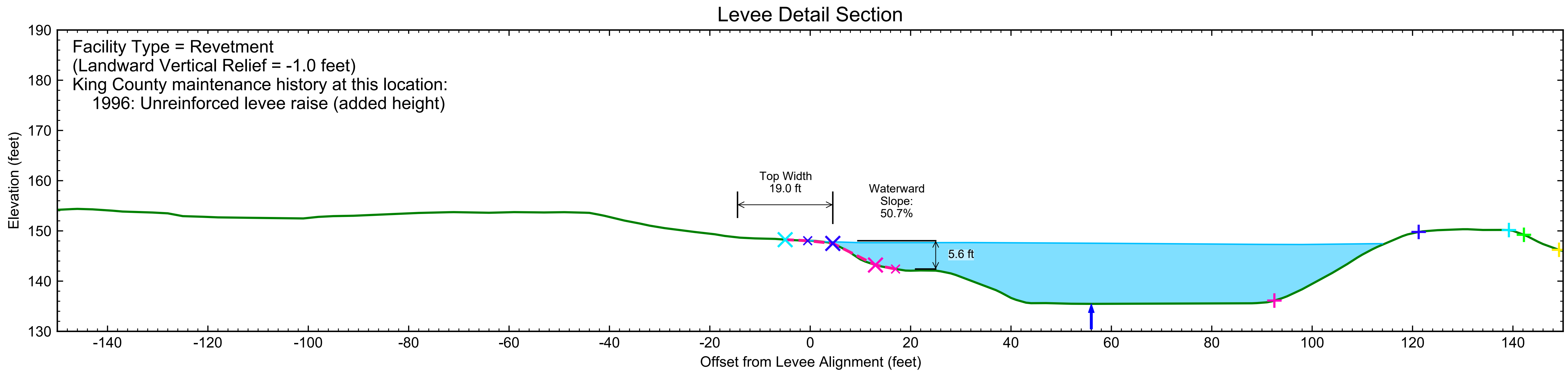
FIG. A-118





LiDAR Ground Surface
Approximate River Thalweg
Simplified Geometry
LB-L-LOW-EL
LB-L-TOE
LB-L-CREST
LB-LEVEE-CENTER
LB-W-CREST
LB-W-TOE
RB-W-TOE
RB-W-CREST
RB-LEVEE-CENTER
RB-L-CREST
RB-L-TOE
RB-L-LOW-EL
500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 59+50, RM 1.21

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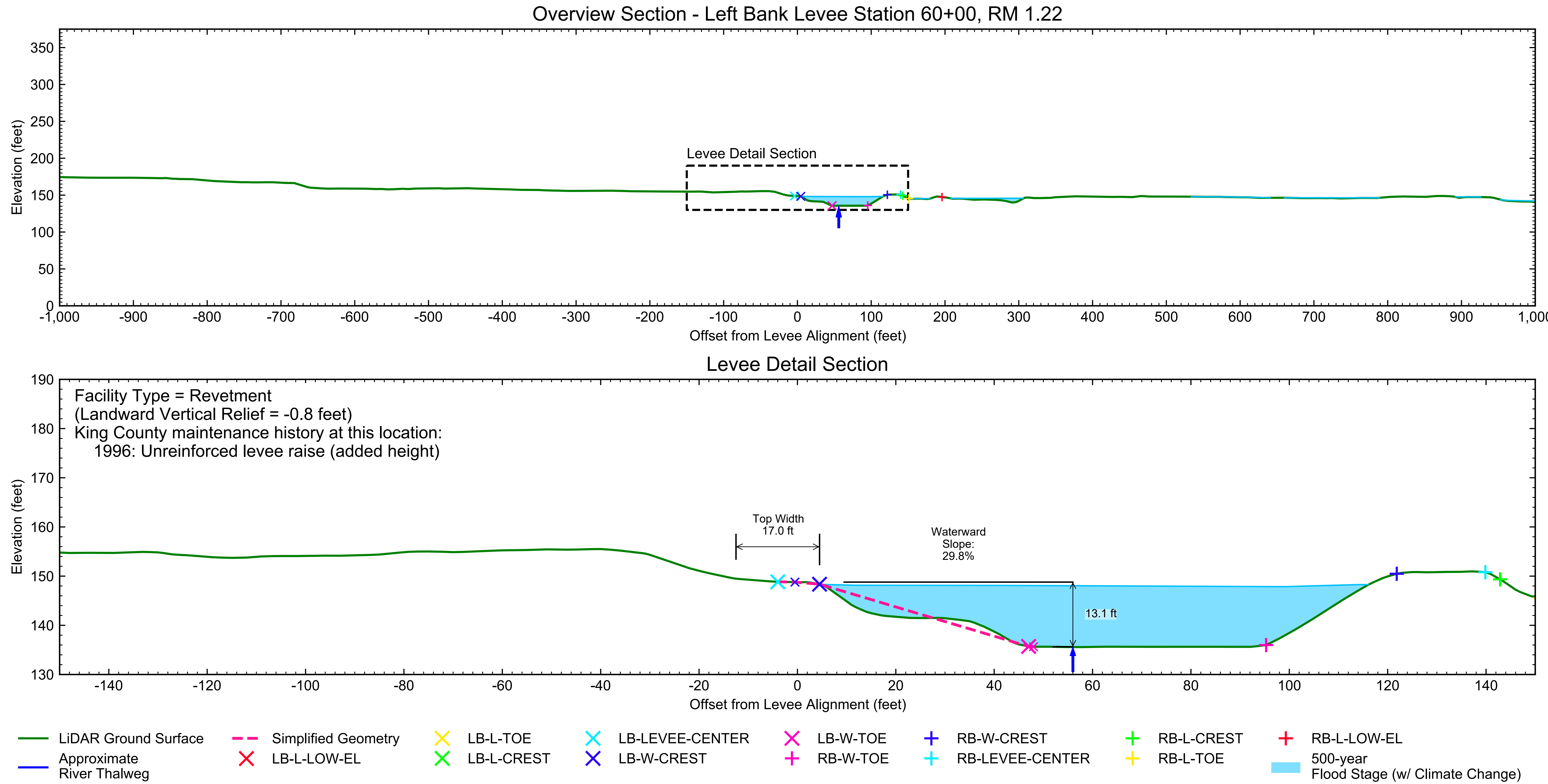
FIG. A-119



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 60+00, RM 1.22

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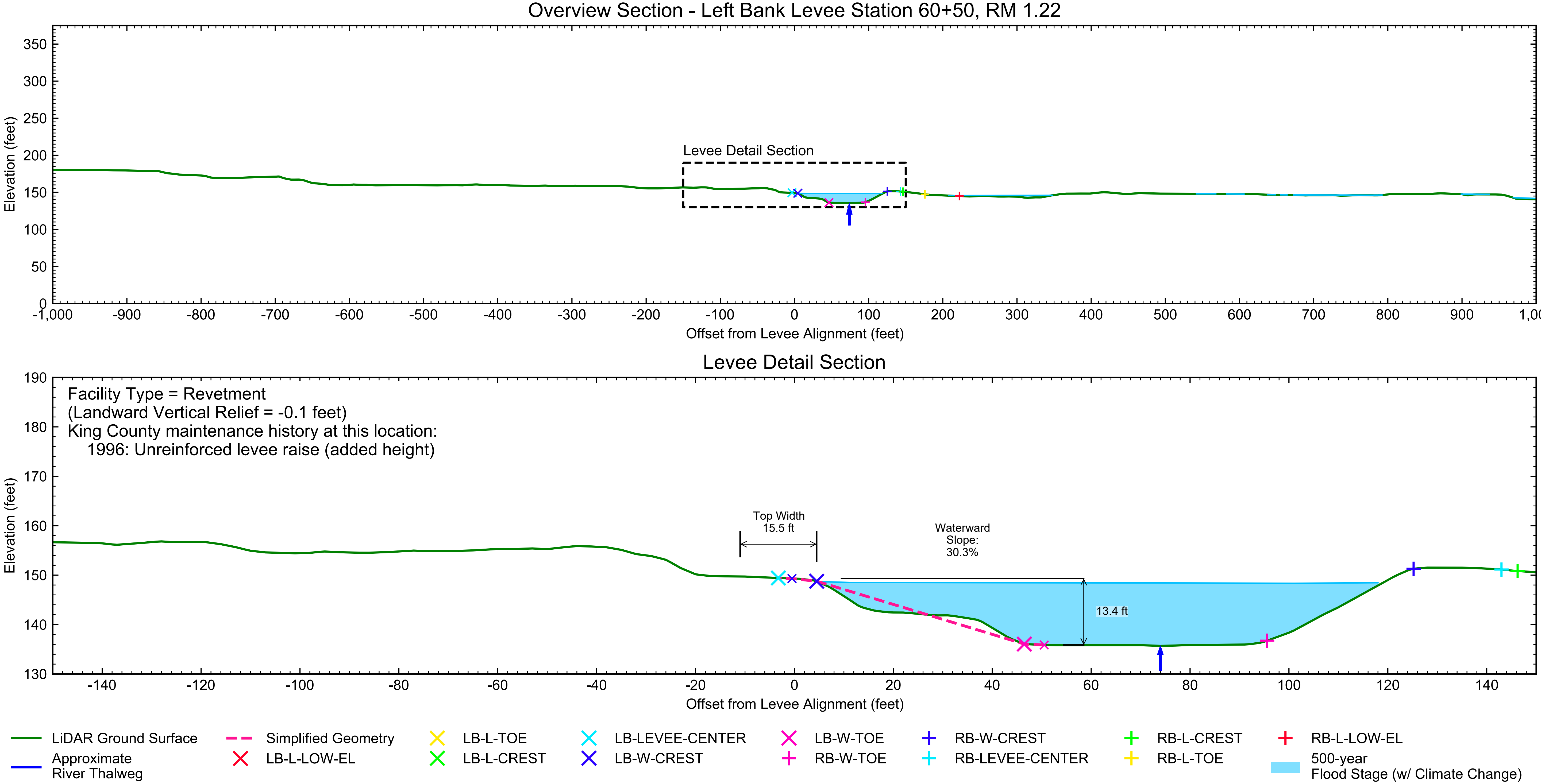
FIG. A-120



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 60+50, RM 1.22

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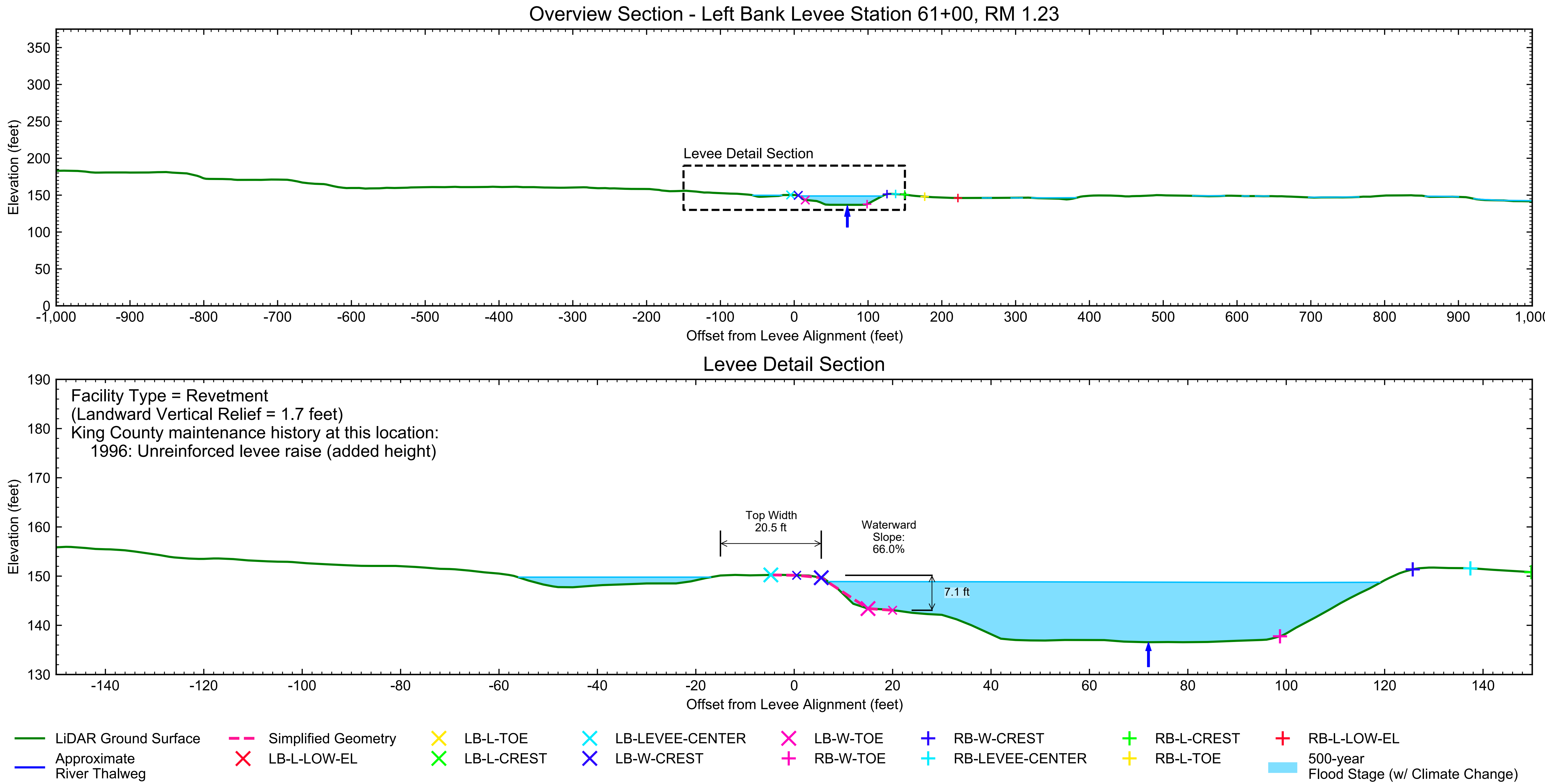
FIG. A-121



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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 61+00, RM 1.23

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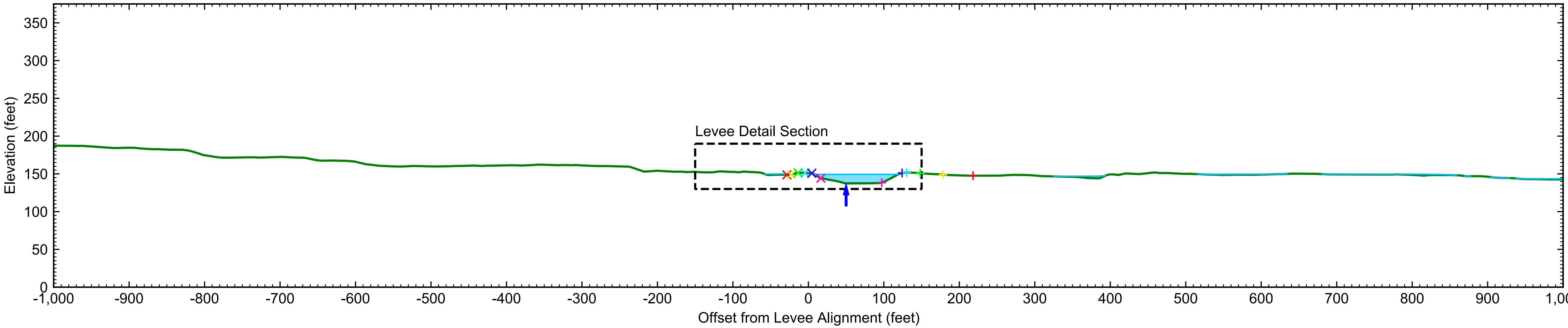
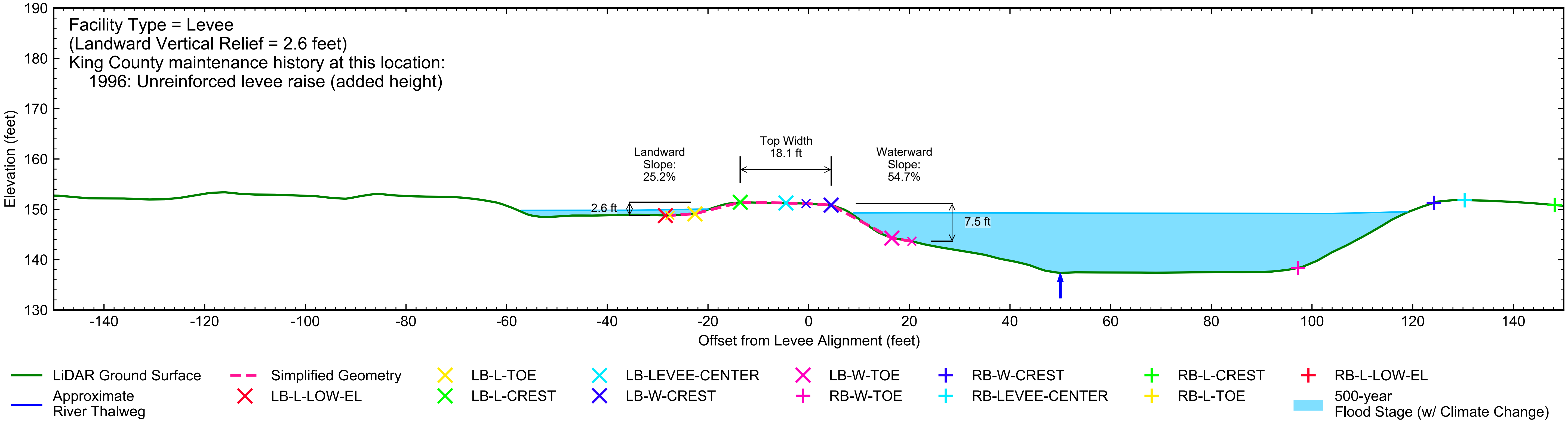
FIG. A-122

Overview Section - Left Bank Levee Station 61+50, RM 1.24



Levee Detail Section



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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Levee Breach Analysis Mapping and Risk Assessment Segmentation and Stability Approach Report King County, Washington	
LIDAR CROSS SECTION LOWER RAGING RIVER LEFT BANK STA 61+50, RM 1.24	
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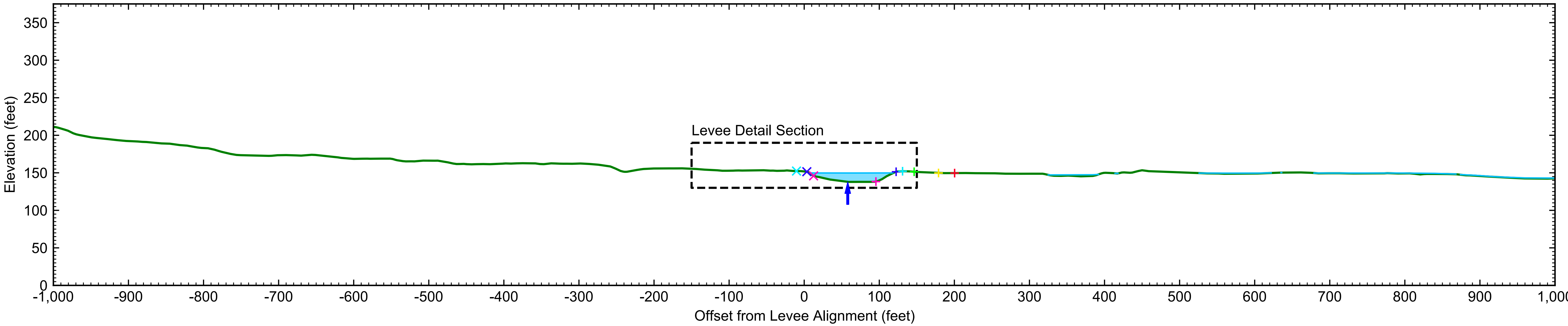
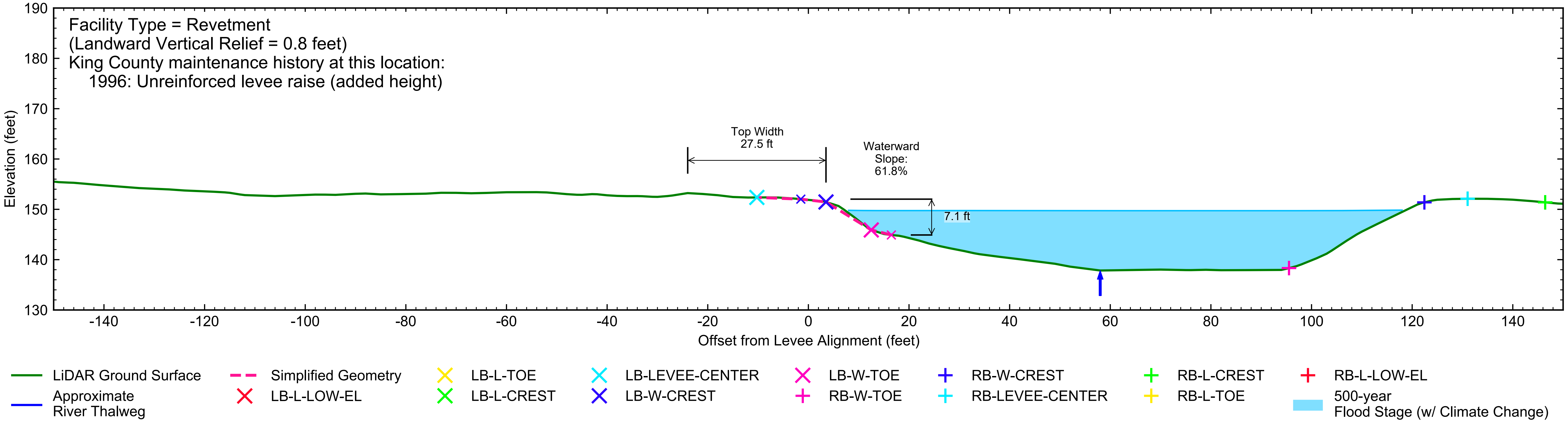
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-123

Overview Section - Left Bank Levee Station 62+00, RM 1.25



Levee Detail Section



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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 62+00, RM 1.25

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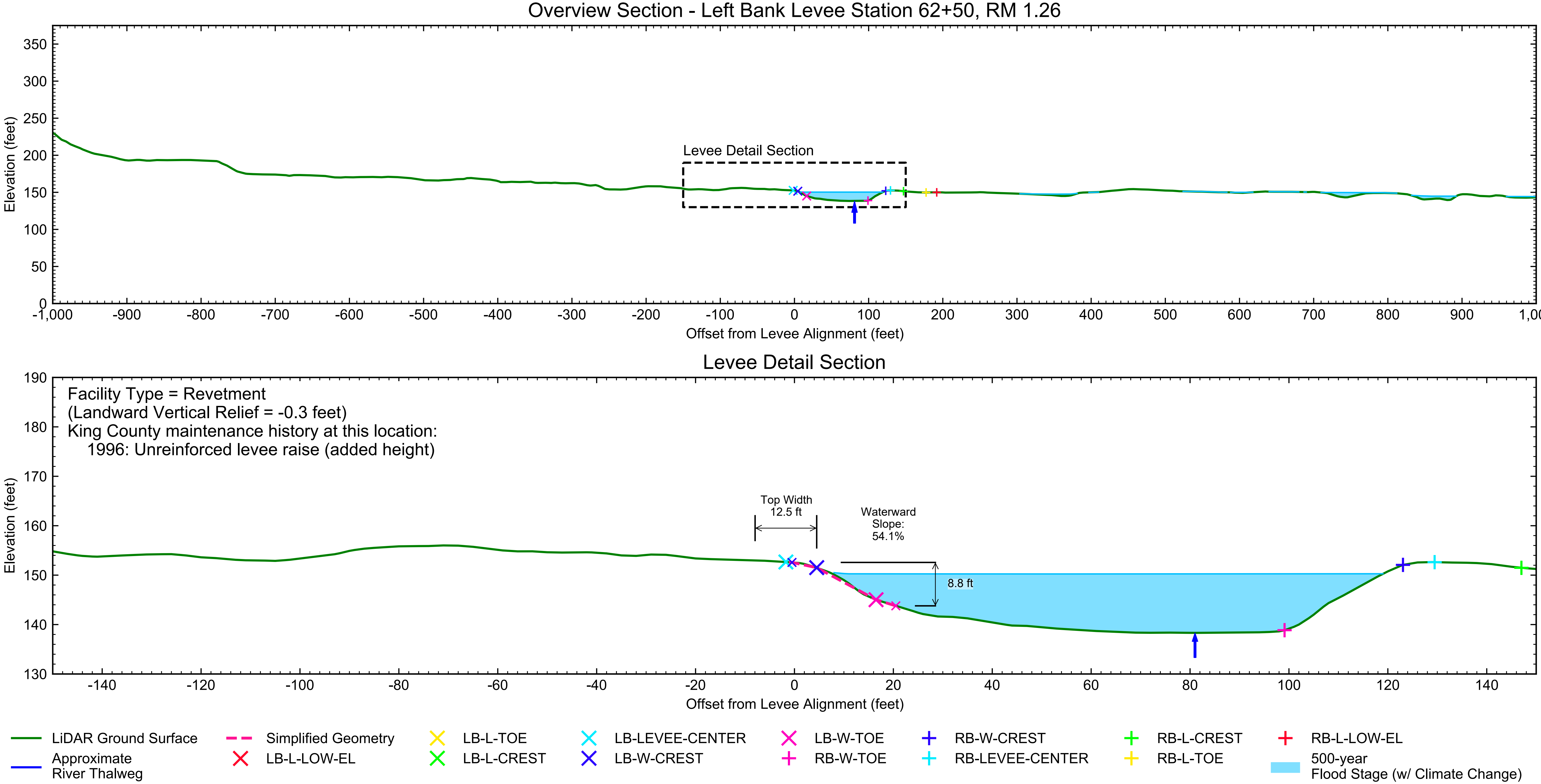
FIG. A-124



Notes:
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LIDAR CROSS SECTION
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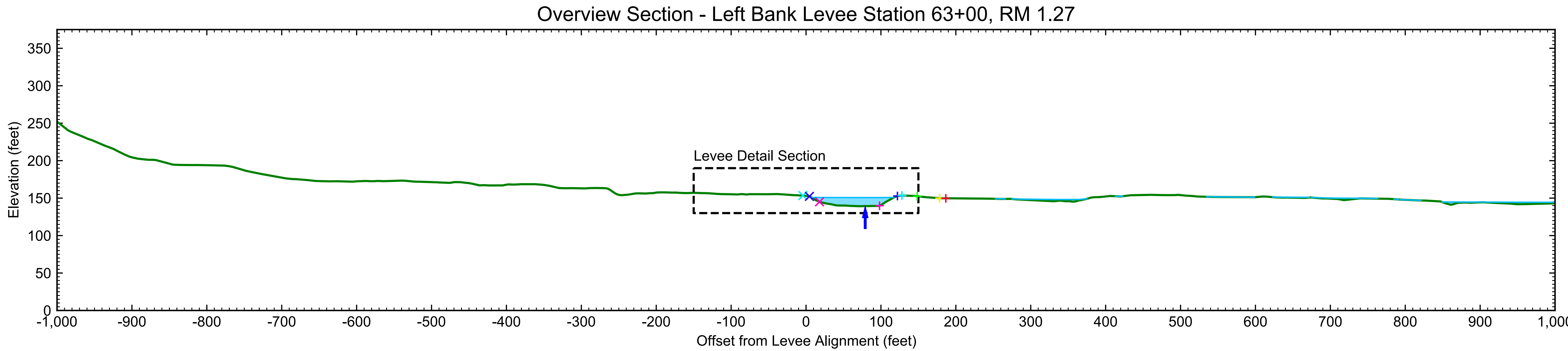
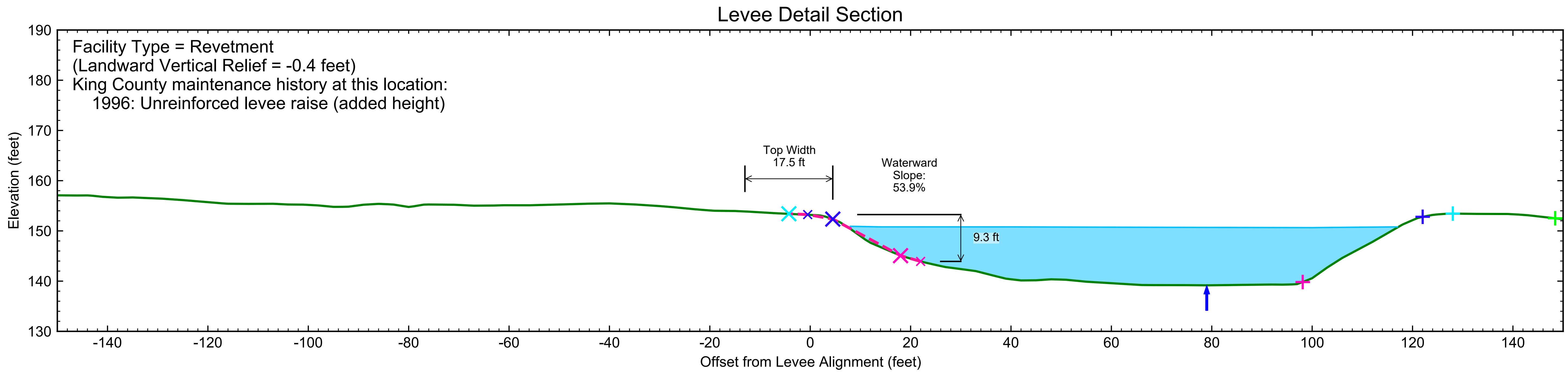
FIG. A-125





LiDAR Ground Surface — Approximate River Thalweg — Simplified Geometry — LB-L-LOW-EL — LB-L-TOE — LB-L-CREST — LB-LEVEE-CENTER — LB-W-CREST — LB-W-TOE — RB-W-TOE — RB-W-CREST — RB-LEVEE-CENTER — RB-L-CREST — RB-L-TOE — RB-L-LOW-EL — 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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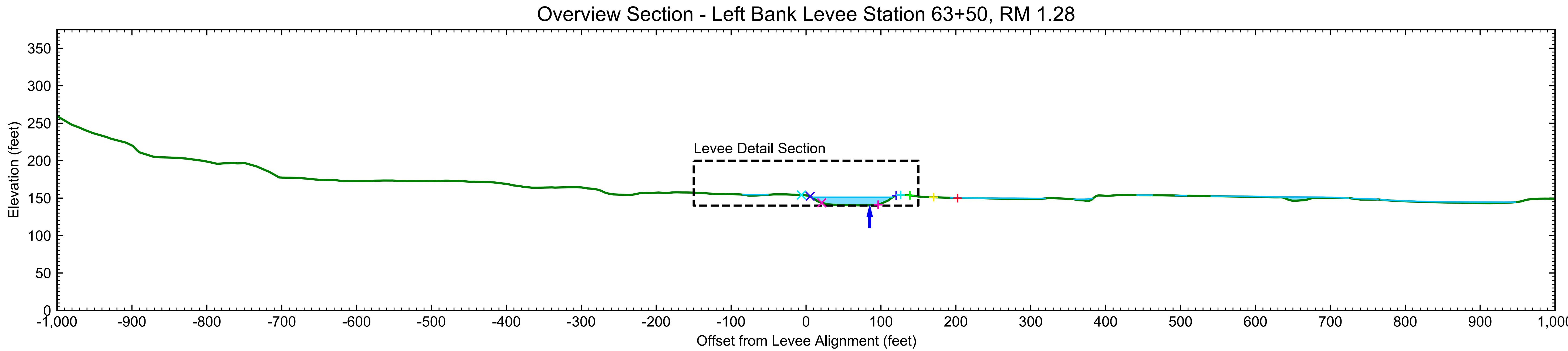
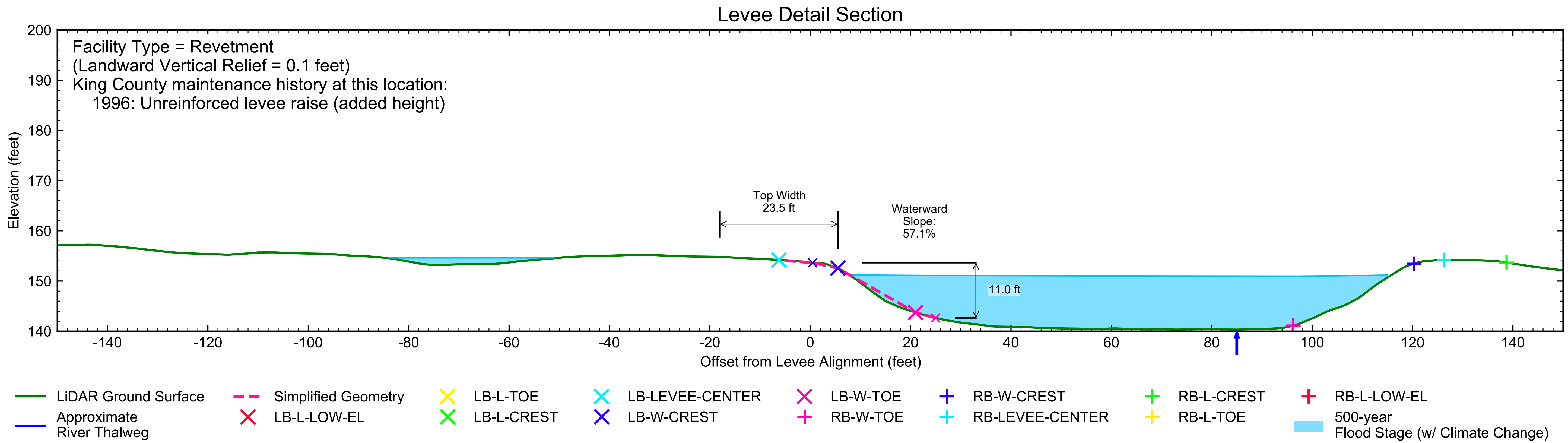
FIG. A-126





Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
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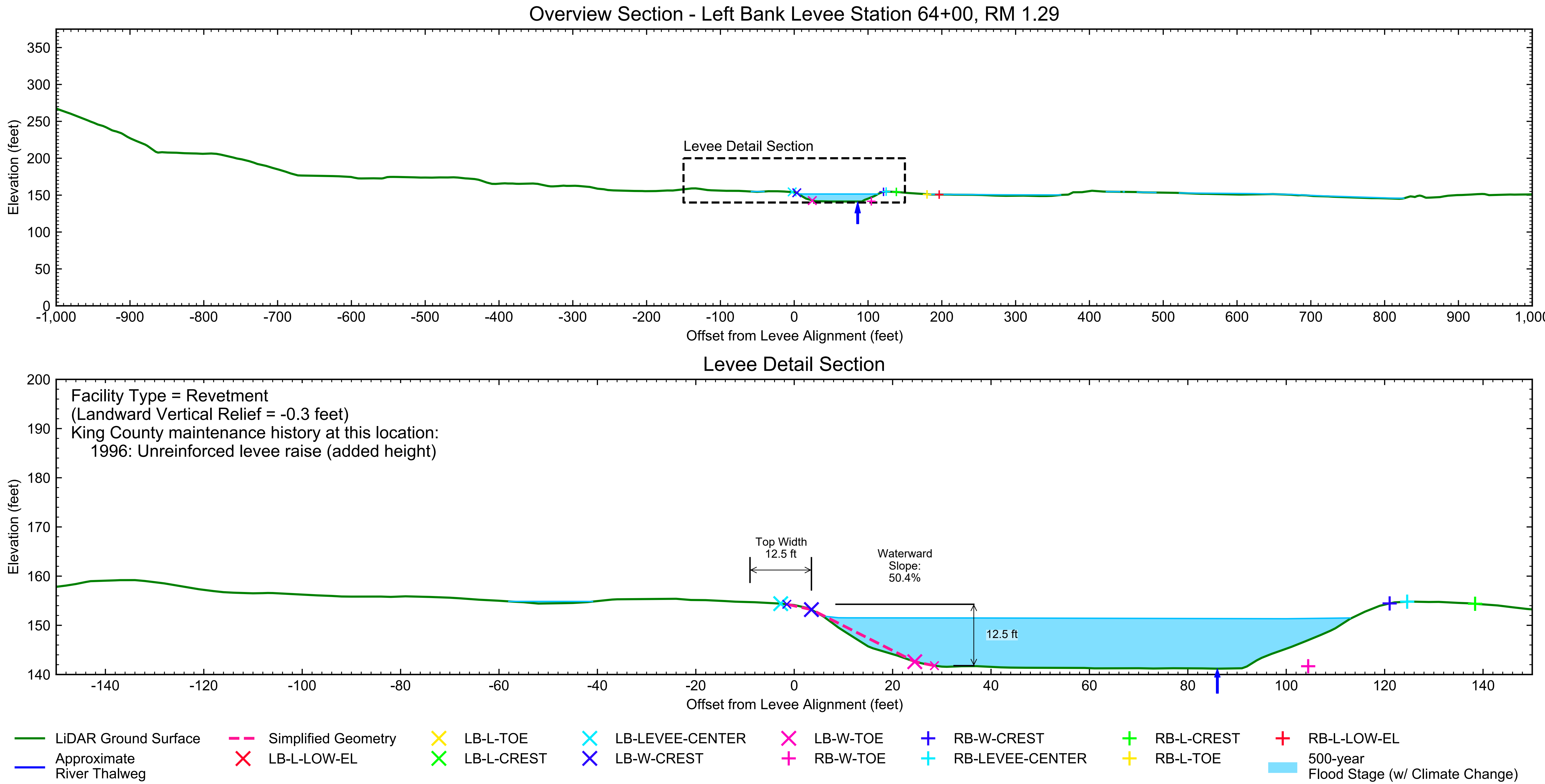
FIG. A-127



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LIDAR CROSS SECTION
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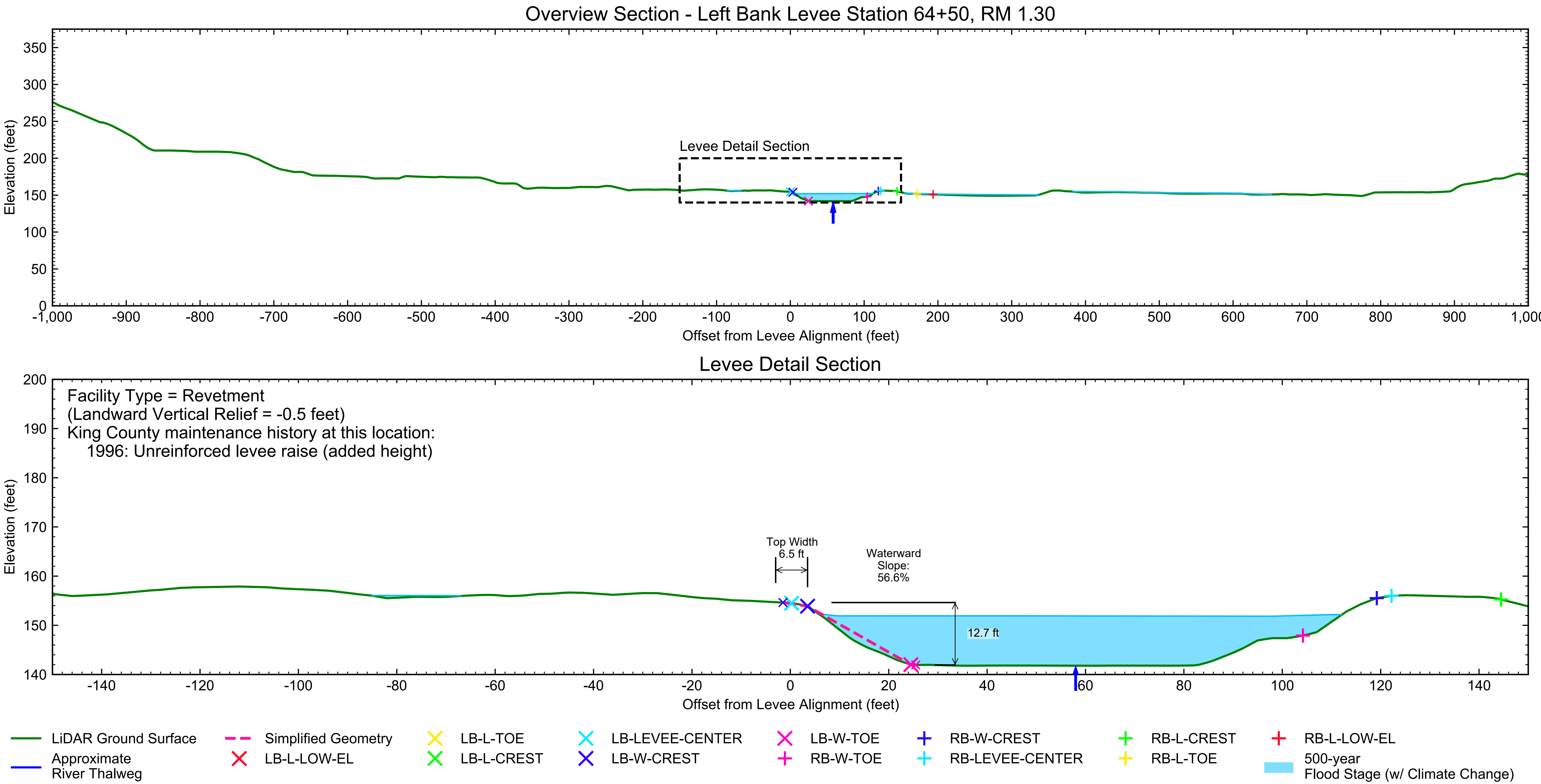
FIG. A-128



Notes:
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LIDAR CROSS SECTION
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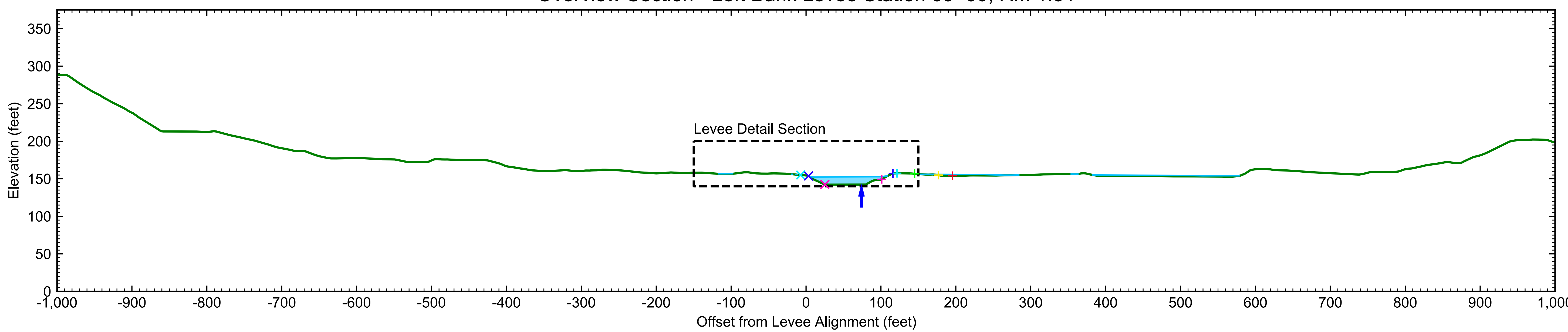
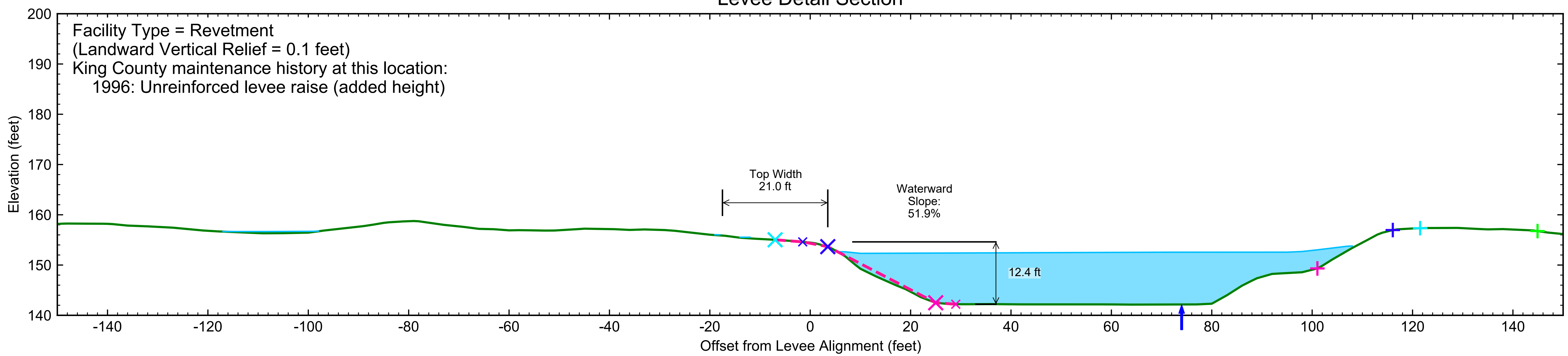
FIG. A-129

Overview Section - Left Bank Levee Station 65+00, RM 1.31



Levee Detail Section



- LiDAR Ground Surface
- Approximate River Thalweg
- Simplified Geometry
- LB-L-LOW-EL
- LB-L-TOE
- LB-L-CREST
- LB-LEVEE-CENTER
- LB-W-CREST
- LB-W-TOE
- RB-W-TOE
- RB-W-CREST
- RB-LEVEE-CENTER
- RB-L-CREST
- RB-L-TOE
- RB-L-LOW-EL
- 500-year Flood Stage (w/ Climate Change)

Notes:
LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION LOWER RAGING RIVER LEFT BANK STA 65+00, RM 1.31	
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SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-130

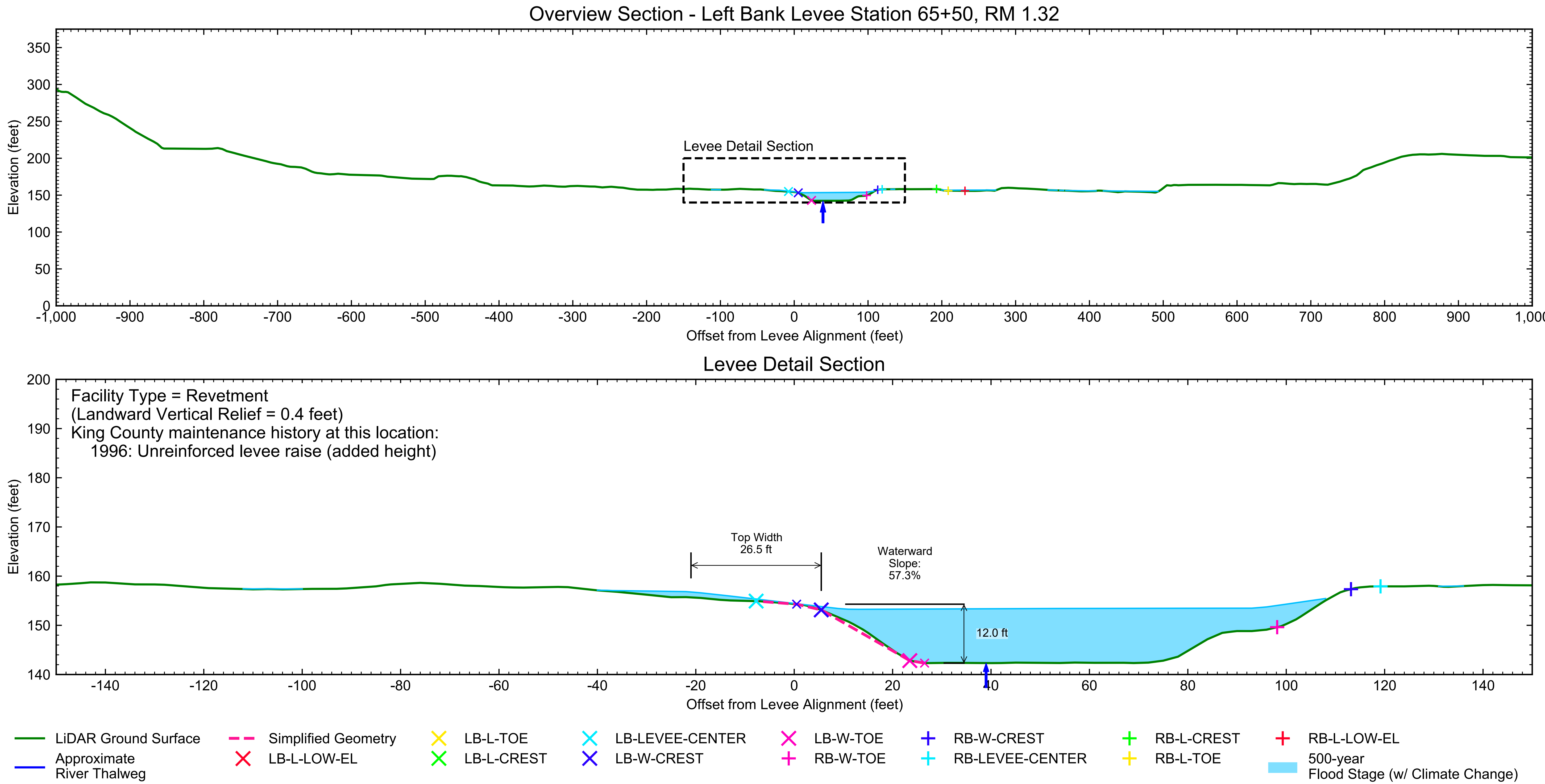

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FIG. A-131

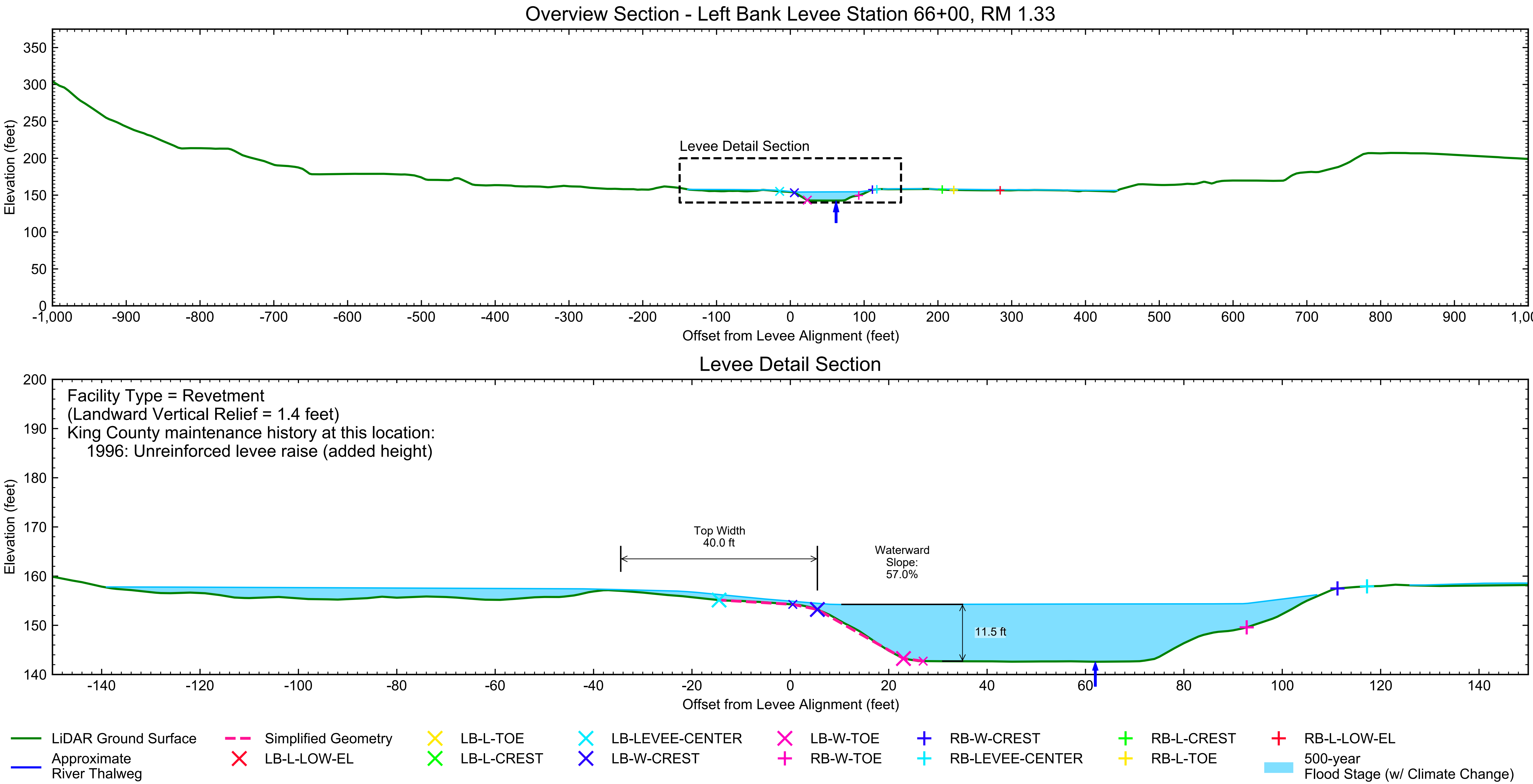

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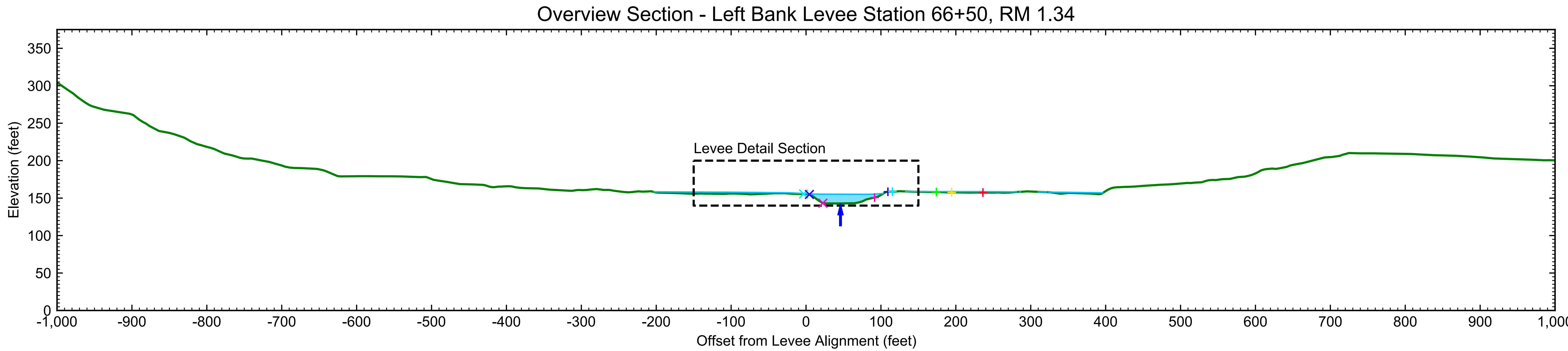
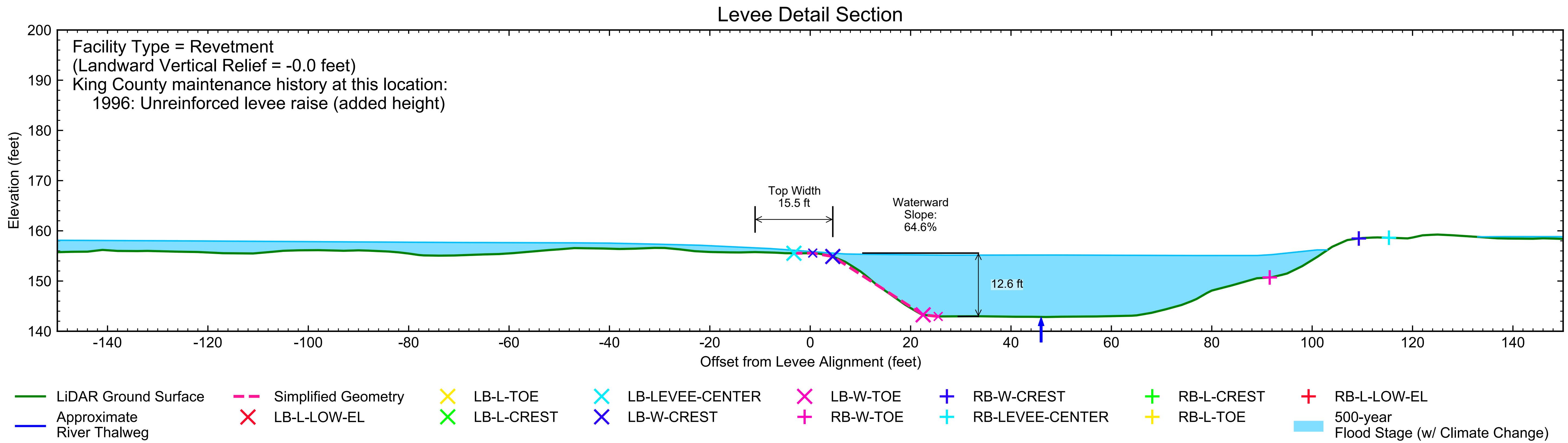
FIG. A-132





Notes:
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FIG. A-133

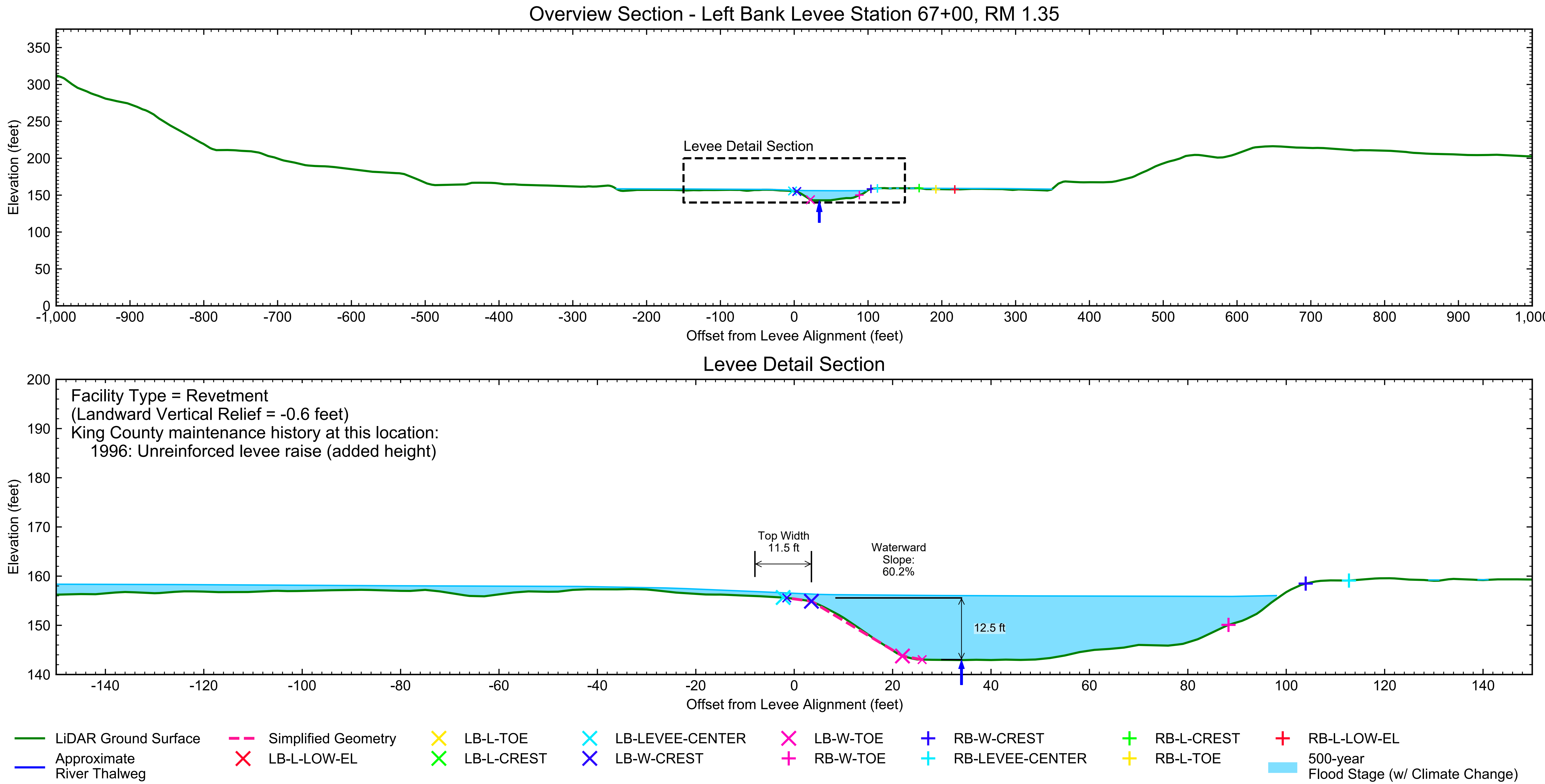

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FIG. A-134

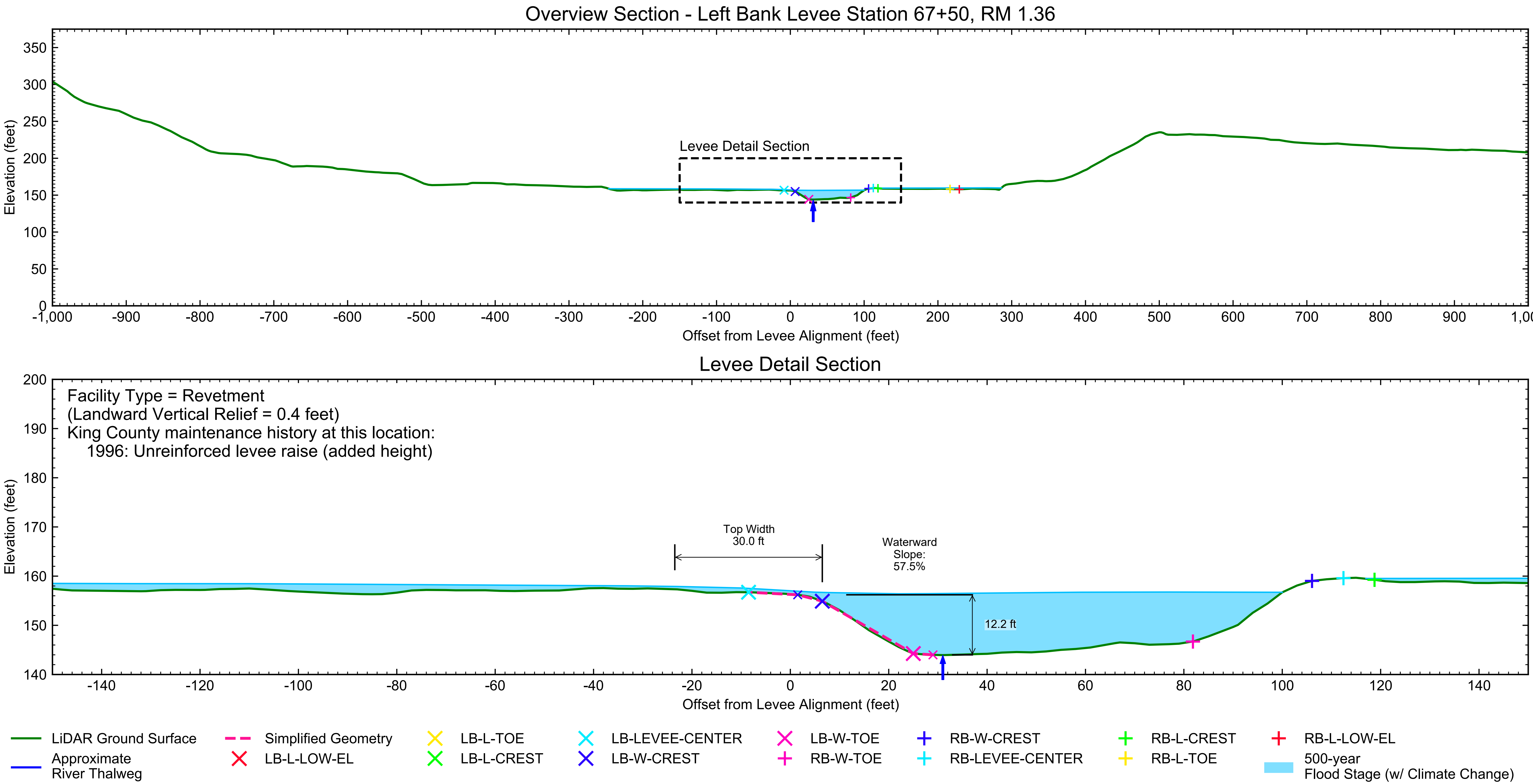

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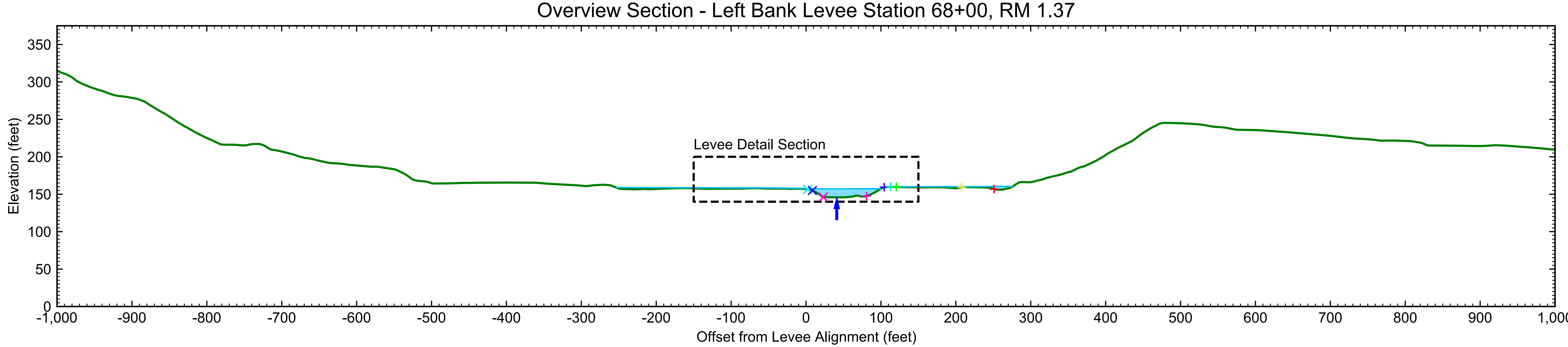
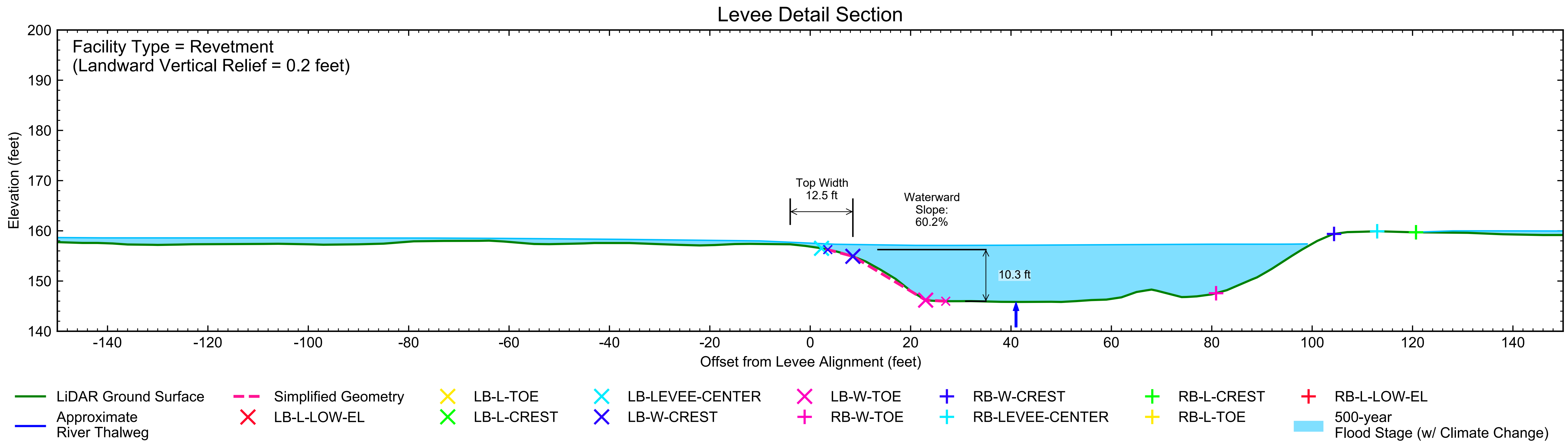
FIG. A-135





Notes:
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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 68+00, RM 1.37

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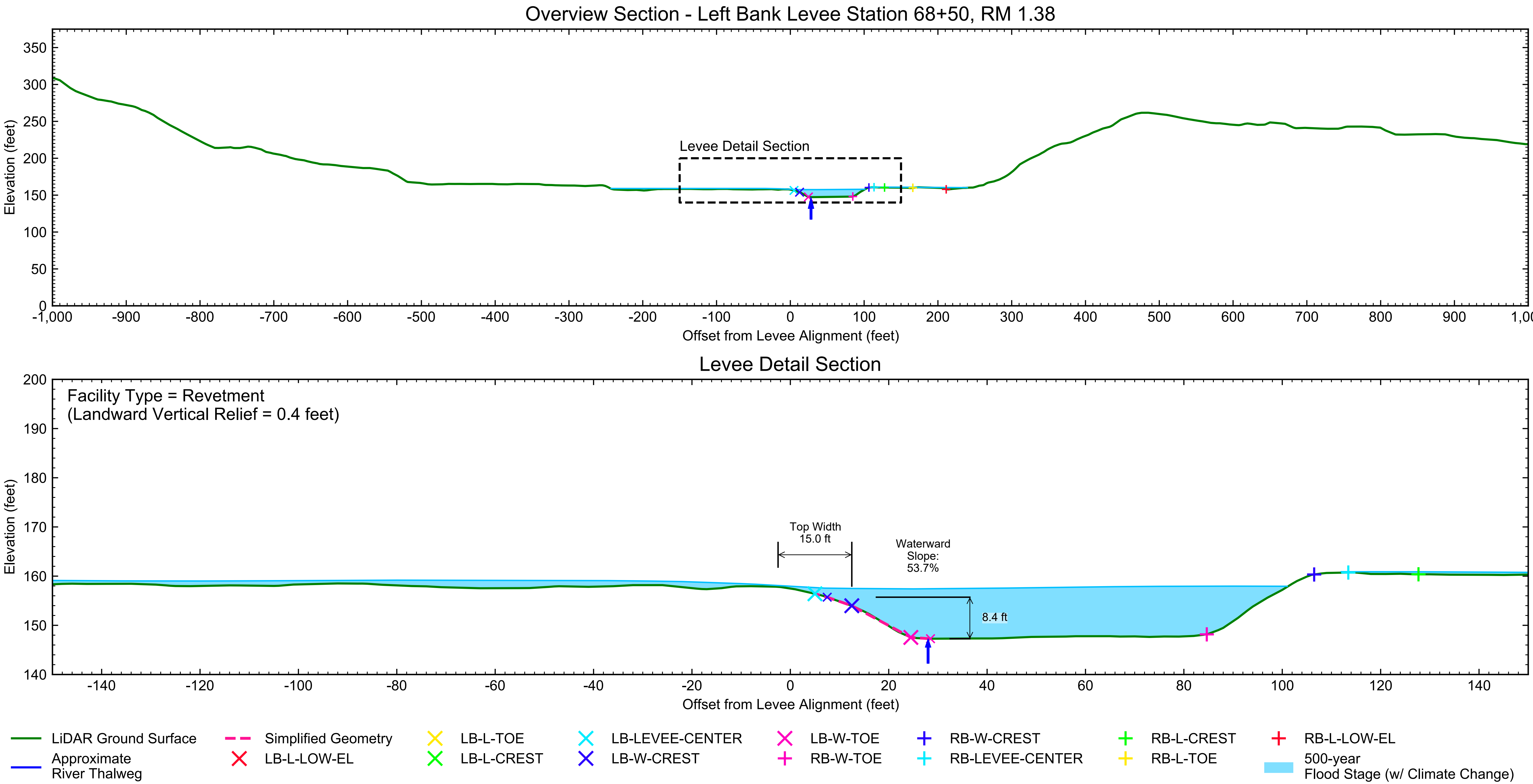
FIG. A-136



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 68+50, RM 1.38

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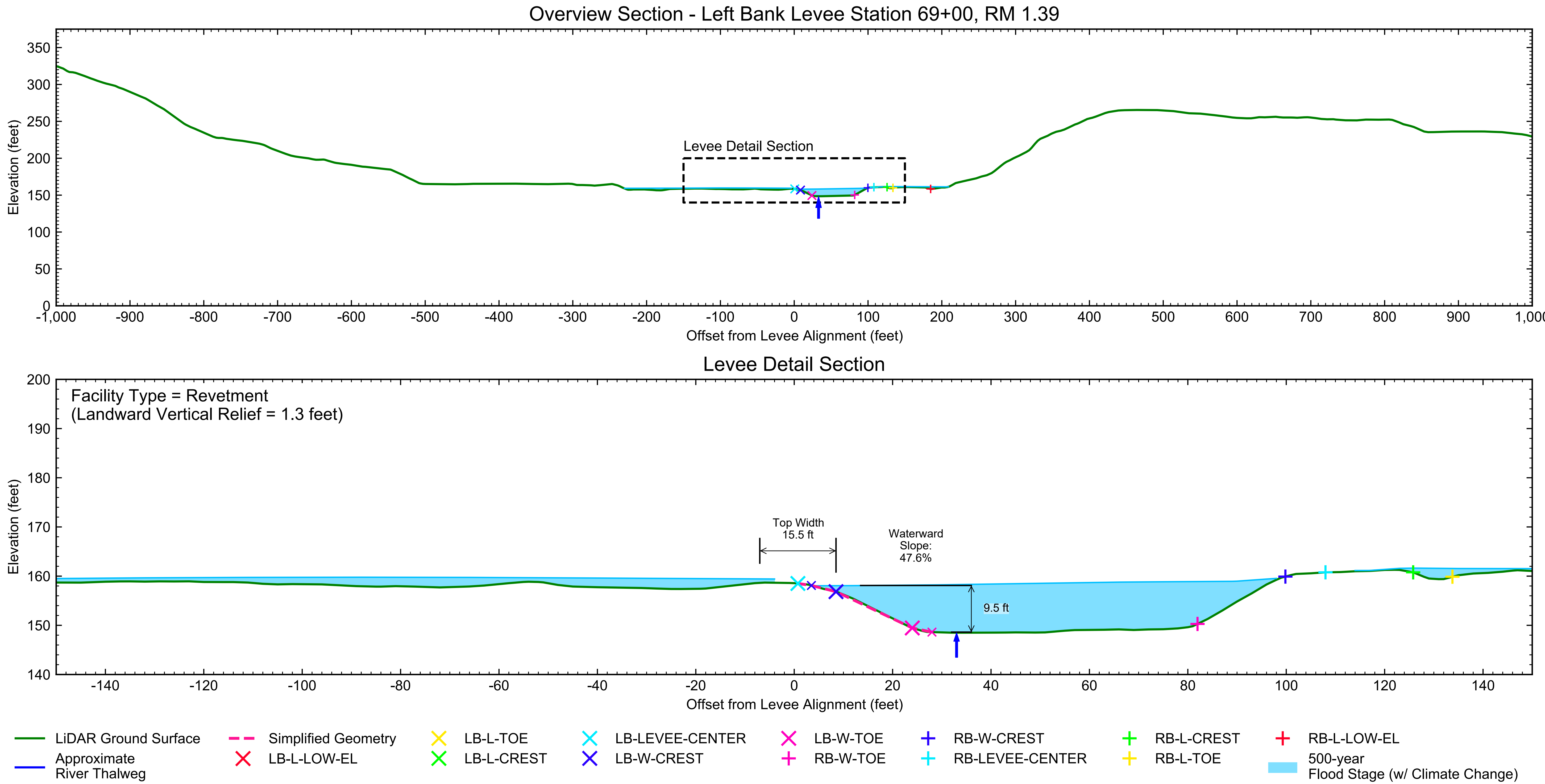
FIG. A-137



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 69+00, RM 1.39

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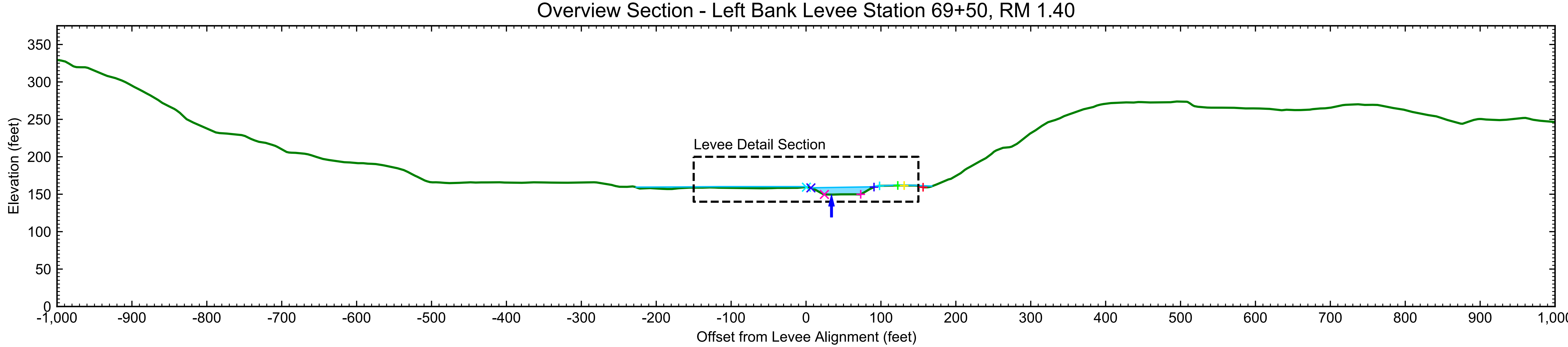
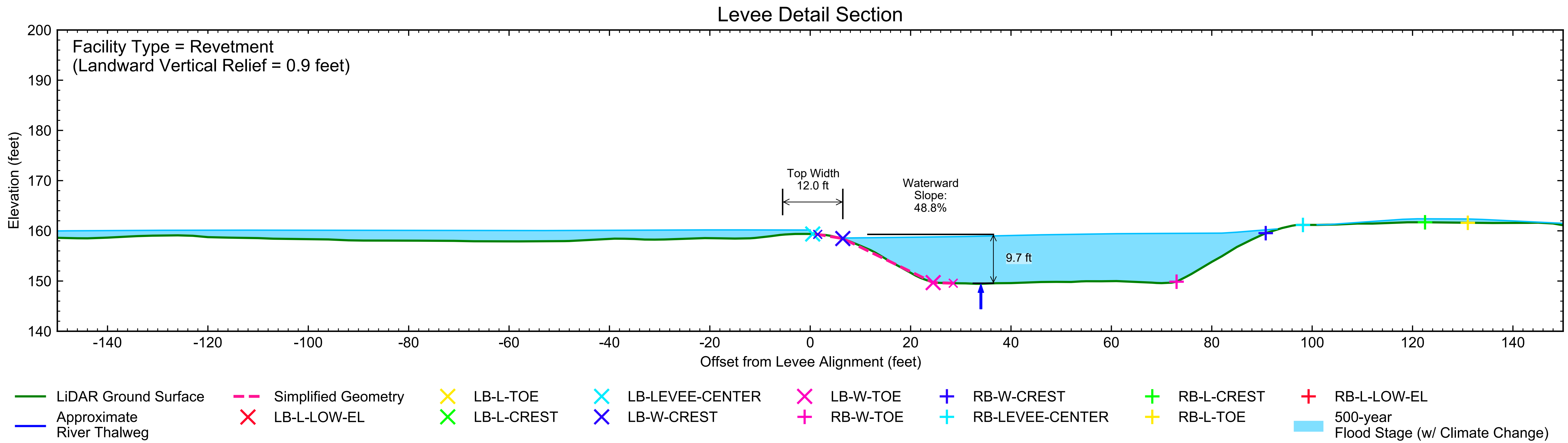
FIG. A-138





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 69+50, RM 1.40

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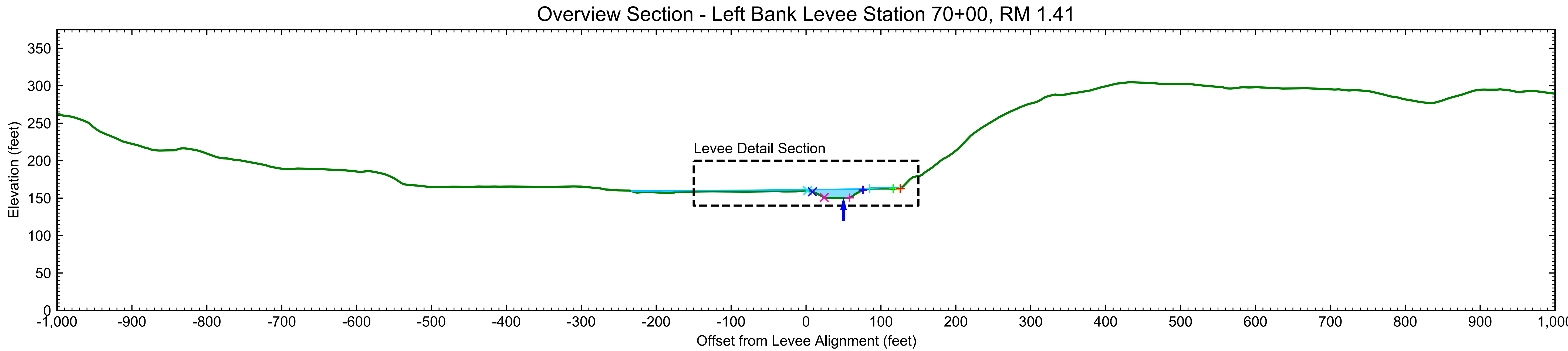
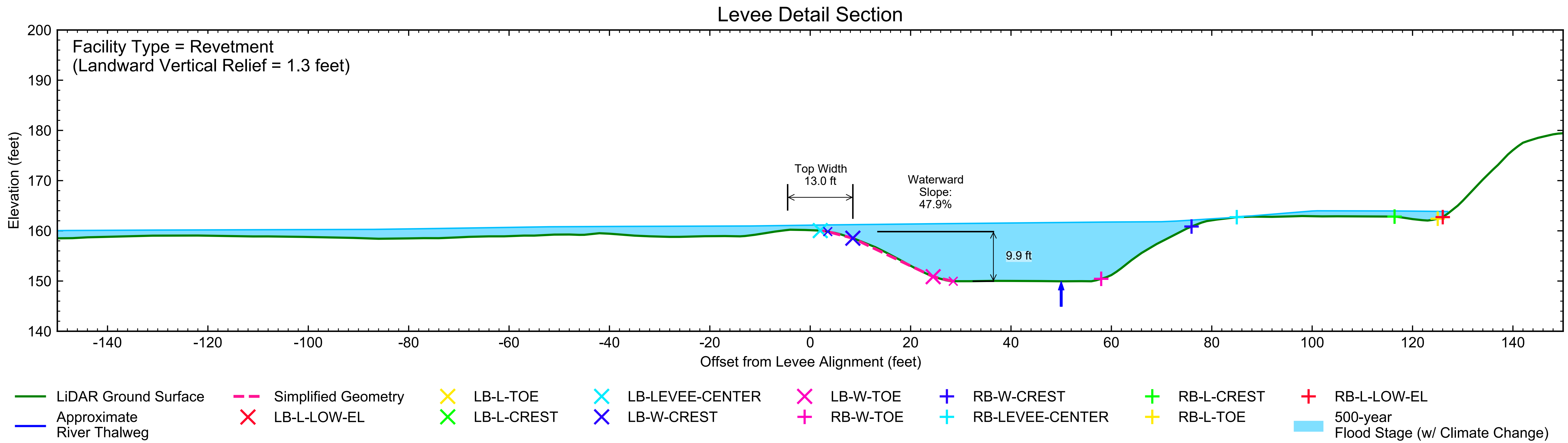
FIG. A-139





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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 70+00, RM 1.41

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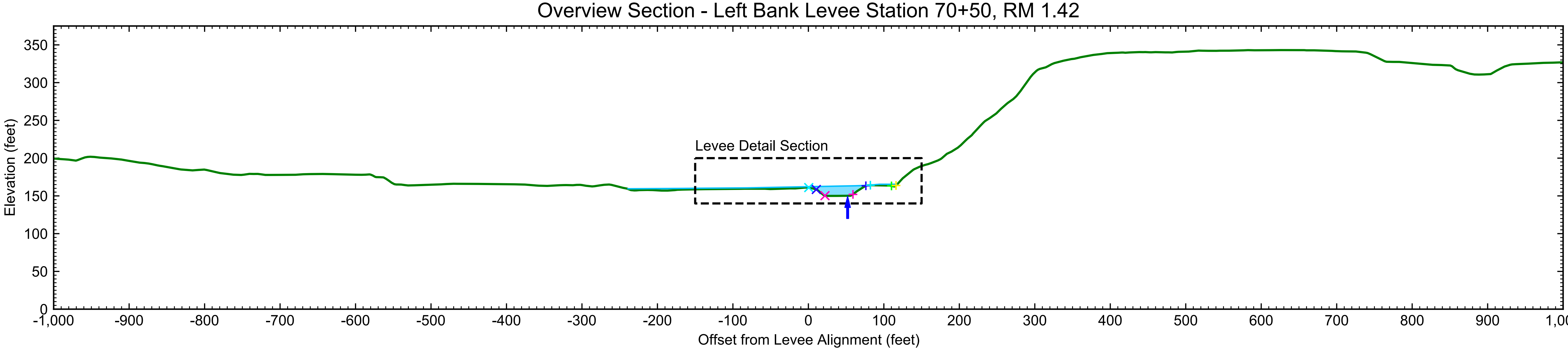
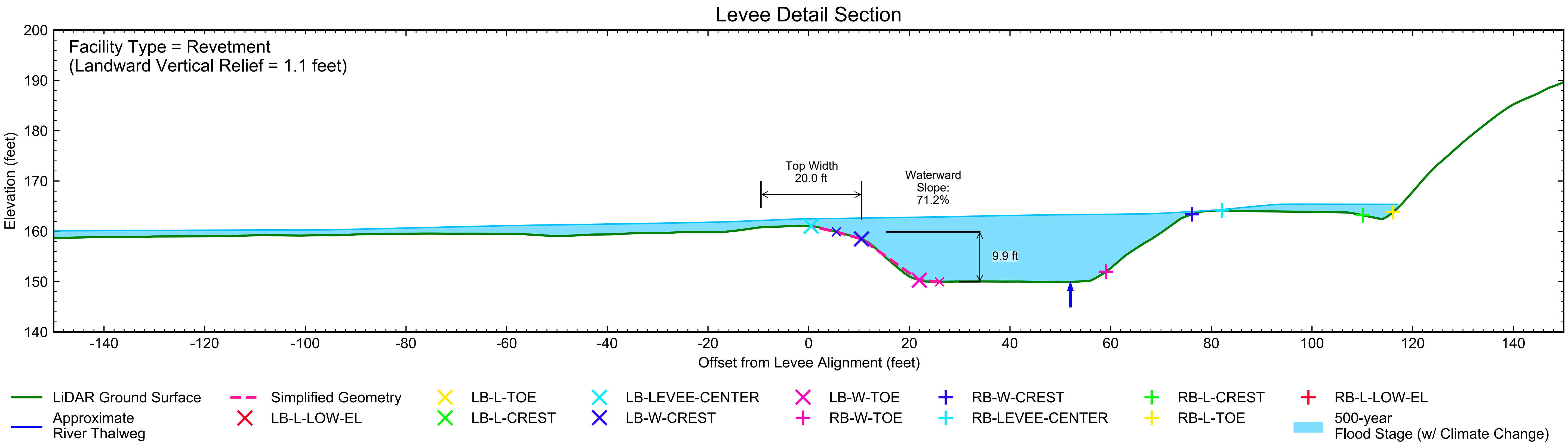
FIG. A-140





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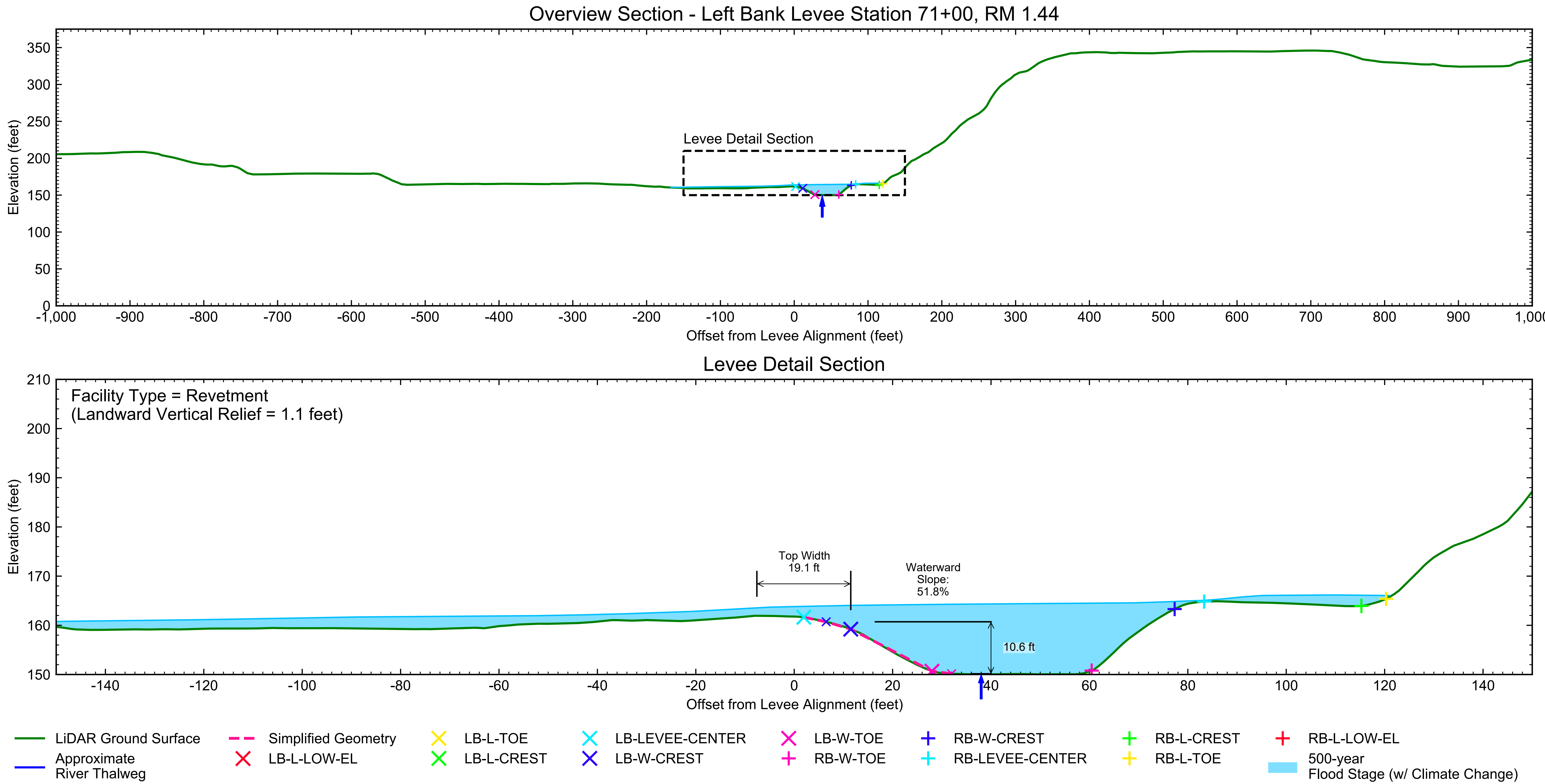
Levee Breach Analysis Mapping and Risk Assessment Segmentation and Stability Approach Report King County, Washington
LIDAR CROSS SECTION **LOWER RAGING RIVER** **LEFT BANK STA 70+50, RM 1.42**
April 2022 — 103692-304
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants — FIG. A-141



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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 71+00, RM 1.44

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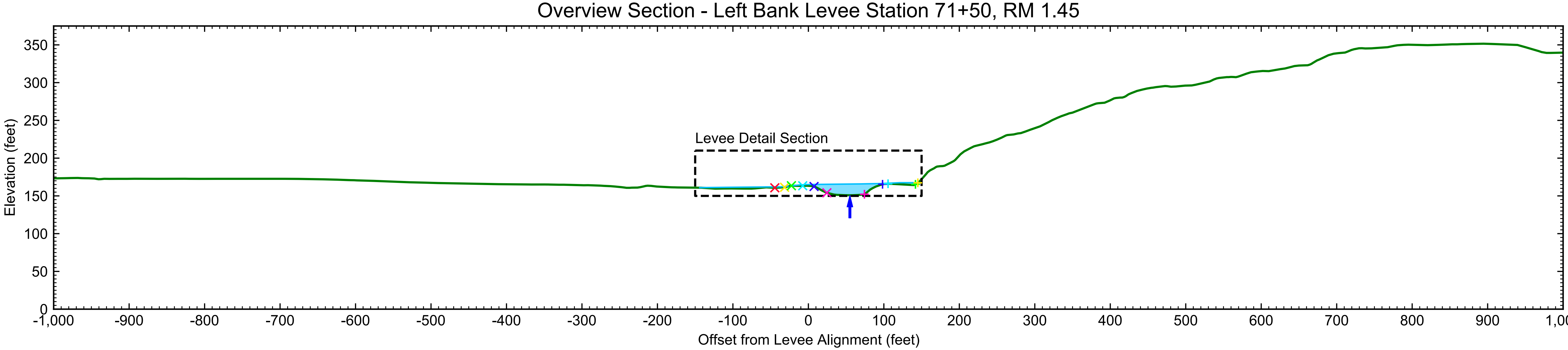
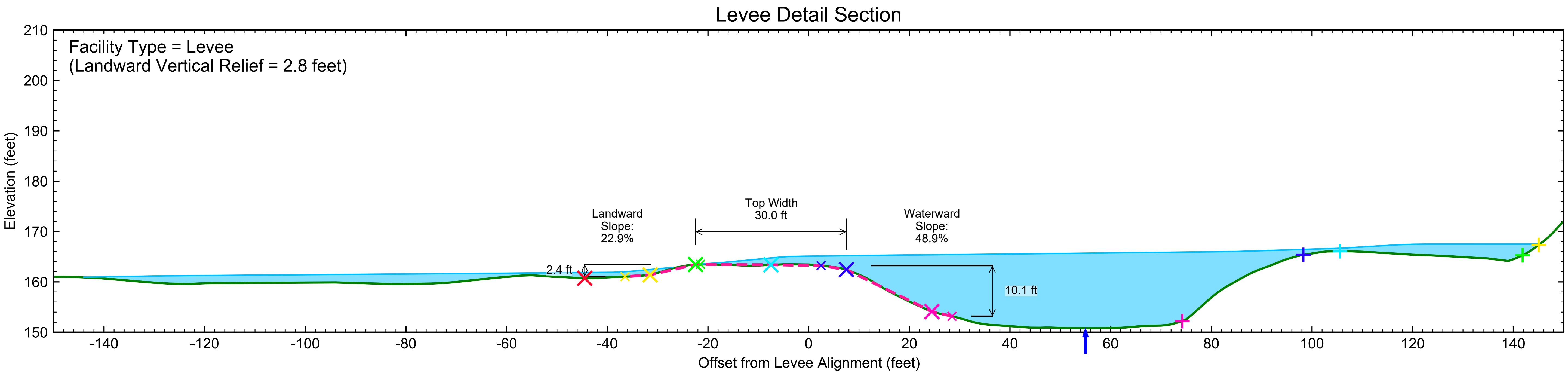
FIG. A-142

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data
ver0.14.0.post1+gf81b80b_by:OTH





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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 71+50, RM 1.45

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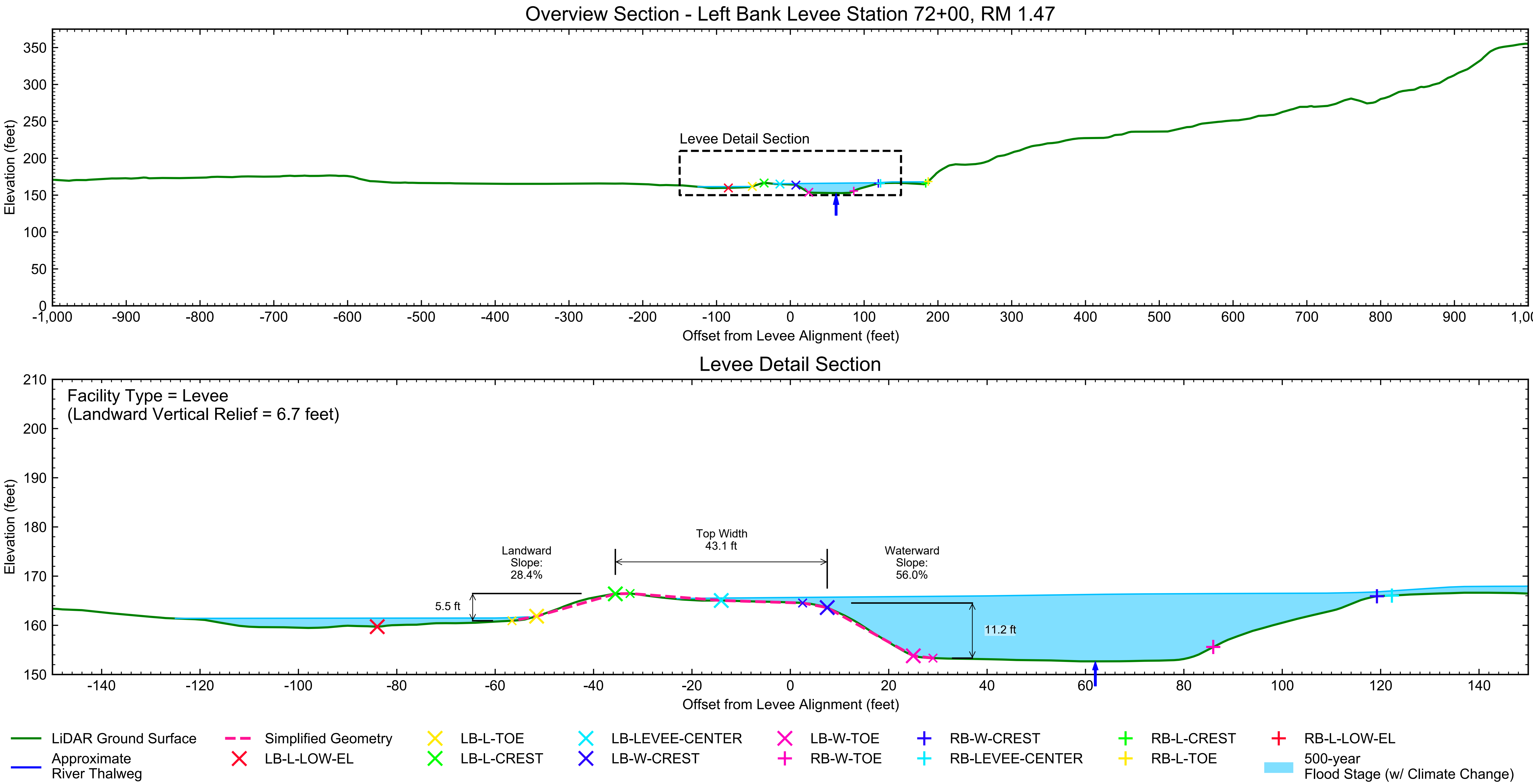
Geotechnical and Environmental Consultants

FIG. A-143



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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 72+00, RM 1.47

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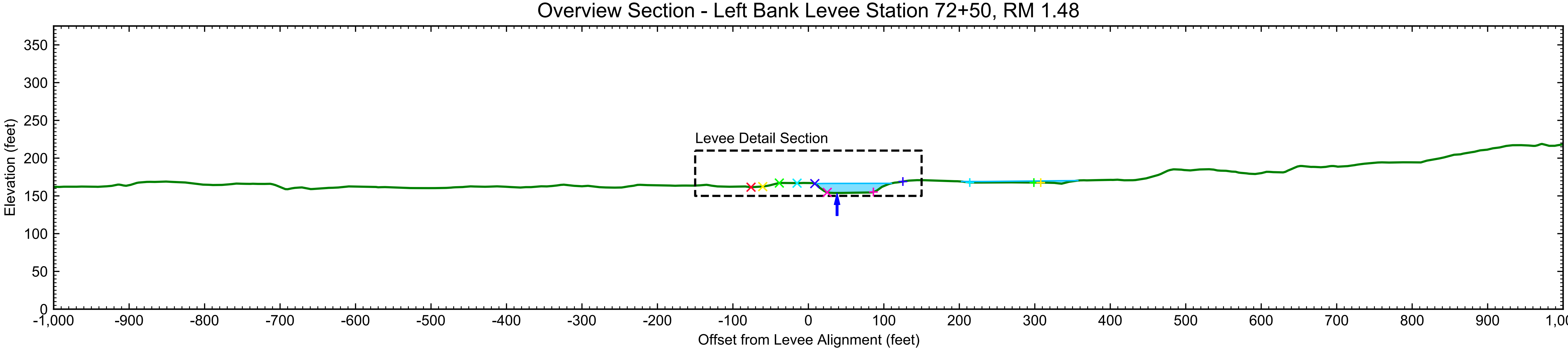
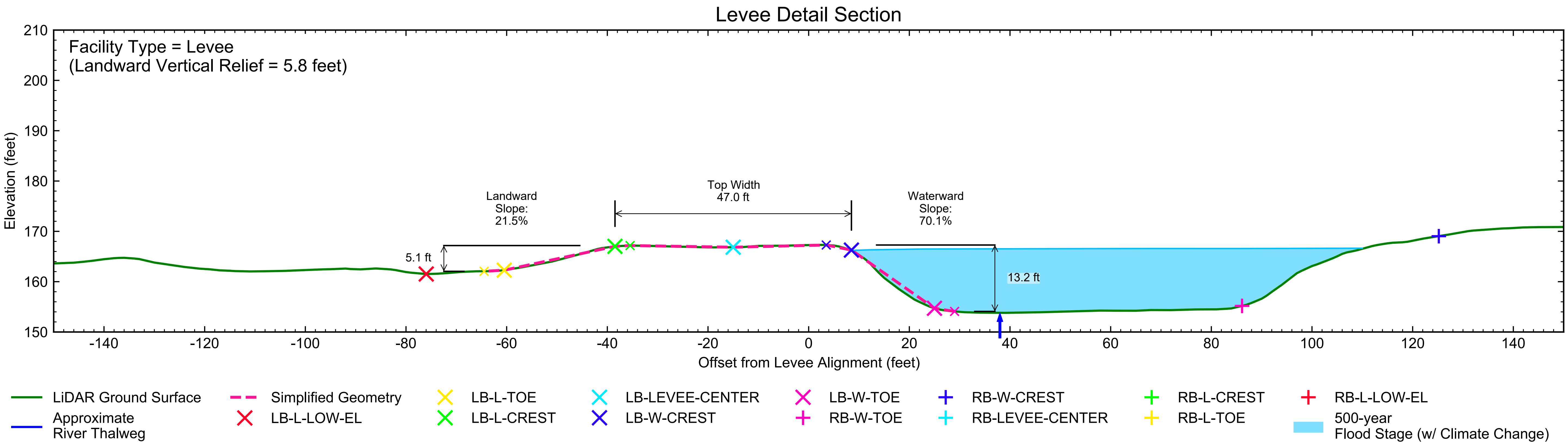
FIG. A-144





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
LEFT BANK STA 72+50, RM 1.48

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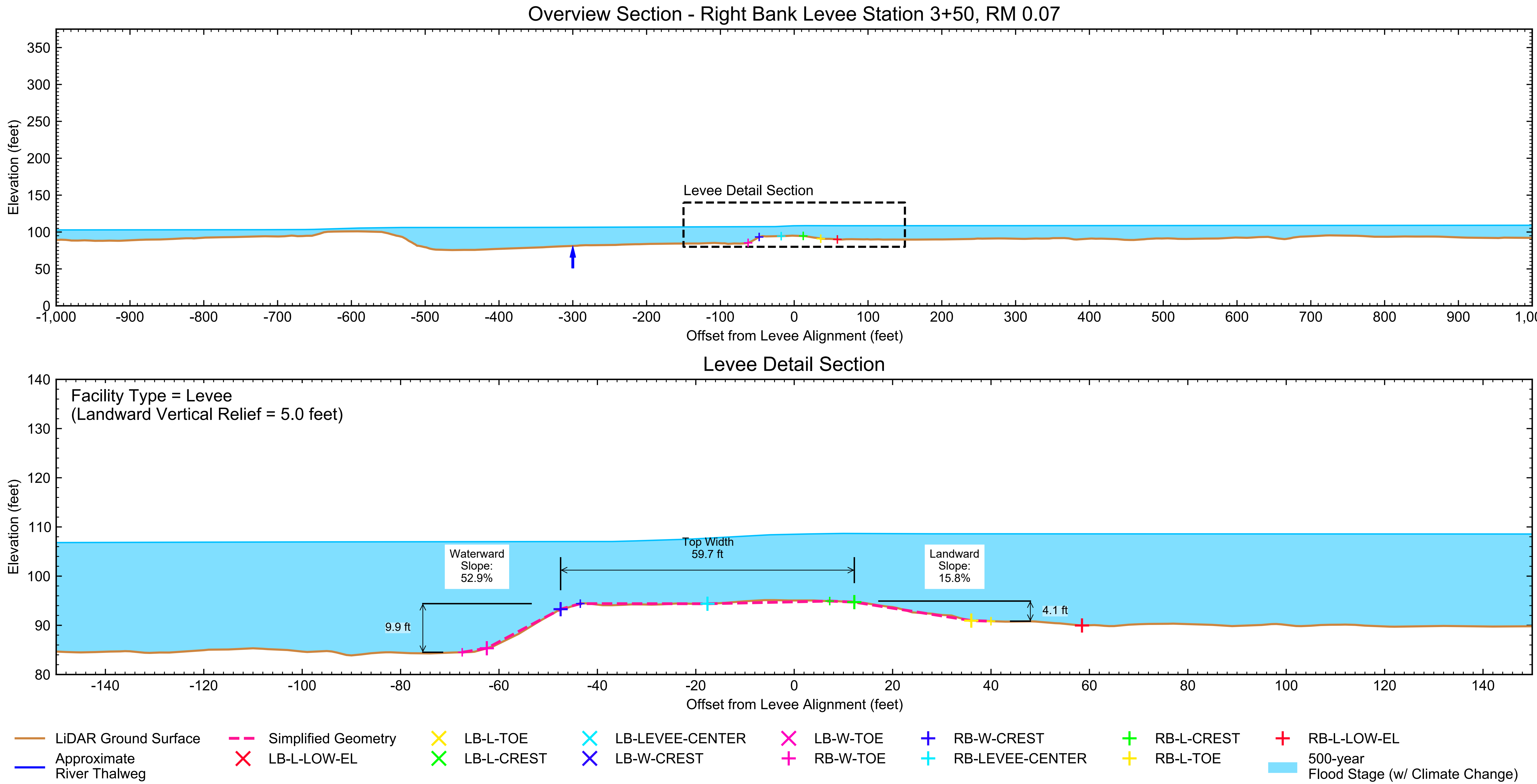
FIG. A-145



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 3+50, RM 0.07

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SHANNON & WILSON, INC.
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FIG. A-146

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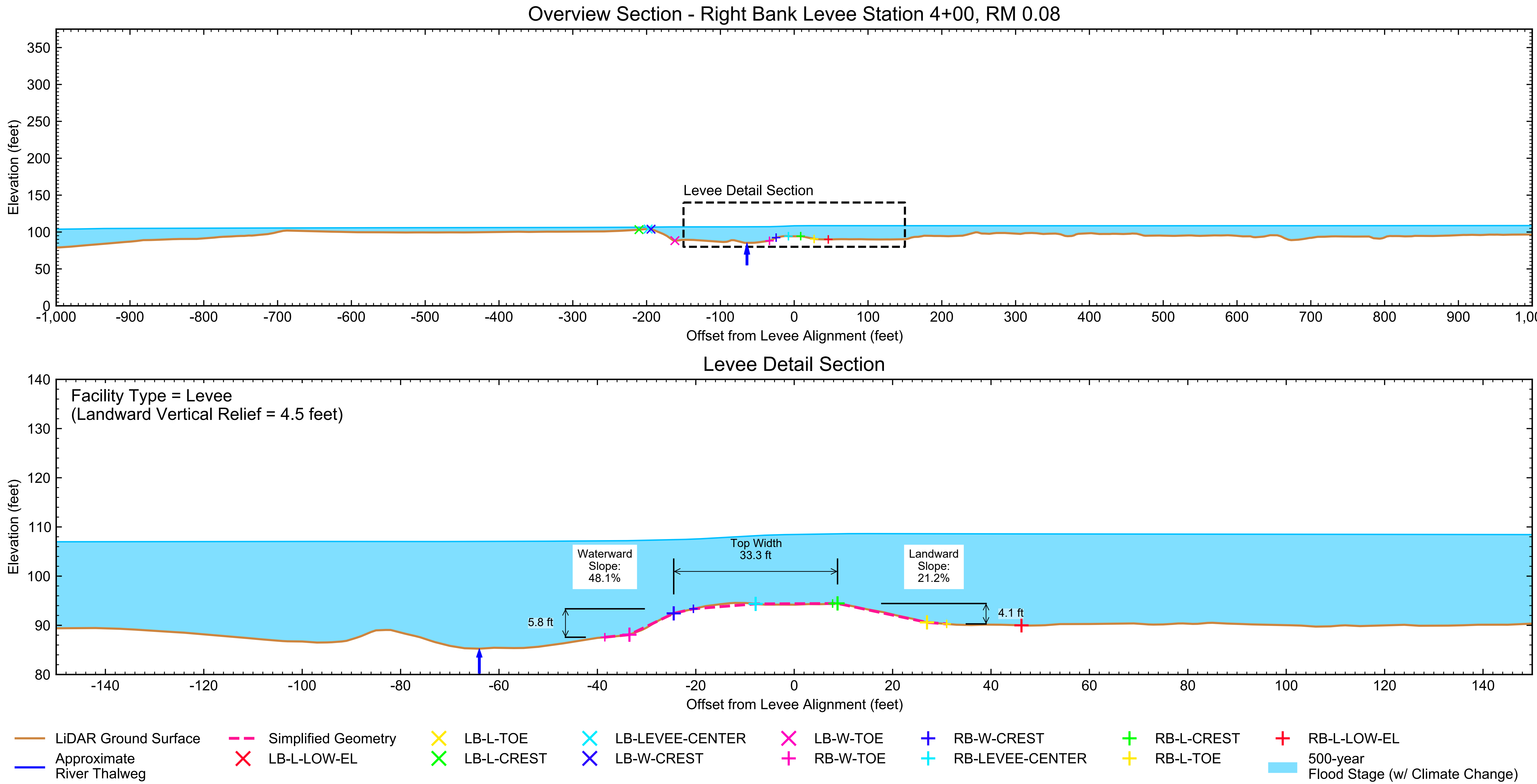
\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data



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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 4+00, RM 0.08

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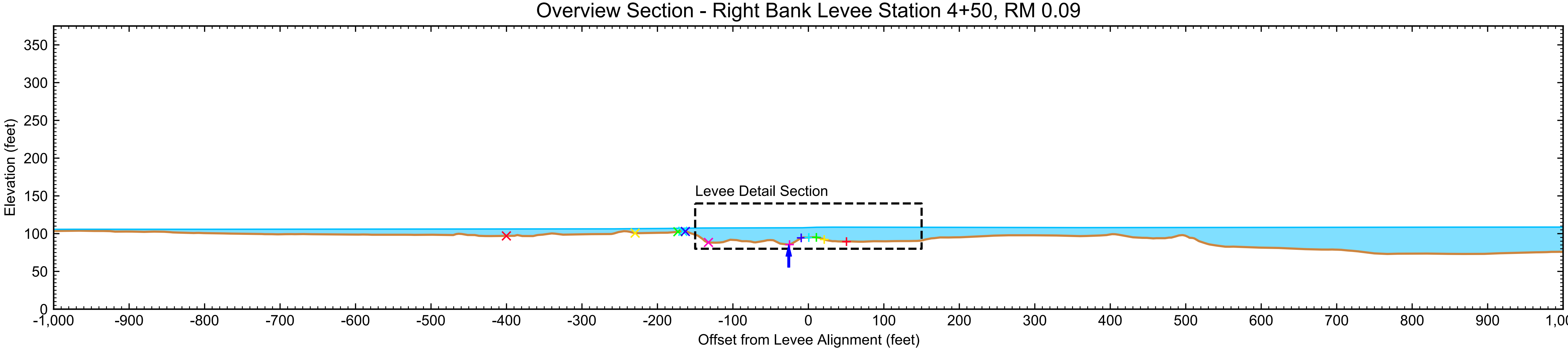
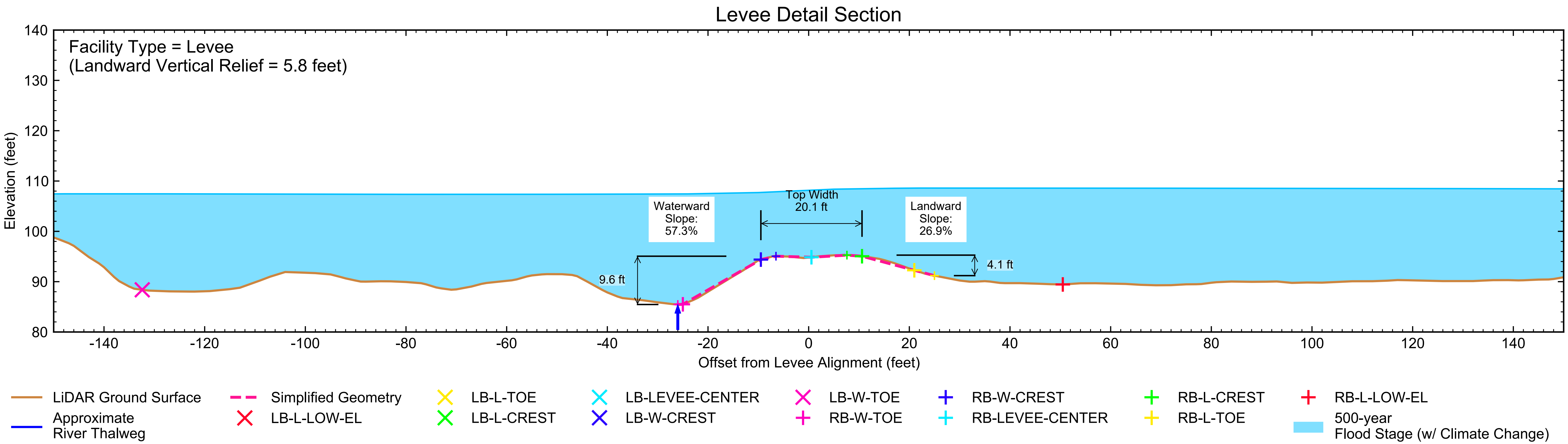
FIG. A-147





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 4+50, RM 0.09

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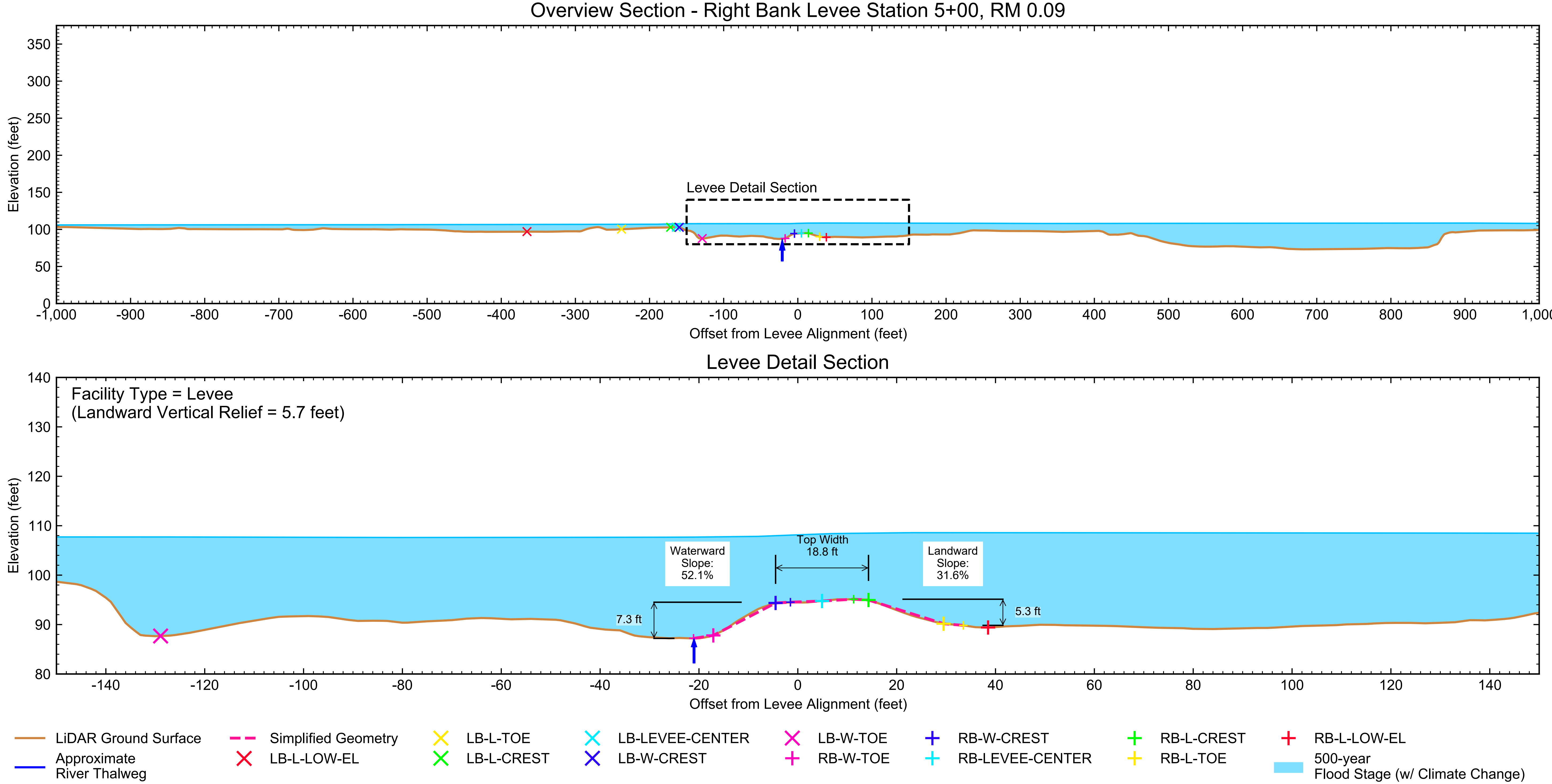
FIG. A-148



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 5+00, RM 0.09

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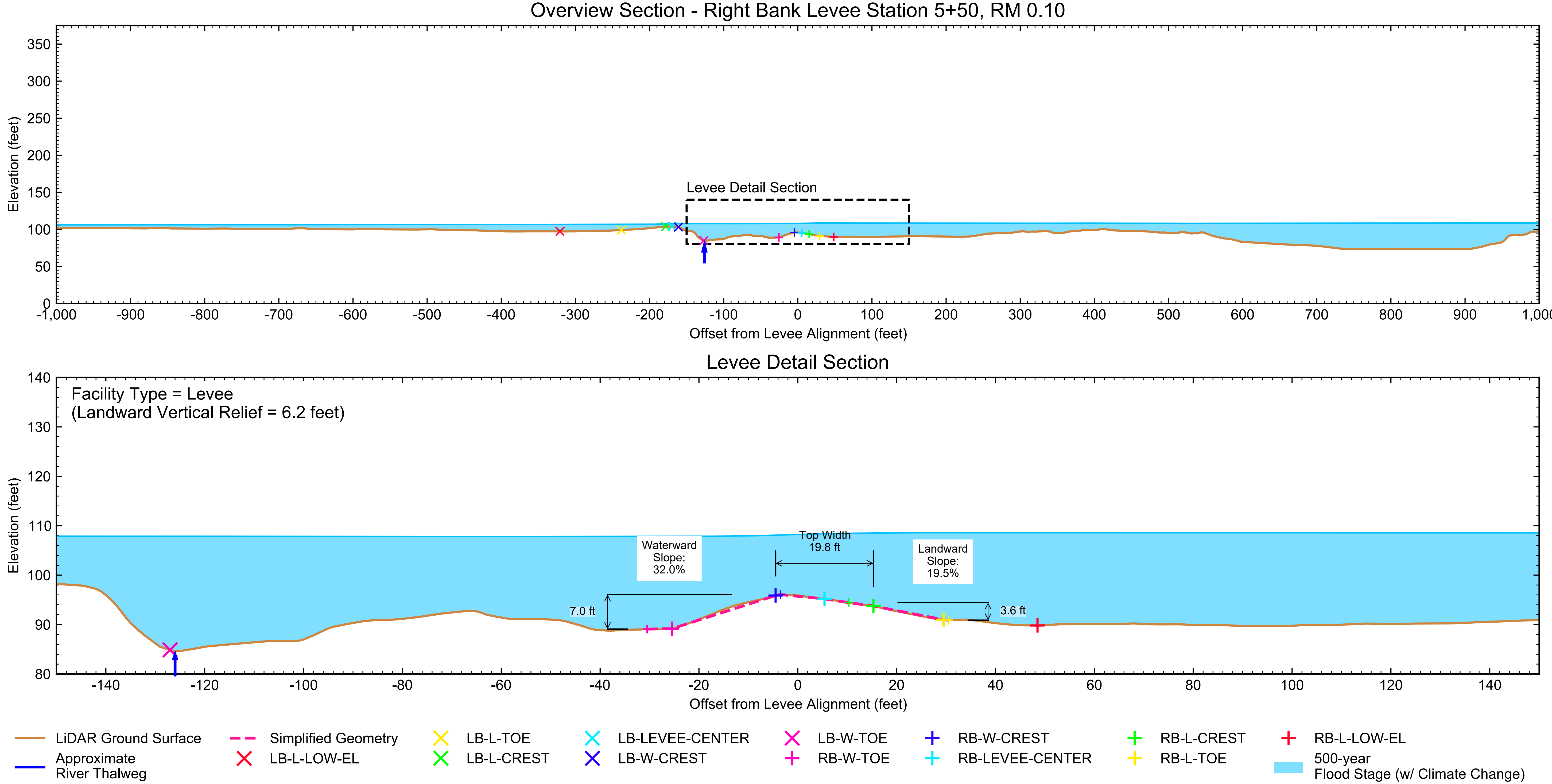
FIG. A-149



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LOWER RAGING RIVER
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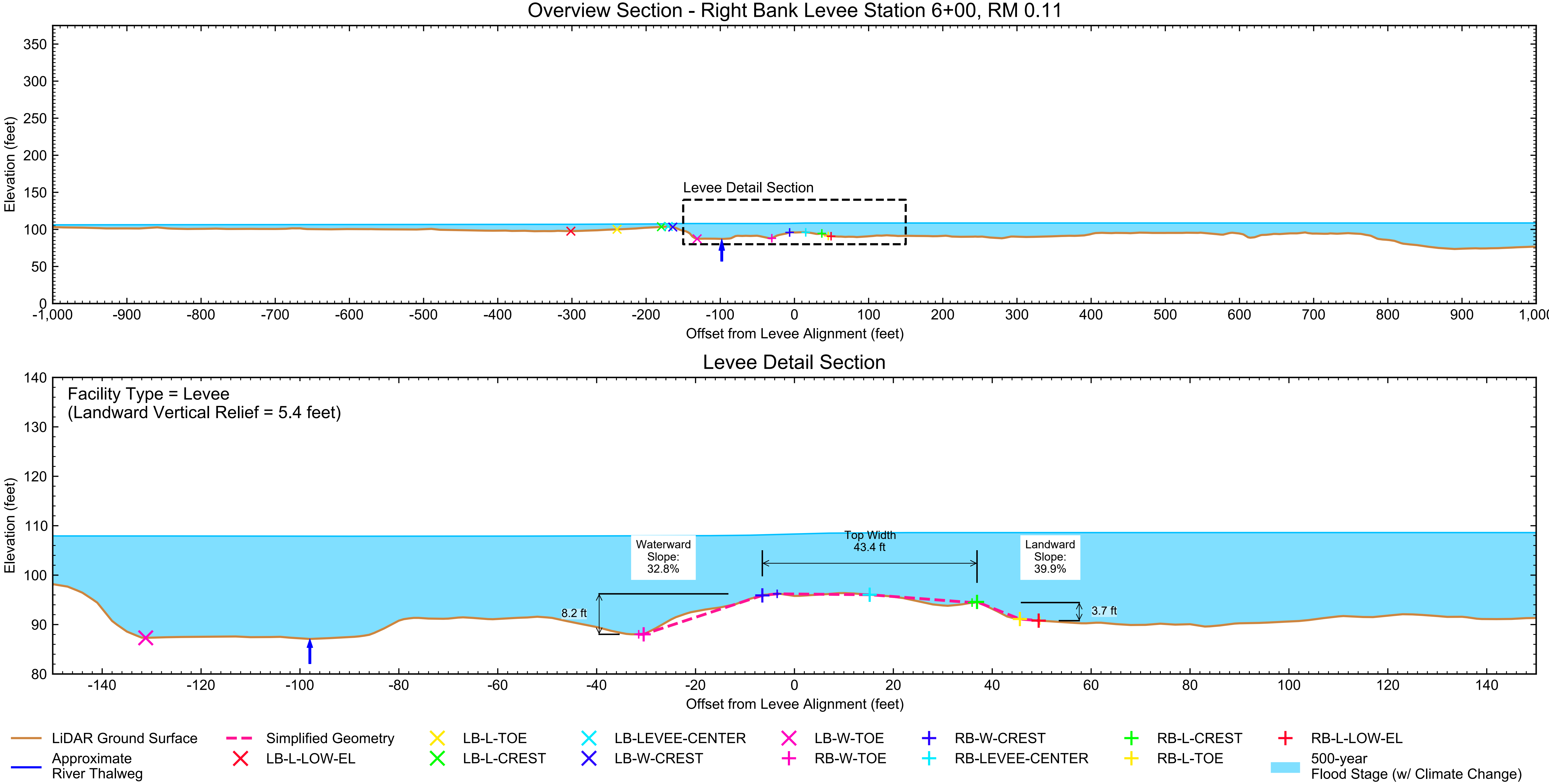
FIG. A-150



Notes:

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LIDAR CROSS SECTION
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RIGHT BANK STA 6+00, RM 0.11

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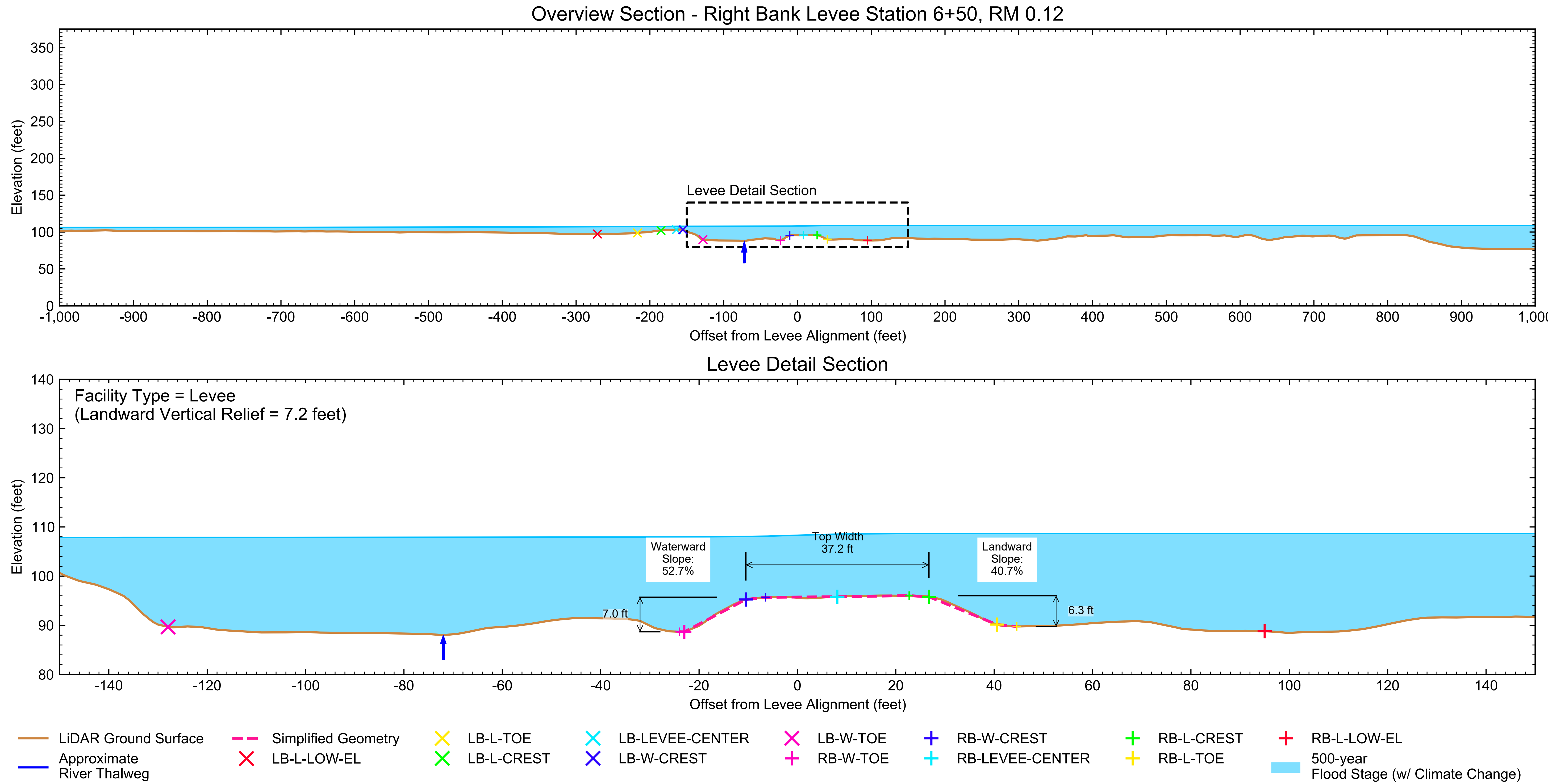
FIG. A-151



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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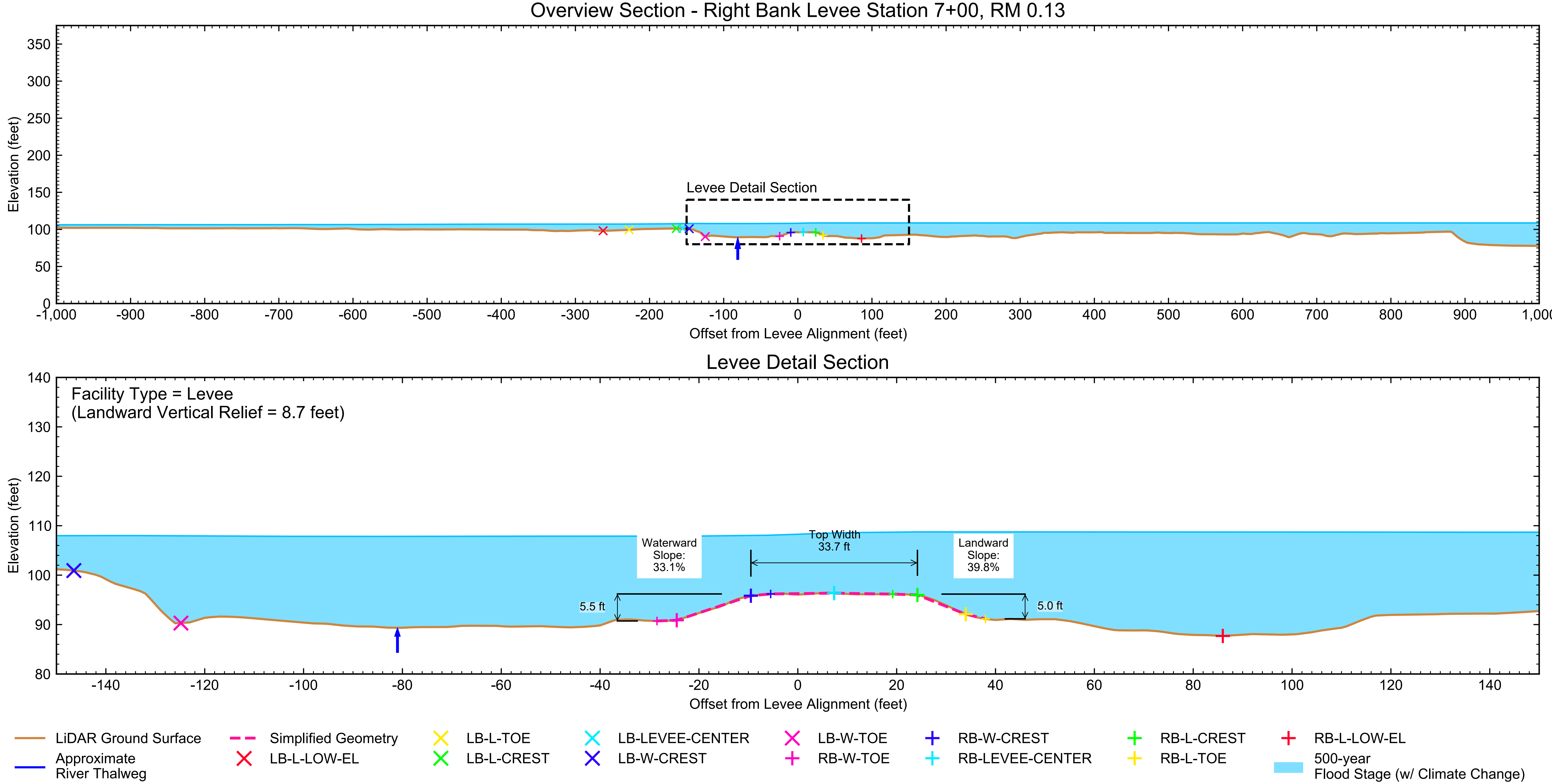
FIG. A-152



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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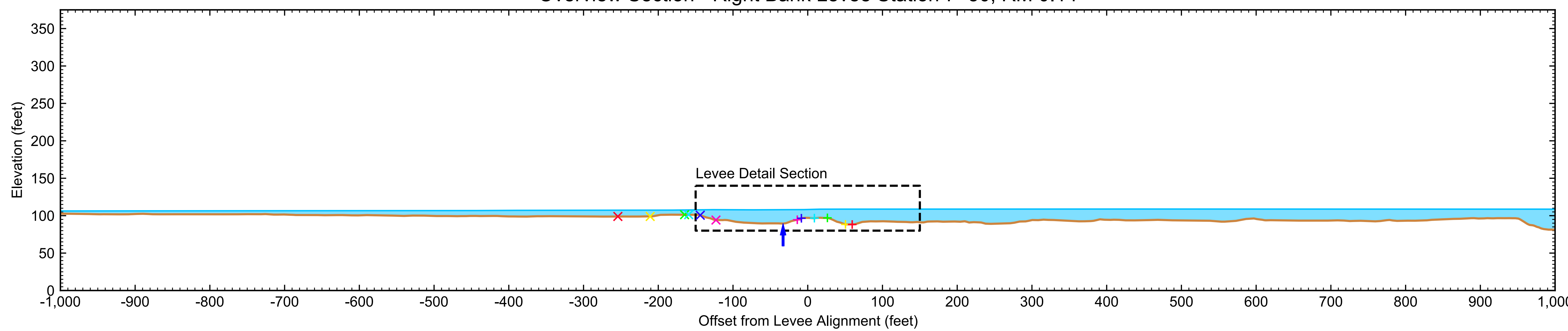
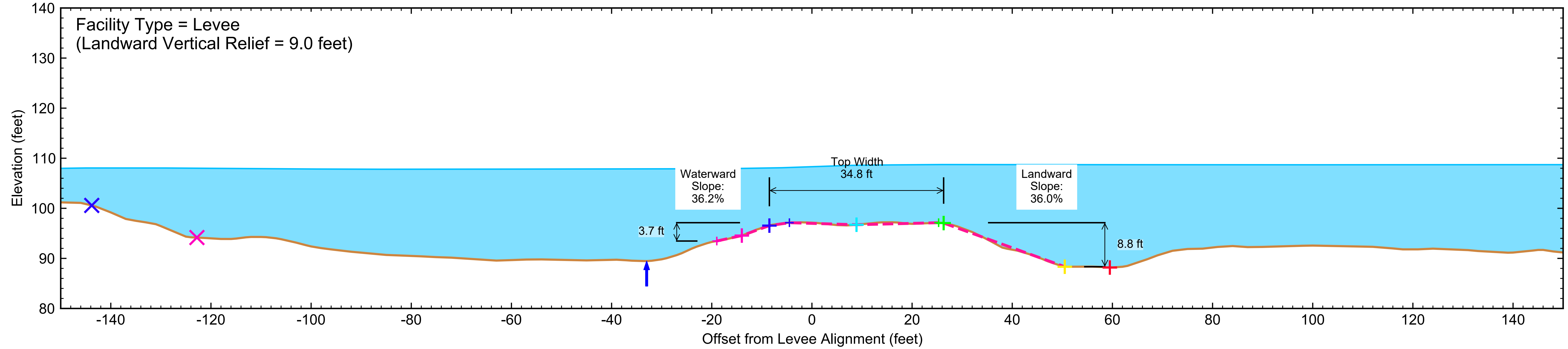
FIG. A-153

Overview Section - Right Bank Levee Station 7+50, RM 0.14



Levee Detail Section



LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL

Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
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LOWER RAGING RIVER
RIGHT BANK STA 7+50, RM 0.14

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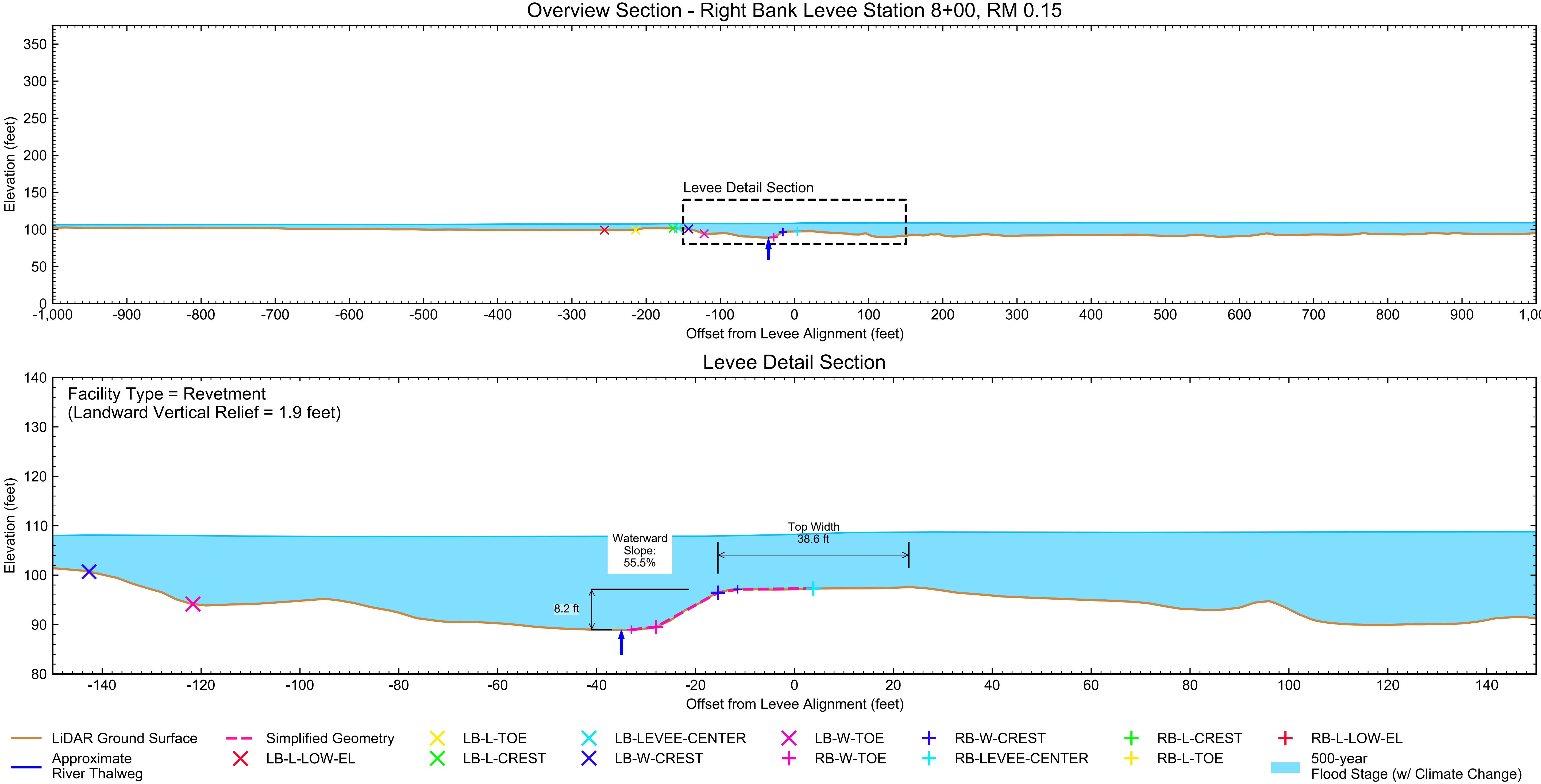
FIG. A-154



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LIDAR CROSS SECTION
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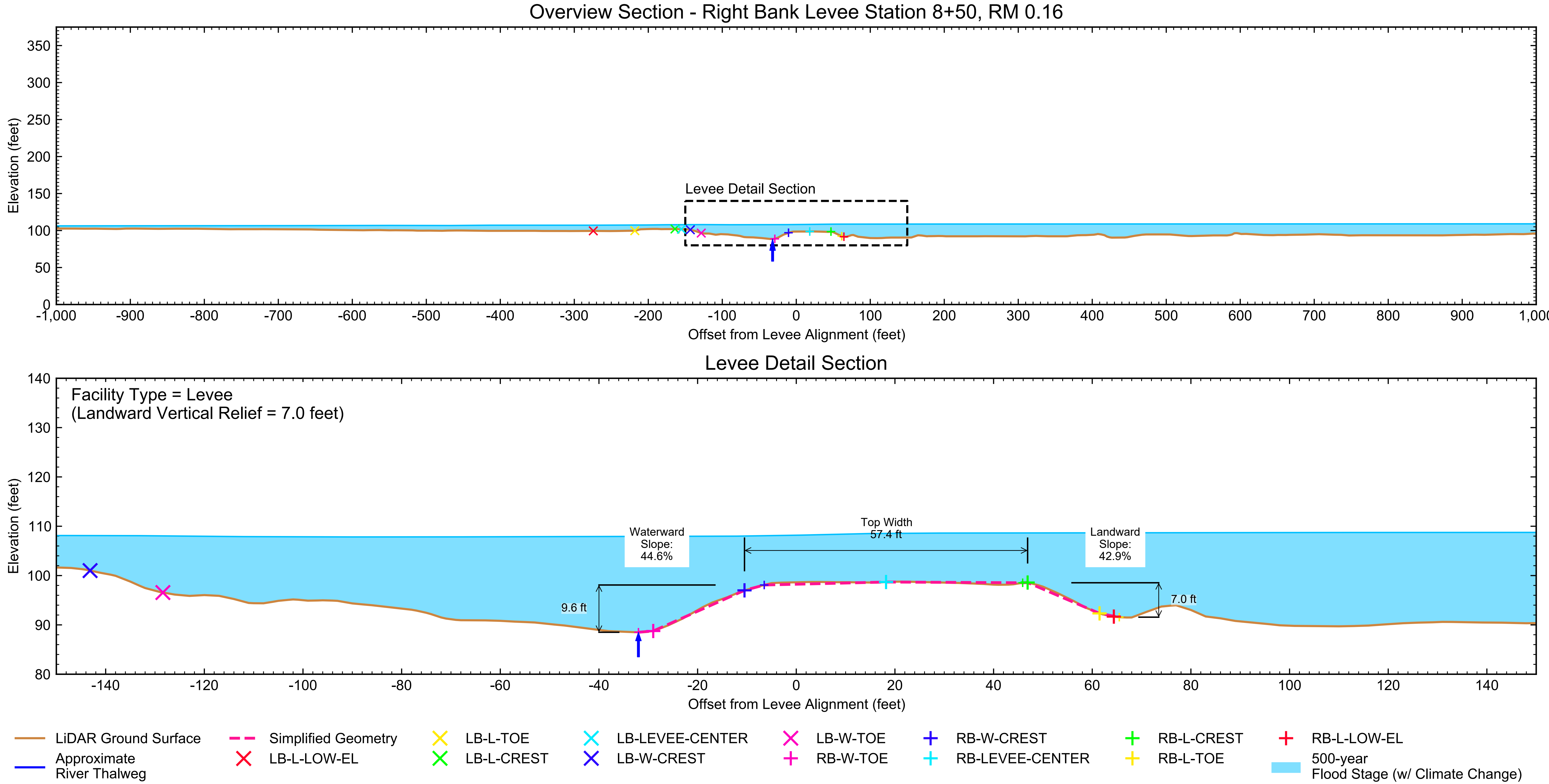
FIG. A-155



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LIDAR CROSS SECTION
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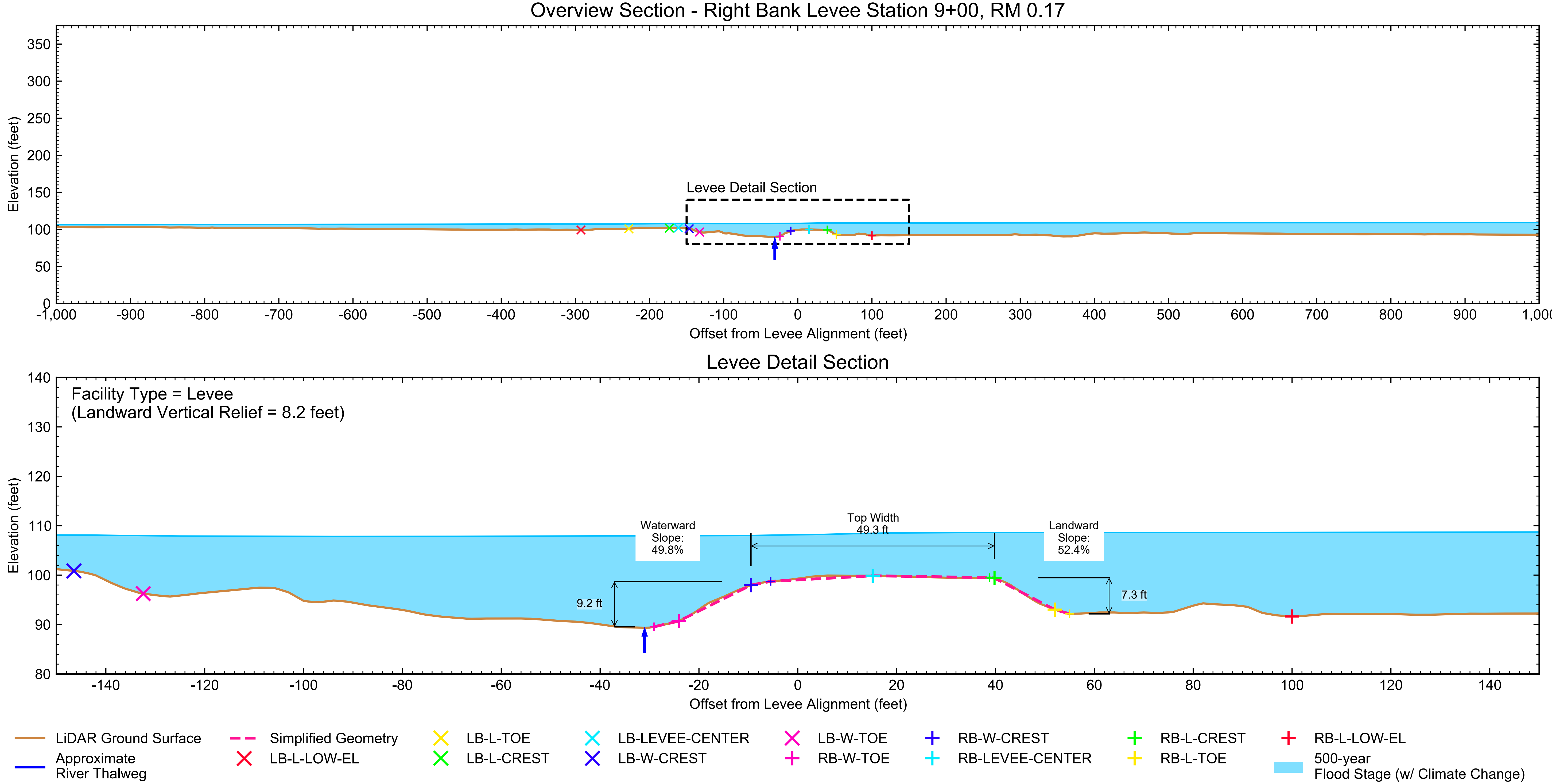
FIG. A-156



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LIDAR CROSS SECTION
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FIG. A-157

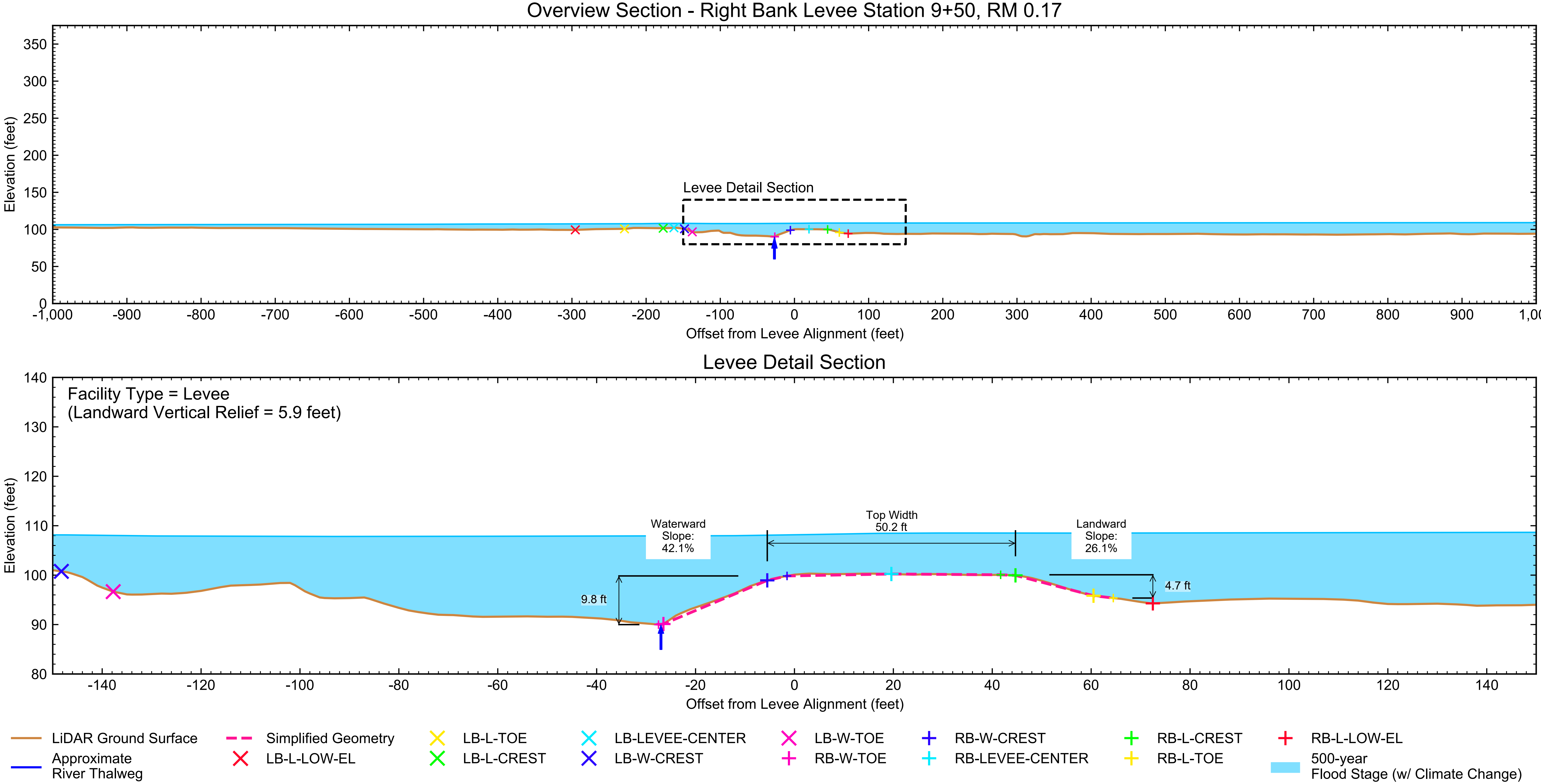

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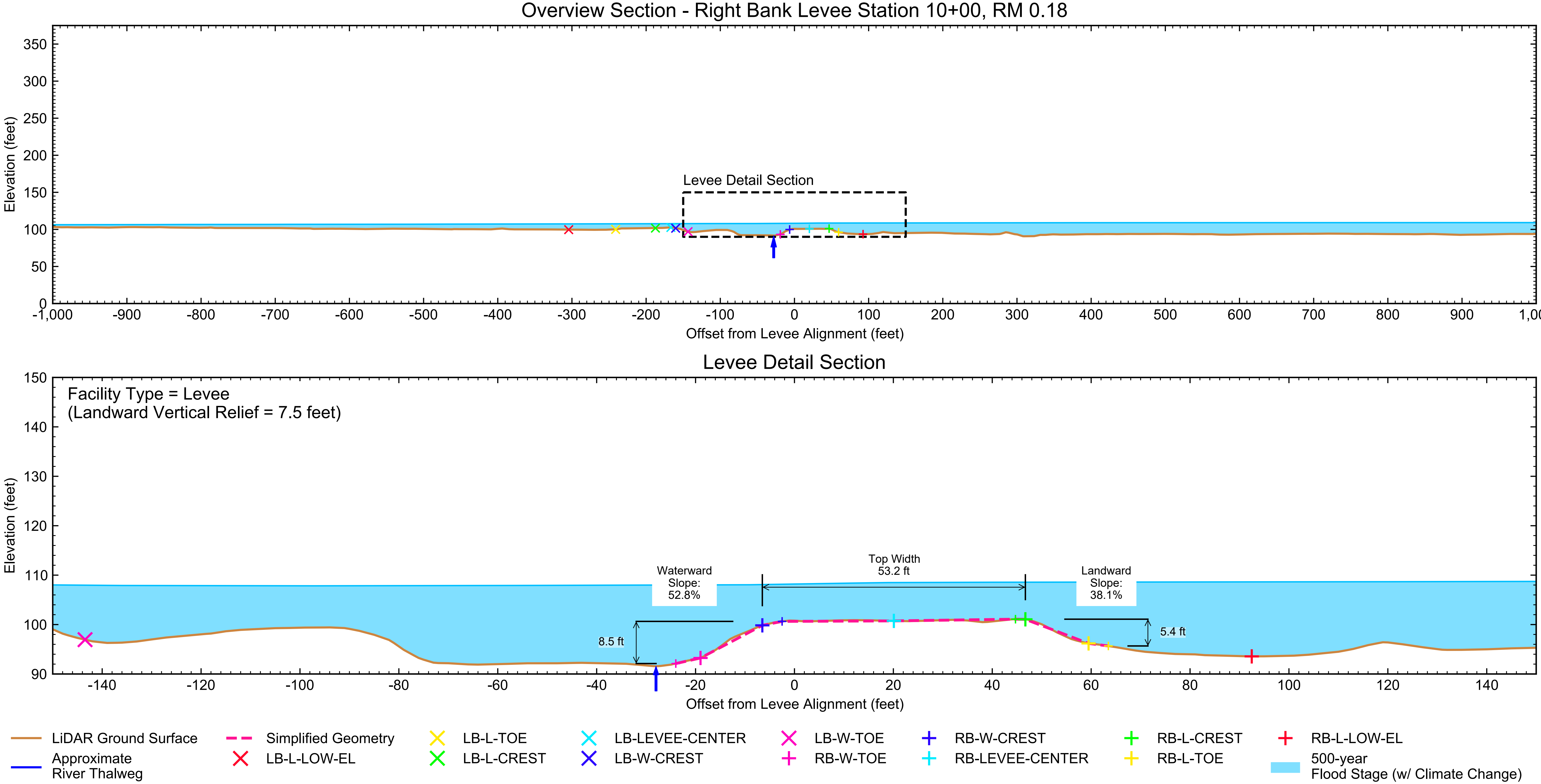
FIG. A-158



Notes:
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

Levee Breach Analysis Mapping and Risk Assessment
Segmentation and Stability Approach Report
King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 10+00, RM 0.18

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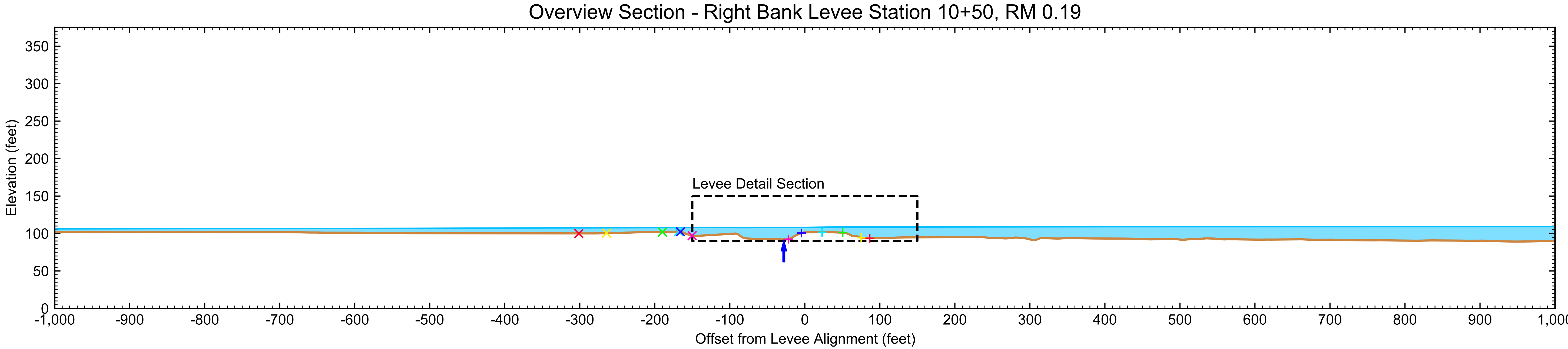
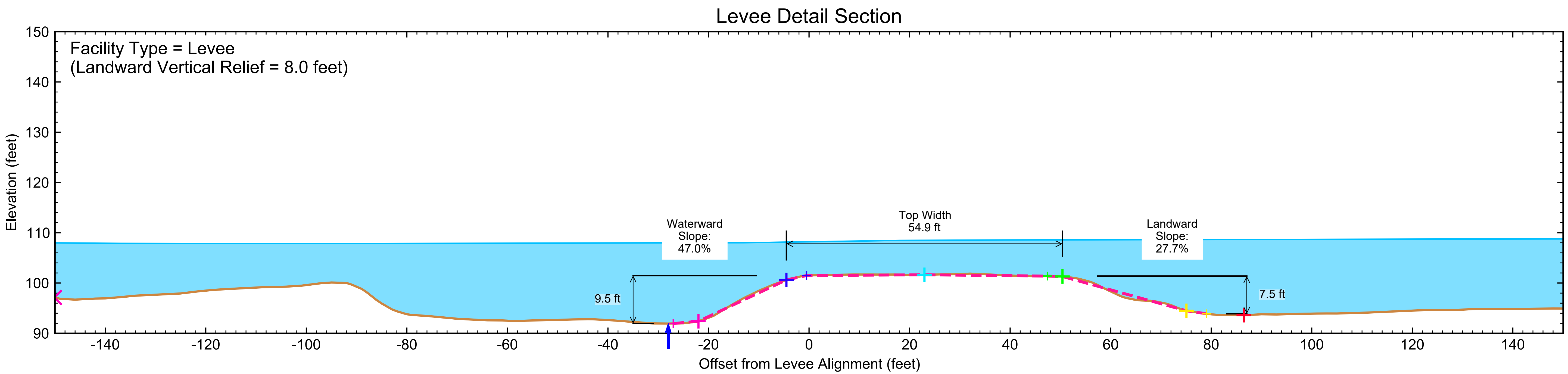
FIG. A-159





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL
Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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Levee Breach Analysis Mapping and Risk Assessment
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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 10+50, RM 0.19

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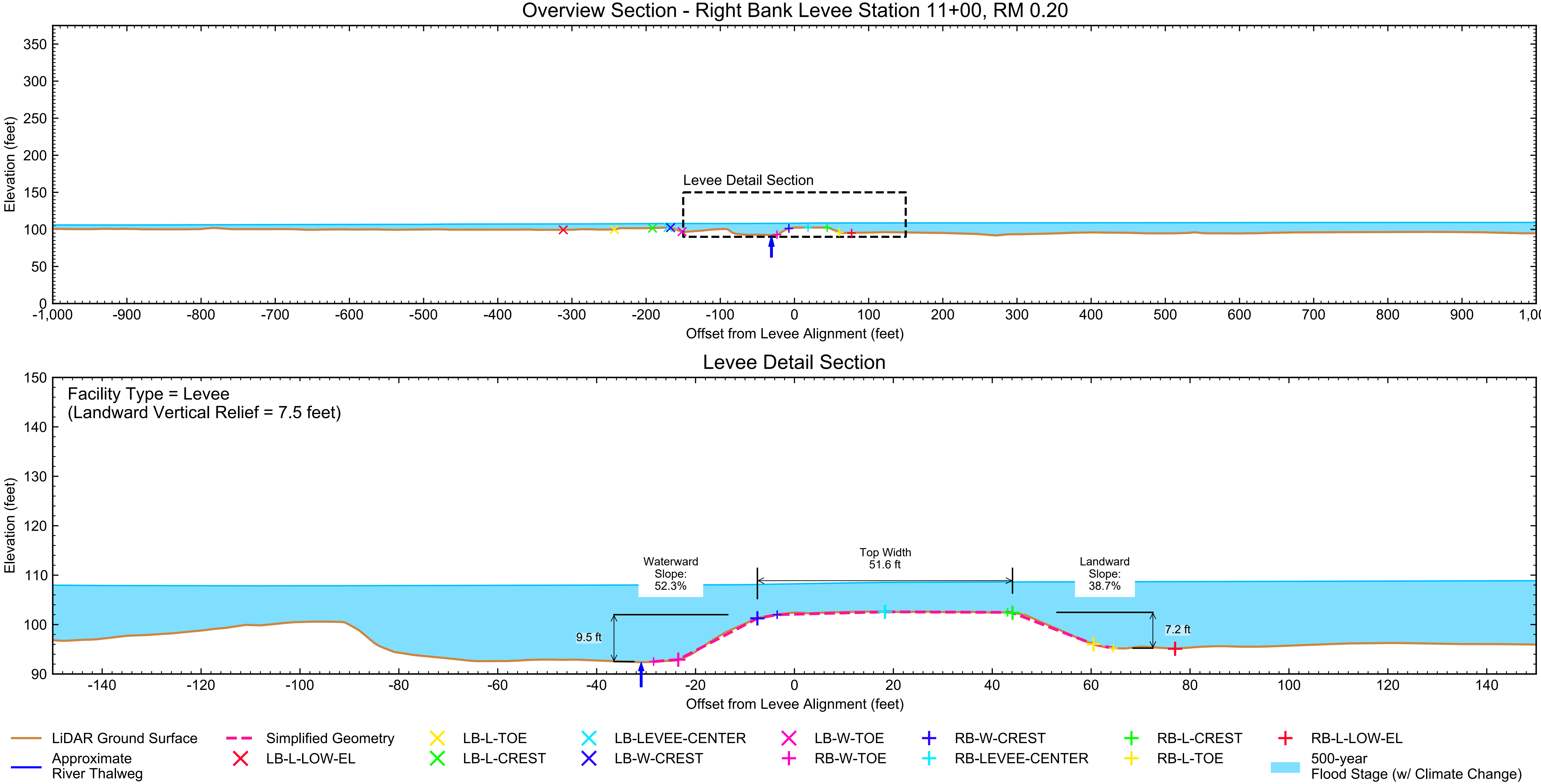
FIG. A-160



Notes:

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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 11+00, RM 0.20

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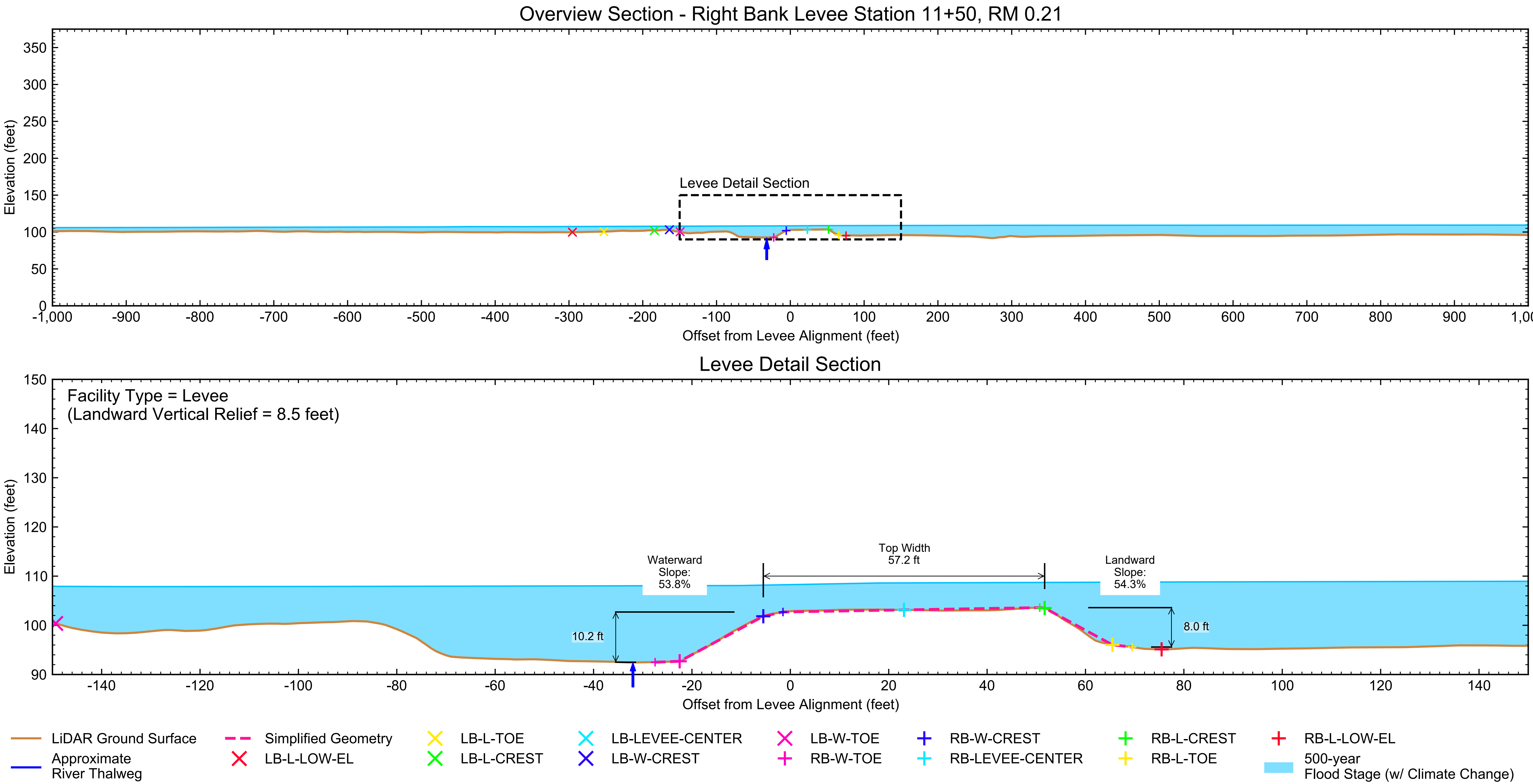
FIG. A-161



Notes:
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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 11+50, RM 0.21

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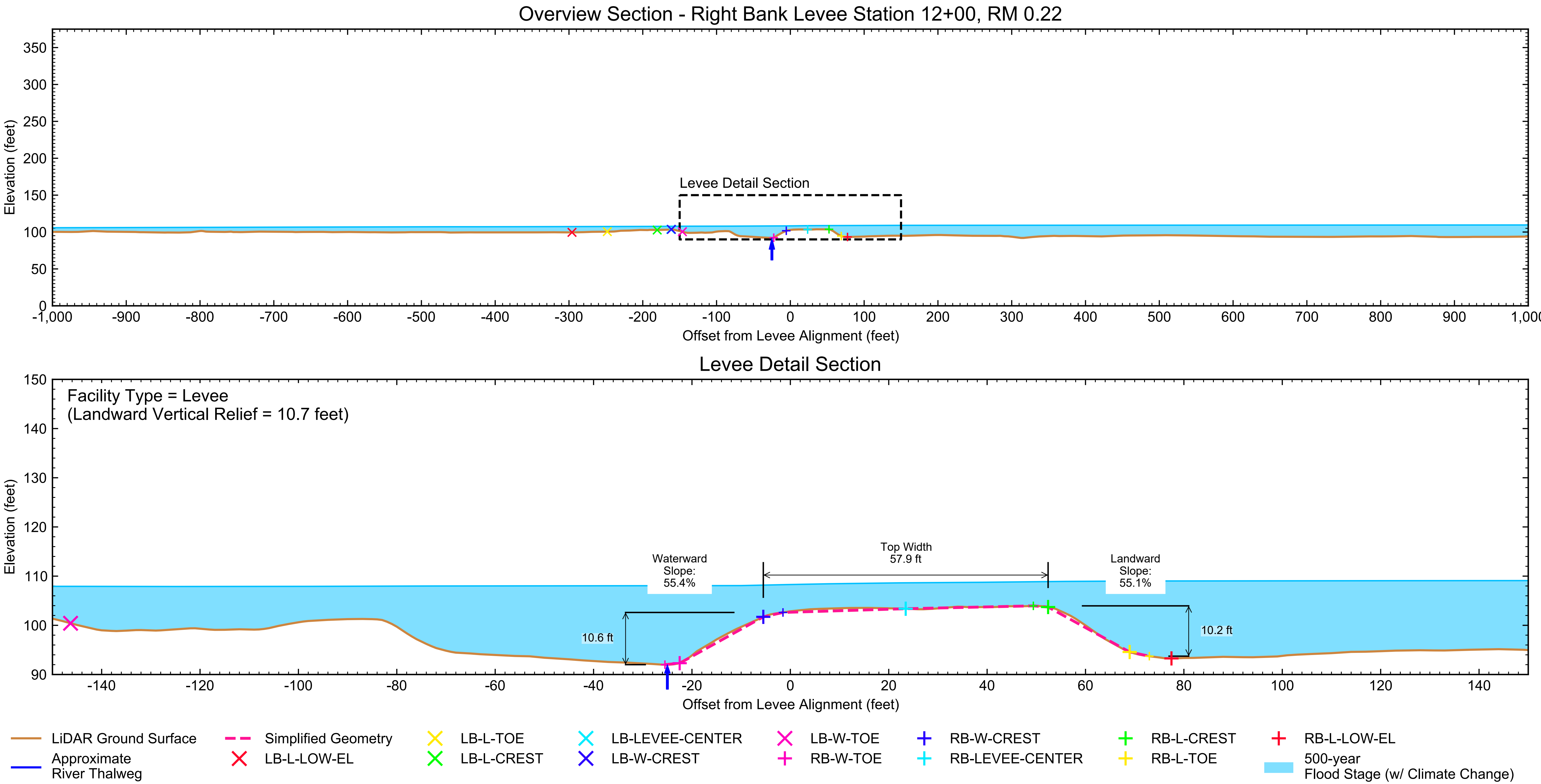
FIG. A-162



Notes:

1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 12+00, RM 0.22

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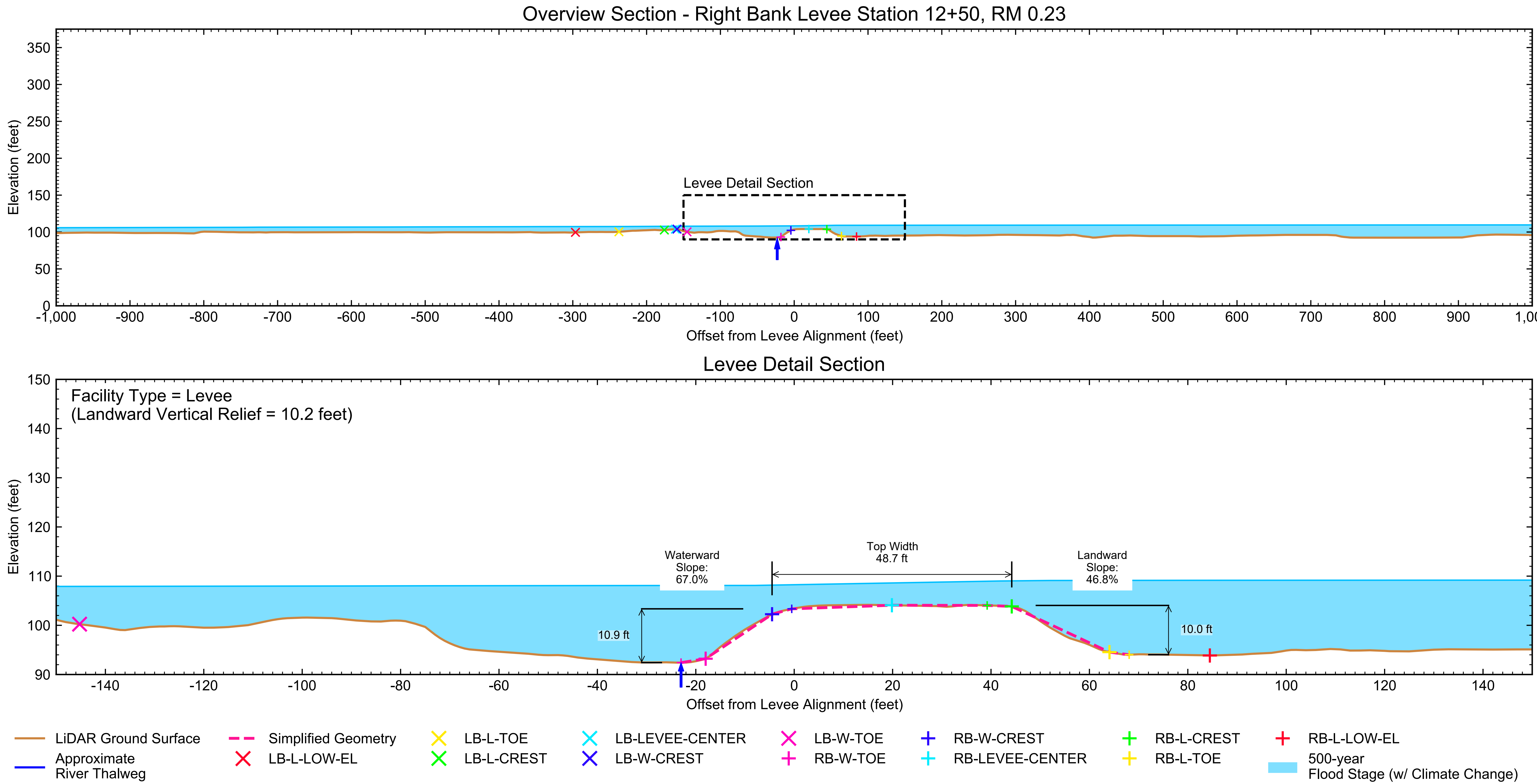
FIG. A-163



Notes:
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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 12+50, RM 0.23

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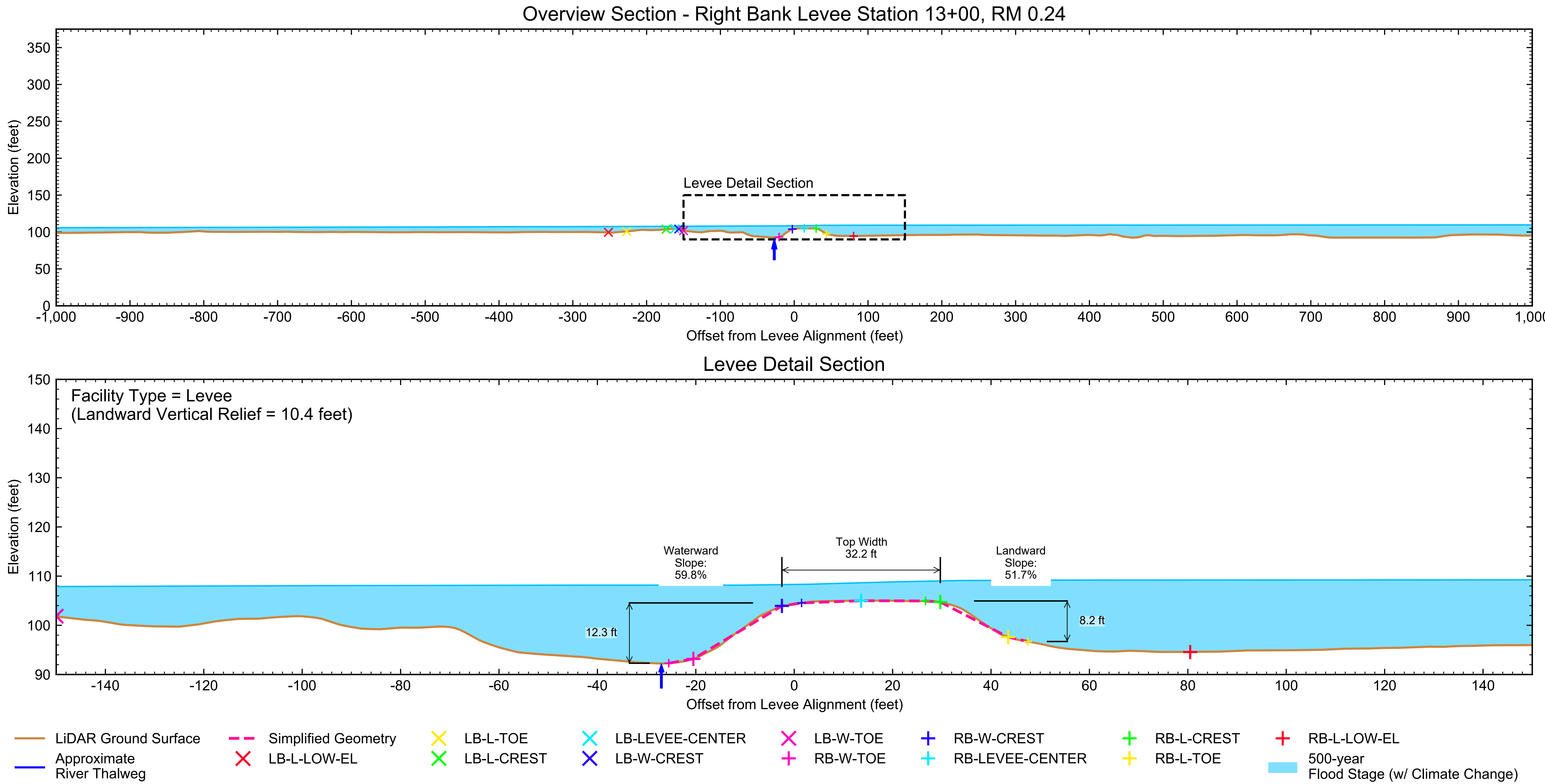
FIG. A-164



Notes:
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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 13+00, RM 0.24

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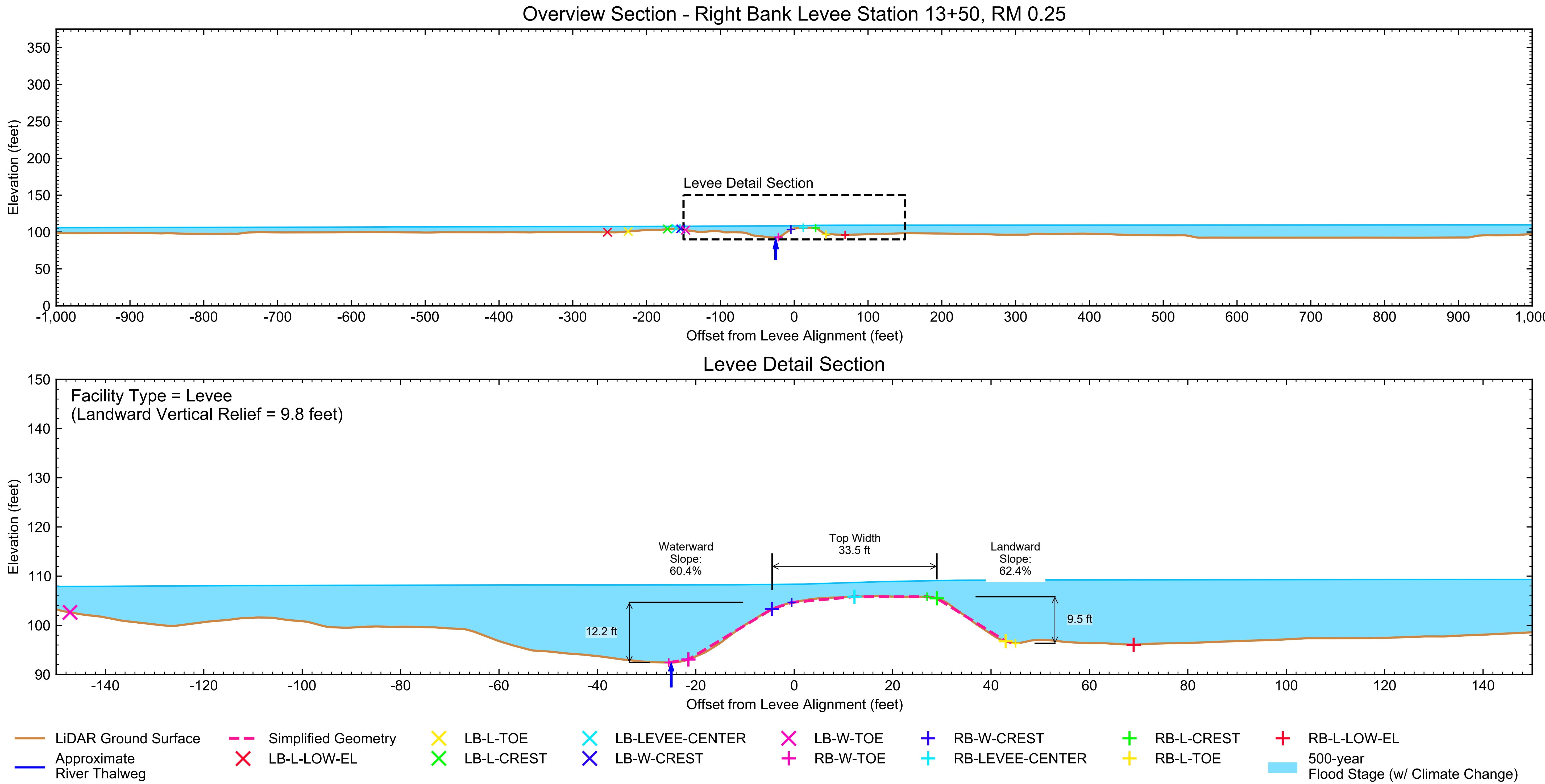
FIG. A-165



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 13+50, RM 0.25

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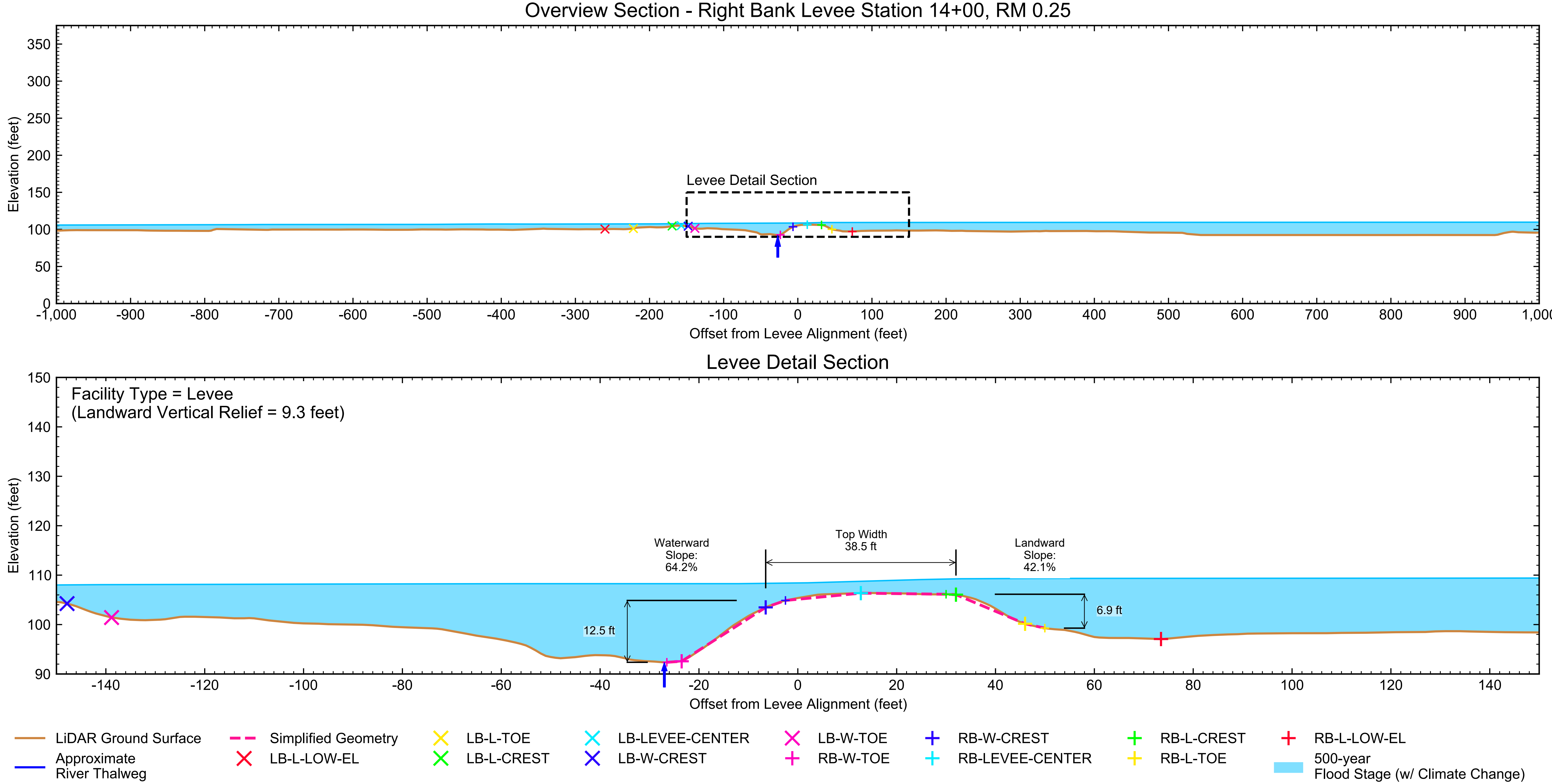
FIG. A-166



Notes:

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Levee Breach Analysis Mapping and Risk Assessment
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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 14+00, RM 0.25

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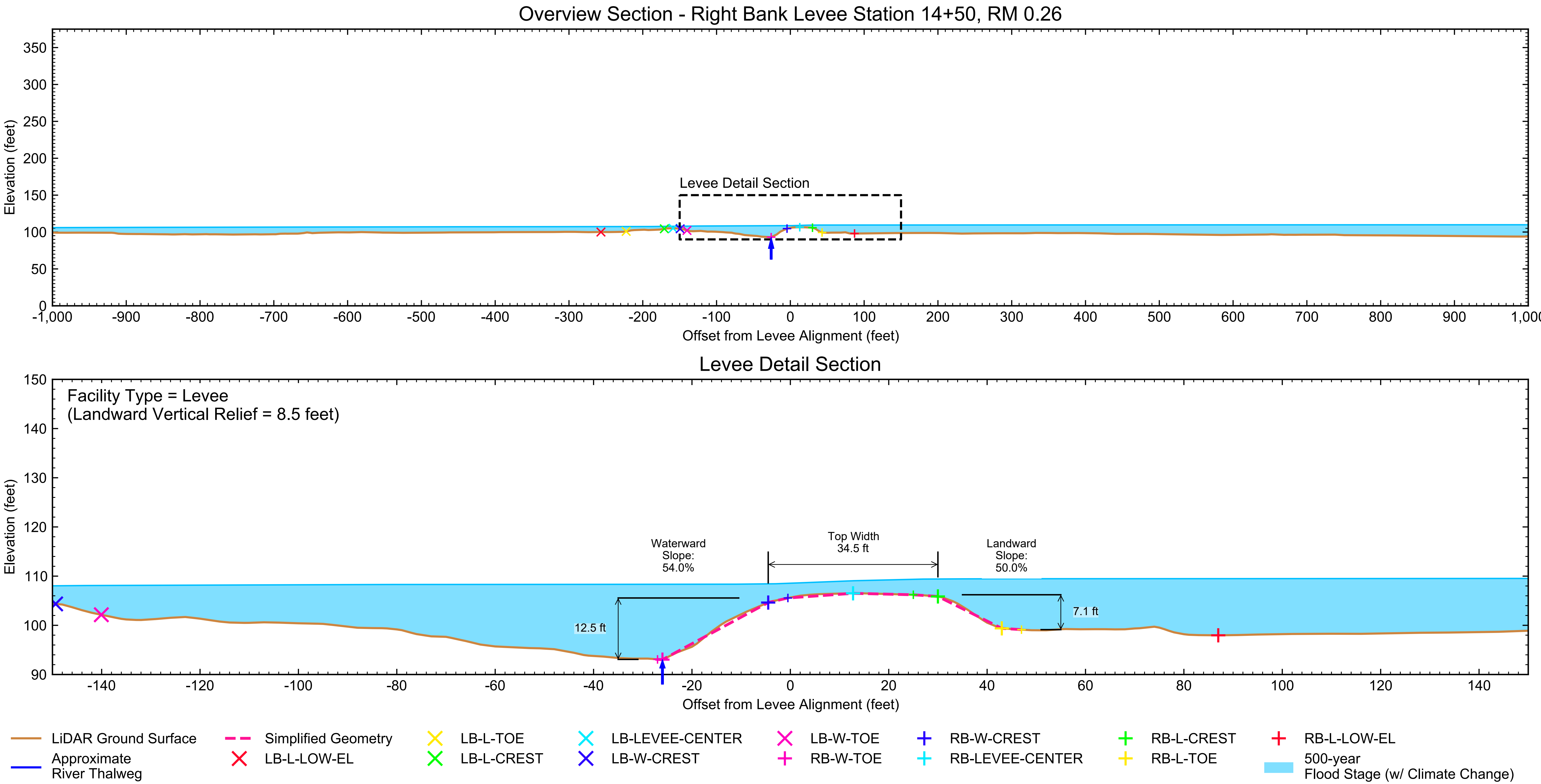
FIG. A-167



Notes:

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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 14+50, RM 0.26

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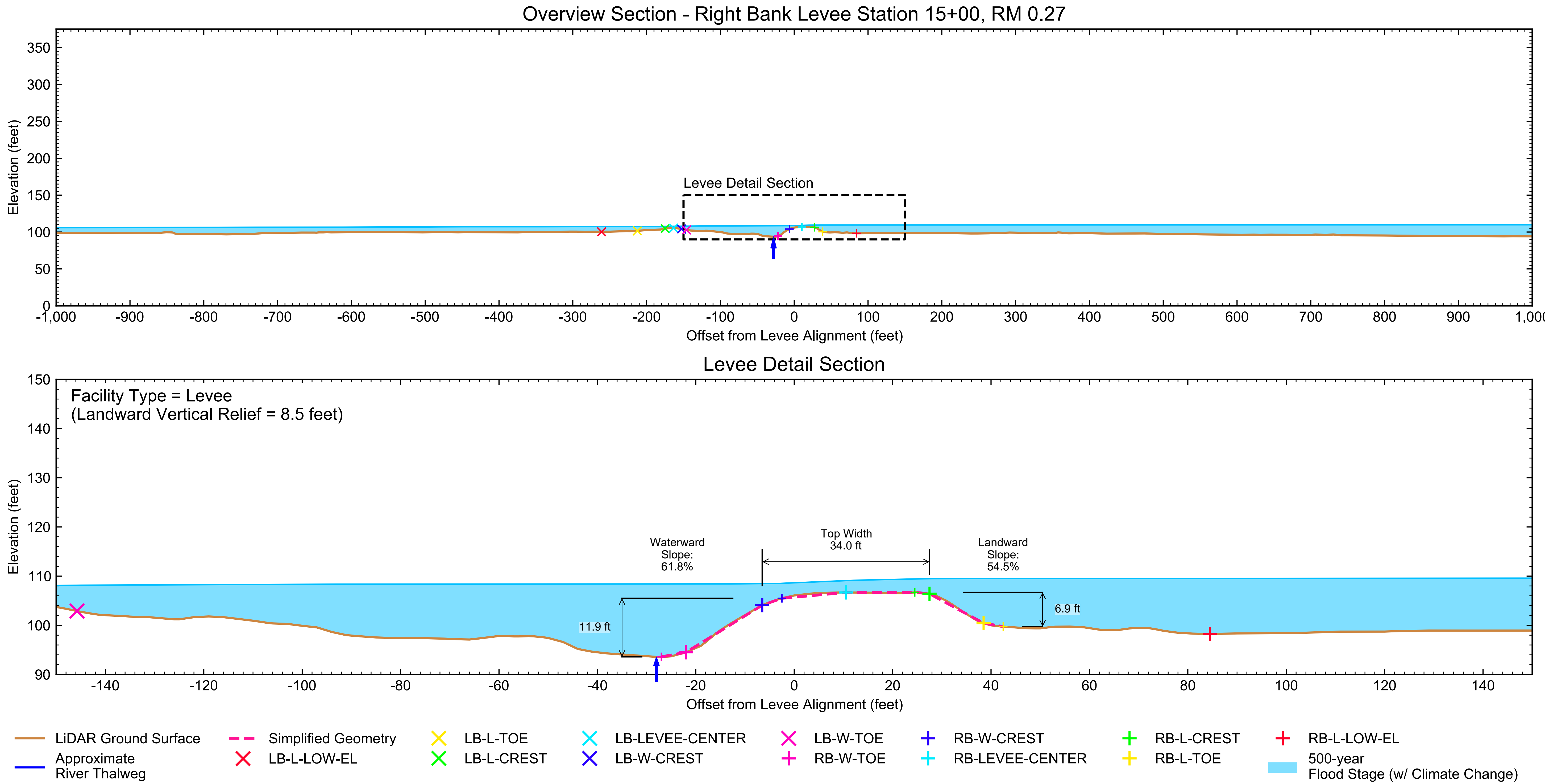
FIG. A-168



Notes:
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Levee Breach Analysis Mapping and Risk Assessment Segmentation and Stability Approach Report King County, Washington	
LIDAR CROSS SECTION **LOWER RAGING RIVER** **RIGHT BANK STA 15+00, RM 0.27**	
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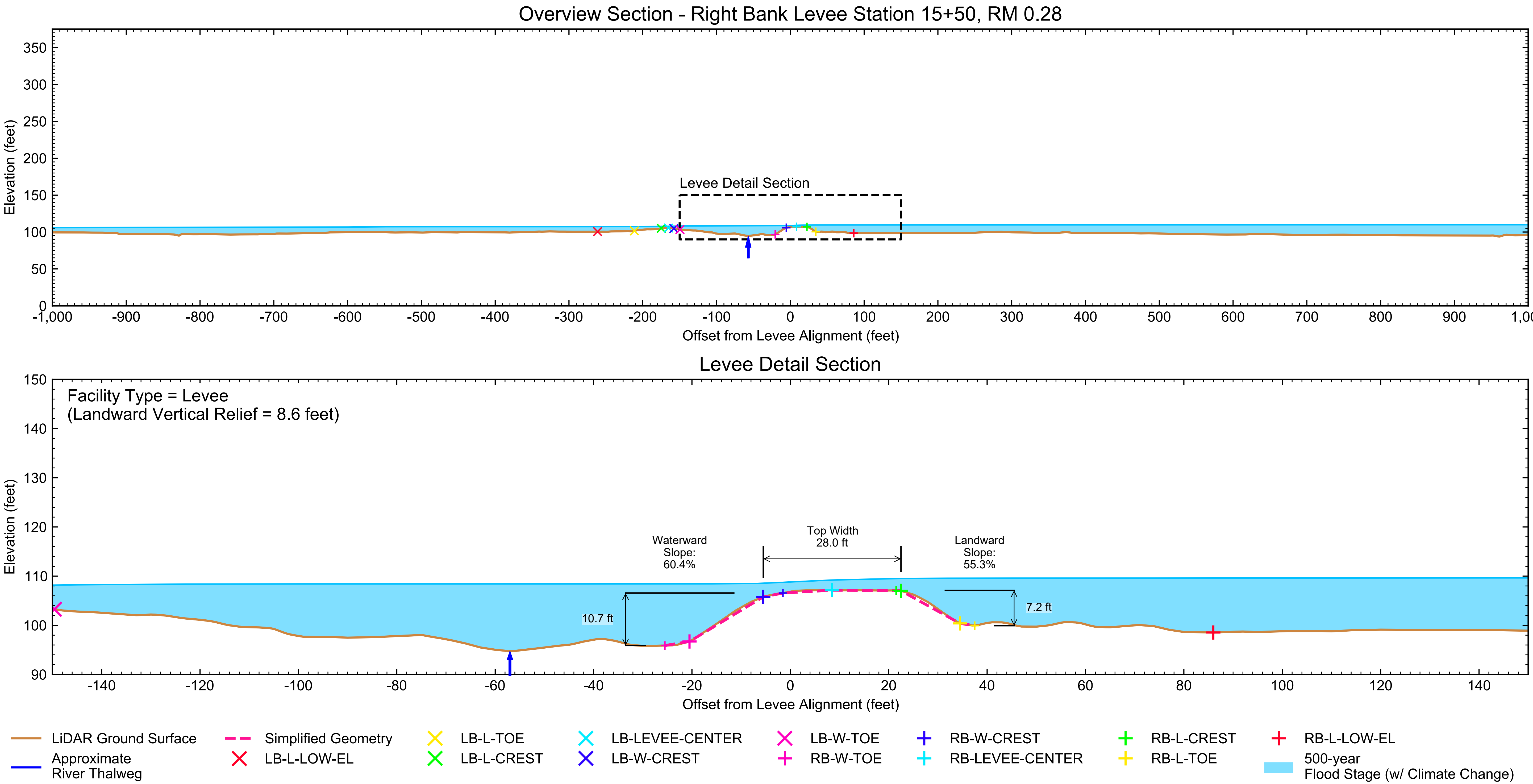
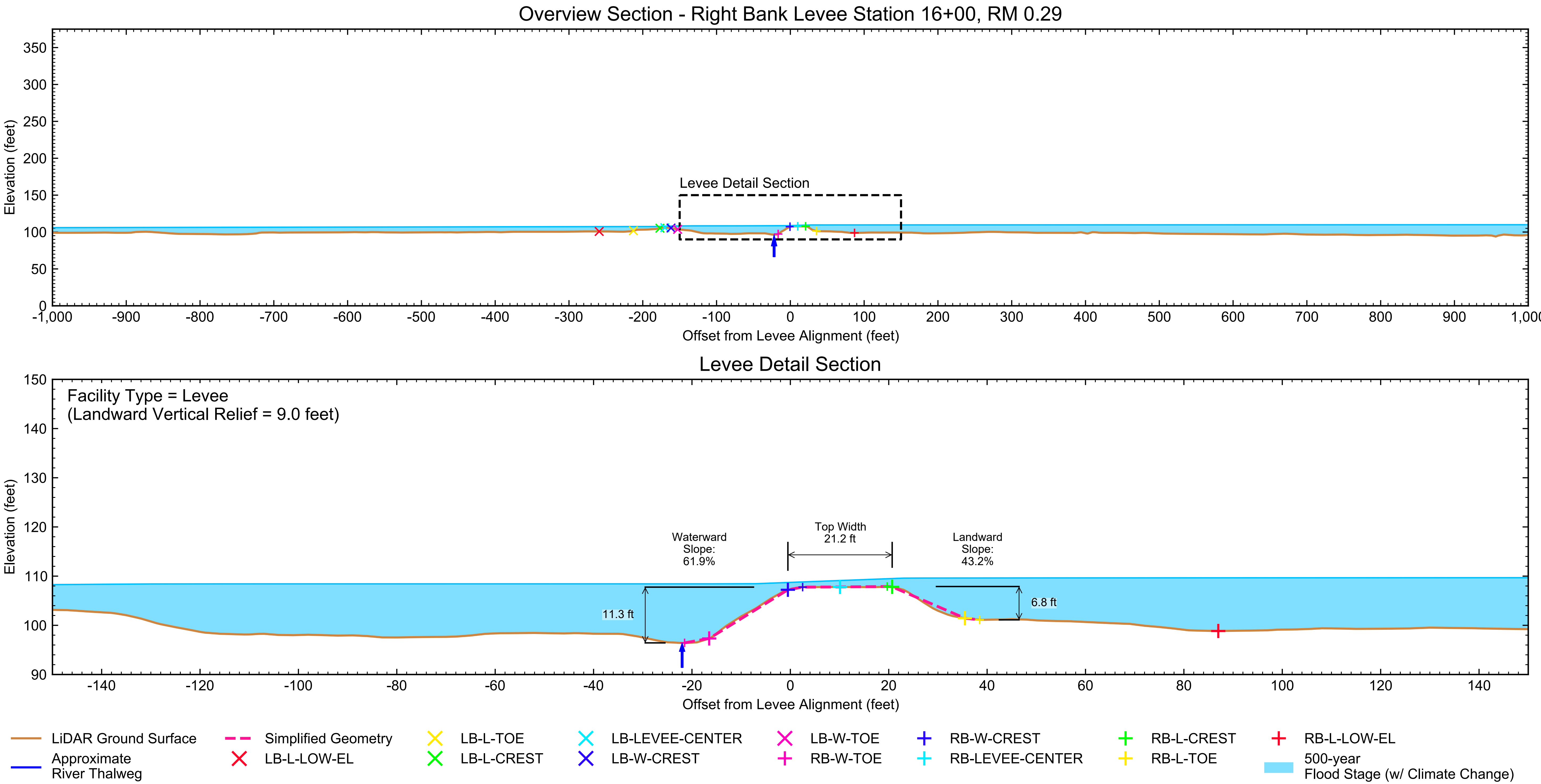
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-169



Overview Section - Right Bank Levee Station 15+50, RM 0.28
Levee Detail Section
Elevation (feet)
Offset from Levee Alignment (feet)
Levee Detail Section
Facility Type = Levee
(Landward Vertical Relief = 8.6 feet)
Waterward Slope: 60.4%
Top Width 28.0 ft
Landward Slope: 55.3%
10.7 ft
7.2 ft
Elevation (feet)
Offset from Levee Alignment (feet)
LiDAR Ground Surface
Approximate River Thalweg
Simplified Geometry
LB-L-LOW-EL
LB-L-TOE
LB-L-CREST
LB-LEVEE-CENTER
LB-W-CREST
LB-W-TOE
RB-W-TOE
RB-W-CREST
RB-LEVEE-CENTER
RB-L-CREST
RB-L-TOE
RB-L-LOW-EL
500-year Flood Stage (w/ Climate Change)



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 16+00, RM 0.29

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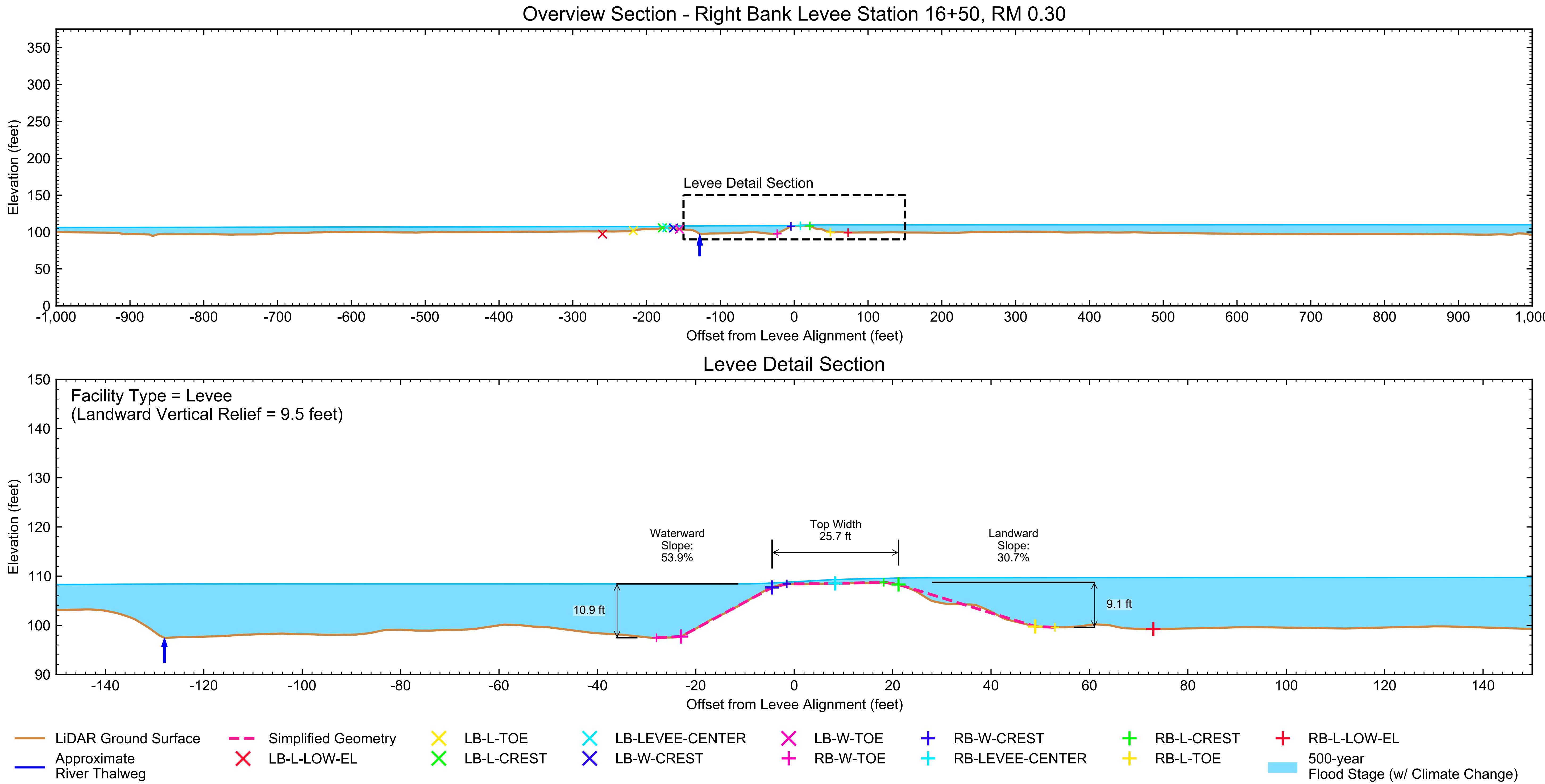
FIG. A-171



Notes:
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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 16+50, RM 0.30

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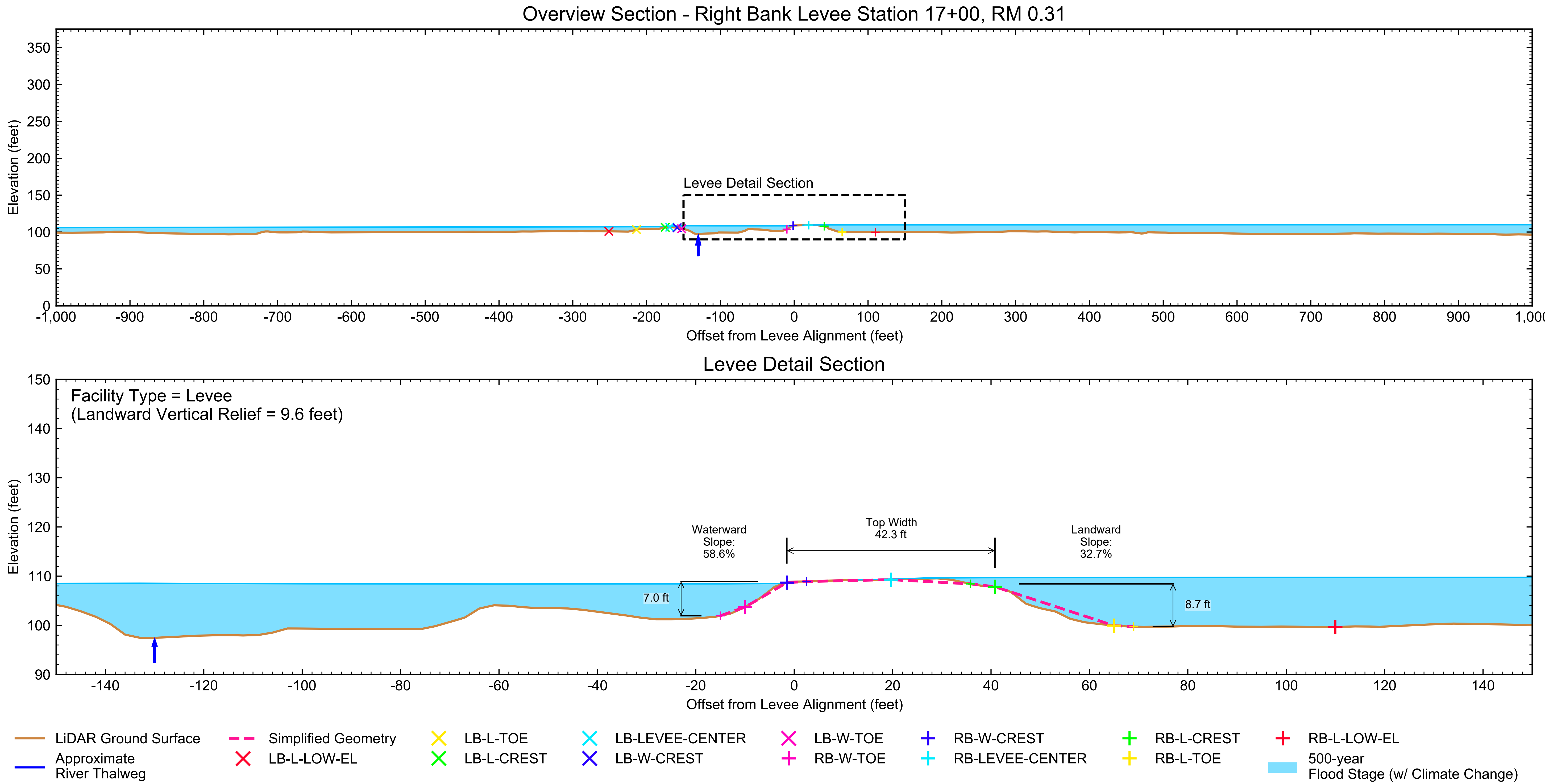
FIG. A-172



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 17+00, RM 0.31

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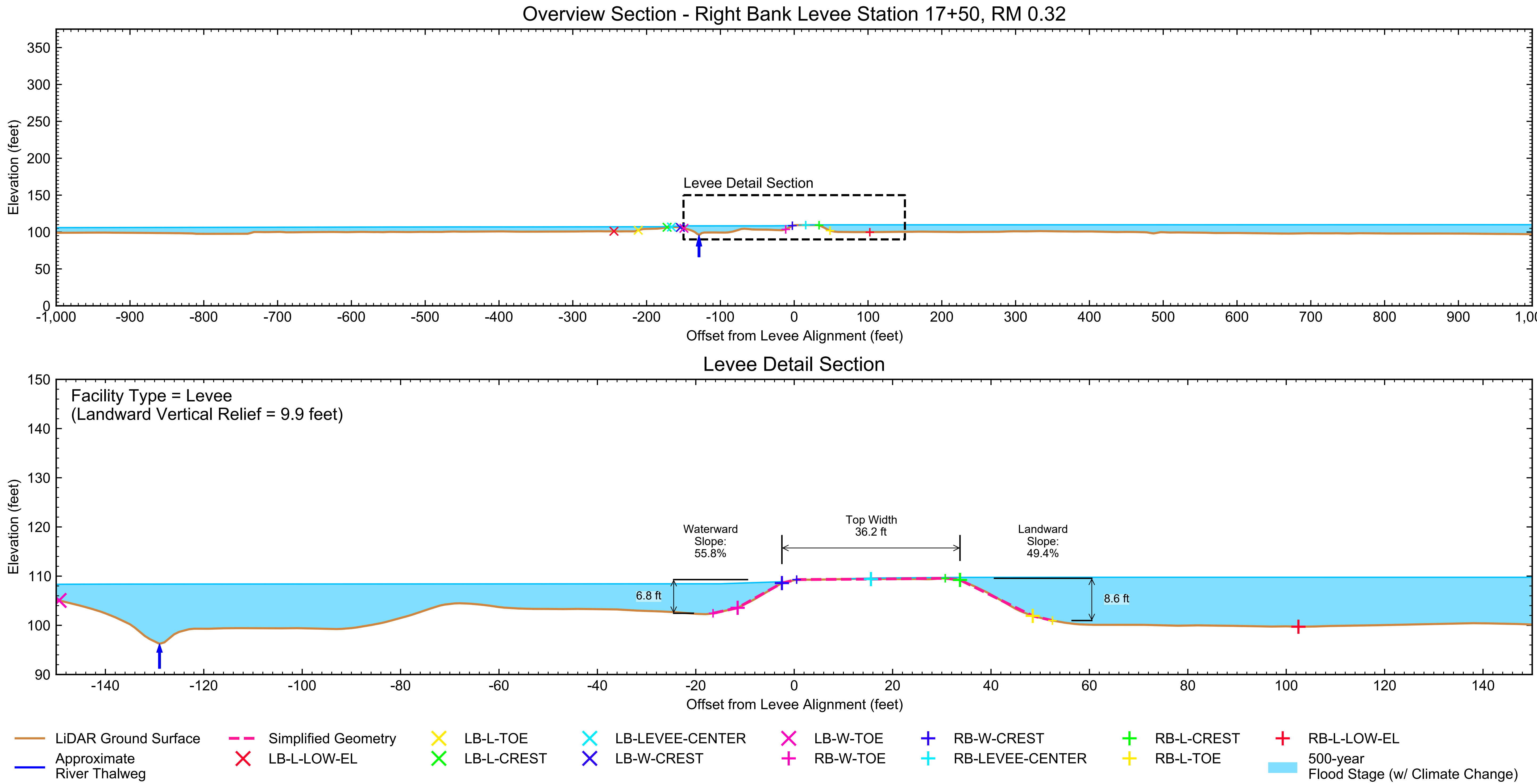
FIG. A-173



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 17+50, RM 0.32

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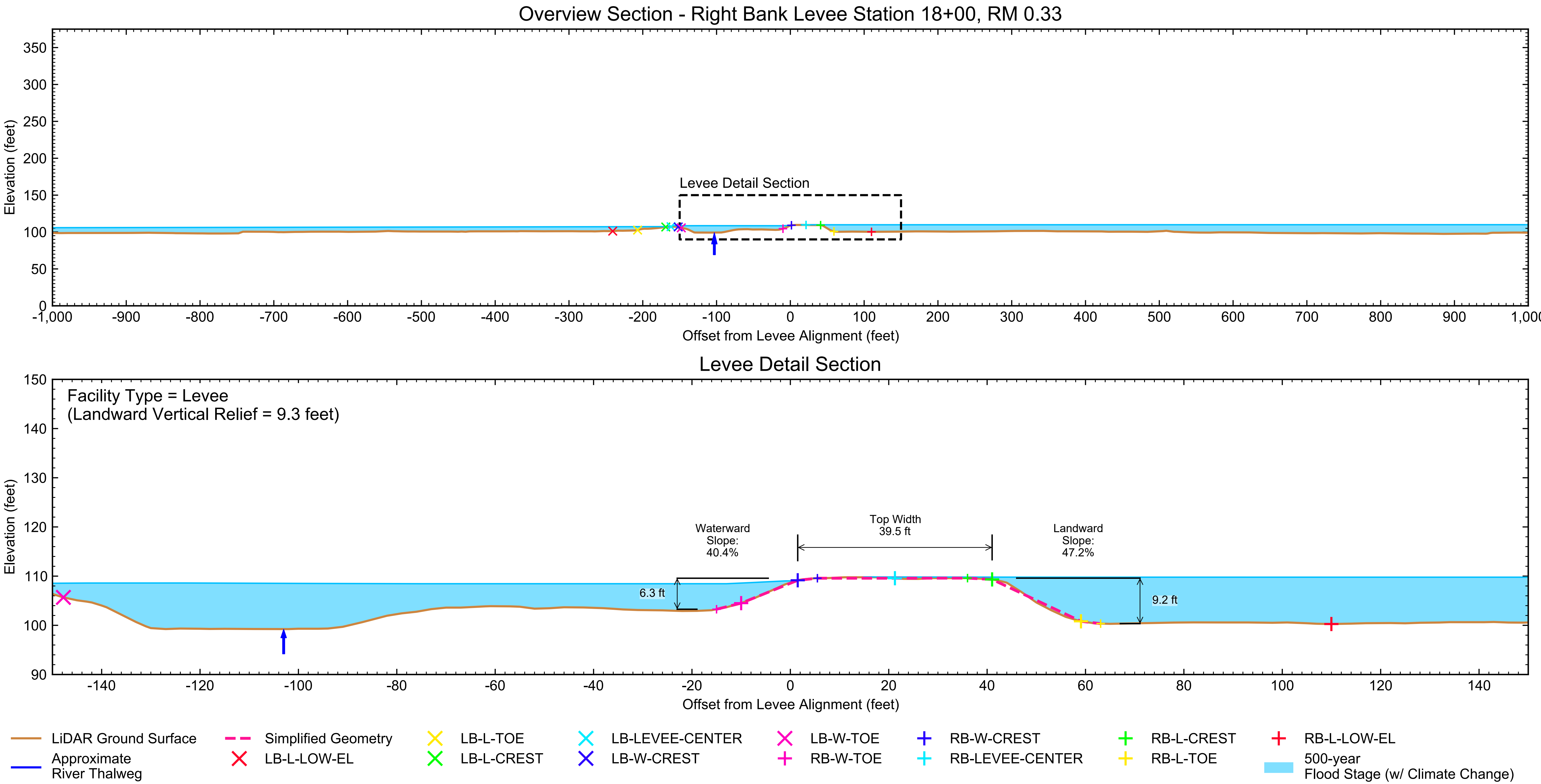
FIG. A-174



Notes:

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2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 18+00, RM 0.33

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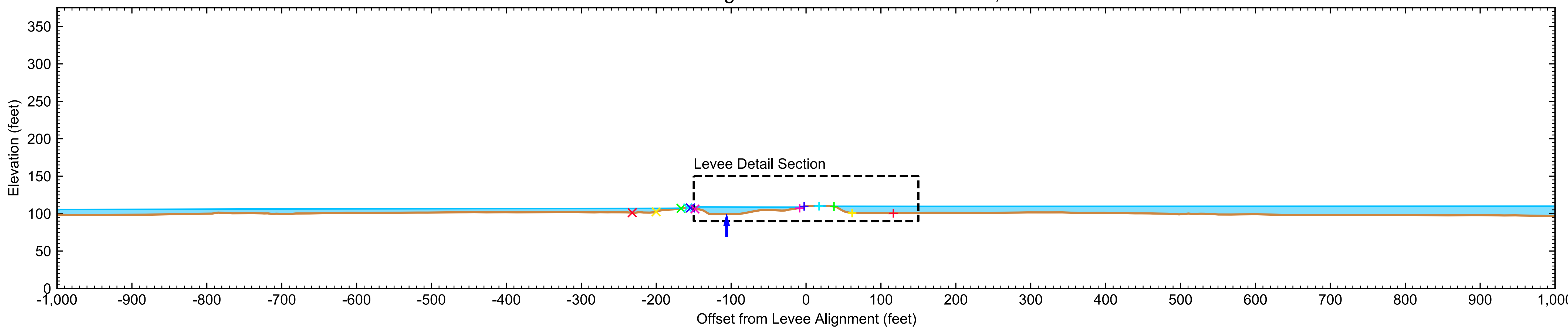
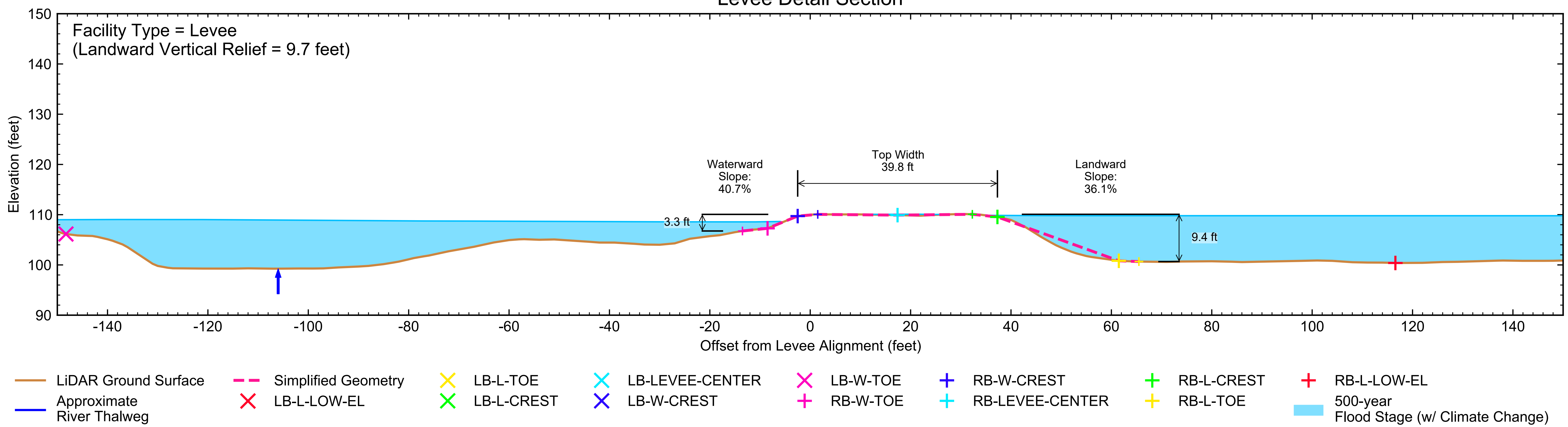
FIG. A-175

Overview Section - Right Bank Levee Station 18+50, RM 0.35



Levee Detail Section



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 18+50, RM 0.35

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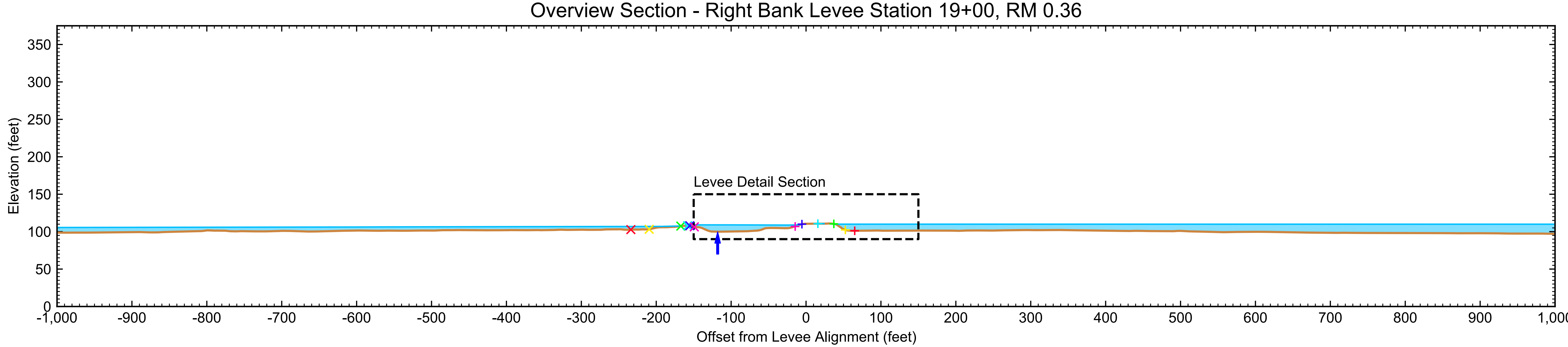
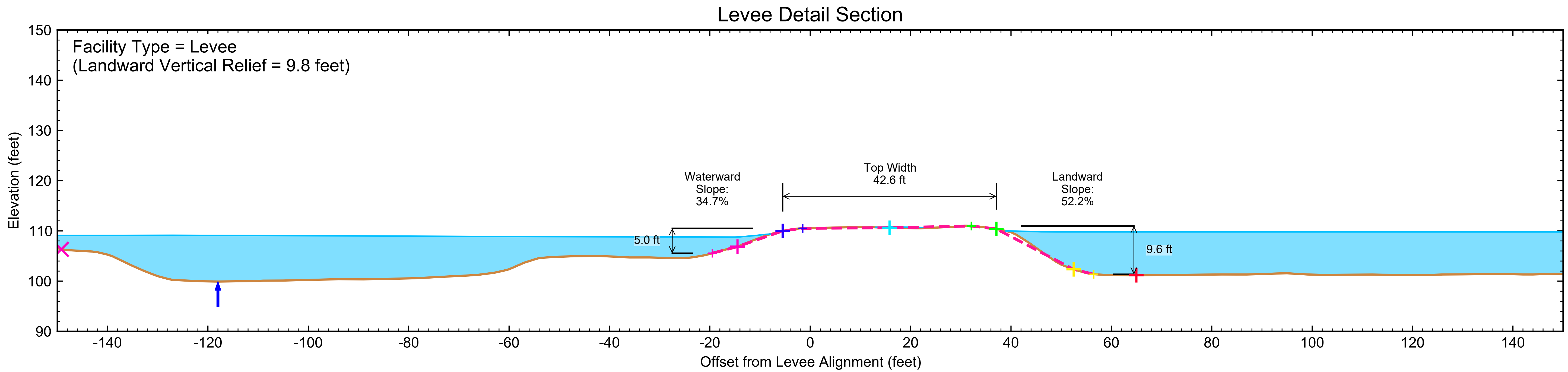
FIG. A-176





LiDAR Ground Surface; Approximate River Thalweg; Simplified Geometry; LB-L-LOW-EL; LB-L-TOE; LB-L-CREST; LB-LEVEE-CENTER; LB-W-CREST; LB-W-TOE; RB-W-TOE; RB-W-CREST; RB-LEVEE-CENTER; RB-L-CREST; RB-L-TOE; RB-L-LOW-EL; 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 19+00, RM 0.36

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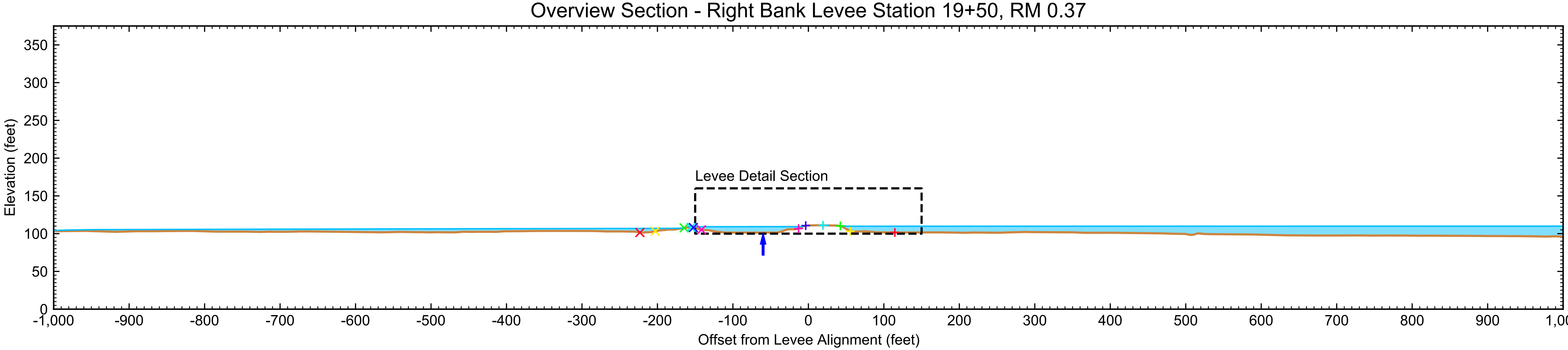
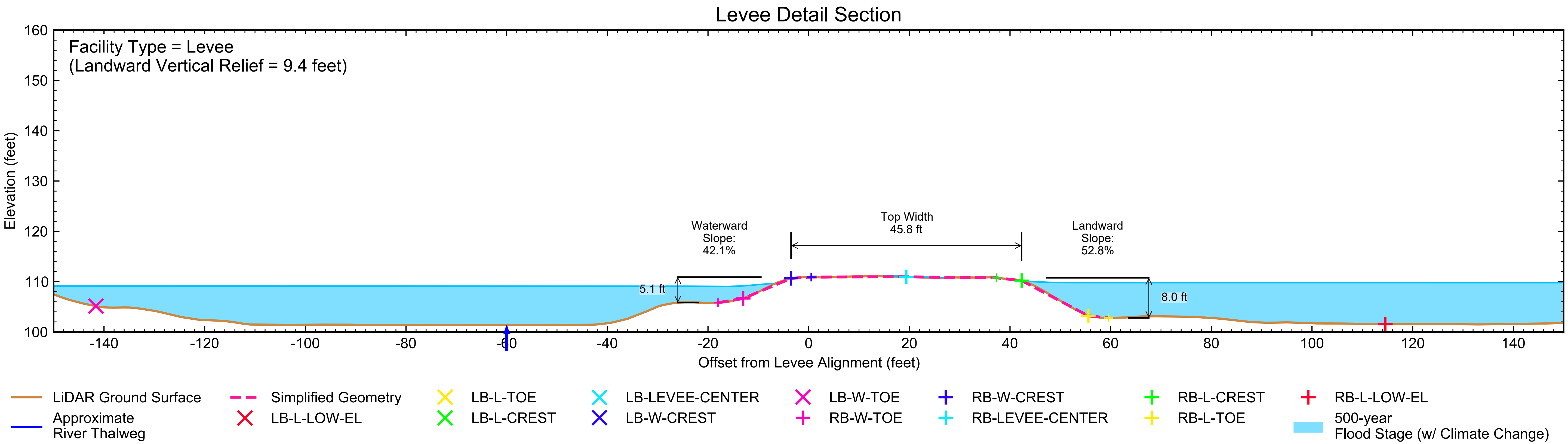
FIG. A-177





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 19+50, RM 0.37

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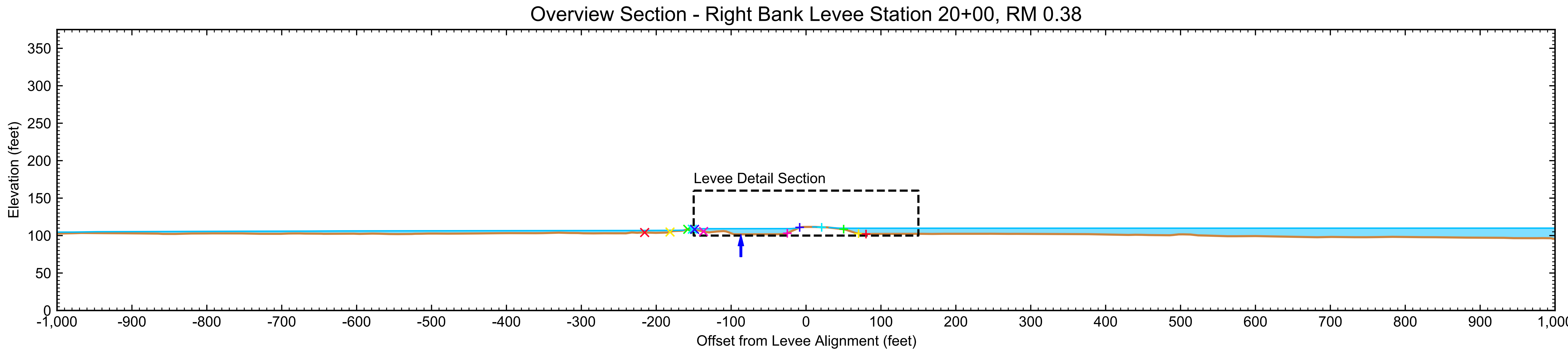
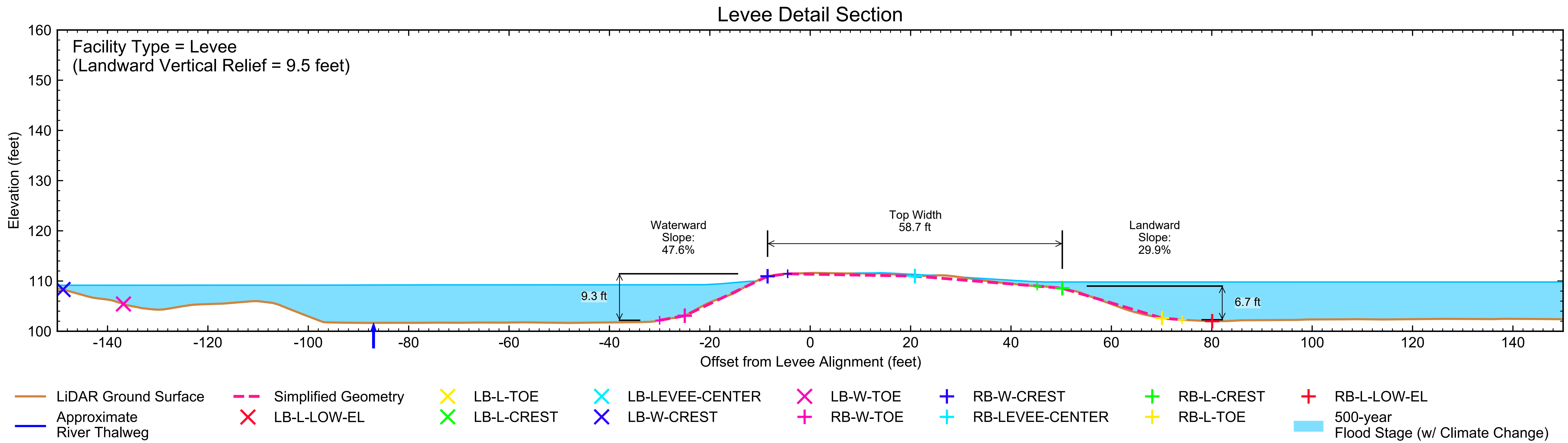
FIG. A-178





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 20+00, RM 0.38

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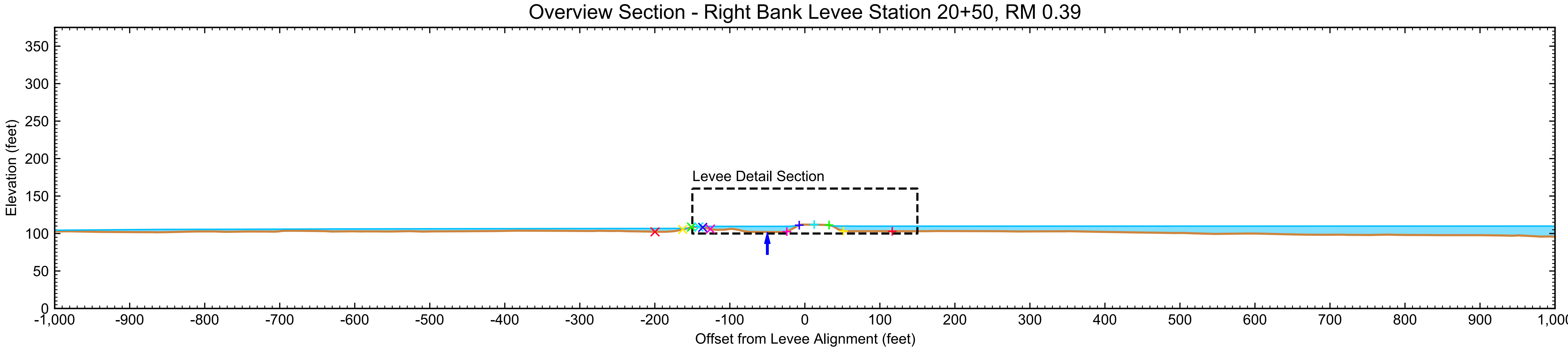
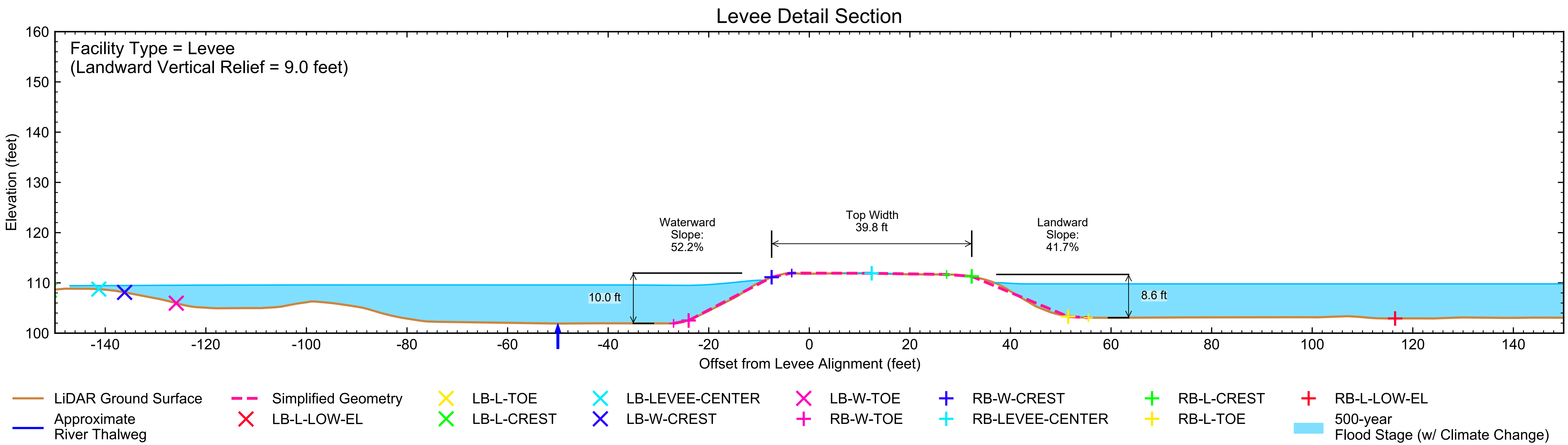
FIG. A-179





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 20+50, RM 0.39

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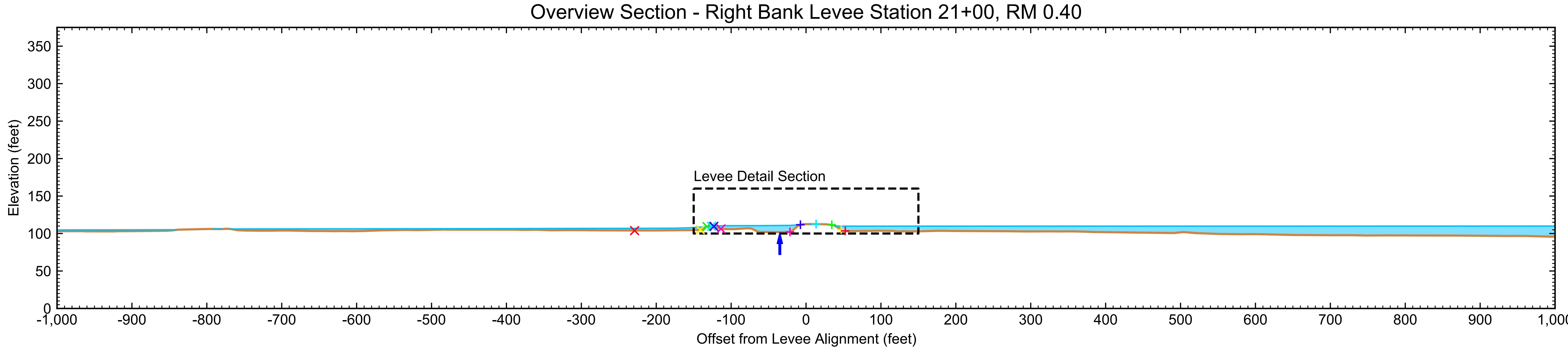
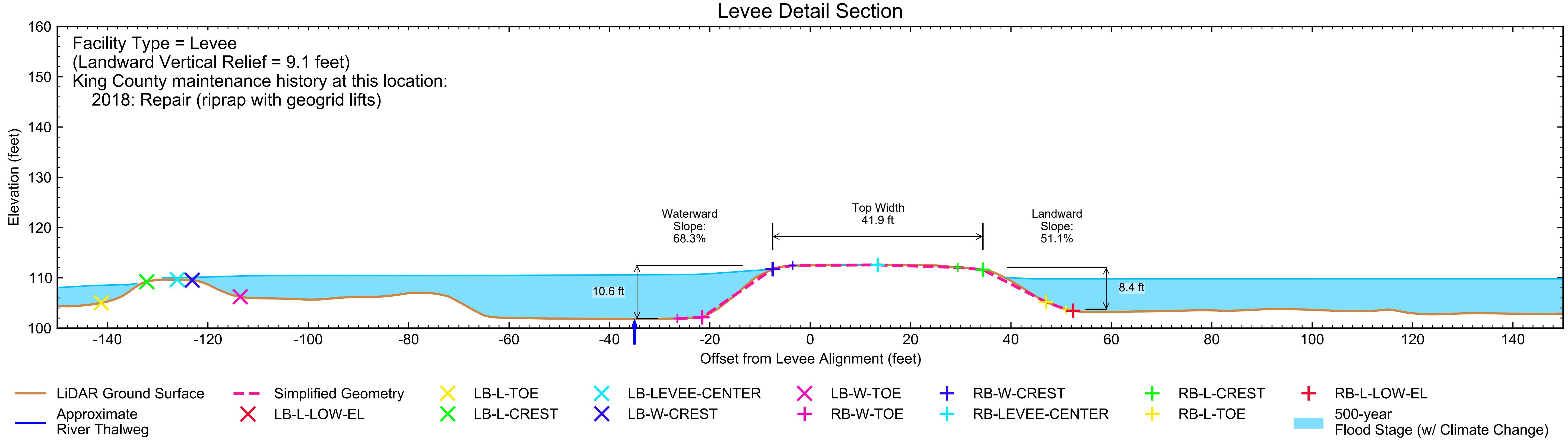
FIG. A-180





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 21+00, RM 0.40

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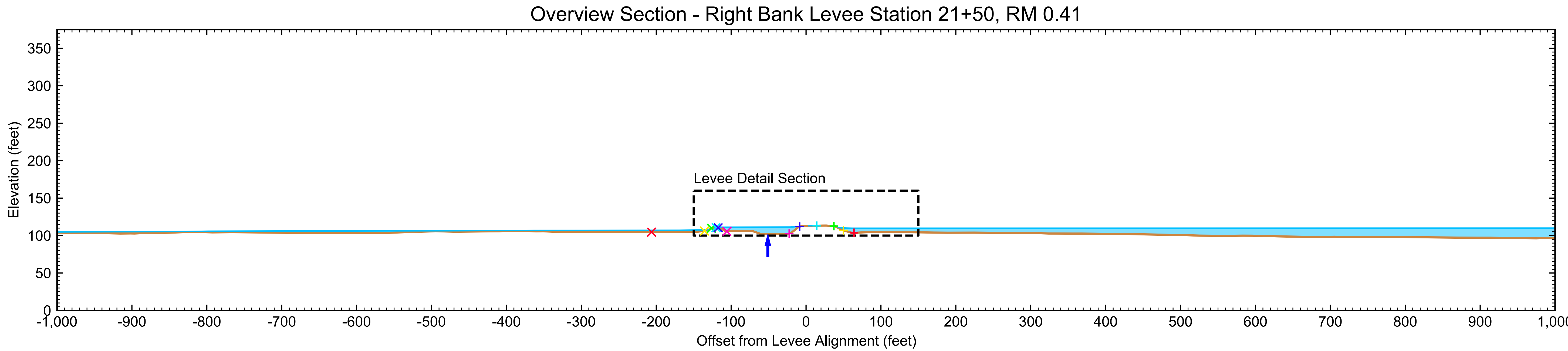
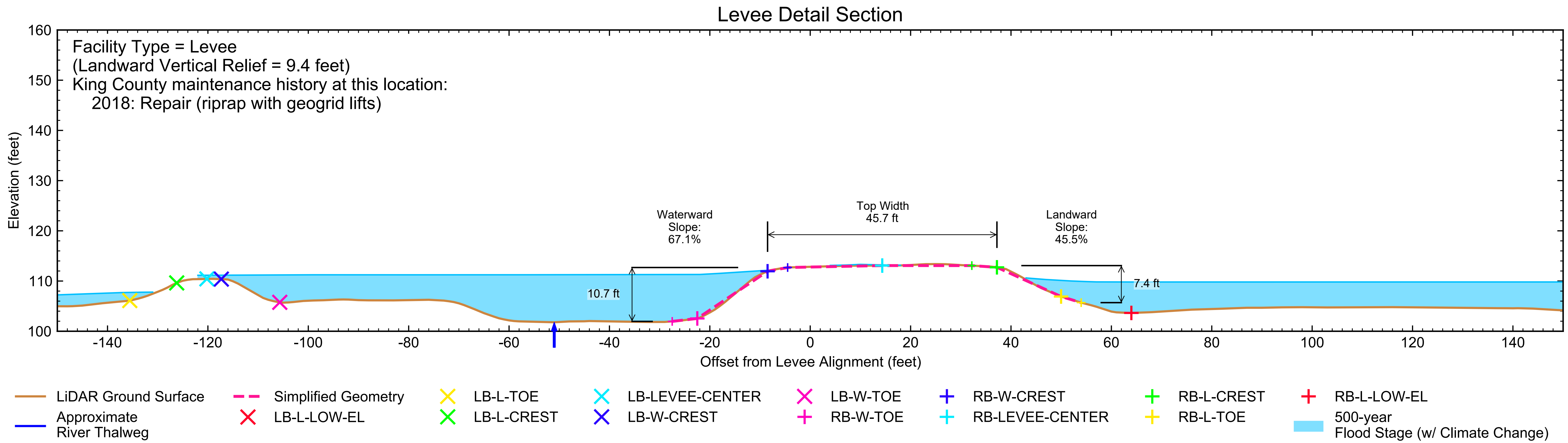
FIG. A-181





Notes:

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LIDAR CROSS SECTION
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RIGHT BANK STA 21+50, RM 0.41

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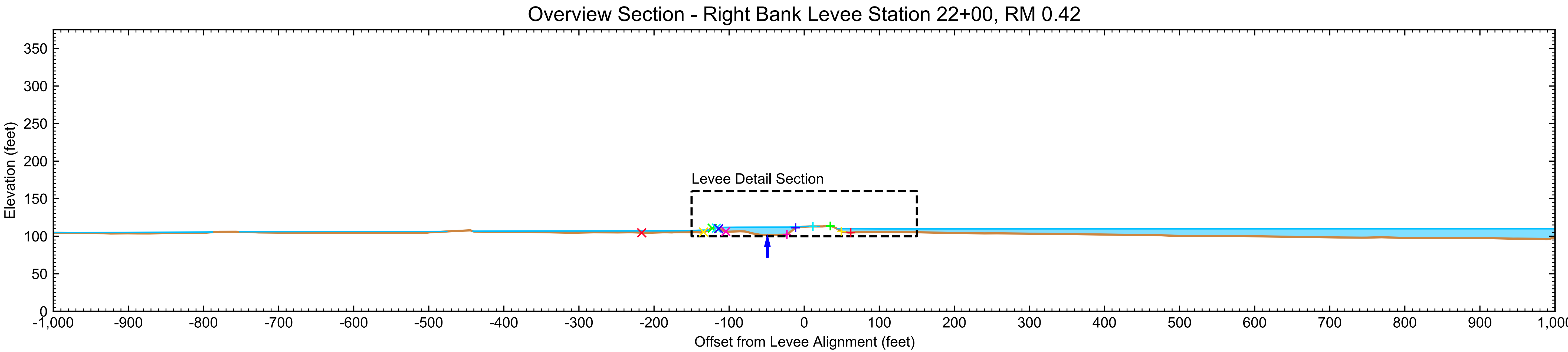
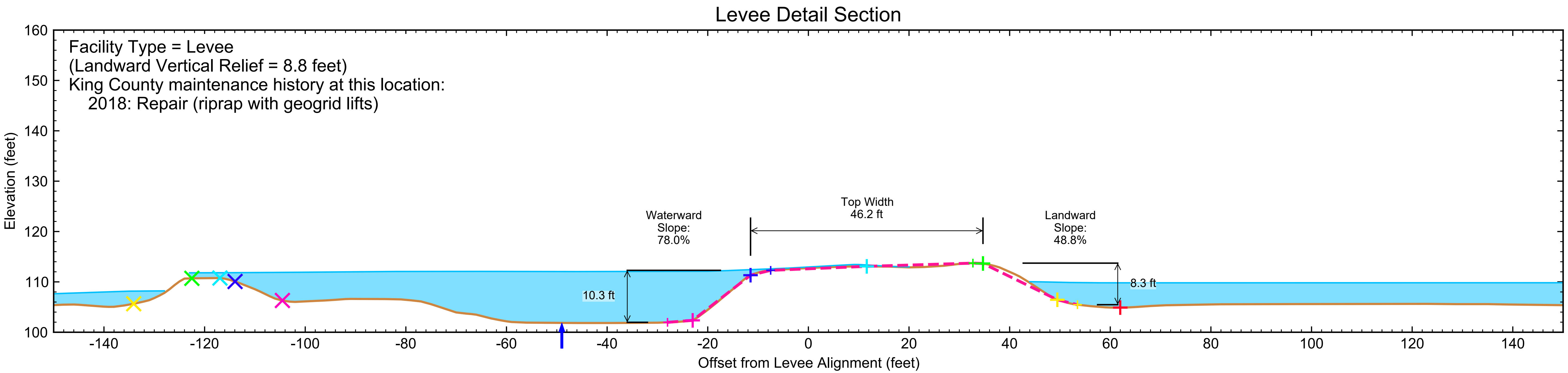
FIG. A-182

Overview Section - Right Bank Levee Station 22+00, RM 0.42



Levee Detail Section



LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL

Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 22+00, RM 0.42

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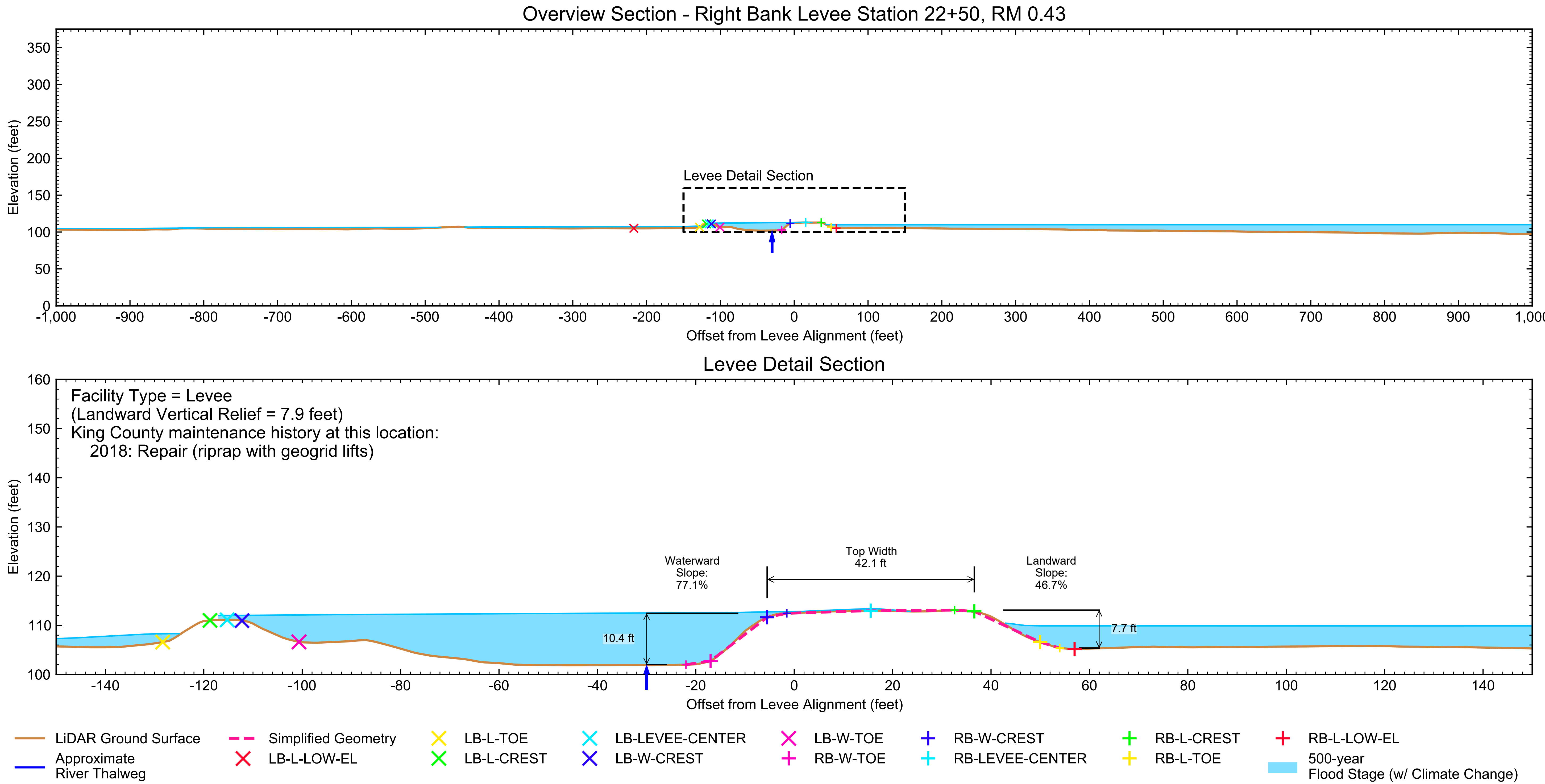
FIG. A-183



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 22+50, RM 0.43

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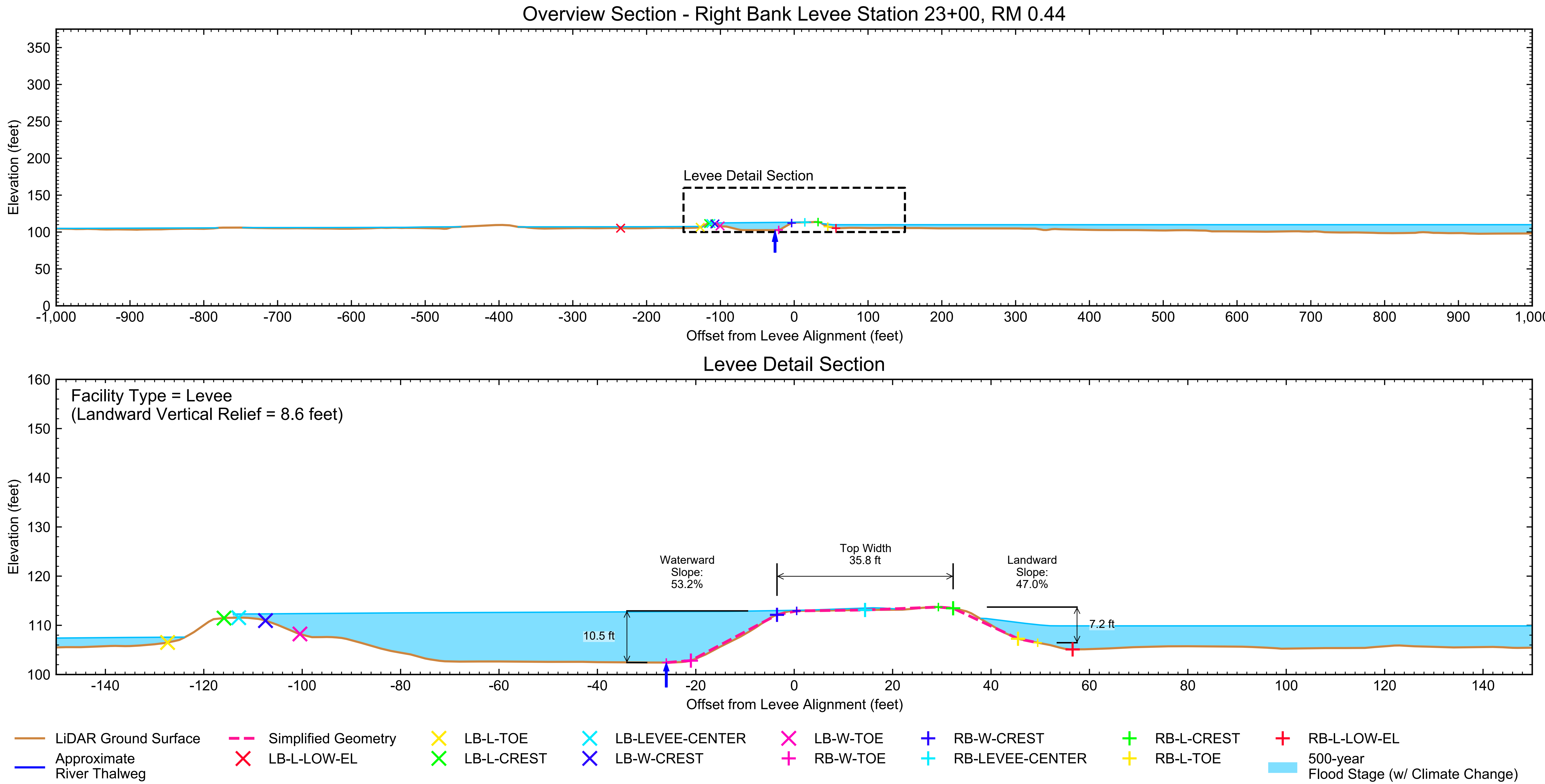
FIG. A-184



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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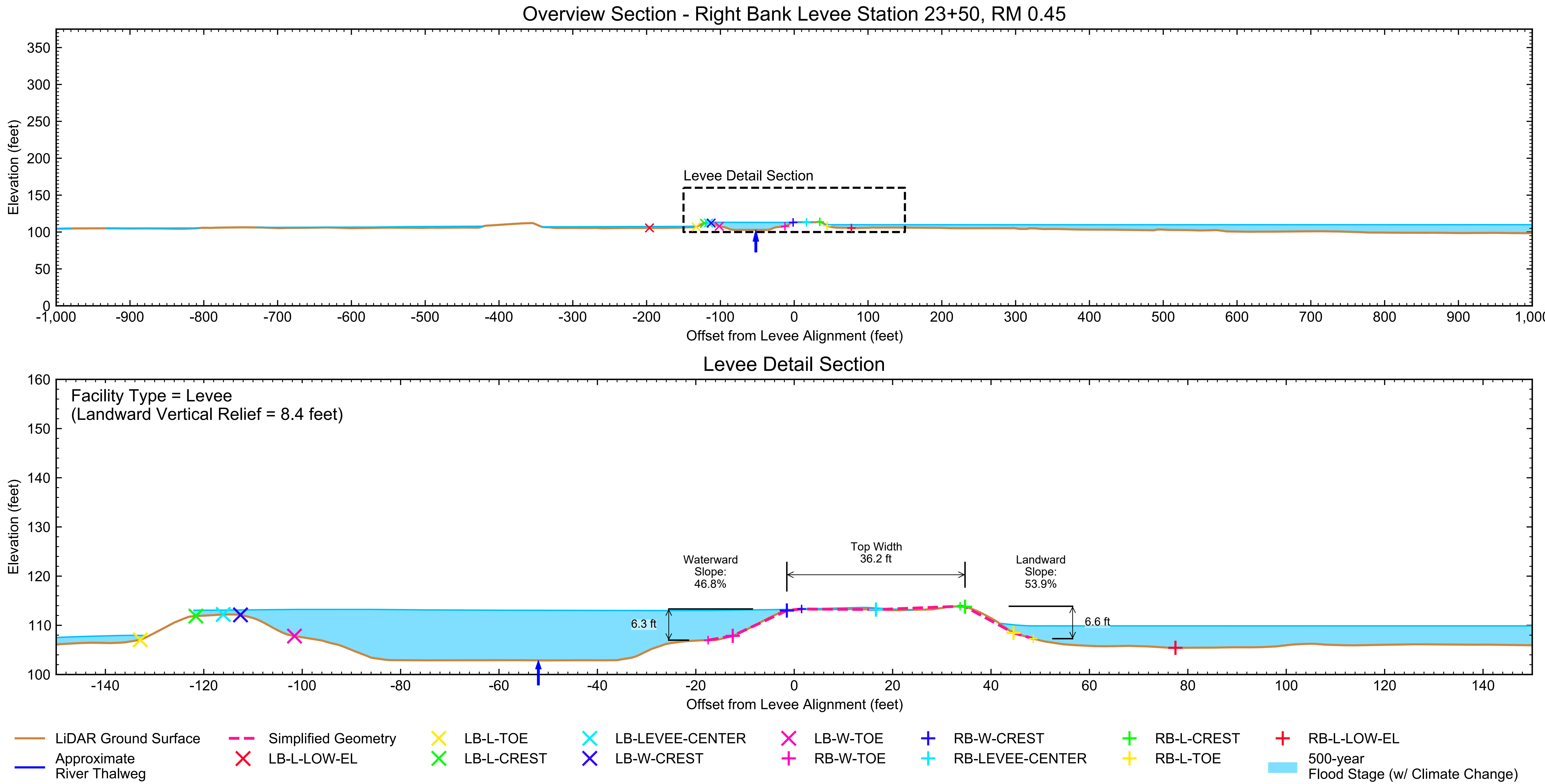
FIG. A-185



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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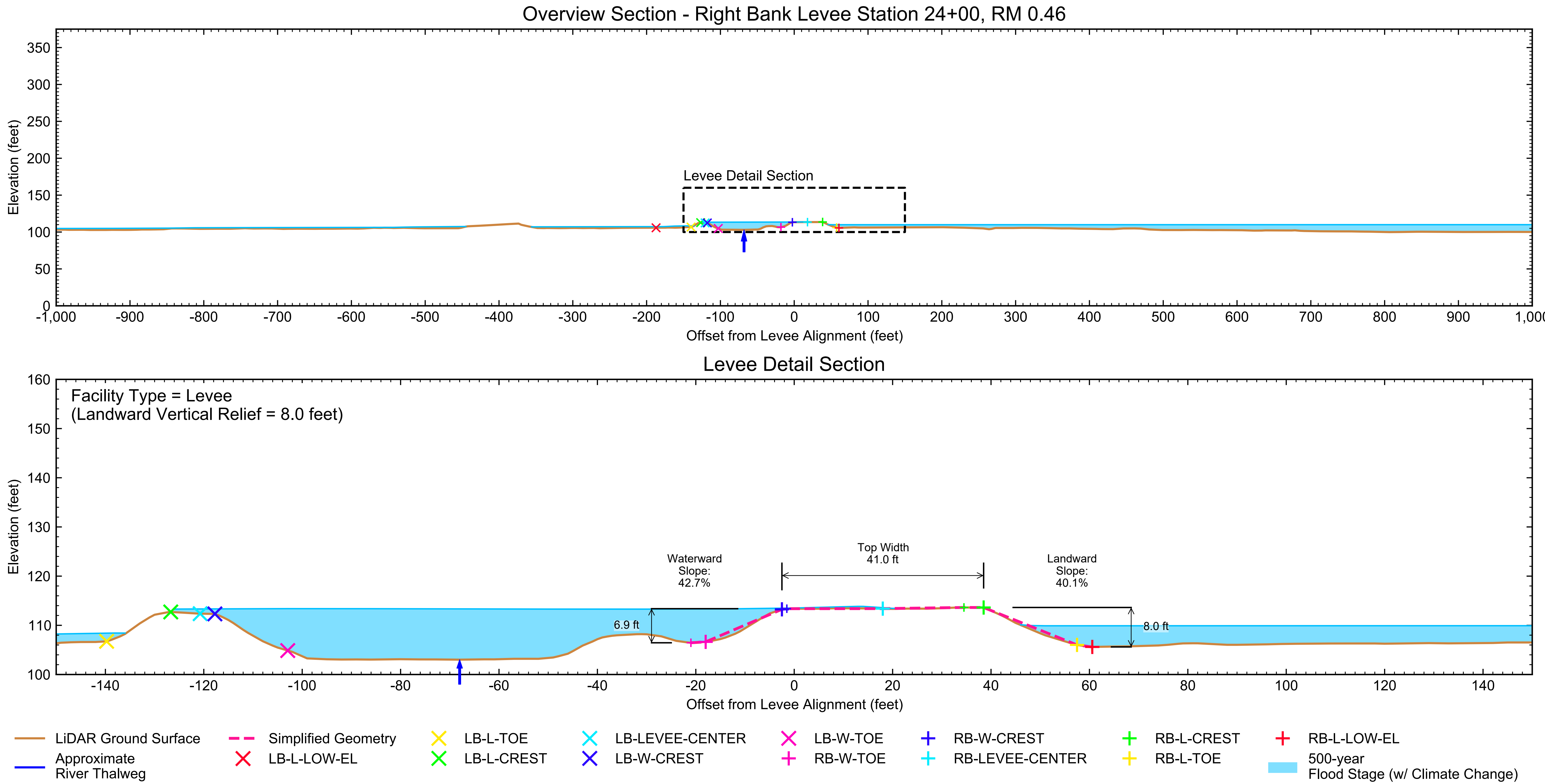
FIG. A-186



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 24+00, RM 0.46

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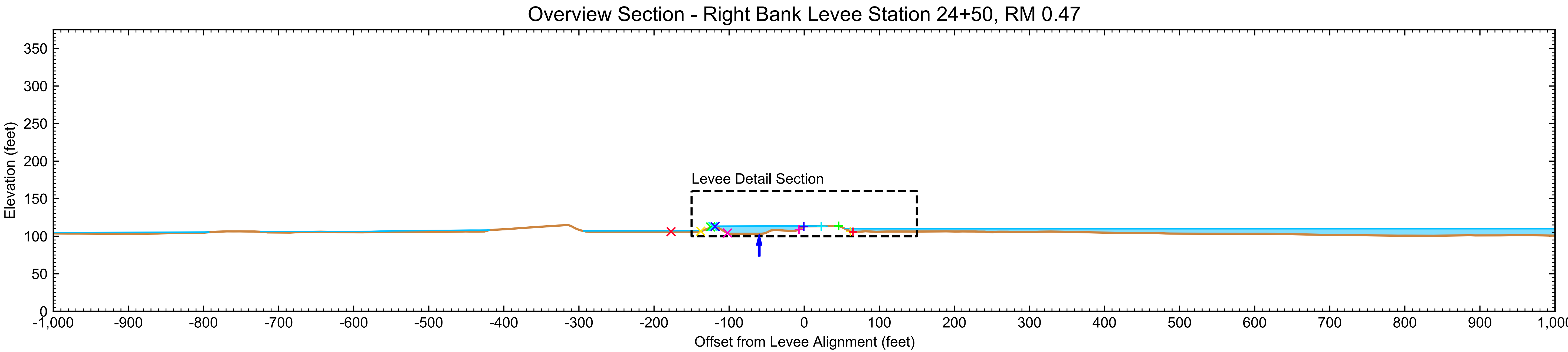
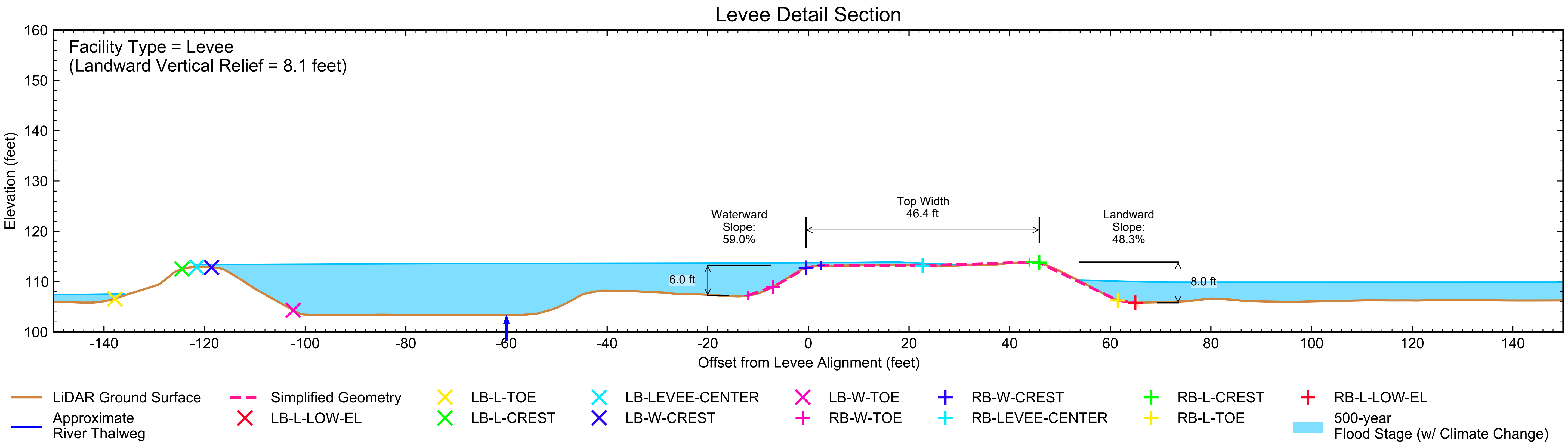
FIG. A-187





Notes:
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LIDAR CROSS SECTION
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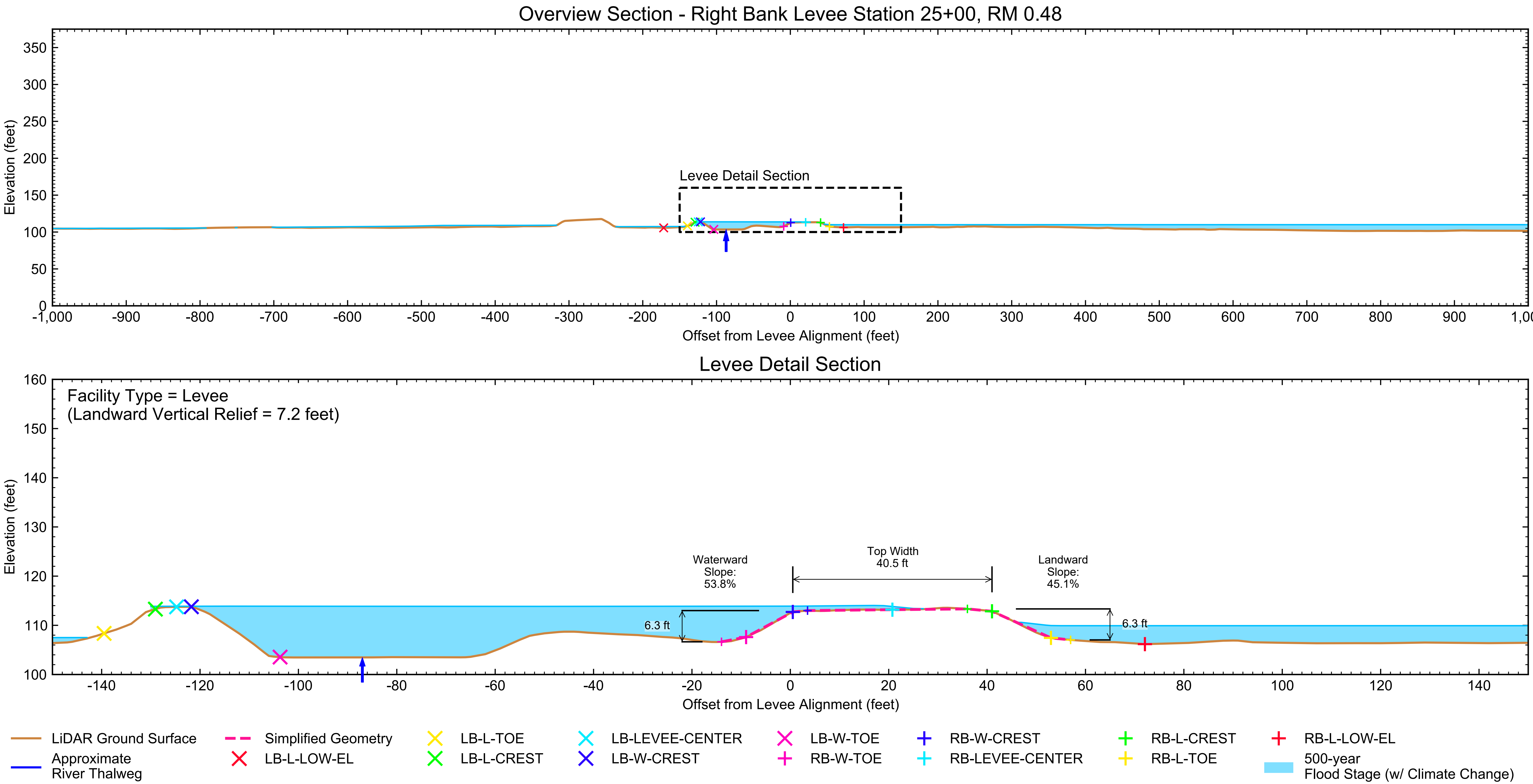
FIG. A-188



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LIDAR CROSS SECTION
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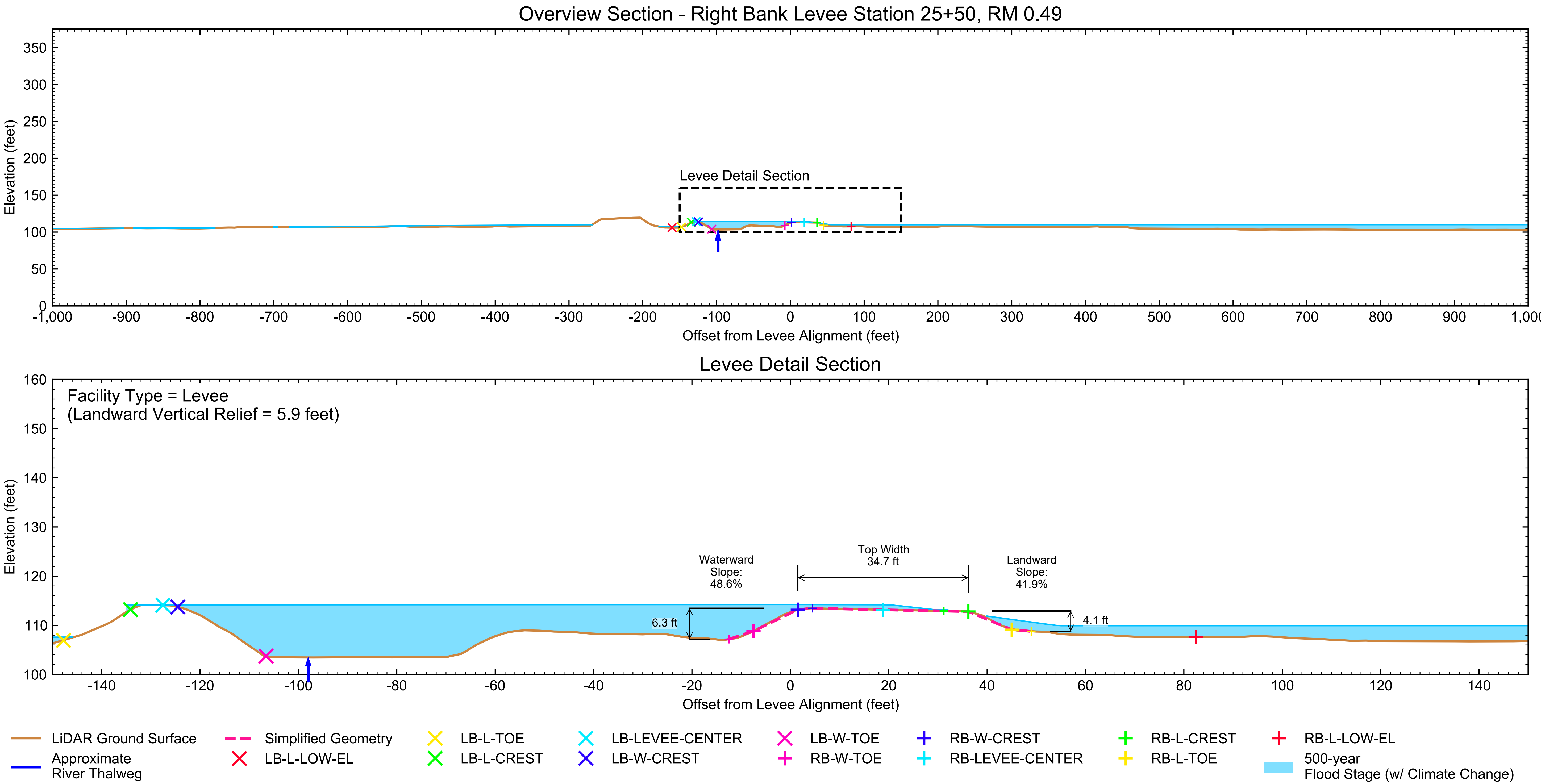
FIG. A-189



Notes:
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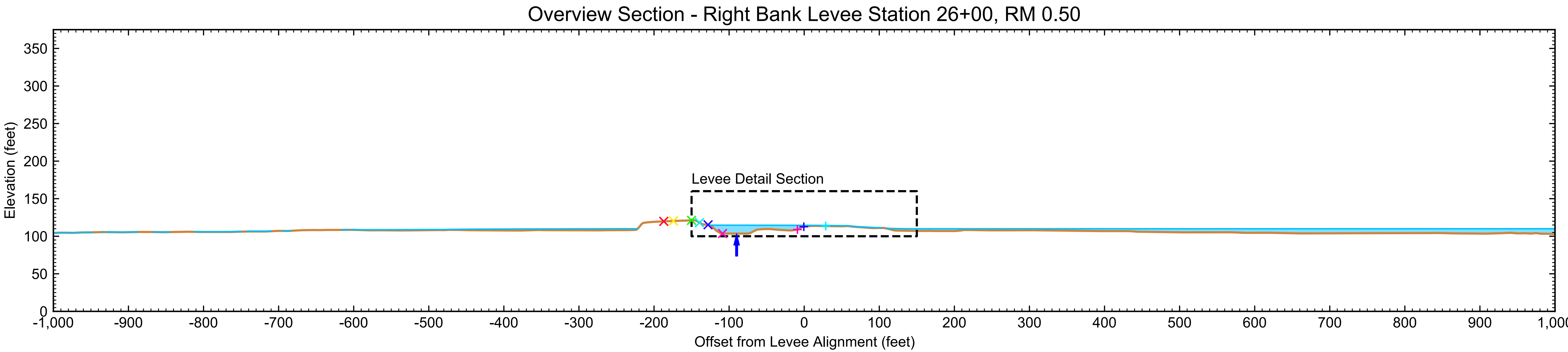
FIG. A-190



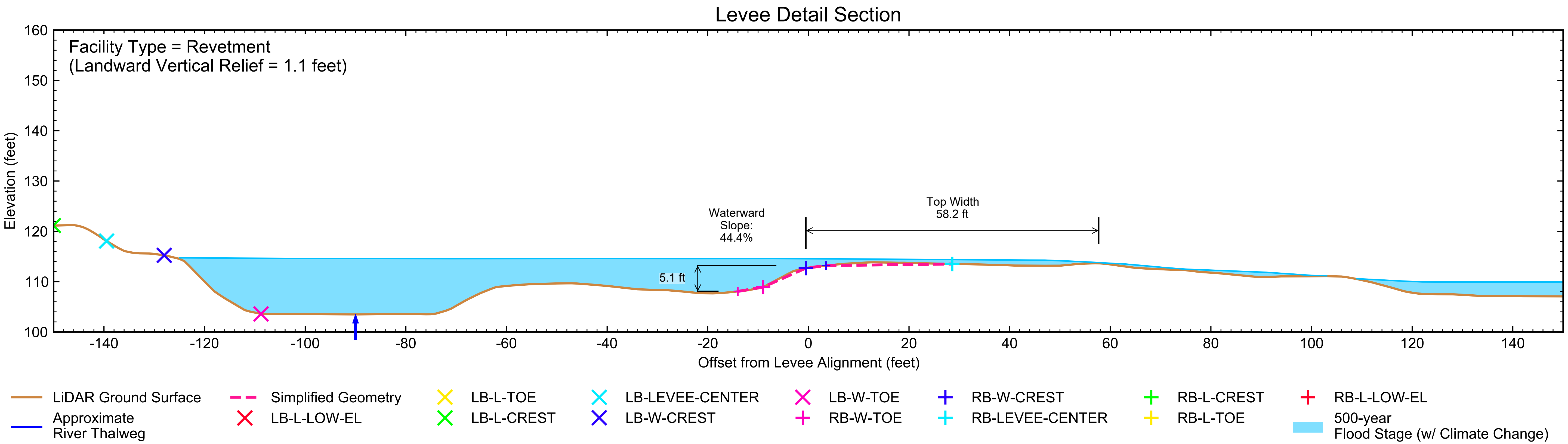


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FIG. A-191

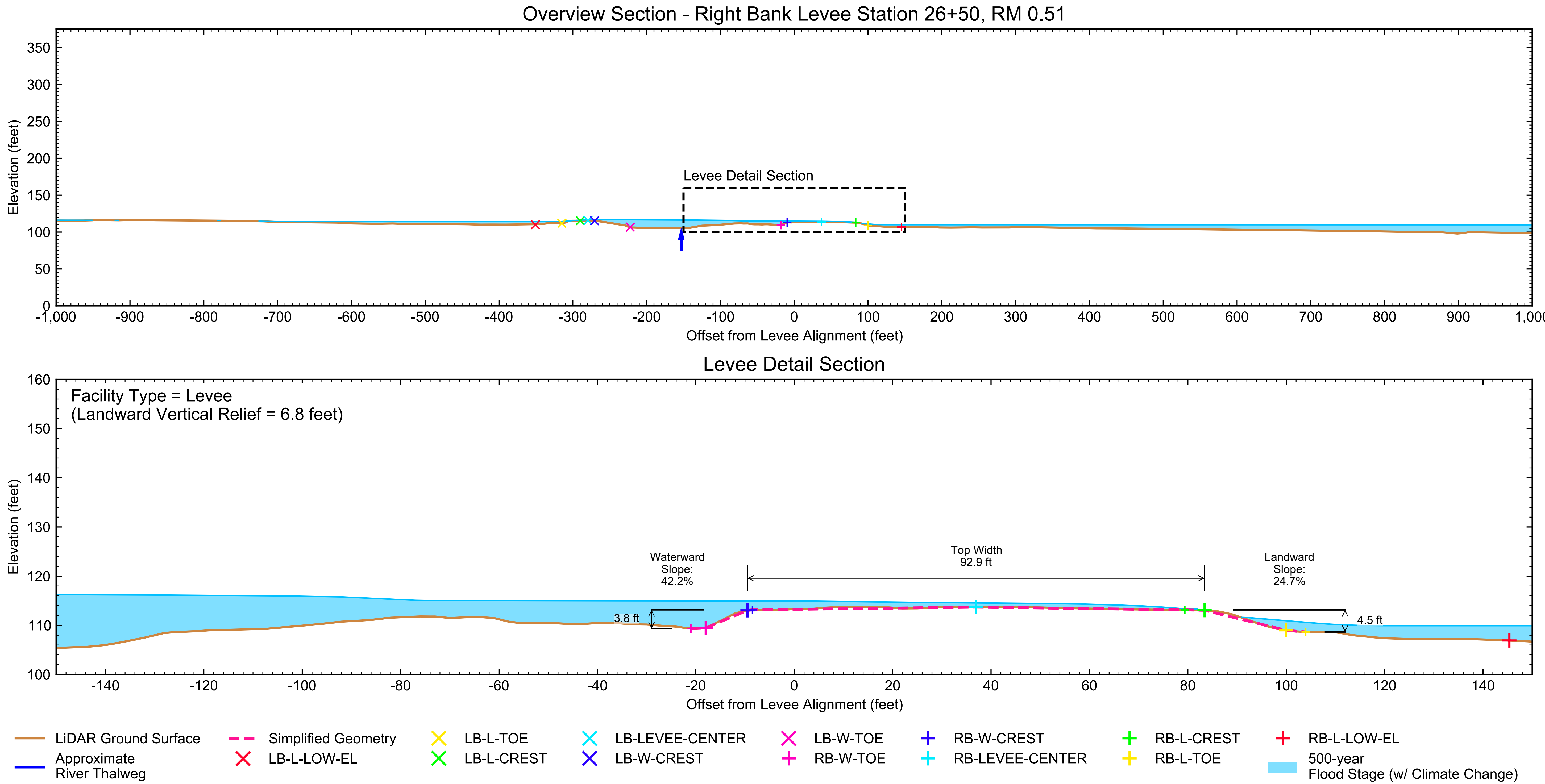

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FIG. A-192

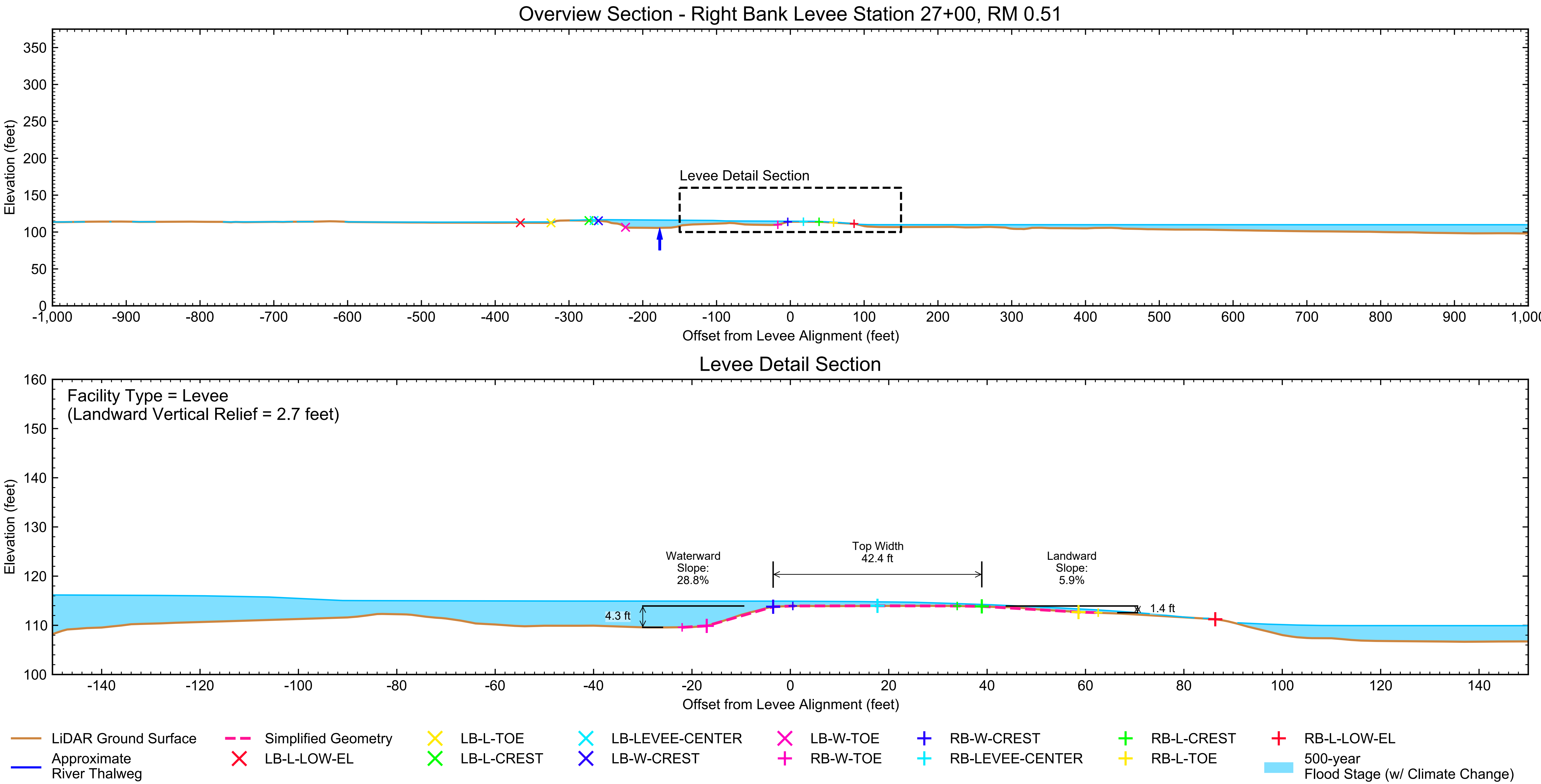

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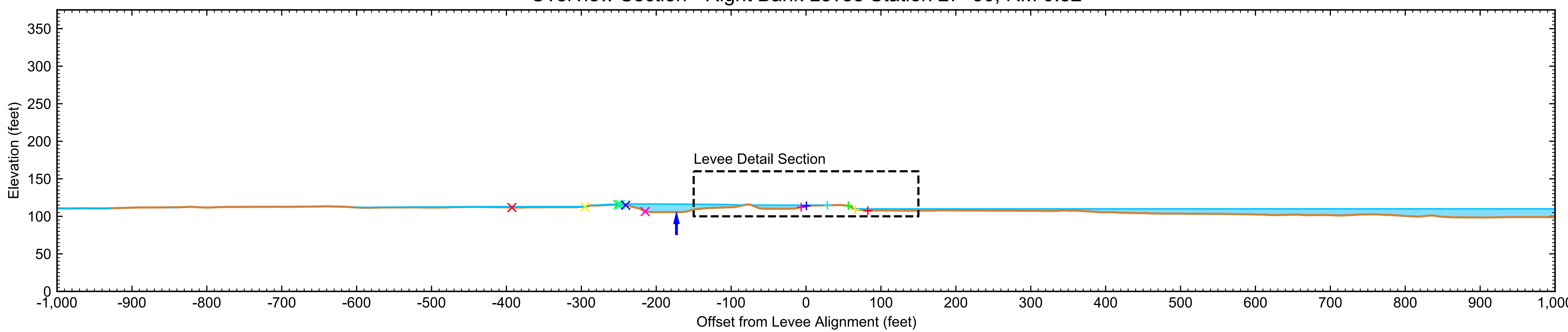
FIG. A-193

Overview Section - Right Bank Levee Station 27+50, RM 0.52



Levee Detail Section

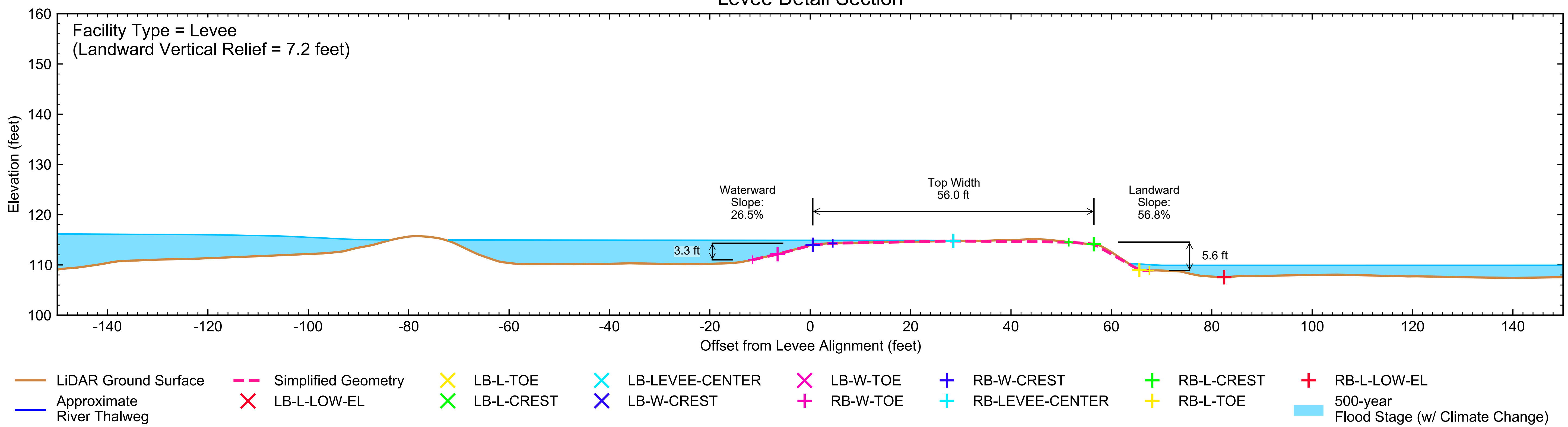


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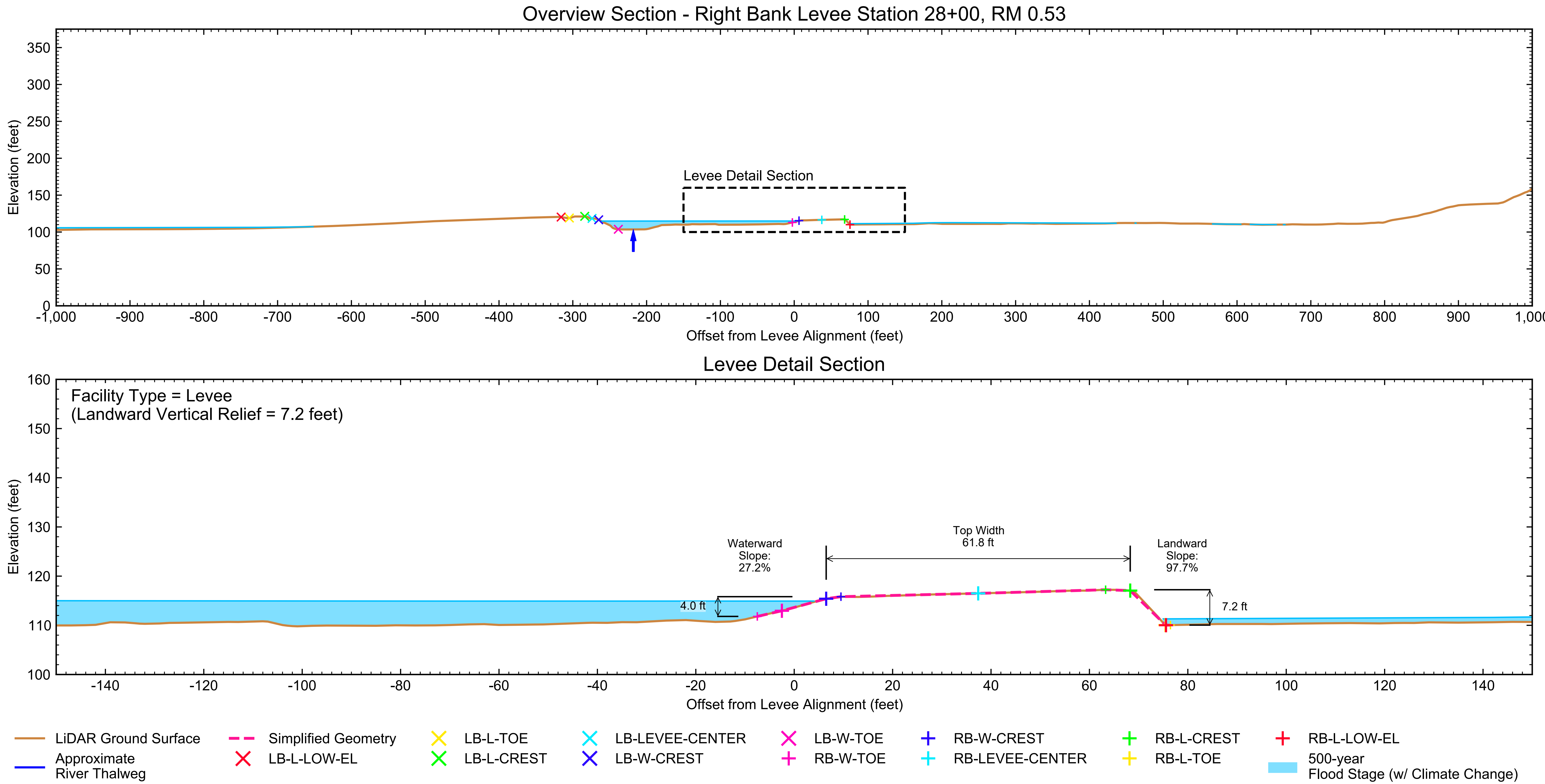
FIG. A-194



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6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 28+00, RM 0.53

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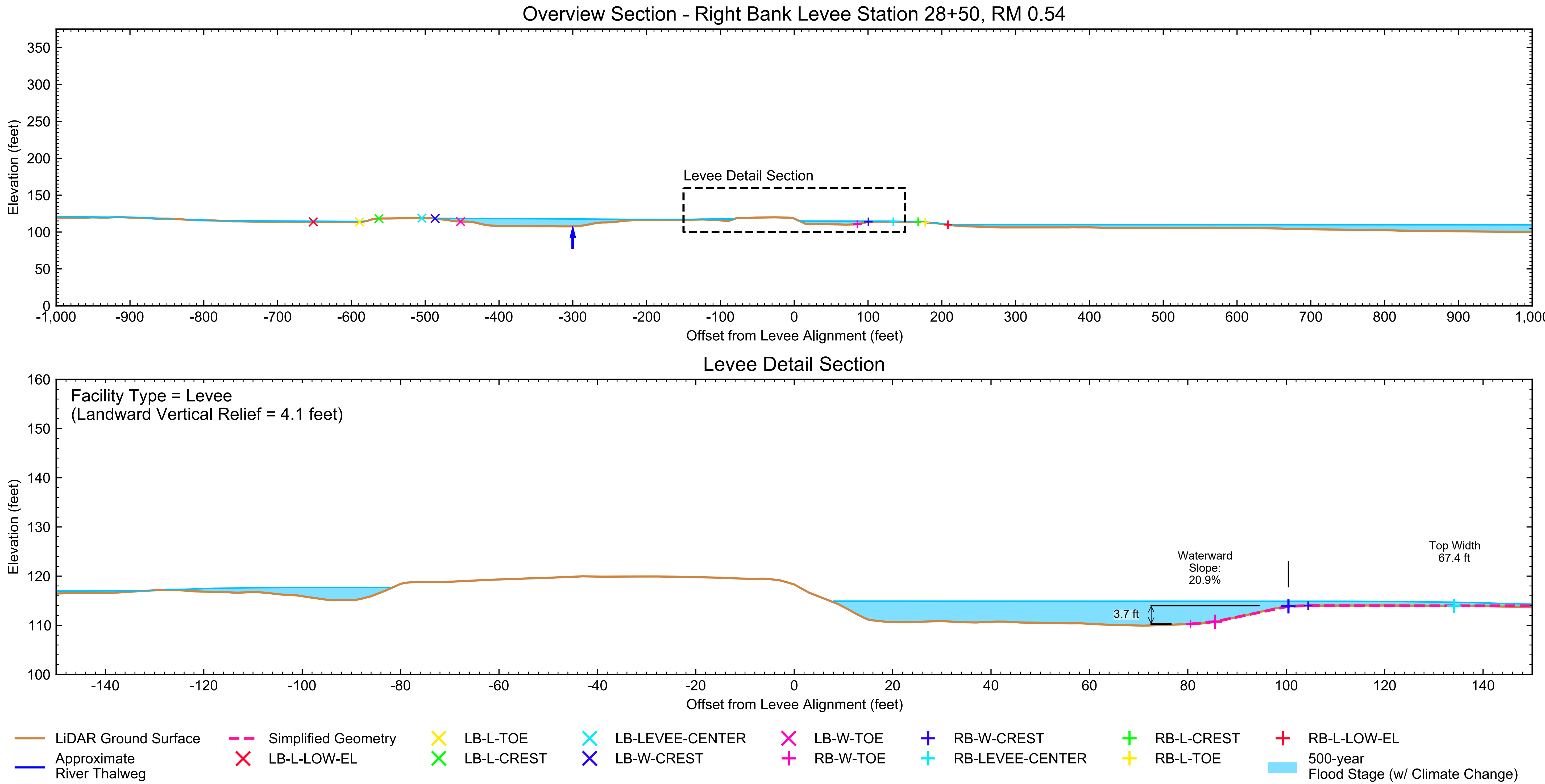
FIG. A-195



Notes:
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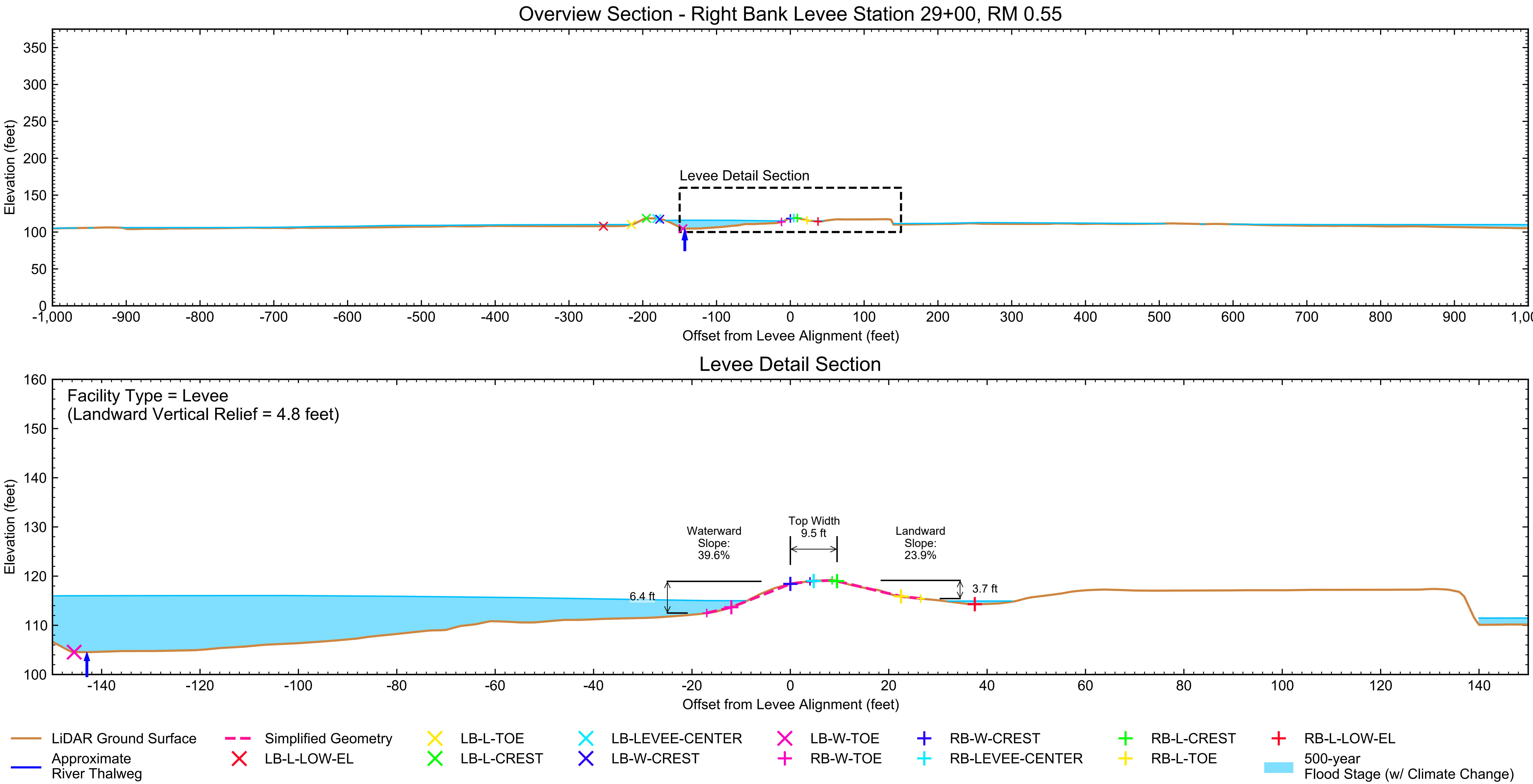
FIG. A-196



Notes:
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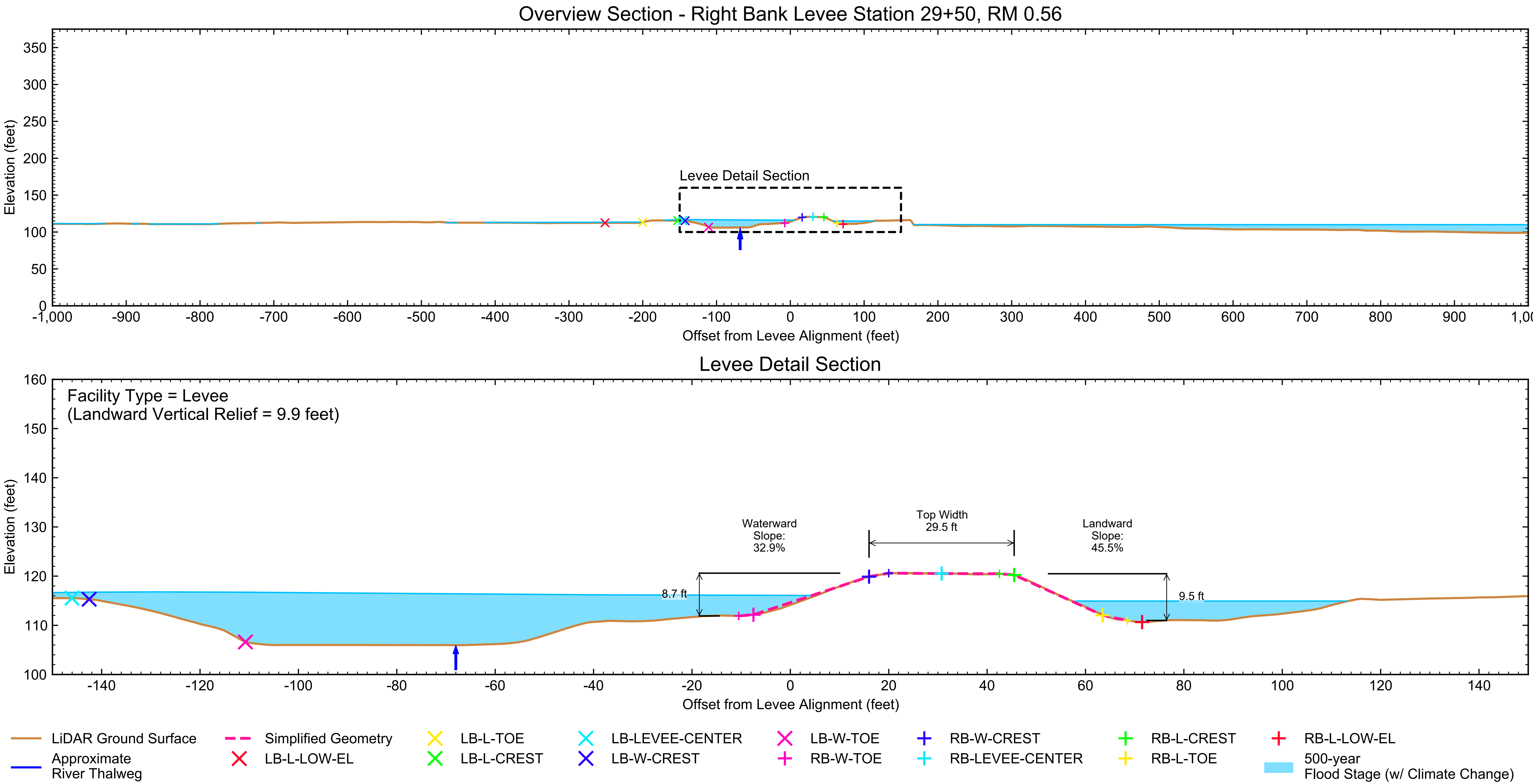
FIG. A-197



Notes:
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LIDAR CROSS SECTION
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RIGHT BANK STA 29+50, RM 0.56

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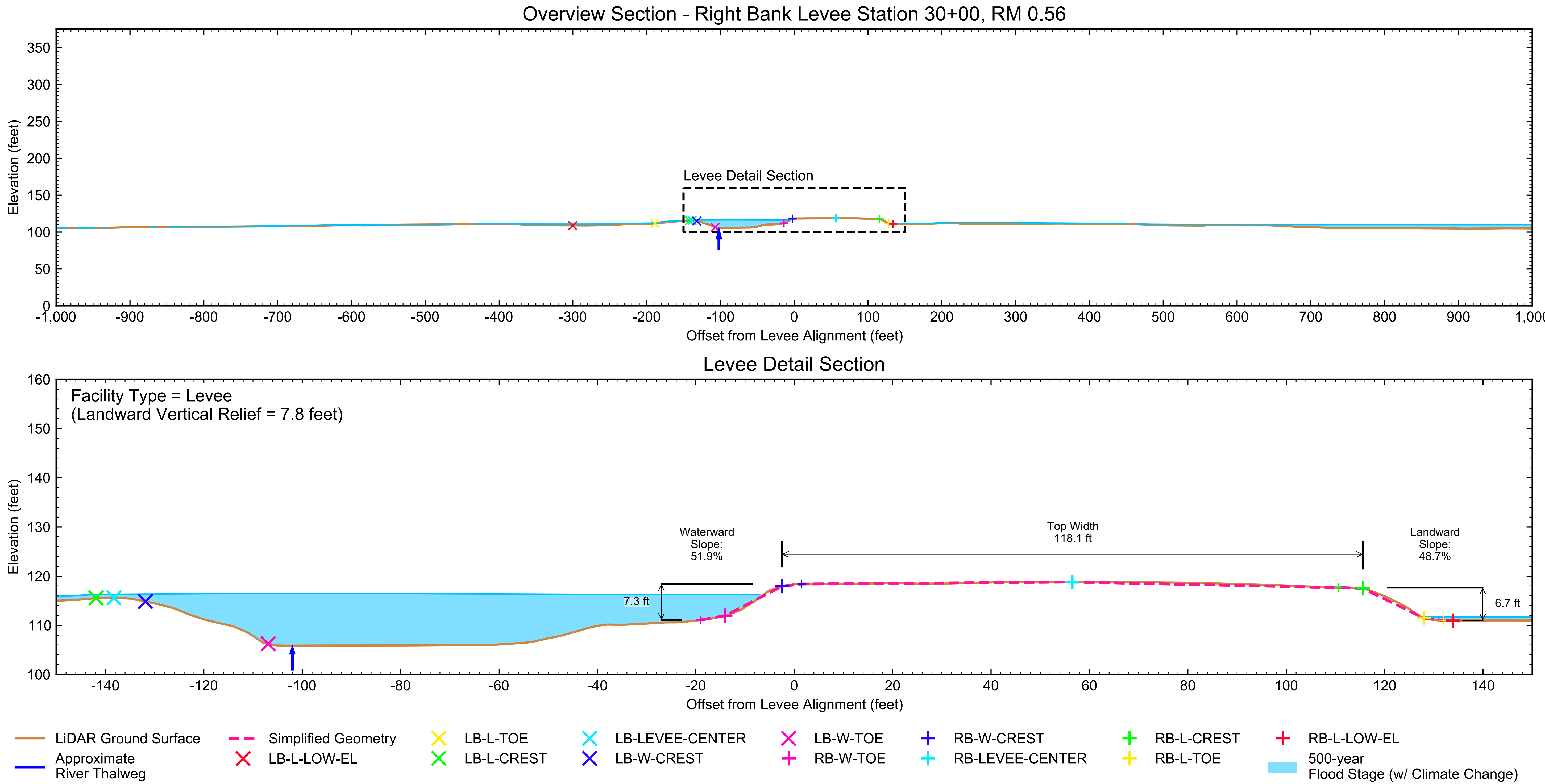
FIG. A-198



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 30+00, RM 0.56

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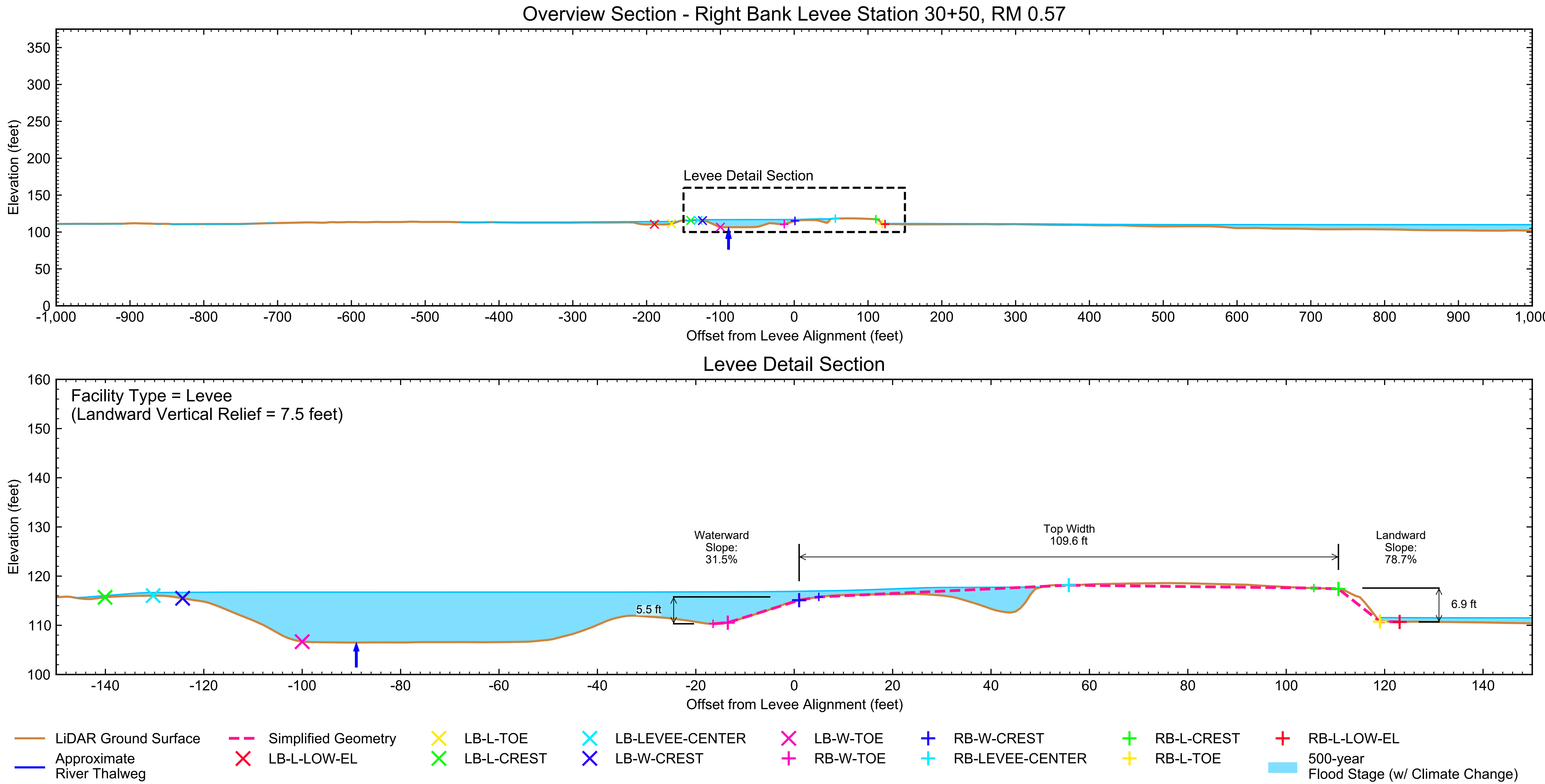
FIG. A-199



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 30+50, RM 0.57

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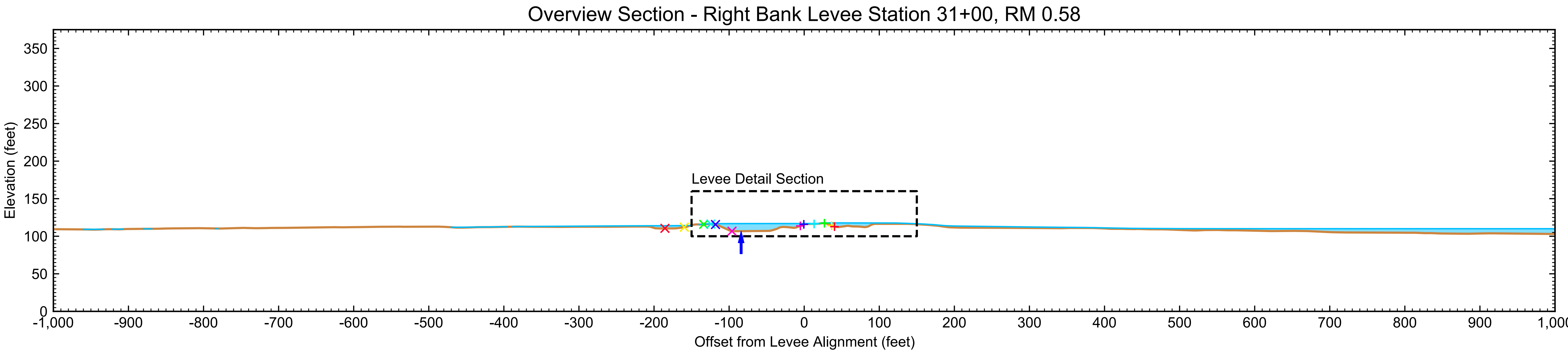
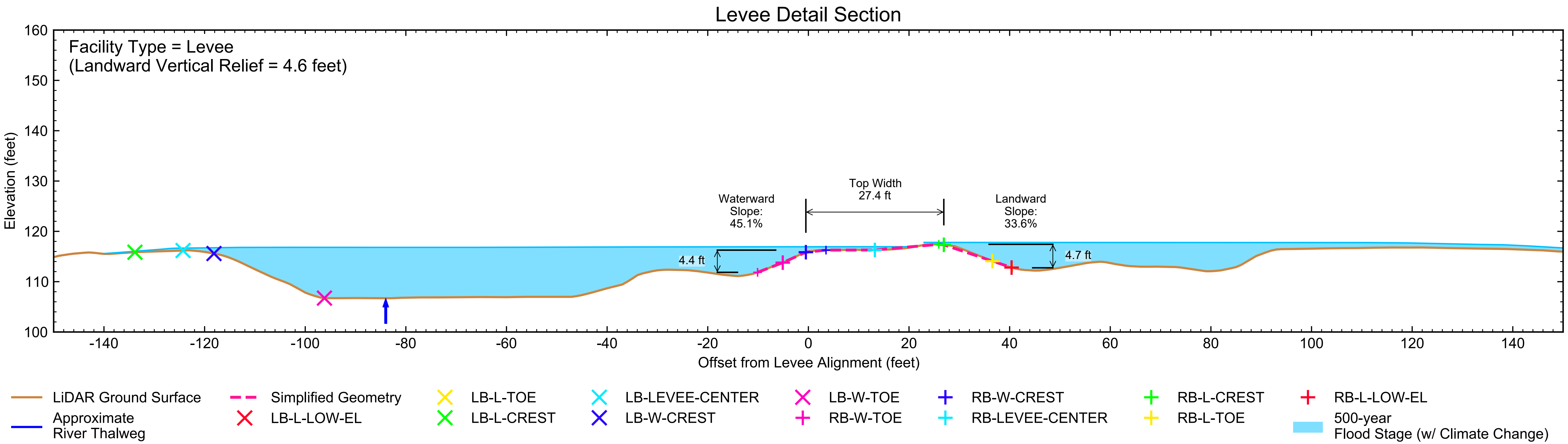
FIG. A-200





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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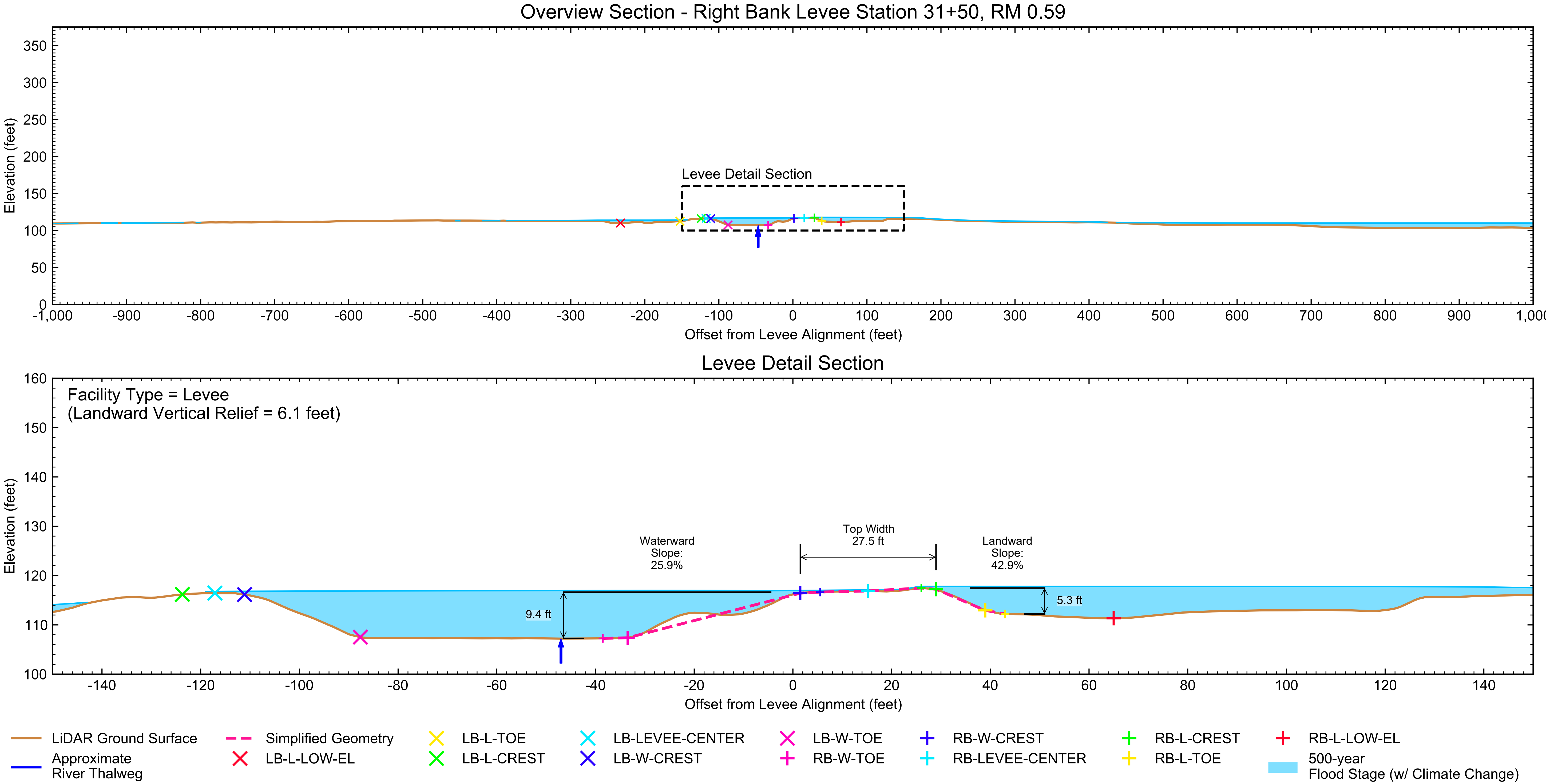
FIG. A-201

ver0.14.0.post1+gf81b80b_byOTH
\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 31+50, RM 0.59

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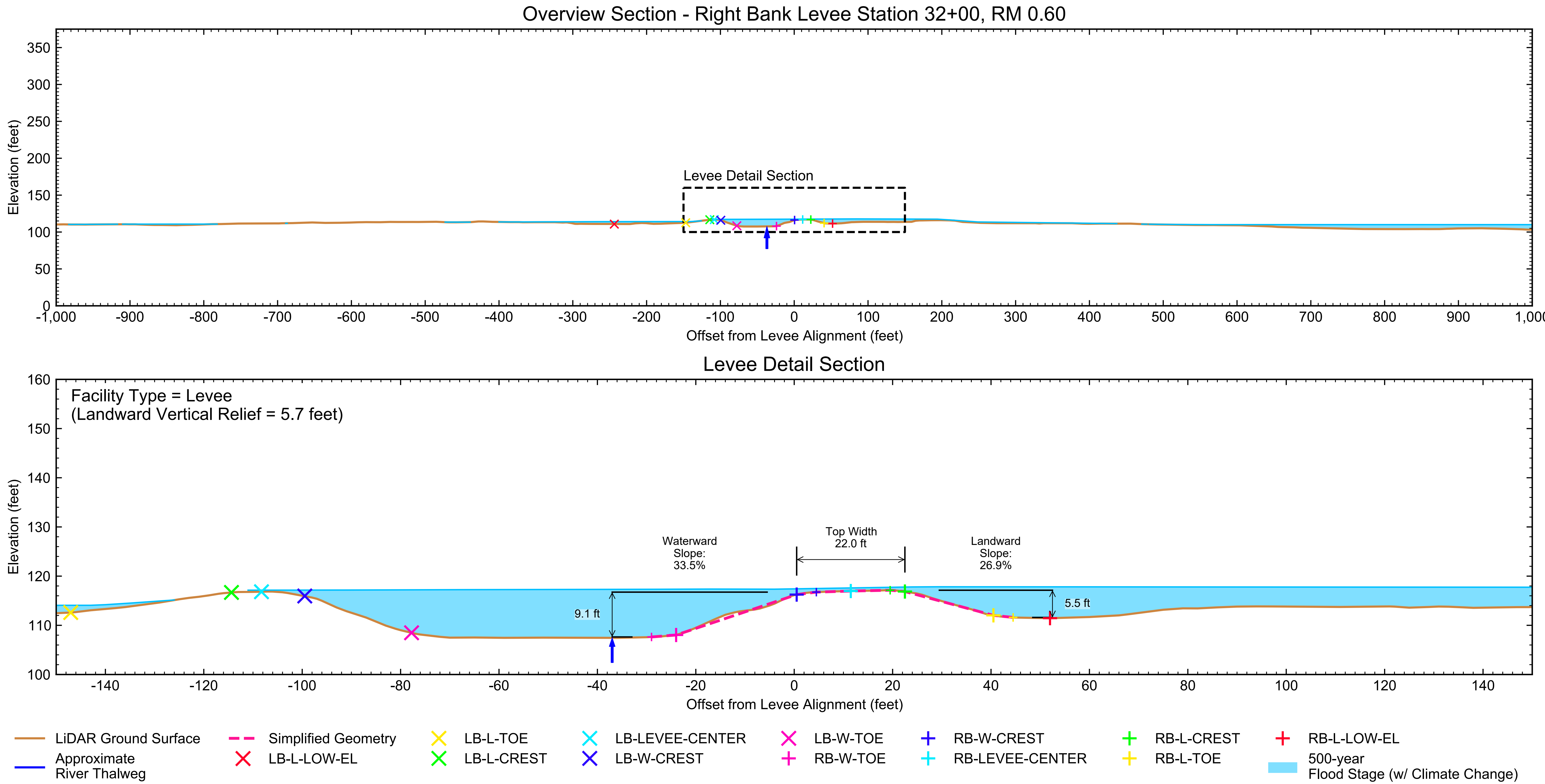
FIG. A-202



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 32+00, RM 0.60

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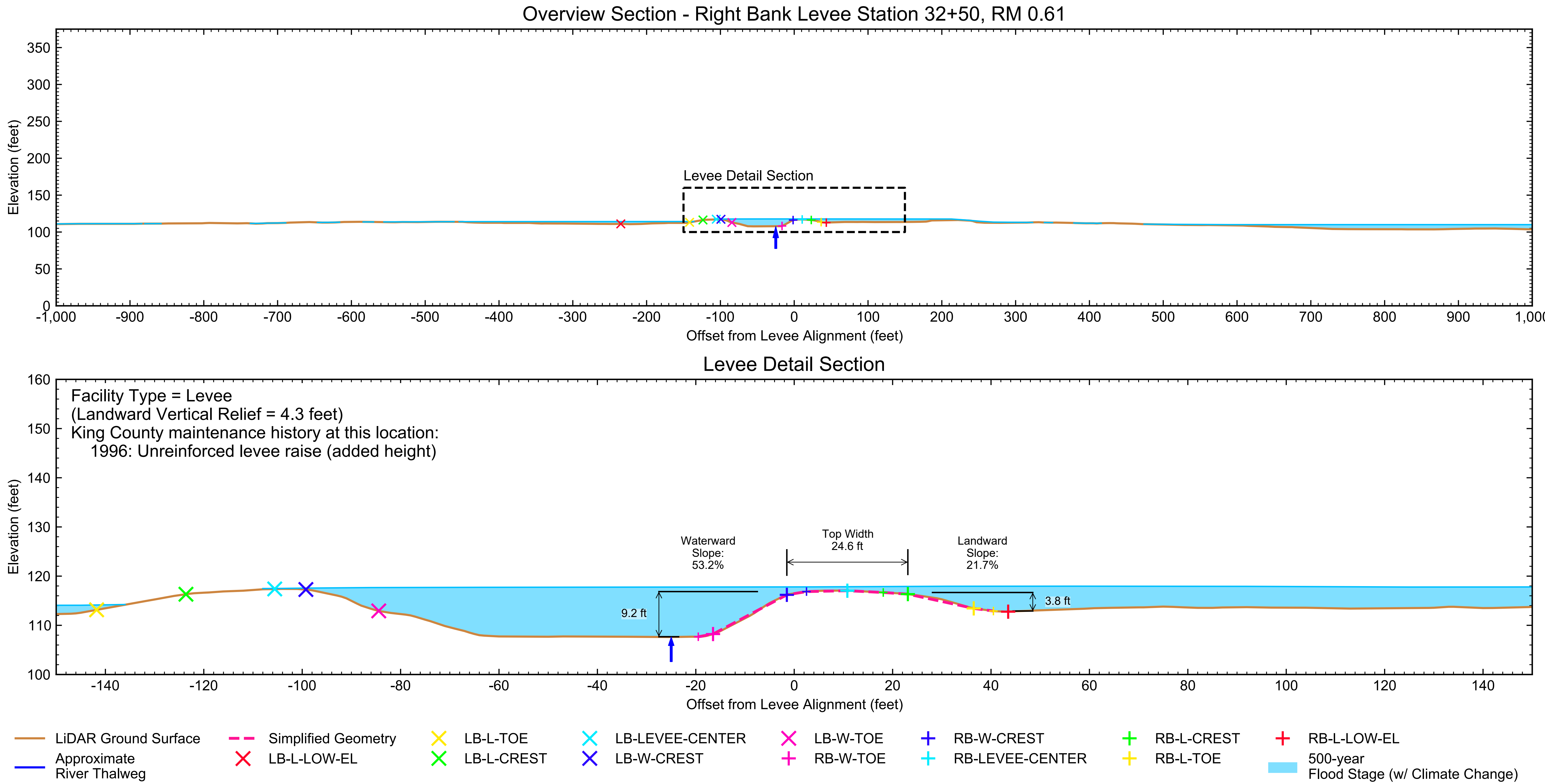
FIG. A-203



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LIDAR CROSS SECTION
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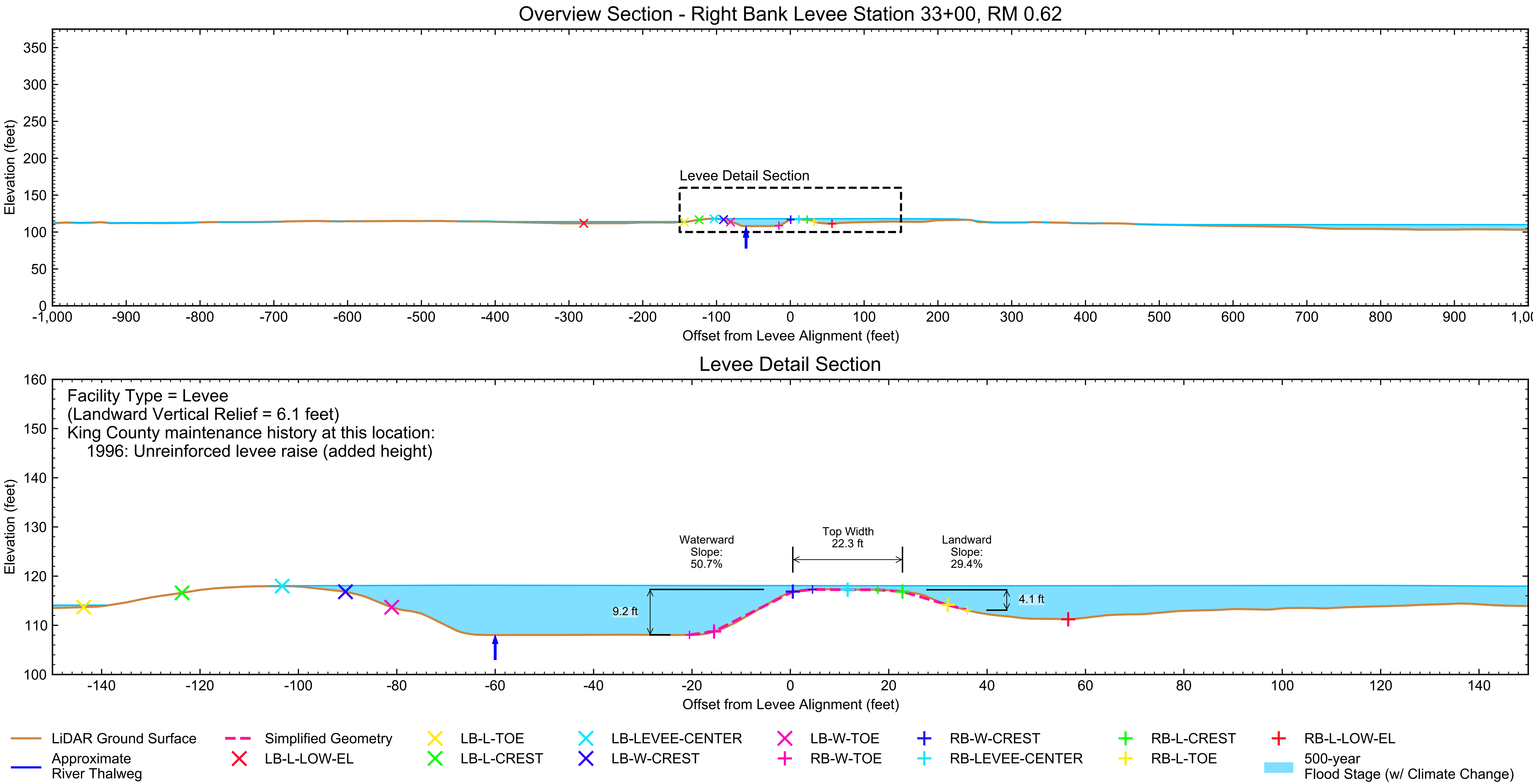
FIG. A-204



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LIDAR CROSS SECTION
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FIG. A-205

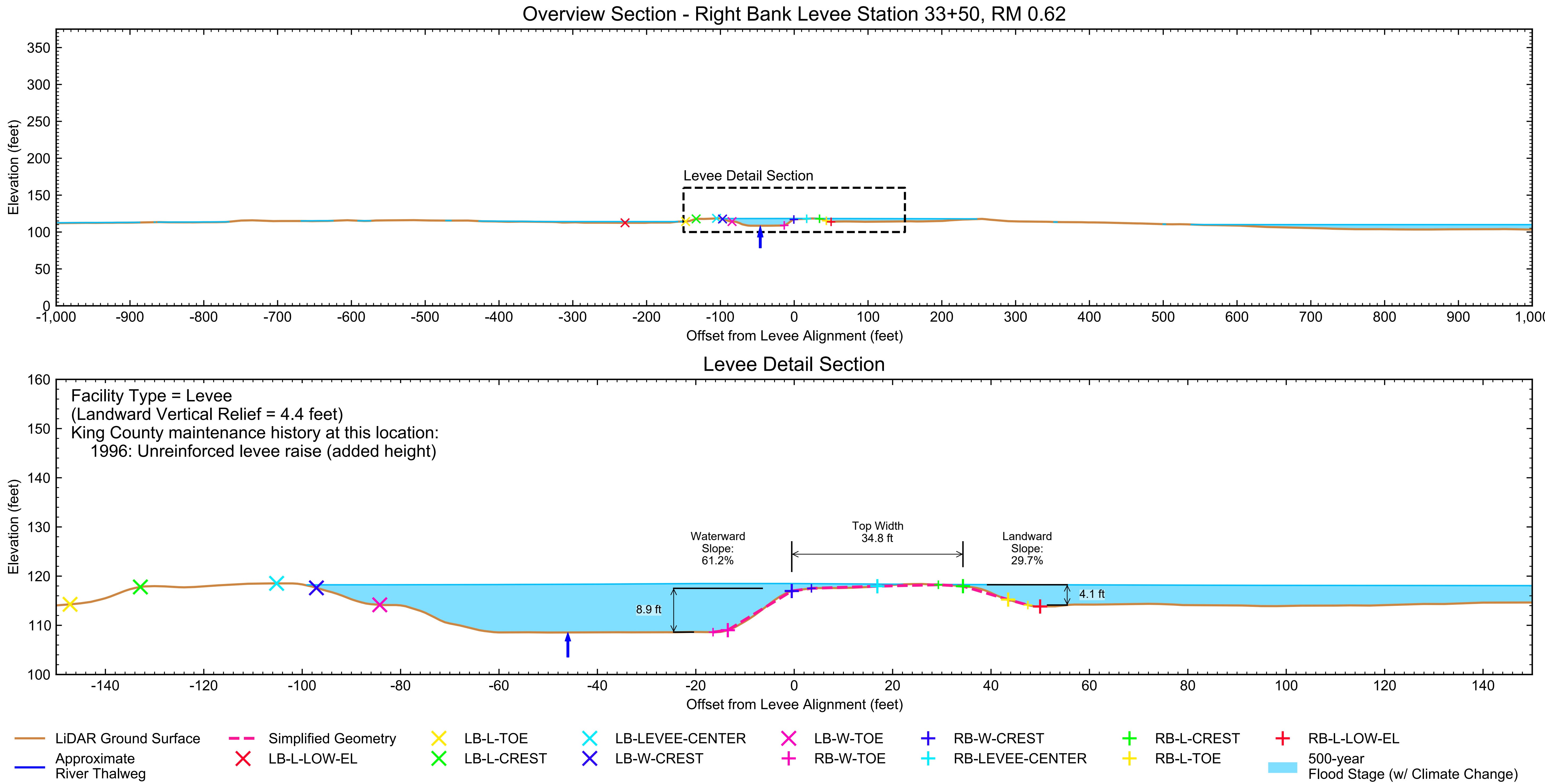

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FIG. A-206

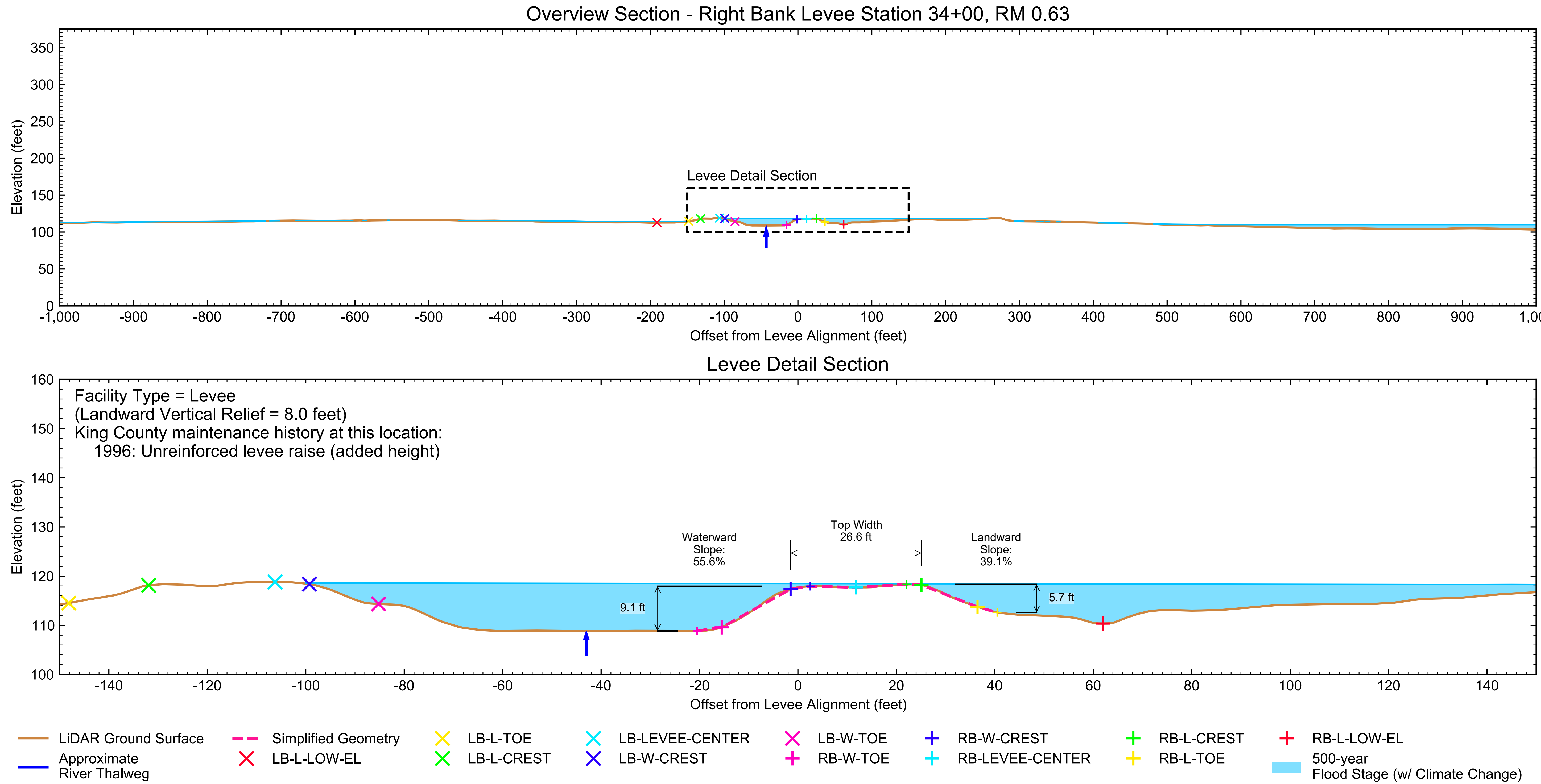

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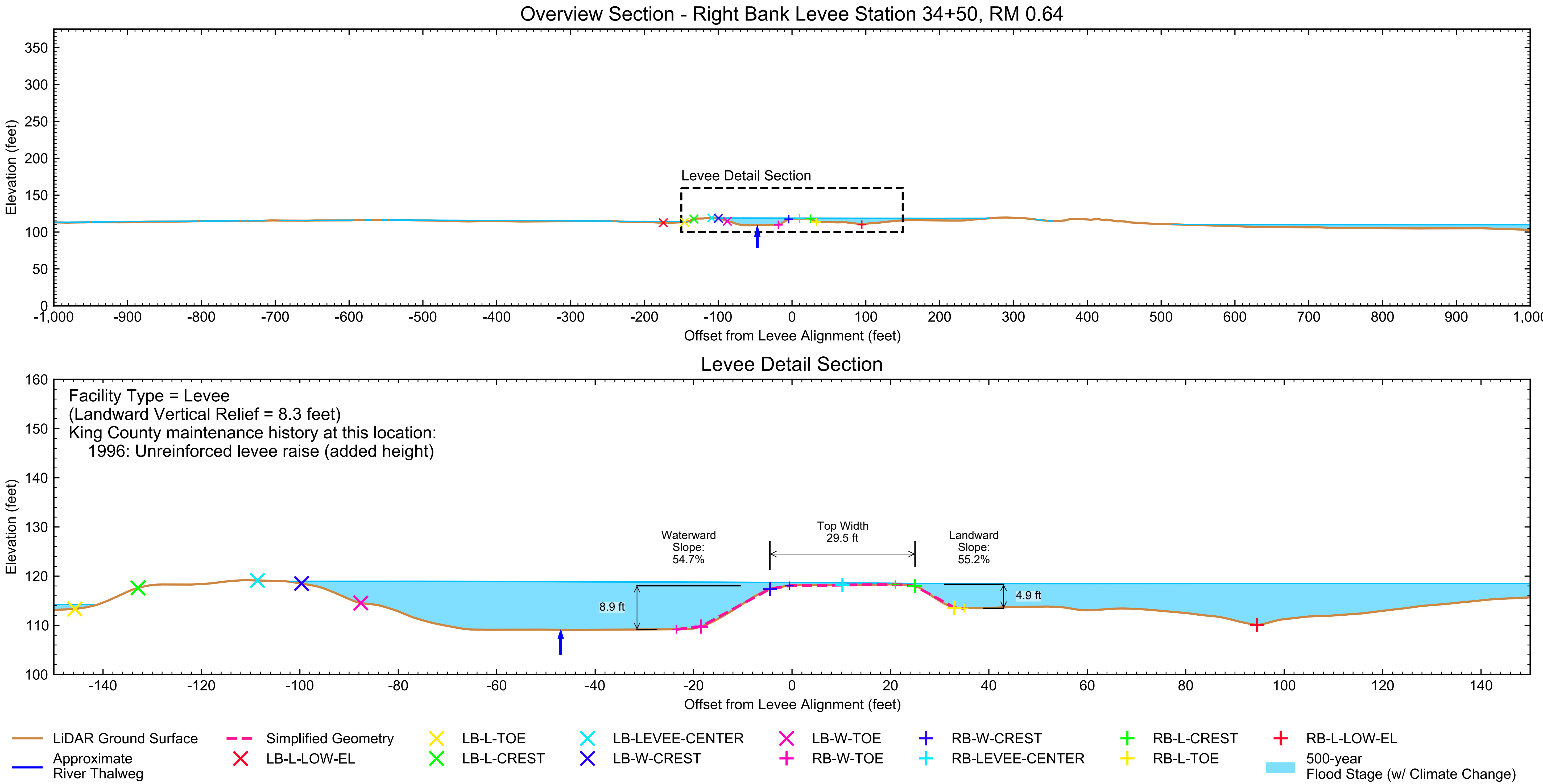
FIG. A-207



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 34+50, RM 0.64

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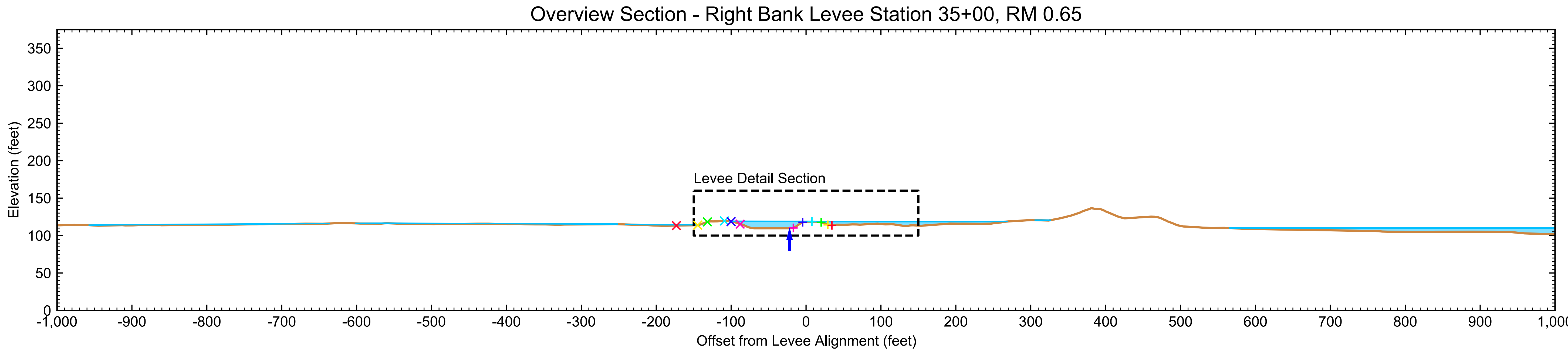
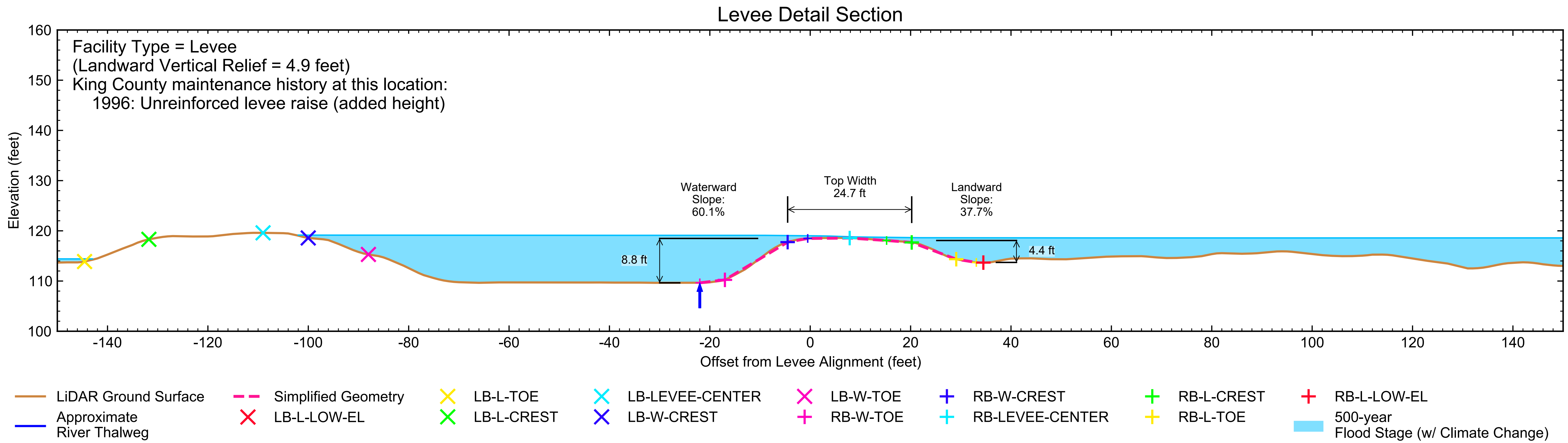
FIG. A-208





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LIDAR CROSS SECTION LOWER RAGING RIVER RIGHT BANK STA 35+00, RM 0.65	
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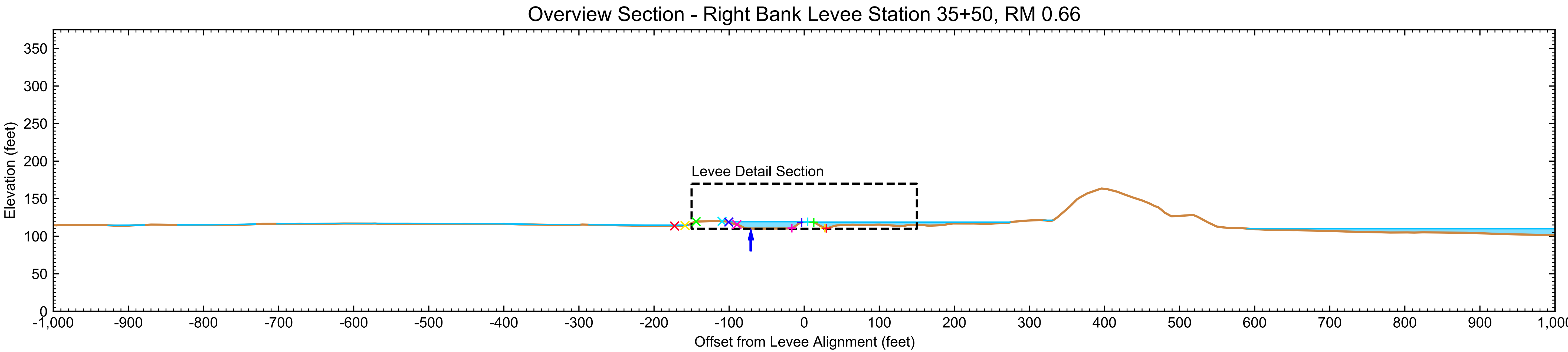
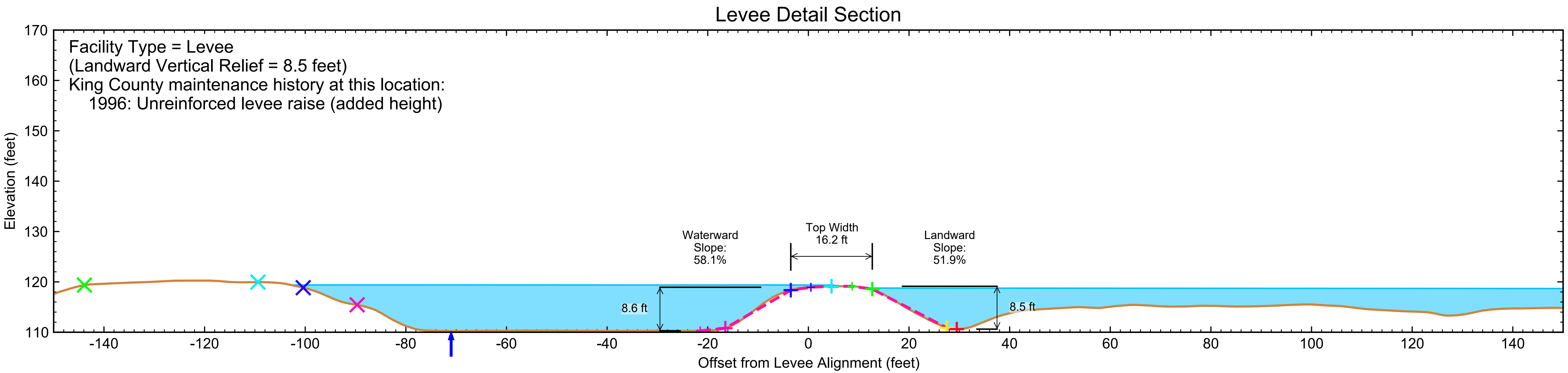
SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	FIG. A-209





LiDAR Ground Surface
Approximate River Thalweg
Simplified Geometry
LB-L-LOW-EL
LB-L-TOE
LB-L-CREST
LB-LEVEE-CENTER
LB-W-CREST
LB-W-TOE
RB-W-TOE
RB-W-CREST
RB-LEVEE-CENTER
RB-L-CREST
RB-L-TOE
RB-L-LOW-EL
500-year Flood Stage (w/ Climate Change)

Notes:

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 35+50, RM 0.66

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Geotechnical and Environmental Consultants

FIG. A-210

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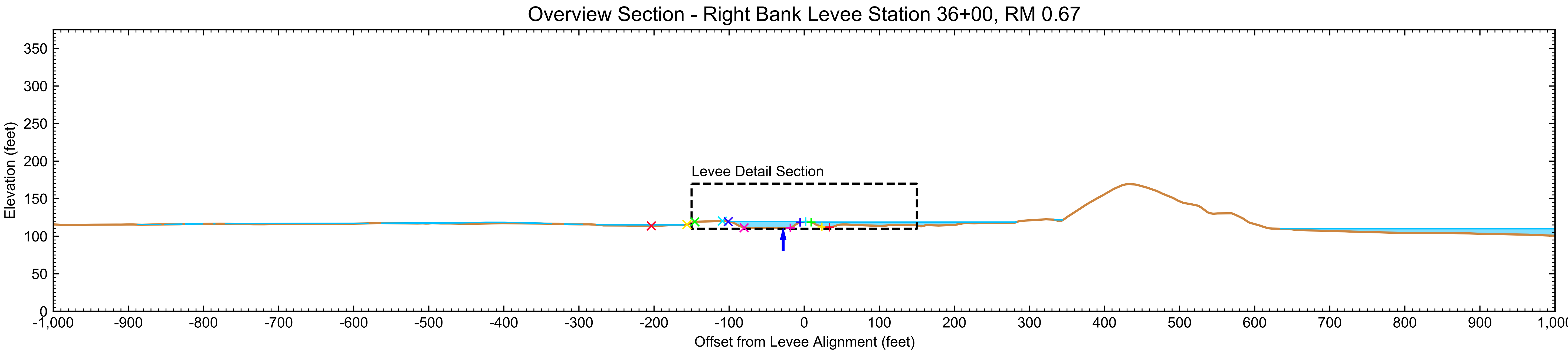

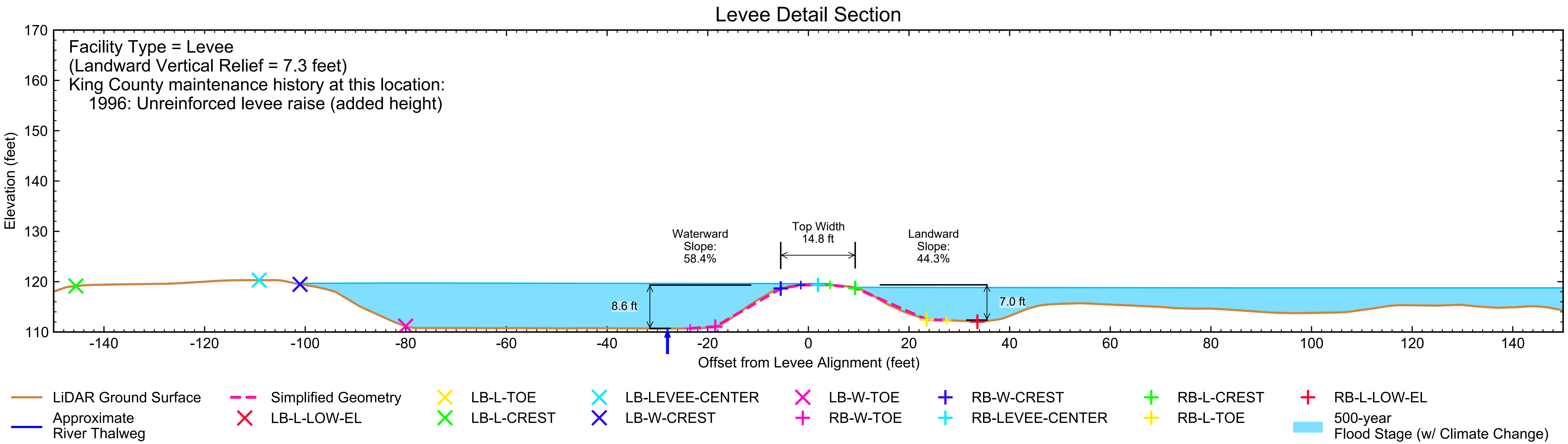

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RIGHT BANK STA 36+00, RM 0.67

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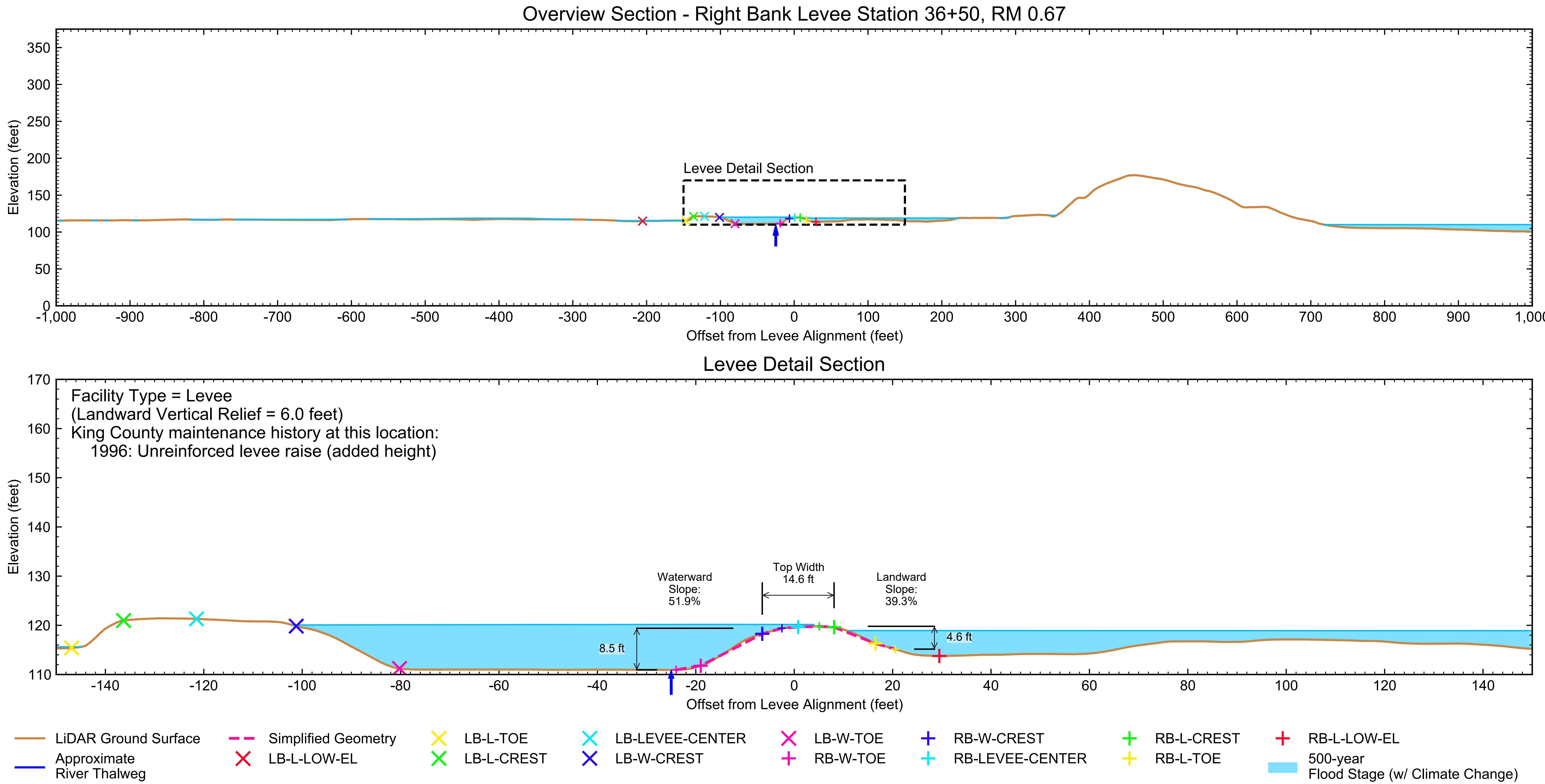
FIG. A-211

\\SEA-FS1\Vol1\EP\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data



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LOWER RAGING RIVER
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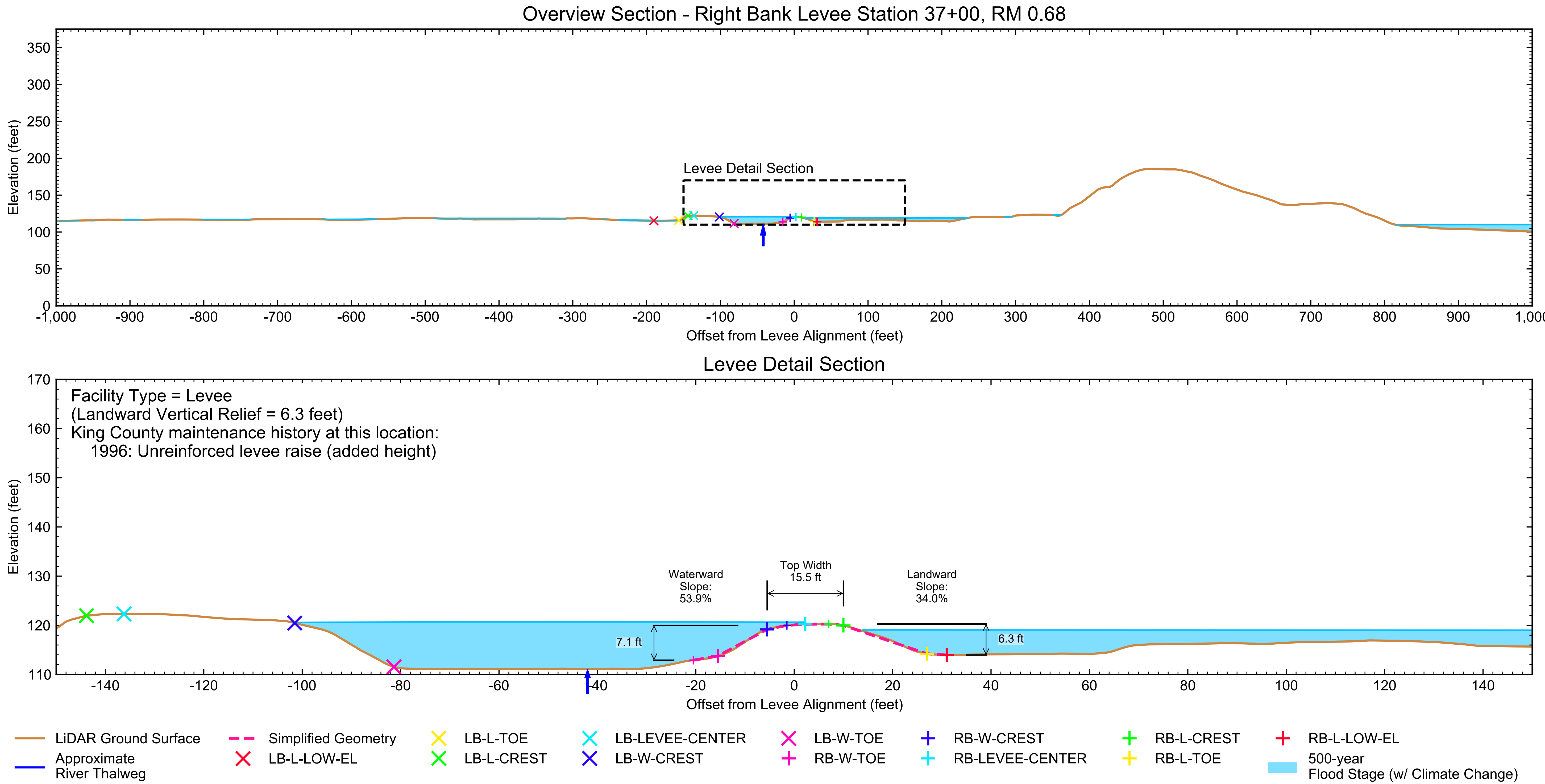
FIG. A-212



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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FIG. A-213

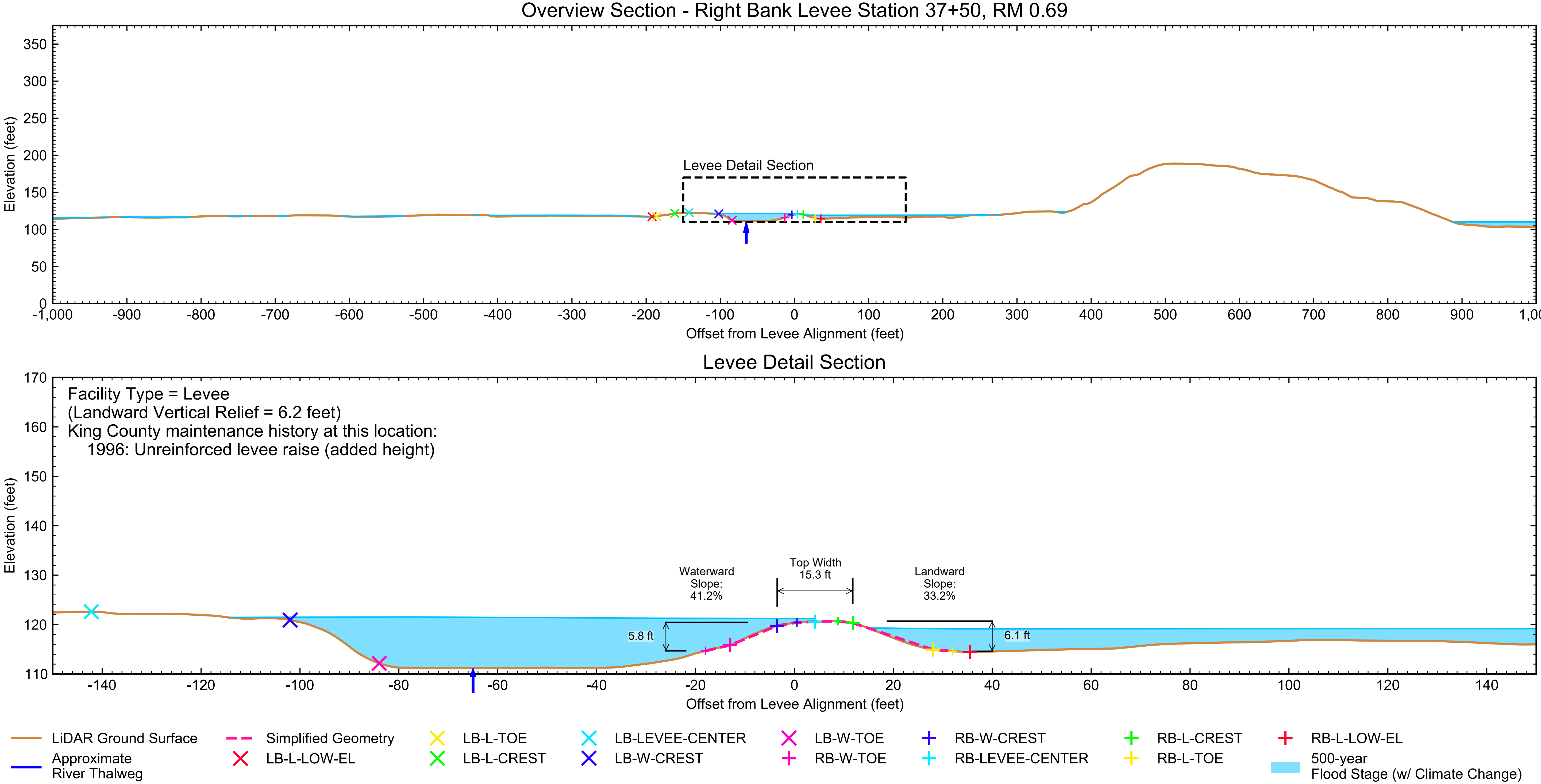

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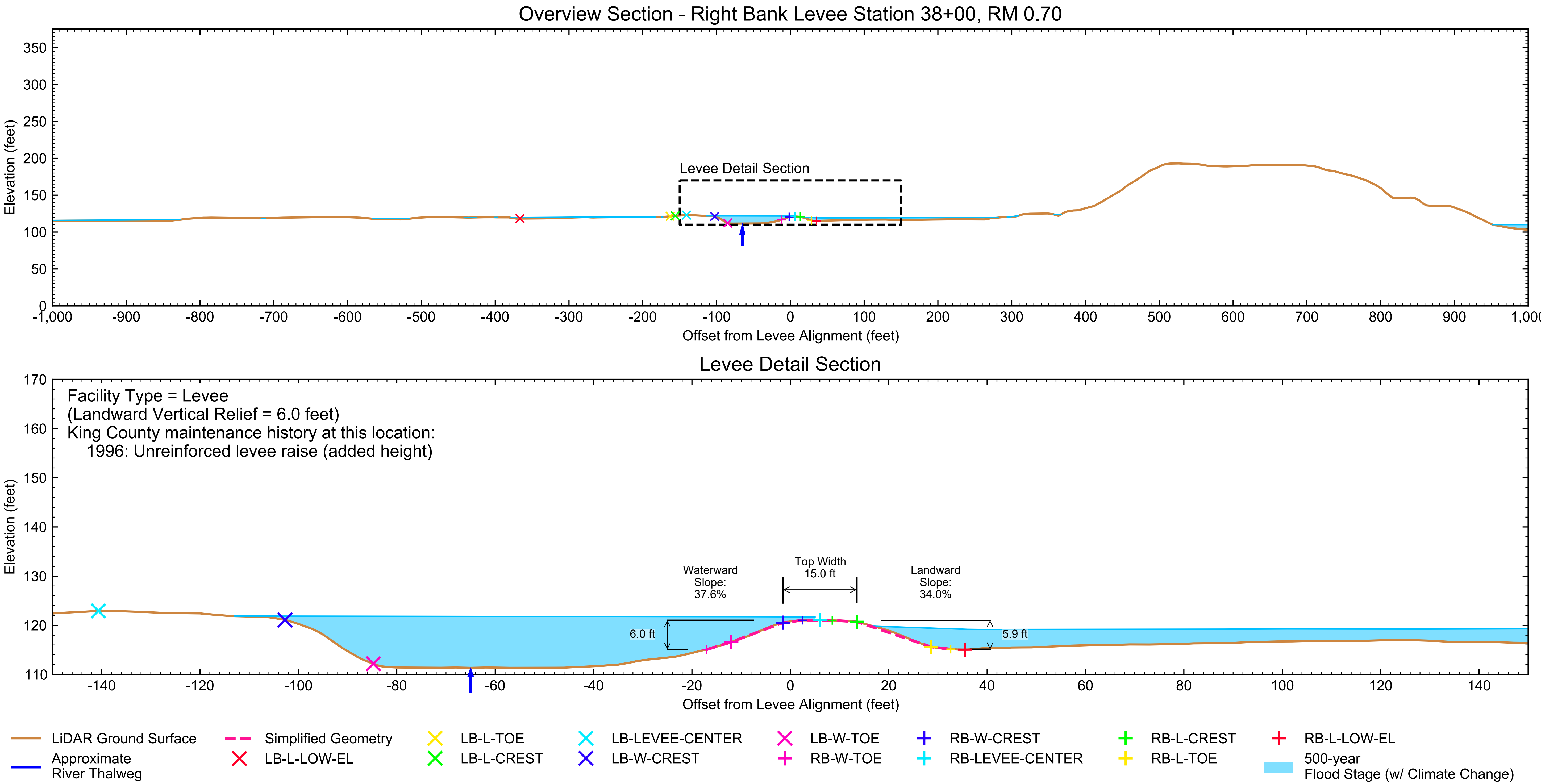
FIG. A-214



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LIDAR CROSS SECTION
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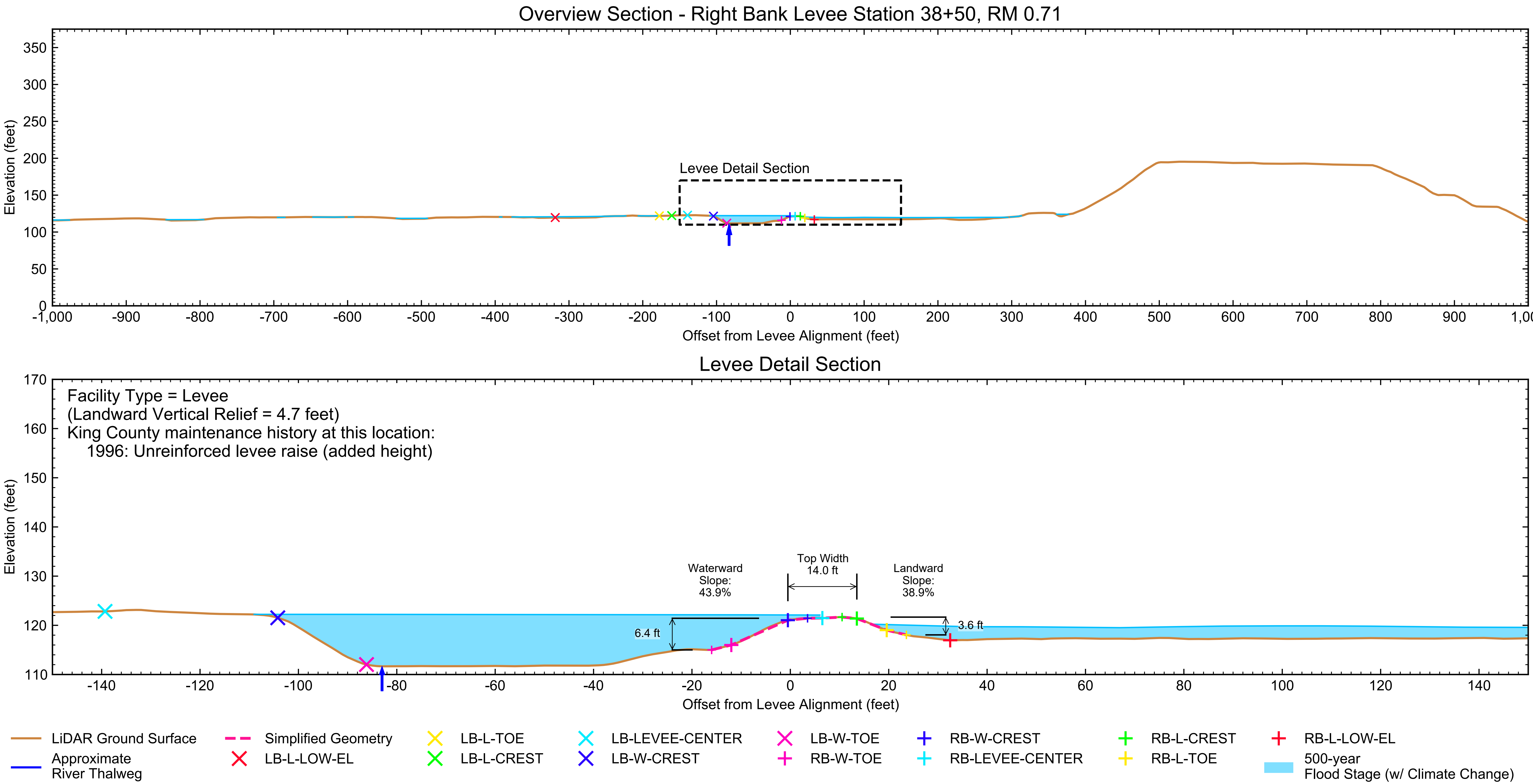
FIG. A-215



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LIDAR CROSS SECTION
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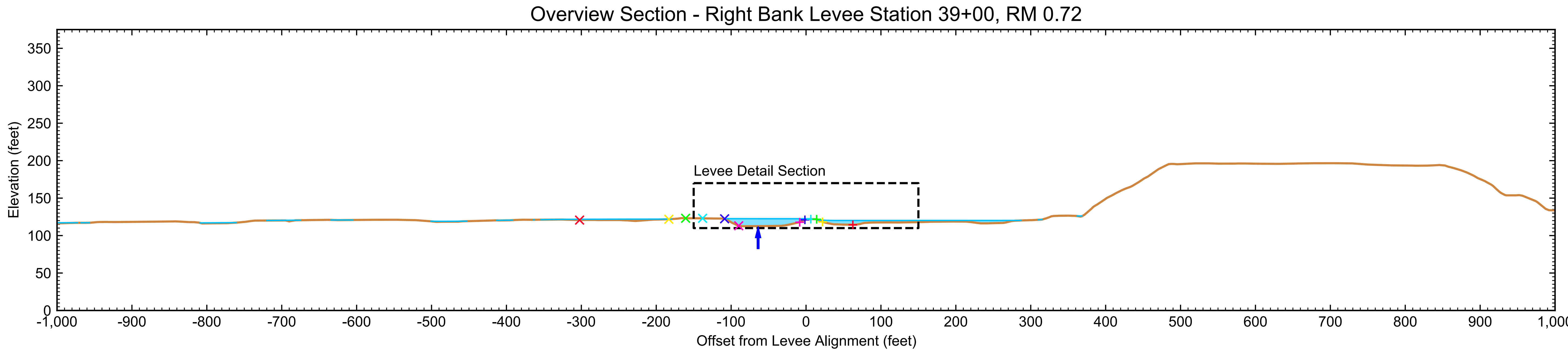
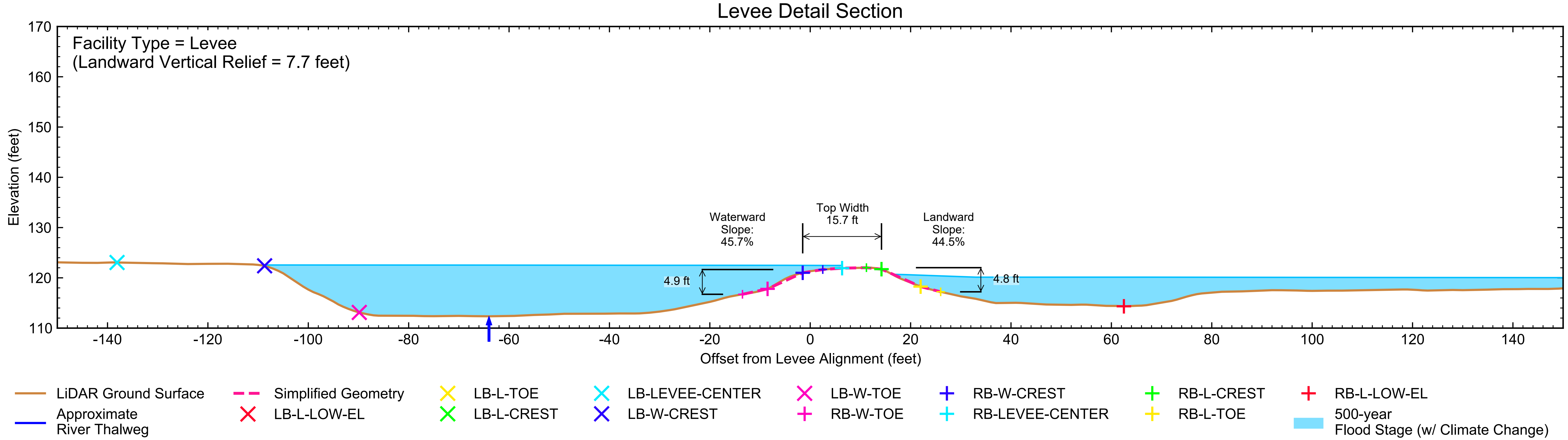
FIG. A-216





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LIDAR CROSS SECTION
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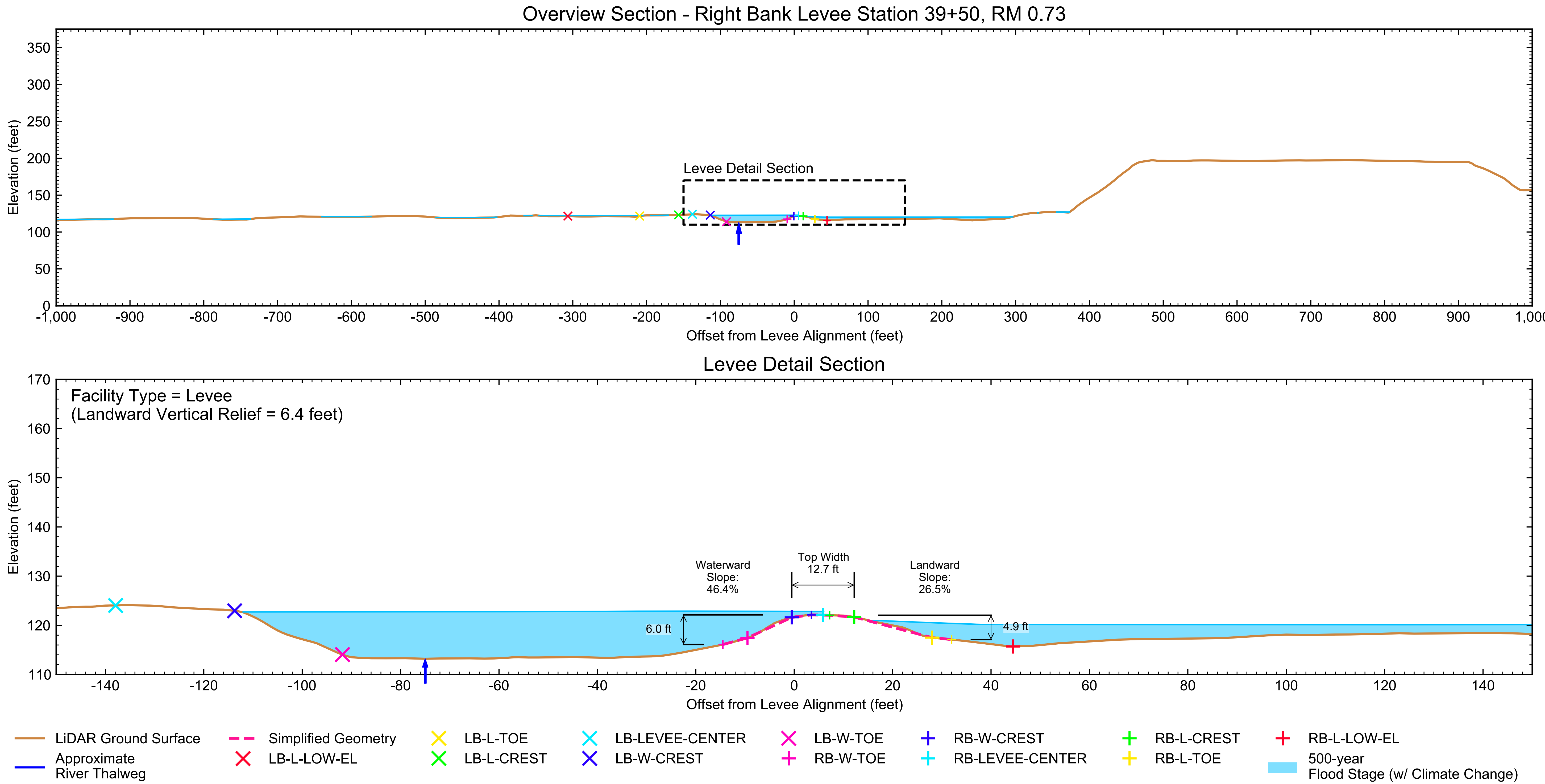
FIG. A-217



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 39+50, RM 0.73

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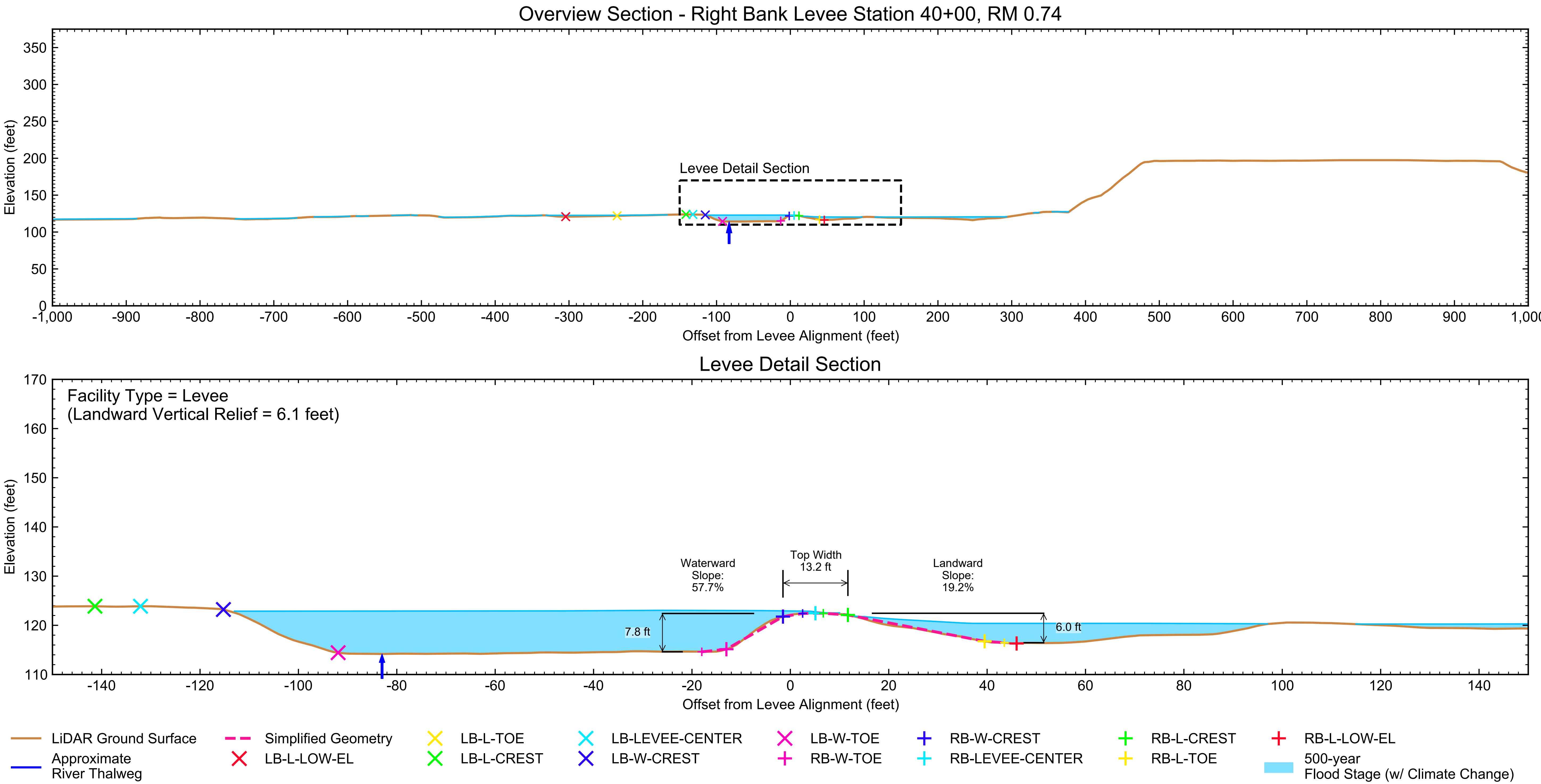
FIG. A-218



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 40+00, RM 0.74

April 2022 | 103692-304

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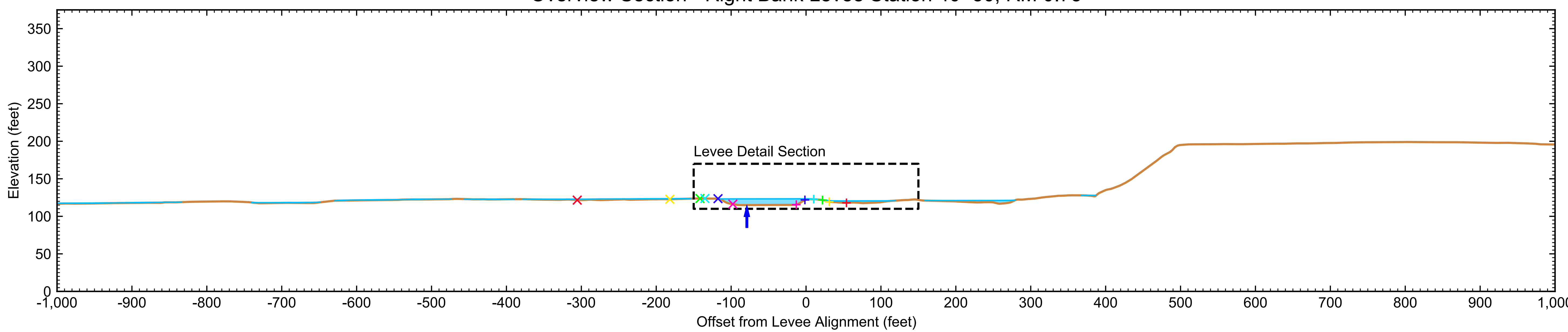
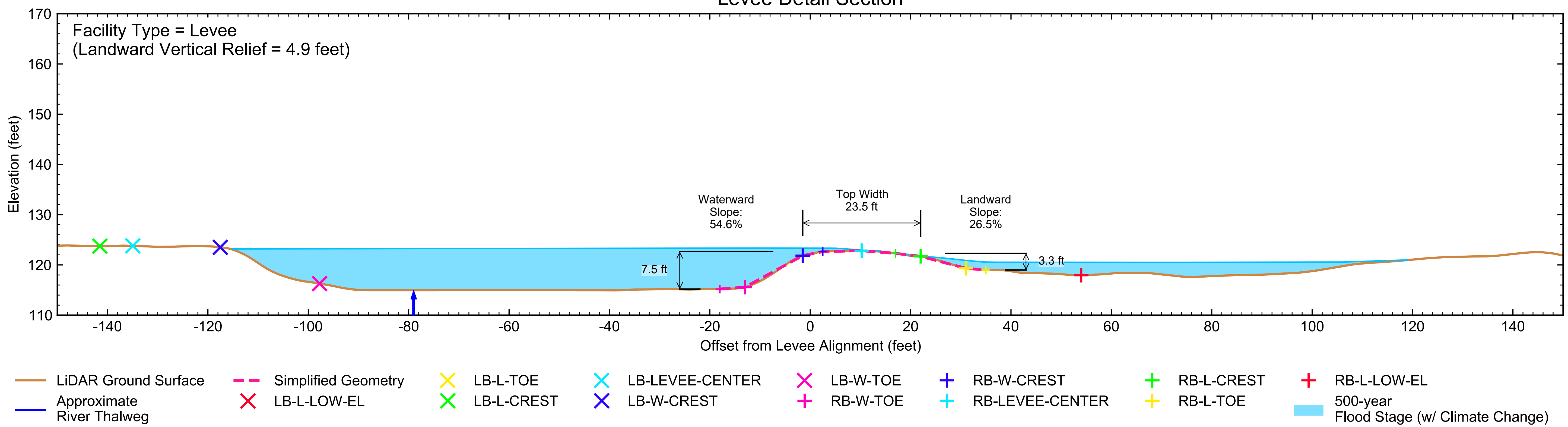
FIG. A-219

Overview Section - Right Bank Levee Station 40+50, RM 0.75



Levee Detail Section



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 40+50, RM 0.75

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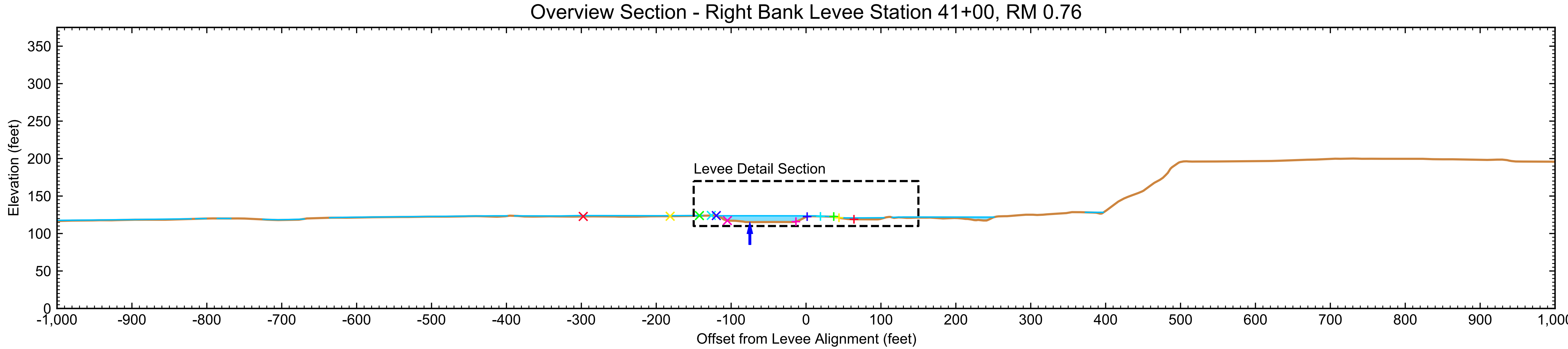
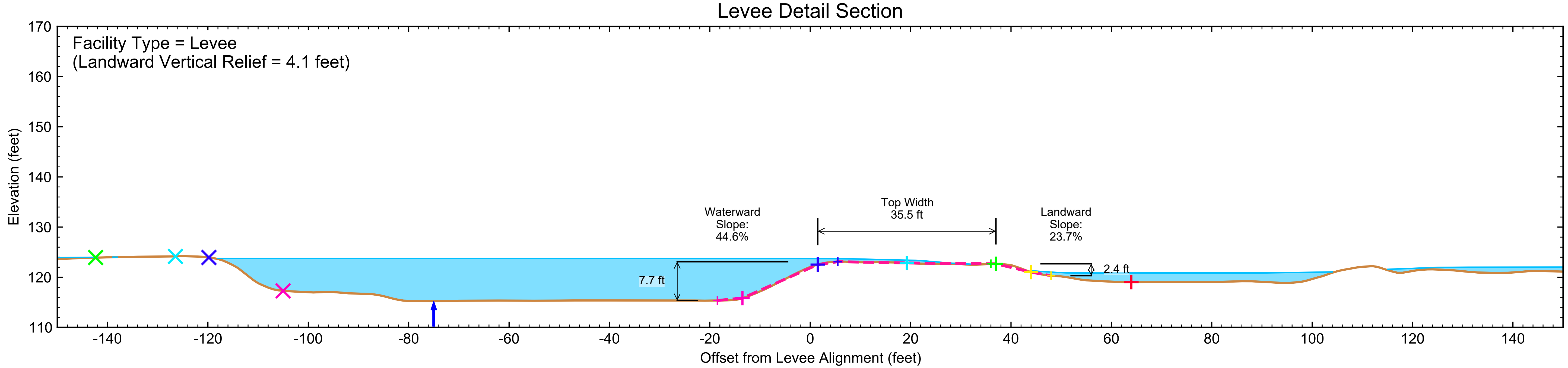
FIG. A-220





- LiDAR Ground Surface
- Approximate River Thalweg
- Simplified Geometry
- LB-L-LOW-EL
- LB-L-TOE
- LB-L-CREST
- LB-LEVEE-CENTER
- LB-W-CREST
- LB-W-TOE
- RB-W-TOE
- RB-W-CREST
- RB-LEVEE-CENTER
- RB-L-CREST
- RB-L-TOE
- RB-L-LOW-EL
- 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 41+00, RM 0.76

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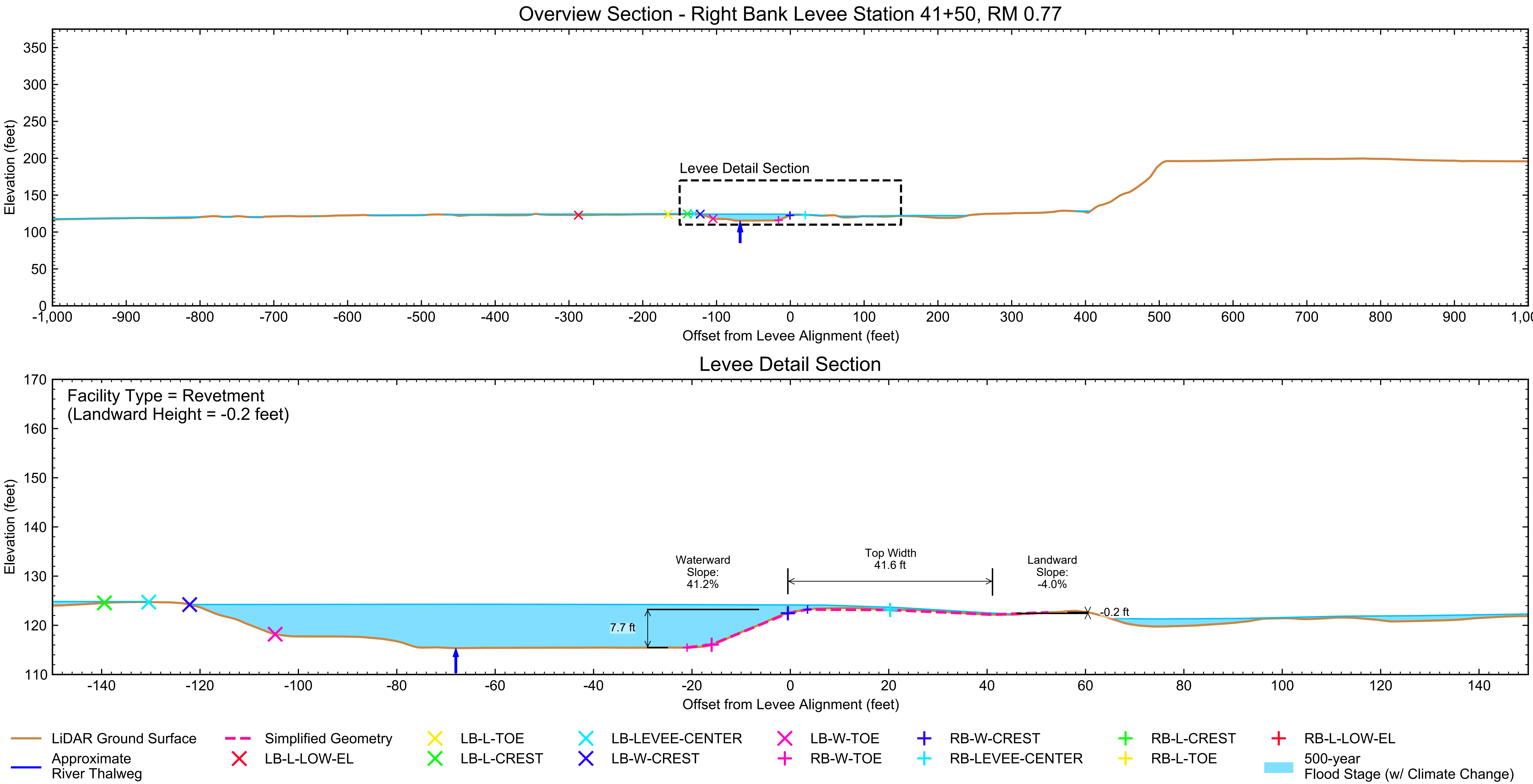
FIG. A-221



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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 41+50, RM 0.77

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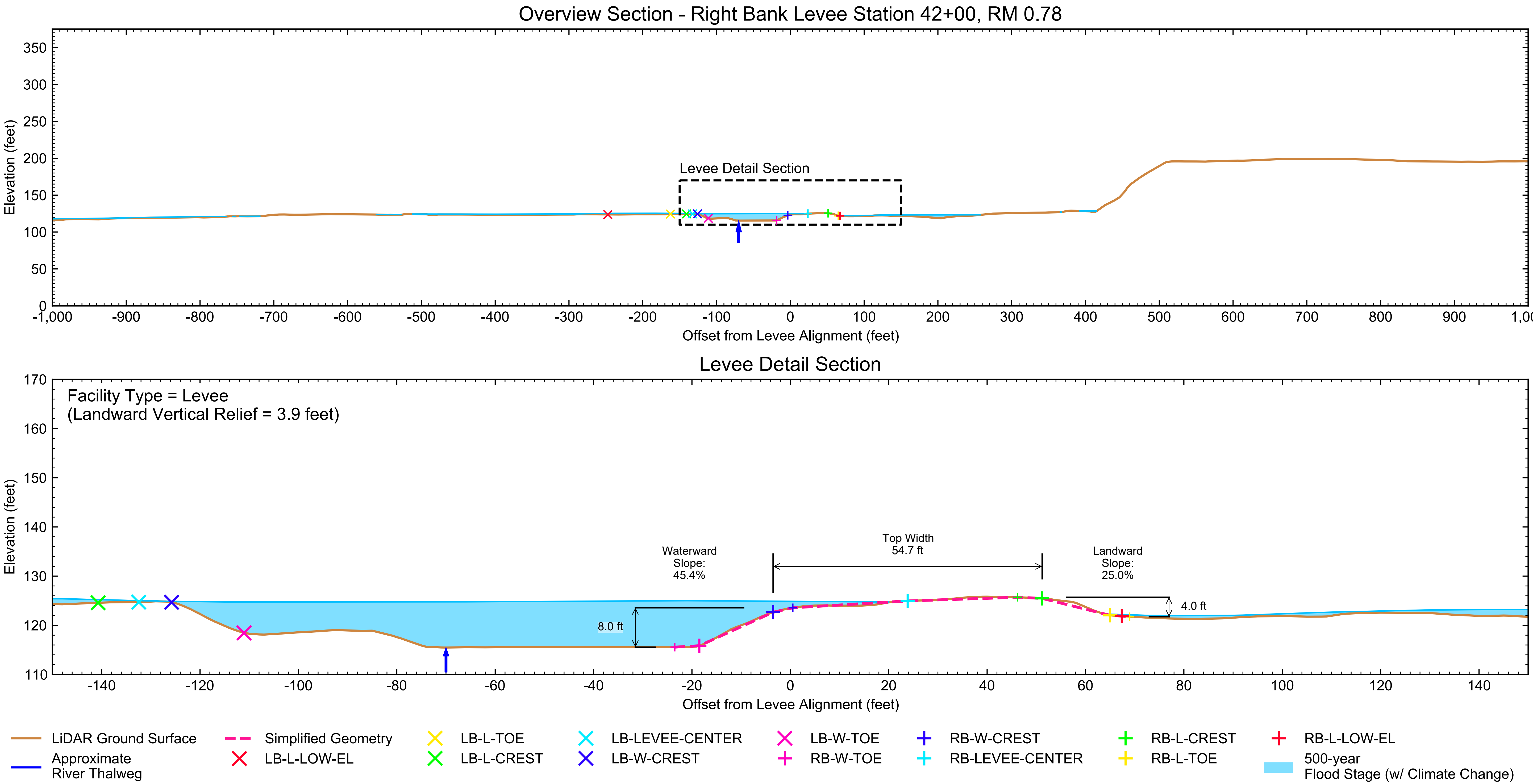
FIG. A-222



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 42+00, RM 0.78

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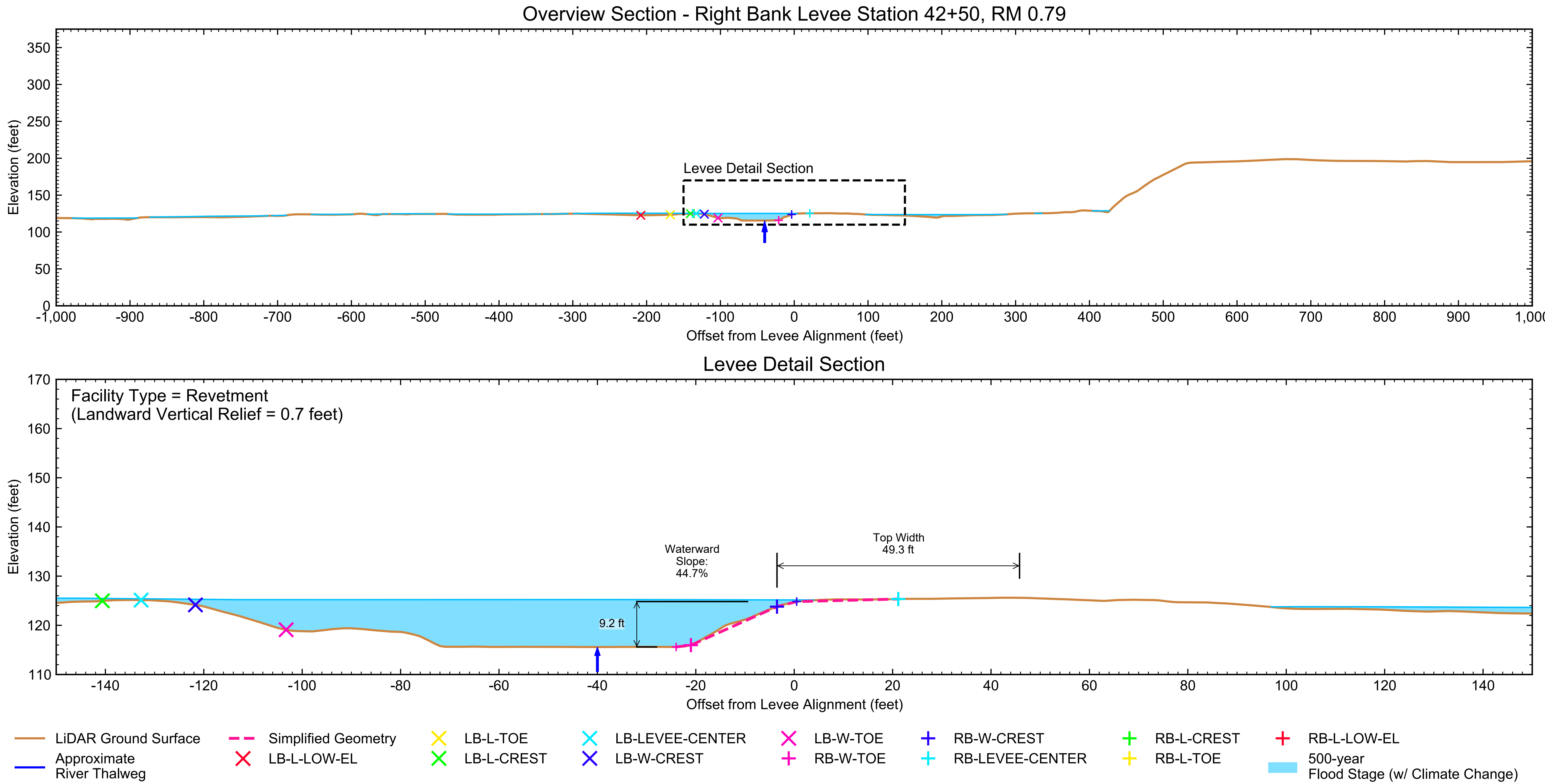
FIG. A-223



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 42+50, RM 0.79

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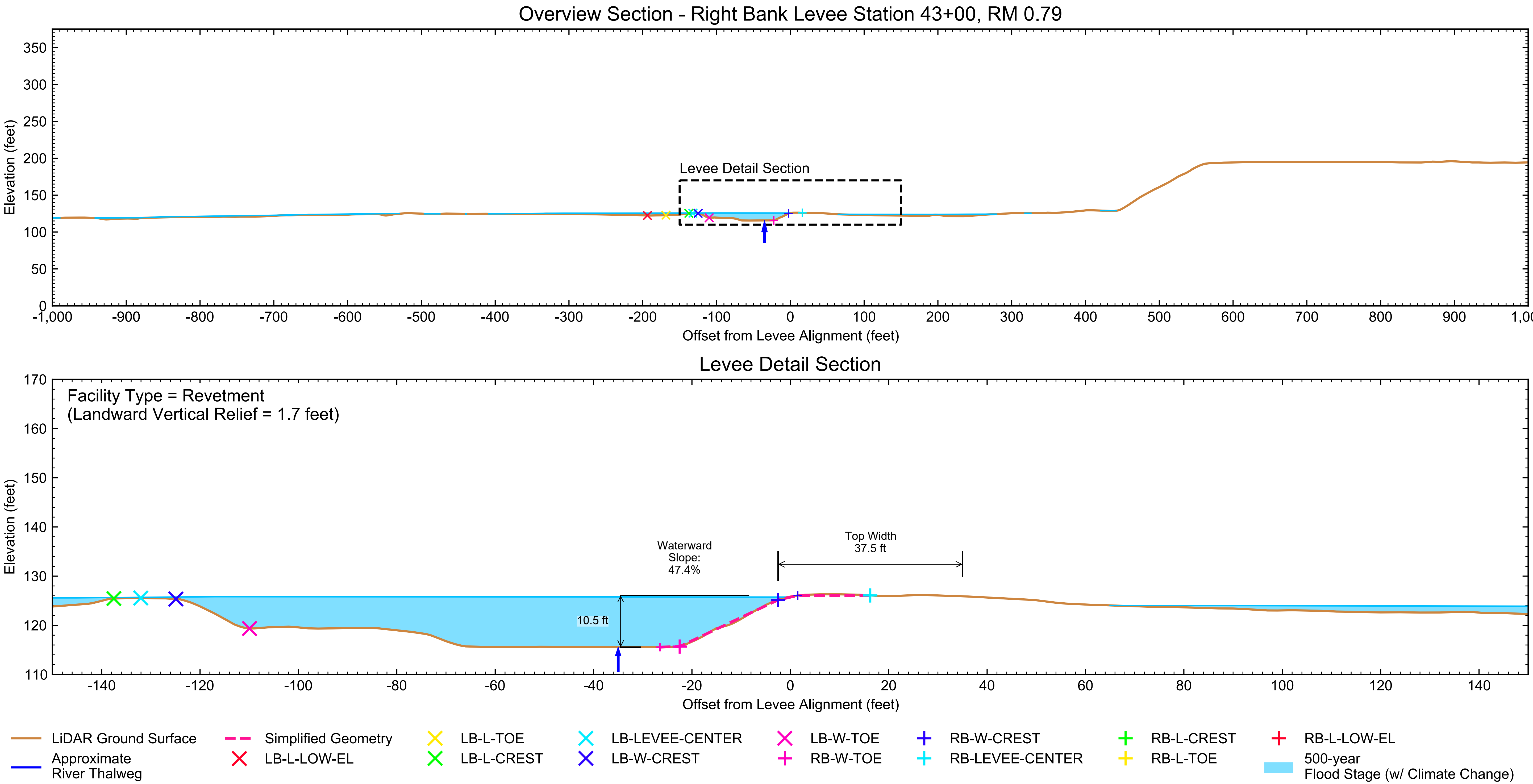
FIG. A-224



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Levee Breach Analysis Mapping and Risk Assessment
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 43+00, RM 0.79

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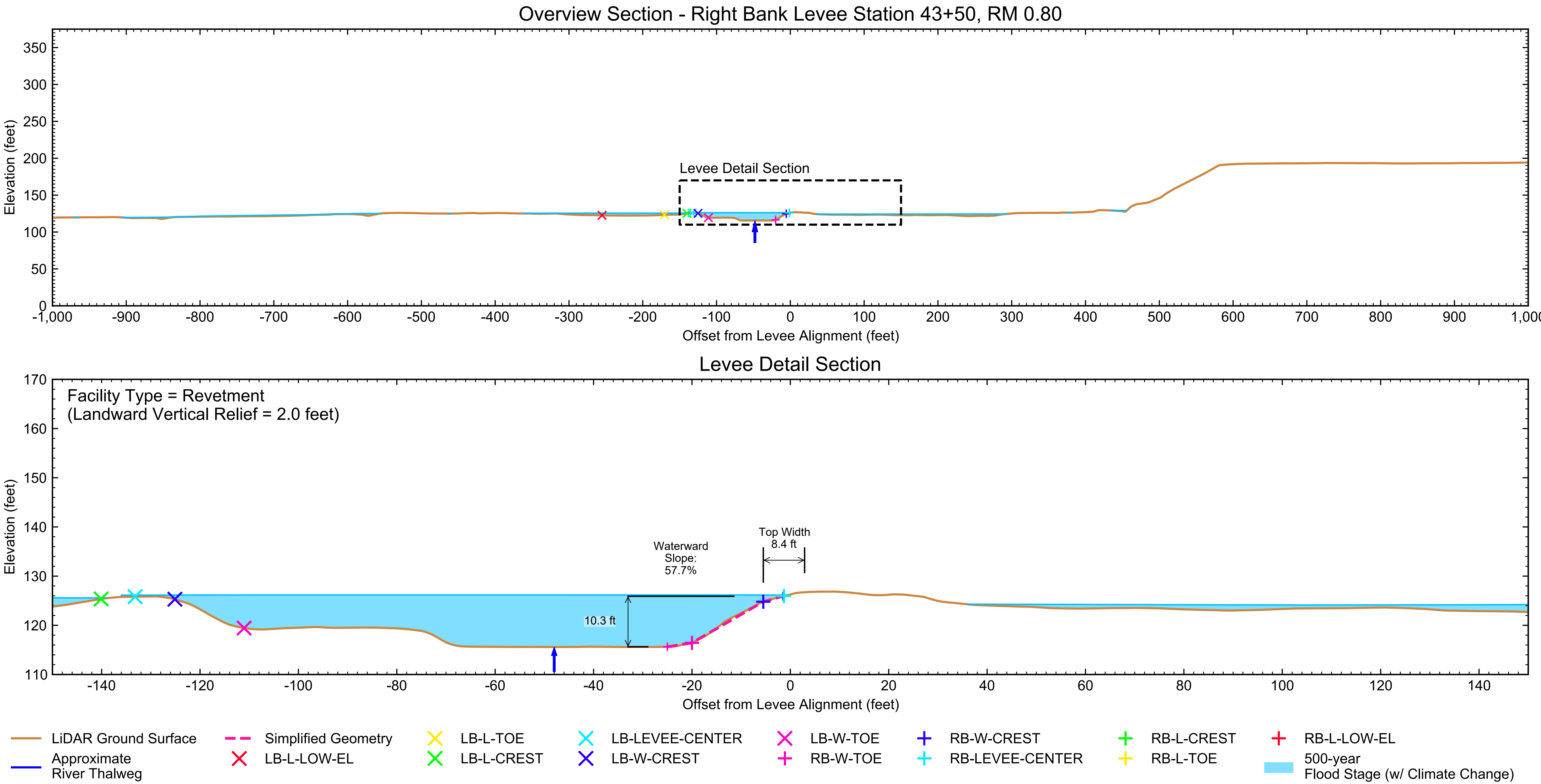
FIG. A-225



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 43+50, RM 0.80

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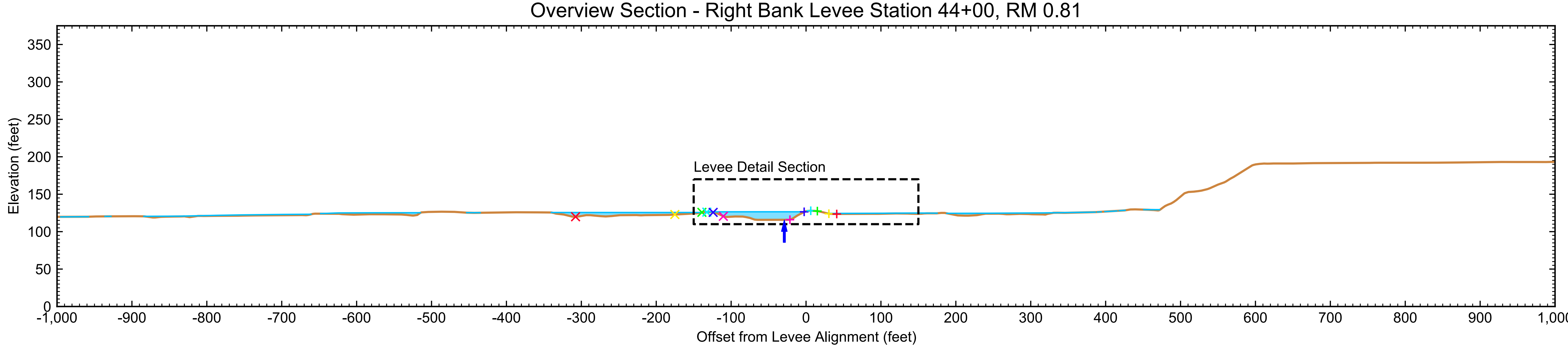
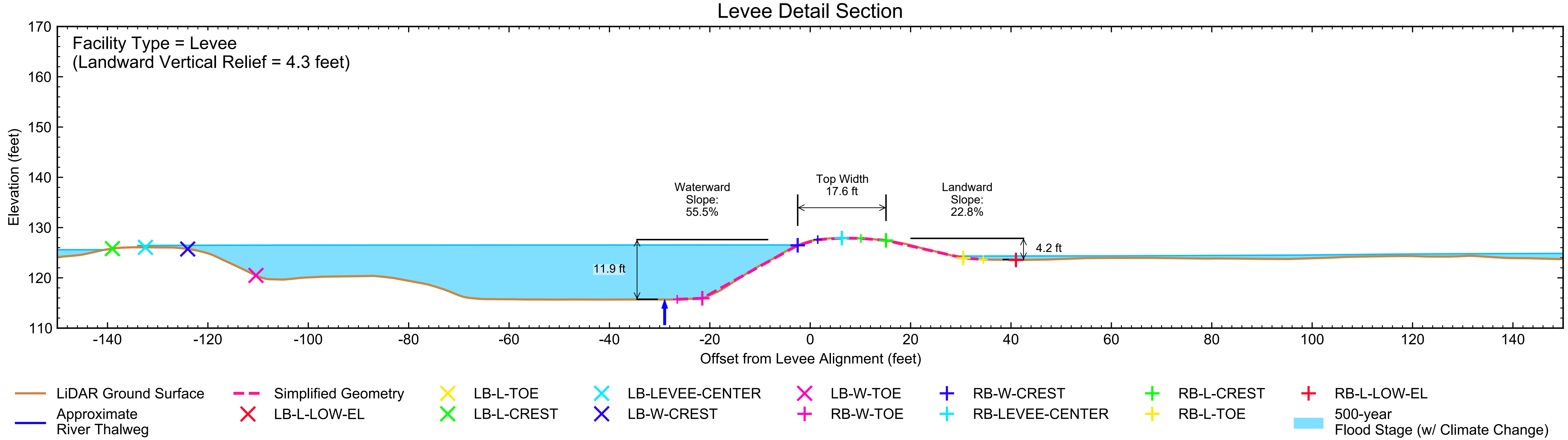
FIG. A-226





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LIDAR CROSS SECTION
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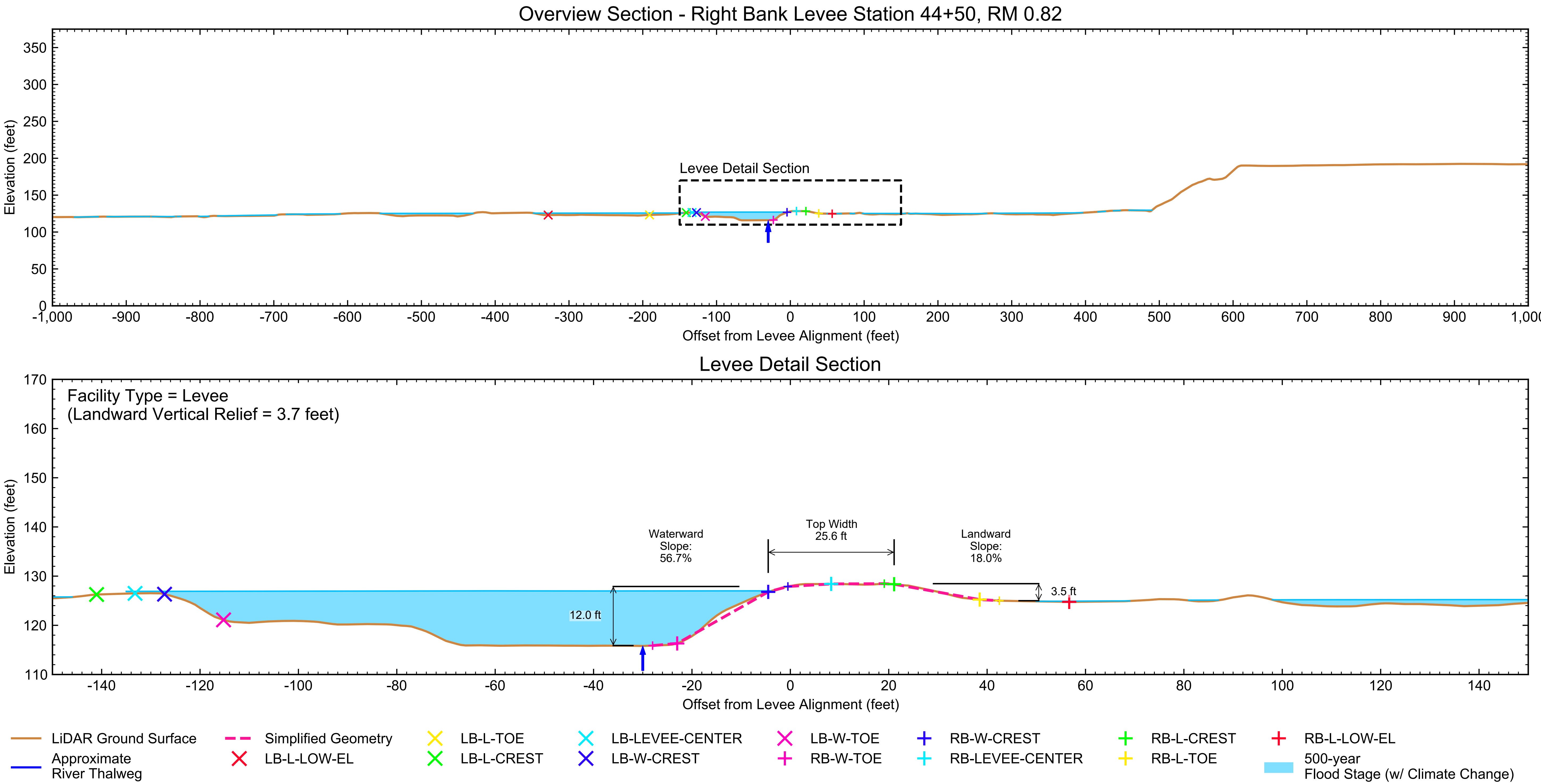
FIG. A-227



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LIDAR CROSS SECTION
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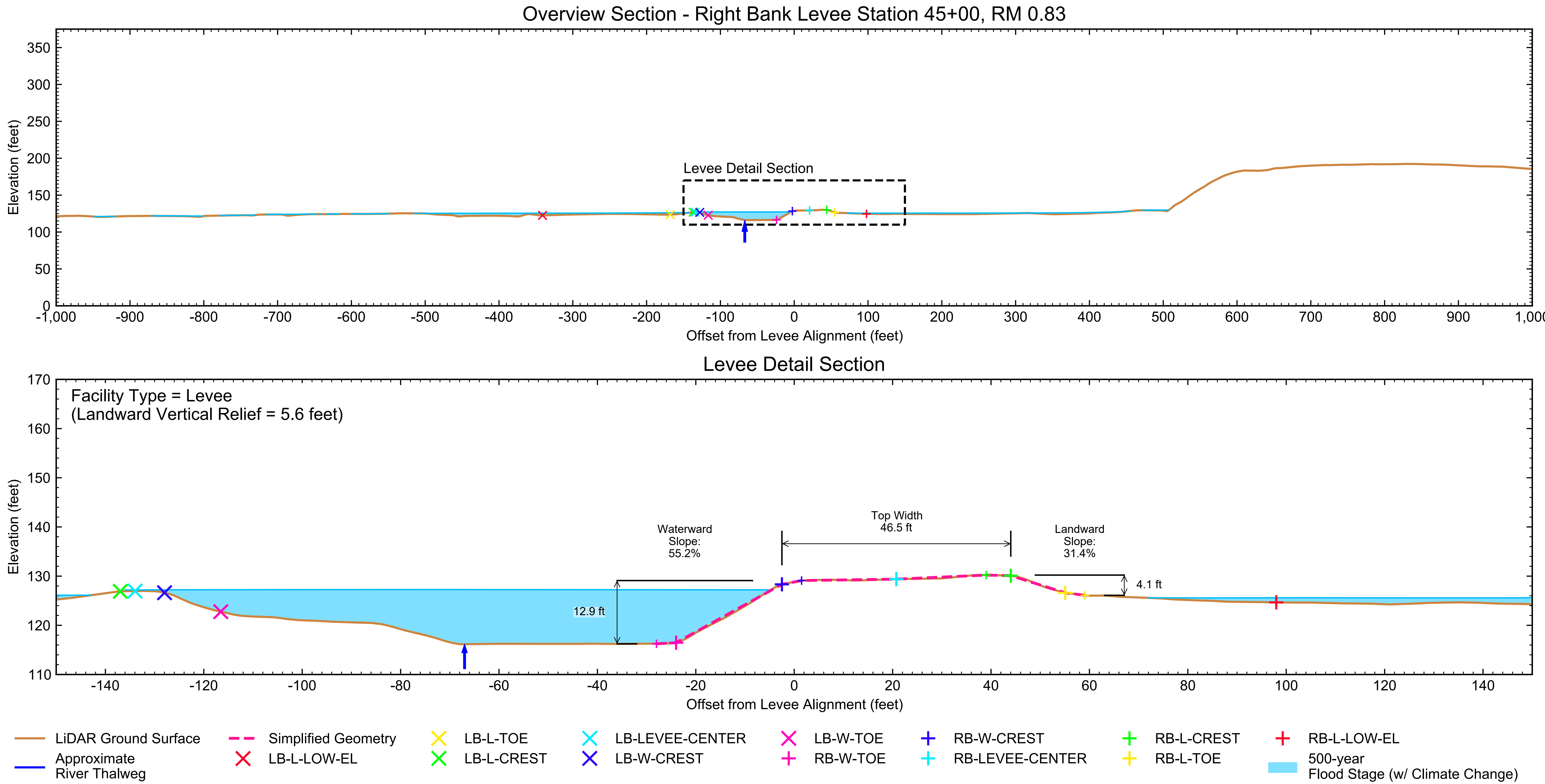
FIG. A-228



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 45+00, RM 0.83

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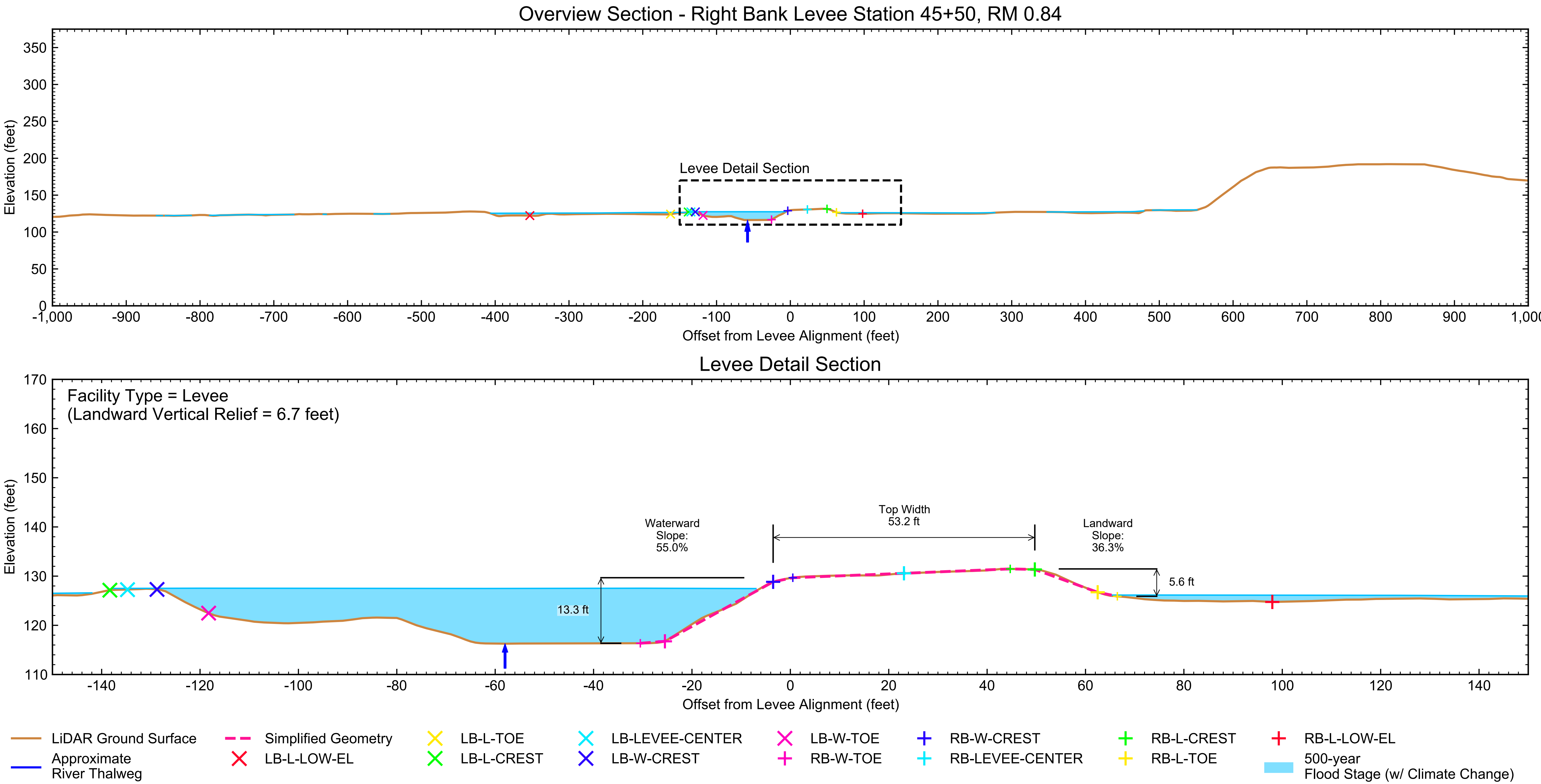
FIG. A-229



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LIDAR CROSS SECTION
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RIGHT BANK STA 45+50, RM 0.84

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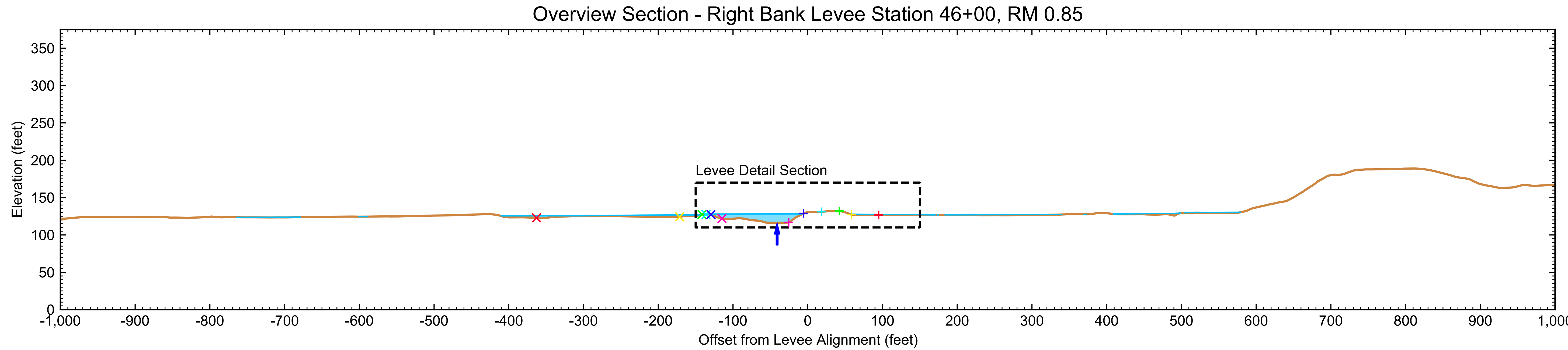
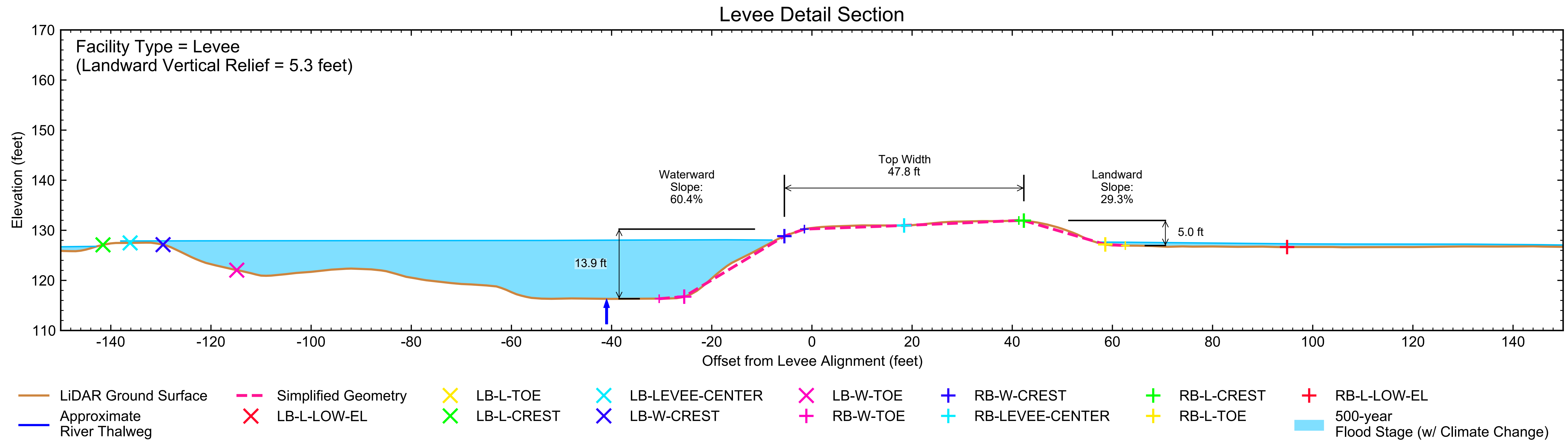
SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. A-230





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 46+00, RM 0.85

April 2022 | 103692-304

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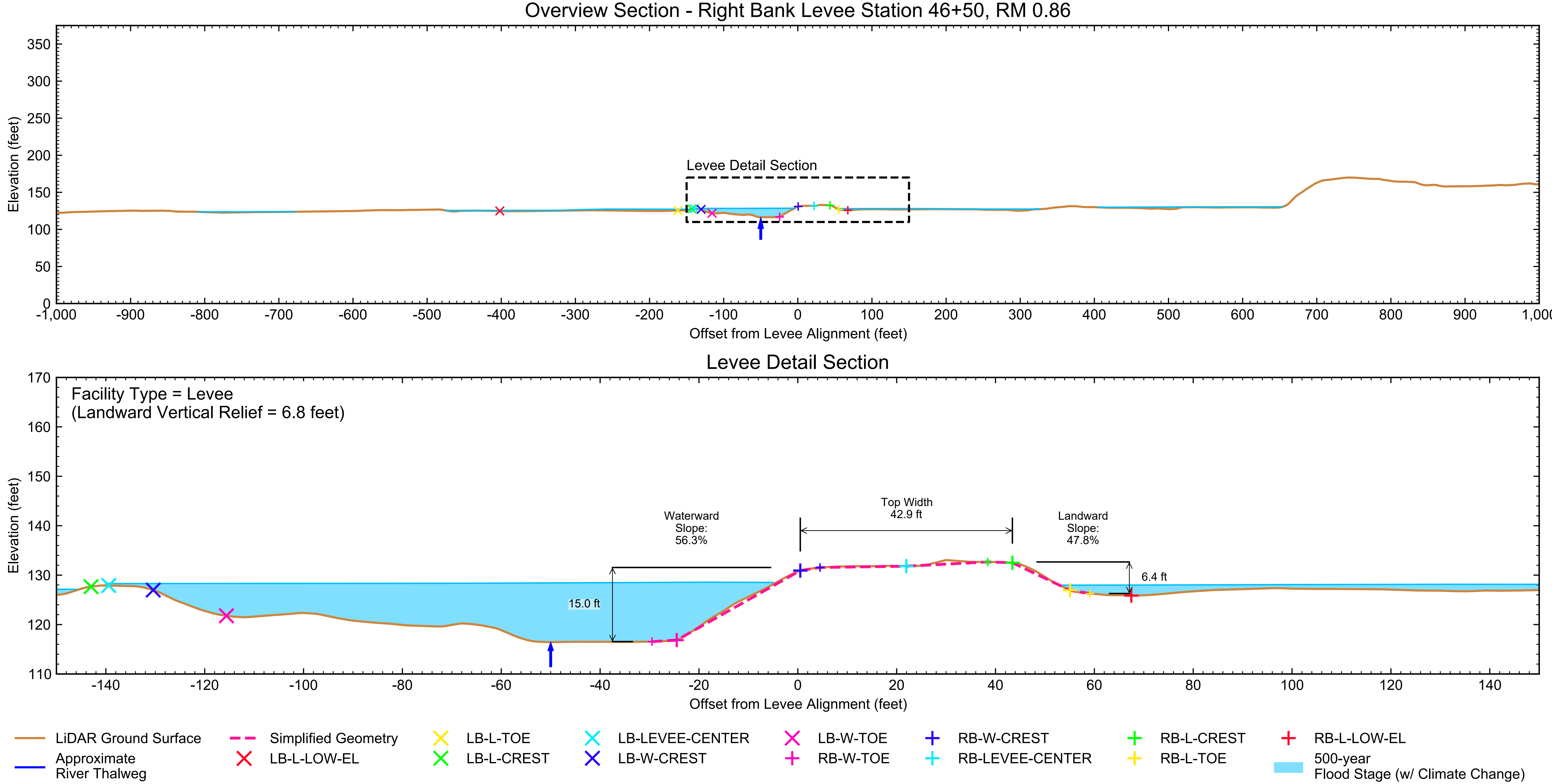
FIG. A-231



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 46+50, RM 0.86

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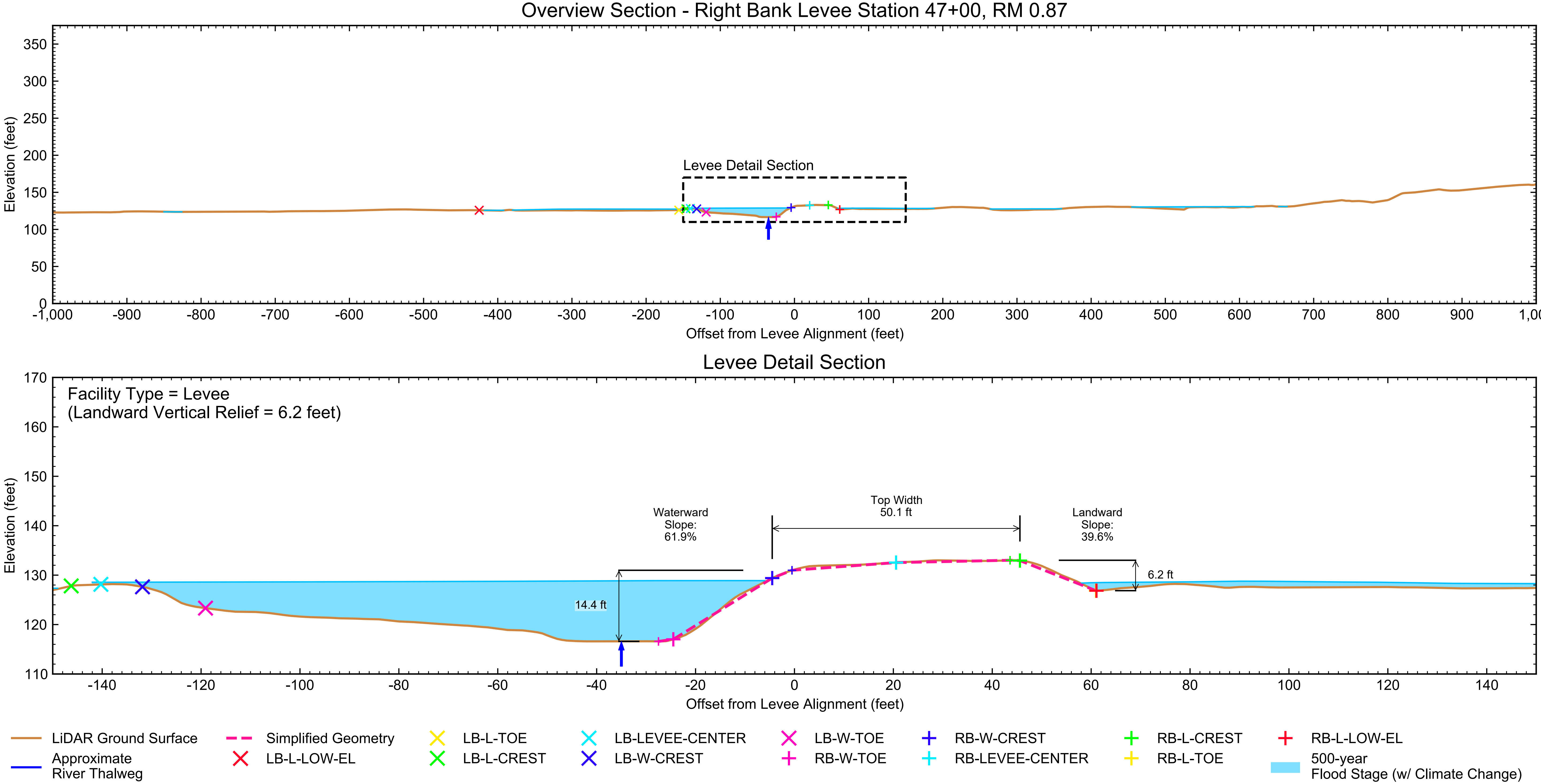
FIG. A-232



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 47+00, RM 0.87

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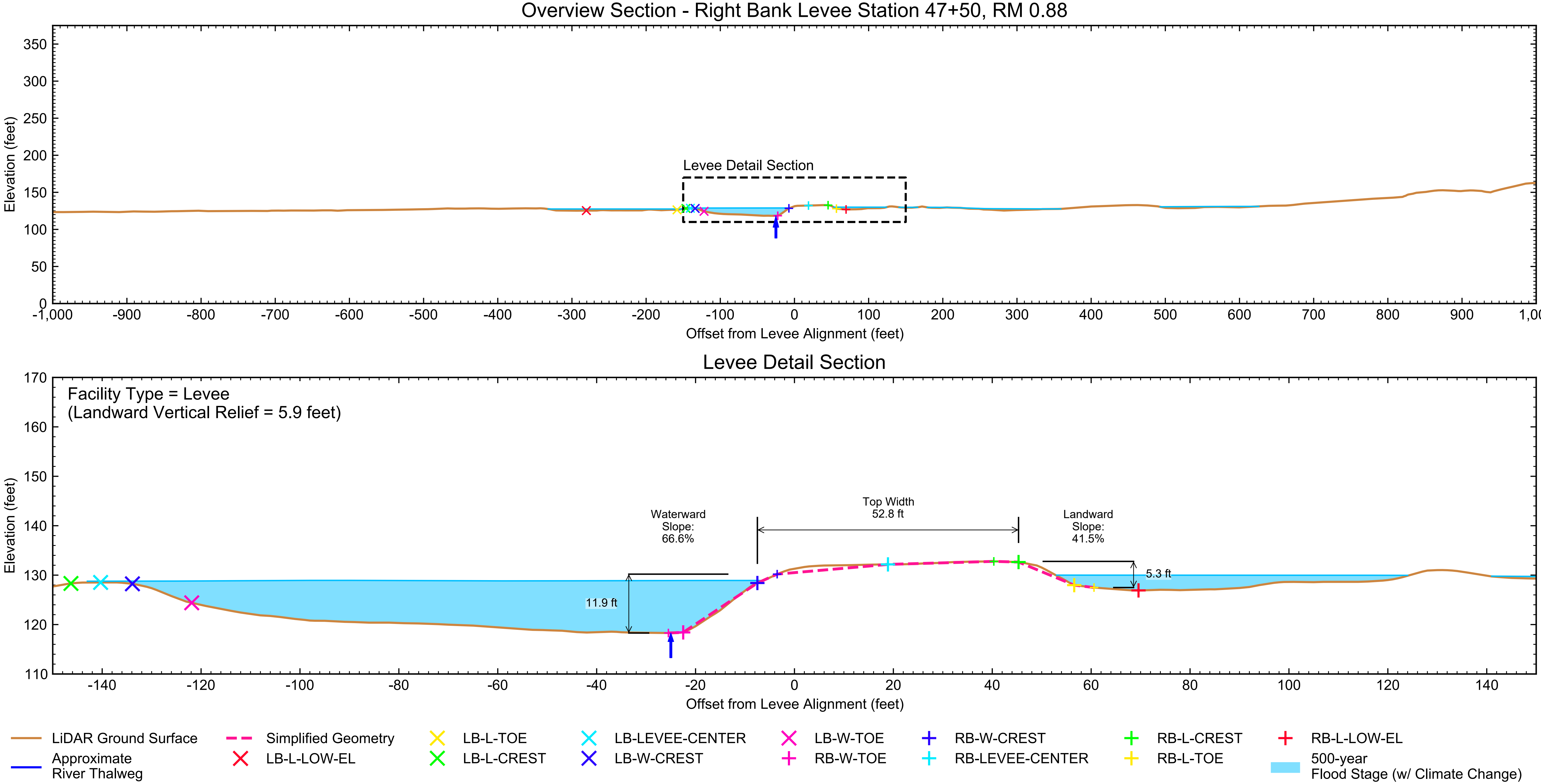
FIG. A-233



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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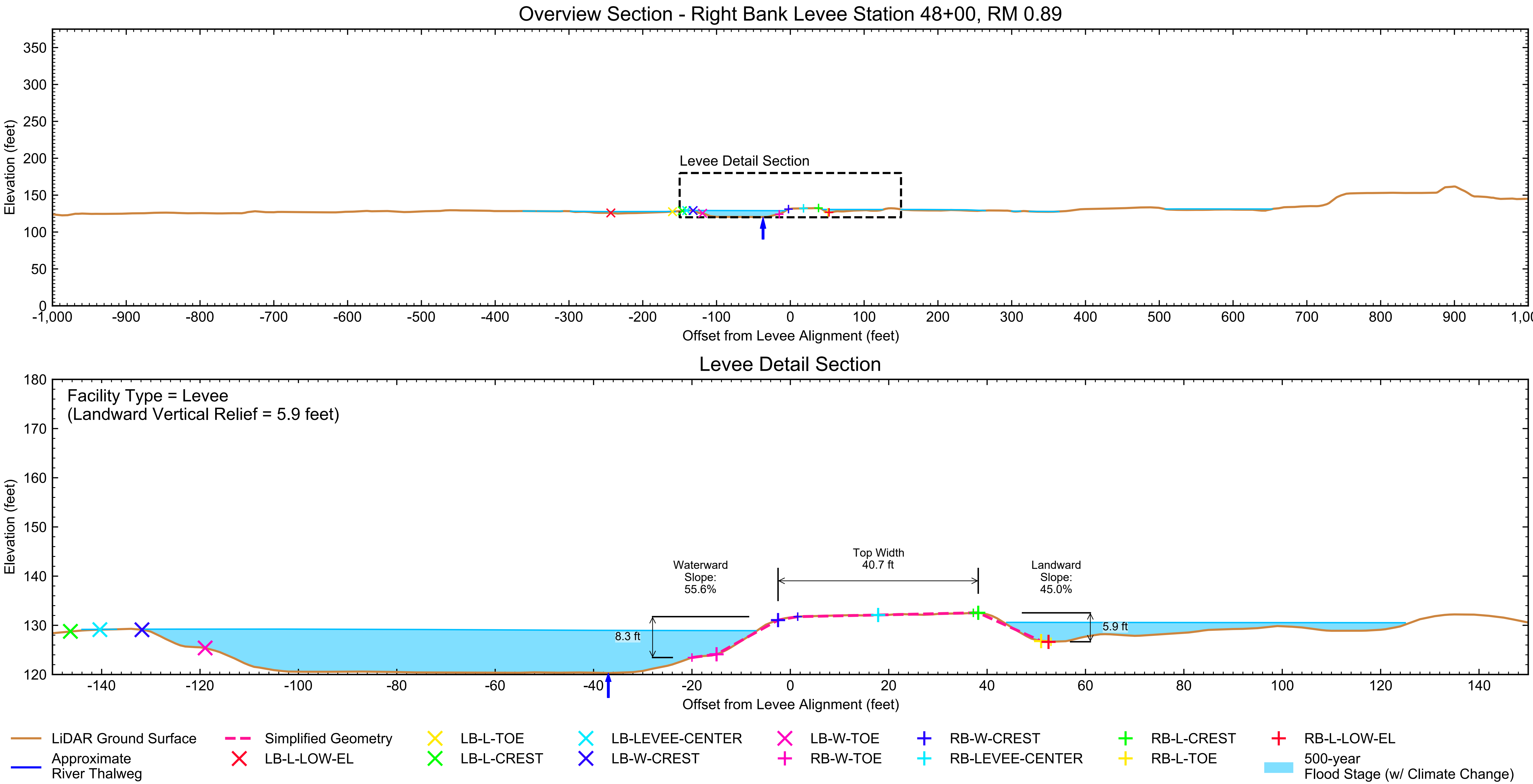
FIG. A-234



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 48+00, RM 0.89

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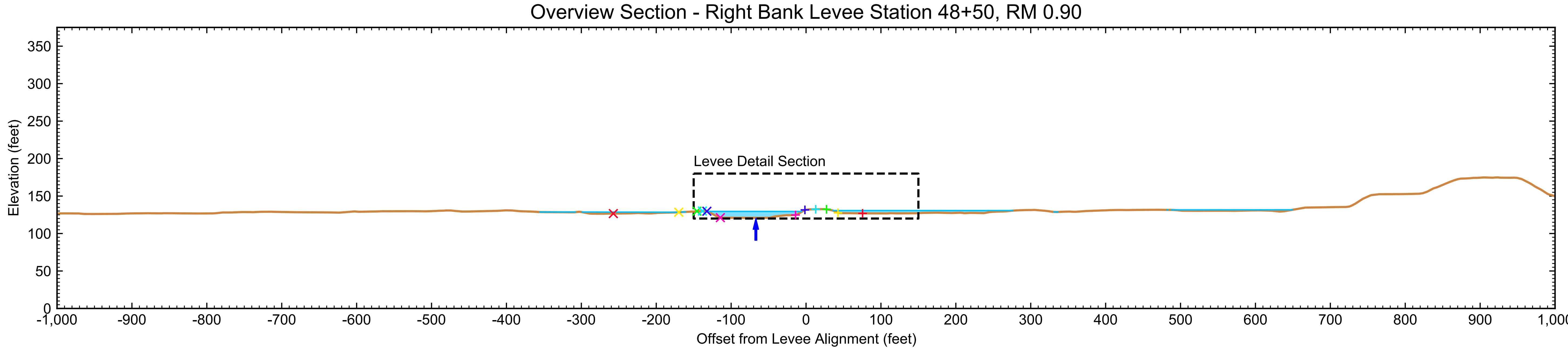
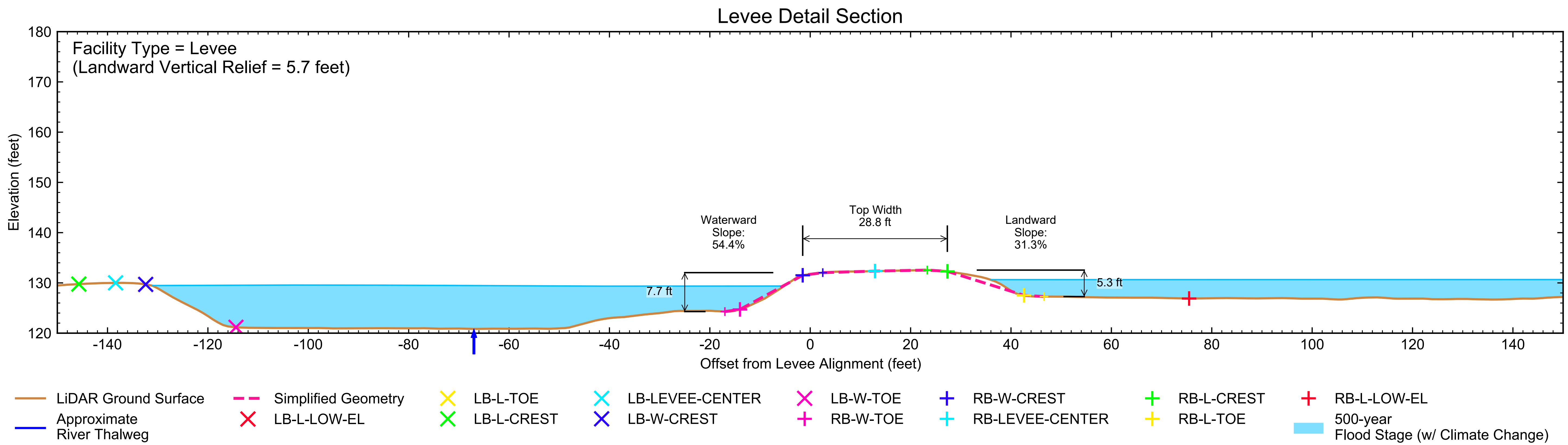
FIG. A-235





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 48+50, RM 0.90

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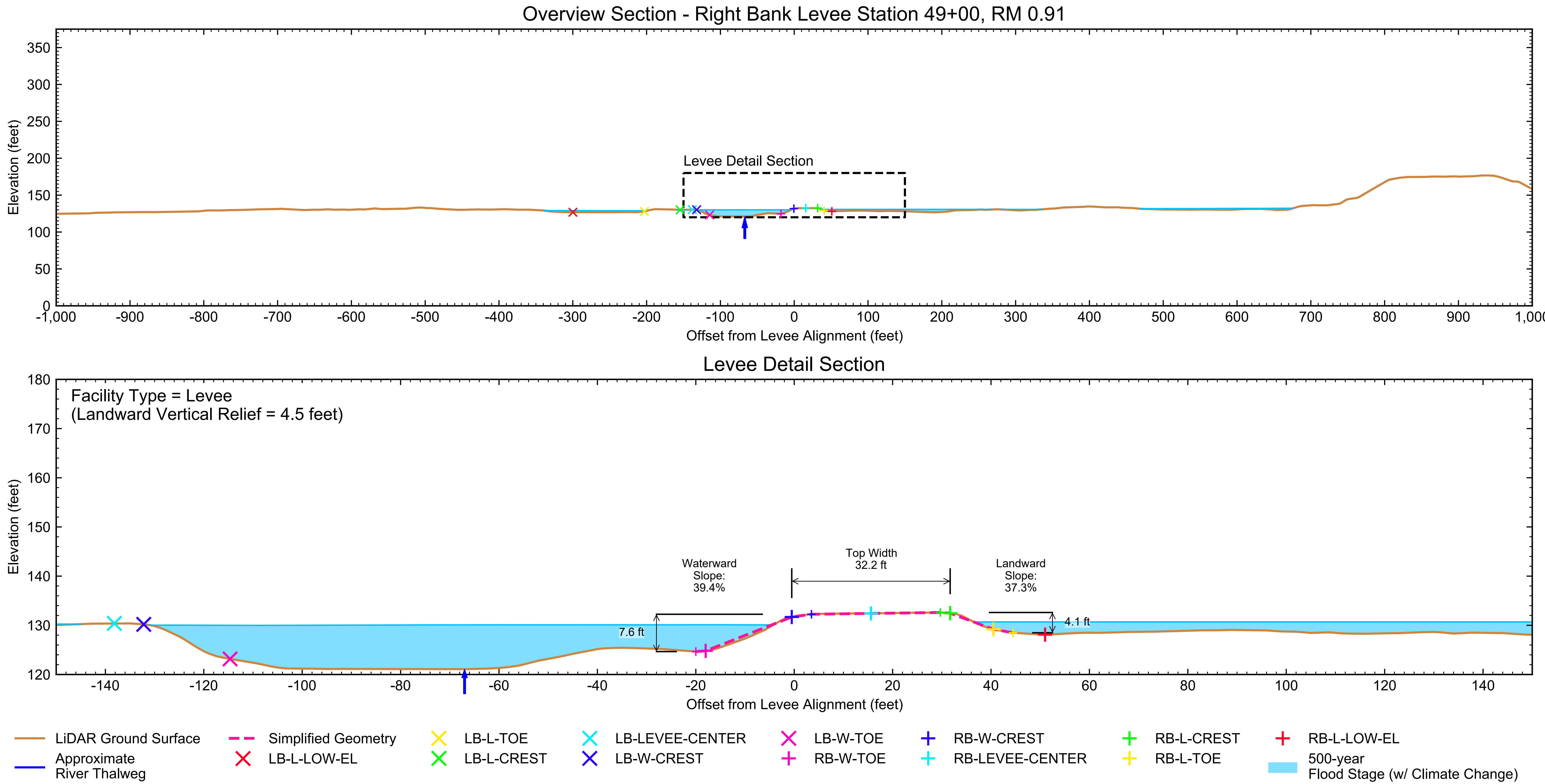
FIG. A-236



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 49+00, RM 0.91

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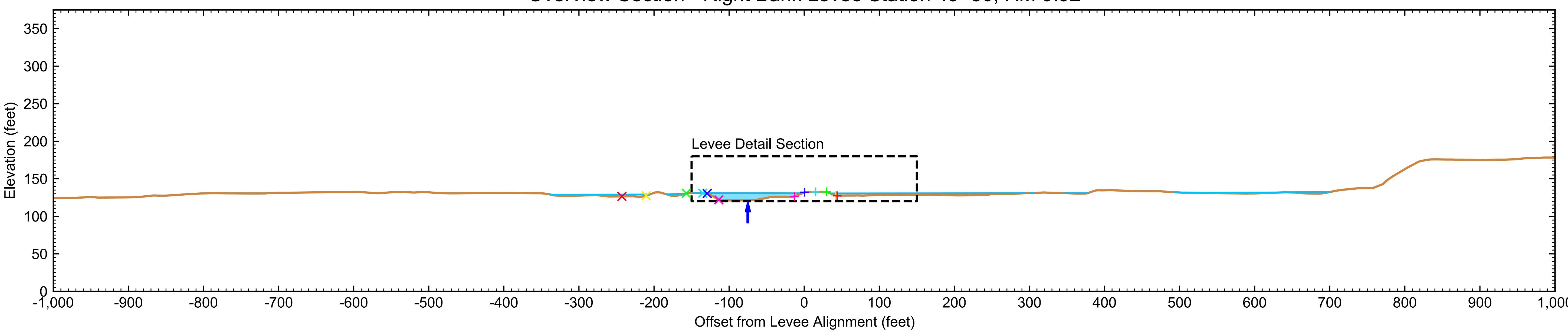
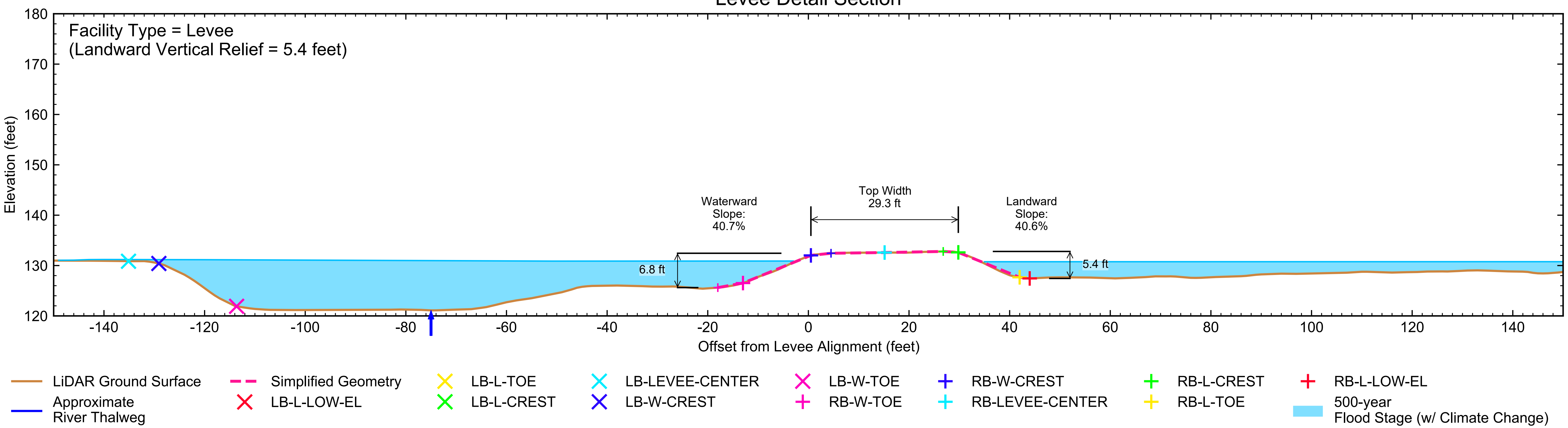
Geotechnical and Environmental Consultants

FIG. A-237

Overview Section - Right Bank Levee Station 49+50, RM 0.92



Levee Detail Section



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 49+50, RM 0.92

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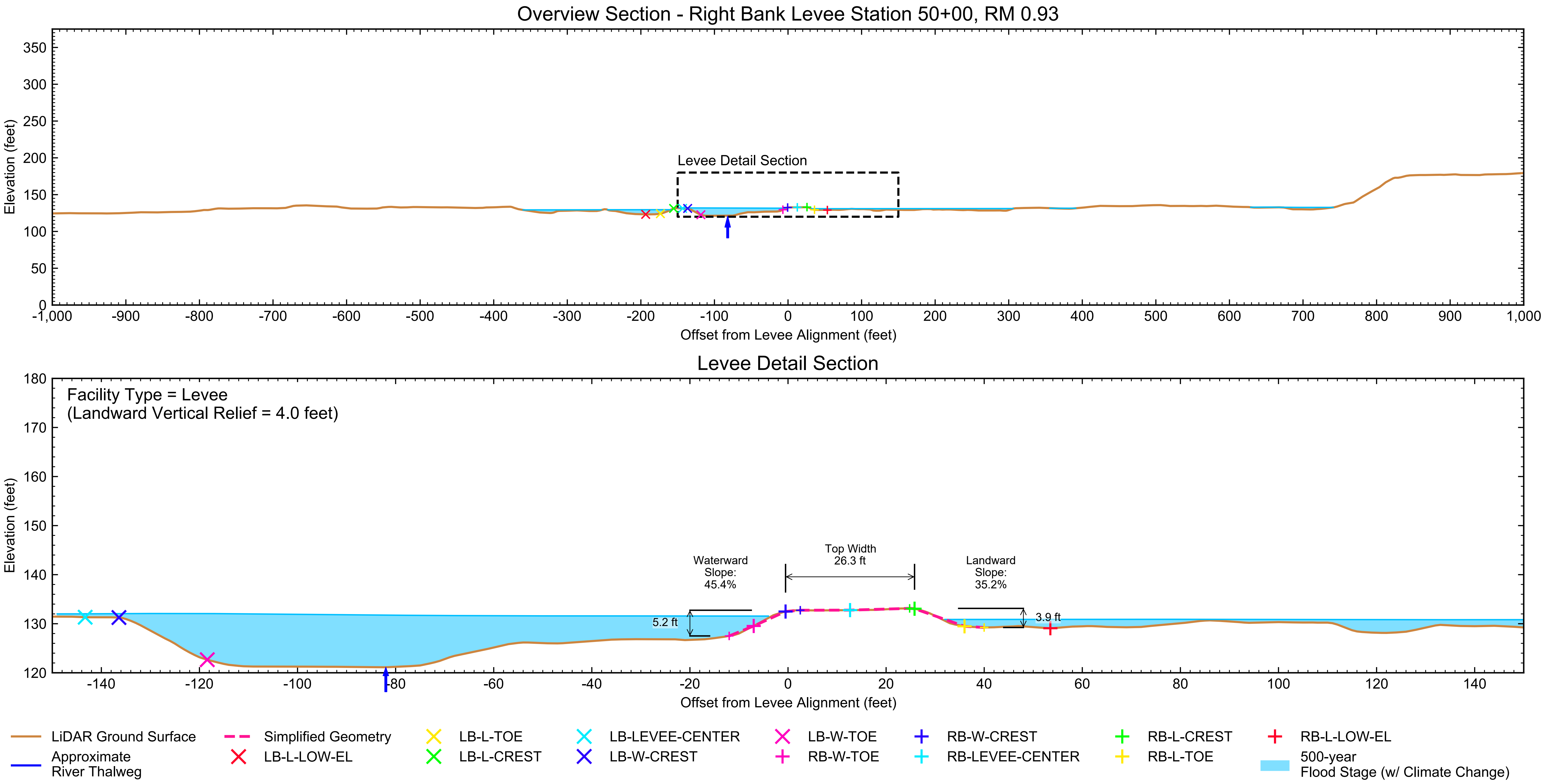
FIG. A-238



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 50+00, RM 0.93

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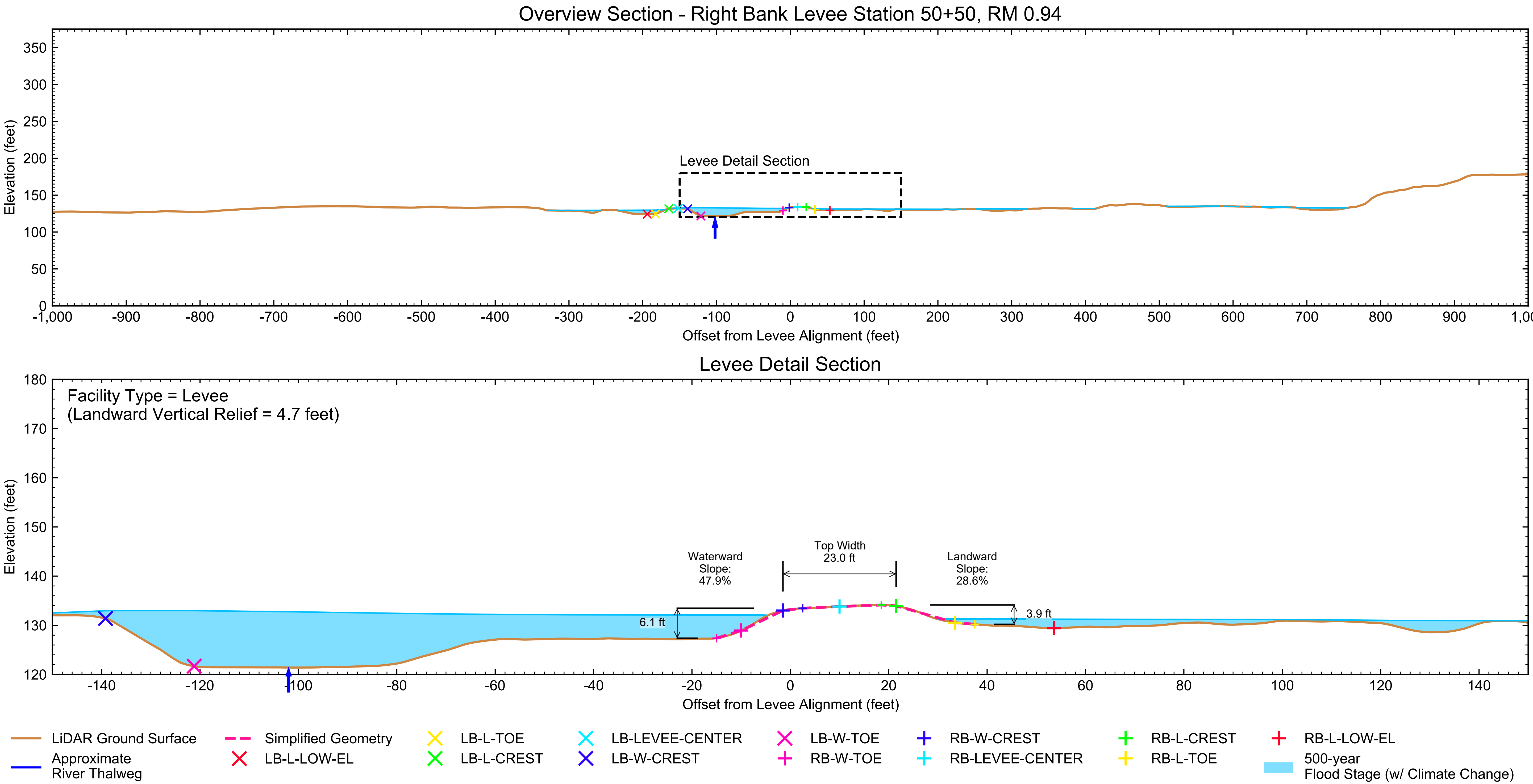
FIG. A-239



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LIDAR CROSS SECTION
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RIGHT BANK STA 50+50, RM 0.94

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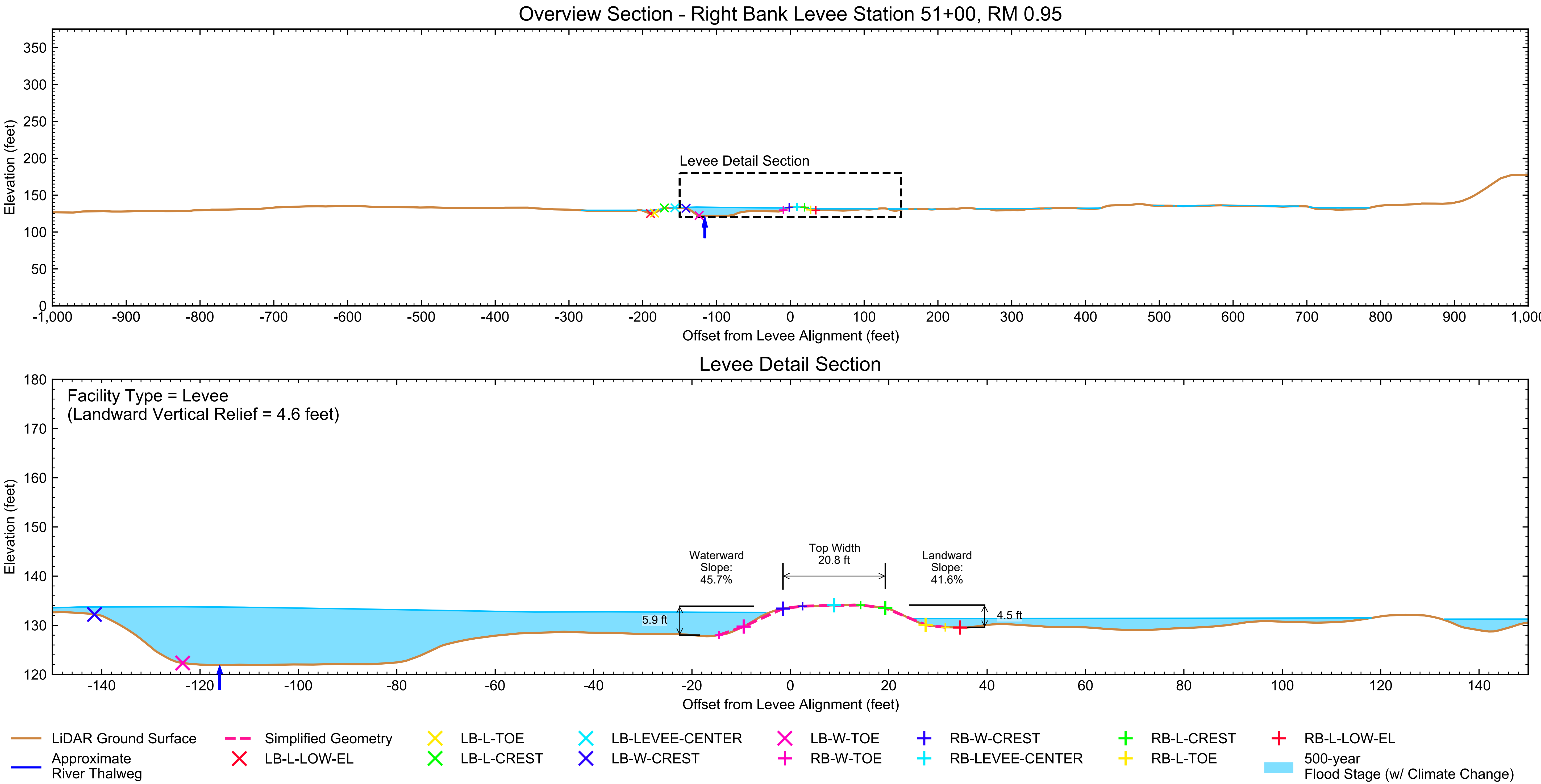
FIG. A-240



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 51+00, RM 0.95

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FIG. A-241

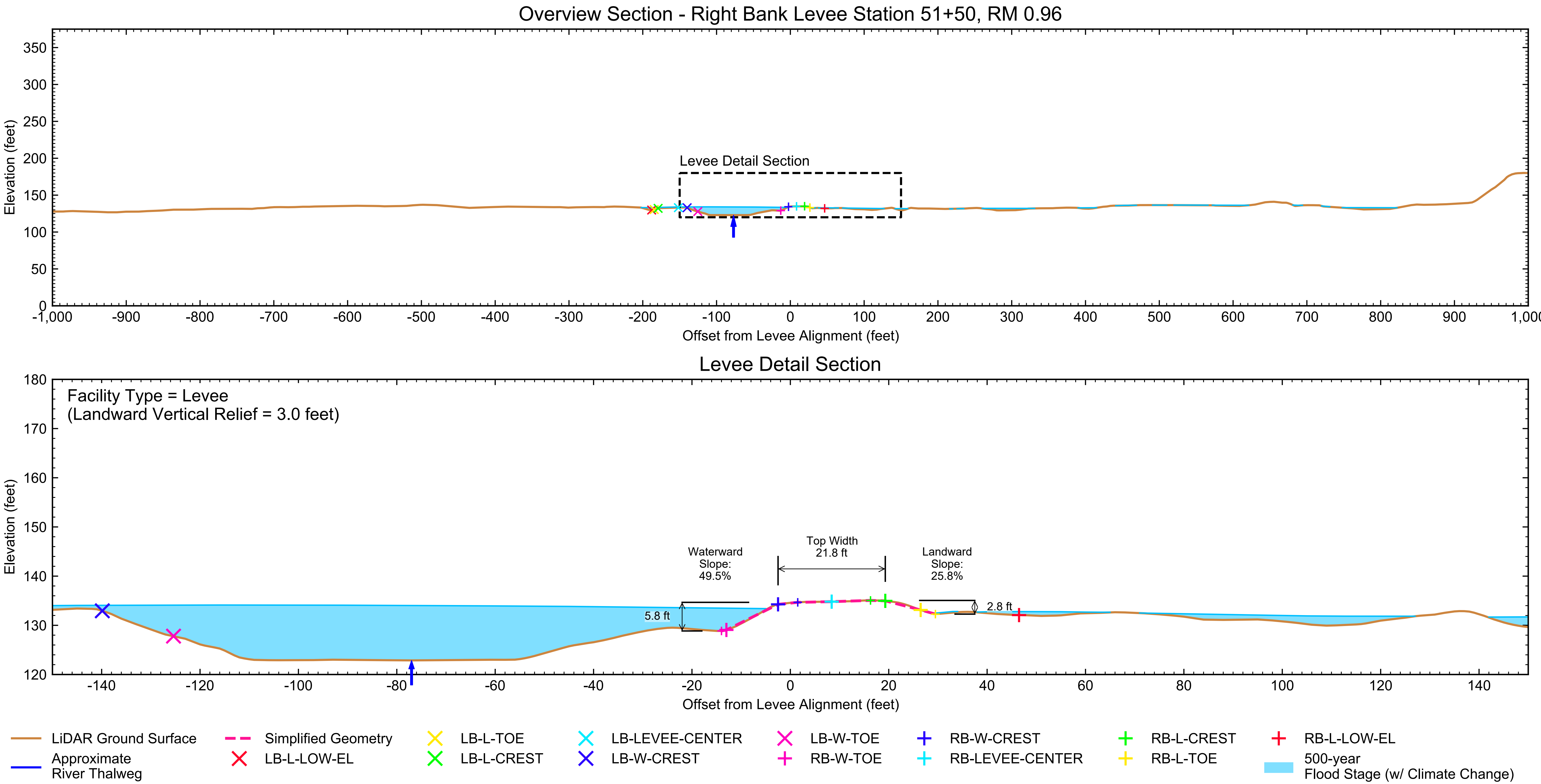

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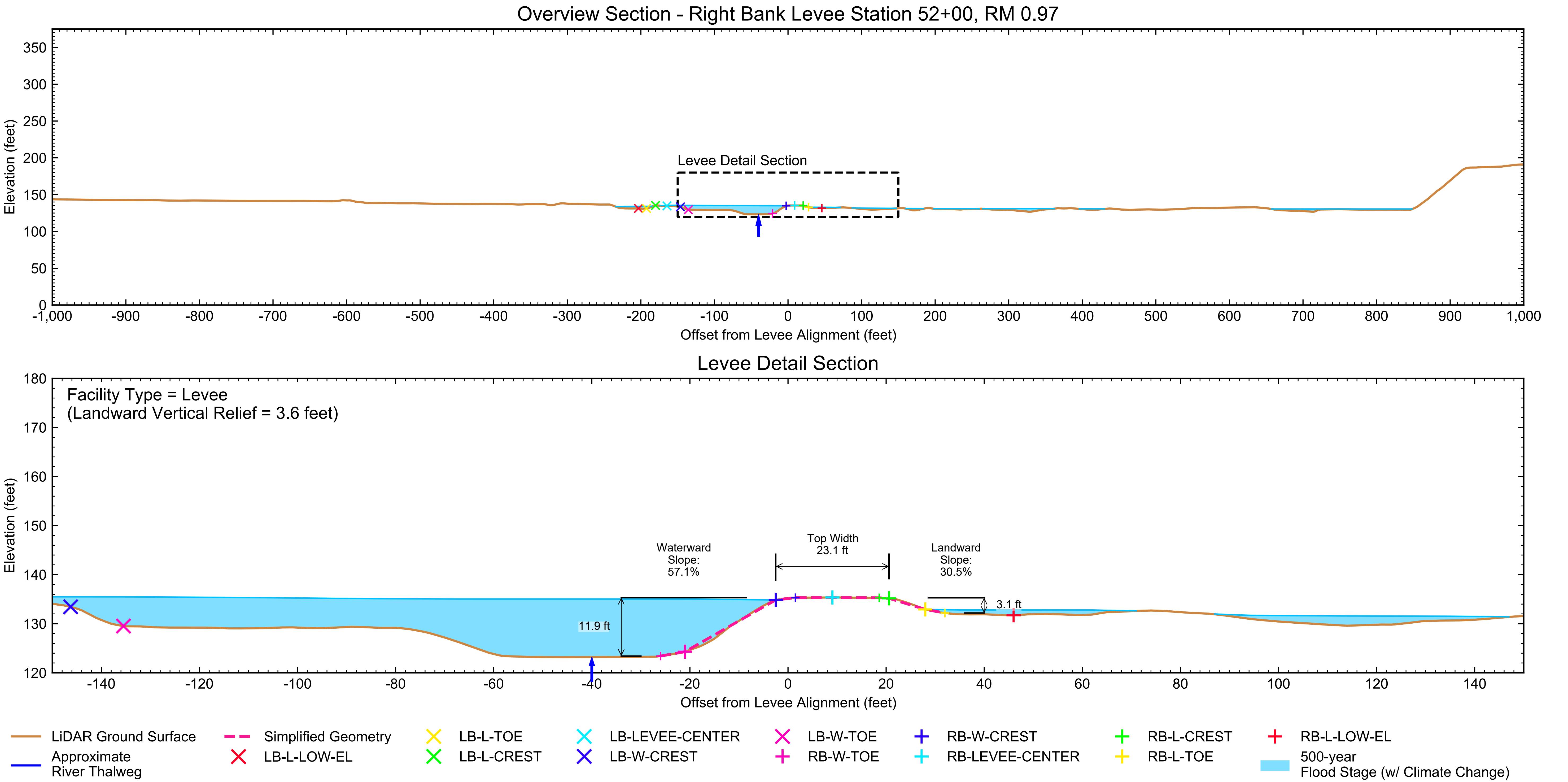
FIG. A-242

\\SEA-FS1\Vol1\EF\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data
ver:0.14.0.post1+gf81b80b, by:OTH



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LIDAR CROSS SECTION
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RIGHT BANK STA 52+00, RM 0.97

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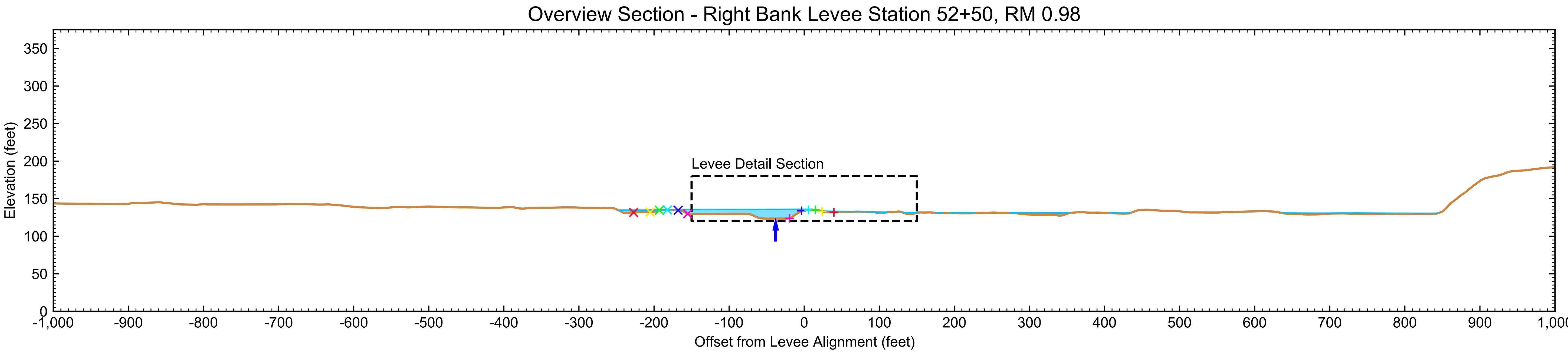
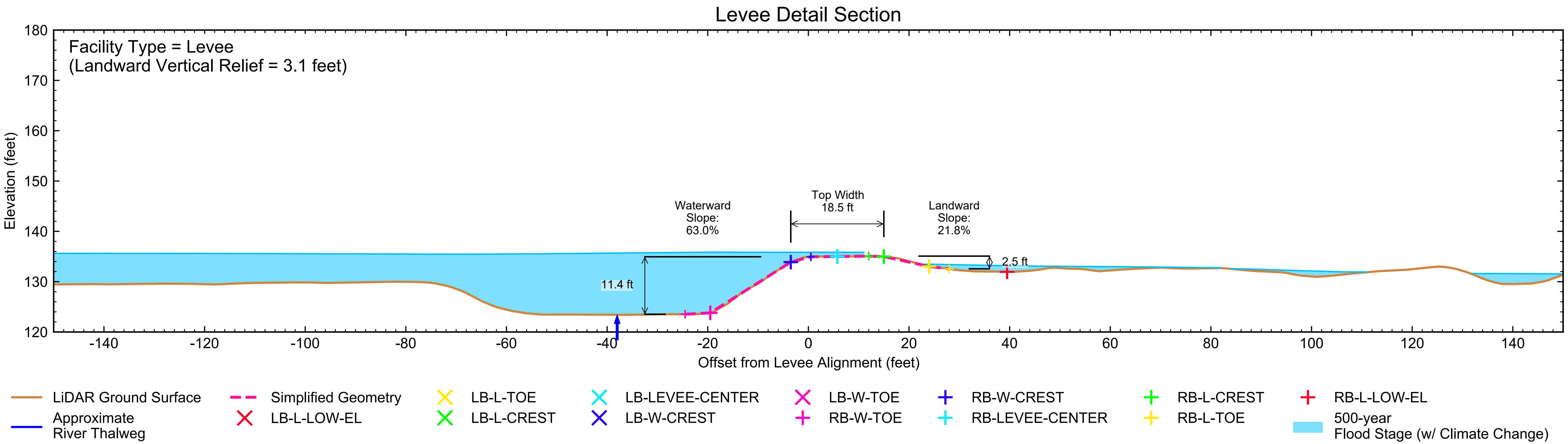
FIG. A-243





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3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 52+50, RM 0.98

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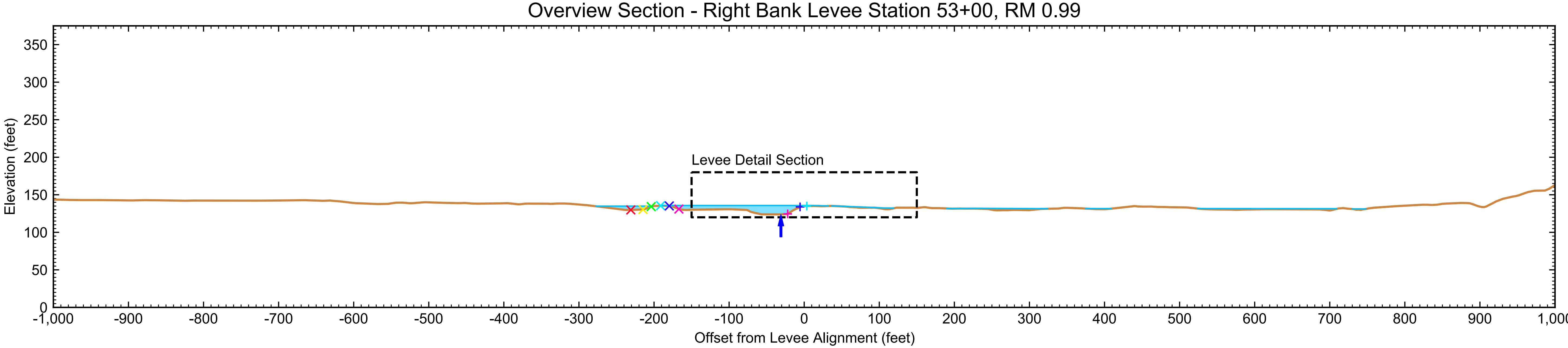
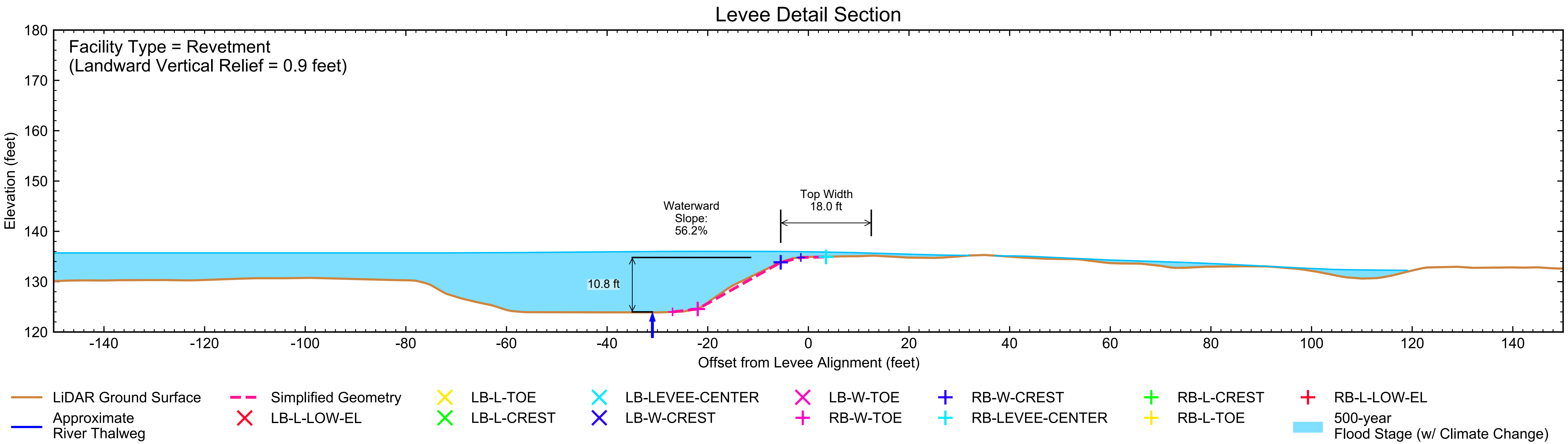
FIG. A-244





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 53+00, RM 0.99

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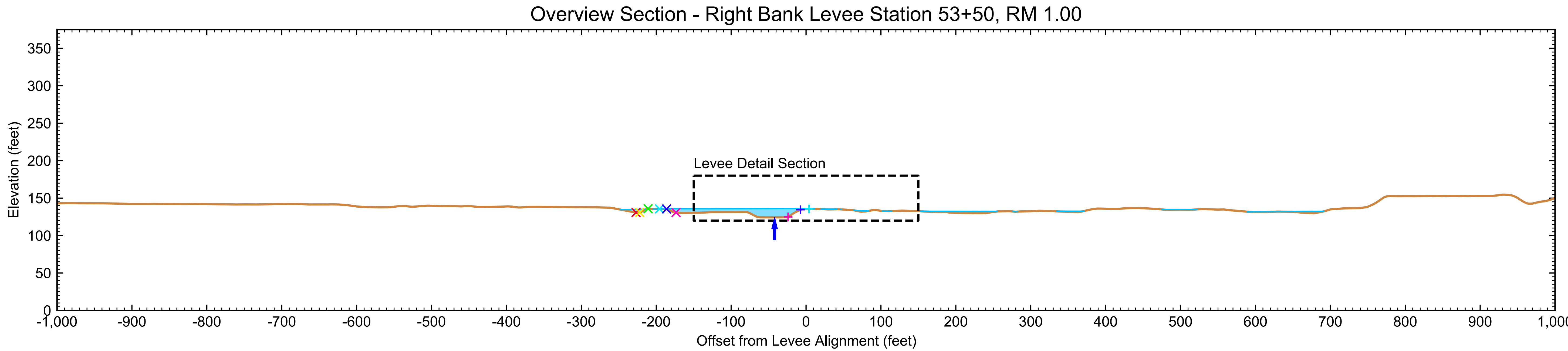
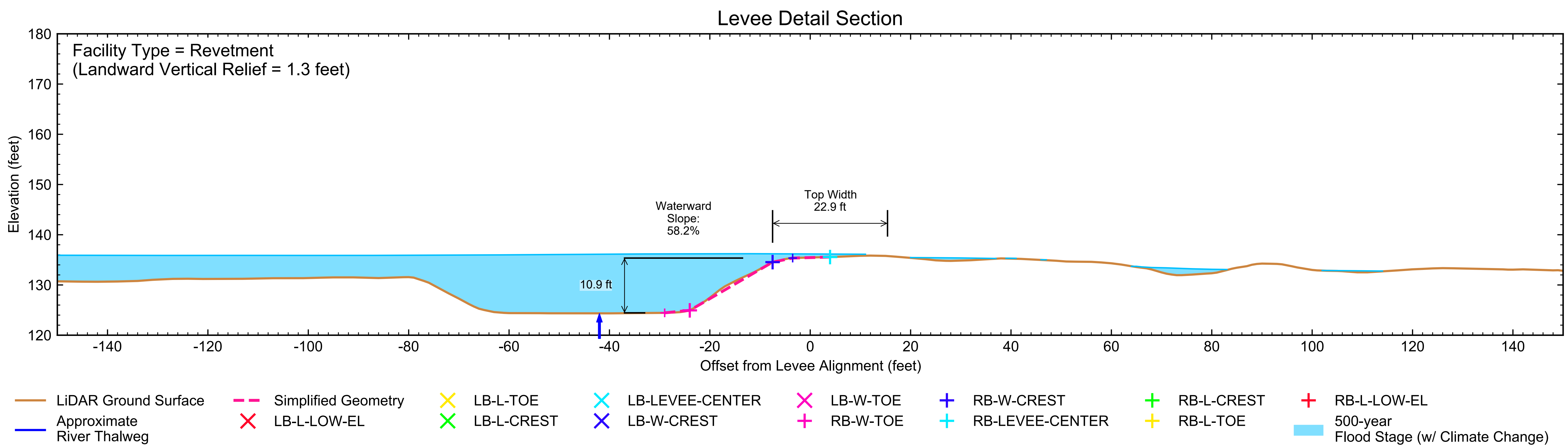
FIG. A-245





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 53+50, RM 1.00

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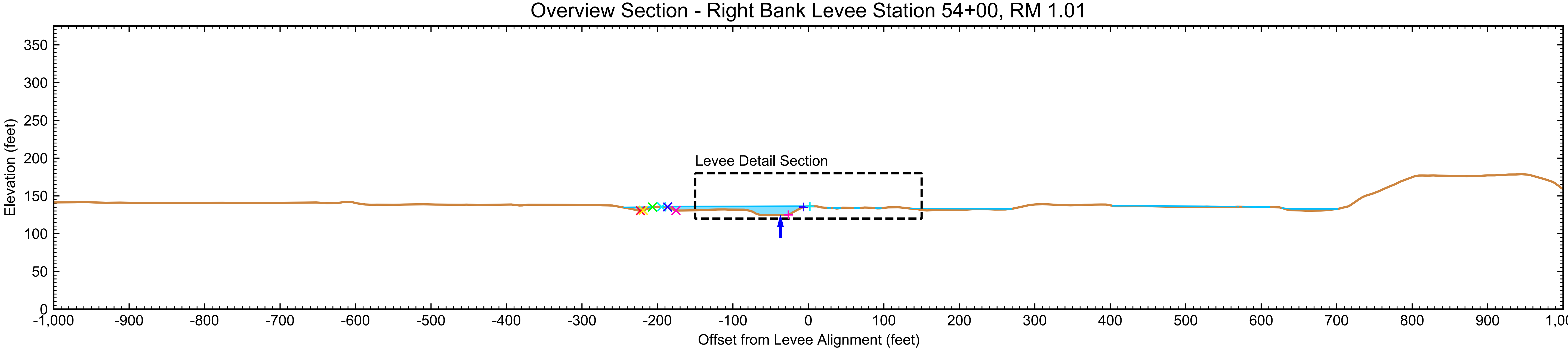
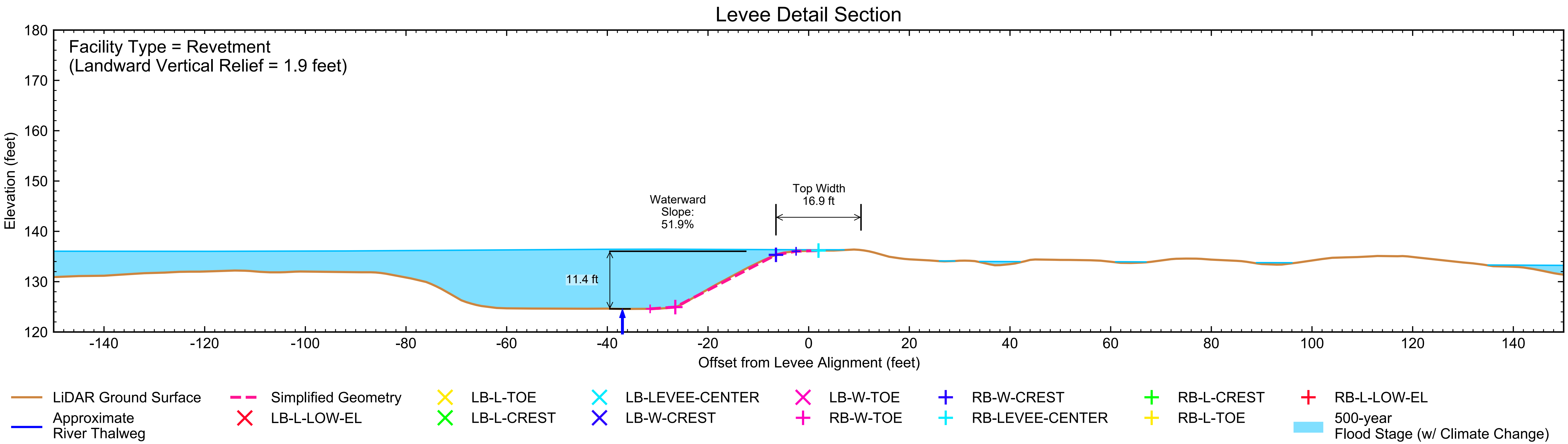
FIG. A-246





Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 54+00, RM 1.01

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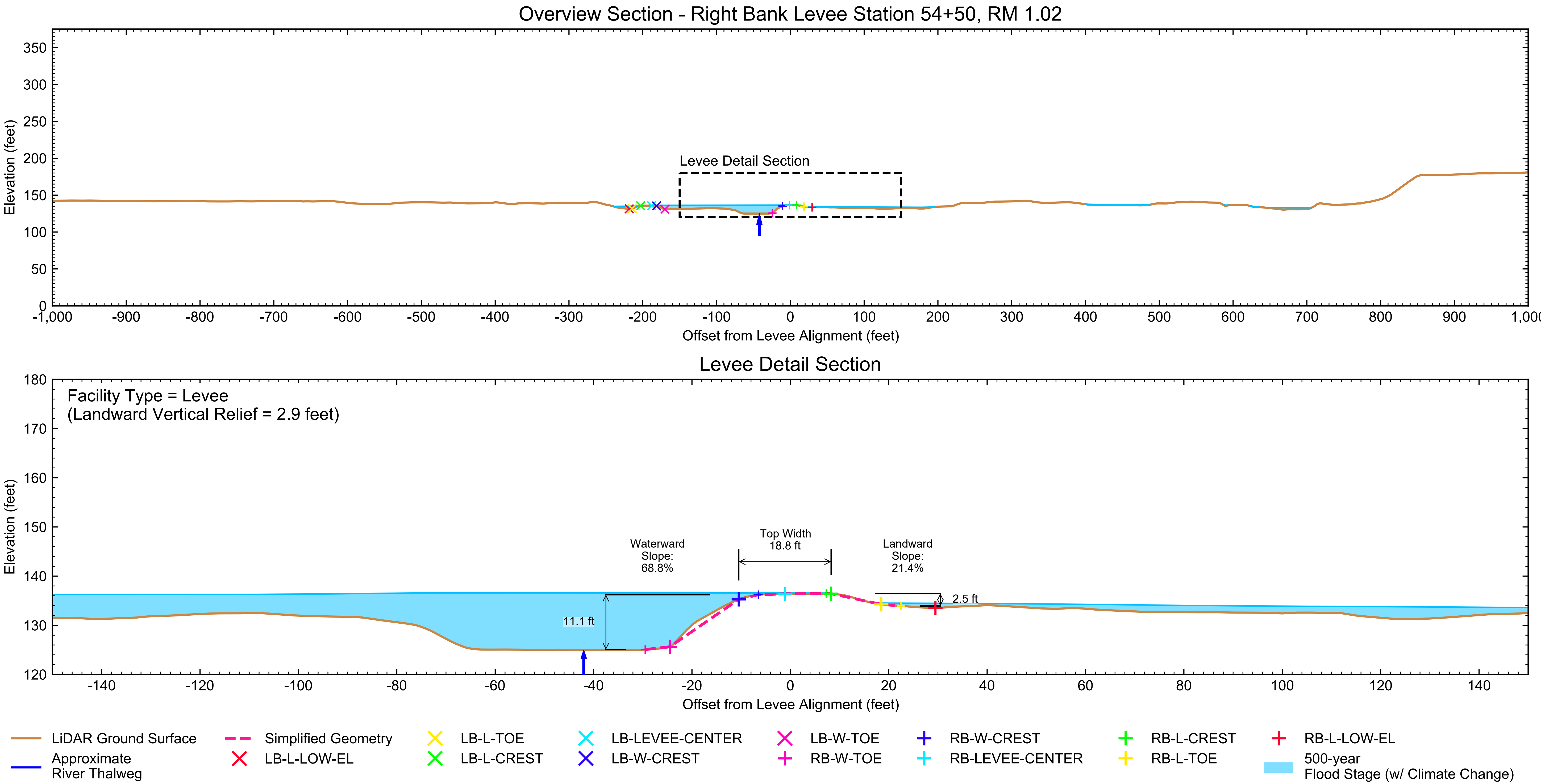
FIG. A-247



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 54+50, RM 1.02

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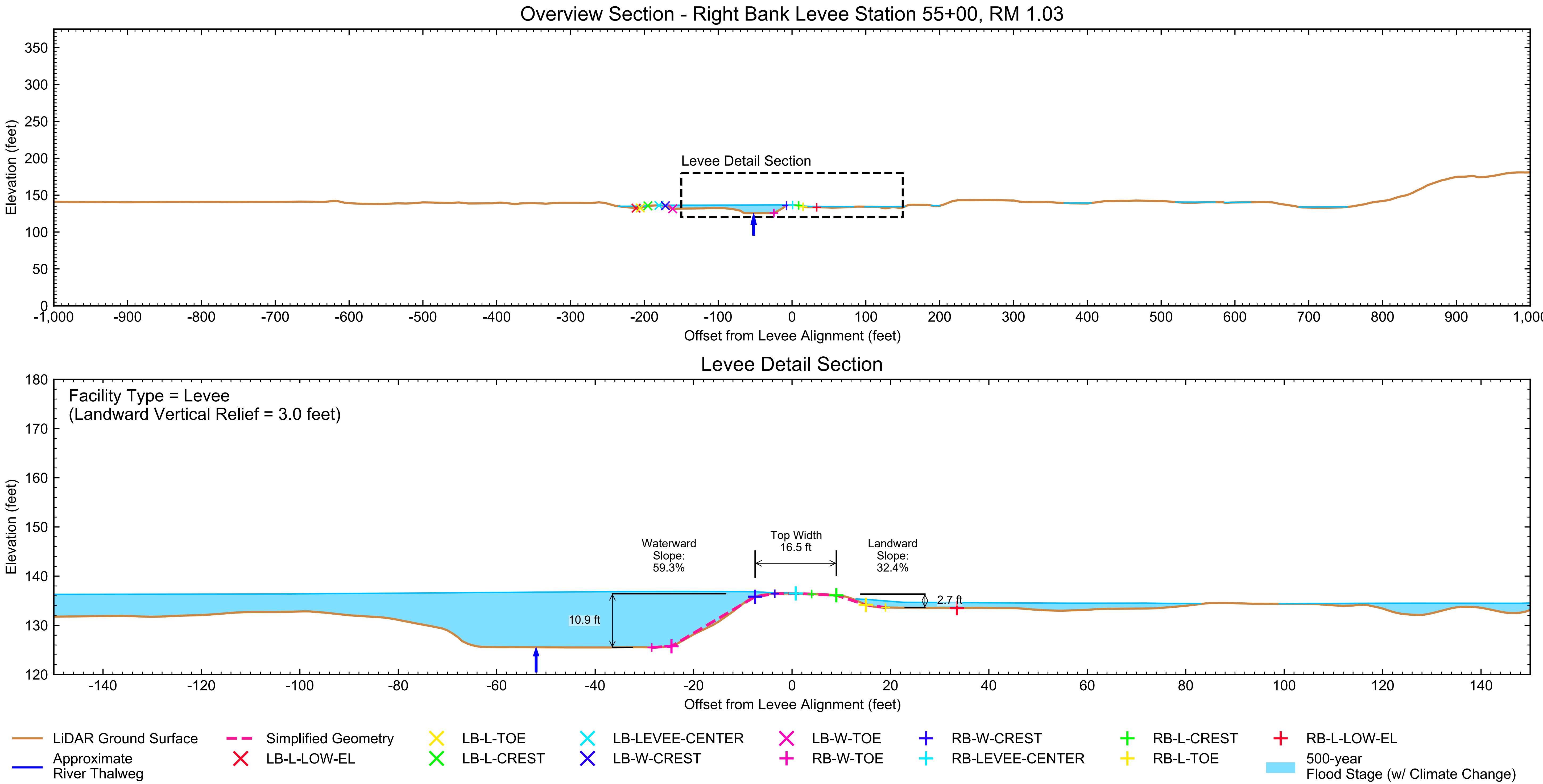
FIG. A-248

\\SEA-FS1\Vol1\EP\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data
ver:0.14.0.post1+gf81b80b, by:OTH



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 55+00, RM 1.03

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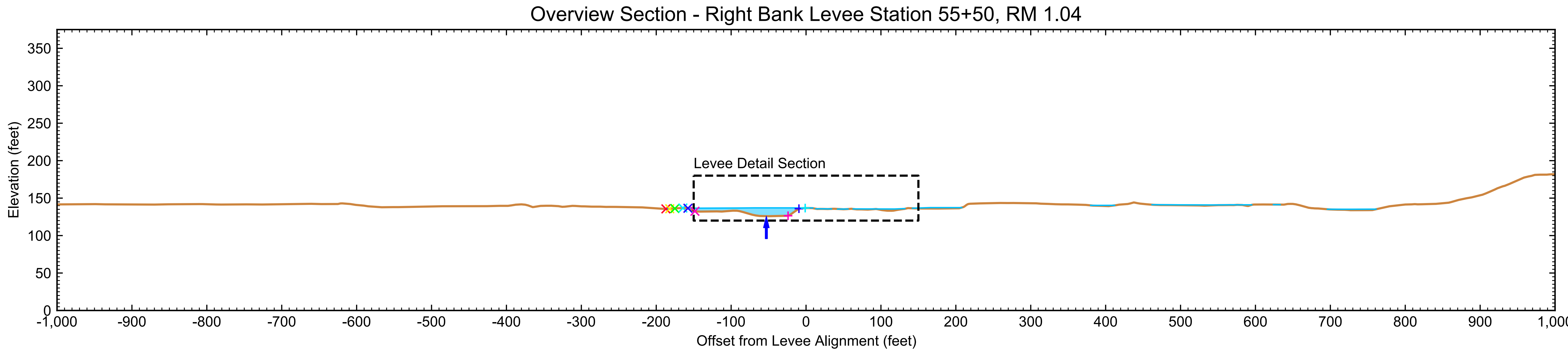
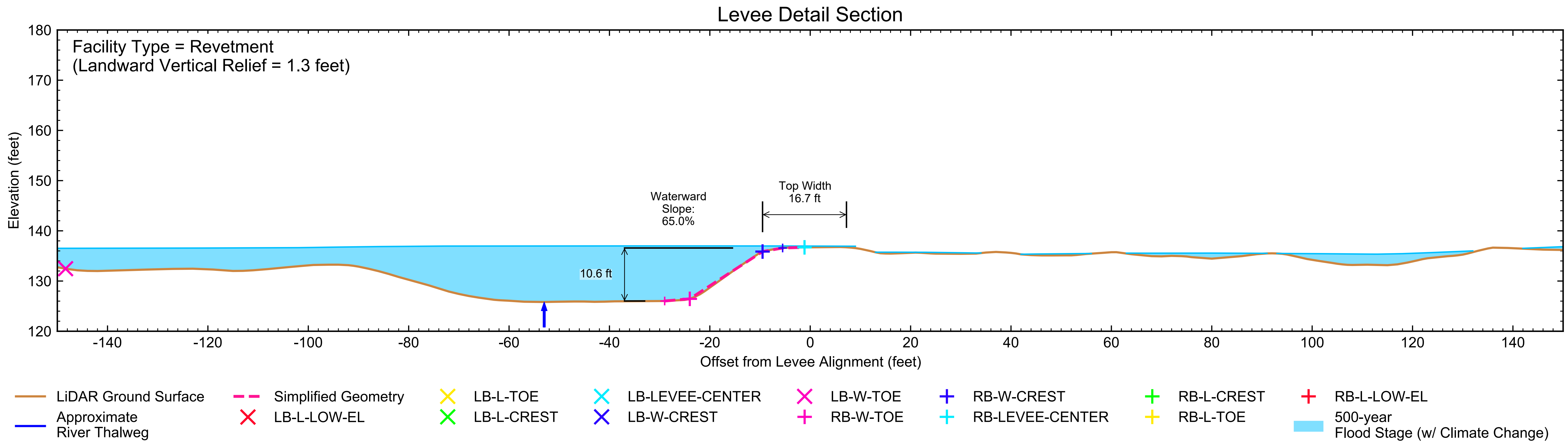
FIG. A-249





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 55+50, RM 1.04

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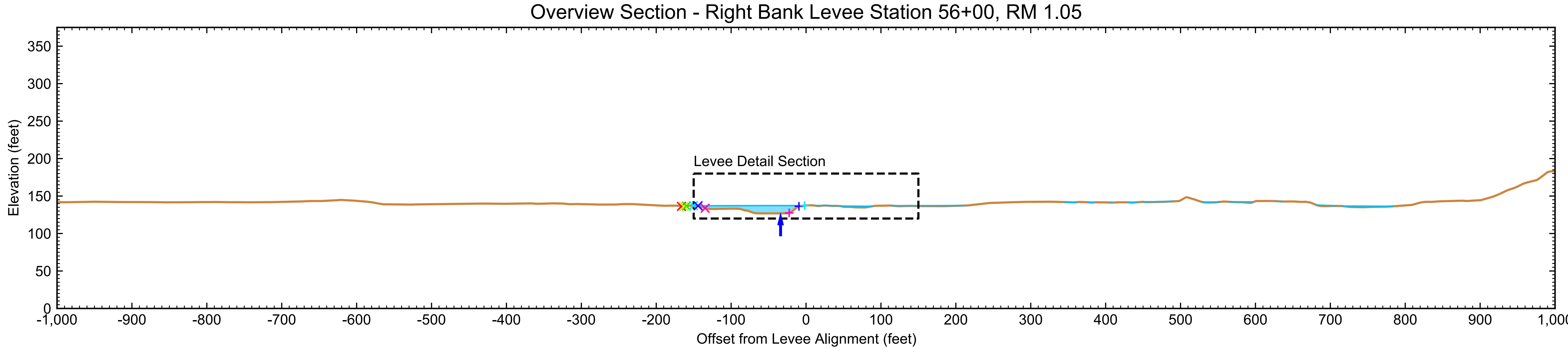
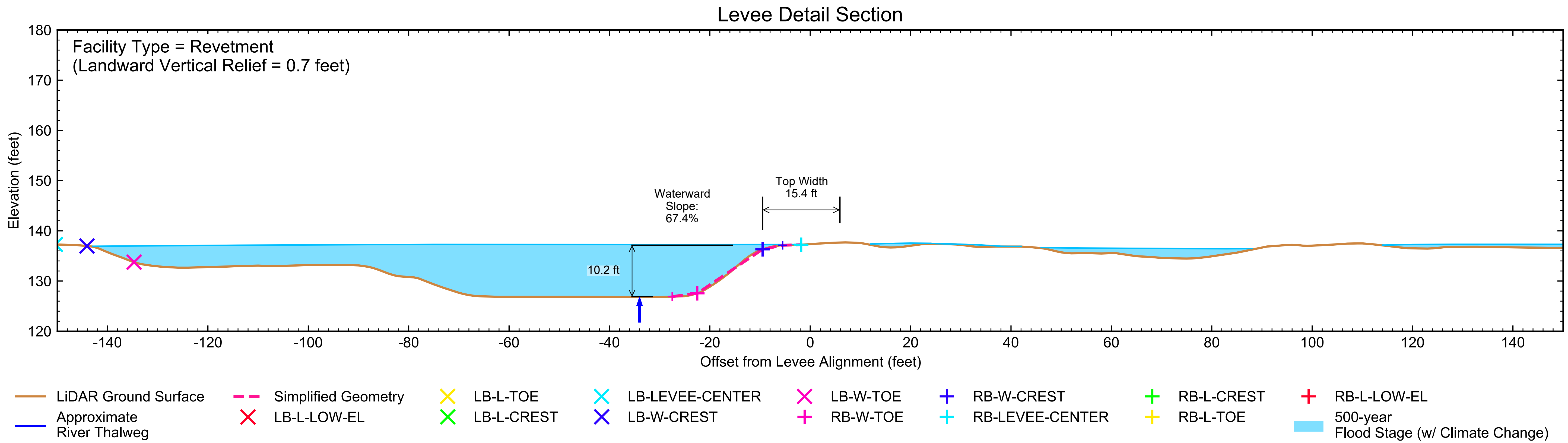
FIG. A-250





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 56+00, RM 1.05

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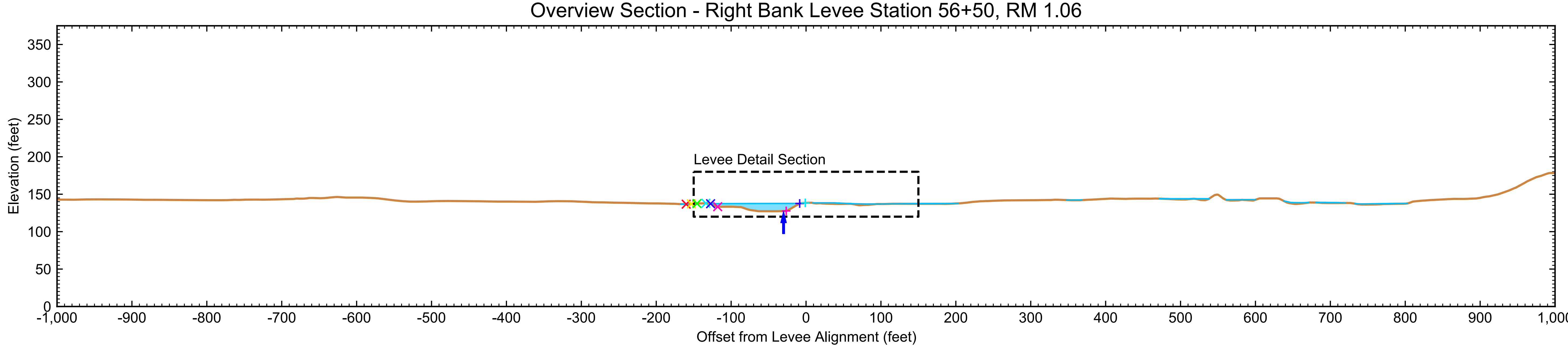
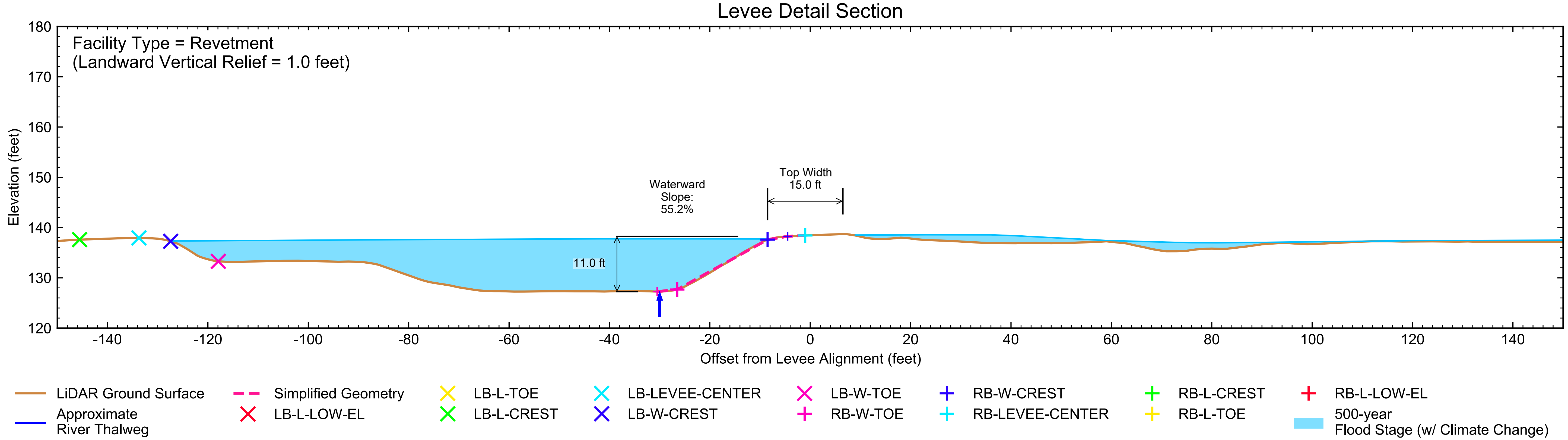
FIG. A-251





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 56+50, RM 1.06

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FIG. A-252

Overview Section - Right Bank Levee Station 57+00, RM 1.07

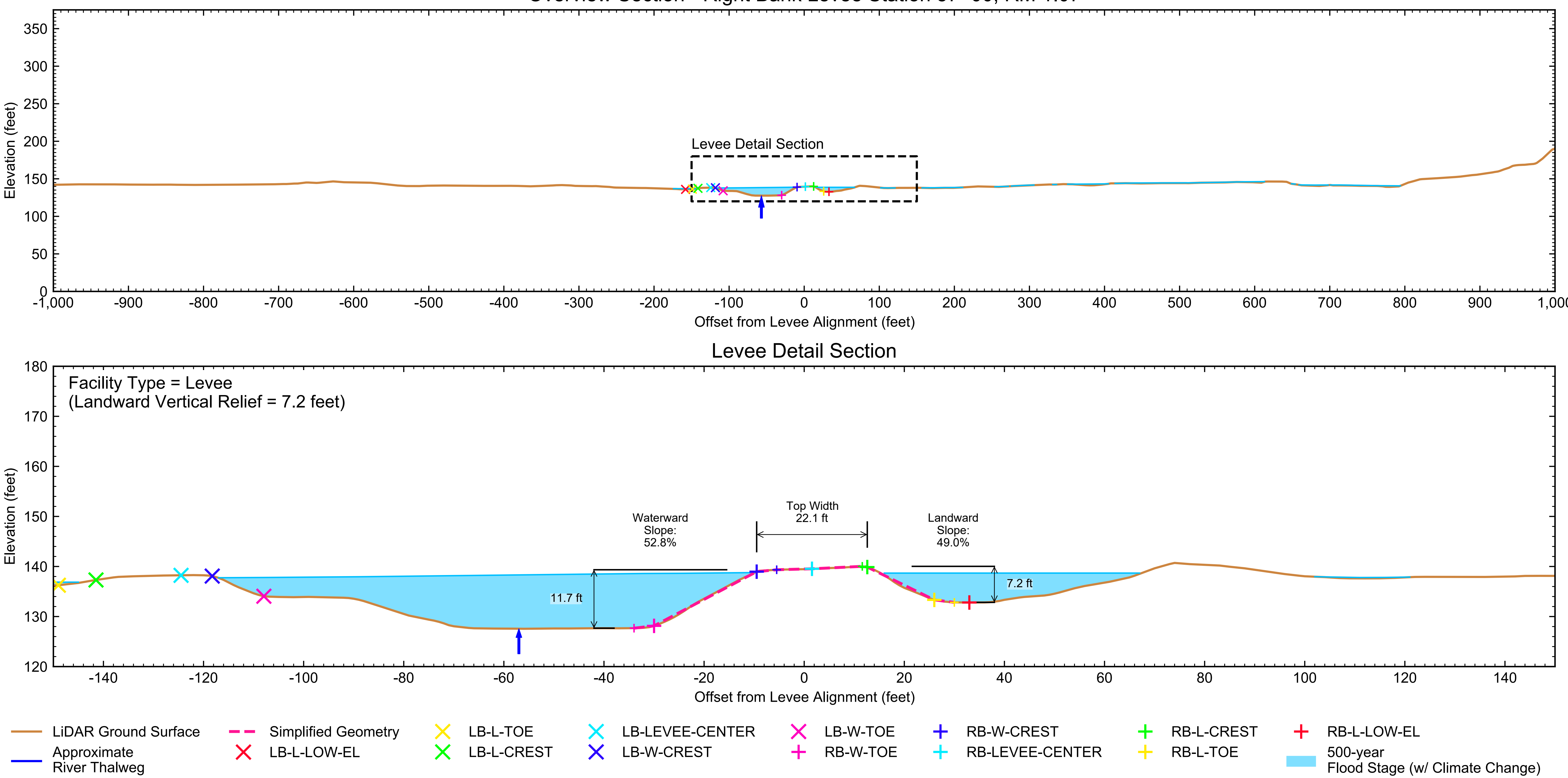

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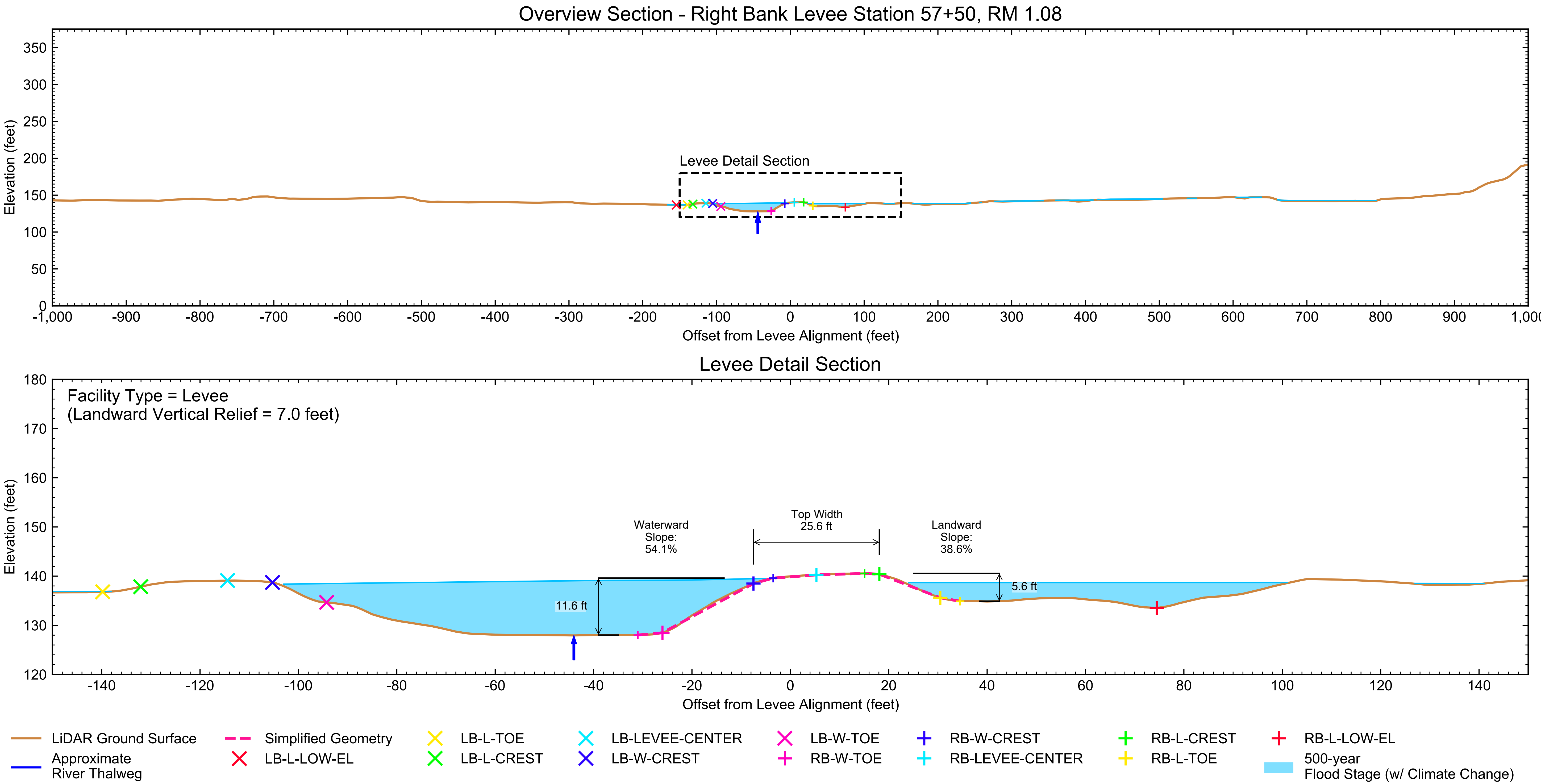
FIG. A-253



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LIDAR CROSS SECTION
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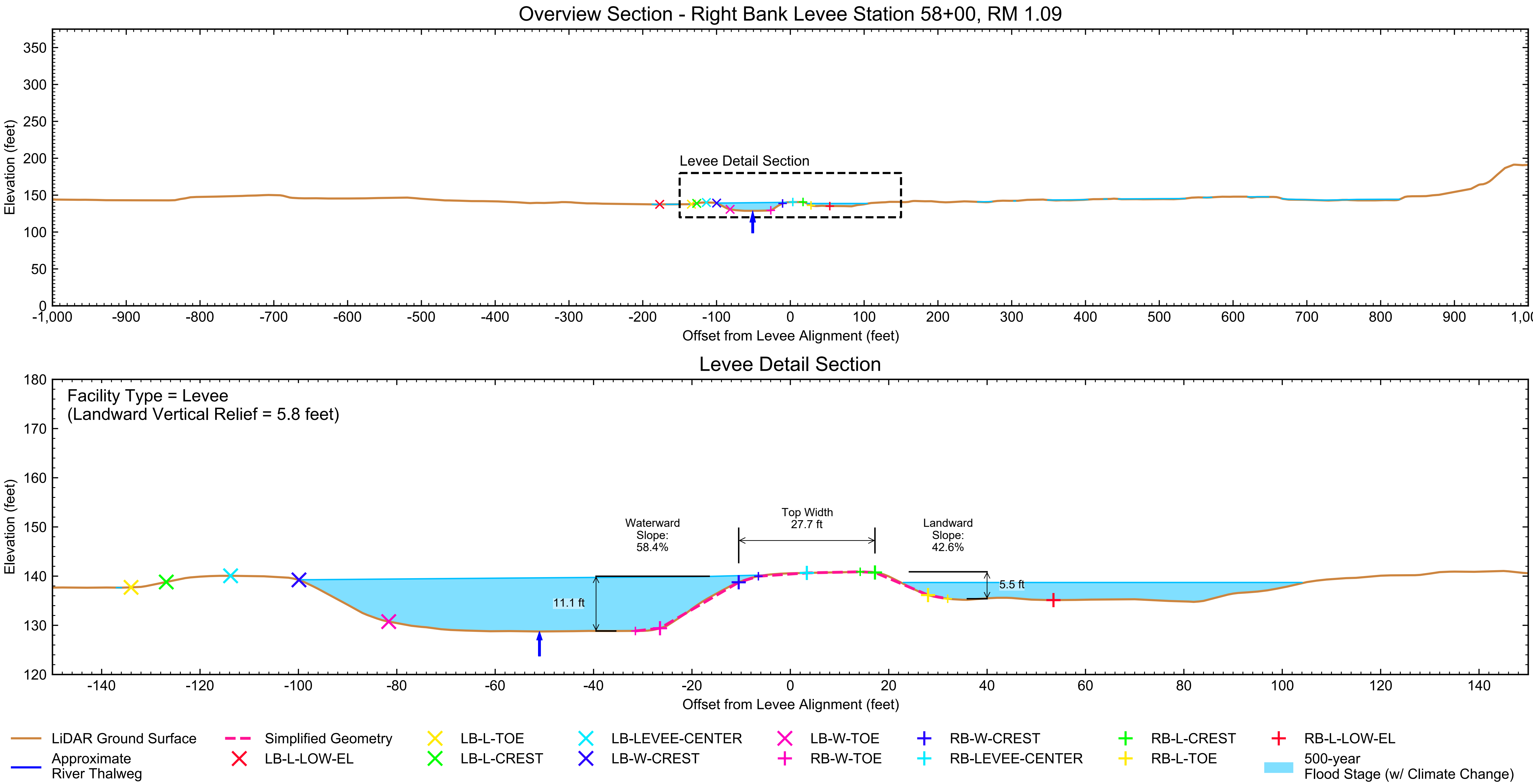
FIG. A-254



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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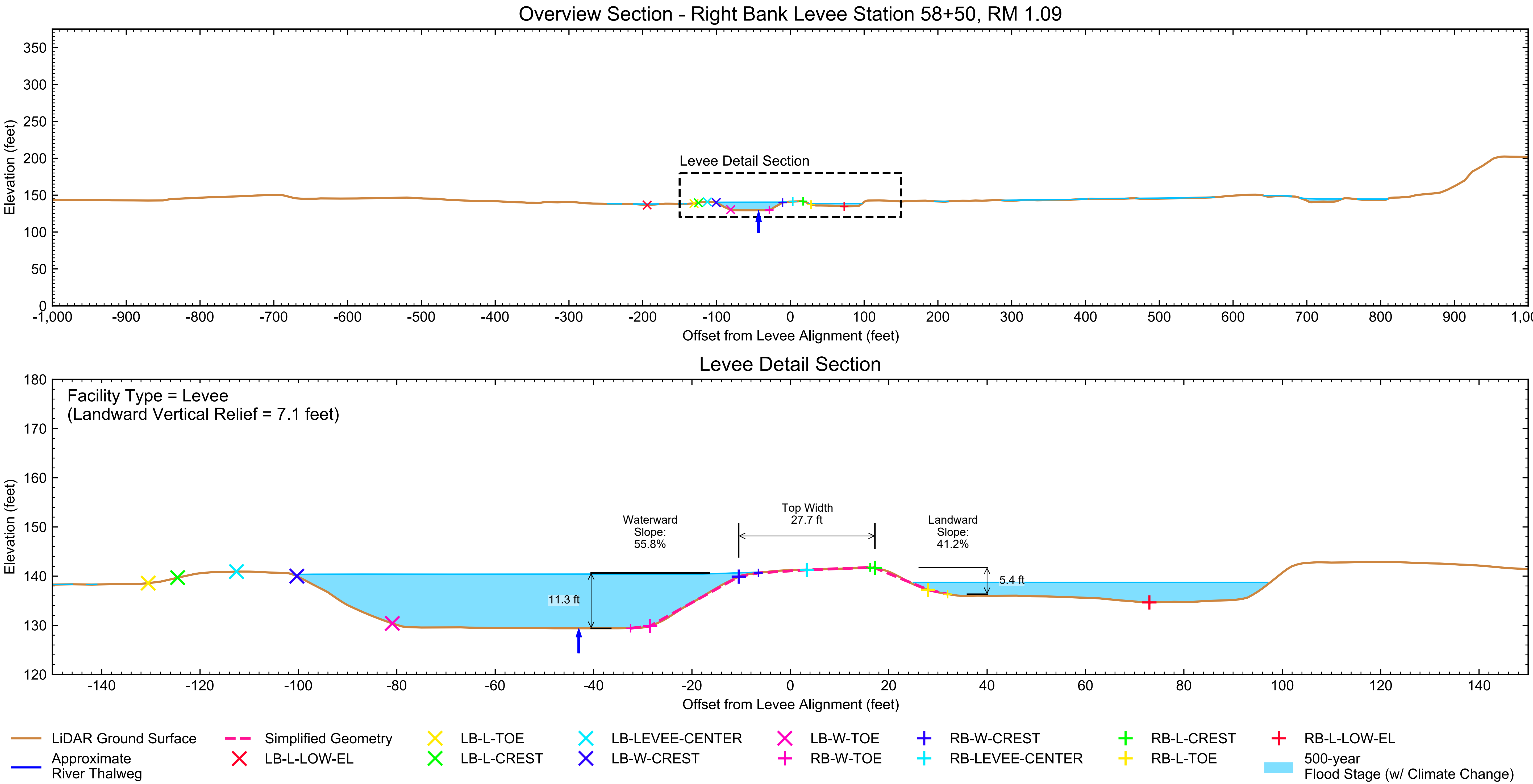
FIG. A-255



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 58+50, RM 1.09

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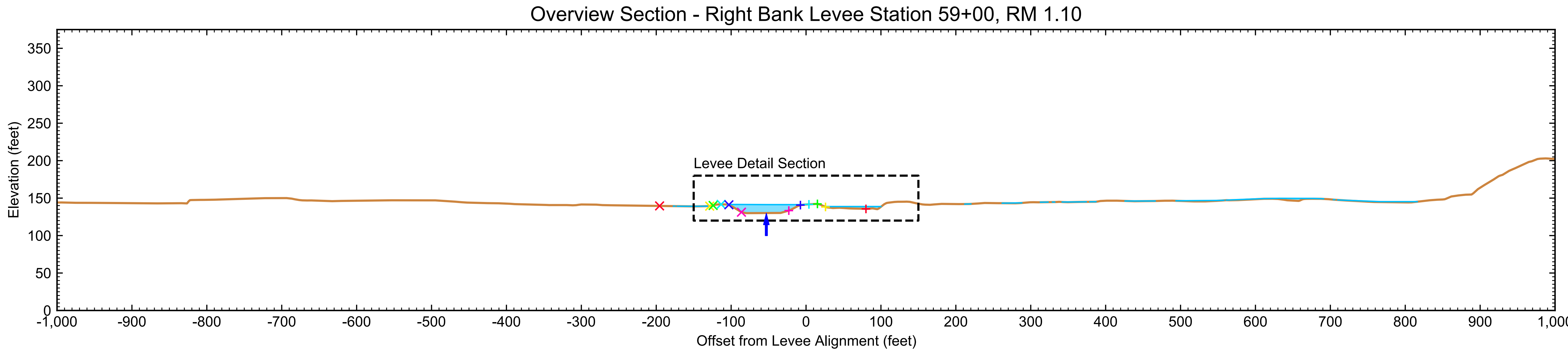
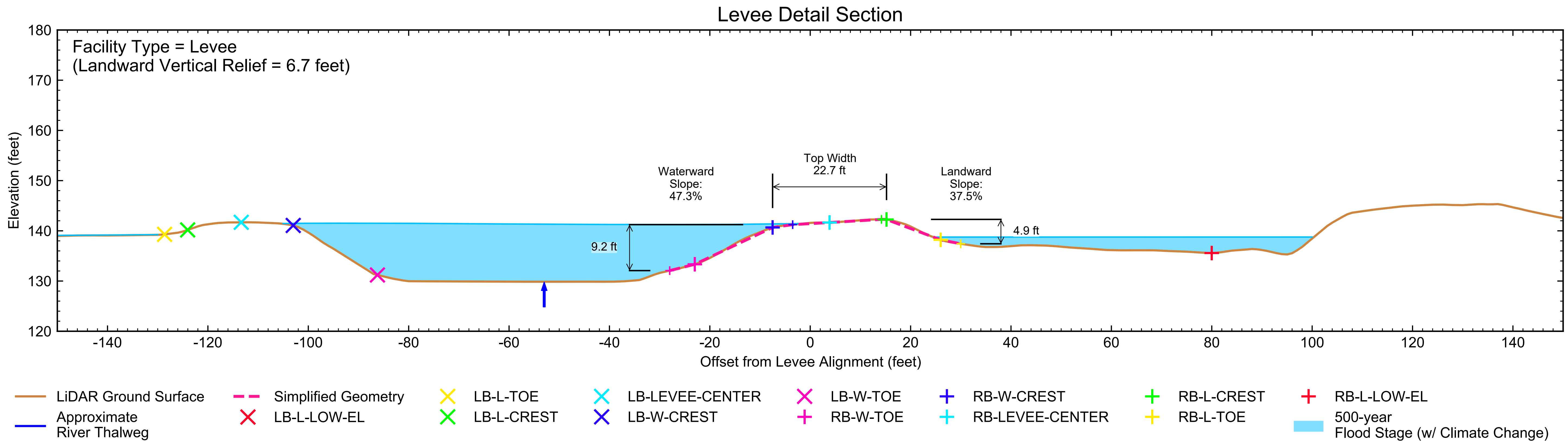
FIG. A-256





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 59+00, RM 1.10

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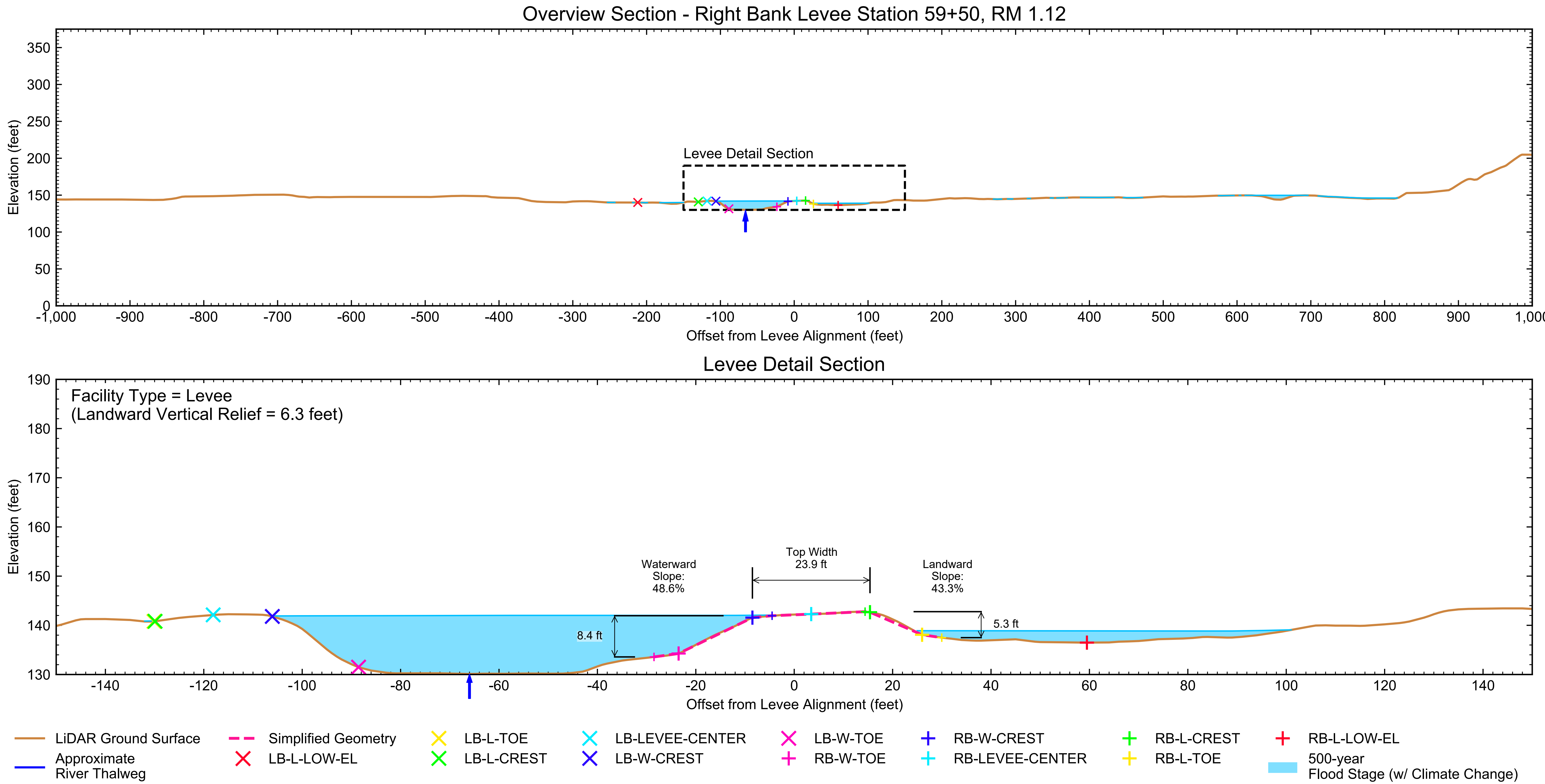
FIG. A-257



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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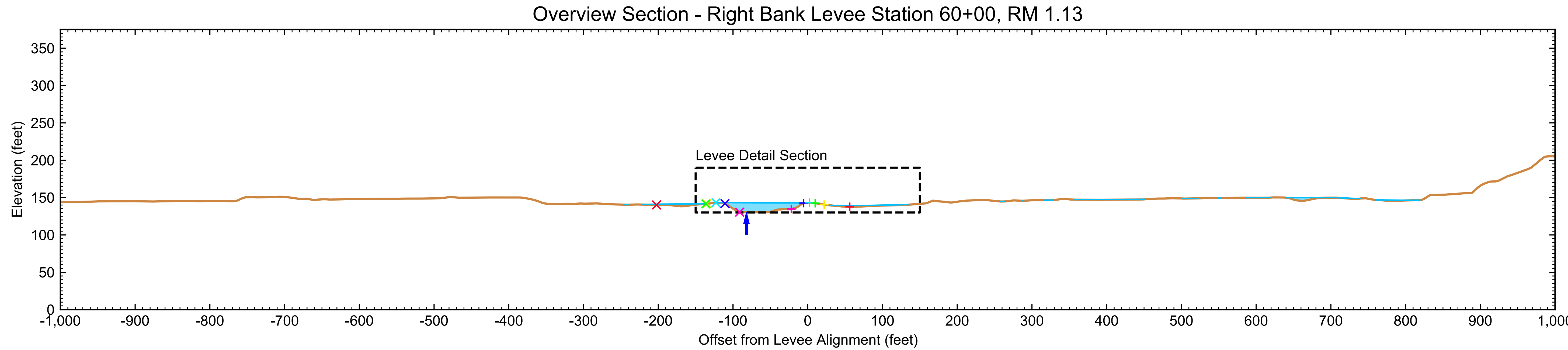
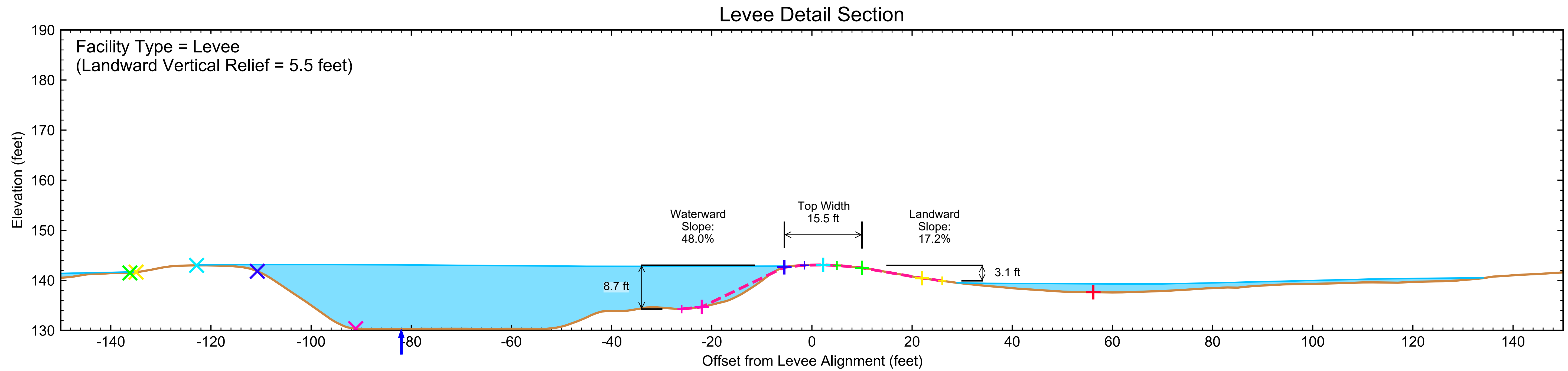
FIG. A-258





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL
Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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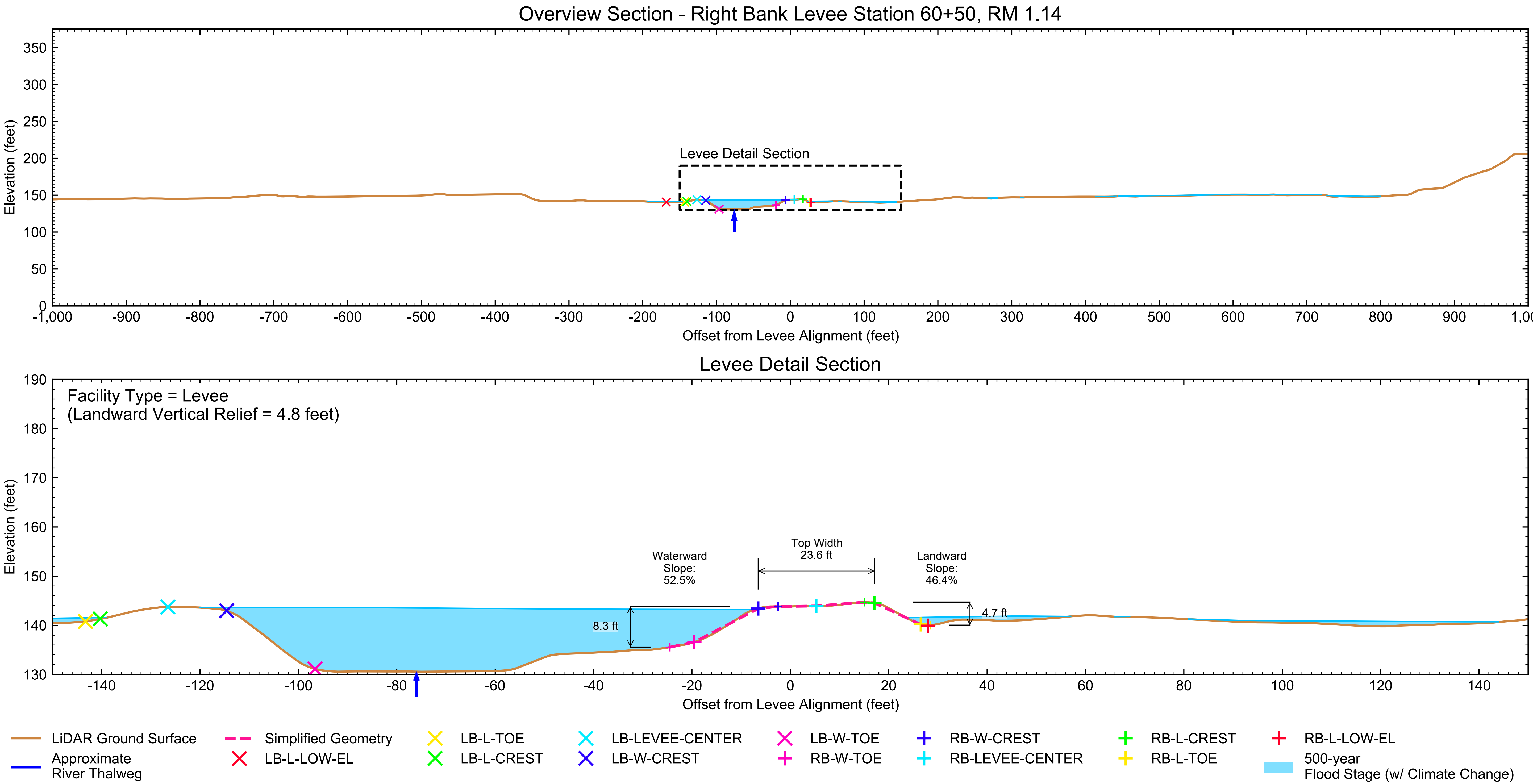
FIG. A-259



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LIDAR CROSS SECTION
LOWER RAGING RIVER
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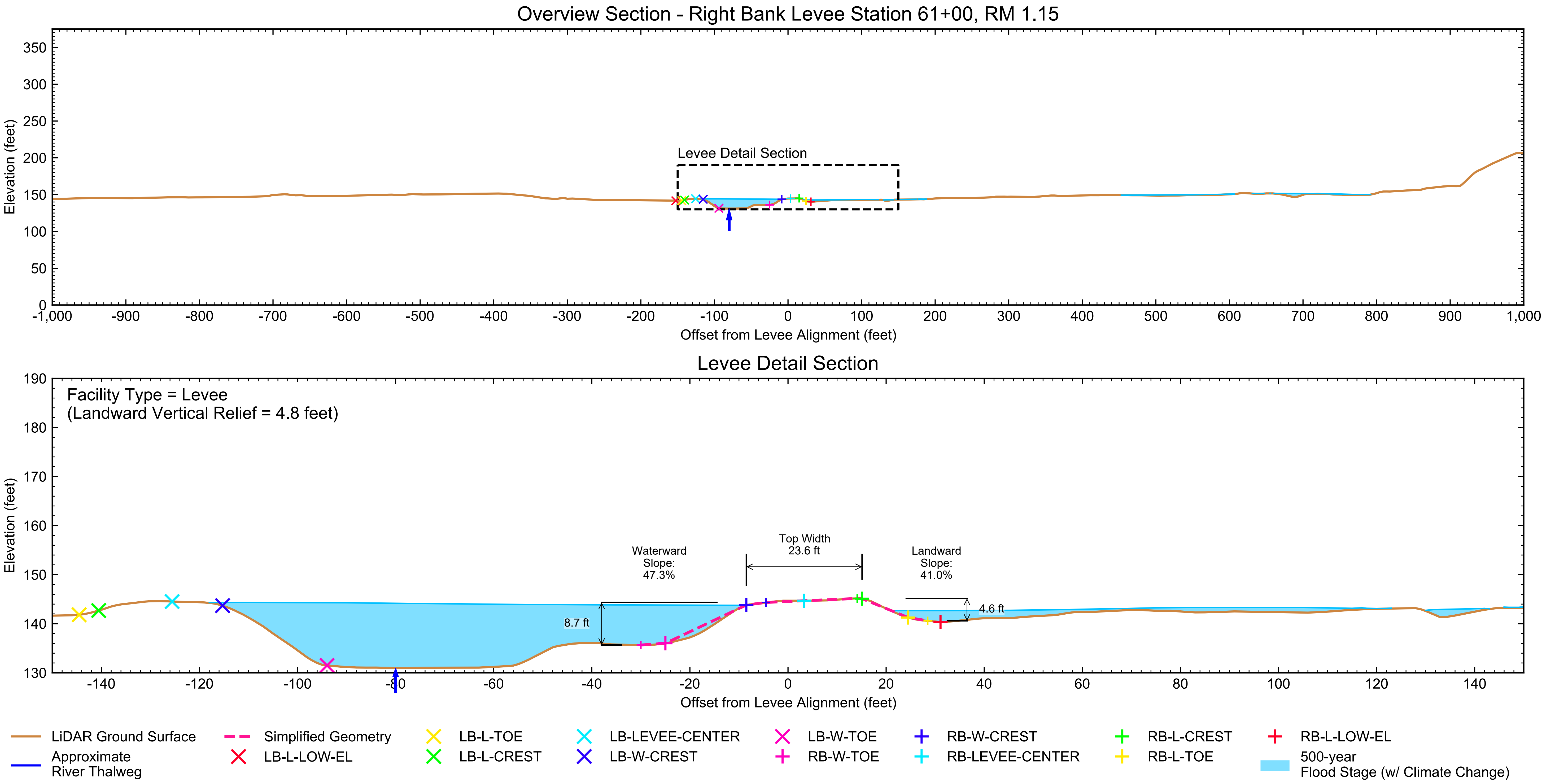
FIG. A-260



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LIDAR CROSS SECTION
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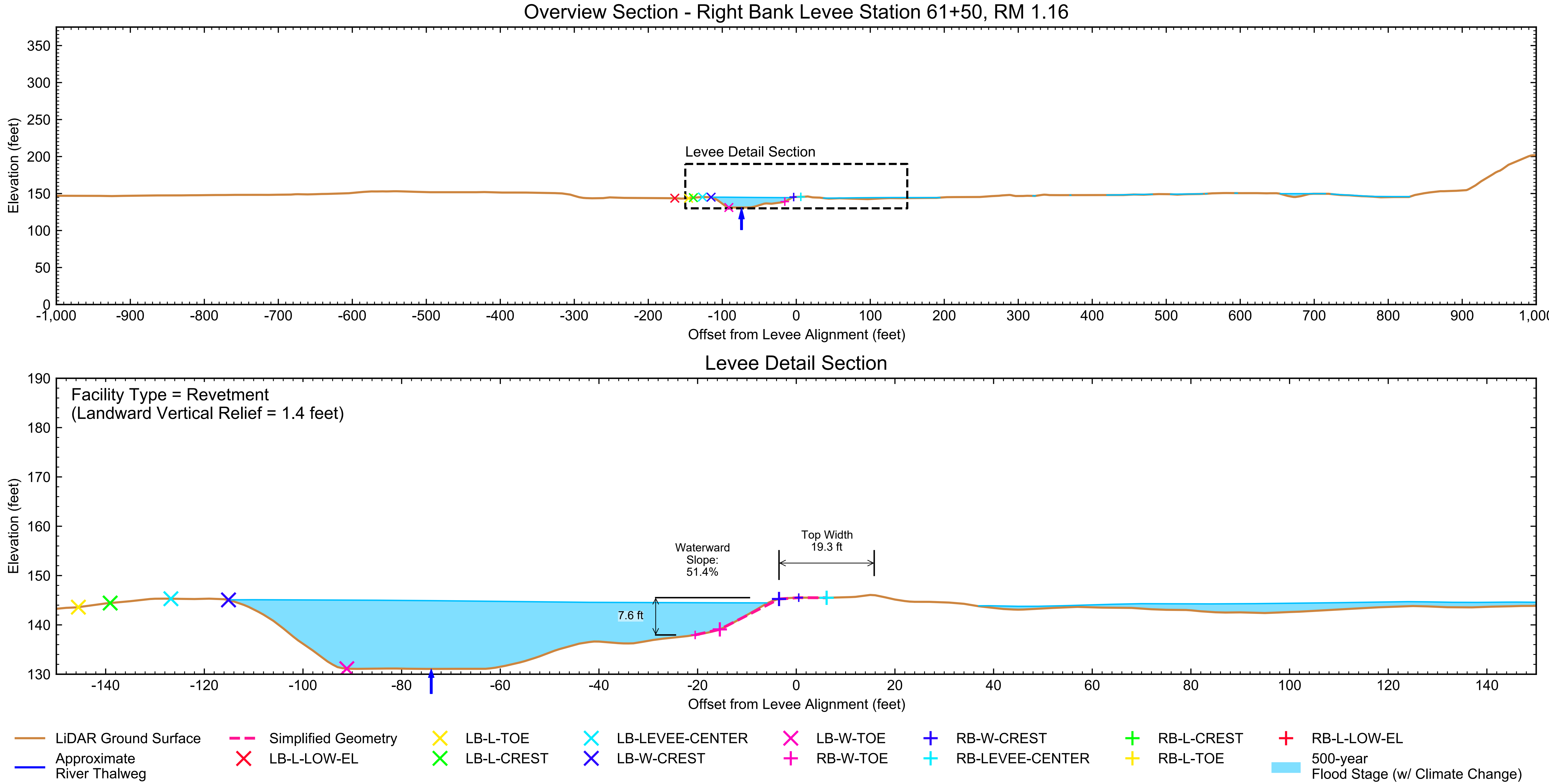
FIG. A-261



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 61+50, RM 1.16

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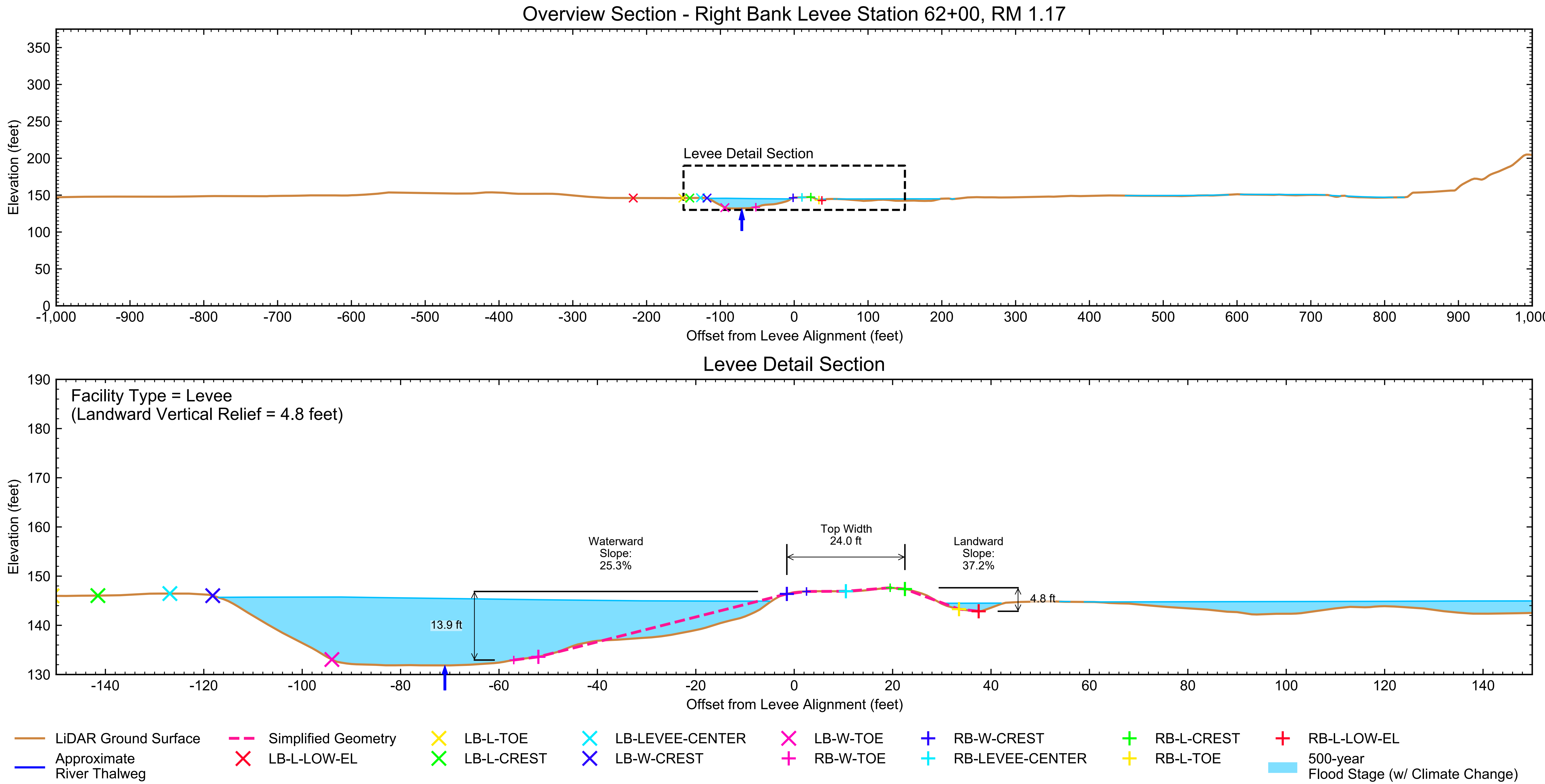
FIG. A-262



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LIDAR CROSS SECTION
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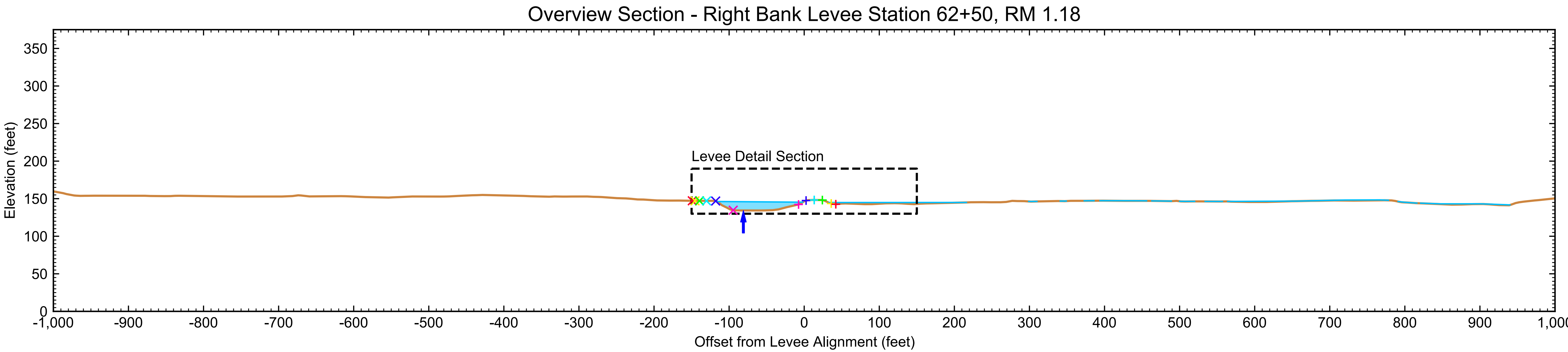
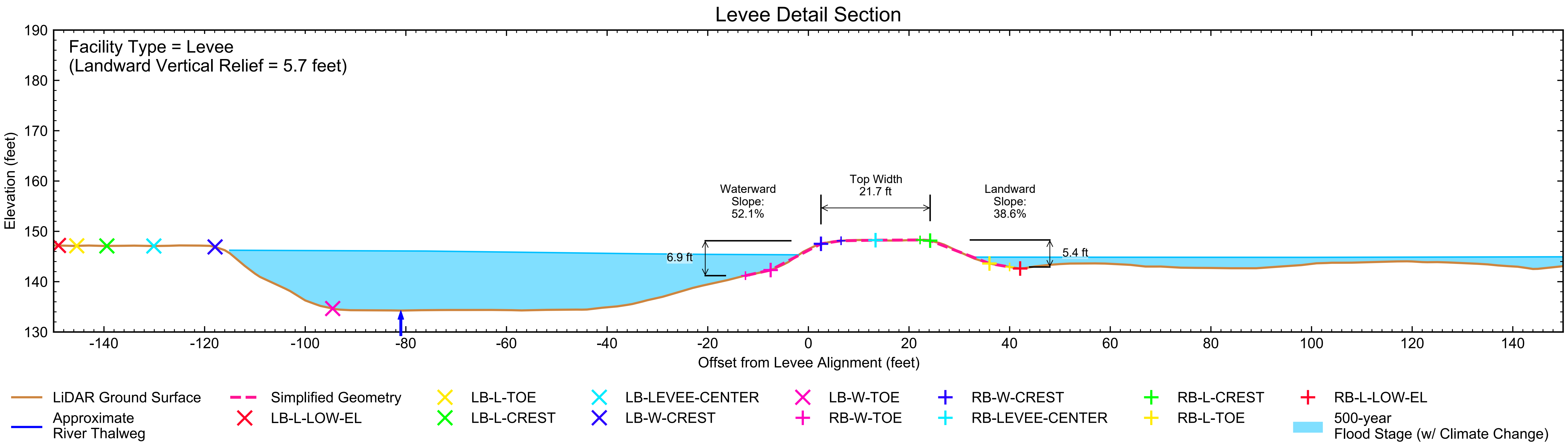
FIG. A-263





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LIDAR CROSS SECTION
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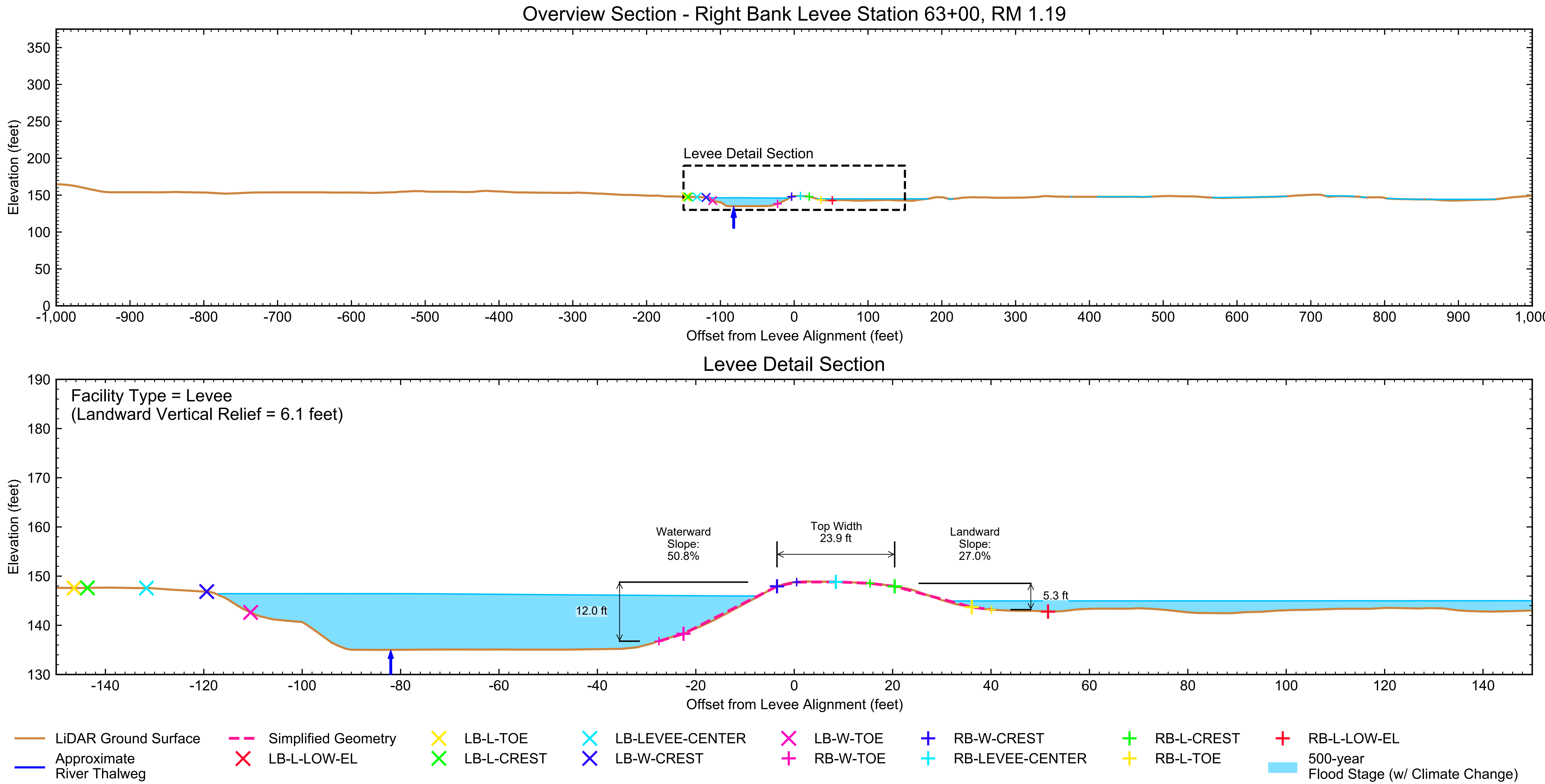
FIG. A-264



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 63+00, RM 1.19

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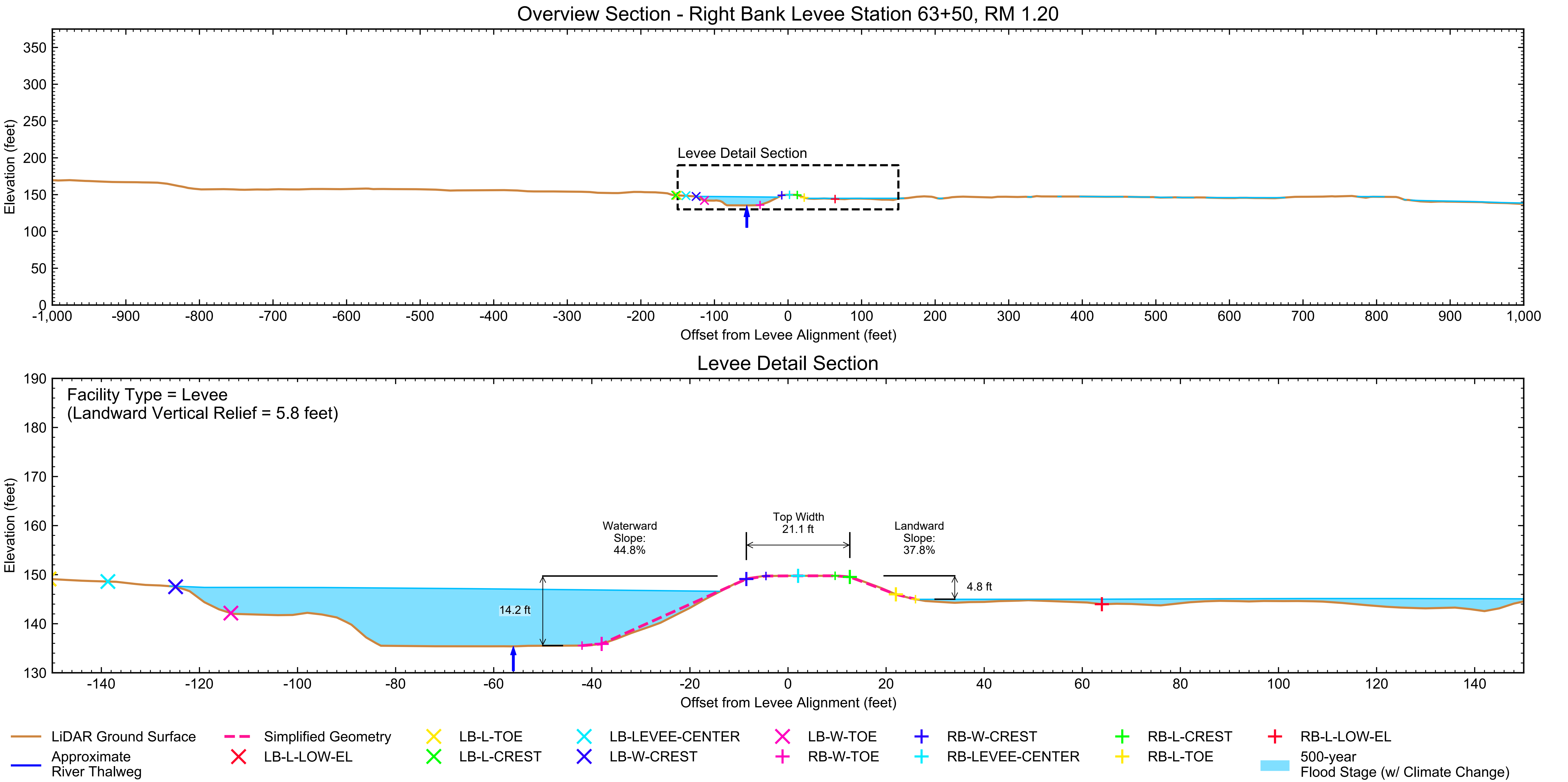
FIG. A-265



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LIDAR CROSS SECTION
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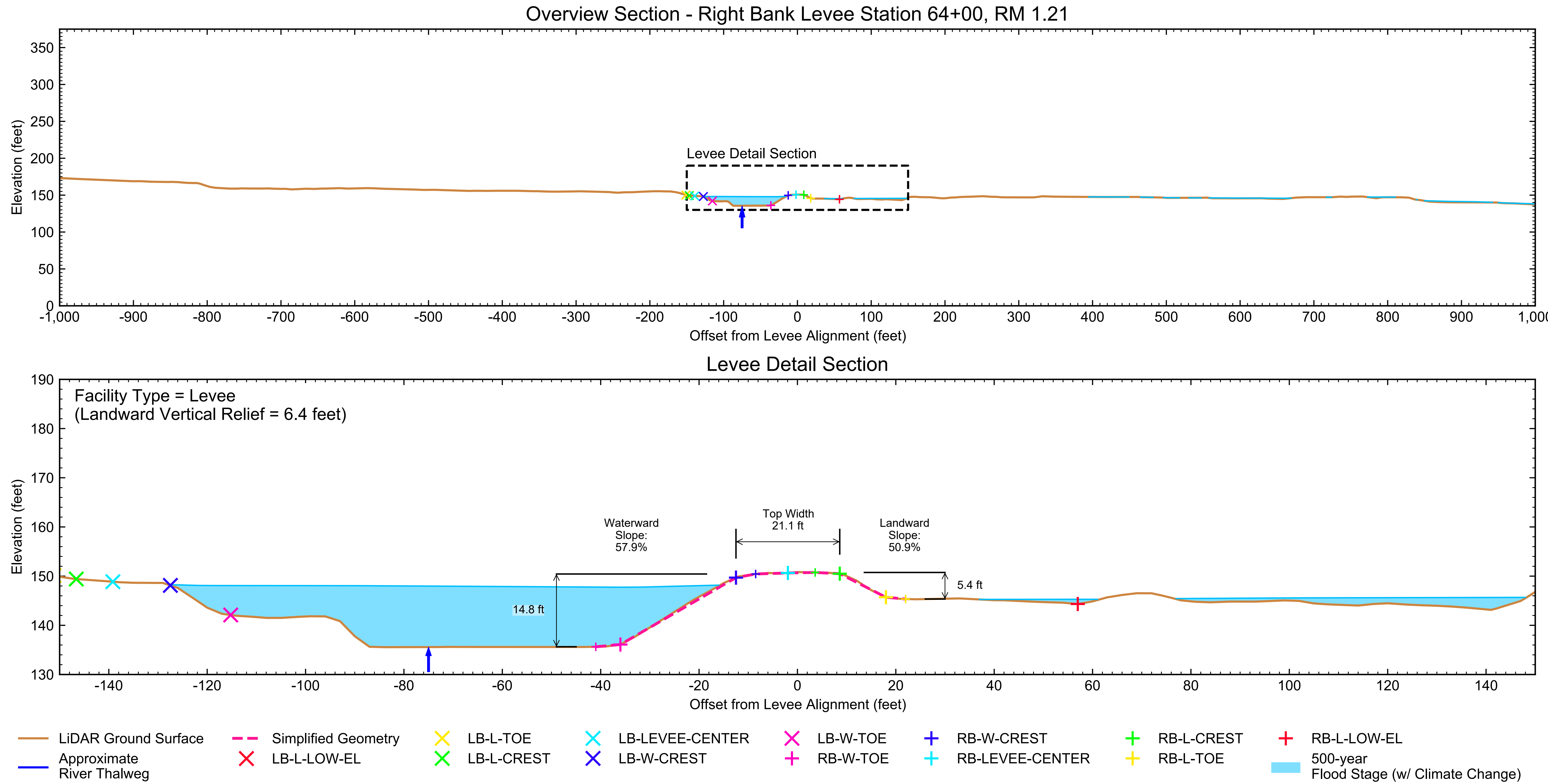
FIG. A-266



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LIDAR CROSS SECTION
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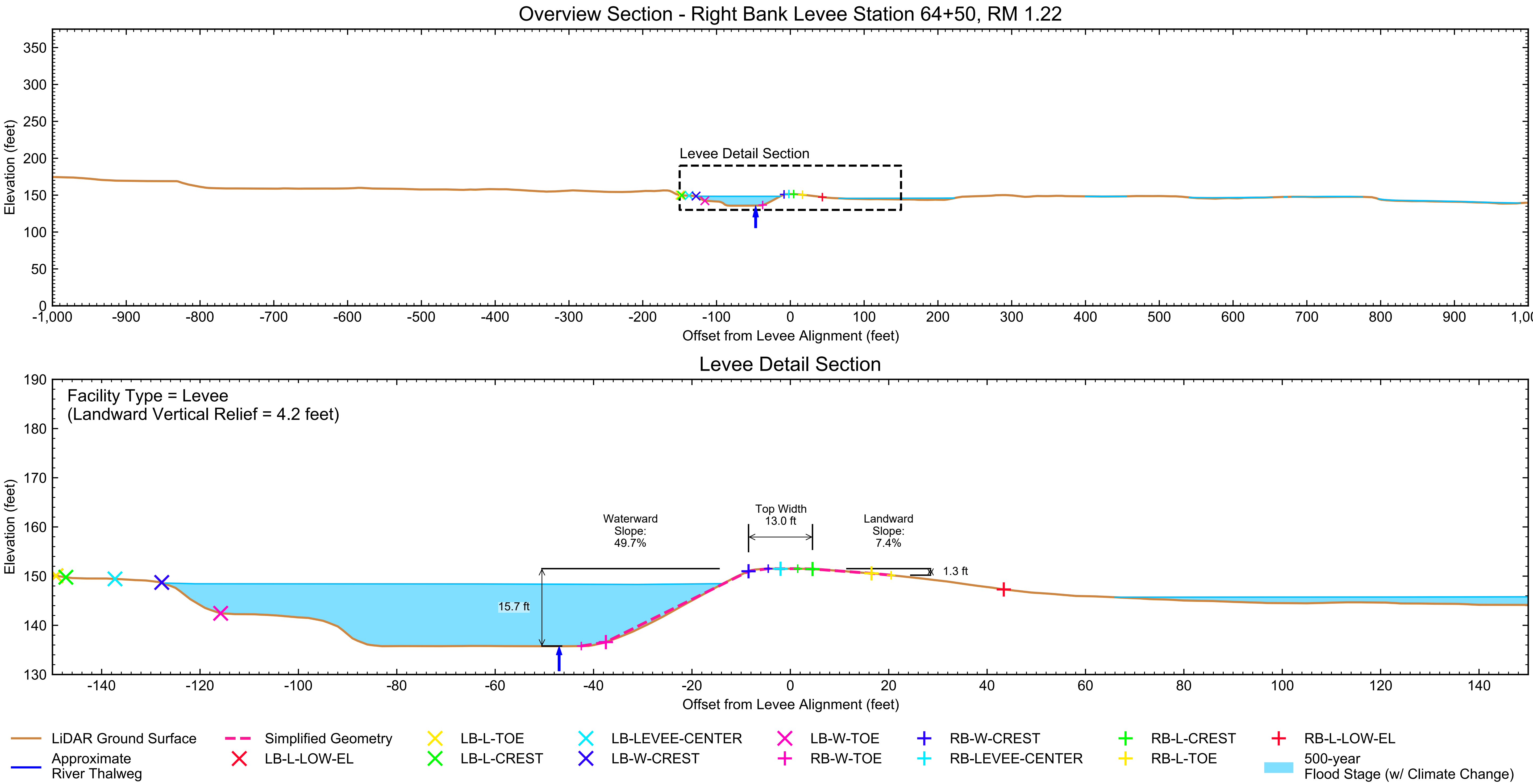
FIG. A-267

\\SEA-FS1\Vol1\EP\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data
ver:0.14.0.post1+gf81b80b_by:OTH



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 64+50, RM 1.22

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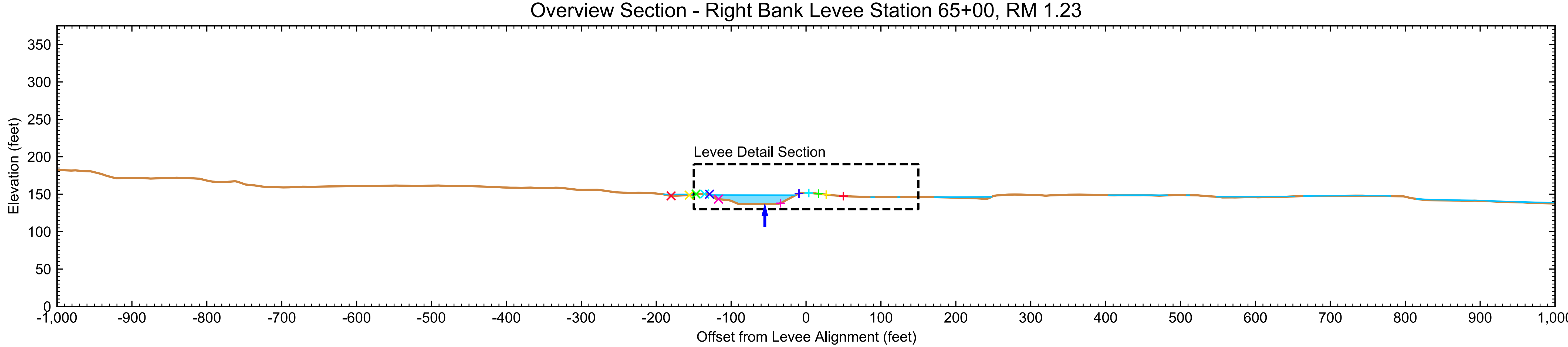
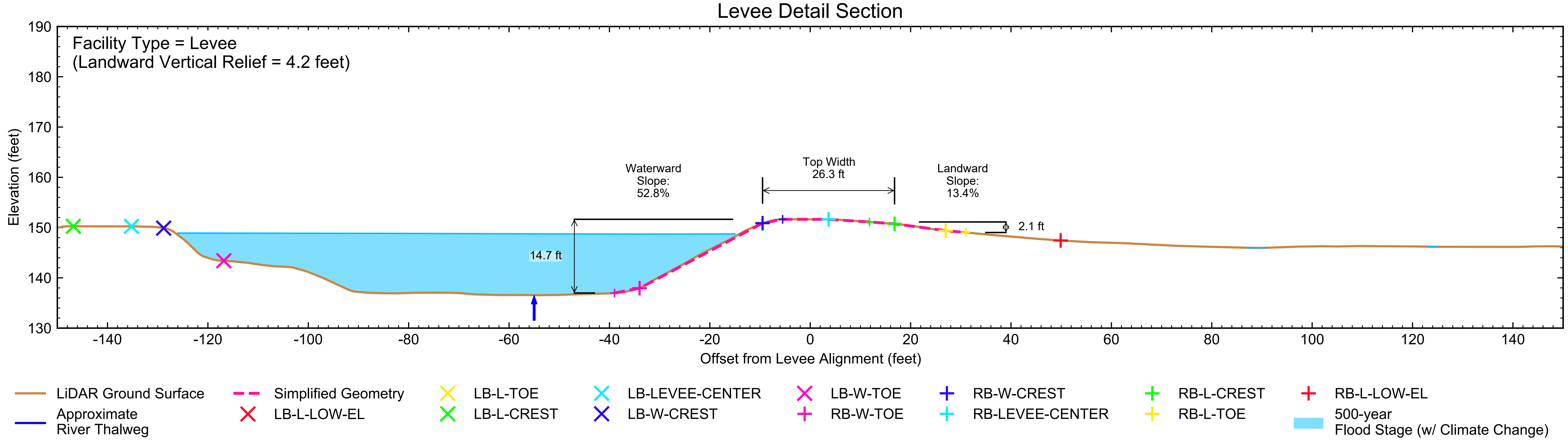
FIG. A-268





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 65+00, RM 1.23

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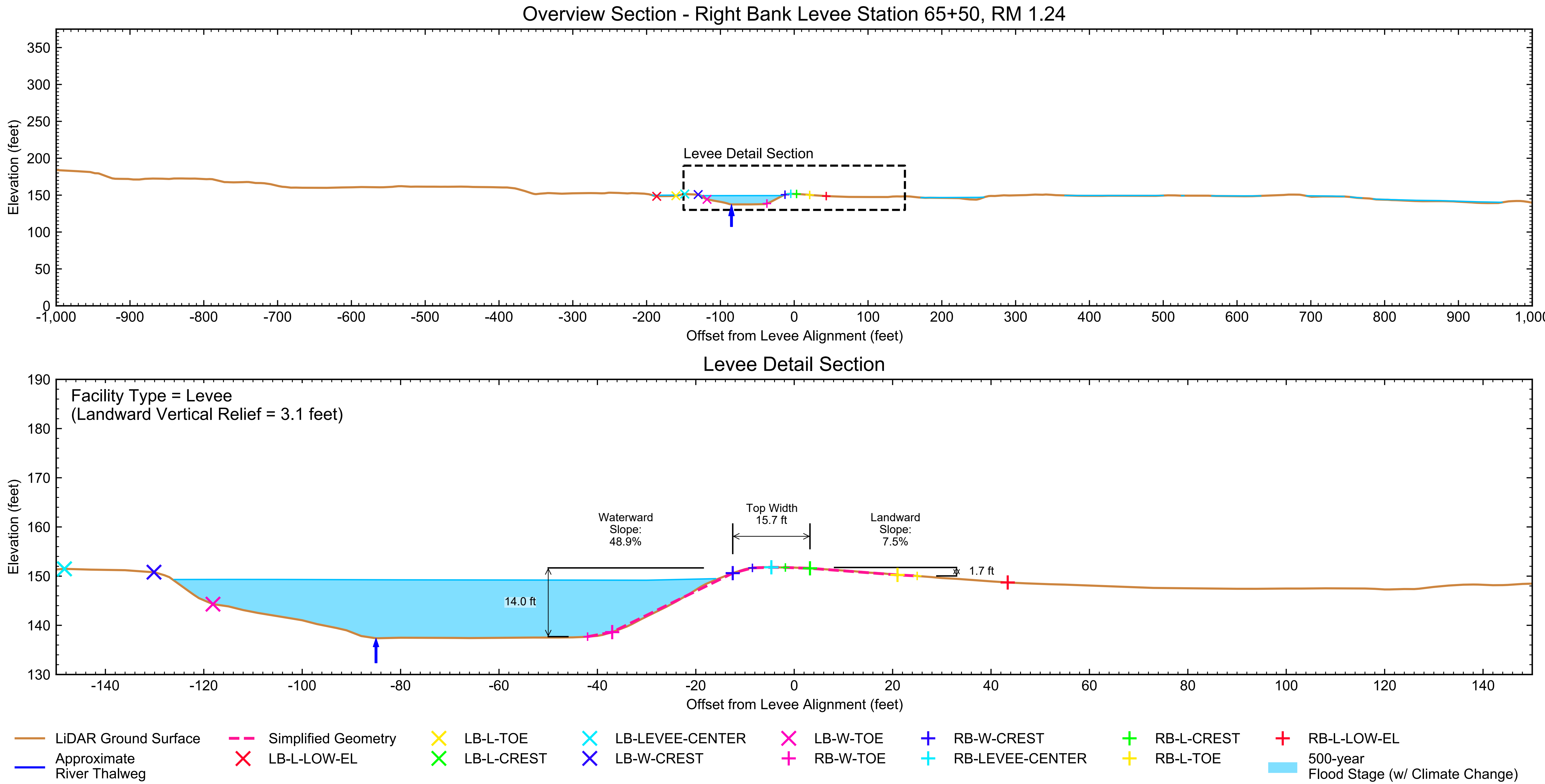
FIG. A-269



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
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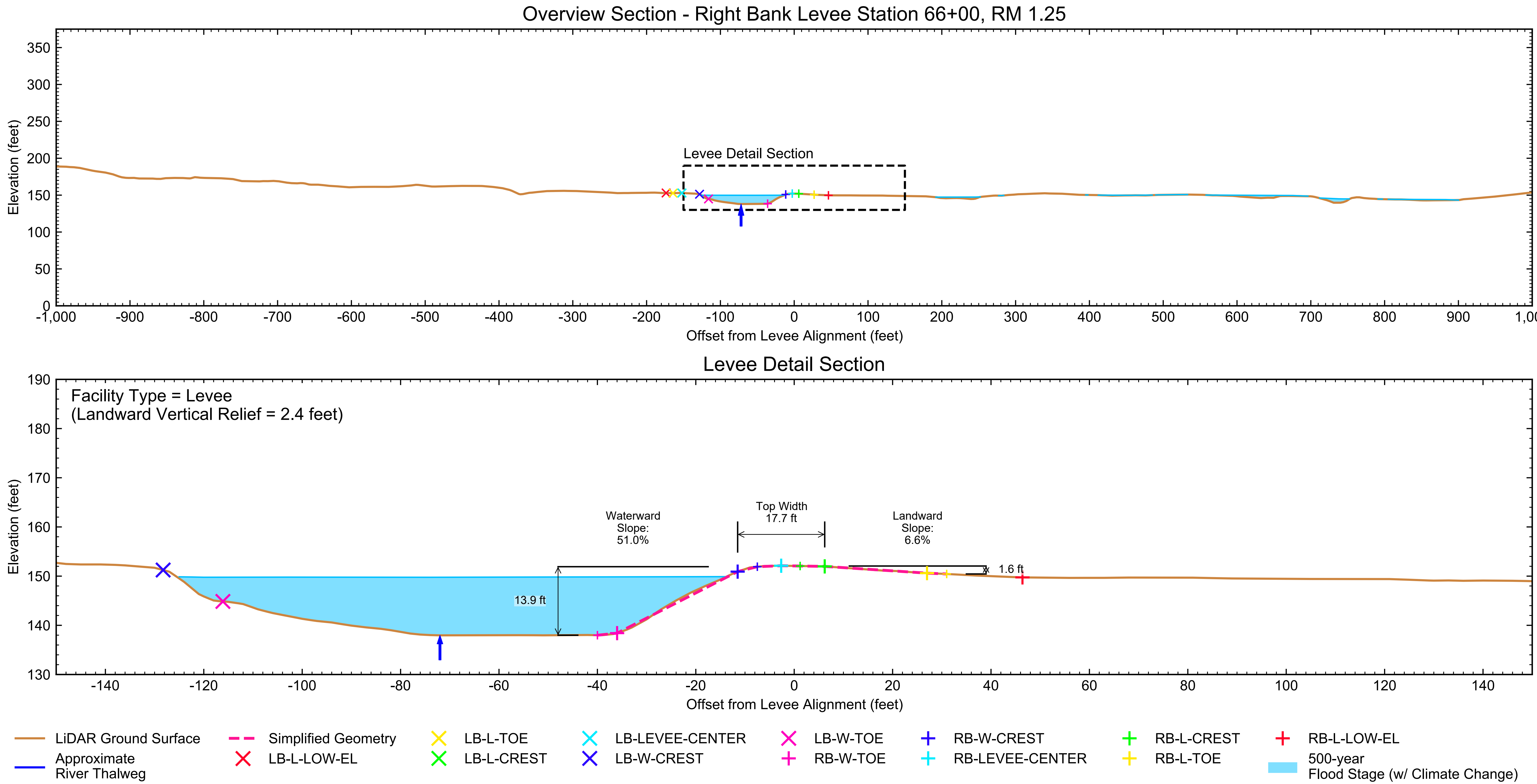
FIG. A-270



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 66+00, RM 1.25

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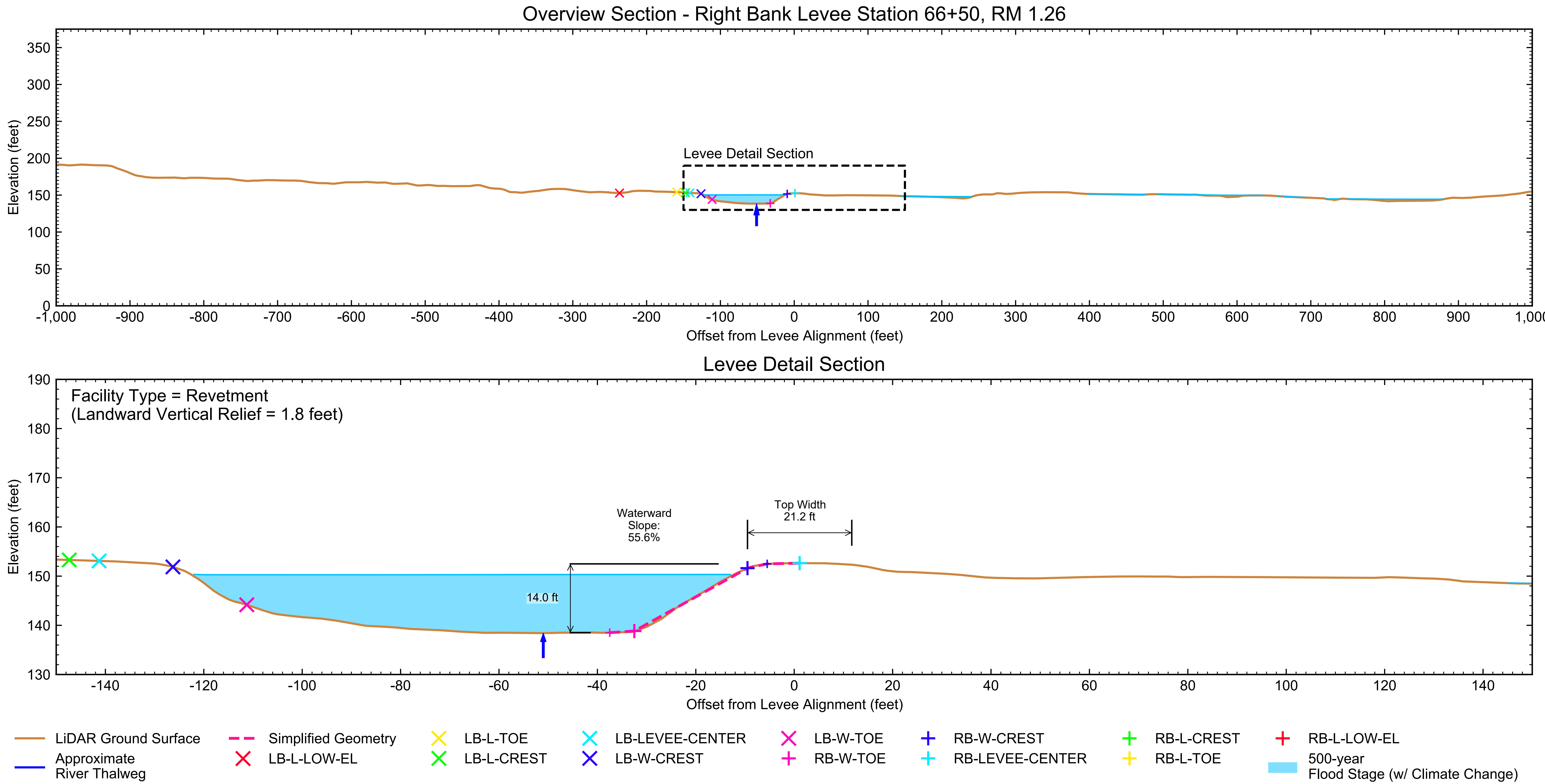
FIG. A-271



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 66+50, RM 1.26

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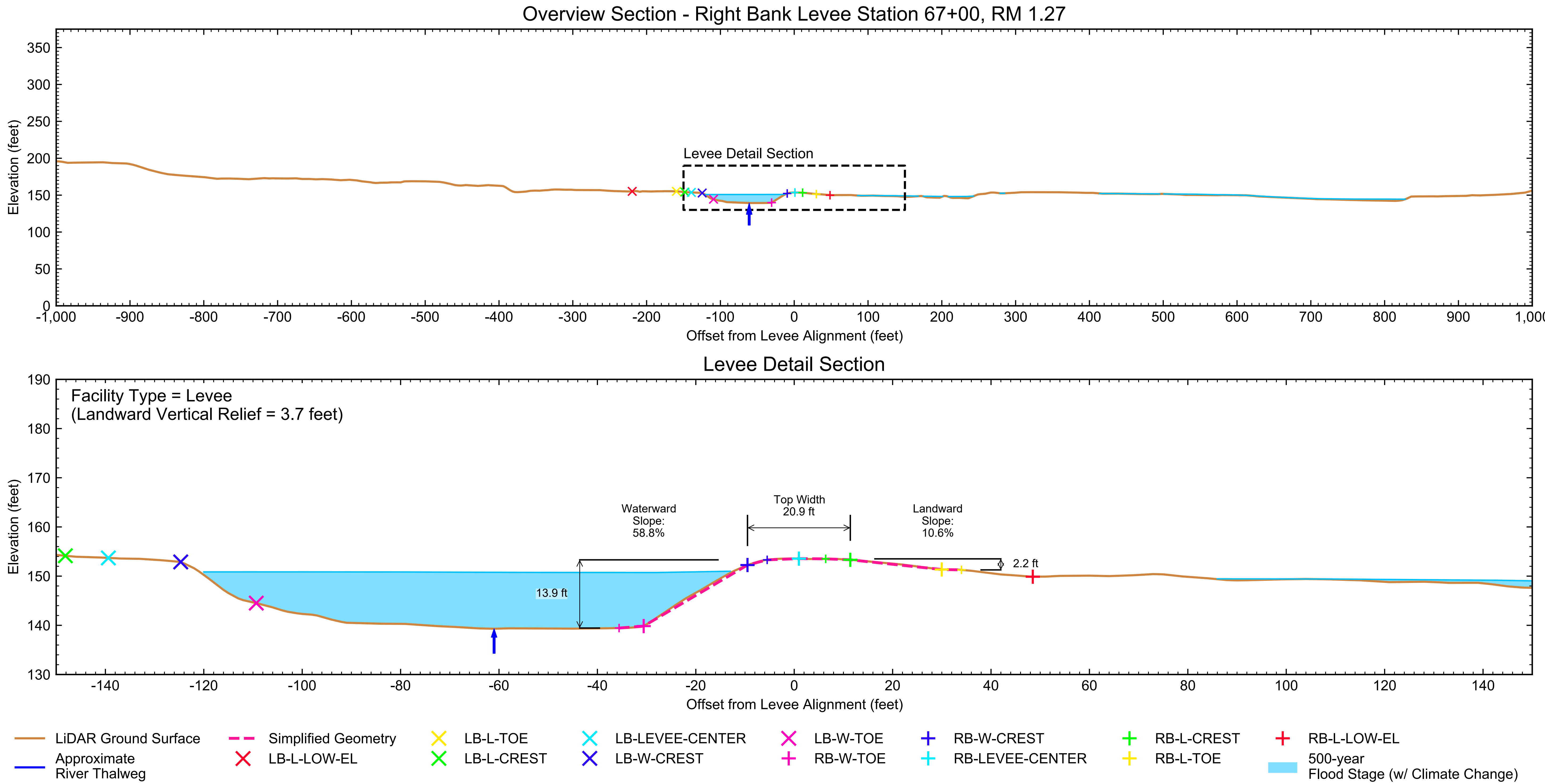
FIG. A-272



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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LOWER RAGING RIVER
RIGHT BANK STA 67+00, RM 1.27

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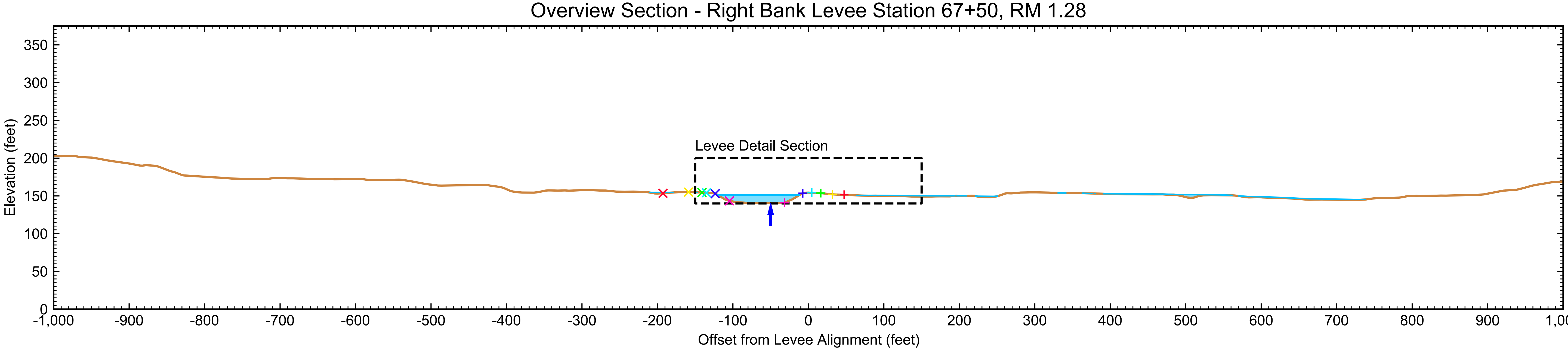
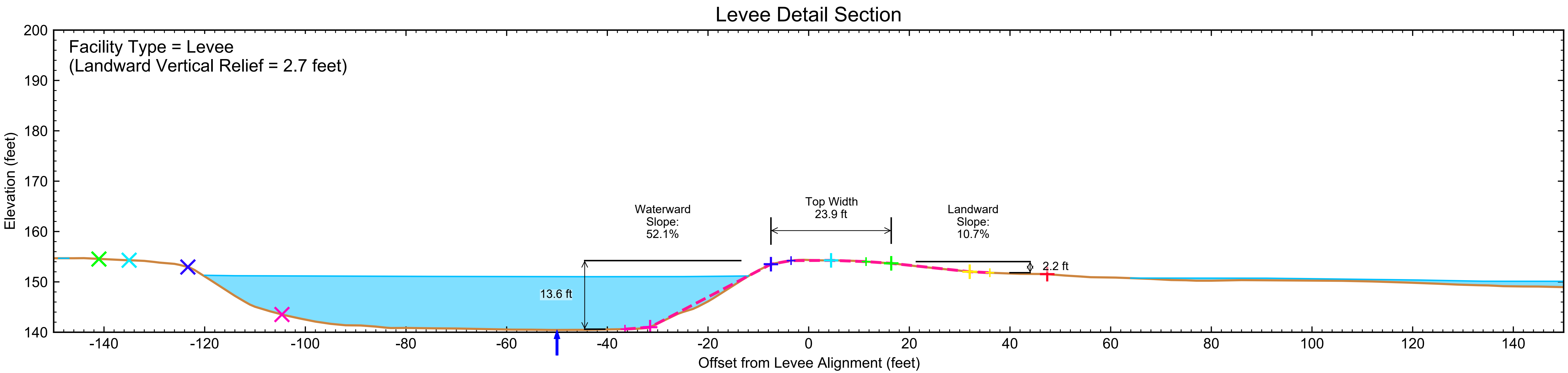
FIG. A-273





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 67+50, RM 1.28

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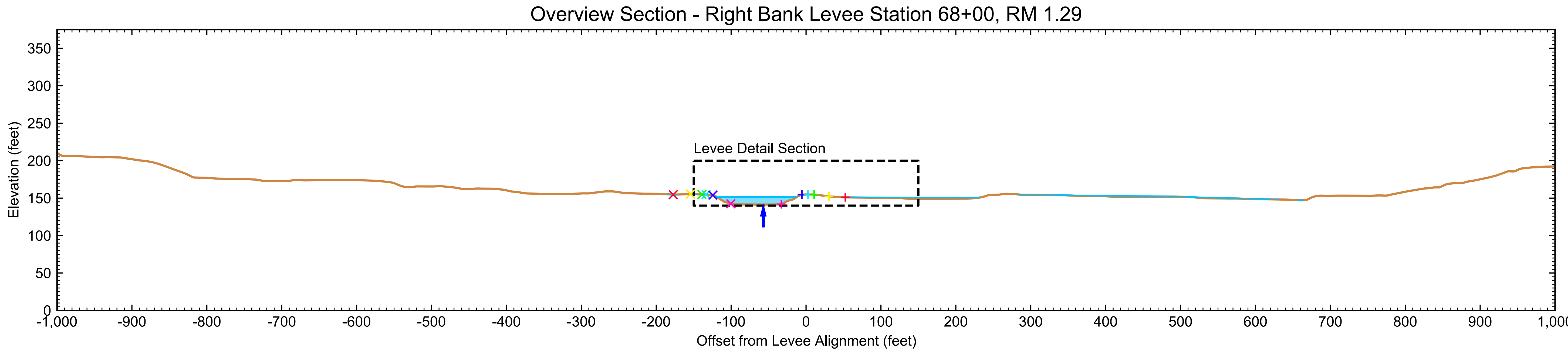
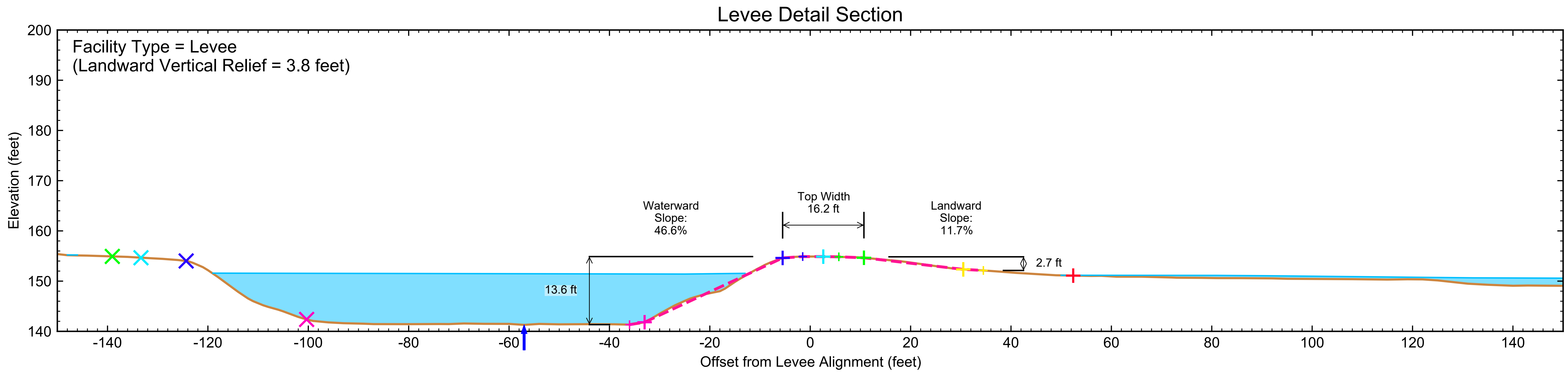
FIG. A-274





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL
Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 68+00, RM 1.29

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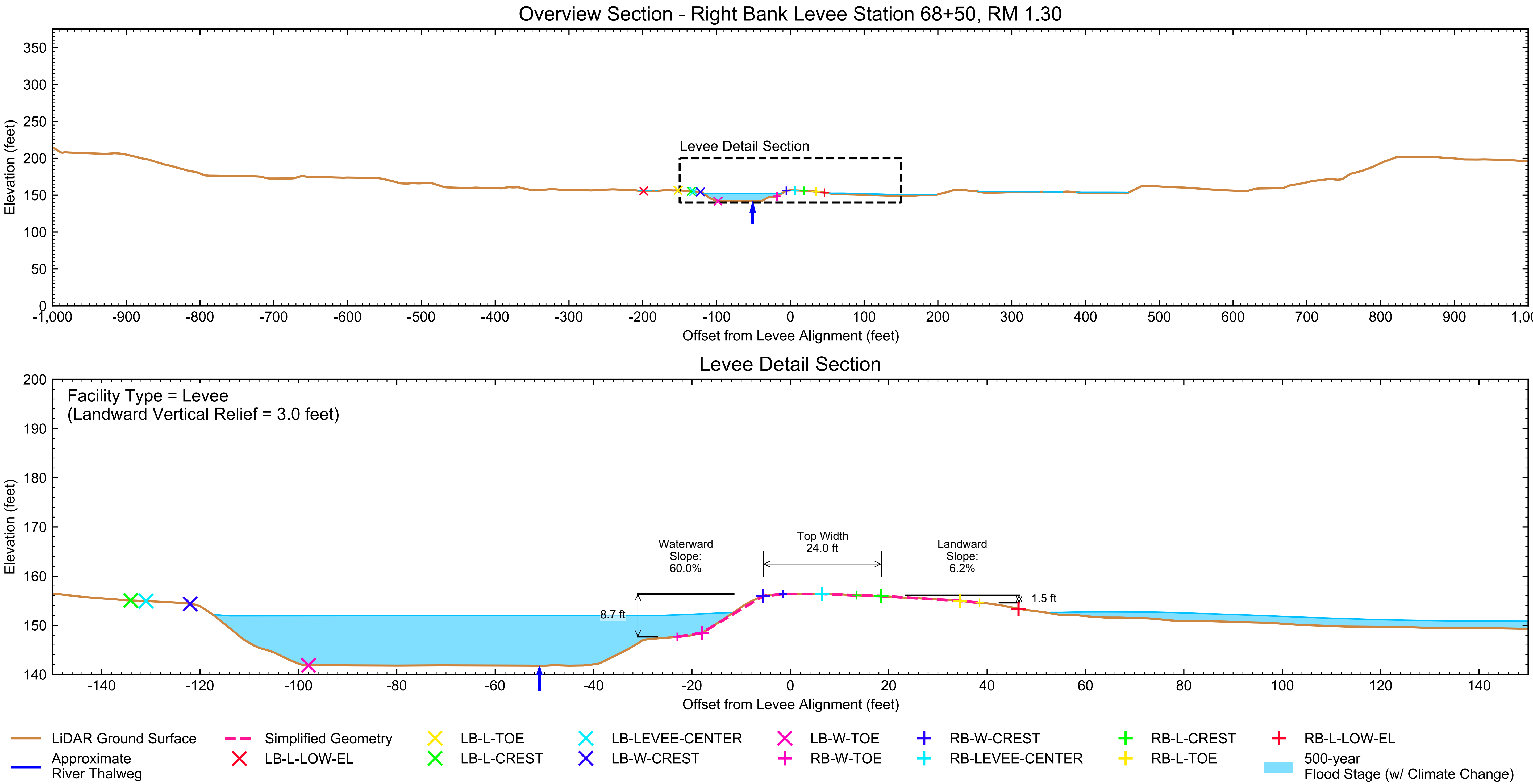
FIG. A-275



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 68+50, RM 1.30

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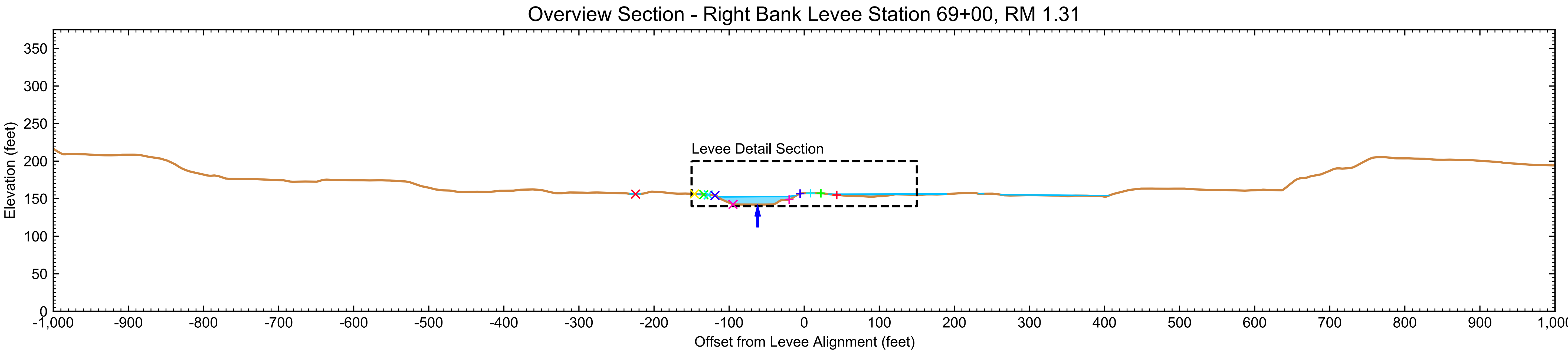
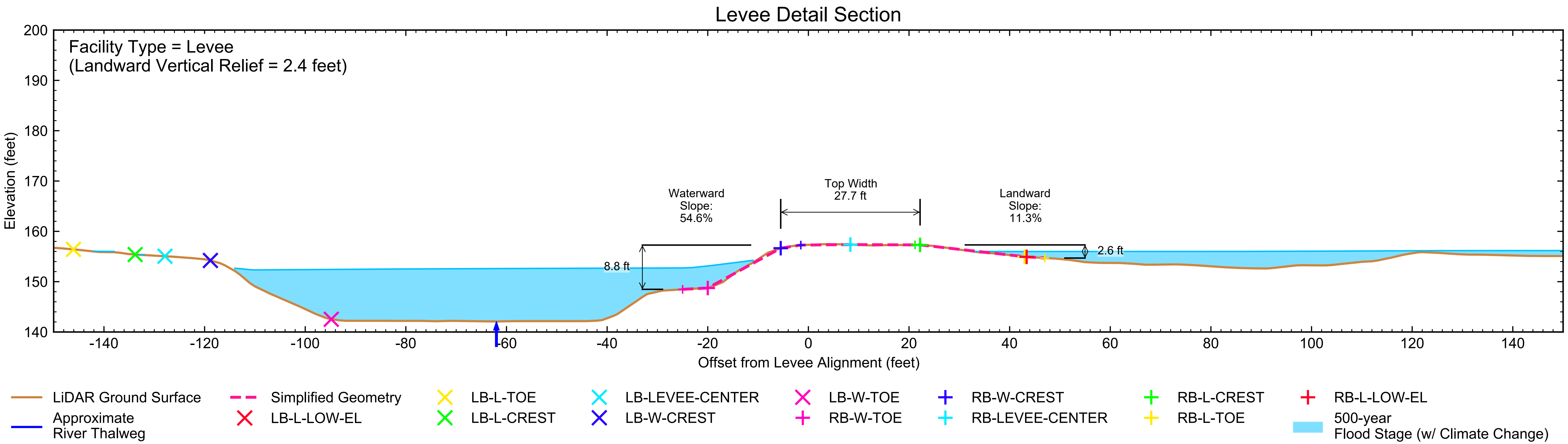
FIG. A-276





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 69+00, RM 1.31

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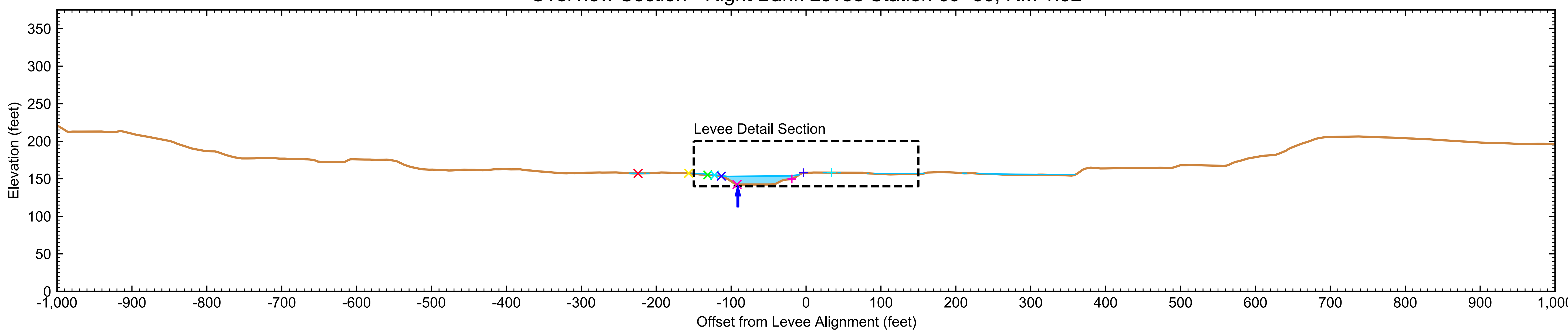
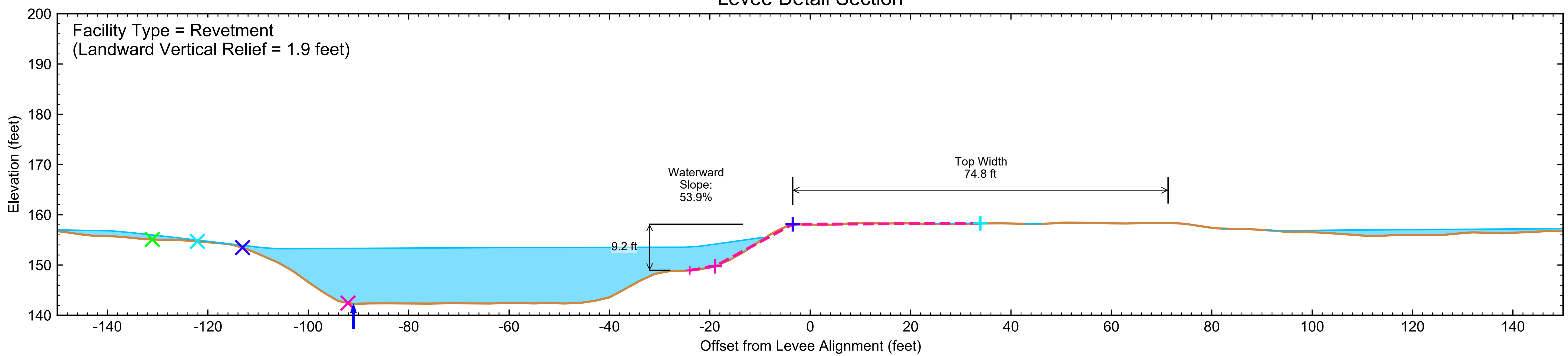
FIG. A-277

Overview Section - Right Bank Levee Station 69+50, RM 1.32



Levee Detail Section



LiDAR Ground Surface; Approximate River Thalweg; Simplified Geometry; LB-L-LOW-EL; LB-L-TOE; LB-L-CREST; LB-LEVEE-CENTER; LB-W-CREST; LB-W-TOE; RB-W-TOE; RB-W-CREST; RB-LEVEE-CENTER; RB-L-CREST; RB-L-TOE; RB-L-LOW-EL; 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
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LIDAR CROSS SECTION
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RIGHT BANK STA 69+50, RM 1.32

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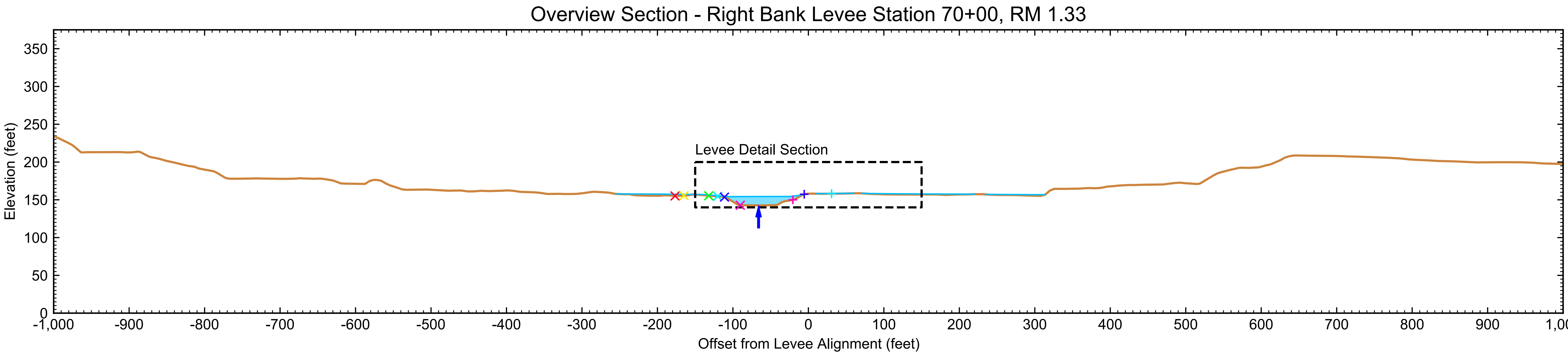
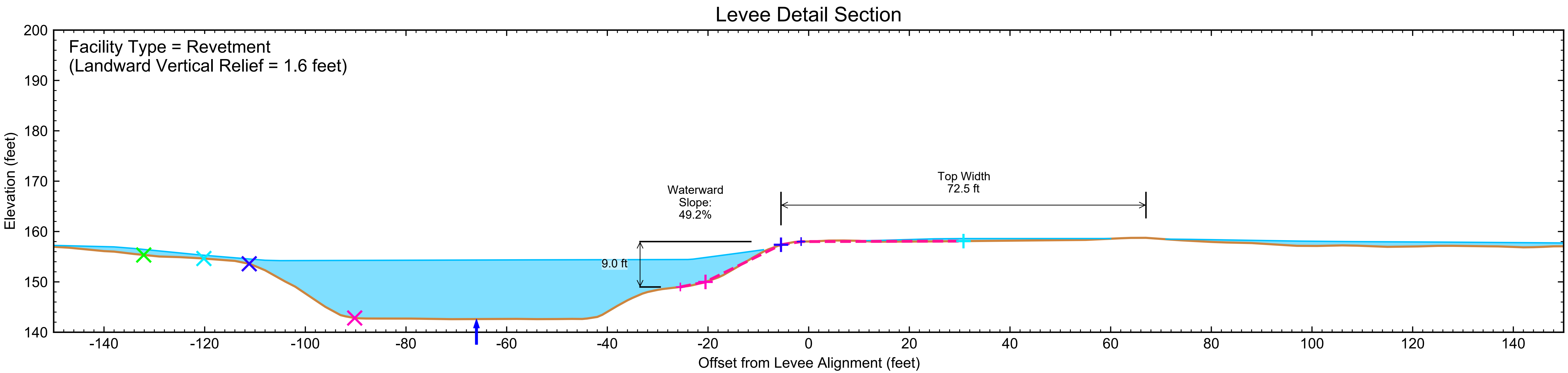
FIG. A-278





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL

Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:

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7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

Levee Breach Analysis Mapping and Risk Assessment
Segmentation and Stability Approach Report
King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 70+00, RM 1.33

April 2022 | 103692-304

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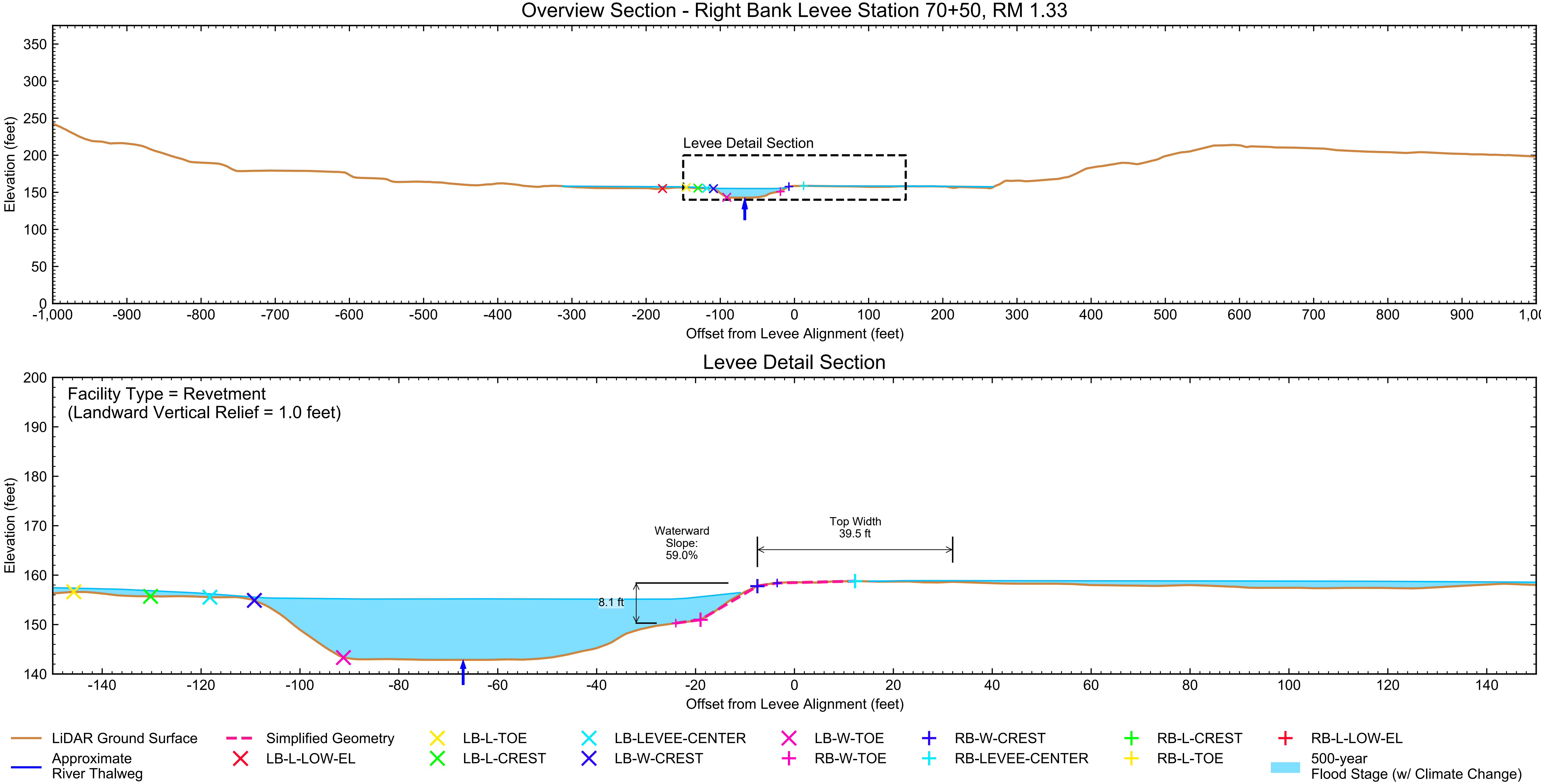
FIG. A-279



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 70+50, RM 1.33

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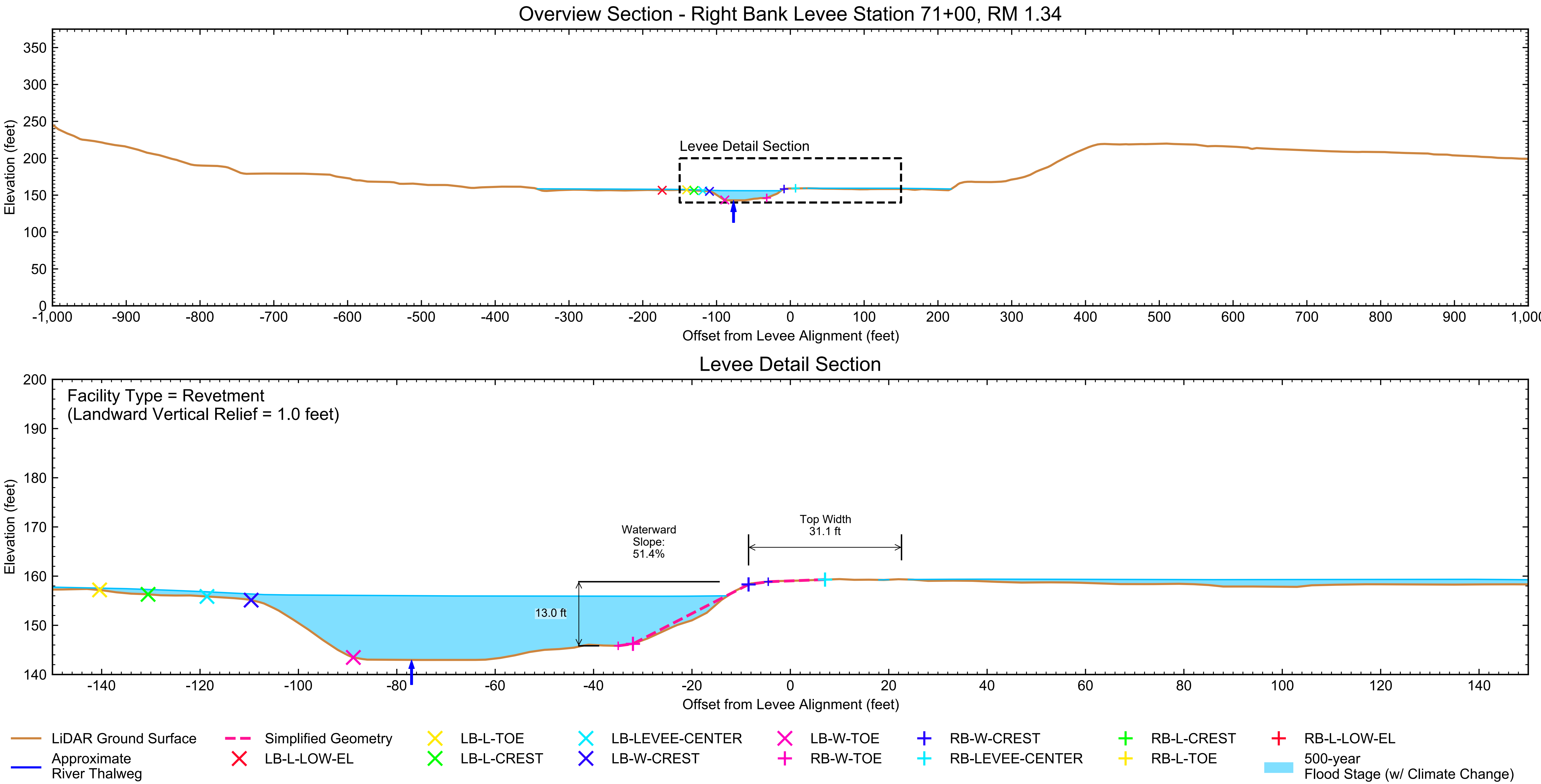
FIG. A-280



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 71+00, RM 1.34

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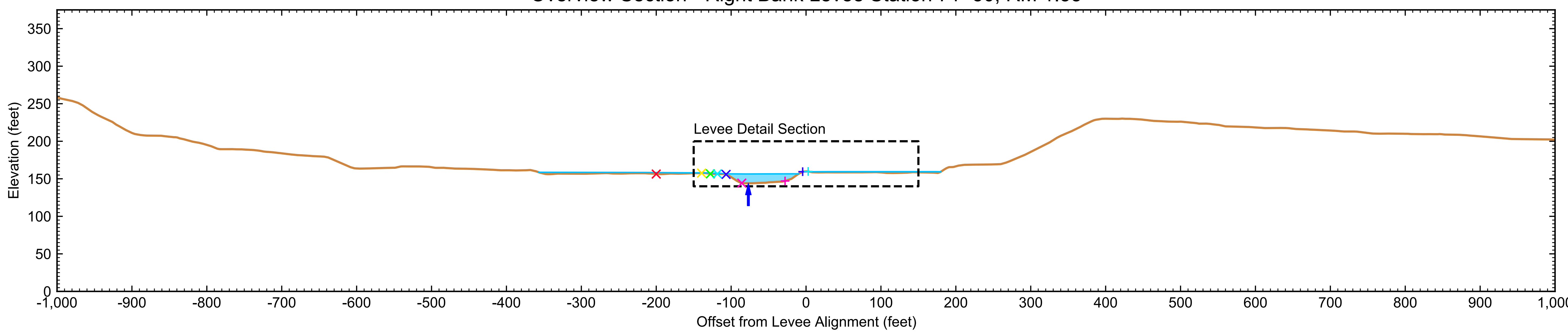
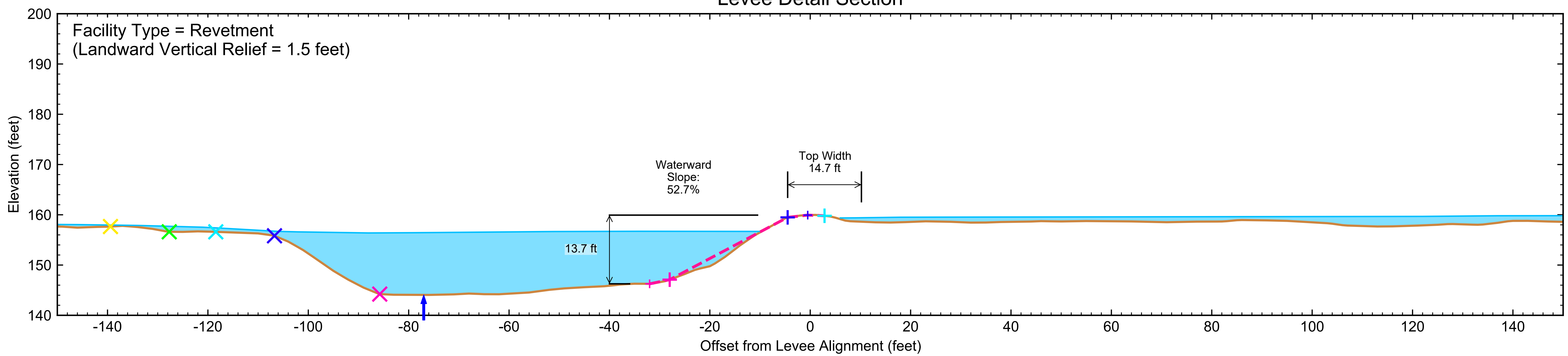
FIG. A-281

Overview Section - Right Bank Levee Station 71+50, RM 1.35



Levee Detail Section



LiDAR Ground Surface — Approximate River Thalweg — Simplified Geometry — LB-L-LOW-EL — LB-L-TOE — LB-L-CREST — LB-LEVEE-CENTER — LB-W-CREST — LB-W-TOE — RB-W-TOE — RB-W-CREST — RB-LEVEE-CENTER — RB-L-CREST — RB-L-TOE — RB-L-LOW-EL — 500-year Flood Stage (w/ Climate Change)

Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 71+50, RM 1.35

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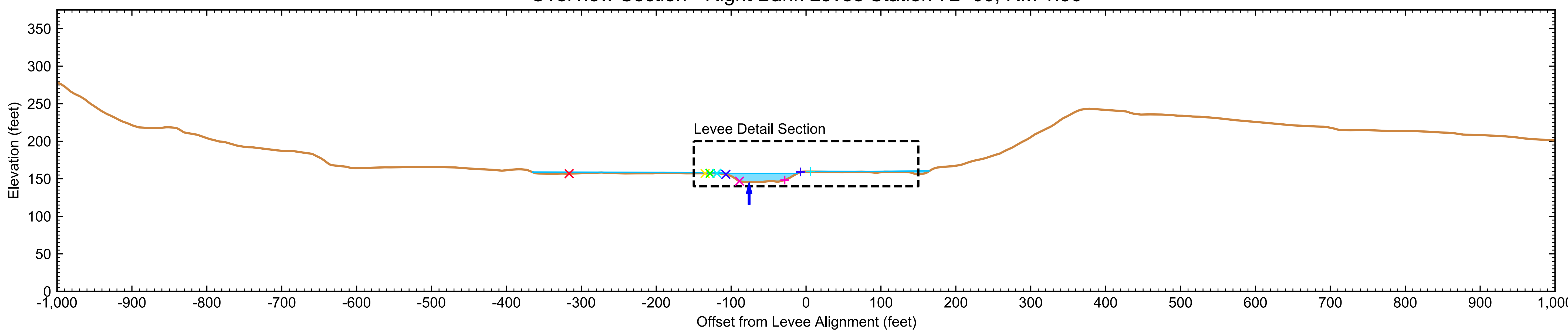
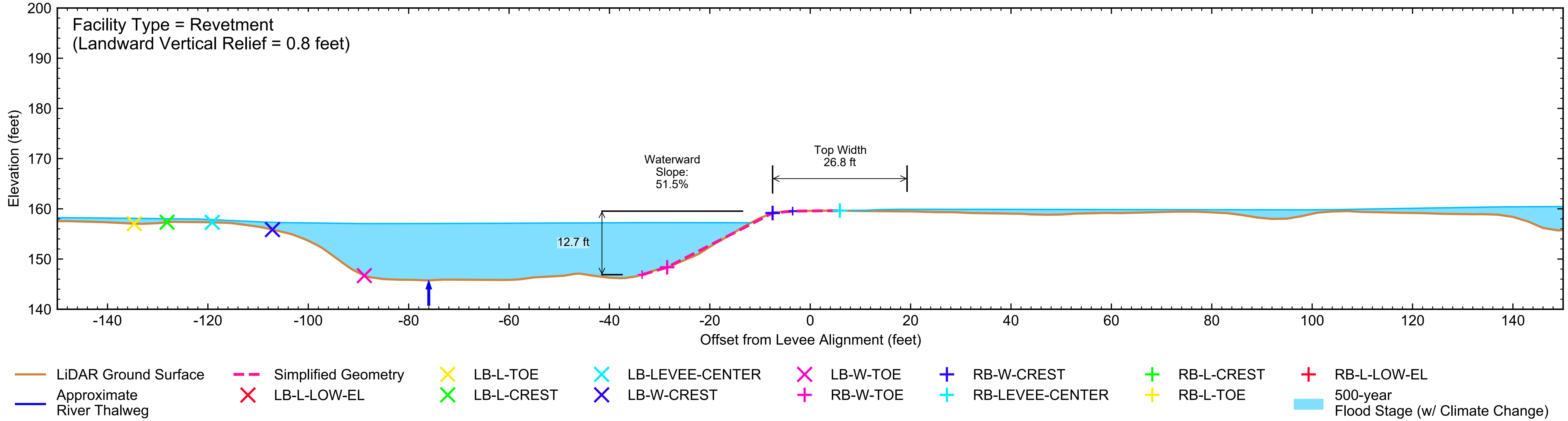
FIG. A-282

Overview Section - Right Bank Levee Station 72+00, RM 1.36



Levee Detail Section



Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 72+00, RM 1.36

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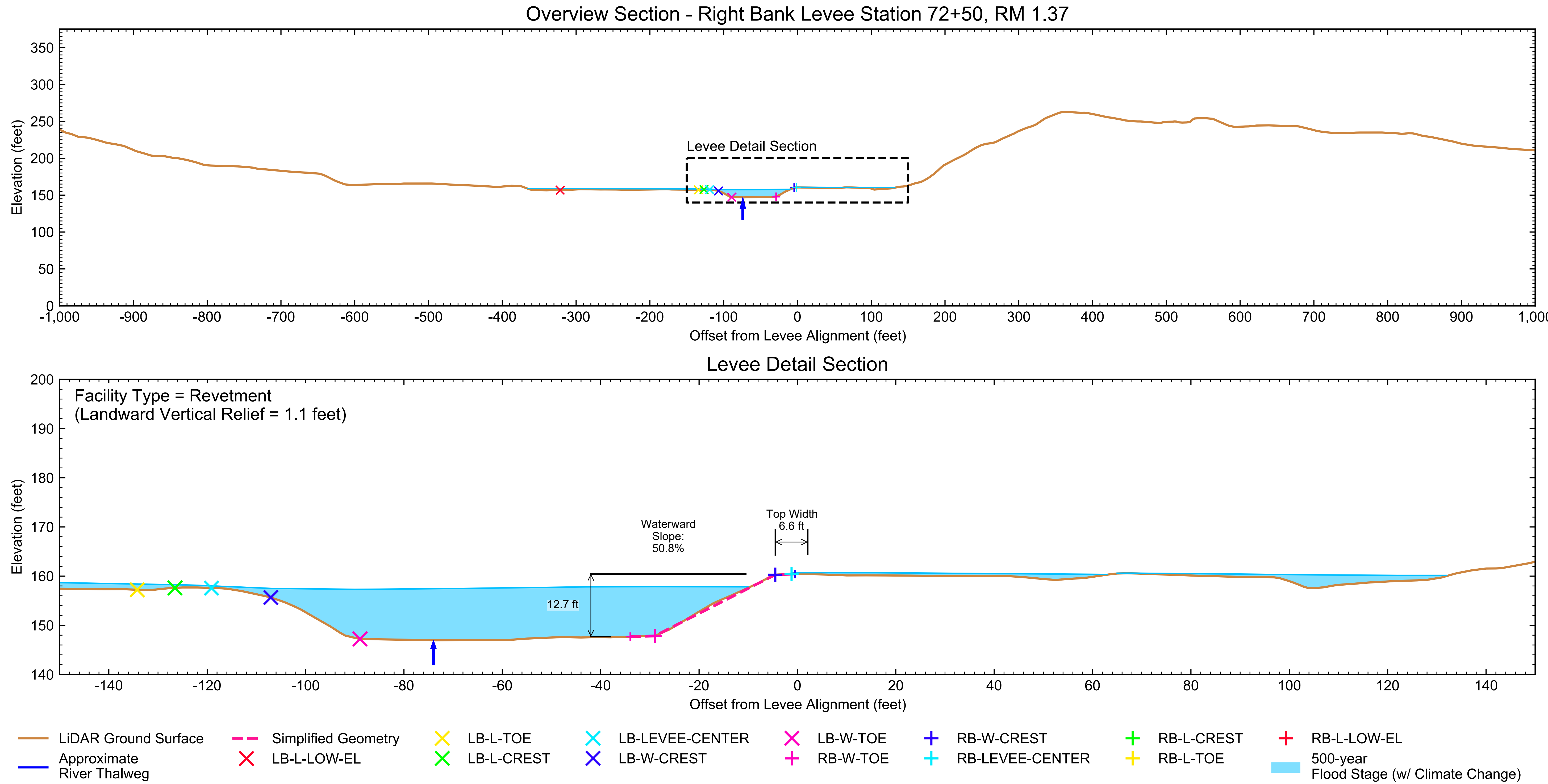
FIG. A-283



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 72+50, RM 1.37

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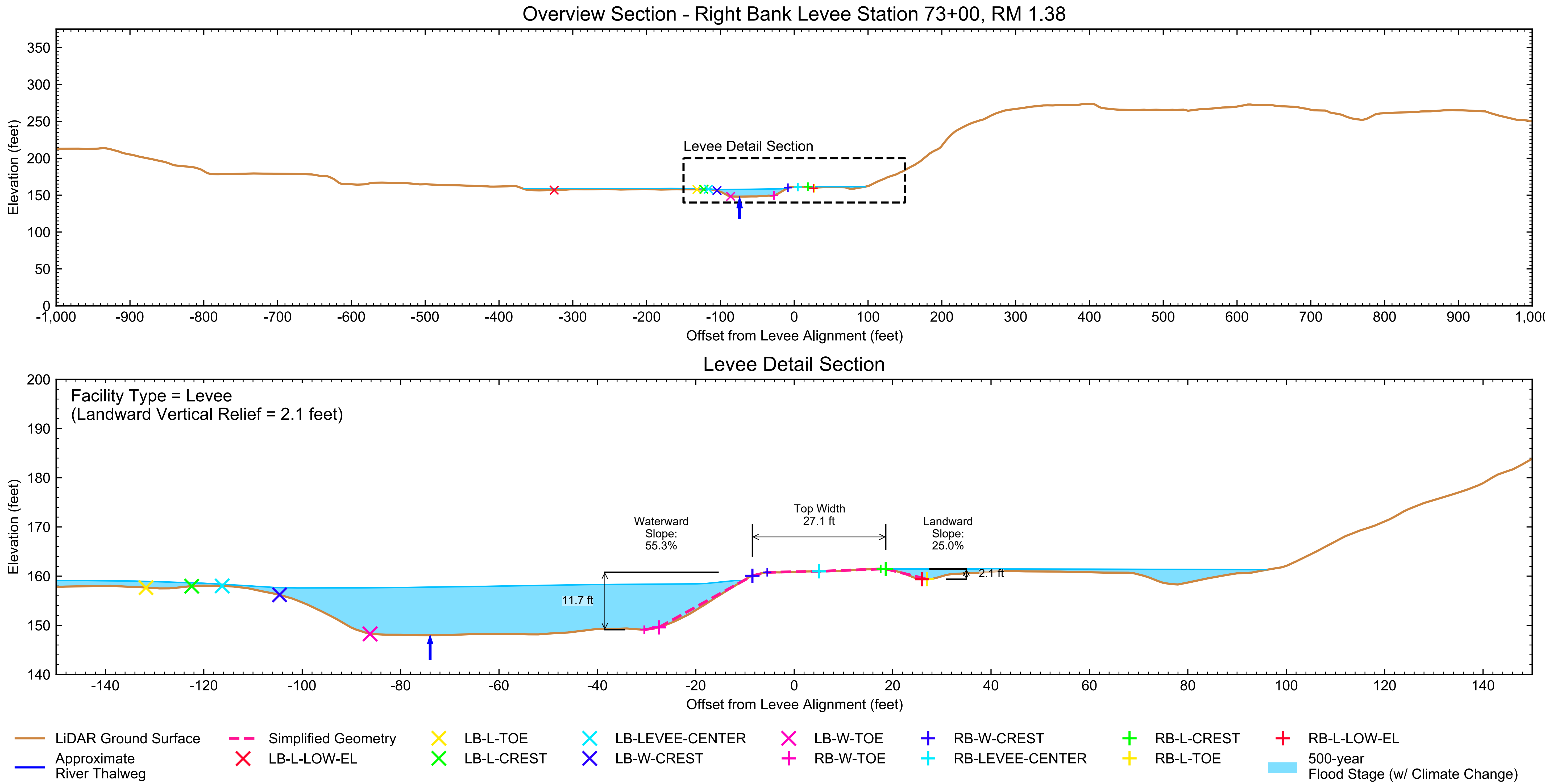
FIG. A-284



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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 73+00, RM 1.38

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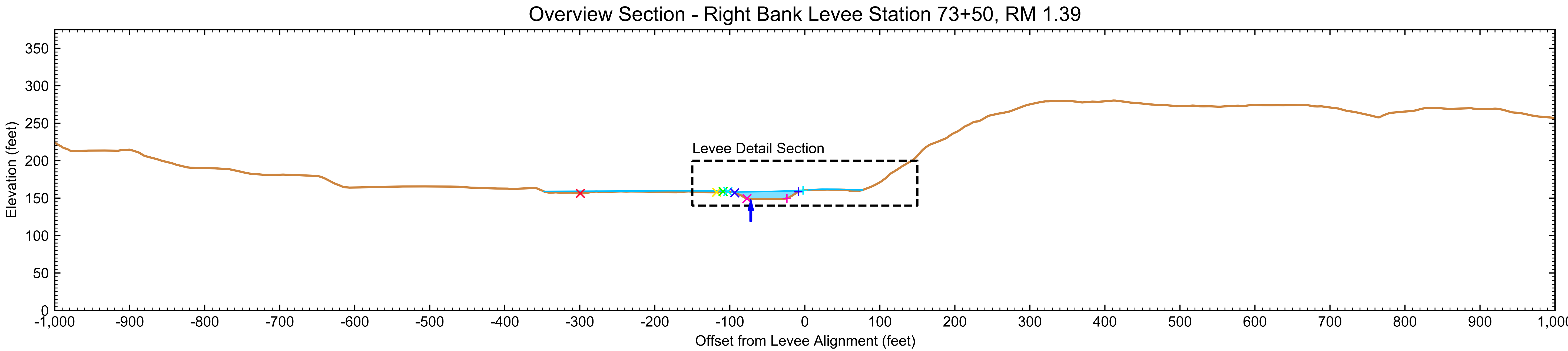
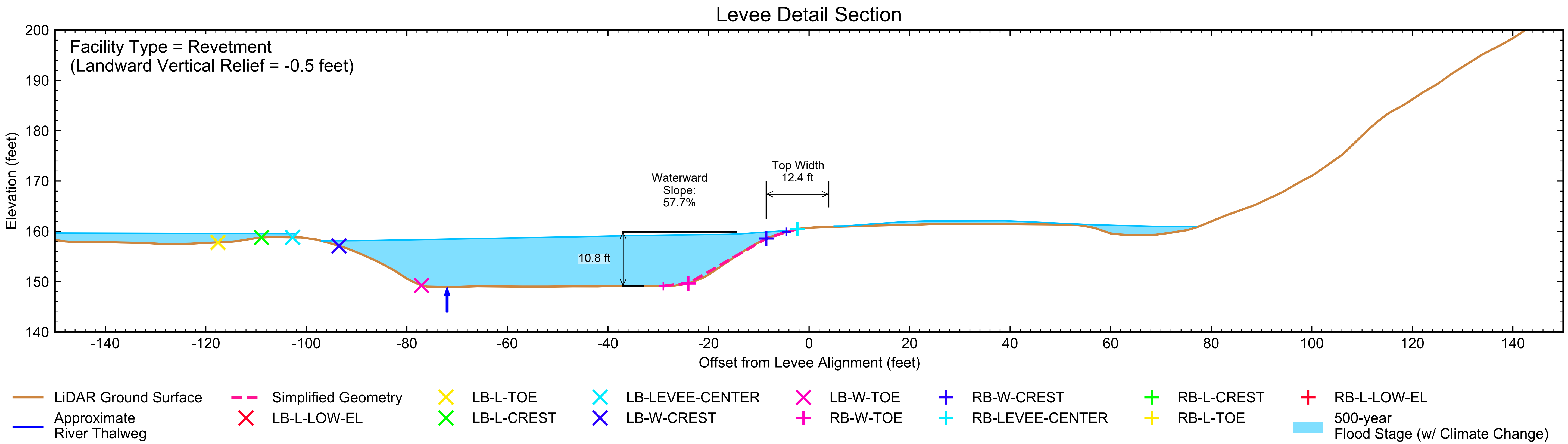
FIG. A-285





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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 73+50, RM 1.39

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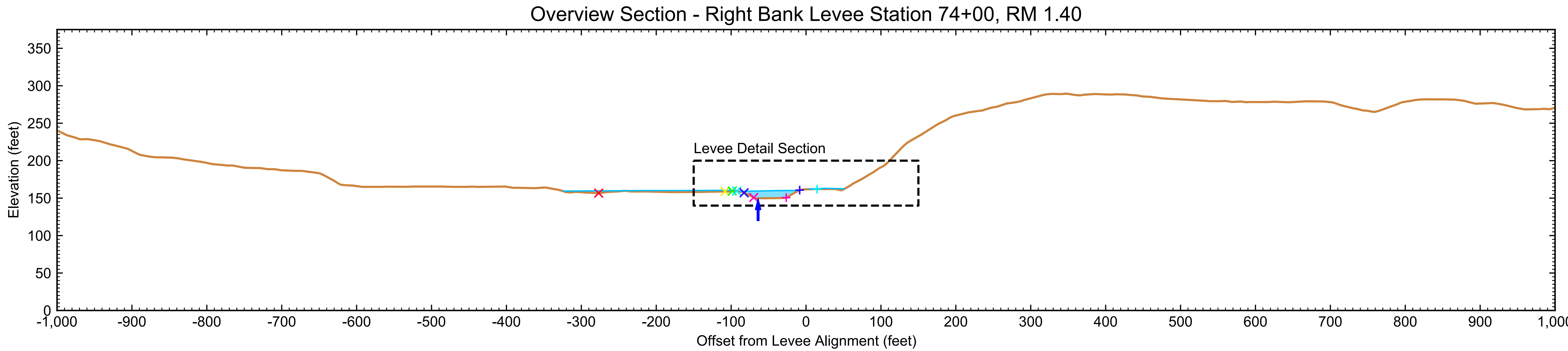
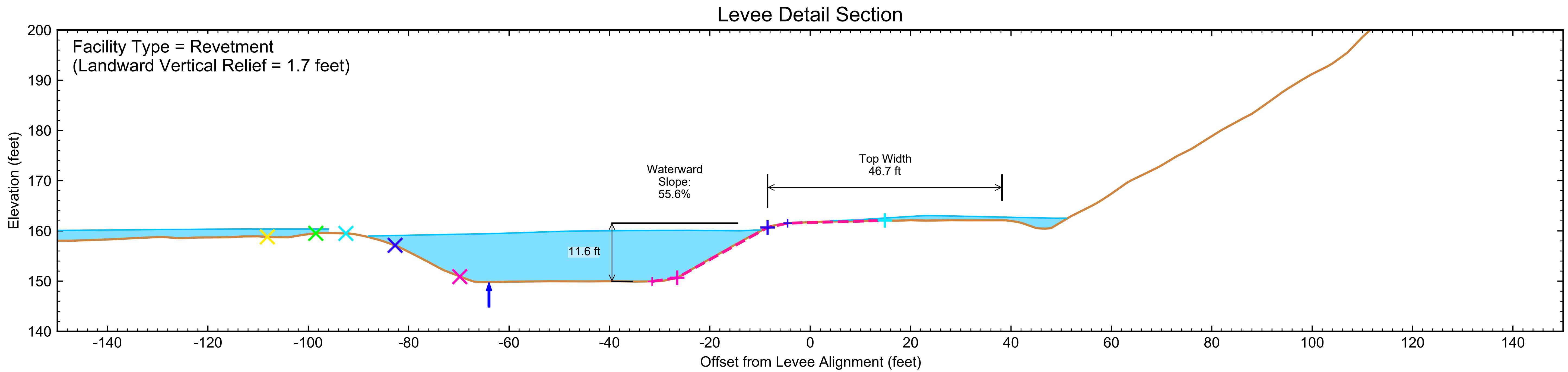
FIG. A-286





LiDAR Ground Surface — Approximate River Thalweg — Simplified Geometry — LB-L-LOW-EL — LB-L-TOE — LB-L-CREST — LB-LEVEE-CENTER — LB-W-CREST — LB-W-TOE — RB-W-TOE — RB-W-CREST — RB-LEVEE-CENTER — RB-L-CREST — RB-L-TOE — RB-L-LOW-EL — 500-year Flood Stage (w/ Climate Change)

Notes:
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 74+00, RM 1.40

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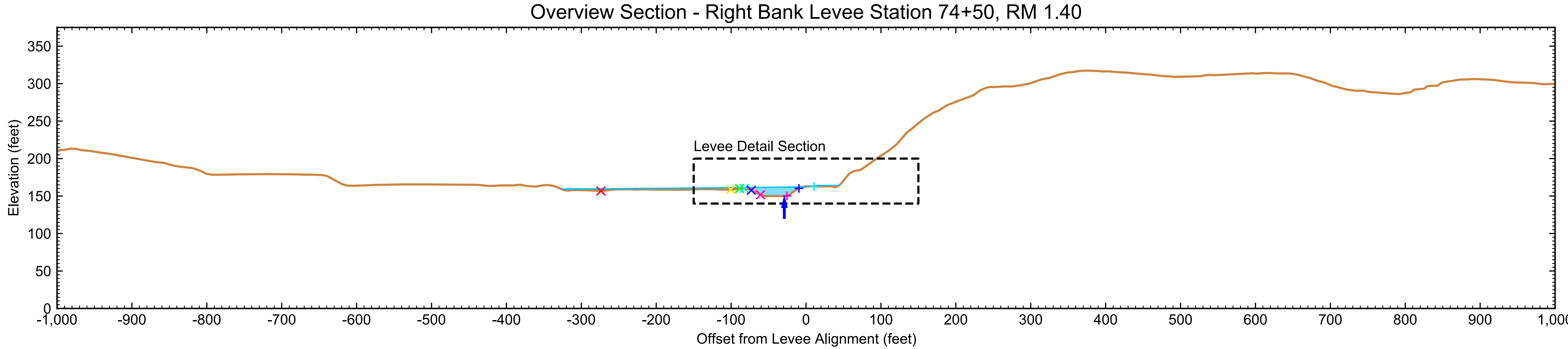
FIG. A-287



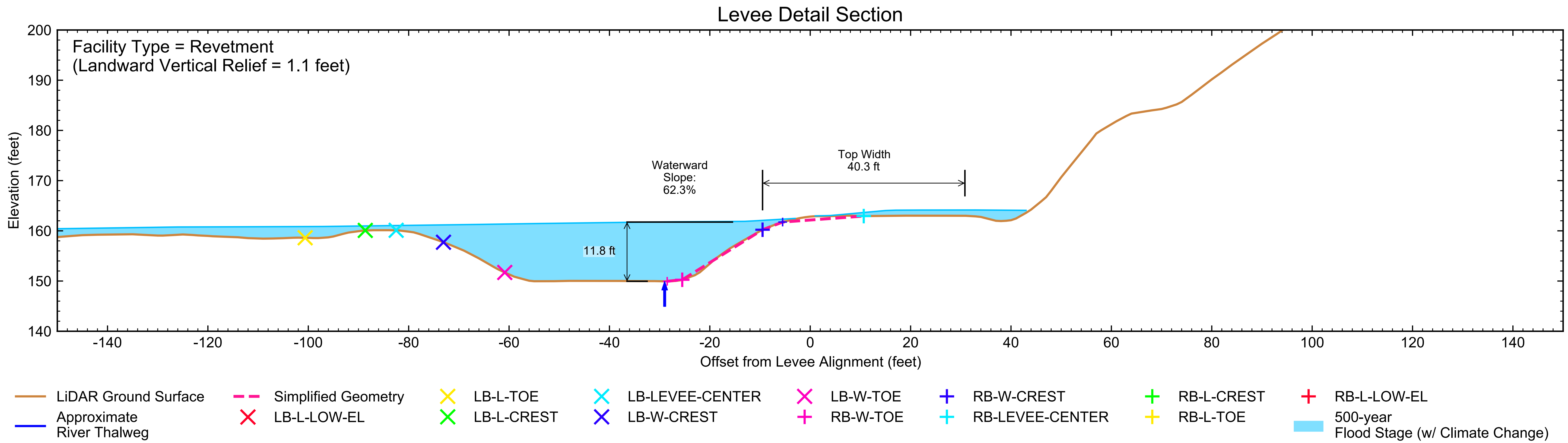


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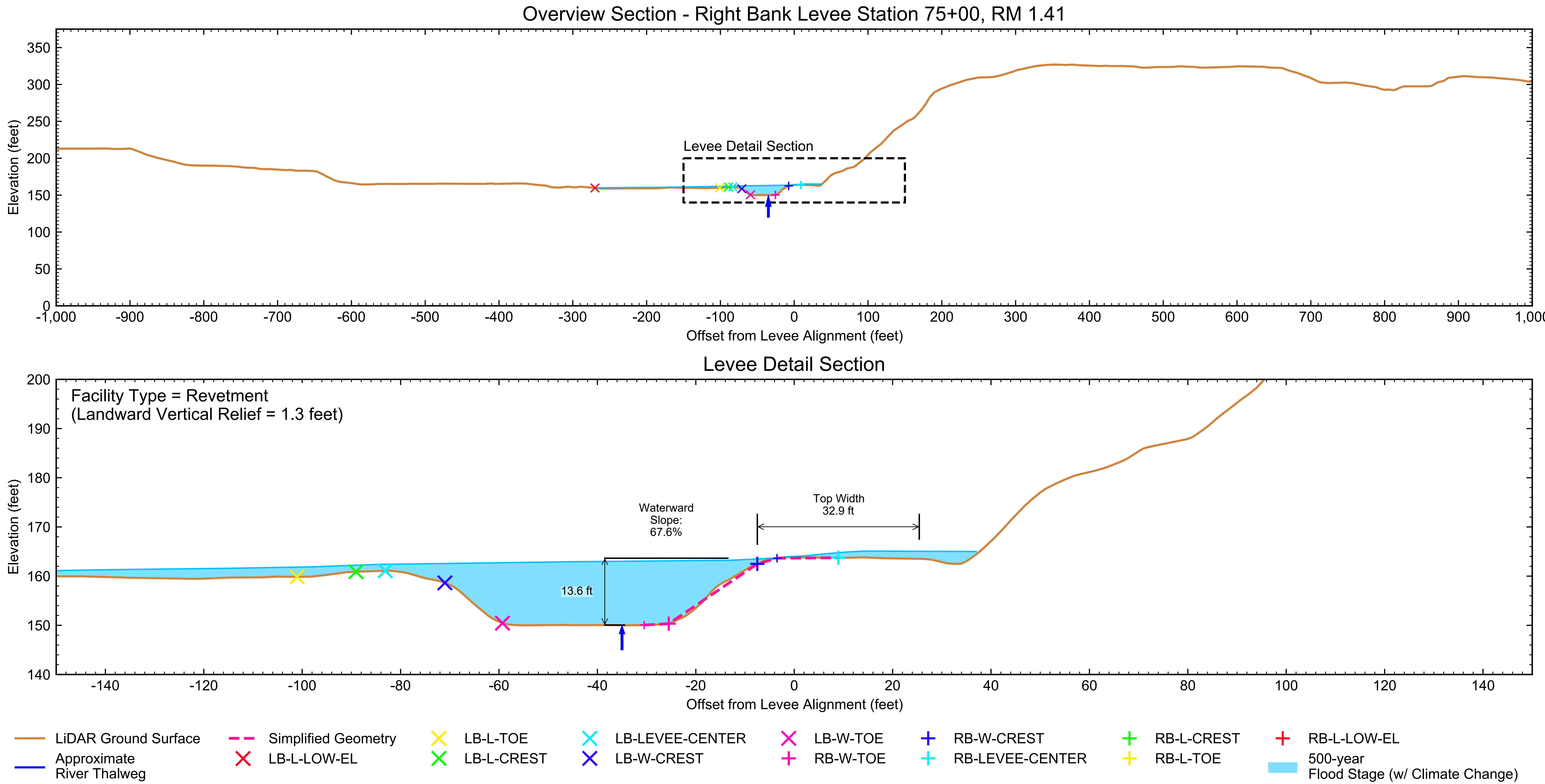
FIG. A-288



Notes:
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2. Station numbering runs from downstream to upstream along the Lower Raging River.
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4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
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LIDAR CROSS SECTION
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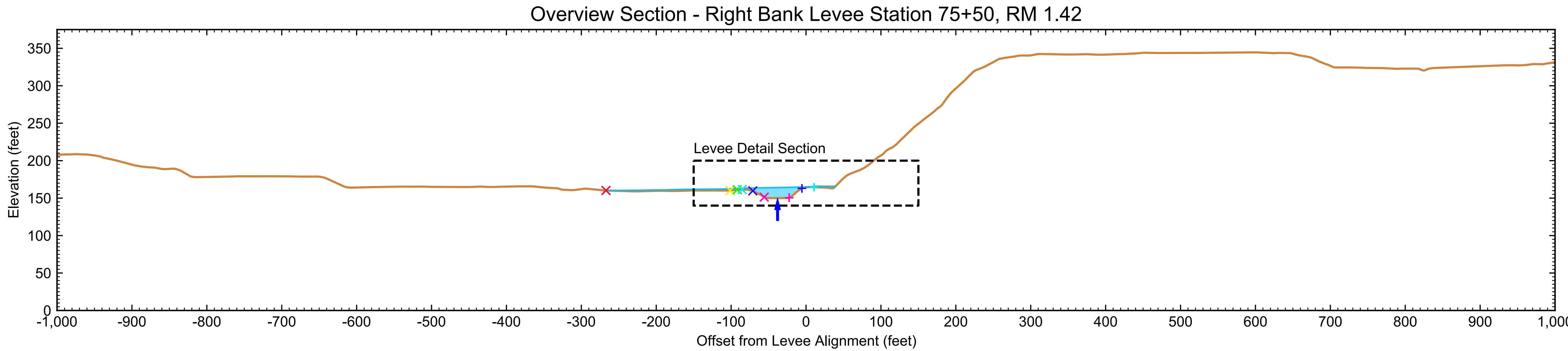
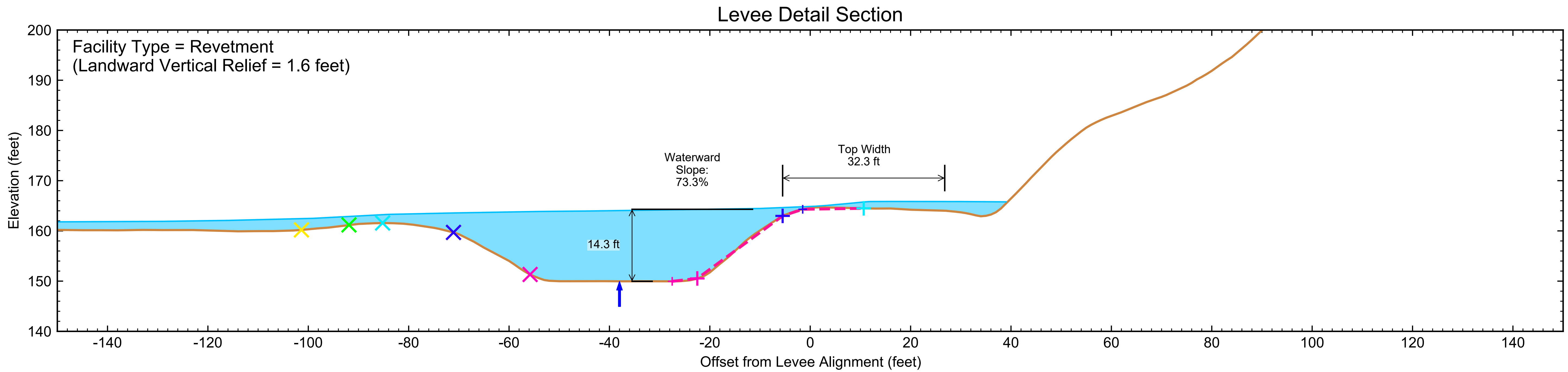
FIG. A-289





LiDAR Ground Surface | Simplified Geometry | LB-L-TOE | LB-LEVEE-CENTER | LB-W-TOE | RB-W-CREST | RB-L-CREST | RB-L-LOW-EL
Approximate River Thalweg | LB-L-LOW-EL | LB-L-CREST | LB-W-CREST | RB-W-TOE | RB-LEVEE-CENTER | RB-L-TOE | 500-year Flood Stage (w/ Climate Change)

Notes:
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4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
7. Vertical dimensions shown in this figure are the vertical distance between the highest point within 5 feet of the delineated crest and the lowest point within 5 feet of the delineated toe. These minimum and maximum points are indicated with smaller versions of the crest and toe point markers.
8. Slope angles shown in this figure are considered representative of the slope as a whole and may be less than the maximum tangential angle along the slope.

Levee Breach Analysis Mapping and Risk Assessment
Segmentation and Stability Approach Report
King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 75+50, RM 1.42

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FIG. A-290

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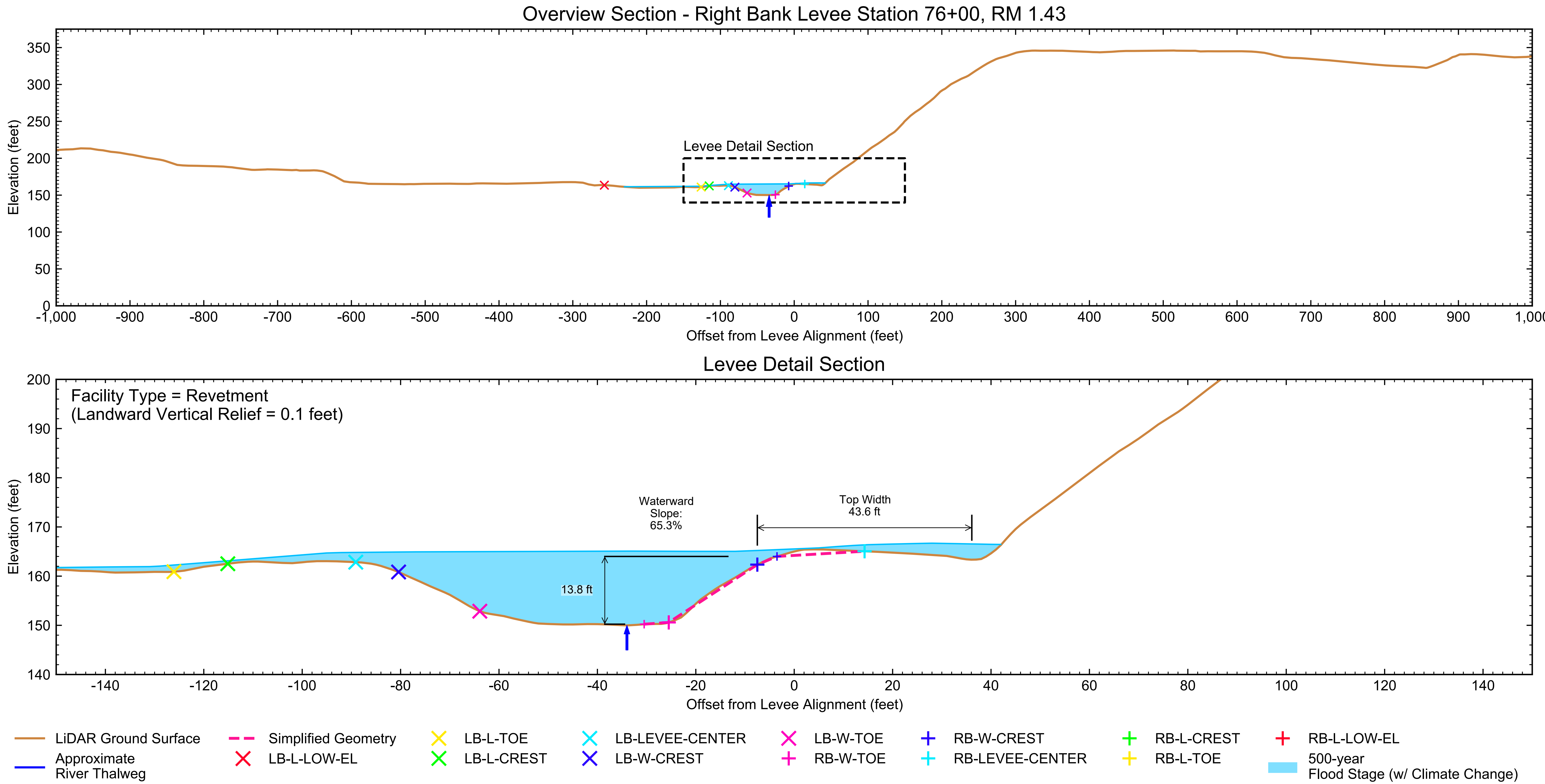
\\SEA-FS1\Vol1\EP\SEA\103000s\103692 KC Levee Breach\300 LRR\04_Levee Stability Assess\Levee Geometric Data



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
3. Approximate river thalweg determined by taking the minimum elevation point within the river.
4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
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LIDAR CROSS SECTION
LOWER RAGING RIVER
RIGHT BANK STA 76+00, RM 1.43

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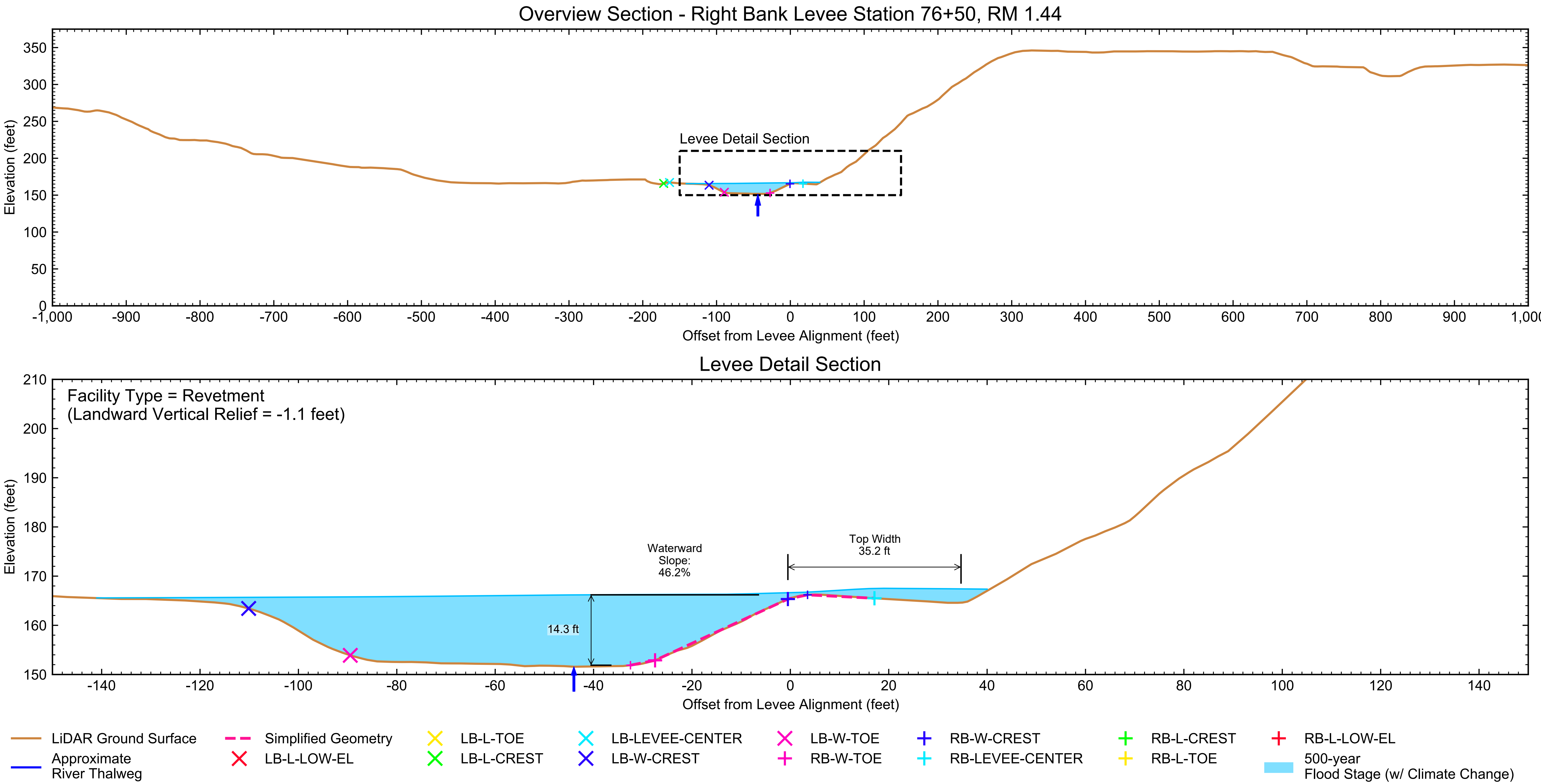
FIG. A-291



Notes:
1. LB = Left Bank; L = Landward; RB = Right Bank; W = Waterward; RM = River Mile.
2. Station numbering runs from downstream to upstream along the Lower Raging River.
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4. 500-year flood water surface elevation (WSE) including climate change shown for reference only. WSE provided by NHC January 10, 2022.
5. In this study, we define a revetment as any flood protection facility where the total vertical relief between the highest point within the facility and the lowest elevation on the low ground point landward side is 2 feet or less. We consider facilities with landward vertical reliefs higher than 2 feet to be levees. We defined the low ground point as the point within a zone from the delineated landward crest and the point where trial lines from the crest intersects the ground surface. These lines and intersection points are indicated in light gray for reference. We do not consider land outside of a 10 Horizontal to 1 Vertical (10H:1V) zone to contribute to levee instability.
6. We also used these gray lines to guide an algorithm that identifies the levee toe points. In this algorithm, the toe is located by rotating the ground surface curve under the gray line by the angle of the gray line and then finding the lowest point of the rotated ground curve. We used a similar approach to refine levee crests, except the crest was located by taking the high point of the rotated curve.
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King County, Washington

LIDAR CROSS SECTION
LOWER RAGING RIVER
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FIG. A-292

APPENDIX B: SCOUR ANALYSIS

Appendix B
Scour Analysis

CONTENTS

APPENDIX B: SCOUR ANALYSIS

B.1 SCOUR APPROACH AND RESULTS

For this study, the hydraulic engineer for the Lower Raging, NHC, will evaluate scour at the selected representative cross sections for the 1% annual exceedance probability flood, which is equivalent to the 100-year recurrence period flood. NHC's scour estimation approach for the Lower Raging River is summarized in this Appendix.

To calculate bend scour at the representative section, NHC first conducted a literature review to determine the most appropriate bend scour equation for this setting. NHC visually estimated a median particle diameter (D_{50}) for this site of 5 inches from photos and notes taken during the site visit. The literature review revealed that there are no bend scour equations tailored for coarse cobble-bed rivers such as the Raging River - most bend scour equations were developed by regression analysis against a dataset of field measurements from primarily sand-bed rivers. Given the lack of methods for scour estimation in cobble bedded rivers, NHC developed scour estimates for the 100-year flood event using two different equations.

The Ettema and others (2010) equation is a semi-empirical scour equation originally developed to predict scour around bridge abutments but has been successfully applied to coarse gravel bed rivers to provide scour depth estimates in unobstructed and obstructed flows (i.e., around bank flow deflection structures) using appropriate parameters. The form of the equation (from Ettema and others, 2010) is:

$$d_{sm} = \left(\alpha \left(\frac{\tau_0}{\tau_c} \right)^{\frac{3}{7}} * \left(\frac{q_b}{q_0} \right)^{\frac{6}{7}} - 1 \right) H$$

Where d_{sm} is the maximum scour depth below plane bed; τ_0 and τ_c are the bed shear stress upstream of the bend and the critical shear stress, respectively; q_b and q_0 are the unit discharges in the bend and upstream of the bend, respectively; H is the average depth upstream of the bend; and α is an amplification factor, i.e., a correction to the ambient bed shear stress to account for stress amplification due to flow acceleration in bends or presence of a shear layer due to turbulence at the toe of structures.

Most of these values were extracted directly from the hydraulic model, considering only the main channel portion of the results and excluding the slower, shallower flow in the floodplain. Variables that required determination from outside sources included τ_c and α. τ_c, the critical shear stress, was estimated using the methods of Kilgore and Young (1993), which is applicable for particles up to 16 inches in size. The method requires the Froude number as input, which was once again extracted from the main channel portion of the model. α, the amplification factor, is meant to represent the magnitude of increase in shear stress caused by turbulence from the features in question, which could be bends, boulder clusters, barbs, bridge abutments, etc. For the case of a bend, Kashyap and others (2012) found increases in bed shear of approximately 100% (α=2) in tight bends with a radius of curvature equal to 1.5. With parameters as noted above and an α value of 2, NHC calculated a depth of scour of 9.5 feet.

The Thorne equation was developed using data from the sand-dominated Red River in Arkansas and Louisiana (Thorne, 1988); however, it was later tested and found to produce satisfactory results in gravel-bed systems (Thorne and Abt, 1993). This equation has the advantage of being simple to apply- it relies only on the flow depth upstream of the bend, and the bend geometry represented by the ratio of the bend radius to top width. This bend geometric ratio was calculated to be approximately 1.5 at the representative section, and the Thorne equation is only valid for ratios greater than 2. The Thorne equation predicted a bend scour depth of 11 feet.

B.2 CONCLUSIONS

NHC recommended using the 9.5 feet as the estimated depth of scour for the Raging River representative section. They note that although this value was not derived from an equation specifically developed for bend scour, the most critical input parameter (α) did come from a study examining the impact of bend geometry on shear stress. The fact that the Thorne equation produces a similar depth of scour also increases NHC's confidence in this result. It should be noted that the scour depth of 9.5 feet is a "best estimate," which is appropriate for use in a study aimed at characterizing risk. The result lacks any factor of safety, however, so should not be relied on for design purposes.

It should also be noted that the scope of work for this task included estimation of bend scour only, so the analysis excludes other forms of scour which may occur at the site, including but not limited to local scour around woody debris or long-term bed elevation changes.

B.3 REFERENCES

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APPENDIX C: SEEPAGE ANALYSIS

Appendix C

Seepage Analysis

CONTENTS

APPENDIX C: SEEPAGE ANALYSIS

C.1 INTRODUCTION

We will perform seepage analyses using SEEP/W, which is part of the GeoStudio software package published by Geo-Slope International Ltd. (2021). SEEP/W is a two-dimensional, finite-element software program that simulates fluid flow and estimates pore pressure distribution in saturated and unsaturated porous materials such as soil and rock. Fluid flow and pore pressure distribution can be analyzed under steady-state or transient conditions.

Steady-state seepage analyses will maintain the surface water elevation on the waterward side of the levee embankment and compute the groundwater profile and pore pressure regime in soil within, below, and landward of the levee. Transient seepage analyses will vary with time and will be based on a flood hydrograph. Our seepage analyses will include: underseepage evaluations performed in general accordance with ETL 1110-2-569 (U.S. Army Corps of Engineers, 2005) guidelines; steady-state seepage analyses for seven river stages; and transient seepage analyses for a selected flood hydrograph. The results of our seepage analyses will be used to evaluate levee underseepage and evaluate slope stability factors of safety.

C.2 SURFACE WATER CONDITIONS

To perform our finite element SEEP/W seepage analyses, we will impose hydraulic boundary conditions to each analysis domain based on selected river stages and the flood hydrograph used to perform steady-state and transient seepage analyses, respectively. These boundary conditions are described by the following two categories:

1. **Exterior Boundary Condition**. This condition is applied to the left and right edges of the model domains and account for groundwater conditions beyond the extents of the model.
2. **Surface Boundary Condition**. This condition is either a potential seepage face boundary or a variable water level surface versus time boundary, which models inundation/drawdown events.

C.3 GROUNDWATER CONDITIONS

To develop appropriate groundwater boundary conditions using SEEP/W, groundwater table information is required. We will estimate groundwater levels within the levee and how they vary with river stage from the available groundwater data from the subsurface explorations accomplished at the Lower Raging River site.

C.4 UNDERSEEPAGE

Underseepage can be described as flow of water in a permeable soil layer beneath a levee embankment from the river to the landside of the levee. A factor of safety (FS) for underseepage is defined as follows.

Equation	Variable	Definition
$FS = \frac{i_c}{i}$	i	Calculated steady-state gradient at the landside toe of the levee
	i_c	Critical gradient

The critical gradient (i_c) is defined as follows.

Equation	Variable	Definition
$i_c = \frac{\gamma'_s}{\gamma_w}$	γ'_s	Buoyant unit weight of overbank soil at the landside toe of the levee
	γ_w	Unit weight of water

A seepage gradient greater than or equal to the critical gradient is assumed to cause sand boils or heave (flotation) of the relatively less permeable soils overlying the more pervious underseepage soil layer. Underseepage gradients (i) will be calculated for the selected river stage using SEEP/W.

C.5 UNDERSEEPAGE WITH SEEP/W

The SEEP/W software is based on the assumption that fluid flow through the material obeys Darcy's Law, which is defined as follows.

Equation	Variable	Definition
$q = -K\,i$	q	Specific discharge
	K	Hydraulic conductivity
	i	Hydraulic gradient

The governing equation used in SEEP/W is defined as follows.

Equation	Variable	Definition
$K_x \frac{\partial^2 H}{\partial x^2} + K_y \frac{\partial^2 H}{\partial y^2} + Q = 0$	K_x	Hydraulic conductivity in the x-direction
	K_y	Hydraulic conductivity in the y-direction
	H	Total head
	Q	Applied boundary flux

The general steps required for an analysis with SEEP/W are to:

1. Define the cross section geometry (river bathymetry, levee and ground surface profile, and subsurface soil layer contacts).
2. Create the finite element mesh.
3. Define the material properties for each soil type.
4. Define the flow boundary conditions.

The geometry of a model is defined in its entirety before creating a mesh. A mesh is generally created using an automatic mesh generator and modified by the user as required. Boundary conditions are specified according to the physical conditions and the type of analysis (steady-state or transient). For steady-state analysis, boundary conditions are either fixed-head (or pressure) or fixed-flux values. For transient analysis, one or more boundary conditions can be set as a function of time or a response to flow exiting or entering the flow regime.

C.6 SEEPAGE MATERIAL PROPERTIES

The soil input parameters that will be used to perform the seepage analyses using SEEP/W include:

- Horizontal hydraulic conductivity,
- Ratio of vertical to horizontal hydraulic conductivity, and
- Volumetric water content function.

C.6.1 Horizontal Hydraulic Conductivity

The horizontal hydraulic conductivity is a measure of the rate of the horizontal flow of water through a volume of soil. For a given soil density, the horizontal hydraulic conductivity for a soil is highest when all its pore spaces are filled with water (i.e., the soil is fully saturated). Under these conditions, the horizontal hydraulic conductivity is defined as saturated. For each soil unit used in SEEP/W, the user specifies a saturated horizontal hydraulic conductivity value and whether the soil is governed by saturated-only flow or unsaturated-saturated flow. The latter model is used for soil units that are at or above the piezometric water surface (i.e., unsaturated). Within unsaturated soils, the pore spaces are partially filled with voids or air bubbles which are barriers to flow within the soil matrix. Therefore, the horizontal hydraulic conductivity decreases with decreasing degree of saturation.

Horizontal hydraulic conductivity values for the assumed soils present at the LRR site will be estimated based on typical values reported in the literature and the following correlations to grain size distribution test data from soil samples retrieved from field explorations accomplished at the LRR site:

- Hazen Formula,
- Kozeny-Carman Formula,
- Beyer Formula, and/or
- Slicther Formula.

We will estimate the average (most likely value) and lognormal descriptive statistical parameters of horizontal hydraulic conductivity for use in our analyses.

C.6.2 Ratio of Vertical to Horizontal Hydraulic Conductivity

The ratio of vertical to horizontal hydraulic conductivity describes the relative rate of vertical to horizontal flow of water through a soil mass. The range of this ratio will be estimated from typical values reported in the literature for sands and gravels. A fixed value for the ratio will be used in the seepage FS calculations. However, we will assess the sensitivity of this ratio to FS and on the associated influence on the combined conditional probability of failure of the levees.

C.6.3 Volumetric Water Content Function

The volumetric water content function describes the volume of water stored in voids in a soil mass as function of porewater pressure. This quantity is equal to the product of porosity and the degree of saturation. In SEEP/W, the user specifies a saturated volumetric water content function for each soil unit. For saturated-only soil units, the volumetric water content is constant and equal to the saturated volumetric water content. For unsaturated-saturated soil units, the volumetric water content is defined using a function.

In the absence of site-specific test data for this function we will use built-in functions for sand and gravel provided in the SEEP/W documentation (Geo-Slope, 2021).

C.7 REFERENCES

Geo-Slope International, 2021, SEEP/W v 11.2: Calgary, Alberta, Geo-Slope International.

U.S. Army Corps of Engineers, 2005, Design guidance for levee underseepage, U.S. Army Corps of Engineers, Engineer Technical Letter ETL 1110-2-569: Washington, D.C., May.

APPENDIX D: SLOPE STABILITY ANALYSIS

Appendix D

Slope Stability Analysis

CONTENTS

D.1 INTRODUCTION

We will perform slope stability analyses using SLOPE/W, which is part of the GeoStudio software package published by Geo-Slope International Ltd. (2021), in general accordance with EM 1110-2-1913 (U.S. Army Corps of Engineers, 2000) and EM 1110-2-1902 (USACE, 2003) guidelines. SLOPE/W is a software program that uses two-dimensional limit equilibrium methods to calculate a factor of safety (FS) against sliding along a continuous surface in a soil or rock mass. Limit equilibrium analyses treat a slide mass as a rigid body, subdivide the mass into slices, and calculate the forces acting on each slice. The FS is the ratio of forces resisting sliding to forces driving sliding. If the FS is less than 1.0, then the driving forces are greater than the resisting forces, and the slope is in a state of failure. If the FS is greater than 1.0, the resisting forces are greater than the driving forces, and the slope is in a stable state.

The FS calculation can include the effects of groundwater and seismic (i.e., inertial) forces on the FS. We will compute minimum FSs for failure surfaces using the Morgenstern-Price limit equilibrium method (Morgenstern and Price, 1965), which includes both normal and shear interslice forces, satisfies both moment and force equilibrium, and allows for variable distributions of interslice forces.

The general steps required for the calculation of an FS with SLOPE/W are to:

1. Define the cross section geometry (ground surface profile and subsurface soil layer contacts).
2. Define the material failure criteria and properties for each soil type.
3. Define the groundwater regime, if any.
4. Define the analysis type and limits.

The geometry developed for the SEEP/W models and porewater pressure distributions calculated by SEEP/W (as discussed in Appendix C) will be used for the levee slope stability analyses. The Mohr-Coulomb failure criterion will be used for each of the soil units in the SLOPE/W analyses.

In conventional deterministic slope stability analysis, it is a typical practice to seek a slip surface with the lowest FS, as the consequences of slope failure can only be evaluated after the location of the potential failure surface is determined. For levee risk analysis, however, the primary interest is in slope failures that compromise the ability of the levee to provide the intended protection. To consider slip surfaces that are likely to lead to a levee breach, we will restrict the slip surface to entry points at the levee crest and exit points near the levee toe (waterward or landward toe) such that the failure surface envelopes at least ⅓ of the levee top width. The SLOPE/W slip surface search routine will be used to find the critical slip surface within the entry and exit point limits. In this search method, SLOPE/W generates trial failure surfaces defined by points within the entry and exit ranges and a range of circle radii and calculates the FS for each trial failure surface. The critical failure surface has the lowest calculated FS.

D.2 FACTOR OF SAFETY CALCULATIONS

The FS will be first calculated for the most likely value case at each location (waterward and landward). This is referred to as the deterministic case. The deterministic case will use likely values of the uncertainty input parameters of unit weight, friction angle, and hydraulic conductivity. Additional FSs will then be calculated by sequentially varying one of the input parameters by plus or minus one standard deviation from its most likely value. Most likely value and plus or minus one standard deviation values of steady-state or transient porewater pressures will be imported from the SEEP/W analysis completed for each river stage or flood hydrograph, respectively.

Slip surface entry and exit point limits will be defined separately for the waterward and landward FS calculations, but the same limits will be used for the most likely value case and the associated parameter variation cases. The critical slip surface for each case will be allowed to vary subject to the entry and exit point limits.

D.2.1 Static Factor of Safety Calculations

Static FSs will be calculated for waterward and landward slip surfaces for seven river stages at the critical section location.

D.2.2 Seismic Factor of Safety Calculations

Seismic FSs will be calculated for landward slip surfaces in the same manner as static FSs except with an additional horizontal force applied to represent the inertial forces of an earthquake. The horizontal force is determined from the mass of the soil slices used in the calculation of FS and from an input horizontal seismic acceleration coefficient. The horizontal seismic acceleration coefficient is generally assumed to be one-half of the peak ground acceleration of the earthquake (Hynes-Griffin and Franklin, 1984). The force is applied to the slices in the downslope direction. Seismic FSs will be calculated assuming that there is no reduction of shear strength of the levee and foundations soils as would be considered in an analysis of liquefaction (i.e., post-seismic analyses). Refer to Appendix E for further discussion regarding our seismic analyses. The slip surface entry and exit point limits that will be established for the calculation of static FSs will be used in the seismic FS calculations.

D.2.3 Post-Seismic/Liquefied Factor of Safety Calculations

Post-seismic/liquefied FSs will be calculated for waterward slip surfaces in the same manner as static FSs except that liquefied shear strength parameters will be used for soil layers susceptible to liquefaction. The slip surface entry and exit point limits that will be established for the calculation of static FSs will be used in the post-seismic/liquefied FS calculations.

D.2.4 Rapid and Transient Drawdown Factor of Safety Calculations

Static FSs for the waterward levee under rapid and transient drawdown conditions will be calculated beginning from a selected river stage elevation and selected flood hydrograph, respectively. The slip surface entry and exit point limits that will be established for the calculation of static FSs will be used in the rapid and transient drawdown FS calculations. The rapid drawdown scenario will be modelled per USACE recommended design procedures using the two-stage drawdown method developed by Wright and Duncan (1987) and later modified by Duncan, and others (1990).

D.3 SLOPE STABILITY MATERIAL PROPERTIES

The soil input parameters that will be used to perform the slope stability analyses using SLOPE/W will include:

- Total unit weight,
- Cohesion, and
- Internal friction angle.

D.3.1 Total Unit Weight

The total unit weight describes the weight of a unit volume of soil and water. Total unit weight values for the assumed soils present at the Lower Raging River site will be estimated based on typical values reported in the literature (Peck and others, 1974). We will estimate the average (most likely value) and descriptive statistical parameters of total unit weight for use in our analyses.

D.3.2 Cohesion and Internal Angle of Friction

The cohesion and internal angle of friction describe the shear strength of a Mohr-Coulomb soil. Because the levee and foundation soils are predominantly granular in nature, cohesion will be assumed to be zero and an effective stress analysis will be performed. Static internal angle of friction values for the assumed soils present at the Lower Raging River site will be estimated based on Standard Penetration Test blow counts and typical values reported in the literature (Peck and others, 1974). Liquefied internal angle of friction values will be estimated based on the results of liquefaction analyses. We will estimate the most likely value and descriptive statistical parameters of internal angle of friction for use in our analyses.

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Appendix E

Seismic Analysis

CONTENTS

E.1 INTRODUCTION

We will perform seismic analyses in general accordance with ER 1110-2-1806 (U.S. Army Corps of Engineers, 2016) guidelines, which defines ground motion levels corresponding to an operating basis earthquake (OBE) and a maximum design earthquake (MDE), as follows:

- OBE: "an earthquake that can reasonably be expected to occur within the service life of the project, that is, with a 50-percent probability of exceedance during the service life. The associated performance requirement is that the facility functions with little or no damage and without interruption of function."
- MDE: "maximum level ground motion for which a structure is designed or evaluated. The associated performance requirement is that the project performs without loss of life or catastrophic failure although severe damage or economic loss may be tolerated."

These ground motion levels correspond to about a 144-year return period for the OBE and a 950-return period for the MDE. Potential seismically induced geologic hazards associated with various ground motion levels include, but are not limited to, seismic slope stability (discussed in Appendix D) and liquefaction.

We will perform our seismic analyses for this study using the OBE design earthquake ground motions.

E.2 LIQUEFACTION

Soil liquefaction occurs in loose, saturated, sandy soils when the water pressure in the pore spaces approaches a level that is sufficient to separate the soil particle grains from each other. This phenomenon occurs during ground shaking and results in a reduction of the soil shear strength, i.e., a quicksand-like condition. This reduction in shear strength depends on the degree and extent of the liquefaction. The degree of liquefaction depends on the consistency and density of the soil, the grain-size distribution of the soil, and the level of ground shaking at the site form a given seismic event. Soil liquefaction may result in ground settlement and reduction in bearing resistance and potential failure of foundations founded above or within these soils. Permanent lateral ground displacement, referred to as lateral spreading and flow failure, may occur on gentle slopes or on flat ground towards the nearest free face (e.g., the face of a retaining wall or slope). In addition, settlement could also result from partial liquefaction or densification of unsaturated sands.

Liquefaction or partial liquefaction can result in settlement or lateral spreading of a levee and its foundation. The settlement or lateral spreading can result in a lowering of the levee crest or an embankment failure which would compromise the ability of the levee to provide its intended protection. Although the likelihood of an earthquake occurring simultaneously with a high river stage may be low, liquefaction may occur at any river stage. The damage may occur without sufficient time to repair before the next high river stage, or the damage may not be clearly evident but still sufficiently severe to reduce the design level or protection provided by the levee.

E.3 LIQUEFACTION SUSCEPTIBILITY

We will evaluate the liquefaction potential at the representative section using an in-house spreadsheet. Our analyses will be based on the Boulanger and Idriss (2014) empirical procedure.

For empirical liquefaction evaluation, the Standard Penetration Test (SPT) N-value is correlated to the liquefaction resistance of the soil (expressed as cyclic resistance ratio). Other factors affecting the liquefaction resistance include the fines content for a granular soil and the Atterberg Limits plasticity index for a cohesive soil. The soil resistance is compared to the earthquake-induced loading (expressed as cyclic stress ratio), and a corresponding factor of safety against liquefaction is calculated.

E.4 GROUND MOTIONS

Liquefaction analyses for a seismic event depend on moment magnitude (M) and peak ground acceleration (PGA) at the ground surface. We will estimate the M and PGA values for the OBE ground motion level.

The M value for the Lower Raging River site will be estimated based on results of latest, publicly available, U.S. Geological Survey (USGS) Probabilistic Seismic Hazard Analysis data, using the online USGS National Seismic Hazard Model (NSHM) Hazard Tool.

The ground surface PGA for a seismic event depends on the anticipated soft bedrock PGA and the stiffness of the overlying soil strata. The EM 1110-2-6053 (U.S. Army Corps of Engineers, 2007) refers to the ground surface PGA as the effective PGA. We will select one overall seismic Site Class for the levee system using the SPT N-values noted in subsurface explorations accomplished at the site. The ground surface PGA will be the product of the soft bedrock PGA value, which will be estimated using the USGS NHSM Hazard Tool, and the site amplification factor, which will be based on the Site Class.

E.5 LIQUEFIED STRENGTH PARAMETERS AND LIQUEFACTION-INDUCED SETTLEMENT

The results of our liquefaction analyses will be used to estimate liquefied internal angle of friction values to be used in post-seismic/liquefied slope stability analyses (discussed in Appendix D).

Potential effects of liquefaction also include post-earthquake settlement. We will estimate the magnitude of liquefaction induced settlement associated with soil particle rearrangement that might occur in response to the OBE ground motion using our in-house spreadsheet.

Several factors influence the post-earthquake settlement of liquefied soils, including soil density, induced shear strains, and maximum excess porewater pressures. We will use the widely accepted empirical methods developed by Tokimatsu and Seed (1987) and Ishihara and Yoshimine (1992) to estimate post-earthquake settlement. Both empirical methods are based on case histories and laboratory testing of clean, saturated sands. SPT blow counts for soil with significant fines content are adjusted to an equivalent clean sand blow count during the liquefaction analysis.

E.6 FAULT-RELATED GROUND RUPTURE

Based on our review of the USGS Fault and Fold Database (USGS and California Geological Survey, 2021) there are faults mapped within the Project limits. The Project site is situated within the vicinity of the Seattle Fault Zone and there are mapped splays of the Rattlesnake Mountain Fault Zone which cross part of the levee system. Consequently, there is a potential for fault-related ground rupture at the Project site. The scope of our geotechnical services does not include evaluations regarding fault-related ground rupture.

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Appendix F

Fragility Curve Development

CONTENTS

APPENDIX F: FRAGILITY CURVE DEVELOPMENT

F.1 GENERAL PRINCIPLES

Levee failure is generally defined as a failure of the levee to provide the intended protection to the people and property on the landside of the levee. The intended protection is typically defined in terms of a specific return period water level (e.g., protection from a 100-year return period event). Levee fragility curves are a description of the likelihood of levee failure for a range of water levels. Fragility curves can be used to compare different levee designs or locations and provide input to an analysis of levee failure consequences.

An analysis of levee failure consequences typically begins from a fragility curve but must also consider potential breach characteristics. A breach is generally defined as the opening created after failure of the levee embankment. The depth and width of the breach generally depends on the water level, duration, and levee material properties. Many potential levee failure modes can lead to a levee breach.

The potential failure modes we will evaluate for the Lower Raging River levees are summarized in the main text of this report. Some of the identified failure modes can be analyzed by conventional quantitative methods to estimate conditional probabilities of failure; others require qualitative or semi-quantitative approaches to estimate conditional probability of failure. Not all levee failures are equally catastrophic. For example, underseepage failure in the absence of slope failure may not immediately lead to significant flooding. The analysis that is generally performed, however, treats each failure mode equally and may lead to a conservative estimate of the likelihood of levee failure.

The hydraulic characteristics of the river that are relevant to a risk analysis of a levee are the geometry of the channel and flow velocity. Channel bathymetry and levee profile form the riverward slope that is to be analyzed. Flow velocity and channel impingements are determinants of scour potential. For this study, we will evaluate both unscoured and scoured conditions with scour depths that are correlated to river stage.

For purposes of a levee risk and reliability analysis, the hydrologic characteristics of the river are only indirectly relevant. A risk and reliability analysis is based on conditional probabilities of failure where the assumed condition is one or more river stages. The analysis does not depend on knowledge of the likelihood of occurrence of a given river stage; however, the assumed maximum river stages must be consistent with the river's hydrologic regime and hydraulic characteristics.

F.2 REPRESENTATIVE SECTIONS

As described in the main text, we are scoped to perform one representative analysis section for the Lower Raging River system (Left Bank Station 45+50). Therefore, the baseline ground elevation for all our seepage and stability analyses will be based on that section.

F.3 UNCERTAINTY PARAMETERS

As described in the main text, we will incorporate several uncertainty variables into our seepage and stability analyses. These can be divided into two general categories: material parameters and geometric parameters.

F.3.1 Material Parameters

We will assess the material uncertainty parameters, hydraulic conductivity, soil shear strength, and soil unit weight, based on the available subsurface field and laboratory test data. See Appendices C and D for details about soil parameter estimation.

We will group the subsurface data into engineering soil units based on the spatial distributions and value ranges of the parameter estimates. For each soil group, we will estimate the statistical distributions of the parameters and what elevation ranges to assign it to in the representative analysis section.

We will perform a limited parametric evaluation for each parameter to evaluate whether it contributes significantly to the overall uncertainty in levee stability. For example, if unit weight of lower soil units does not contribute to changes in factor of safety (FS) then we will eliminate that as an uncertainty variable for those soil units.

F.3.2 Geometric Parameters

We are scoped to evaluate the following geometric parameters for this study:

- Waterward side slope angle (S_w),
- Landward levee height (H_L),
- River stage correlated scour depth, and
- Confining layer thickness.

Distributions of the S_w and H_L parameters are presented in the main text of this report. During initial scoping for this project, we discussed handling S_w and H_L in the same manner as material parameters in terms of their contributions to conditional probabilities of failure. However, after additional internal discussions, we consider this to be problematic because we selected the representative section primarily on the basis of geometry. Instead, we may model multiple geometric combinations of S_w and H_L and produce separate fragility curves for each combination. The geometric variability will be used to assess the level of fit of the representative section results as applied to the levee system.

We discuss scour potential in Appendix B. Scour analyses will be performed using the 1% annual exceedance probability hydrograph.

As noted in the main text, the available subsurface information along the Lower Raging River suggests there is no confining layer. Therefore, we will not include it as an uncertainty parameter in this study.

F.4 PROBABILITY OF FAILURE COMPUTATION

The methods used to calculate probabilities of failure (P_f) based on seepage and stability FSs are described in the following sections.

F.4.1 Factor of Safety as a Performance Function

Evaluation of the capability of geotechnical system (e.g., a levee, retaining wall, embankment, etc.) to withstand design loads without failing has traditionally been evaluated using a FS. The design FS is the ratio of maximum load under which a system can resist without failing, R, and the load or demand, L, applied to the system under design conditions:

$$F = \frac{R}{L} = Factor\ of\ Safety\ (FS)$$

We use this equation as the primary performance function in our risk and reliability analyses. A computed FS greater than 1.0 suggests a margin of safety exists while a FS less than one suggests failure.

There are uncertainties in both R and L. However, in a geotechnical risk and reliability analysis for levees, the primary loading is river stage, which is treated as a conditional (given) model parameter within geotechnical risk and reliability analyses of levee systems. Therefore, most uncertainty variables involved in the computation of P_f are associated with R. Unit weight is one exception because it contributes to both R in terms of soil effective stresses and the associated influence on soil strength and L in terms of the driving mass in stability analyses.

F.4.2 Taylor Series Method

River stage versus probability-of-failure functions are commonly developed using the Taylor Series method (U.S. Army Corps of Engineers, 1992 and 1995; Wolff and Wang, 1992; Shannon & Wilson and Wolff, 1994; Wolff and others, 1996). The Taylor Series method is one of several first-order second-moment methods (FOSM) used to assess reliability. These methods are based on the concept that uncertainty in the performance function (i.e., the FS) can be estimated from the uncertainty in the model input parameters (e.g., soil strength parameters, permeability parameters, and geometric parameters).

The general procedure for using the Taylor Series method to determine a probability of failure is as follows: first, the expected value of the performance function is obtained by evaluating the performance function using the expected values of the input parameters (uncertainty variables), x_N. This results in the most likely value of the performance function, F_{MLV}. This value is also commonly referred to as the deterministic FS.

After computation of the F_{MLV}, the standard deviation of the performance function, σ_F, is then determined using the following equation:

$$\sigma_F = \sqrt{\left(\frac{\partial F}{\partial x_1}\right)^2 \sigma_{x,1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 \sigma_{x,2}^2 + \cdots + \left(\frac{\partial F}{\partial x_N}\right)^2 \sigma_{x,N}^2}$$

where $\partial F / \partial x_N$ is the partial derivative of the performance function with respect to the N^{th} input parameter and σ_{xN} is the standard deviation of the N^{th} input parameter. Each partial derivative represents how the performance function F changes due to slight change in a given input parameter, x.

In a FOSM, the partial derivatives are approximated numerically as linear relationship between F and x over an interval centered on the expected value. To evaluate partial derivatives, we typically use an interval of plus one to minus one standard deviation as is generally recommended in the literature (USACE, 1999; Shannon & Wilson and Wolff, 1994).

When an interval of plus one to minus one standard deviation is used to evaluate the partial derivatives, the equation for σ_F simplifies to:

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \cdots + \left(\frac{\Delta F_N}{2}\right)^2}$$

where $\Delta F_N = (F_N^+ - F_N^-)$. F_N^+ is the value of the performance function evaluated with the N^{th} parameter value increased one standard deviation from its expected value, and F_N^- is the value performance function evaluated with the N^{th} parameter variable decreased one standard deviation from its expected value. In calculating F_{N^+} and F_{N^-} for the Nth parameter, the values of the other parameters are kept at their expected values. Once the expected value and standard deviation of the performance function are determined, the coefficient of variability of the performance function, V_F, and log-normal reliability index, β_{LN}, are calculated as follows:

$$V_F = \frac{\sigma_F}{F_{MLV}} \quad \text{and} \quad \beta_{LN} = \frac{ln\left(\frac{F_{MLV}}{\sqrt{1+V_F{}^2}}\right)}{\sqrt{ln(1+V_F{}^2)}}$$

Because the reliability index is assumed to be from a standard normal distribution (mean = 0.0 and standard deviation = 1.0), the probability of non-failure, P_{nf}, can be determined from a table of the standard normal distribution and the probability of failure from $P_f = 1 - P_{nf}$.

F.4.3 Monte Carlo Method

We may use the Monte Carlo method to estimate conditional P_f values for unit weight and soil strength uncertainty variables. The Monte Carlo method is an alternative to the Taylor Series method for estimating the conditional P_f. Whereas the Taylor Series method assumes that the FS for a slope is log-normally distributed, the Monte Carlo method uses the individual distributions of the input uncertainty variables (e.g., unit weight, friction angle) to determine the distribution of F. The distribution is determined by making repeated calculations of FS, each time randomly drawing a complete set of input uncertainty variables from the individual variable distributions.

The limit equilibrium software we will use for the project, SLOPE/W (see Appendix D), has a built-in Monte Carlo analysis option and therefore use of this method may yield efficiencies in our analyses. The input parameters that can be entered into SLOPE/W using uncertainty distributions are 1) unit weight of the soils and 2) soil strength (failure criteria). Groundwater seepage and geometric uncertainty parameters cannot be incorporated into the built-in Monte Carlo module. Therefore, if we decide to use the Monte Carlo option within SLOPE/W, we will combine the resulting partial P_f values from those analyses with Taylor-Series-based results to obtain overall P_f values for each failure mode. This combination of methods is not conventional. Therefore, we will assess the feasibility of this approach during our analyses.

We also may utilize the Monte Carlo method to perform parameter sensitivity analyses on our uncertainty parameters. For example, we can test if the unit weight of a given soil layer significantly contributes to P_f by performing two Monte Carlo runs: 1) one with that unit weight modeled as an uncertainty variable and 2) one with it as a fixed value. If the P_f does not differ significantly between these runs then we would eliminate that soil layer unit weight as an uncertainty variable and thereby reduce the overall quantity of stability cases we need to perform to develop the fragility curve.

F.4.4 Response Surface Method

Another approach that we may consider is the response surface method. In some situations, the relationship between F and any given x variable is not linear (as is assumed in FOSM) and determination of F is computationally demanding, making a full Monte Carlo simulation impractical. The response surface method overcomes these challenges through use of a relatively small number of numerical model analyses (Schultz and others, 2010).

This response surface method can be understood by thinking of the performance function F as a multidimensional surface. Each limit equilibrium analysis with a given set of soil input uncertainty parameters defines one point on of this surface. Given a sufficient number of points, a function can be fitted using multi-dimensional regression. This function is the response surface. Different approaches for developing response surface functions have been presented in the literature. Kingston and others (2011) introduced the approach of using neural networks to efficiently approximate the response surface. Once the response surface is complete, F can be estimated for different combinations of uncertainty variables – even values not specifically modeled in the seepage and stability analyses – by allowing interpolation within the surface.

A response surface can be used to perform a Monte Carlo simulation by randomly sampling any combination of uncertainty variables within the domain of the surface, producing an F result for each combination.

F.5 FRAGILITY CURVE DEVELOPMENT

We will develop fragility curves for each failure mode and a combined fragility curve for all failure modes. The combined conditional probability of failure will be calculated under an assumption of independence of the individual failure modes. Based on this assumption, the combined conditional probability of failure (P_{fc}) can be computed as:

$$P_{fc} = 1 - (1 - P_{f1})\times(1 - P_{f2})\times \ldots (1 - P_{fn})$$

where P_{f1} through P_{fn} are the conditional probabilities of failure for failure modes 1 through n.

As noted Section F.3.2, we may produce multiple fragility curves, each corresponding to a range of geometric parameters. Depending on the variability of the resulting fragility curves and based on discussions with other members of the project team, we may decide to:

- Combine them into a single fragility curve,
- Pick one fragility curve as representative of the overall levee system, or
- Assign different fragility curves to different subsegments within the levee system.

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IMPORTANT INFORMATION

Important Information

About Your Geotechnical/Environmental Report

IMPORTANT INFORMATION

CONSULTING SERVICES ARE PERFORMED FOR SPECIFIC PURPOSES AND FOR SPECIFIC CLIENTS.

Consultants prepare reports to meet the specific needs of specific individuals. A report prepared for a civil engineer may not be adequate for a construction contractor or even another civil engineer. Unless indicated otherwise, your consultant prepared your report expressly for you and expressly for the purposes you indicated. No one other than you should apply this report for its intended purpose without first conferring with the consultant. No party should apply this report for any purpose other than that originally contemplated without first conferring with the consultant.

THE CONSULTANT'S REPORT IS BASED ON PROJECT-SPECIFIC FACTORS.

A geotechnical/environmental report is based on a subsurface exploration plan designed to consider a unique set of project-specific factors. Depending on the project, these may include the general nature of the structure and property involved; its size and configuration; its historical use and practice; the location of the structure on the site and its orientation; other improvements such as access roads, parking lots, and underground utilities; and the additional risk created by scope-of-service limitations imposed by the client. To help avoid costly problems, ask the consultant to evaluate how any factors that change subsequent to the date of the report may affect the recommendations. Unless your consultant indicates otherwise, your report should not be used (1) when the nature of the proposed project is changed (for example, if an office building will be erected instead of a parking garage, or if a refrigerated warehouse will be built instead of an unrefrigerated one, or chemicals are discovered on or near the site); (2) when the size, elevation, or configuration of the proposed project is altered; (3) when the location or orientation of the proposed project is modified; (4) when there is a change of ownership; or (5) for application to an adjacent site. Consultants cannot accept responsibility for problems that may occur if they are not consulted after factors that were considered in the development of the report have changed.

SUBSURFACE CONDITIONS CAN CHANGE.

Subsurface conditions may be affected as a result of natural processes or human activity. Because a geotechnical/environmental report is based on conditions that existed at the time of subsurface exploration, construction decisions should not be based on a report whose adequacy may have been affected by time. Ask the consultant to advise if additional tests are desirable before construction starts; for example, groundwater conditions commonly vary seasonally.

Construction operations at or adjacent to the site and natural events such as floods, earthquakes, or groundwater fluctuations may also affect subsurface conditions and, thus, the continuing adequacy of a geotechnical/environmental report. The consultant should be kept apprised of any such events and should be consulted to determine if additional tests are necessary.

MOST RECOMMENDATIONS ARE PROFESSIONAL JUDGMENTS.

Site exploration and testing identifies actual surface and subsurface conditions only at those points where samples are taken. The data were extrapolated by your consultant, who then applied judgment to render an opinion about overall subsurface conditions. The actual interface between materials may be far more gradual or abrupt than your report indicates. Actual conditions in areas not sampled may differ from those predicted in your report. While nothing can be done to prevent such situations, you and your consultant can work together to help reduce their impacts. Retaining

IMPORTANT INFORMATION

your consultant to observe subsurface construction operations can be particularly beneficial in this respect.

A REPORT'S CONCLUSIONS ARE PRELIMINARY.

The conclusions contained in your consultant's report are preliminary, because they must be based on the assumption that conditions revealed through selective exploratory sampling are indicative of actual conditions throughout a site. Actual subsurface conditions can be discerned only during earthwork; therefore, you should retain your consultant to observe actual conditions and to provide conclusions. Only the consultant who prepared the report is fully familiar with the background information needed to determine whether or not the report's recommendations based on those conclusions are valid and whether or not the contractor is abiding by applicable recommendations. The consultant who developed your report cannot assume responsibility or liability for the adequacy of the report's recommendations if another party is retained to observe construction.

THE CONSULTANT'S REPORT IS SUBJECT TO MISINTERPRETATION.

Costly problems can occur when other design professionals develop their plans based on misinterpretation of a geotechnical/environmental report. To help avoid these problems, the consultant should be retained to work with other project design professionals to explain relevant geotechnical, geological, hydrogeological, and environmental findings, and to review the adequacy of their plans and specifications relative to these issues.

BORING LOGS AND/OR MONITORING WELL DATA SHOULD NOT BE SEPARATED FROM THE REPORT.

Final boring logs developed by the consultant are based upon interpretation of field logs (assembled by site personnel), field test results, and laboratory and/or office evaluation of field samples and data. Only final boring logs and data are customarily included in geotechnical/environmental reports. These final logs should not, under any circumstances, be redrawn for inclusion in architectural or other design drawings, because drafters may commit errors or omissions in the transfer process.

To reduce the likelihood of boring log or monitoring well misinterpretation, contractors should be given ready access to the complete geotechnical engineering/environmental report prepared or authorized for their use. If access is provided only to the report prepared for you, you should advise contractors of the report's limitations, assuming that a contractor was not one of the specific persons for whom the report was prepared, and that developing construction cost estimates was not one of the specific purposes for which it was prepared. While a contractor may gain important knowledge from a report prepared for another party, the contractor should discuss the report with your consultant and perform the additional or alternative work believed necessary to obtain the data specifically appropriate for construction cost estimating purposes. Some clients hold the mistaken impression that simply disclaiming responsibility for the accuracy of subsurface information always insulates them from attendant liability. Providing the best available information to contractors helps prevent costly construction problems and the adversarial attitudes that aggravate them to a disproportionate scale.

READ RESPONSIBILITY CLAUSES CLOSELY.

Because geotechnical/environmental engineering is based extensively on judgment and opinion, it is far less exact than other design disciplines. This situation has resulted in wholly unwarranted claims being lodged against consultants. To help prevent this problem, consultants have developed a number of clauses for use in their contracts, reports, and other documents. These responsibility clauses are not exculpatory clauses designed to transfer the consultant's liabilities to other parties; rather, they are definitive clauses that identify where the consultant's responsibilities begin and end. Their use helps all parties involved recognize their individual responsibilities and take appropriate action. Some of these definitive clauses are likely to appear in your report, and you are encouraged to read them closely. Your consultant will be pleased to give full and frank answers to your questions.

The preceding paragraphs are based on information provided by the GBA, Silver Spring, Maryland