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# APPENDIX A – HYDROLOGY & HYDRAULICS

## I. General Documentation

### A. Study Area Description

#### 1. Basin Description

The Colorado River watershed extends diagonally northwest to southeast from southeast New Mexico to the Gulf of Mexico near Matagorda, Texas. The basin is bounded on the east by the Brazos River basin, and on the west by the Guadalupe, Nueces, Lavaca-Navidad and Rio Grande basins. The length of the watershed is about 595 miles, its maximum width is about 170 miles, and its total drainage area is 42,344 square miles. The width of the extreme upper part of the watershed is about 85 miles. This width increases gradually to about 170 miles near Milburn; then decreases to 30 miles at Austin, maintaining this width to Columbus; below Columbus the width gradually diminishes toward the Gulf of Mexico.

The upper portion of the basin lies in the Great Plains, a flat semiarid region with numerous closed basins, of which 11,403 square miles do not contribute to the Colorado River drainage. From the eastern limits of the Great Plains to the vicinity of Austin, the river traverses the North Central Plains, the topography of which varies from gentle rolling plains to the rough broken terrain of the Edwards Plateau. Leaving the plains area at the Balcones Escarpment above Austin, the river enters the Coastal Plains, an area of rolling hills extending to the vicinity of Columbus, and then enters the flat coastal prairie extending to the Gulf. The Colorado River basin has a total contributing drainage area of 30,941 square miles.

The general land elevation of the Colorado River basin decreases gradually from 4,500 feet NGVD in the High Plains sections southeasterly to 2,600 feet NGVD in the Big Spring area. Between Big Spring and the western edge of the Balcones Escarpment above Austin, the elevation decreases southeastwardly from 2,600 to 1,000 feet NGVD. Between the escarpment and the coastline, the land elevations decrease to a foot above sea level near the coast.

The Colorado River system consists principally of the main stream and six major tributaries. The six major tributaries are Beals Creak, Concho River, Pecan Bayou, San Saba River, Llano River, and Pedernales River. All of the tributaries enter the Colorado River above Austin, and all except Pecan Bayou enter from the western bank. Table A-1 lists key locations of the Colorado River system, the river mileage above the Gulf of Mexico, and the contributing drainage area at each location. The contributing area above Mansfield Dam (Lake Travis), the major flood control structure on the Colorado River main stem, is approximately 27,565 square miles.

**Table A- 1. River Miles and Drainage Areas**

| Location on | River | Drainage Area in Sq Mi | |
|---|---|---|---|
| Colorado River | Mile (1) | Total | Contributing |
| Below Concho River | 628.9 | 24,128 | 12,725 |
| Below Pecan Bayou | 513.1 | 28,163 | 16,760 |
| Below San Saba River | 479.8 | 31,473 | 20,070 |
| Below Llano River | 400.3 | 36,712 | 25,309 |
| Below Pedernales River | 354.6 | 38,763 | 27,360 |
| At Austin Gauge (08158000) | 290.3 | 39,009 | 27,606 |
| At Bastrop Gauge | 236.6 | 39,979 | 28,576 |
| At Columbus Gauge | 135.1 | 41,640 | 30,237 |
| At Wharton Gauge | 66.6 | 42,003 | 30,600 |
| At Bay City Gauge | 32.5 | 42,240 | 30,837 |

(1) RM from USGS Water Resources Data Texas Water Year 1999

In the Colorado River basin above Austin, there are four federal and 14 non-federal reservoirs existing or under construction with an individual capacity greater than 5,000 acre-feet. Of the four federal reservoirs, O.C. Fisher Lake on the North Concho River and Hords Creek Lake on Hords Creek are the only existing Corps of Engineers' projects. Twin Buttes Reservoir on the South and Middle Concho Rivers and Mansfield Dam (Lake Travis) on the mainstem Colorado River were constructed by the Bureau of Reclamation. Congress has given the Corps of Engineers responsibility for flood control for the above-mentioned Bureau of Reclamation reservoirs. Brady Creek Reservoir on Brady Creek was constructed by the Soil Conservation Service (SCS) in cooperation with the City of Brady. Pertinent data for these federal and non-federal reservoirs are presented in Table A-2.

**Table A- 2. Existing Reservoirs**[1]

| Reservoir | Stream | River Mile | Contributing Drainage Area (sq mi) | Total Storage (ac-ft) |
|---|---|---|---|---|
| | | **FEDERAL** | | |
| O.C. Fisher | North Concho River | 6.6 | 1,383 | 396,400 |
| Twin Buttes | South Concho River<br>Middle Concho River | 13.0<br>4.0 | 3,015 | 640,600 |
| Hords Creek | Hords Creek | 27.8 | 48 | 25,310 |
| Brady Creek | Brady Creek | 34.0 | 508 | 90,480 |
| | | **NON-FEDERAL** | | |
| J. B. Thomas | Colorado River | 837.0 | 987 | 204,000 |
| Colorado City | Morgan Creek | 2.5 | 290 | 32,000 |
| Champion Creek | Champion Creek | 0.9 | 203 | 42,000 |
| E.V. Spence | Colorado River | 730.9 | 4,044 | 489,000 |
| Oak Creek | Oak Creek | 20.0 | 244 | 39,000 |
| Nasworthy | South Concho River | 7.6 | 2,655 | 14,000 |
| O.H. Ivie | Colorado River | 615.1 | 12,647 | 550,000 |
| Brownwood | Pecan Bayou | 57.1 | 1,544 | 150,000 |
| Coleman | Jim Ned Creek | 52.2 | 292 | 40,000 |
| Buchanan | Colorado River | 413.6 | 20,685 | 992,000 |
| Inks | Colorado River | 409.4 | 20,724 | 17,000 |
| Lyndon B. Johnson | Colorado River | 388.0 | 25,750 | 137,000 |
| Marble Falls | Colorado River | 381.8 | 25,810 | 9,000 |
| Lake Travis | Colorado River | 318.0 | 27,567 | 1,951,400 |
| Lake Austin | Colorado River | 297.6 | 27,670 | 21,000 |

(1) U.S. Army Corps of Engineers, Reconnaissance Report, Central Colorado River Basin, September 1989.

2. **Climatology**

Climatological conditions over the watershed are generally mild and vary from subtropical along the Gulf Coast to semiarid in the upper headwater regions. The rainfall decreases rather uniformly from the Gulf toward the headwaters. At San Angelo in the upper Colorado River basin, the average rainfall is about 20 inches annually. The average yearly rainfall over the Highland Lakes is about 30 inches, while Bay City near the Gulf Coast gets about 44 inches annually. Rainfall in Central Texas also varies greatly from year to year. Even though Austin receives about 32 inches annually on average, the rainfall is less than 26 inches in about one-fourth of the years. The average annual temperatures over the basin are generally moderate, with the highest at the Gulf and decreasing gradually with the increase in latitude and elevation. Winter temperatures are generally mild, but occasional cold periods of short duration result from the rapid moving of cold high-pressure air masses from the northwest. Snowfall and subfreezing temperatures are rare in the lower section of the basin near the Gulf, but are experienced occasionally during the winter season in the northerly parts of the basin. Summer temperatures are high throughout the basin. The National Oceanic and Atmospheric Administration (NOAA) have a first order recording station at Austin, Texas. Records at this station are shown below.

| | **MEANS** | **EXTREMES** |
|---|---|---|
| Rainfall (Annual) | 32.69 in. | |
| | Maximum (1919) | 64.68 in. |
| | Minimum (1954) | 11.42 in. |
| Temperature (Monthly) | 68.0 degrees F. | |
| | Daily Maximum (July 1954) | 109 degrees |
| | Daily Minimum (Jan. 1949) | -2 degrees |
| Relative Humidity | 67 percent | |

Mean annual precipitation over the Colorado River basin ranges from a minimum of about 18 inches in the northwest extremity of the Colorado River basin (contributing drainage area) to a maximum of about 33 inches at Austin. Table A-3 presents average annual precipitation at rainfall gauges in the Colorado River basin upstream of Austin.

**Table A- 3. Average Annual Precipitation**

| Station | Years of Record | Average Annual Precipitation |
|---|---|---|
| Big Spring | 39 | 18.01 inches |
| Colorado City | 69 | 22.19 inches |
| San Angelo WSO AP | 41 | 19.02 inches |
| Ballinger | 88 | 22.73 inches |
| Coleman | 90 | 27.29 inches |
| Llano | 90 | 26.84 inches |
| Fredericksburg | 67 | 28.87 inches |
| Austin WSO AP | 57 | 32.69 inches |

## B. Historical Flood Data

### 1. USGS Stream Gauges

The observation of Colorado River streamflow began in 1898 when the U.S. Geological Survey (USGS) established a gauge on the Colorado River at Austin. In 1903, NOAA established gauges on the Colorado River at Columbus and Ballinger. For the period 1898-1988, stage and discharge records of varying lengths are available for about 91 streamflow and reservoir gauges in the Colorado River basin. The primary gauges used in this Colorado River basin study are shown in Table A-4.

### 2. LCRA Stream Gauges

The LCRA operates a hydrometeorological (Hydromet) data collection system of automated precipitation and stage gauges along the Colorado River (See Table A-4).

**Table A- 4. Stream Gauges**

| GAUGE NAME | LCRA ID | USGS ID | Latitude (DMS) | Longitude (DMS) |
|---|---|---|---|---|
| Colorado River at Winchell | 1199 | 08138000 | 312807 | -990944 |
| Pecan Bayou near Mullin | 1390 | 08143600 | 313102 | -984429 |
| San Saba River at Menard | 1499 | 08144500 | 305509 | -994708 |
| San Saba River near Brady | 1563 | 08144600 | 310013 | -991608 |
| San Saba River at San Saba | 1769 | 08146000 | 311250 | -984311 |
| Colorado River near San Saba | 1911 | 08147000 | 311304 | -983349 |
| Cherokee Creek near Bend | 1929 | | 310156 | -983439 |
| Lake LBJ at 1431 Bridge | 2096 | | 303927 | -982539 |
| Llano River near Junction | 2306 | 08150000 | 303013 | -994405 |
| Johnson Fork near Junction | 2313 | | 302538 | -994047 |
| James River near Mason | 2399 | | 303516 | -991833 |
| Comanche Creek near Mason | 2424 | | 304308 | -991152 |
| Llano River near Mason | 2431 | 08150700 | 303936 | -990631 |
| Beaver Creek near Mason | 2435 | | 303839 | -990548 |
| Willow Creek near Mason | 2443 | | 304418 | -990704 |
| Hickory Creek near Castell | 2498 | | 304255 | -984914 |
| San Fernando Creek near Llano | 2616 | | 304518 | -984911 |
| Llano River at Llano | 2641 | 08151500 | 304504 | -984011 |
| Little Llano River near Llano | 2669 | | 304821 | -983431 |
| Lake LBJ at 2900 Bridge | 2699 | | 303833 | -982648 |
| Sandy Creek near Willow City | 2851 | | 303310 | -984205 |
| Sandy Creek near Kingsland | 2891 | 08152000 | 303328 | -982820 |
| Lake LBJ at Sandy Harbor | 2899 | | 303337 | -982549 |
| Backbone Creek at Marble Falls | 2992 | | 303501 | -981703 |
| Pedernales River near Fredericksburg | 3299 | 08152500 | 301314 | -985212 |
| Pedernales River near Johnson City | 3385 | 08153500 | 301732 | -982358 |
| Miller Creek near Johnson City | 3491 | | 301702 | -981753 |

**Table A- 4. (Continued)**

| GAUGE NAME | LCRA ID | USGS ID | Latitude (DMS) | Longitude (DMS) |
|---|---|---|---|---|
| Lake Austin at Davenport Ranch | 3990 | | 302055 | -974748 |
| Bull Creek at Loop 360, Austin | 3992 | 08154500 | 302219 | -974706 |
| Barton Creek at Loop 360, Austin | 4520 | 08155300 | 301439 | -974808 |
| Town Lake near Longhorn Dam | 4543 | | 301457 | -974313 |
| Colorado River at Austin | 4553 | 08158000 | 301440 | -974140 |
| Walnut Creek at Webberville Road, Austin | 4561 | 08158600 | 301658 | -973917 |
| Onion Creek at Buda | 4595 | | 300512 | -975055 |
| Onion Creek at Hwy 183, Austin | 4598 | 08159000 | 301038 | -974120 |
| Gilleland Creek near Manor | 5417 | | 301752 | -973405 |
| Wilbarger Creek near Elgin | 5464 | | 301355 | -972558 |
| Big Sandy Creek near Elgin | 5473 | 08159170 | 301556 | -971941 |
| Colorado River at Bastrop | 5499 | 08159200 | 300617 | -971909 |
| Cedar Creek below Bastrop | 5523 | | 300211 | -971850 |
| Colorado River at Smithville | 5541 | 08159500 | 300043 | -970944 |
| Colorado River above La Grange | 5599 | 08160500 | 295445 | -965349 |
| Buckners Creek near Muldoon | 5608 | | 295043 | -970241 |
| Cummins Creek near Frelsburg | 5696 | | 294933 | -963450 |
| Colorado River at Columbus | 6300 | 08161000 | 294223 | -963214 |
| Colorado River near Garwood | 6399 | | 293055 | -962432 |
| Colorado River at Wharton | 6499 | 08162000 | 291834 | -960613 |
| San Bernard River at East Bernard | 6637 | | 293159 | -960322 |
| Colorado River near Lane City | 6537 | | 291125 | -960411 |
| Colorado River at Bay City | 6599 | 08162500 | 285829 | -960039 |
| Lake LBJ at 1431 Bridge | 2096 | | 303927 | -982539 |
| Llano River near Junction | 2306 | 08150000 | 303013 | -994405 |
| Johnson Fork near Junction | 2313 | | 302538 | -994047 |
| James River near Mason | 2399 | | 303516 | -991833 |
| Comanche Creek near Mason | 2424 | | 304308 | -991152 |
| Llano River near Mason | 2431 | 08150700 | 303936 | -990631 |
| Beaver Creek near Mason | 2435 | | 303839 | -990548 |
| Willow Creek near Mason | 2443 | | 304418 | -990704 |
| Hickory Creek near Castell | 2498 | | 304255 | -984914 |
| San Fernando Creek near Llano | 2616 | | 304518 | -984911 |
| Llano River at Llano | 2641 | 08151500 | 304504 | -984011 |
| Little Llano River near Llano | 2669 | | 304821 | -983431 |
| Lake LBJ at 2900 Bridge | 2699 | | 303833 | -982648 |
| Sandy Creek near Willow City | 2851 | | 303310 | -984205 |
| Sandy Creek near Kingsland | 2891 | 08152000 | 303328 | -982820 |
| Lake LBJ at Sandy Harbor | 2899 | | 303337 | -982549 |
| Backbone Creek at Marble Falls | 2992 | | 303501 | -981703 |
| Pedernales River near Fredericksburg | 3299 | 08152500 | 301314 | -985212 |
| Pedernales River near Johnson City | 3385 | 08153500 | 301732 | -982358 |

**Table A- 4. (Continued)**

| GAUGE NAME | LCRA ID | USGS ID | Latitude (DMS) | Longitude (DMS) |
|---|---|---|---|---|
| Miller Creek near Johnson City | 3491 | | 301702 | -981753 |
| Lake Austin at Davenport Ranch | 3990 | | 302055 | -974748 |
| Bull Creek at Loop 360, Austin | 3992 | 08154500 | 302219 | -974706 |
| Barton Creek at Loop 360, Austin | 4520 | 08155300 | 301439 | -974808 |
| Town Lake near Longhorn Dam | 4543 | | 301457 | -974313 |
| Colorado River at Austin | 4553 | 08158000 | 301440 | -974140 |
| Walnut Creek at Webberville Road, Austin | 4561 | 08158600 | 301658 | -973917 |
| Onion Creek at Buda | 4595 | | 300512 | -975055 |
| Onion Creek at Hwy 183, Austin | 4598 | 08159000 | 301038 | -974120 |
| Gilleland Creek near Manor | 5417 | | 301752 | -973405 |
| Wilbarger Creek near Elgin | 5464 | | 301355 | -972558 |
| Big Sandy Creek near Elgin | 5473 | 08159170 | 301556 | -971941 |
| Colorado River at Bastrop | 5499 | 08159200 | 300617 | -971909 |
| Cedar Creek below Bastrop | 5523 | | 300211 | -971850 |
| Colorado River at Smithville | 5541 | 08159500 | 300043 | -970944 |
| Colorado River above La Grange | 5599 | 08160500 | 295445 | -965349 |
| Buckners Creek near Muldoon | 5608 | | 295043 | -970241 |
| Cummins Creek near Frelsburg | 5696 | | 294933 | -963450 |
| Colorado River at Columbus | 6300 | 08161000 | 294223 | -963214 |
| Colorado River near Garwood | 6399 | | 293055 | -962432 |
| Colorado River at Wharton | 6499 | 08162000 | 291834 | -960613 |
| San Bernard River at East Bernard | 6637 | | 293159 | -960322 |
| Colorado River near Lane City | 6537 | | 291125 | -960411 |
| Colorado River at Bay City | 6599 | 08162500 | 285829 | -960039 |

3. **Flood History**

The storms that cause precipitation on the Colorado River basin are of three general types: (1) thunderstorms, sometimes causing devastating cloudbursts (2) frontal storms, and (3) cyclonic storms originating in the tropics or the western Gulf of Mexico. In addition, the Colorado River crosses the Balcones Escarpment area above Austin in which the physical features of the land exercise some influence on rainfall. Some of the highest rainfall rates experienced in the United States have been recorded in this area. Table A-5 presents historical peak discharges for stream gauges on the Colorado, Llano, and Pedernales Rivers.

**Table A- 5. Historical Flood Data**

**COLORADO RIVER NEAR SAN SABA – D.A. = 20,111 SQ. MI.**

| Date of Flood | Peak Discharge (cfs) |
|---|---|
| September 25, 1900 | 184,000 |
| November 10, 1918 | 77,100 |
| April 26, 1922 | 130,000 |
| October 17, 1930 | 78,900 |
| May 19, 1935 | 86,000 |
| September 21, 1936 | 179,000 |
| July 23, 1938 | 224,000 |
| September 11, 1952 | 69,000 |
| May 14, 1957 | 66,200 |

**COLORADO RIVER AT AUSTIN – D.A. = 27,835 SQ.MI.**

| Date of Flood | Peak Discharge (cfs) |
|---|---|
| July 7, 1869 | 550,000 |
| June 8, 1899 | 113,000 |
| April 7, 1900 | 151,000 |
| December 4, 1914 | 164,000 |
| May 1, 1922 | 120,000 |
| June 15, 1935 | 481,000 |
| September 28, 1936 | 234,000 |
| July 25, 1938 | 276,000 |

**LLANO RIVER AT LLANO – D.A. = 4,197 SQ. MI.**

| Date of Flood | Peak Discharge (cfs) |
|---|---|
| June 14, 1935 | 380,000 |
| September 10, 1952 | 232,000 |
| October 5, 1969 | 154,000 |
| October 13, 1973 | 154,000 |
| August 3, 1978 | 139,000 |
| September 8, 1980 | 210,000 |

**Table A-5.(continued)**

**PEDERNALES RIVER NEAR JOHNSON CITY – D.A. = 900 SQ.MI.**

| Date of Flood | Peak Discharge (cfs) |
|---|---|
| September 11, 1952 | 441,000 |
| April 24, 1957 | 125,000 |
| October 4, 1959 | 142,000 |
| August 3, 1978 | 127,000 |

C. **FEMA Flood Insurance Study Discharges**

See Table A-6 for a summary of various effective (as of 1998) FEMA flood insurance study discharges for the 10-, 50-, 100-, and 500- year floods.

**Table A- 6. Summary of Colorado River Flood Insurance Study Discharges**

| LOCATION | FIS DATE | 10-YR | 50-YR | 100-YR | 500-YR |
|---|---|---|---|---|---|
| **Burnet County** | November 16, 1990 | | | | |
| ▪ At Inks Dam | | 66,865 | 126,756 | 161,410 | 304,101 |
| ▪ At Alvin Wirtz Dam | | 117,938 | 259,824[(1)] | 330,269 | 481,505 |
| ▪ At Max Starke Dam | | 117,741 | 268,336 | 329,033 | 480,512 |
| **Travis County** | June 5, 1997 | | | | |
| • Lake Travis | | 691[(2)] | 710[(2)] | 716[(2)] | 728.5[(2)] |
| ▪ At Tom Miller Dam | | 25,000 | 102,000 | 170,000 | 335,000 |
| ▪ At Confluence of Onion Creek | | 50,000 | 102,000 | 170,000 | 335,000 |
| ▪ At Travis/Bastrop County Boundary | | 75,000 | 150,000 | 210,000 | 350,000 |
| **Bastrop County** @ Loop 150 | December 8, 1998 | 63,386 | 119,464 | 149,310 | 231,296 |
| | | | | | |
| **Colorado County** @ US Route 90 | January 3, 1990 | n/a | n/a | 136,000 | n/a |
| | | | | | |
| **Wharton, TX** @ US 59 | March 16, 1982 | 70,000 | 127,500[(3)] | 139,500[(3)] | 247,000 |

(1) Typo in FIS

(2) Stillwater Pool Elevations (Computed at upstream face of dam)

(3) Adjusted for overflow loss

D. **Study Tasks – Overview**

Several major tasks were involved in completing the hydrologic & hydraulic study. These included:

- Prepare a Period-of-Record Flow Analysis
- Prepare Historical Frequency Analysis at Each Gauge
- Prepare Initial/Preliminary HEC-RAS Hydraulic Model
- Prepare Initial/Preliminary UNREGULATED Basin-wide HEC-HMS Hydrologic Model
- Generate Rainfall Information for HMS Model
- Simulate HEC-HMS Storm Reproduction (Calibration) PHASE
- Simulate HMS Verification Phase (Unregulated Conditions)
- Prepare HEC-5 Reservoir Operation Model for Regulated Basin Conditions
- Simulate Final RAS Hydraulic Model(s) for Main Stem
- Simulate Final HMS/ HEC-5/ RAS Model(s) for Main Stem
- Convert Flood Profiles to Floodplain Inundation Layers for GIS Mapping

## E. Coordination Efforts During Study

### 1. Technical Meetings

Numerous technical meetings were held during the study's conduct, including two large meetings.

On January 17, 2001, a formal Technical Meeting was held at the LCRA. Attendees included staff from the LCRA, Corps of Engineers, FEMA, and the study team. The stated objective of that meeting was "to discuss the technical issues related to hydrologic and hydraulic modeling of the Colorado River basin and to come to a decision or firm direction on each issue." Issues included discharge-frequency analysis, distribution of rainfall, routing, overall technical approach, and reservoir operation issues.

On November 6, 2001, another formal Technical Meeting was held in Fort Worth. Representatives of the LCRA, Corps of Engineers, FEMA's technical consultant (PBS&J), and the study team were present. This meeting was primarily held to discuss the Draft Flood Frequency Analysis Report, the Period-of-Record (SUPER) analysis, and the rainfall generator being developed for the study.

## F. Previous Studies

See the *Previous Studies* section of this appendix (Section V).

## G. Limitations of Data and Models Used in Study

### 1. Mapping Data

a. Digital contour mapping to national map accuracy standards, 4-foot interpolated to 2-foot in most areas, some urban areas 2-foot interpolated to 1-foot.

b. Upstream limits of detailed mapping is the Burnet/Lampasas county line.

c. Hydrology (watershed divides) based upon USGS 30 meter resolution terrain data, plus or minus 10-foot vertical accuracy.

d. Field surveyed cross sections average 2 cross section per mile, channel interpolation based upon these surveys.

2. **GIS Data**

a. Individual arcs limited to 500 vertices, affects stationing line.

b. Amount of terrain data required the use of multiple TINs to define the mainstem.

3. **HEC-5 Model**

a. HEC-5 is a Corps of Engineers' program developed primarily for Corps' flood control reservoir systems.

b. HEC-5, Version 8.0 has certain limitations in modeling a system such as the Highland Lakes along the Colorado River.

i. The current HEC-5 model cannot forecast to interim pool elevations and increase releases based upon those forecasts. HEC-5 can only increase releases when the top of flood pool is forecast to be exceeded.

ii. HEC-5 uses the same forecast time for inflows into Lake Travis and for looking downstream at control points. These limitations could not be addressed in the current HEC-5 model.

c. Two other limitations of Version 8.0 were overcome by changing parameters iteratively within the model.

i. Currently, the pre-release option must be used universally for all reservoirs. In order to keep inflow = outflow up to the maximum outlet capacity at pass through reservoirs, the model was forced to release inflow (by adding a QA card) for the few time periods that the pre-release (outflow > inflow) occurred. This had no effect on the final pool elevation.

ii. Another problem was that the releases from Lake Travis never allowed the river at the Austin gauge to reach its full channel capacity. In order to overcome this limitation, the channel capacity in HEC-5 at Austin was altered until the maximum allowable flow was achieved by the combination of the Travis releases and Austin local flows. This resulted in the proper peak flow rate at Austin and Travis outflows for various frequency storm events.

d. Lake Buchanan Operations – The Lake Buchanan Operation, in accordance with the 1990 FEMA/LCRA agreement, could not be input directly into HEC-5. A spreadsheet was used to compute a Buchanan outflow hydrograph based upon Buchanan inflows and San Saba gauge flows (from HMS) in accordance with the 1990 FEMA/LCRA agreement. The computed outflow hydrograph was input directly into HEC-5 as Buchanan releases (by adding QA cards).

4. **RESPROB Program**

RESPROB is a basic (single) reservoir operation program. It can only look at one downstream control point with one maximum channel capacity (Columbus in this case), and no routing of flow to the downstream control point is considered. This is another reason that RESPROB and the joint probability analysis should only be used to extrapolate the SUPER period-of-record frequency curve to larger storms.

5. **Limitations of Lake Travis Joint Probability Analysis:**

The Total Probability Theorem was applied to extend the computed period-of-record frequency pool elevation curve for larger events at Lake Travis. The Total Probability Theorem requires independence between the events. In the case of the Lake Travis analysis, the two events are starting pool elevation and inflow hydrograph (storm frequency). Since the starting pool elevation probabilities were determined from the period-of-record analysis, the effects of large storm events influenced these starting pool elevations. This is a major reason why the period-of-record (SUPER) results should be used except for the large (less frequent) events. The joint probability analysis is only used to extrapolate the SUPER period-of-record frequency curve to these larger storms.

6. **SUPER Model**

i. The SUPER period-of-record analysis uses a daily time step which will not capture instantaneous peaks.

   a. Instantaneous peaks were calculated based upon the slope of a line between the daily peak flow and the instantaneous peak flows observed at the gauging stations. These instantaneous peak flows were used in HEC-FFA to calculate unregulated and regulated frequencies.

   b. Hourly inflow hydrograph ordinates for Lake Travis were estimated based upon preserving total daily volume and the general shape of the hydrographs. This hydrograph was used to produce the peak stage for Lake Travis in the Joint Probability procedure.

ii. The SUPER simulation assumes that the Reservoir Operation Plan is not deviated from during the period of simulation for all reservoirs.

7. **HEC-HMS**

The HEC-HMS model was developed for the entire Colorado River basin below Lake O.H. Ivie. This basin-wide model should not be applied to smaller tributaries in the basin. These small basins would need to have their own hydrologic model assembled. The same principles could be used for the smaller tributary watersheds but the sub-basins would need to be more defined to produce an acceptable model to predict peak flows in the watershed.

8. **HEC-RAS**

a. No Peak Discharges - Unsteady HEC-RAS models were used primarily to compute the maximum water surface profiles for the 474 studied river miles. Inherently, the unsteady HEC-RAS model generates stage and flow hydrographs at any cross section in the model. We do not recommend taking a peak flow value from these flow hydrographs to be used for any purpose other than this study. Note, for the sections that will be converted to steady HEC-RAS, peak flows will be adjusted to generate the maximum water surface profile developed using the unsteady HEC-RAS models.

b. As part of the calibration to frequency events, flow hydrographs at gauged points were compared to those resulting from the hydrology and reservoir operation study components. Routing of the flood frequency hydrographs using the unsteady HEC-RAS models prepared for this study reproduce the HEC-HMS and HEC-5 results at comparison points with less than a 10% difference. Hydrographs computed by the three components of the study: HEC-HMS Hydrology, HEC-5 Reservoir Operations, and HEC-RAS flood profiles, for the different points of interest are not expected to be identical. For this study, the peak flows computed with HEC-RAS were generally lower than those computed with HEC-5 or HEC-HMS. However, the stage hydrograph used as a downstream boundary for each RAS model is the maximum stage generated by either HEC-5 at the dams, or by HMS peaks at the various gauges downstream of Longhorn Dam.

c. Energy Approach - In order to create stable, robust, unsteady models for the various reaches, most bridges were modeled using the energy approach method for high and low flows. Although, the momentum, Yarnell, or weir equations may yield slightly higher results, the differences were considered negligible, typically ranging below 0.2', although a few values reached 0.5'. Tables developed for each bridge comparing results from all modeling approach methods are included in the discussions for each HEC-RAS model reach.

d. Relation to Topographic Mapping - Computed water surface elevations are only as accurate as the topography used.

e. Roughness Coefficients – Manning's "n" values were calibrated using only one historical flood event, either June 1997 or October 1998. Due to changing conditions in the river, "n" values need to be reviewed when using the models.

## II. Engineering Analyses – Methodology

### A. **General Overview Of Technical Approach** (Hydrologic And Hydraulic Analyses)

#### 1. Period-of-Record Flow Analysis

The study team prepared a historical period-of-record analysis for development of unregulated flows on the Colorado River basin, using the best available gauge data and the Corps' Southwestern Division Modeling System for the Simulation of the Regulation of a Multi-Purpose Reservoir System (SUPER) program. This analysis provided a full 70-year period-of-record, unregulated and regulated set of historical basin flows (peaks) at all gauges. This analysis also provided a regulated set of historical volume based flows for Lake Travis. The data was in a daily time step format. Another Corps' program, RESPROB, was also used as a tool to extend the period-of-record study for less frequent events at Lake Travis. A by-product of this analysis was a historical discharge-frequency analysis for both unregulated and regulated basin conditions, to be used for calibration and for comparison to other historical frequency analyses. A summary of results is contained in the Summary of Findings.

2. **Historical Frequency Analysis at Each Gauge**

   Utilizing the WRC Bulletin 17B guidelines, other possible criteria, and the HEC-FFA Flood Flow Frequency Analysis software, the study team computed frequency versus peak flows for unregulated conditions at 16 gauges on the Colorado River and tributaries. These results were used in conjunction with the period-of-record analysis results and allowed the study team to develop an unregulated, data set to use for hydrologic model calibration (HMS). This step provided the basis for calibration of the hydrology models. A summary of results is contained in the Summary of Findings.

3. **Initial/Preliminary HEC-RAS Hydraulic Model**

   This preliminary model was developed for hydrologic routing purposes, using GIS-generated TIN's (LCRA detailed mapping topo DEM's) and Geo-RAS. The model limits were from the San Saba, Texas gauge on the Colorado River to the mouth at Matagorda Bay. A summary of results is contained in the Summary of Findings.

4. **Initial/Preliminary UNREGULATED Basin-Wide HMS Model**

   The steps in this process included:

   a. Finalized sub-basins for the entire study area, starting with UT-CRWR base.
   b. Reproduced the UT-CRWR basin delineations using HEC-GeoHMS
   c. Utilized existing sub-basin parameter utility program, developed sub-basin parameters: Snyder's unit hydrograph parameters, revised loss rates, urbanization, etc.
   d. Tributary Routing – Used GIS-generated Modified puls routing tables for all routing reaches outside of the main stem Colorado River. Used USGS DEM's and Geo-RAS.
   e. Main Stem Routing - Used GIS-generated (LCRA detailed mapping topo DEM's) and Geo-RAS, prepared the preliminary RAS (steady) model of river, developed Modified puls routing tables (from Lake Buchanan to Matagorda Bay). From upper Buchanan to Ivie Reservoir, used USGS DEM.
   f. Routing through the original river portion of the now existing reservoirs (Highland Lakes) was based upon using old topographic maps, sediment ranges, or other cross section sources, as available.

5. **Rainfall Information for HMS Model**

   The steps in this process included:

   a. Prepared the Hypothetical Storm Rainfall
   b. Used 96-hour storm duration and a centered temporal storm.

c. Rainfall data was obtained from TP-40, TP-49, and Hydro-35. For SPF, used Corps' Engineer Bulletin 52-8 (SPF), EM 1110-2-1411.

d. STORM CENTERS FOR SPECIAL POINTS OF INTEREST (POI'S) – Six Special POI's, were at Colorado River near San Saba Gauge, Llano River at Llano Gauge, Buchanan Dam, Mansfield Dam (Travis), Bastrop Gauge, and Wharton Gauge.

e. Contouring for Centering of critical rainfall storms for the Special POI's

    i. Prepared setup grid pattern and input files for automated, multiple storm-centering HMS runs.

    ii. One search grid (sub-basin centroids)

    iii. Shape – one elliptical shape

    iv. Orientation – Used one only, the preferred orientation (HMR-51 & 52)

f. Post-Contouring Phase - Selected final storm centers for each frequency

6. **HMS Storm Reproduction (Calibration) PHASE**

Input was actual NEXRAD rainfall and stream gauge data from floods that occurred in the 1990's and 2000.

a. Used NEXRAD historical rainfall data (for 3 storms –June 1997; October 1998; and November 2000).
b. Generated flood hydrographs, from the recorded storm rainfall and compared to the historical gauge records for those storms.
c. At this point, we had a calibrated HMS runoff model (still unregulated). All final hydrographs were sent to DSS for further verification (HMS) and processing by HEC-5 and RAS (unsteady)

7. **HMS Verification Phase (Unregulated Conditions)**

The purpose of this phase was to test and verify the response of our calibrated HMS model using the historical frequency data derived from the FFA Analysis and the Period-of-Record analysis.

a. Executed HMS for initial unregulated basin calibration (For 6 POI's for each of 8 frequencies – 2-, 5-, 10-, 25-, 50-, 100-, 500-year, and SPF). Total of 48 calibrations/verifications.
b. Calibrated the HMS model parameters, primarily loss rates, to match, as closely as possible, the peak discharges (historical frequency) at the 6 points of interest, with checks at other stream gauges in basin (at least 16 total gauges).
c. Iterate through b. and c. until calibration is completed.
d. Product: A calibrated and verified, unregulated HMS model of basin with peak discharges at <u>all points of interest</u> (including all gauges and the six Special POI's).

8. **HEC-5 Reservoir Operation Model for Regulated Basin Conditions**

   a. Prepared detailed HEC-5 model including all significant reservoirs (Starts at Buchanan and goes downstream to Matagorda Bay. Columbus is last control point).

   b. Inflow hydrographs came from HMS (DSS), started at Buchanan and included all local contributing area hydrographs from HMS runs. HEC-5 routed the hydrographs downstream, added in the local hydrographs, and routed through the reservoirs, based upon LCRA-provided operation policies/rules. These policies/rules were: For Lake Travis - 1996 USACE document Part 208.19, Title 33 CFR, Standard Operating Procedures Mansfield Dam as of December 1996. For Lake Buchanan - Gate operation was in accordance with 1990 FEMA/LCRA agreement. Other reservoirs - Operated as inflow equals outflow based upon rating curve and storage data provided by LCRA.

   c. Routing with HEC-5 – Used the same Modified Puls routing from the HMS model. In the reservoirs, classic reservoir routing methods were used.

   d. The output from HEC-5 included computed inflows, releases, and pool elevation hydrographs for each reservoir; and computed flow hydrographs for each control point. Output goes to DSS for use with RAS (unsteady). See Step 9.

9. **Final RAS Hydraulic Model(s) for Main Stem**

   Prepared the final HEC-RAS unsteady hydraulic model for final flood profiles/delineation. These models have the Corps' field surveyed channel sections and include all bridges.

   a. Inflow hydrographs at the upstream end of overall study (San Saba gauge) were from HMS/DSS. Downstream boundary condition (stage hydrograph), at Buchanan was from HEC-5. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

   b. From Buchanan Dam downstream to Lake LBJ, used HEC-5 outflow hydrographs (releases) as upstream boundary condition and Lake LBJ stage hydrograph as downstream boundary. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

   c. From Lake LBJ downstream to Lake Marble Falls, used HEC-5 outflow hydrographs (releases) as upstream boundary condition and Lake Marble Falls stage hydrograph as downstream boundary. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

   d. From Lake Marble Falls downstream to Lake Travis, used HEC-5 outflow hydrographs (releases) as upstream boundary condition and Lake Travis stage hydrograph as downstream boundary. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

   e. From Travis downstream to Tom Miller Dam (Lake Austin), used HEC-5 outflow hydrographs (releases) as upstream boundary condition and Tom Miller Dam stage hydrograph as downstream boundary. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

f. From Tom Miller Dam downstream to Longhorn Dam (Town Lake), used HEC-5 outflow hydrographs (releases) as upstream boundary condition and Longhorn Dam stage hydrograph as downstream boundary. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

g. From Longhorn Dam downstream to the Intercoastal Waterway (Matagorda Bay) used HEC-5 outflow hydrographs (releases) as upstream boundary condition and normal depth at the terminal point. Lateral inflow hydrographs accounted for intervening areas, and came from HMS/DSS.

h. Iteration between HEC-5 and RAS (Unsteady Model) was required until final/satisfactory calibration was reached.

i. At each stream gauge the RAS-routed peak discharge was compared to historical discharge-frequency curves (From Steps 1 and 2).

j. Final flood profiles for each frequency event were computed and stored for future uses.

10. **Convert Flood Profiles to Floodplain Inundation Layers for GIS Mapping**

Once the final RAS (unsteady) models were completed and the final flood profiles computed, a developed ArcInfo AML was used for floodplain delineation (in lieu of grid-based HEC-Geo-RAS), with the existing GIS-based DTM. A quality control check, by hand, for any abnormalities was made between the hydraulic model output and the floodplain delineation. This automated floodplain mapping layer for the various frequency floods was preserved as separate levels in the GIS, for use in other tasks, such as flood damage assessment, and for non-structural alternative analysis.

## III. Mapping and Geographic Information System – (GIS) Applications

### A. Data Sources

Several different types of mapping data were available for this study area. The primary source of terrain data was developed from traditional aerial mapping procedures and included two foot contours in rural areas, one foot contours in some urban areas, and point elevations derived from USGS DEMs.

#### 1. Terrain Data

The Lower Colorado River Authority mapped approximately 451 linear miles along the Colorado River, extending from the Burnet - Lampasas County line down to the Gulf of Mexico at Matagorda Bay. Components of this mapping project included: aerial digital orthophotography, digital contour maps to national map accuracy standards (4-foot contours interpolated to 2-foot contours); in urban areas including Matagorda, Garwood, Columbus, La Grange, and Wharton, digital contour mapping to national map accuracy standards (2-foot contours interpolated to 1-ft); parcel maps and parcel data for river front property; planimetric maps (digital coverage layers ) for all visible structures; and integration of mapping data into ESRI's ArcGIS software. The spatial extent of the aerial mapping was the approximate 500-year floodplain based upon FEMA's Q3 data set. To supplement the aerial mapping, U.S. Geological Survey (USGS) 30m Digital Elevation Model (DEM) data was used outside the spatial extent of the aerial mapping to fill in a one half mile buffer zone. For hydrology uses, the base data for watershed sub-basin delineation came from available USGS 30-meter DEM data.

2. **Field Survey Data**

The aerial mapping did not provide any elevation data below the water surface so 165 channel cross sections were field surveyed along the river. In addition, data from bathymetry surveys were collected for the lakes within the study area. Using GIS tools, all of these data sets were combined to form a seamless terrain model, in the form of a TIN.

B. **Hydrology Study Applications**

1. **Pre-Pro (UT-CRWR)**

The original GIS based HEC-HMS basin file was developed by the University of Texas, Center for Research in Water Resources (UT-CRWR) using their basin delineation program Pre-Pro in ArcView 3.2. Pre-Pro is actually a set of GIS commands arranged in a step-by-step procedure that produces a basin input file as the final product. The base data for the sub-basin delineation was the 30-meter USGS DEM data. The GIS-generated basin model for the study area was broken into two separate delineation areas due to the size of the basin and software limitations. The break occurred at Mansfield Dam (Lake Travis). The Colorado River basin was originally subdivided into 232 sub-basins, averaging about 79 square miles. This original basin file lacked unit hydrograph parameters and loss rate parameters.

2. **HEC-GeoHMS**

Based upon other parameters, it was decided that there was a need for a greater number of sub-basins. Pre-Pro was not programmed to calculate a few key parameters (basin centroid, basin centroidal length, and longest flow path) needed to develop input parameters using the Corps' utility program. The study team also wanted the delineations to be reproducible with the Corps of Engineers program HEC-GeoHMS. The study team took some of the original Pre-Pro generated grids and re-delineated the watershed. Several basins were added to the original delineation. The final basin delineation produced 290 sub-basins, averaging 63 square miles. The Corps' sub-basin parameter utility program was executed to generate parameters for the HEC-HMS model. Another utility program was used to extract the sub-basin parameters from the text file and insert them into the basin file created using HEC-GeoHMS. The initial hydrologic model parameter estimates were then assembled into the initial HEC-HMS model.

C. **Hydraulic Study Applications**

1. **TIN Development**

TINs for the Colorado River basin were generated for use in HEC-GeoRAS for the purposes of a ground surface elevation model and to extract river cross sections. Due to the amount of topographic data, the detailed study area had to be broken into 20 subsets to stay within the processing limitations. The topographic data layers used for the TINs included:

- USGS 30m DEMs (Maidment)
- Spot elevations from aerial survey (LCRA)
- Derived 2-foot and 1-foot contour lines from aerial survey (LCRA)
- Spot elevations from lake bathymetry survey (LCRA)
- Channel field surveys (Corps)

2. **HEC-GeoRAS**

   To assist in moving data from the GIS environment to a HEC-RAS hydraulic model geometry file, the Corps of Engineers has developed a software extension for ArcView GIS, developed by ESRI, Inc., called HEC-GeoRAS. This extension is designed to take GIS data representing stream centerlines, cross sections, bank lines, flow paths, land cover, and terrain data in the form of a TIN and process them into a HEC-RAS geometry file. This extension works very well, but some limitations were found with the data and the extension's capabilities when working with a project of this size.

3. **River Channel Issues**

   In addition to combining different types of elevation data, a GIS utility was developed to generate interpolated channel geometry between the survey locations. Unlike the cross section interpolater built into HEC-RAS, which can only interpolate in a straight line, the utility that was developed accounted for bends in the river. This interpolated channel geometry was incorporated into the TIN along with all the other terrain data sets. Incorporating the channel geometry into the TIN provided the benefit of being able to take cross sections at any point along the river and not just at survey locations.

4. **River Centerline Issues**

   HEC-GeoRAS was found to have a limitation when processing arcs representing the river centerline. The original line, stored in an ArcView shapefile, was based upon the USGS National Hydrography Dataset (NHD). This shapefile was represented by multiple arc segments for the purpose of defining the changes that occur along the river in accordance with the NHD database. Approximately 940 arc segments existed within the 480-mile study reach. When HEC-GeoRAS processes a river centerline a junction is placed at each node in the shapefile (a node is where two or more arc segments are connected). This causes a problem because HEC-RAS only expects to have junctions where a tributary connects to the main stem of the river. HEC-RAS does have the ability to delete junctions, but that would have required deleting 940 junctions by hand. To work around this problem the number of arc segments that represent the river needed to be reduced. The tools to combine arcs already existed within the GIS, but a procedure was needed to reduce the number of vertices that defined the line. To accomplish these tasks a utility was developed that analyzed the angle formed by three vertices, if that angle was within a user specified tolerance for forming a "straight" line then the middle vertex was deleted. During the processing, this utility also combined arc segments up to the software limit of 500 vertices. This utility was able to reduce the number of arc segments defining the centerline from 940 arcs to 59 arcs.

5. **Floodplain Delineation Issues**

HEC-GeoRAS uses a rasterization procedure used to delineate the floodplain after running HEC-RAS. After running HEC-RAS each cross section in the hydraulic model has a water surface elevation assigned to it for a given flood profile. This elevation data can be brought back into the GIS environment and then used to delineate floodplain polygons. The floodplain is based upon the intersection of the ground surface and the water surface. The ground surface is already represented by the terrain TIN. A water surface TIN is generated by "TINing" the cross sections based upon the flood profile elevation assigned to each cross section. When HEC-GeoRAS goes to intersect the ground and water surfaces it first rasterizes the two TINs (rasterization is the process of converting a TIN to grid or DEM). The cells representing the same spatial location are then compared and a new grid is then generated with cells being marked as wet or dry. All cells marked as wet represent the inundated area. The first problem with this procedure is that the resulting inundation area has a blocky appearance. The second problem is that HEC-GeoRAS has a one million cell limitation. For a small area this is not a problem, but when very large areas are being analyzed the cell sizes start to get very large; sometimes cell sizes can reach 1,000 feet or more on a side. When this occurs poor inundation areas are defined. The solution to this problem was to develop a procedure that intersects the ground and water surface TINs without rasterization. Using GIS tools outside of HEC-GeoRAS a utility was developed to intersect the two TINs. The results of using this utility allowed for large areas to be analyzed at one time and smoother, more natural looking, inundation polygons were generated to represent the floodplains.

## IV. Summary Of Findings

### A. General

This hydrologic and hydraulic analysis of the Colorado River basin includes 482 river miles of the Colorado River, covers 18,000 square miles of watershed, includes seventy years of historical flood data, and delineates floodplains for eight different flood events (2-year to 500-year floods and the SPF).

### B. Flood Peak Discharges

A summary of 100-year frequency flood peak discharges at selected locations is shown in Table A-7. In general, the peak discharges computed for this study were slightly lower than the published FEMA flood insurance study values. In some cases, lower peak discharges do not always produce lower flood elevations, due to updated modeling data and techniques. Earlier studies utilized steady-state hydraulic models while this study uses unsteady modeling along the Colorado River.

**Table A- 7. Summary and Comparison of 100-Year Flood Peak Discharges**

| Location On the Colorado River | Current Study Computed 100-year Discharge (1) | FEMA 100-year Discharge |
|---|---|---|
| Red Bluff Gauge Near San Saba | 237,100 | N/A |
| Tom Miller Dam (Lake Austin) | 90,100(2) | 170,000 (3) |
| Austin Gauge Upstream of U.S. 183 | 90,300(2) | 170,000 (3) |
| Below Mouth of Onion Creek | 138,300 | 210,000 (4) |
| Bastrop Gauge at Loop 150 | 142,000 | 149,300 |
| Columbus Gauge at U.S. 90 | 135,200 | 136,000 |
| Wharton Gauge at U.S. 59 (Business) | 114,100 | 139,500 |

(1) Computed values used to determine flood elevations.
(2) Releases from Mansfield Dam, 90,000 cfs.
(3) Value in Published Flood Insurance Study is 170,000 cfs. Values in the effective FEMA models range from 90,000 to 100,000 cfs.
(4) Value from Travis County FIS at Travis-Bastrop County Line.

C. **Flood Elevations**

A summary of the peak flood elevations on the Highland Lakes and Town Lake is shown in Table A-8.

**Table A- 8. Colorado River Reservoir Summary**

***(All elevations are computed at upstream face of the dam. Flood elevations on each lake will rise along the river upstream from the dams.)***

**Lake Buchanan** (Historic High = 1021.6', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 1020.0 | N/A | N/A |
| 5-Year | 1020.0 | N/A | N/A |
| 10-Year | 1020.5 | 1020.7 | -0.2 |
| 25-Year | 1020.5 | N/A | N/A |
| 50-Year | 1020.5 | 1020.7 | -0.2 |
| 100-Year | 1021.0 | 1021.2 | -0.2 |
| 500-Year | 1022.7 | 1022.1 | +0.6 |
| SPF | 1025.9 | N/A | N/A |

**Table A- 8. (continued)**

**Inks Lake** (Historic High = 903.0', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 890.0 | N/A | N/A |
| 5-Year | 892.9 | N/A | N/A |
| 10-Year | 895.0 | 895.2 | -0.2 |
| 25-Year | 896.9 | N/A | N/A |
| 50-Year | 900.0 | 900.2 | -0.2 |
| 100-Year | 901.7 | 901.9 | -0.2 |
| 500-Year | 909.0 | 908.7 | +0.3 |
| SPF | 912.4 | N/A | N/A |

**Lake LBJ** (Historic High = 836.4', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 825.0 | N/A | N/A |
| 5-Year | 825.0 | N/A | N/A |
| 10-Year | 825.0 | 825.2 | -0.2 |
| 25-Year | 825.0 | N/A | N/A |
| 50-Year | 825.4 | 826.2 | -0.8 |
| 100-Year | 828.1 | 828.1 | 0.0 |
| 500-Year | 839.4 | 841.2 | -1.8 |
| SPF | 843.3 | N/A | N/A |

**Lake Marble Falls** (Historic High = 756.6', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 738.0 | N/A | N/A |
| 5-Year | 738.0 | N/A | N/A |
| 10-Year | 742.8 | 739.2 | +3.6 |
| 25-Year | 748.0 | N/A | N/A |
| 50-Year | 752.2 | 749.7 | +2.5 |
| 100-Year | 754.3 | 753.2 | +1.1 |
| 500-Year | 762.1 | 762.7 | -0.6 |
| SPF | 771.4 | N/A | N/A |

Elevation based upon old rating, LCRA to provide new rating.

**Table A- 8. (continued)**

**Lake Travis** (Historic High = 710.2', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 685.2 | N/A | N/A |
| 5-Year | 691.1 | N/A | N/A |
| 10-Year | 697.0 | 691.2 | +5.8 |
| 25-Year | 713.7 | N/A | N/A |
| 50-Year | 716.7 | 710.2 | +6.5 |
| 100-Year | 722.0 | 716.2 | +5.8 |
| 500-Year | 732.6 | 728.7 | +3.9 |
| SPF | 734.4 | N/A | N/A |

**Lake Austin** (Historic High = 495.5', NAVD88)

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 492.8 | N/A | N/A |
| 5-Year | 492.8 | N/A | N/A |
| 10-Year | 492.8 | 493.1 | -0.3 |
| 25-Year | 492.8 | N/A | N/A |
| 50-Year | 492.8 | 493.3 | -0.5 |
| 100-Year | 492.8 | 493.3 | -0.5 |
| 500-Year | 506.3 | 503.5 | +2.8 |
| SPF | 507.7 | N/A | N/A |

**Town Lake**

| Frequency | Current Study Computed Elevation (Feet NAVD88) | FEMA Elevation (Feet NAVD88) | Difference Current – FEMA (Feet) |
|---|---|---|---|
| 2-Year | 428.3 | N/A | N/A |
| 5-Year | 428.3 | N/A | N/A |
| 10-Year | 428.3 | 429.1 | -0.8 |
| 25-Year | 430.3 | N/A | N/A |
| 50-Year | 438.6 | 436.5 | +2.1 |
| 100-Year | 438.6 | 439.8 | -1.2 |
| 500-Year | 458.2 | 450.3 | +7.9 |
| SPF | 459.6 | N/A | N/A |

**<u>100-year Flood Elevations</u>** - A summary of 100-year frequency peak flood elevations at selected locations is shown in Table A-9. Note that the peak flood elevations computed for this study differ from earlier FEMA flood insurance study values. For the computed pool elevations at the upstream face of the dams, this study has equal or lower flood elevations at the upstream face of five dams (Buchanan, LBJ, Inks, Austin, and Town Lake); and higher elevations on two dams (Marble Falls and Travis). In the Austin area the current study elevations are slightly higher. At Bastrop, the estimated flood elevation is lower and at Wharton the estimated flood level is below the earlier studies. Some minor differences in the vertical elevation datum from the previous studies (NGVD29-1929 mean sea level) to the current datum (NAVD88-1988) does occur as noted in Table A-10 of this appendix.

**Table A- 9. Summary and Comparison of 100-Year Peak Flood Elevations**

| Location on the Colorado River | Current Study Computed 100-year Elevation (Feet NAVD88) | FEMA 100-year Elevation (Feet NAVD88) (3) | Difference Current – FEMA (Feet) (2) |
|---|---|---|---|
| Lake Buchanan (1) | 1021.0 | 1021.2 | -0.2 |
| Inks Lake (1) | 901.7 | 901.9 | -0.2 |
| Lake LBJ (1) | 828.1 | 828.1 | 0.0 |
| Lake Marble Falls (1) | 754.3 | 753.2 | +1.1 |
| Lake Travis (1) | 722.0 | 716.2 | +5.8 |
| Lake Austin (1) | 492.8 | 493.3 | -0.5 |
| Town Lake (1) | 438.6 | 439.8 | -1.2 |
| Austin Gauge Upstream of U.S. 183 | 437.0 | 435.3 | +1.7 |
| Bastrop Gauge at Loop 150 | 352.2 | 353.9 | -1.7 |
| Columbus Gauge at U.S. 90 | 192.2 | 194.1 | -1.9 |
| Wharton Gauge at U.S. 59 (Business) | 102.4 | 103.3 | -0.9 |

(1) Flood Elevation computed at upstream face of the dam. Flood elevations on each lake will rise along the river, upstream of the dam. See flood profiles in Section IV.
(2) See Table A-10 for explanation of vertical datum differences.
(3) Current effective FEMA 100-year elevations adjusted to NAVD88.

### D. Reason for Changes in Flood Elevations

There are several reasons that the 100-year flood elevations have changed along the Colorado River and especially on the Highland Lakes:

1. This is the first detailed, comprehensive, basin-wide approach for modeling, simulating, and computing frequency-based rainfall, runoff, reservoir elevations, and flood elevations along the entire river corridor.

2. There is an additional 25 years of historical flood and rainfall records that have been collected since the previous flood studies of the mid to late 1970's. This provides a more comprehensive statistical database for developing flood frequency estimates.

3. The calibration and verification of the flood models used in the study has been enhanced significantly by the additional historical rainfall and flood data and the computational power of large capacity computers. The use of NEXRAD radar and GIS tools in the collection of data, development of computer models, and display of results has provided a greater degree of accuracy in the floodplain delineation and overall flood analysis process.

4. A more realistic assumption of the long-range river flood forecasting abilities of reservoir operators has had an effect on predicted 100-year pool levels. For example, in earlier flood studies to determine FEMA pool elevations on Lake Travis, an assumption of a reliable 36-hour forecast time was used. Even with advanced NEXRAD radar and additional rainfall and stream gauges, a 12-hour flood forecast is considered by the LCRA and the Corps as the maximum time that can be safely used in dam gate operations.

5. Within the historical period of record (1930-1999) used in this study, the 1938 flood would have caused Lake Travis to reach approximately the projected 100-year flood pool (722') if the lakes had been in place. This 1938 flood, which was a high volume event, is statistically considered to be approximately the 100-year flood. In addition, the 1936 high volume flood would have reached an estimated 719' elevation on Lake Travis.

6. There are some minor vertical elevation datum differences throughout the study area as shown on Table A-10. The changes in datum from the previous studies to this study vary from near zero in the lower basin to a maximum of 0.38 feet near Winchell.

**Table A- 10. Vertical Datum Comparison (NGVD29 vs. NAVD88)**

| Gauge/Dam Name | Elevation feet | | Datum Shift (ft) |
|---|---|---|---|
| | NGVD29 | NAVD88 | NAVD88 - NGVD29 |
| Colorado River at Winchell | 1335.77 | 1336.15 | 0.38 |
| Colorado River near San Saba | 1137.00 | 1137.20 | 0.20 |
| Llano river at Llano | 982.58 | 982.72 | 0.14 |
| Pedernales River near Johnson City | 1134.67 | 1134.92 | 0.25 |
| Lake Austin at Davenport Ranch | 483.48 | 483.72 | 0.24 |
| Town Lake near Longhorn Dam | 439.31 | 439.58 | 0.26 |
| Colorado River at Austin | 407.50 | 407.77 | 0.27 |
| Onion Creek at Buda | 681.81 | 682.13 | 0.32 |
| Onion Creek at Hwy 183, Austin | 471.85 | 472.12 | 0.27 |
| Colorado River at Bastrop | 332.10 | 332.30 | 0.20 |
| Colorado River above La Grange | 256.10 | 256.25 | 0.15 |
| Colorado River at Columbus | 195.43 | 195.49 | 0.06 |
| Colorado River at Wharton | 100.31 | 100.30 | -0.01 |
| Colorado River at Bay City | 46.80 | 46.71 | -0.09 |
| Pedernales River near Fredericksburg | 1597.14 | 1597.33 | 0.19 |
| Llano River near Junction | 1665.51 | 1665.61 | 0.10 |
| Pecan Bayou near Mullin | 1239.68 | 1239.96 | 0.28 |
| San Saba River near Brady | 1549.68 | 1549.88 | 0.20 |
| Tom Miller Dam | 479.29 | 479.55 | 0.26 |
| Mansfield Dam | 510.54 | 510.74 | 0.20 |
| Starcke Dam | 703.85 | 704.03 | 0.18 |
| Wirtz Dam | 762.42 | 762.60 | 0.18 |
| Inks Dam | 852.90 | 853.08 | 0.18 |
| Buchanan Dam | 1019.92 | 1020.10 | 0.18 |

E. **Floodplains**

Based upon the computed flood elevations from this study, the total 100-year floodplain for the Colorado River, from the mouth to the Red Bluff gauge, is about 449 square miles or 287,000 acres. Since this is the first time much of the river has been studied in detail, there are no comparisons from previous studies.

F. **Flood Profiles**

Flood profiles along the Colorado River are shown on Figures A-1 through A-14.

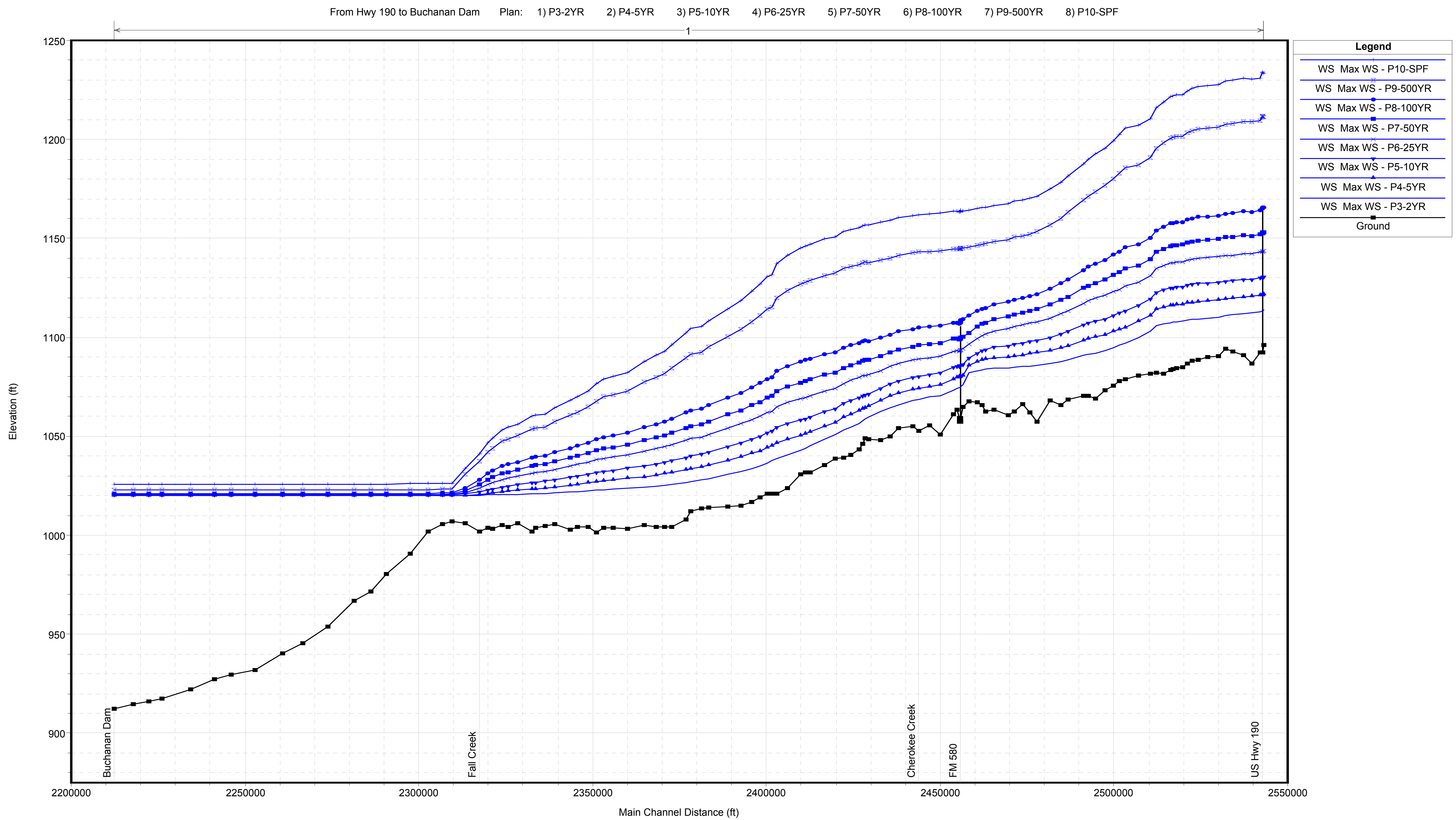


**Figure A-1. Profiles for the Buchanan HEC-RAS Reach**

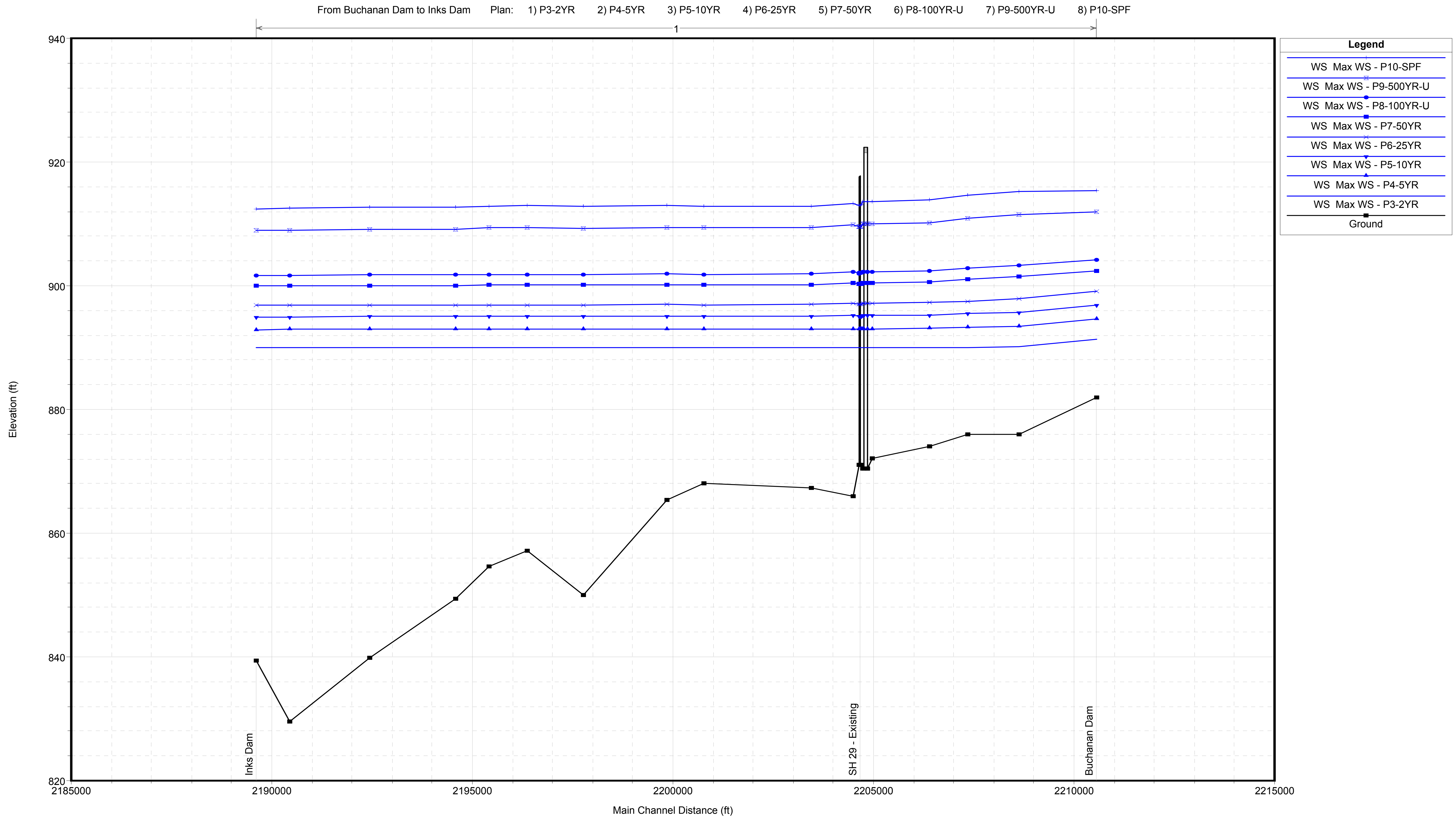


**Figure A- 2. Profiles for the Inks HEC-RAS Reach**

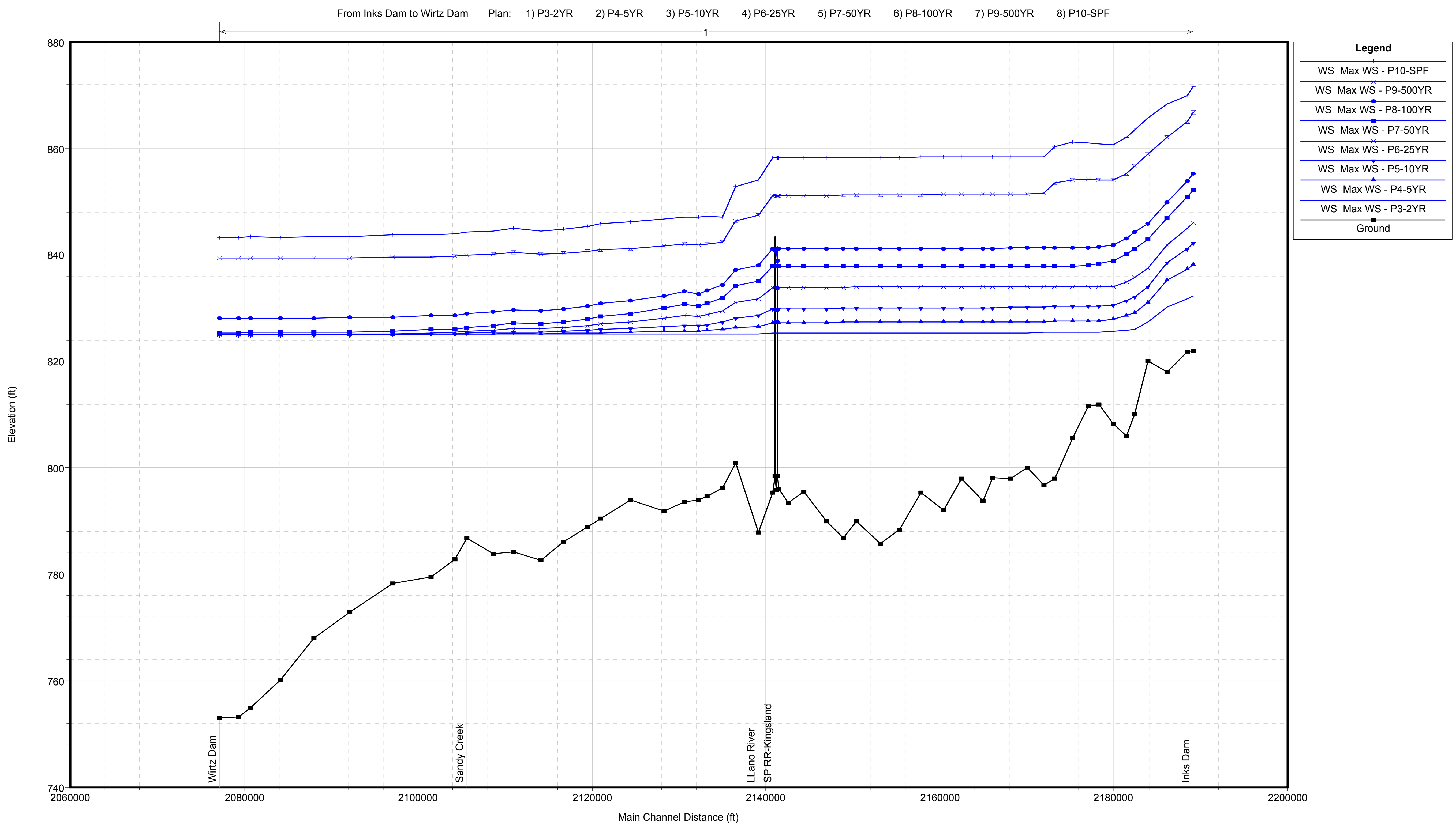


**Figure A- 3. Profiles for the LBJ HEC-RAS Reach**

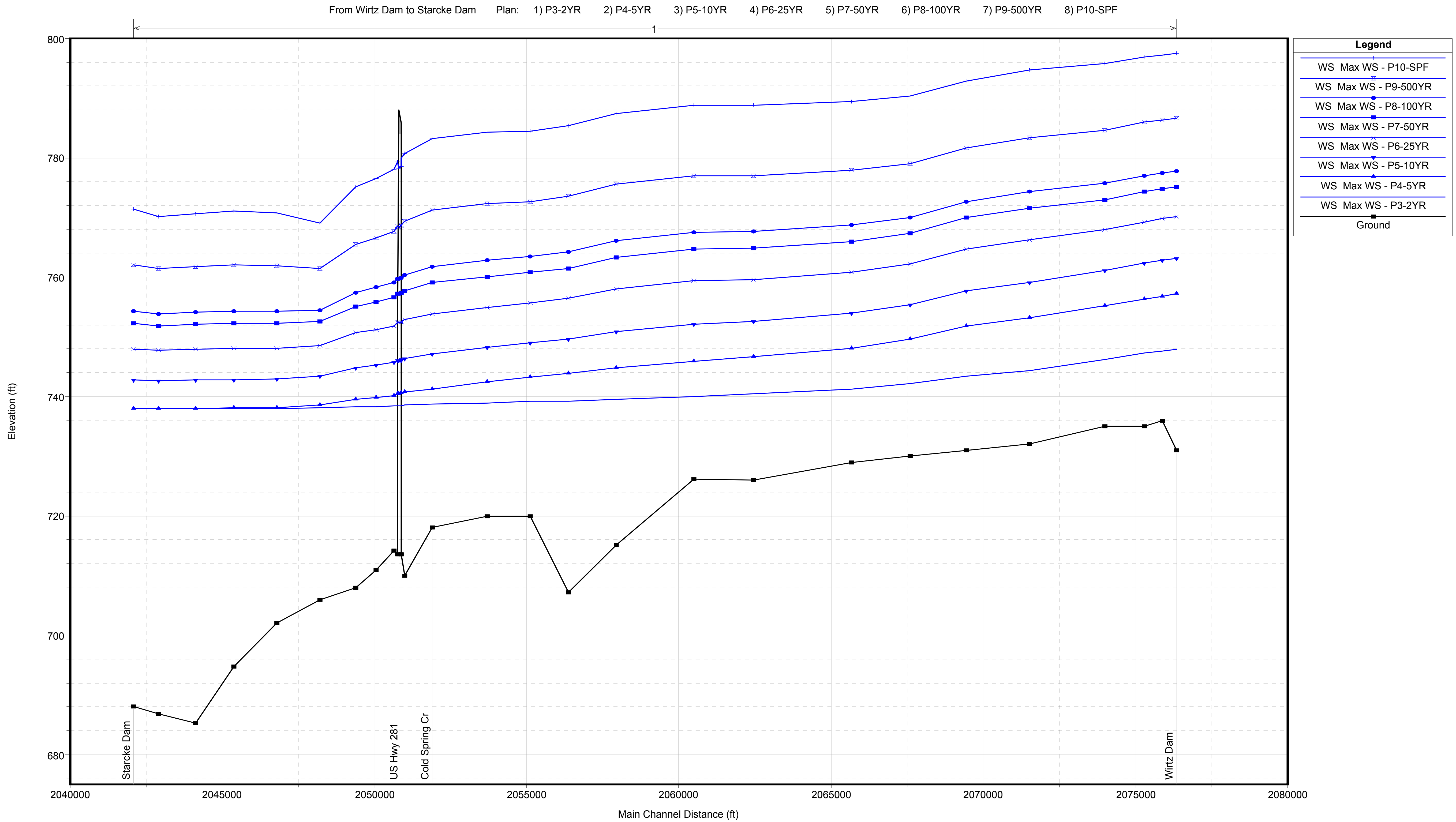


**Figure A-4. Profiles for the Marble Falls HEC-RAS Reach**

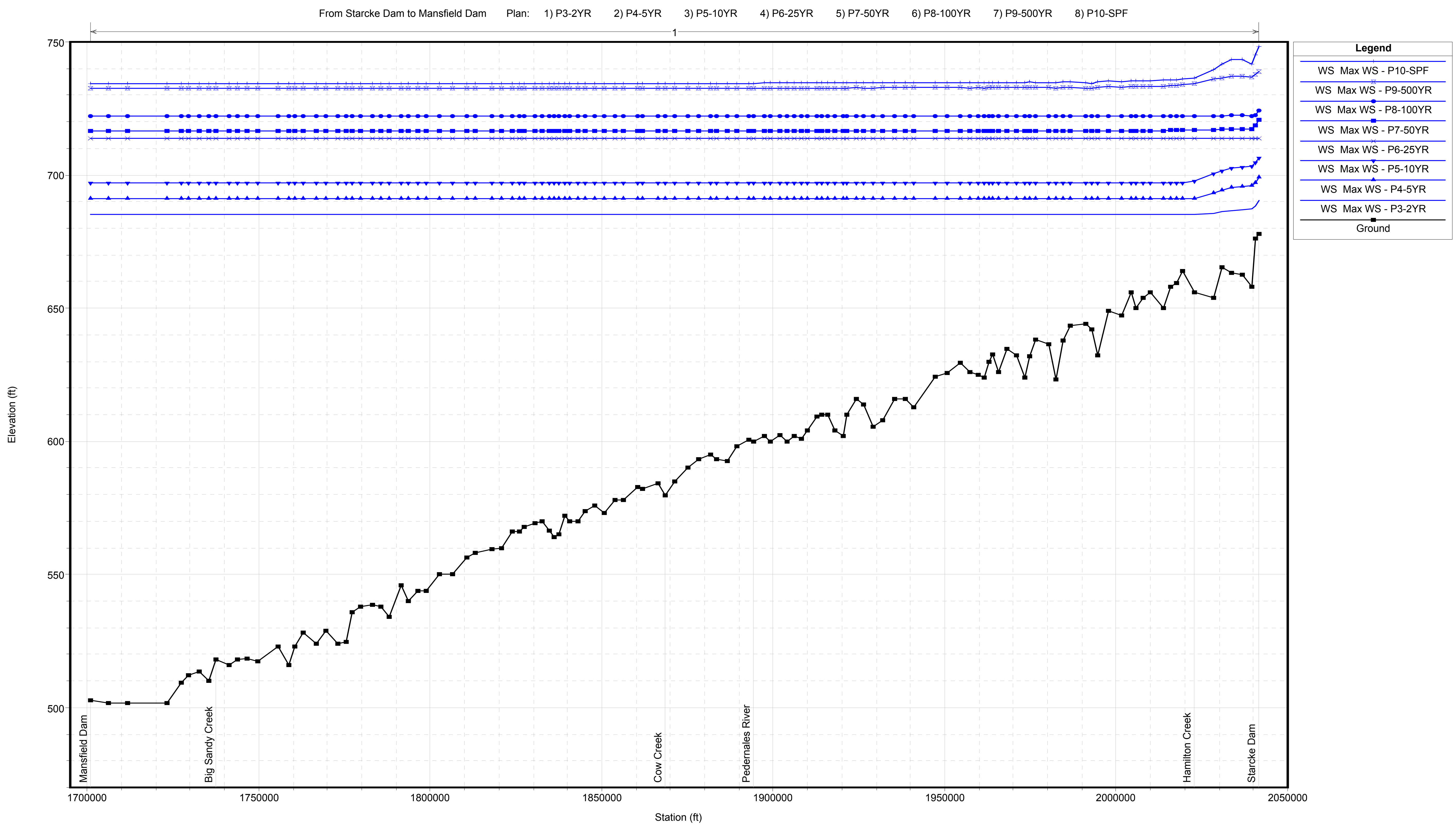


**Figure A-5. Profiles for the Travis HEC-RAS Reach**

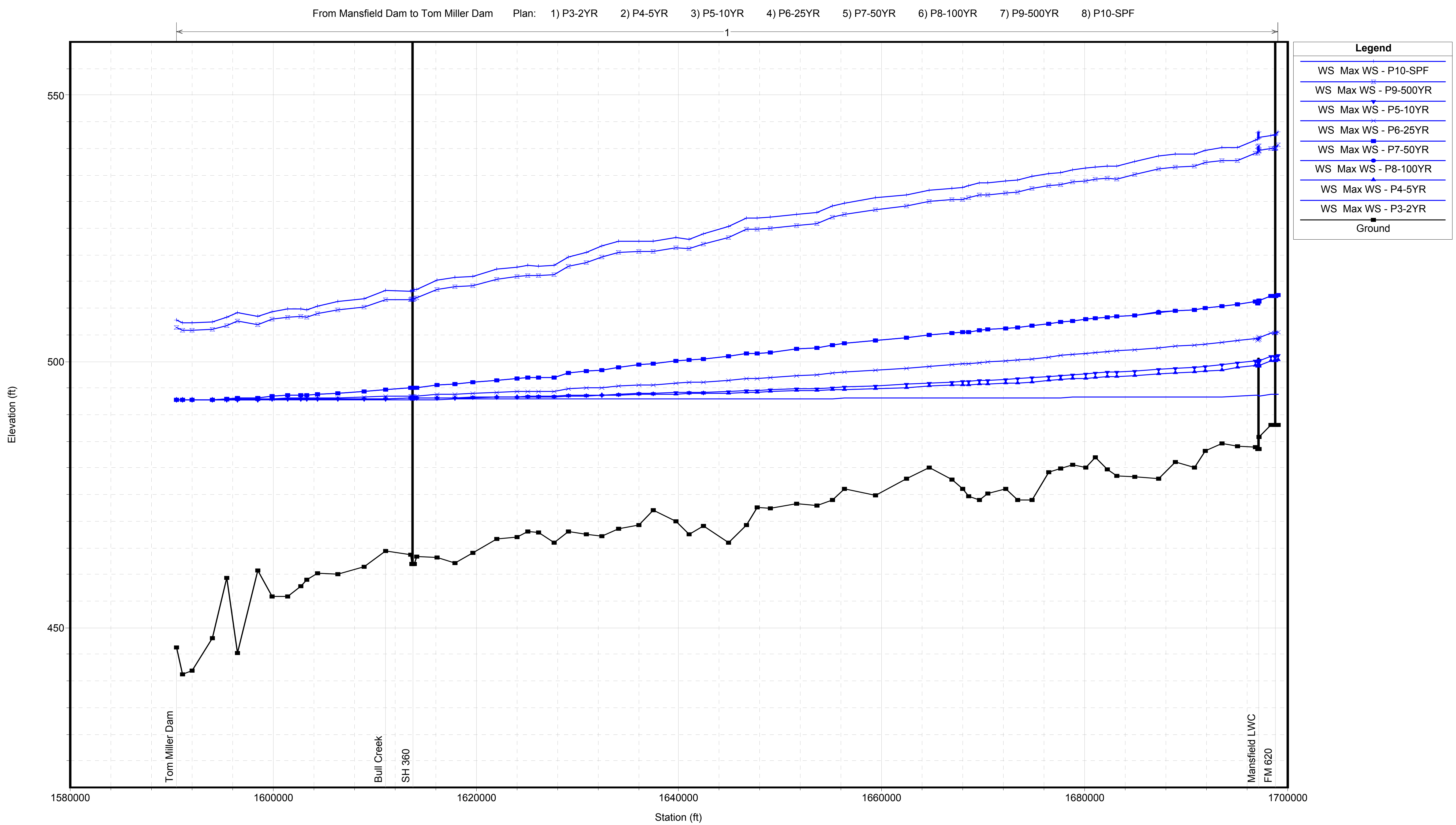


**Figure A- 6. Profiles for the Lake Austin HEC-RAS Reach**

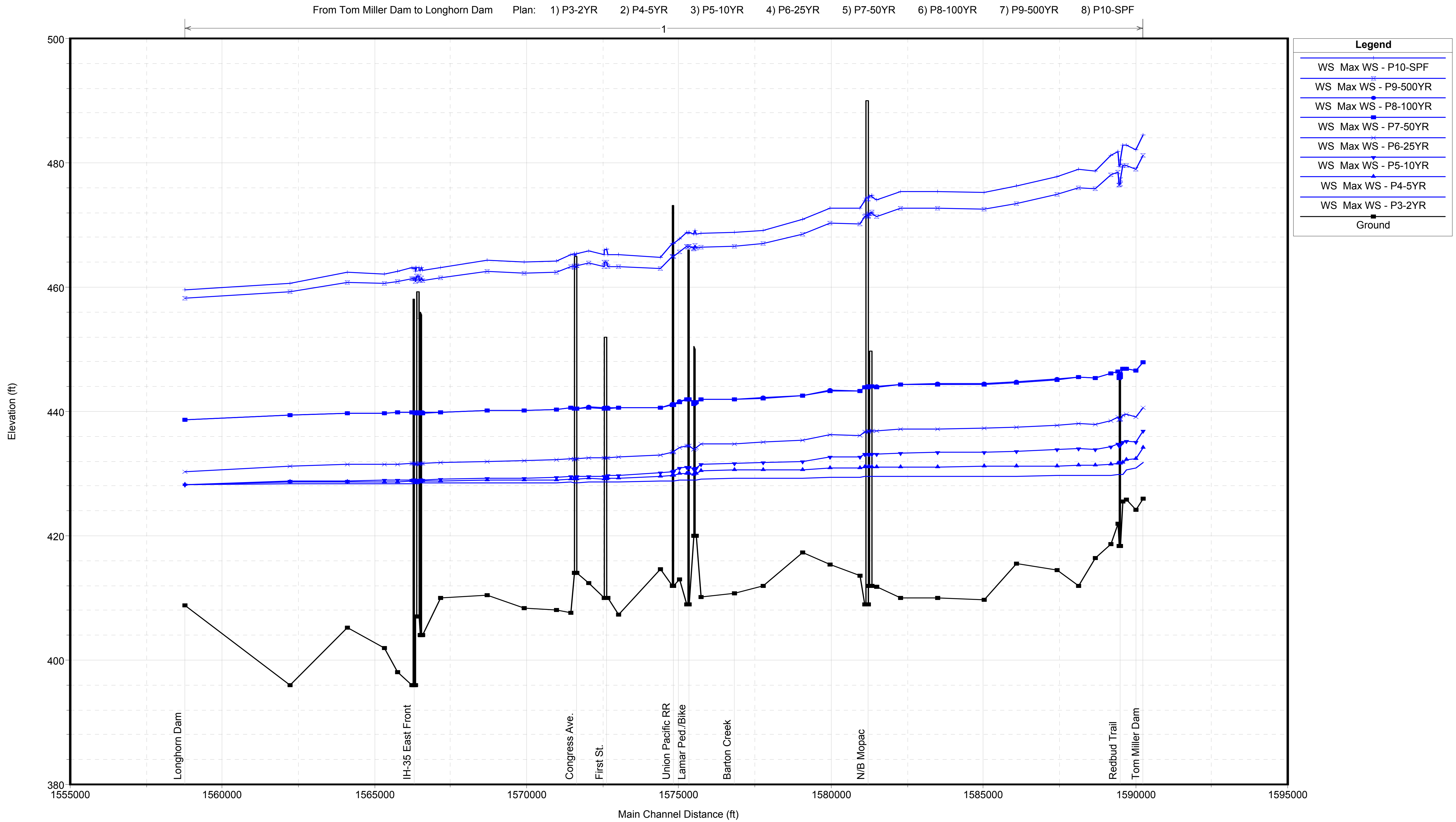


**Figure A-7. Profiles for the Town Lake HEC-RAS Reach**

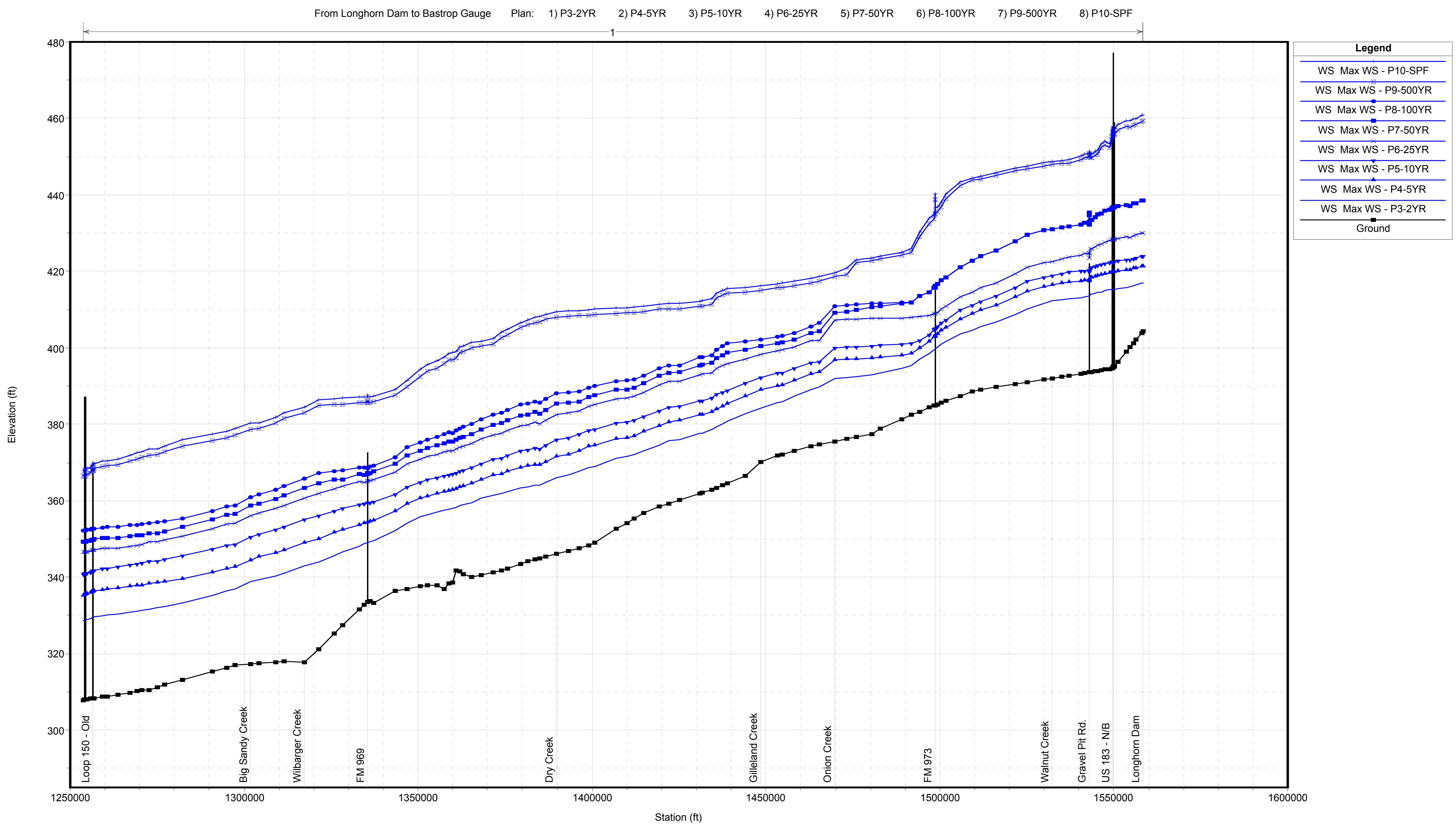


**Figure A-8. Profiles for the Bastrop HEC-RAS Reach**

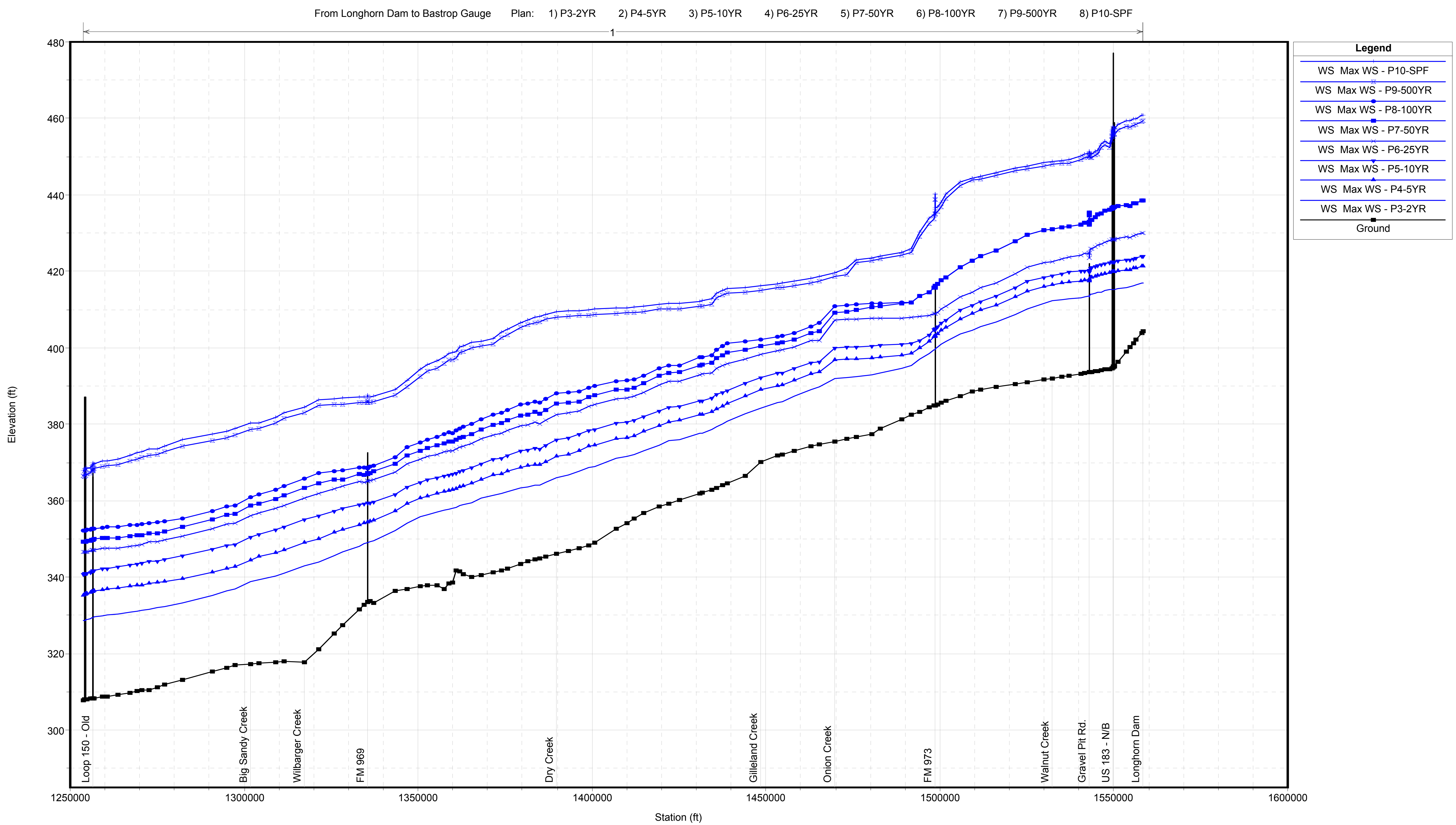


**Figure A-9. Profiles for the La Grange HEC-RAS Reach**

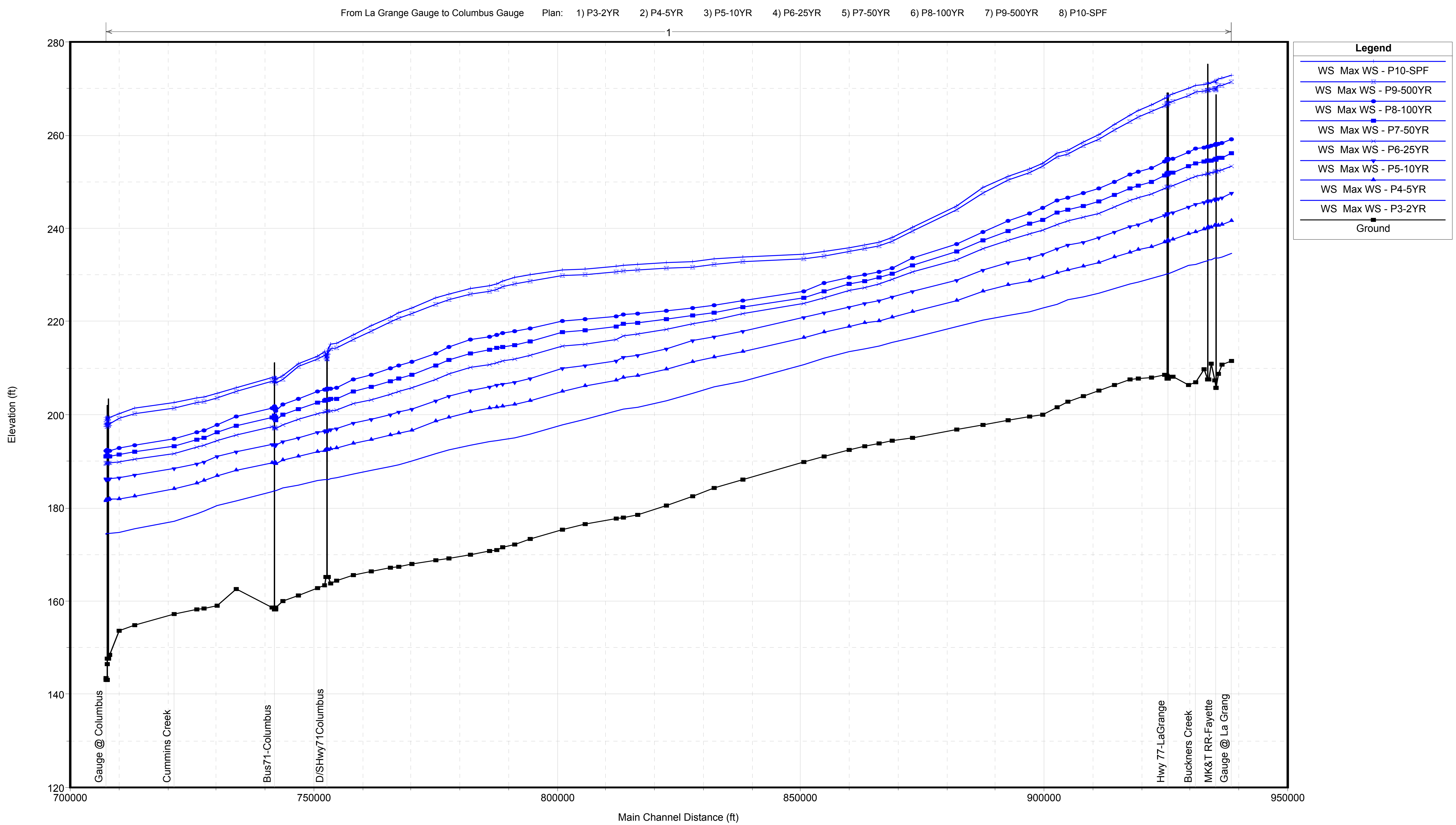


**Figure A-10. Profiles for the Columbus HEC-RAS Reach**

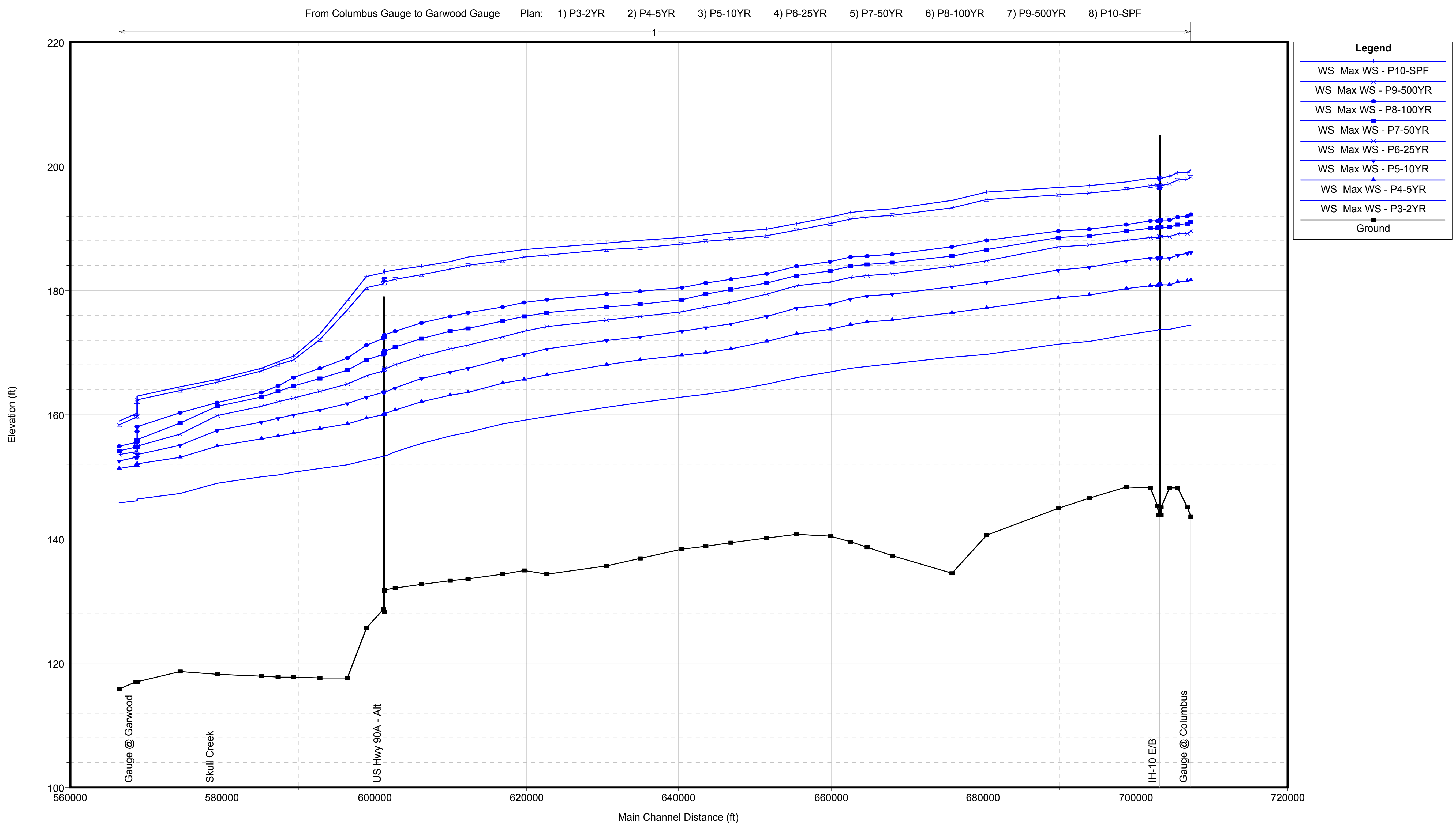


**Figure A-11. Profiles for the Garwood HEC-RAS Reach**

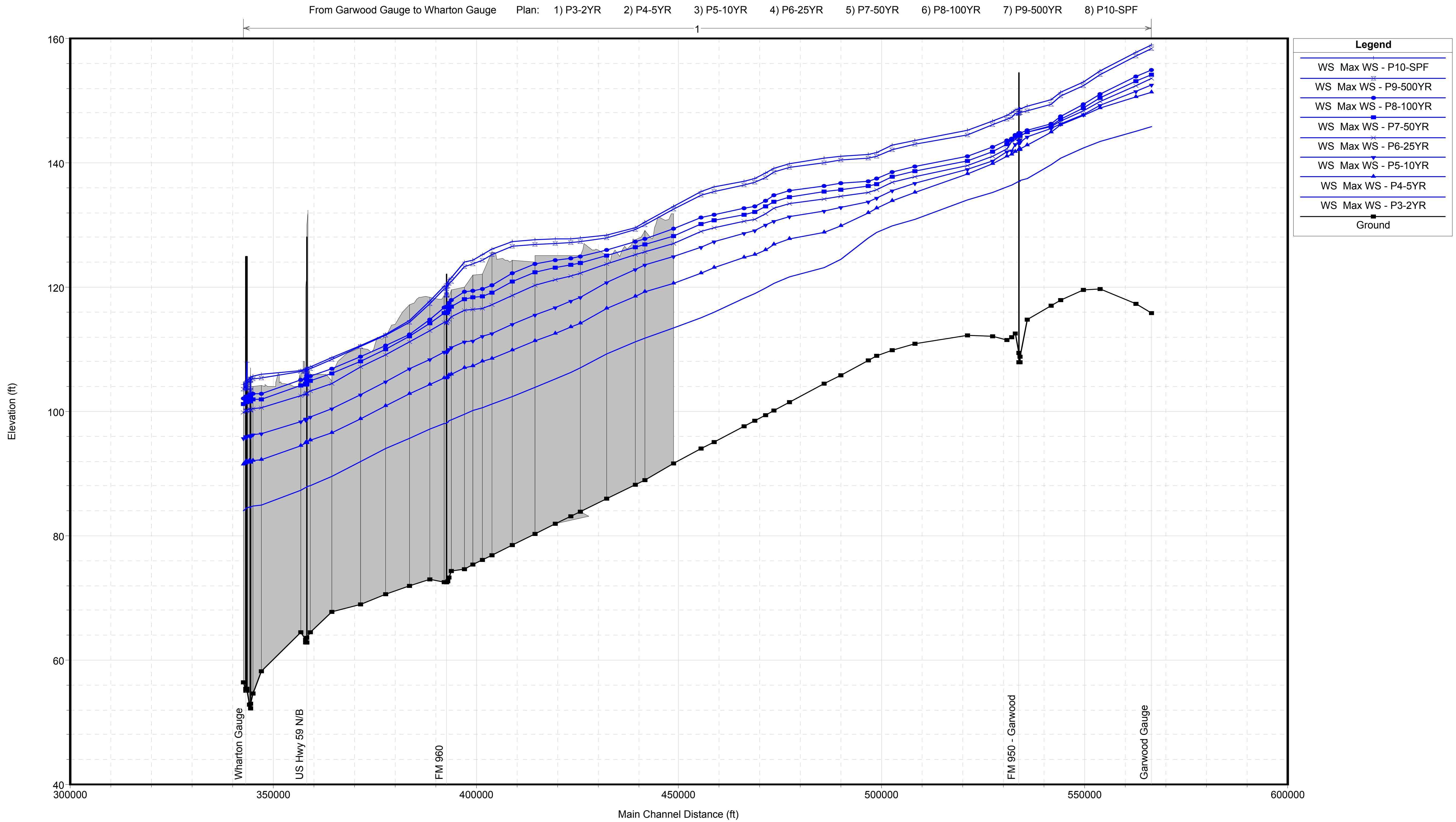


**Figure A-12. Profiles for the Wharton HEC-RAS Reach**

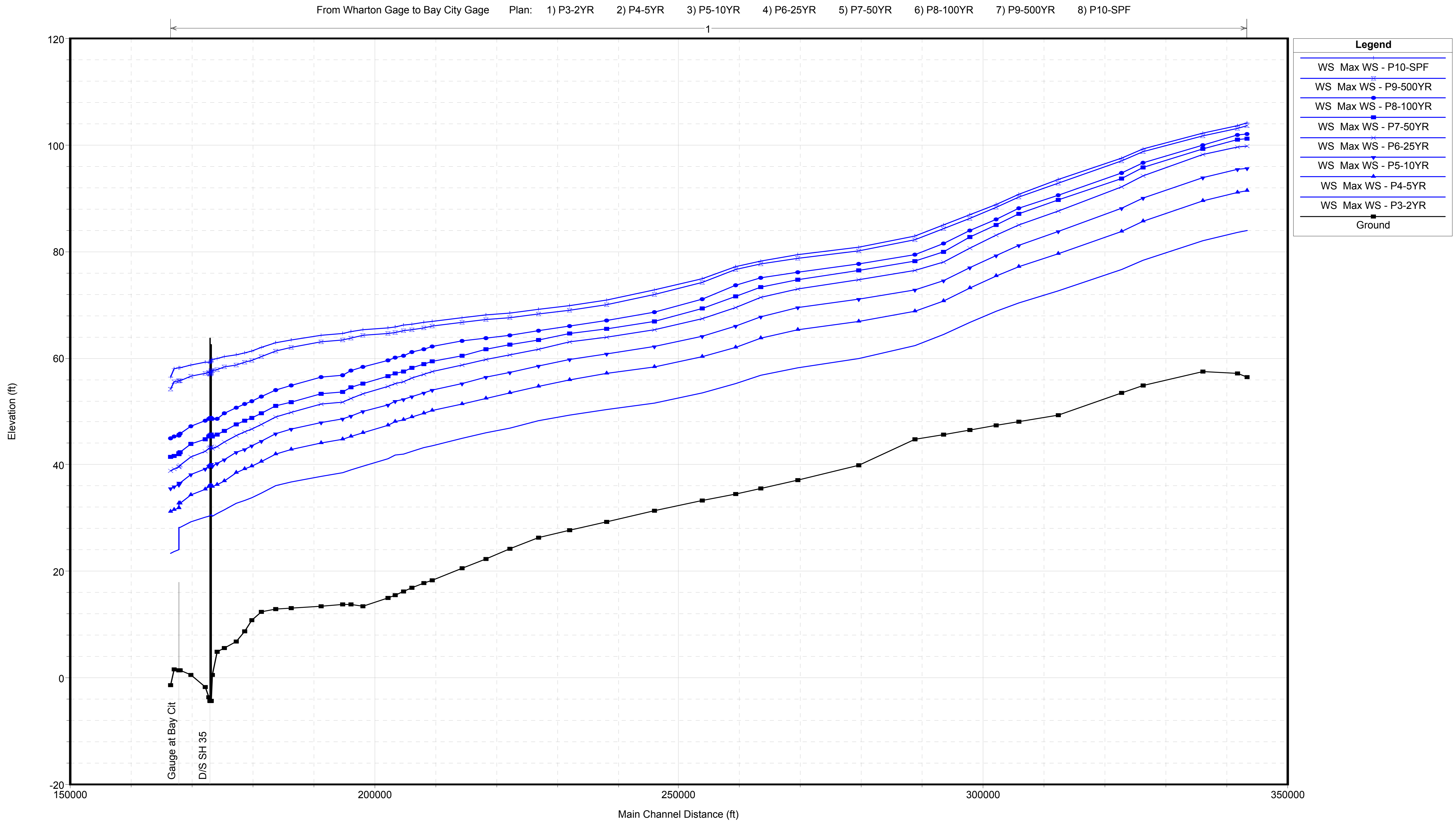


**Figure A-13. Profiles for the Bay City HEC-RAS Reach**

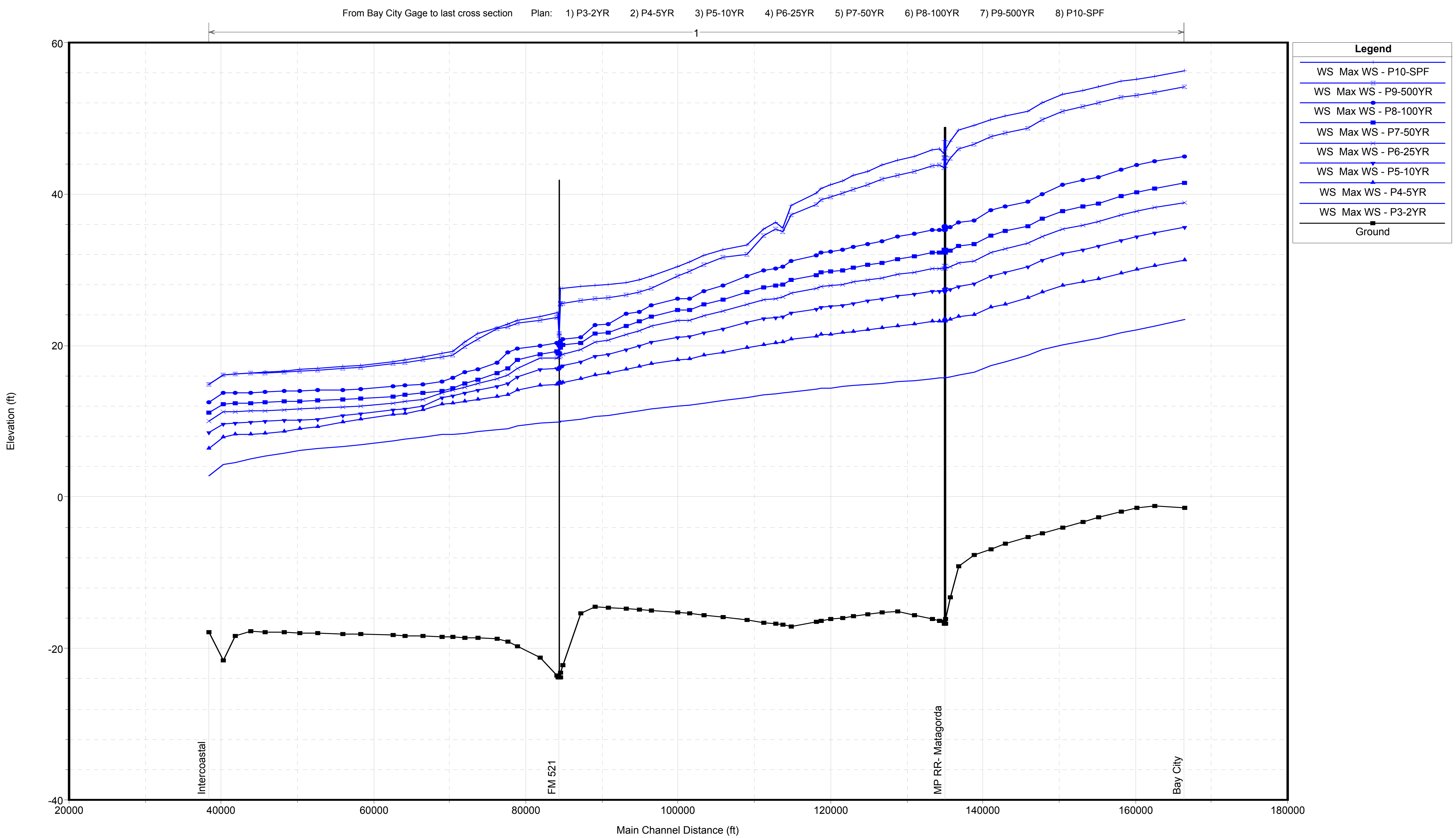


**Figure A-14. Profiles for the Matagorda HEC-RAS Reach**

## V. Previous Studies

This is a partial list of studies compiled by the study team or the LCRA staff as a reference library. Many additional studies are available and are listed in the LCRA library.

1. The Floods in Central Texas in September 1921, C.E. Ellsworth, USGS.

2. Isohyetal Map Storm of Sept 8-11, 1921 from the Corp of Engineers Report of Survey of the Colorado River and Tributaries.

3. Excessive Rainfalls In Texas: State Reclamation Department Bulletin 25, Lowry, USGS, 1929.

4. Major Texas Floods of 1935, Dalrymple, USGS.

5. Major Texas Floods of 1936, Dalrymple, & Tate, USGS, 1937.

6. Colorado River Project: Texas Flood Control by Marshall Ford Reservoir, Lowry, Reclamation Department, 1937.

7. Colorado River Flood-July-August 1938, Report of the State Board of Water Engineers to Senate Investigating Committee of the 45th Legislature, State Board of Water Engineers, September 19, 1938.

8. Texas Floods of 1938 and 1939, Dalrymple, & Tate, USGS, 1940.

9. La Grange, Texas – Area Subject to Flooding, USACE, 1944. Map showing highwater marks thru La Grange for the 1869,1913,1935,1938 floods in La Grange.

10. Columbus, Texas – Area Subject to Flooding, USACE, 1944. Map showing highwater marks thru Columbus for the 1913,1935,1938 floods in Columbus.

11. Reservoir Operation Mansfield Dam, Flood of June 1935, Army Corps of Engineers, 1944.

12. Hydrographs & Mass Curves, Flood of Sept.-Oct. 1936, Army Corps of Engineers, 1944.

13. Reservoir Operation Mansfield Dam, Flood of Sept-Oct 1936, Army Corps of Engineers, 1944.

14. Reservoir Operation Mansfield Dam, Flood of July & August 1938, Army Corps of Engineers, 1944.

15. Texas Floods of 1940, Breeding, USGS, 1948.

16. Floods of September 1952 in the Colorado and Guadalupe River Basin, Breeding, USGS, 1954.

17. General Storm Report Covering the storms of April, May, and June 1957 in Texas, OK & AK, USDA, SCS, September 1957.

18. Texas Floods of April, May, June 1957, Yost, Texas Board of Water Engineers, 1958.

19. Rainfall & Floods of April, May, & June 1957 in the South-Central, United States-TP 33, US Weather Bureau, 1958.

20. Memorandum Report- Flood of 1957, US Army Corps of Engineers, 1959.

21. Flood Flows of Texas Rivers, C.E. Ellsworth, USGS, 1957.

22. Special Flood Hazard Information Report: Barton Creek Austin, Texas, 1969, Army Corps of Engineers.

23. Inflow Design Flood Study, Mansfield (Marshall Ford) Dam – Colorado River Project, Texas – Examination of Existing Structures Program, US Department of Interior Bureau of Reclamation, 1972.

24. Floodplain Information Colorado River and Country Club Creek, Austin, Texas, Army Corps of Engineers, 1975.

25. Floodplain Information Colorado River La Grange, Texas, Corps of Engineers, 1975.

26. Floods in Central Texas August 1978, Schroeder, Massey, USGS, 1979.

27. The Disastrous Texas Flash Floods of August 1-4,1978: A Report to the Administrator, National Weather Service, 1979.

28. Special Flood Hazard Information Report-Pedernales River, Lyndon B. Johnson National Historic Site and State Park, Gillespie County, Texas, Corps of Engineers, December 1979.

29. Special Flood Hazard Information Report, Pedernales River Lyndon B. Johnson National Historic Site and State Park, Gillespie County, Texas. U.S. Army Corps of Engineers, Fort Worth District. December 1979.

30. The Austin, Texas Flood of May 24-25, 1981, Moore, National Academy of Science, 1982.

31. Flood of May 24-25, 1981, in Austin Texas Metropolitan Area, Massey & Reeves, USGS, 1982.

32. Colorado River and Tributaries, Texas, Boggy Creek Austin, Texas Design Memorandum No. 1. U.S. Army Corps of Engineers, Fort Worth District. October 1984.

33. Real-Time Flood Forecasting Model for the Lower Colorado River-Highland Lake System, Unver, UT 1985.

34. The Austin, Texas, Flash Flood: An Examination from Two Perspectives-Forecasting and Research, Maddox & Grice, NOAA, 1986.

35. Floods in Central Texas August 1-4,1978, Schroeder, Massey, USGS, 1987.

36. A Report on June 1987 Storm Event for Lake Travis and Downstream, Unver, LCRA, 1987.

37. Flood Simulation for A Large Reservoir System, Mays 1988, National Water Summary.

38. Reconnaissance Report – Central Colorado River Basin, Colorado, Texas, U.S. Army Corps of Engineers, September 1989.

39. Reconnaissance Flood Protection Report, Central Colorado River Watershed, Colorado River Basin, Texas, U.S. Army Corps of Engineers, Fort Worth District. September 1989.

40. Report on Flooding April-May 1990, US Army Corps of Engineers, 1990.

41. Re-Evaluation of the Probable Maximum Floods for LCRA's Highland Lakes Projects, RAC Engineers and Economist, LCRA, 1991

42. Texas floods, December 1991-January 1992, National Weather Service, 1992.

43. 1991-1992 Flood Event Report, Frithiof, LCRA, 1992.

44. Disastrous Floods on the Trinity, Brazos, Colorado and Guadalupe Rivers in Texas, Dec 1991-Jan 1992, National Weather Service, 1993.

45. Floods in Southeast Texas, October 1994, USGS Fact Sheet, 1995.

46. Inks Flood Plain Study, Mays and Carriaga, 1995.

47. Sandy Creek Storm Report May 1995 Flood Event, Work in Progress by LCRA.

48. Floods of December 20-26, 1991 in Central Texas, Heji, Slade, Jennings, USGS, 1996.

49. Llano/Colorado River Storm Report, October 1996 Flood Event, LCRA, 1997.

50. Llano/Colorado River Storm Report, February-March 1997 Flood Event, LCRA, 1997.

51. Llano/Colorado River Storm Report, June 1997 Flood Event, LCRA, 1997.

52. Flooding on the Colorado River: An Overview of Flood Management and Critique of the June 1997 Flood, LCRA, 1997.

53. Flood Operations Procedure Review Project for the Lower Colorado River Authority. Halff Associates, Inc., December 1998.

54. South Texas Floods, October 17-22,1998, NOAA, Feb. 1999.

55. Storm Report Lower Colorado River Central & Southeast Texas, October 1998 Flood Event, LCRA, 1999.

56. Storm Report Lower Colorado River, Oct.-Nov. 2000 Flood Event, LCRA, 2000.

57. Preliminary Report on Floods in Central Texas November 15-16, 2001, USGS, 2001.

**FEMA – Flood Insurance Studies**: Bastrop, Blanco, Burnet, Colorado, Llano, Matagorda, San Saba, Travis, Wharton Counties and Cities of Lampasas, Sunrise Beach, Bay City, Palacios, El Campo, and Wharton.