THESIS

GEOMORPHIC ANALYSIS OF THE MIDDLE RIO GRANDE – ELEPHANT BUTTE REACH, NEW MEXICO

Submitted by

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ABSTRACT

GEOMORPHIC ANALYSIS OF THE MIDDLE RIO GRANDE –

ELEPHANT BUTTE REACH, NEW MEXICO

The Elephant Butte Reach spans about 30 miles, beginning from the South Boundary of the Bosque del Apache National Wildlife Refuge (River Mile 73.9) to the “narrows” of the Elephant Butte Reservoir (River Mile 44.65), in central New Mexico. Sediment plugs occasionally form along the Middle Rio Grande, completely blocking the main channel of the river. In 1991, 1995, and 2005, the Tiffany Plug was initiated at the upstream end of the Elephant Butte Reach. In 2008, the Bosque del Apache Plug formed just upstream of the Elephant Butte Reach. Sediment plugs occur at the location of a constriction or channel aggradation (Burroughs 2011). As aggradation within the Elephant Butte Reach is known to contribute to a decrease in channel capacity (Reclamation 2007), it is important to understand the influences of Elephant Butte Reservoir levels on channel aggradation/degradation in order to decrease the potential for future sediment plug formation. Further understanding of the historical and spatial changes within Elephant Butte Reach, along with a better understanding of the influences of Elephant Butte Reservoir levels on channel aggradation/degradation, are essential for improvement in future river management practices along the Middle Rio Grande. Using aerial photographs, survey data, reservoir water surface elevation data, and bed material data, the following objectives are addressed in this study:

1. Quantify temporal changes in channel widths and sinuosity from 1935 to 2010.

2. Quantify change in channel slope temporally.
3. Quantify rate of aggradation/degradation in response to a change in base-level (i.e., change in reservoir water surface elevation).
4. Quantify aggradation/degradation wave propagation upstream.
5. Quantify spatial and temporal trends in bed material grain size.

From 1935 to 2010, channel widths and sinuosity decrease over time. The majority of the Reach's channel slope decreases from 1935 to 2010; the downstream-most stretch of the channel, closest to Elephant Butte Reservoir, alternates between increasing and decreasing channel slopes.

As the Elephant Butte Reservoir level (base-level) increases, the channel aggrades in response. As the base-level decreases, the channel degrades. The rates of aggradation and degradation vary between different periods of base-level changes, and are quantified within the report. When the base-level changes a wave of aggradation/degradation travels upstream. The rate of wave propagation upstream varies relative to the rate of base-level change, and is quantified within the report for four sets of aggradation/degradation waves.

Bed material samples obtained from cross-section surveys and at the San Acacia and San Marcial gauges showed a coarsening at a rate of about 0.03 mm/year. In the downstream direction, bed material became slightly finer. The median bed material grain size ranged from 0.11 mm to 0.26 mm.

ACKNOWLEDGEMENTS

I would first like to thank the U.S. Bureau of Reclamation in Albuquerque for providing me with this project and the incredible amount of data. I would especially like to thank Jonathan Aubuchon, of the Albuquerque office, and Drew Baird, of the Denver office, for their insights about the river. Dr. Rathburn and Dr. Thornton, thank you for serving on my committee and providing thoughtful comments to improve my Thesis. Thanks to my advisor, Dr. Pierre Julien, for his constant guidance and encouragement.

Special thanks to Seema Shah-Fairbank for answering all of my questions and guiding me through the vast database. Many thanks to Katharine Anderson who helped me with planform delineations, range line cross-section plots, sinuosity calculations, etc… Thanks to Ted Bender for reading this report and for gracefully listening to my frustrations during those challenging times. Thanks also to Kiyoung Park for his insight and ideas regarding the river's behavior.

And finally, I would like to thank my family and Ben Mapes for supporting me every step of the way. Mom, thanks for always being available for a phone call. Dad and Janet, thanks for your encouragement and belief in me. Will, thanks for being a great role model, setting the example at every stage in life. Ben, I can't even begin to express my thanks for your support and understanding throughout this entire process. Without you I would have never left my computer and would have missed countless adventures; I look forward to more adventures with you.

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SECTION 1: INTRODUCTION

The Rio Grande is about 1890 miles long (3040 kilometers), making it one of the longest rivers in the United States (Kammerer 1990). The headwaters of the Rio Grande begin in southern Colorado near Camby Mountain. The river then flows south through New Mexico, and then becomes a dividing border between Texas and Mexico. For purposes of this report, the Middle Rio Grande is defined as the 180 mile stretch of the Rio Grande River that extends from Cochiti Dam to the narrows of Elephant Butte Reservoir. Figure 1.1 provides a map of the Rio Grande.

Figure 1.1 Map of the Rio Grande Watershed (MRGBI 2009)

Human activities have had an impact on the river for thousands of years. However, it was not until the late 14th century when the Spanish settled near the Rio Grande that humans began to dramatically influence the river (Finch 2004). Since then, the water discharge, sediment discharge, and cross sectional geometry have changed as a result of human colonization. Devastating floods were very common on the Rio Grande up until the early 1900's when large dams and reservoirs were constructed. In addition, large stretches of the river were channelized. These projects helped regulate the water and prevent extensive flooding. Mining, logging and grazing in the beginning of the 20th century destroyed much of the vegetation, resulting in dramatic erosion and a subsequent increase in the sediment load in the river (Scurlock 1998). The increased erosion and sediment load caused a l3% loss of capacity within Elephant Butte Reservoir by the mid 1930's (Clark 1987). The increased sediment and decreased flow also lead to severe aggradation along the river. Between 1880 and 1924, the bed of the river rose 9 feet at the San Marcial gauging station (Scurlock 1998).

1.1 Habitat and Endangered Species

Exotic plants like the Russian olive, Russian thistle, Siberian elm, tree-of-heaven, and tamarisk, whose roots added extra shear strength to the sand near the river, were introduced to try to keep the river more stable (Mussetter Engineering 2001). However, due to the addition of these foreign plants, riparian vegetation, such as native cottonwood trees and willow trees, have declined (Finch 2004, Earick 1999). New animals such as the barbary sheep, ibex, and oryx were also introduced to the area (Finch 2004). Human influences have caused several native species of animals that use the Rio Grande as their habitat, such as the Rio Grande silvery minnow, Rio Grande cutthroat trout, southwestern willow flycatcher, and whooping crane, to teeter on the brink of extinction. Human impacts, coupled with natural events such as droughts, have also led to increased soil erosion along much of the Middle Rio Grande (Scurlock 1998).

In order to resolve many problems regarding the Rio Grande, the Middle Rio Grande Conservancy District (MRGCD) was formed in 1923. The purpose of the MRGCD was to "provide flood protection from the Rio Grande, and make the surrounding area hospitable for urbanization and agriculture" (MRGCD 2006). Between 1923 and 1935, one storage dam, four diversion dams, and 817 miles of drainage and irrigation channels had been constructed by the MRGCD (MRGCD 2006). The work completed by the MRGCD was successful in controlling the river's floods, and the Bureau of Reclamation and the Army Corps of Engineers continued to repair and update the structures established by the MRGCD. Several new levees and Cochiti dam have been constructed to combat flooding and sedimentation problems along the river (MRGCD 2006). A historical timeline of the Middle Rio Grande is shown in Figure 1.2.

These dams and levees were able to control the flow of the river and altered the seasonal flooding patterns that used to exist. The magnitude of the floods within the Rio Grande was greatly reduced due to the construction of these structures. These floods were essential for several species' reproduction habitats. The Rio Grande silvery minnow, shown in Figure *1.3*, used the swampy flooded terrain as the ideal reproduction habitat (Earick 1999; Borgan 2006). The Rio Grande silvery minnow used to flourish within the river from Espanola, NM to the Gulf of Mexico, however, now it is present in only 5% of its former range (Earick 1999; MRGESA 2006a). Today, about 95% of the Rio Grande silvery minnow population is concentrated below the San Acacia diversion dam in the San Acacia Reach of the Middle Rio Grande. It no longer exists below the Elephant Butte Reservoir, and was placed on the endangered species list in 1994 (MRGCD 2002).

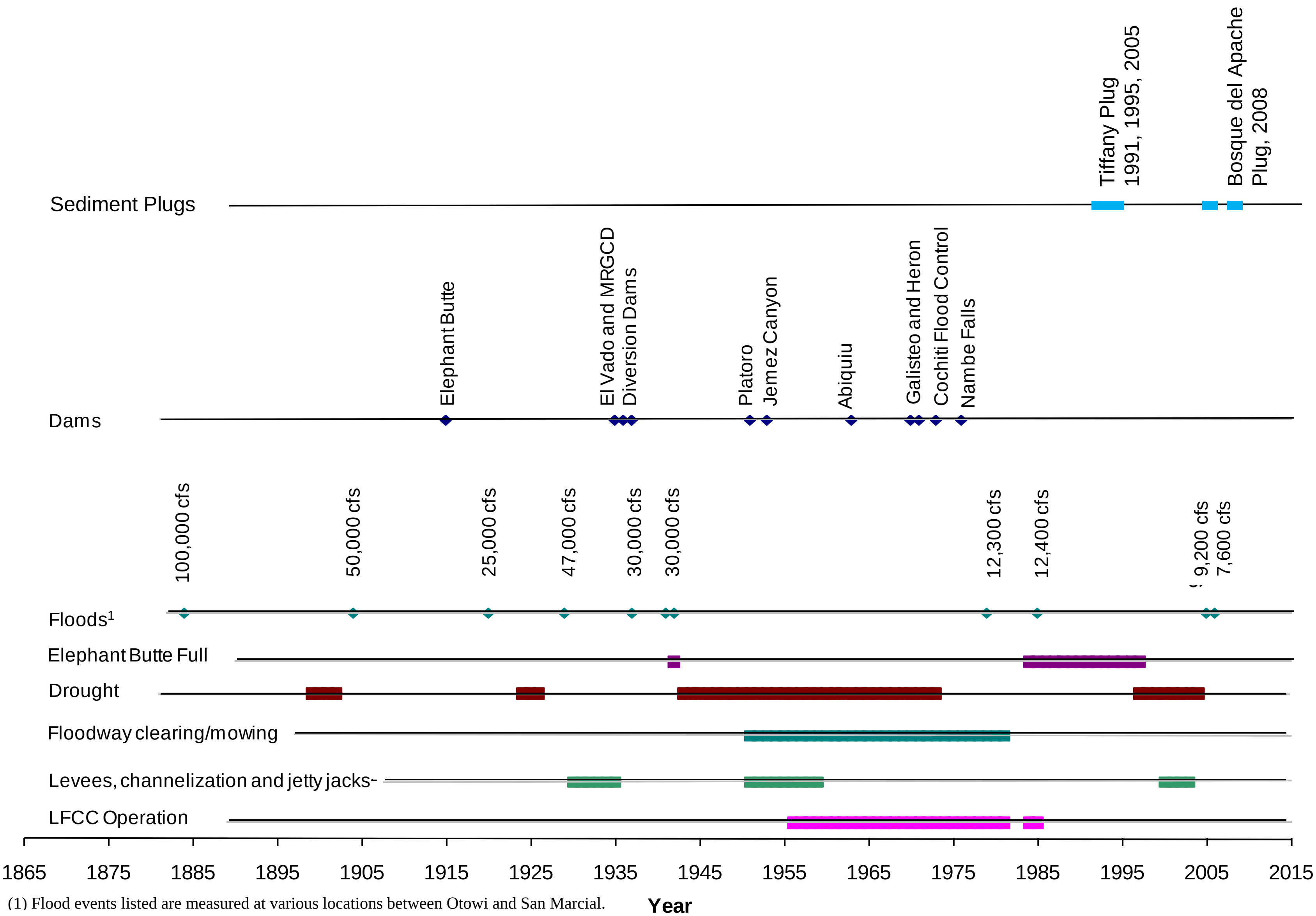

Figure 1.2 Historical Timeline of Middle Rio Grande (Modified After Makar 2011, Pers. Comm.)

Figure 1.3: Rio Grande Silvery Minnow and Southwestern Flycatcher

The southwestern willow flycatcher (Figure 1.3) also uses the Rio Grande's riparian vegetation and wetlands to raise their young chicks. The altered flooding patterns and reduced reproduction habitat have negatively impacted their population as well. In 1995 the southwestern willow flycatcher was placed on the endangered species list as a response to their declining population (MRGCD 2002; MRGESA 2006b).

1.2 Sediment Plugs

Historically, sediment plugs have formed along the Middle Rio Grande, completely blocking the main channel of the river. In 1991, 1995, and 2005, the Tiffany Plug formed in the upstream end of the Elephant Butte Reach at Agg/Deg 1683 (River Mile 70.23), as seen in Figure 1.4. In 2008, the Bosque del Apache Plug formed between Agg/Deg 1531 and 1550 (River Mile 82.5 – 80.81), about 7 miles upstream of the Elephant Butte Reach. Little is known about the formation of sediment plugs; why they form, where they form, and how best to manage river flows to prevent the formation of sediment plugs. The consequences of sediment plugs in the Middle Rio Grande are significant. The presence of sediment plugs blocks the main channel of the Rio Grande and prevents water from reaching Elephant Butte Reservoir due to increased infiltration and evapotranspiration induced by the plugs. The current practice with sediment plugs by the United States Bureau of Reclamation (Reclamation) is to excavate a pilot channel through the plug to encourage water to flow again and re-channelize; this method is expensive and time consuming. Sediment plugs occur at the location of a constriction or channel aggradation (Burroughs 2011). As aggradation within the Elephant Butte Reach is known to contribute to a decrease in channel capacity (Reclamation 2007), it is important to understand the influences of Elephant Butte Reservoir levels on channel aggradation/degradation in order to decrease the potential for future sediment plug formation.

Figure 1.4 Aerial View of Tiffany Plug in 2005

SECTION 2: SITE DESCRIPTION AND BACKGROUND

2.1 Elephant Butte Reach

The section of the Middle Rio Grande examined in detail in this report will be referred to as the Elephant Butte Reach. This reach spans about 30 miles, beginning from the South Boundary of the Bosque del Apache National Wildlife Refuge (River Mile 73.9) to the "narrows" of the Elephant Butte Reservoir (River Mile 44.65). Figure 2.1 shows the location of the project area in New Mexico.

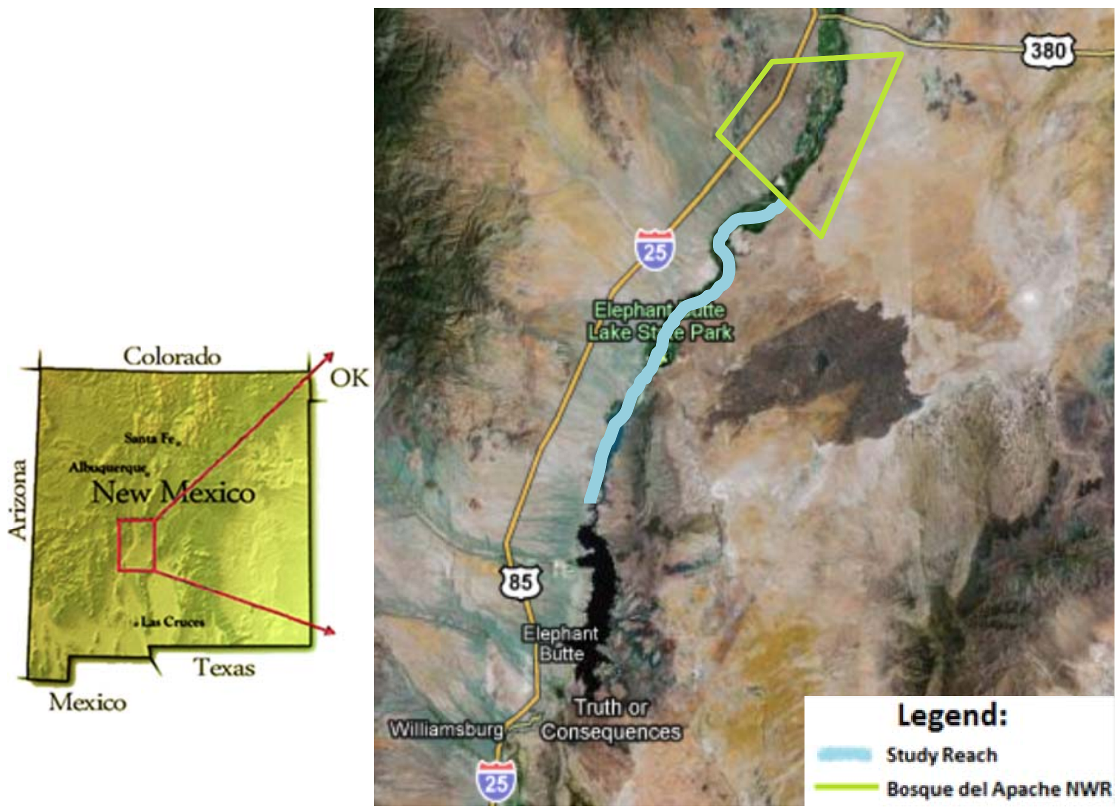

Figure 2.1: Location of the Elephant Butte Reach from Google Maps

Sediment plugs occasionally form along the Middle Rio Grande, completely blocking the main channel of the river. In 1991, 1995, and 2005, the Tiffany Plug was initiated at the upstream end of the Elephant Butte Reach. In 2008, the Bosque del

Apache Plug formed just upstream of the Elephant Butte Reach. Further understanding of the influences of Elephant Butte Reservoir levels on channel aggradation/degradation will provide insight into proper river management practices in order to decrease the potential for sediment plug formation.

The objectives of this study include the following:

1. Quantify temporal changes in channel widths and sinuosity from 1935 to 2010.
2. Quantify change in channel slope temporally.
3. Quantify rate of aggradation/degradation in response to a change in base-level (i.e., change in reservoir water surface elevation).
4. Quantify aggradation/degradation wave propagation upstream.
5. Quantify spatial and temporal trends in bed material grain size.

2.2 Subreach Definition

To thoroughly evaluate the significant changes in the study area, the reach was divided into six subreaches. The subreach definitions were determined by initial assessments of the channel widths and planforms from aerial photos and channel slope.

To determine the subreach divisions, the active channel widths, as measured from edge of vegetation to edge of vegetation, were plotted for the entire Elephant Butte Reach for years 1962, 1972, 1992, and 2002. The thalweg at each Agg/Deg-line was also plotted for each set of years, as shown on Figure 2.2. The subreaches were chosen based on the 2002 dataset because of the abundance of both GIS and Agg/Deg Cross-section data during this year, but subreaches were confirmed using the 1962, 1972, and 1992 datasets.

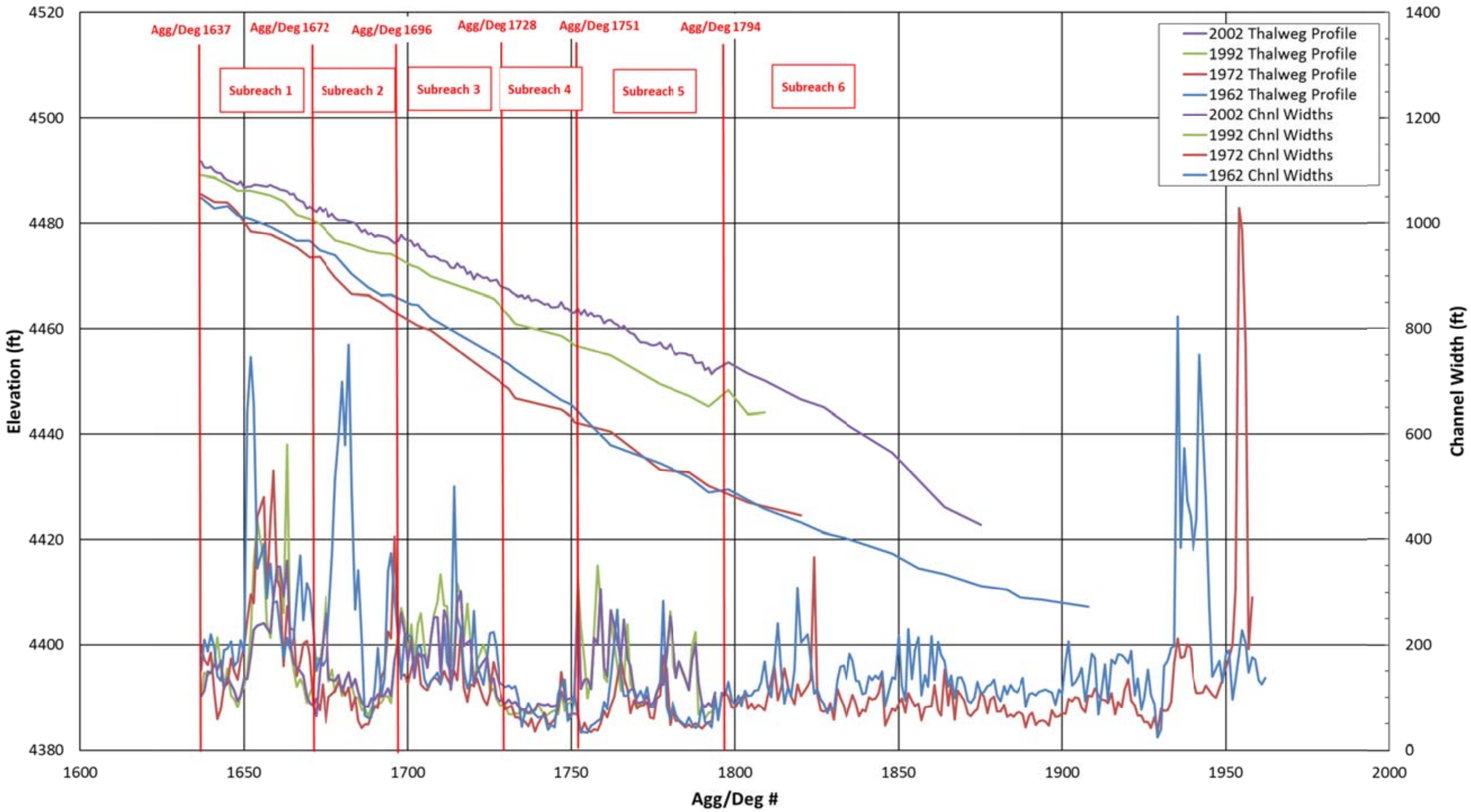

Figure 2.2 Profile of Elephant Butte Reach Widths and Thalweg at Agg/Deg Lines

There are no major slope distinctions along the Elephant Butte Reach in 2002; therefore, subreaches were primarily selected based on width trends. Subreaches 1, 3, and 5 tend to be wider than Subreaches 2, and 4 (based on 2002 data). Subreach 6 is a transitional subreach, which is sometimes river, and sometimes reservoir, depending on the level of Elephant Butte Reservoir. The first subreach begins at the south boundary of the Bosque del Apache NWR, Agg/Deg 1637, and extends to Agg/Deg 1672. The second subreach begins at Agg/Deg 1672 and ends at Agg/Deg 1696. The third subreach begins at Agg/Deg 1696 and ends at Agg/Deg 1728. The fourth subreach begins at Agg/Deg 1728 and ends at Agg/Deg 1751. The fifth subreach begins at Agg/Deg 1751 and ends at Agg/Deg 1794. The sixth, and last, subreach begins at Agg/Deg 1794 and extends to Elephant Butte Reservoir.

Figure 2.3 through Figure 2.9 show the 2008 aerial photographs of the study area and its subreaches. Notice the low-flow conveyance channel located on the west bank of the river. The previous temporary outfall of the low-flow conveyance channel was at Agg/Deg 1794, which marks the end of Subreach 5 and the beginning of Subreach 6. The Black Mesa geologic feature is located east of Subreach 3. Levee construction along the West side of the river has prevented the river from excessive meandering. The Tiffany Plug location is shown on Figure 2.4; the Bosque del Apache Plug is located about 7 miles upstream of the study reach and is, therefore, not shown.

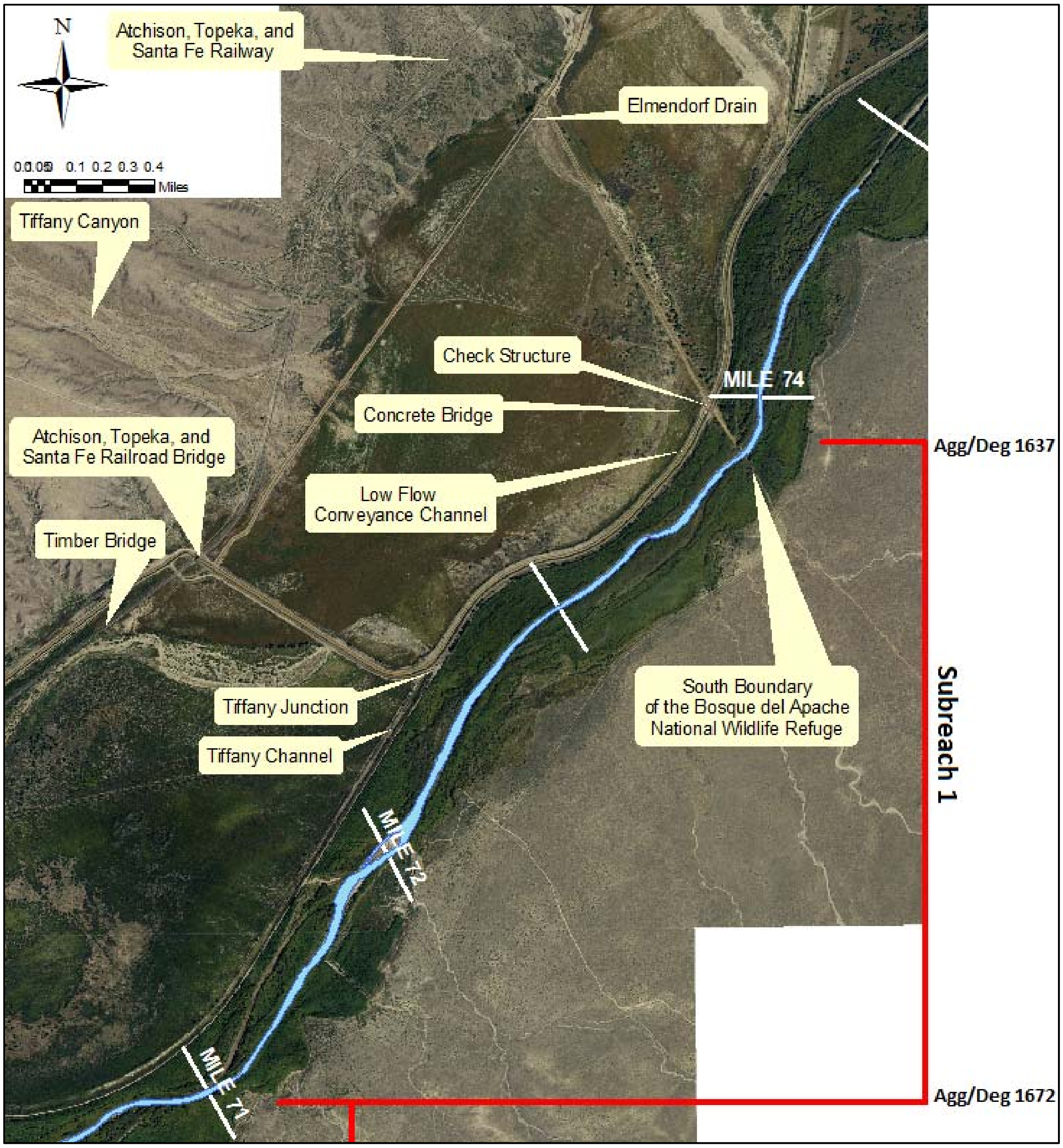

Figure 2.3 2008 Aerial Photo of Subreach 1

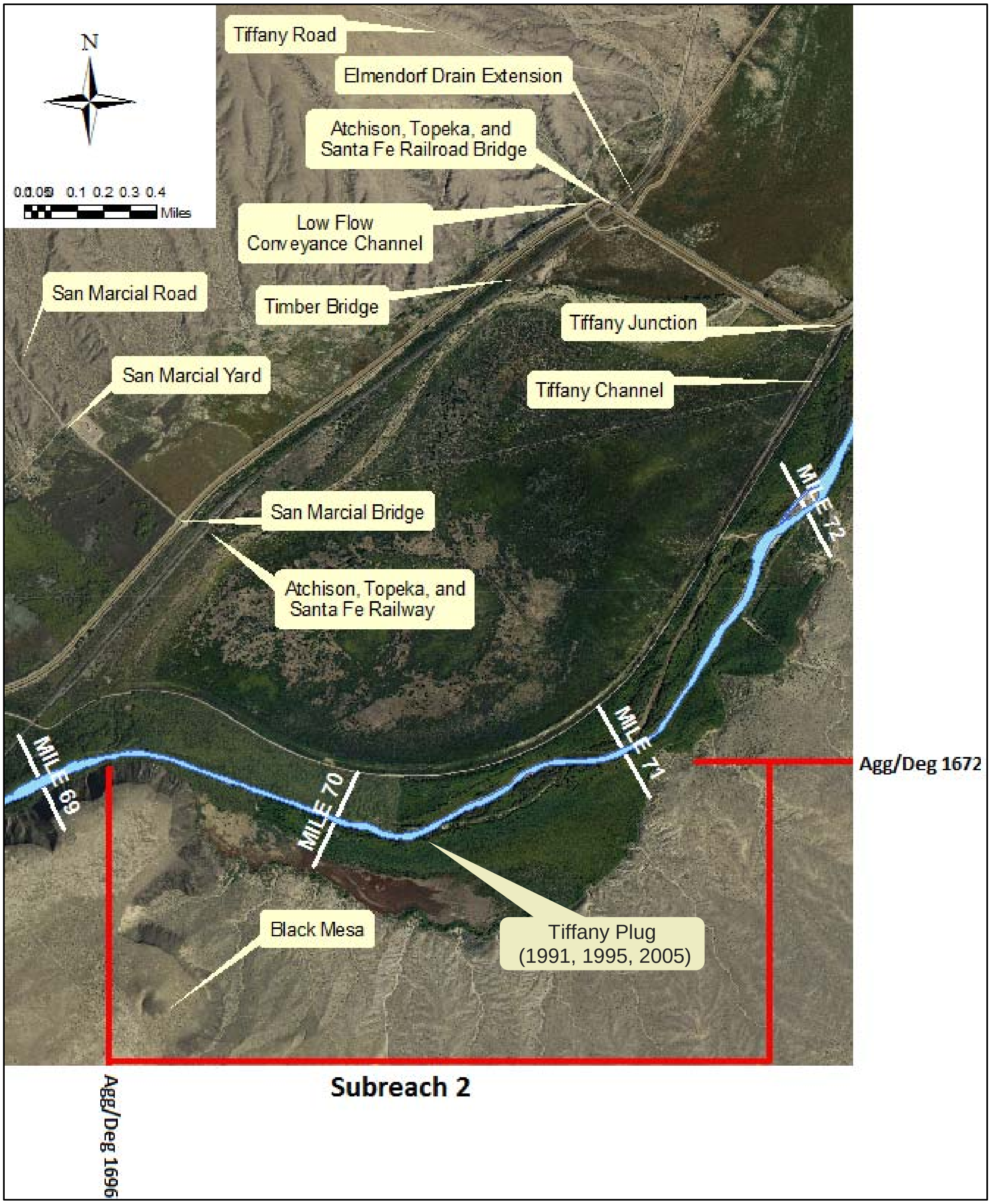

Figure 2.4 2008 Aerial Photo of Subreach 2

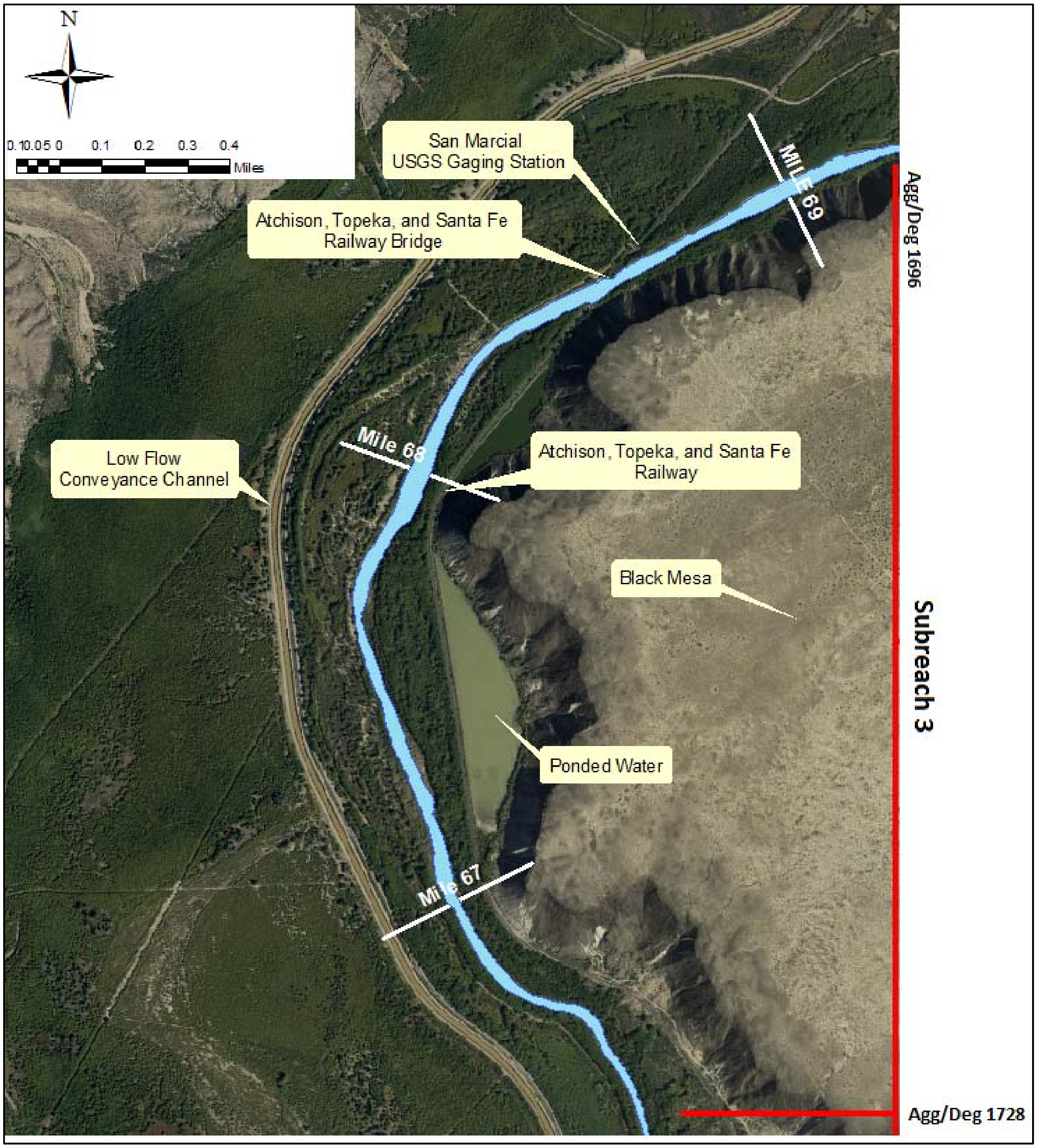

Figure 2.5 2008 Aerial Photo of Subreach 3

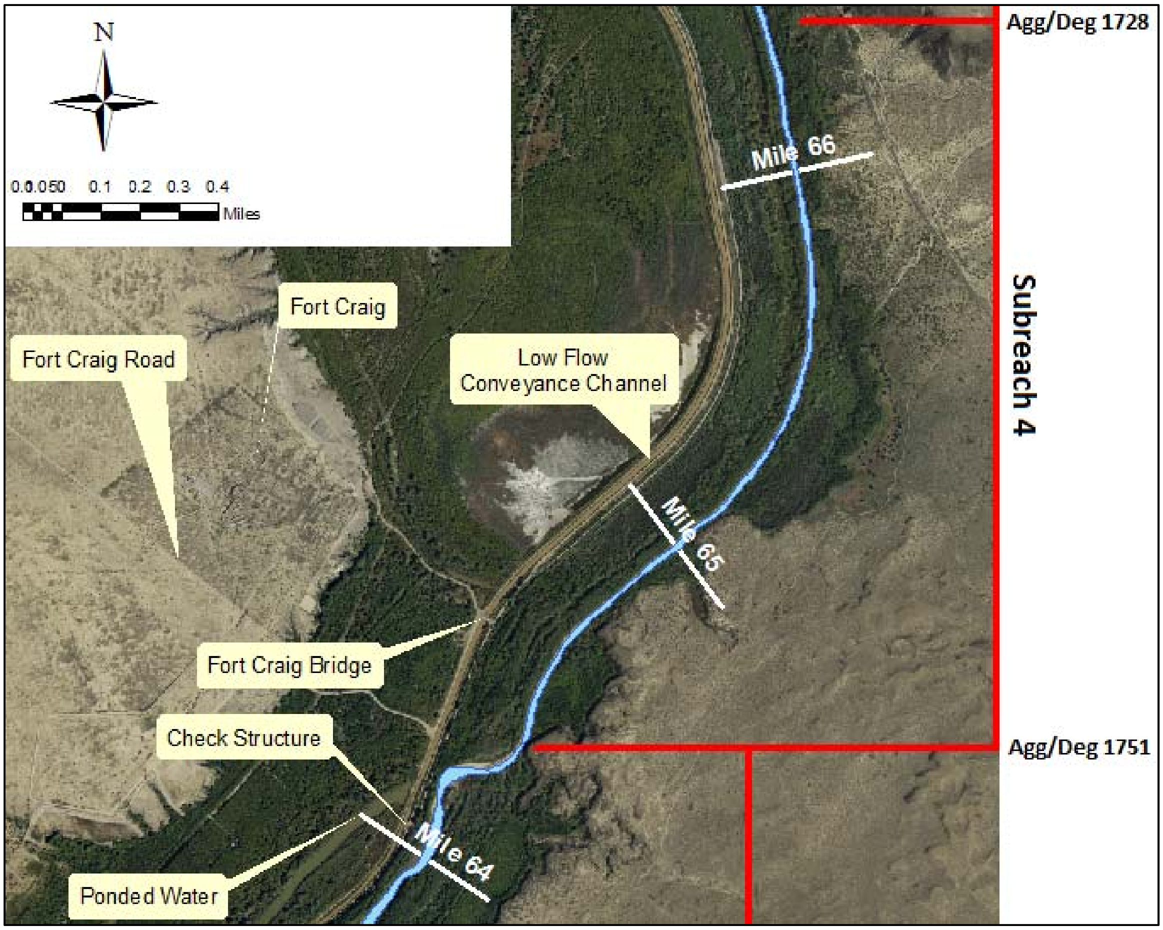

Figure 2.6 2008 Aerial Photo of Subreach 4

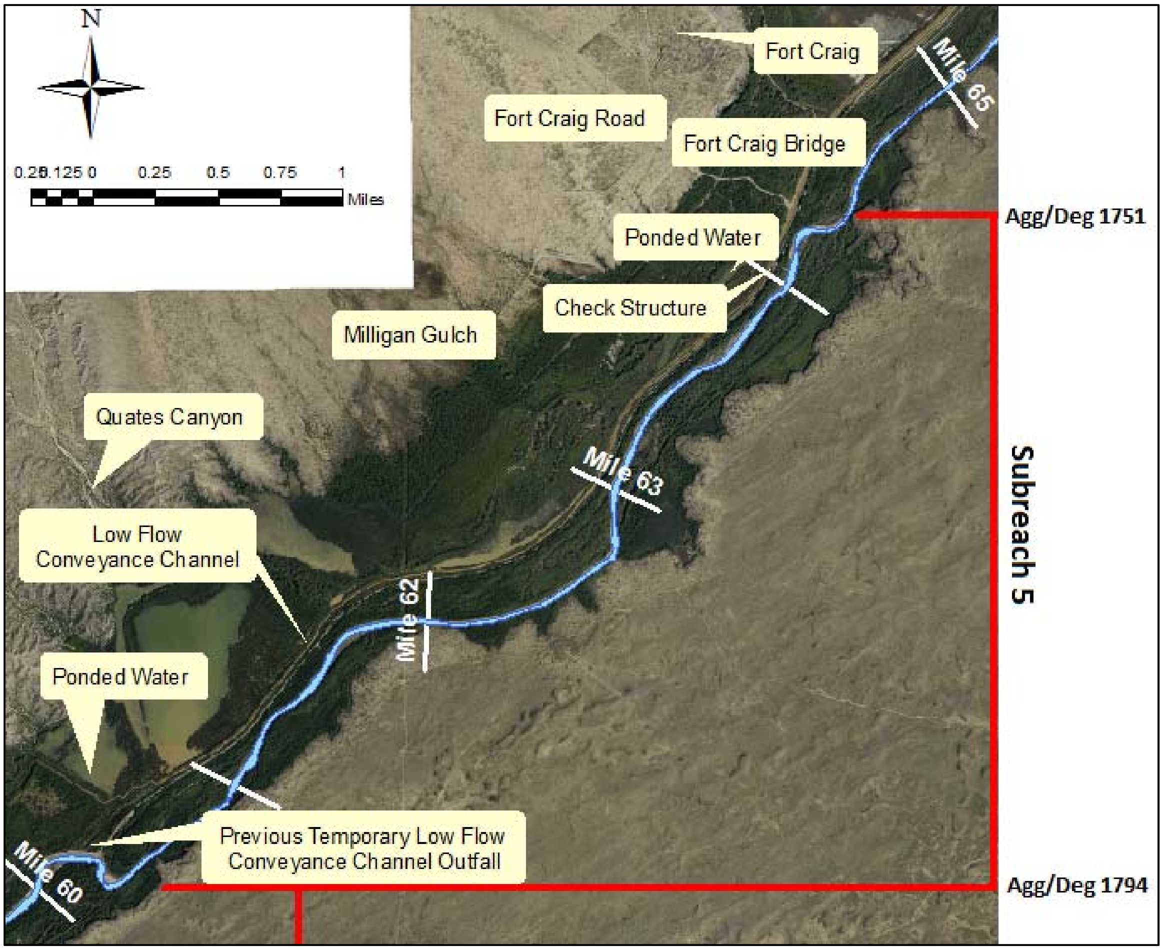

Figure 2.7 2008 Aerial Photo of Subreach 5

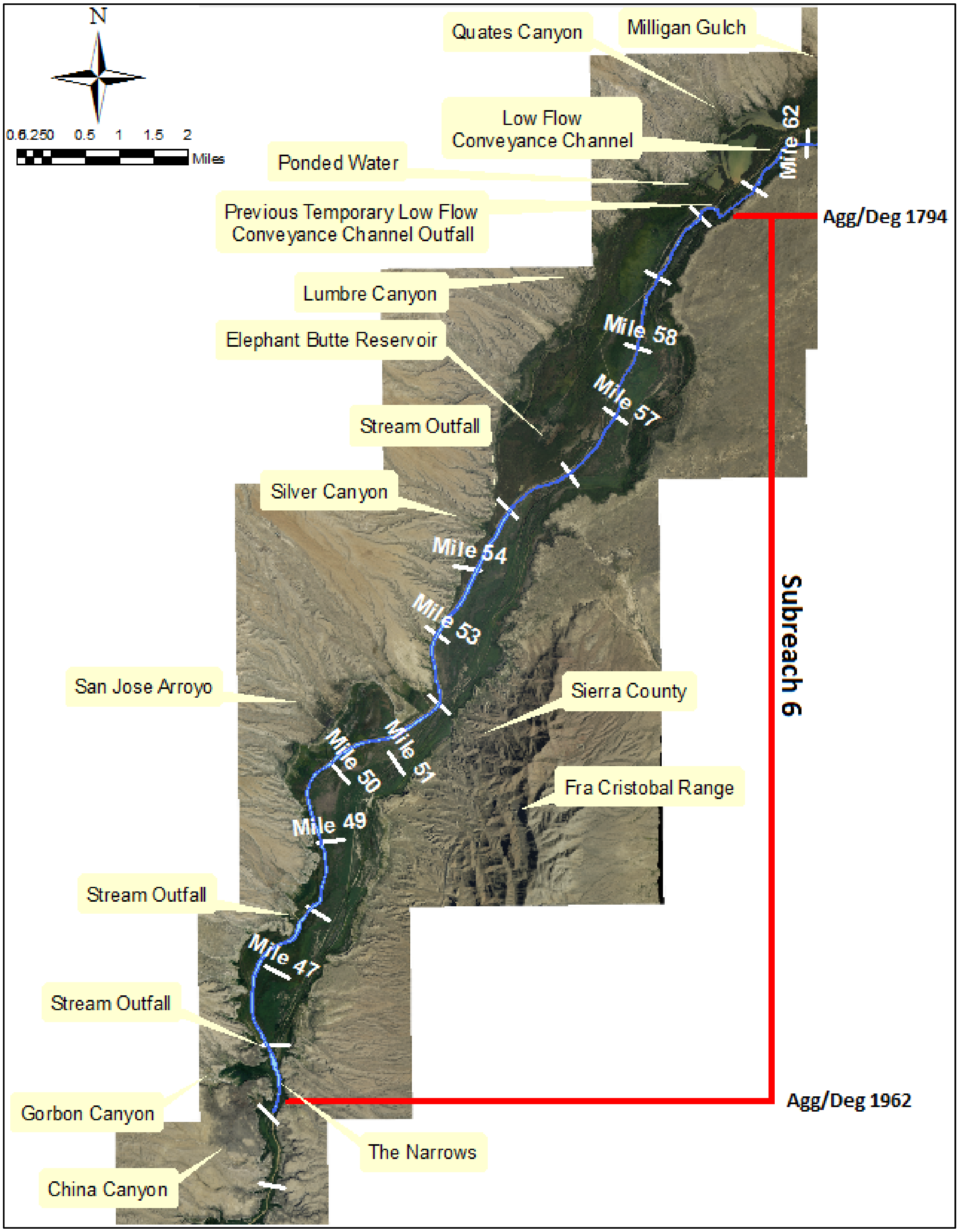

Figure 2.8 2008 Aerial Photo of Subreach 6

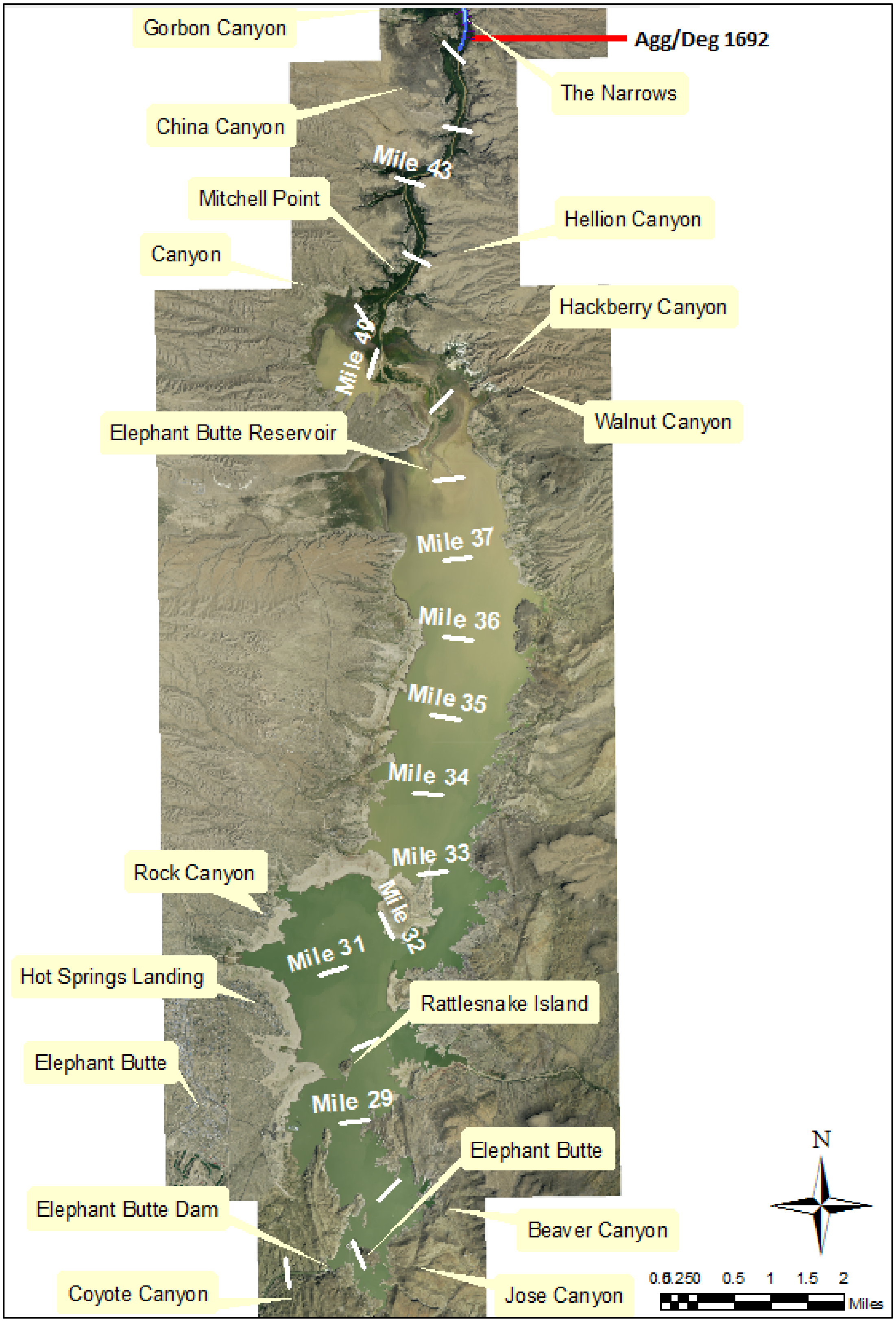

Figure 2.9 2008 Aerial Photo of Elephant Butte Reservoir

2.3 Available Data

The data used in this study was received from a number of different agencies: United States Bureau of Reclamation (Reclamation), National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), and the Middle Rio Grande database compiled at Colorado State University for Reclamation.

2.3.1 Survey Lines and Dates

Cross-sectional survey data was collected by Reclamation using both Aggradation/Degradation line (Agg/Deg-line) surveys; Socorro range line (SO-line), and Elephant Butte range line (EB-line) surveys. Agg/Deg-line elevations were derived using photogrammetry. The Agg/Deg-lines are spaced about 500 feet apart and were surveyed in 1962, 1972, 1992, and 2002. This information was used for the hydraulic and GIS analyses to follow. Figure 2.10 shows the entire Elephant Butte Reach with each of the six defined subreaches, and the Agg/Deg-lines with the 2008 GIS Elephant Butte Reach delineation.

The range lines (SO-lines and EB-lines) were field surveyed by Reclamation beginning in 1980. These surveys are more detailed than the channel cross-sections that were developed from the aerial photographs (i.e., Agg/Deg lines). The spacing of these surveys is greater than that of the Agg/Deg lines, but the field surveyed cross section locations typically coincide with Agg/Deg line locations. Range line survey data was available from 1980 to 2010 from Reclamation. 18 SO-lines and 102 EB-lines are located within the reach. Figure 2.11 shows the location of the SO- and EB-lines and Appendix A provides the dates of available survey data at each SO- and EB-line.

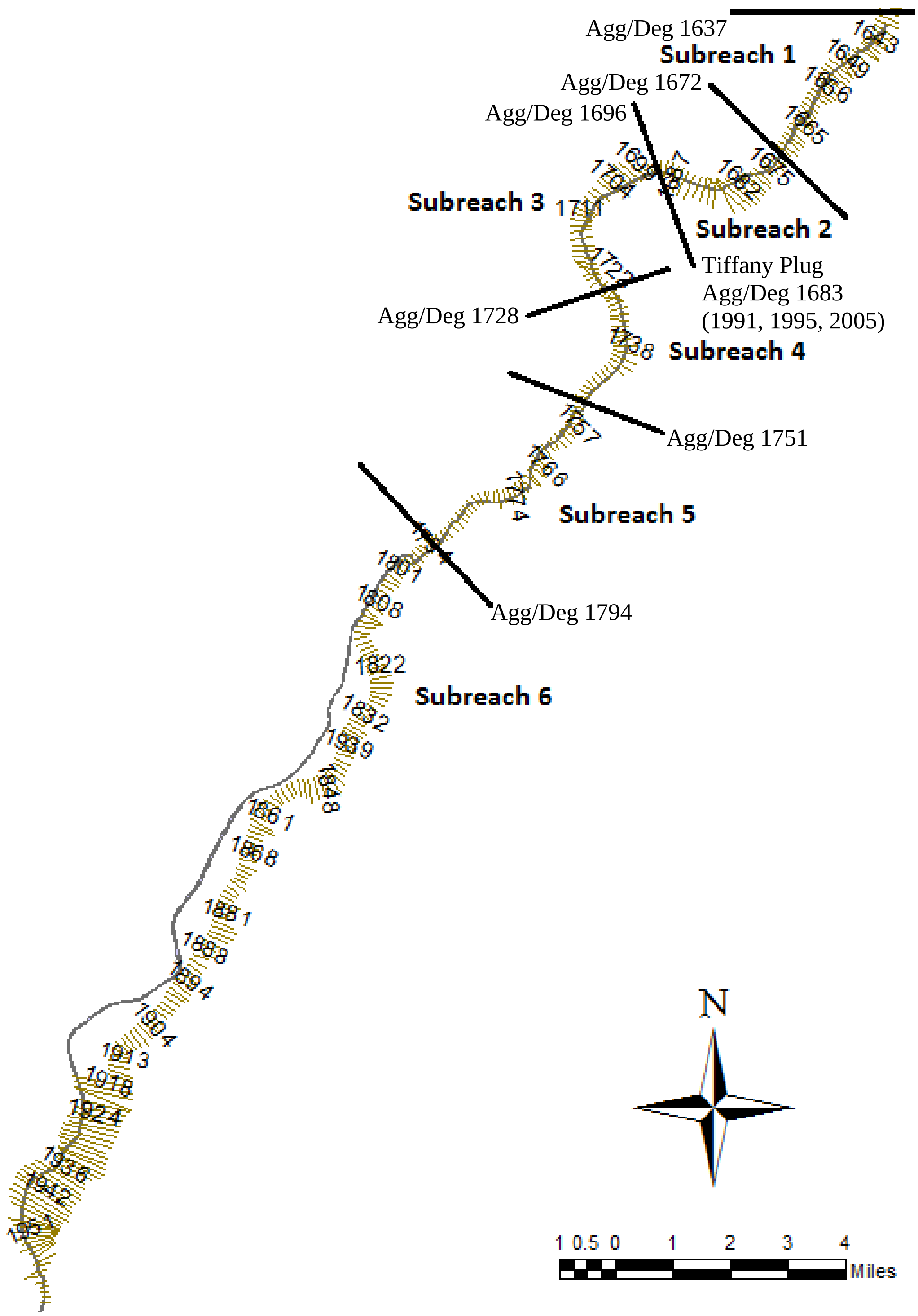

Figure 2.10 Subreach Definitions and Agg/Deg Line Locations (2008 GIS Elephant Butte Reach Delineation Shown)

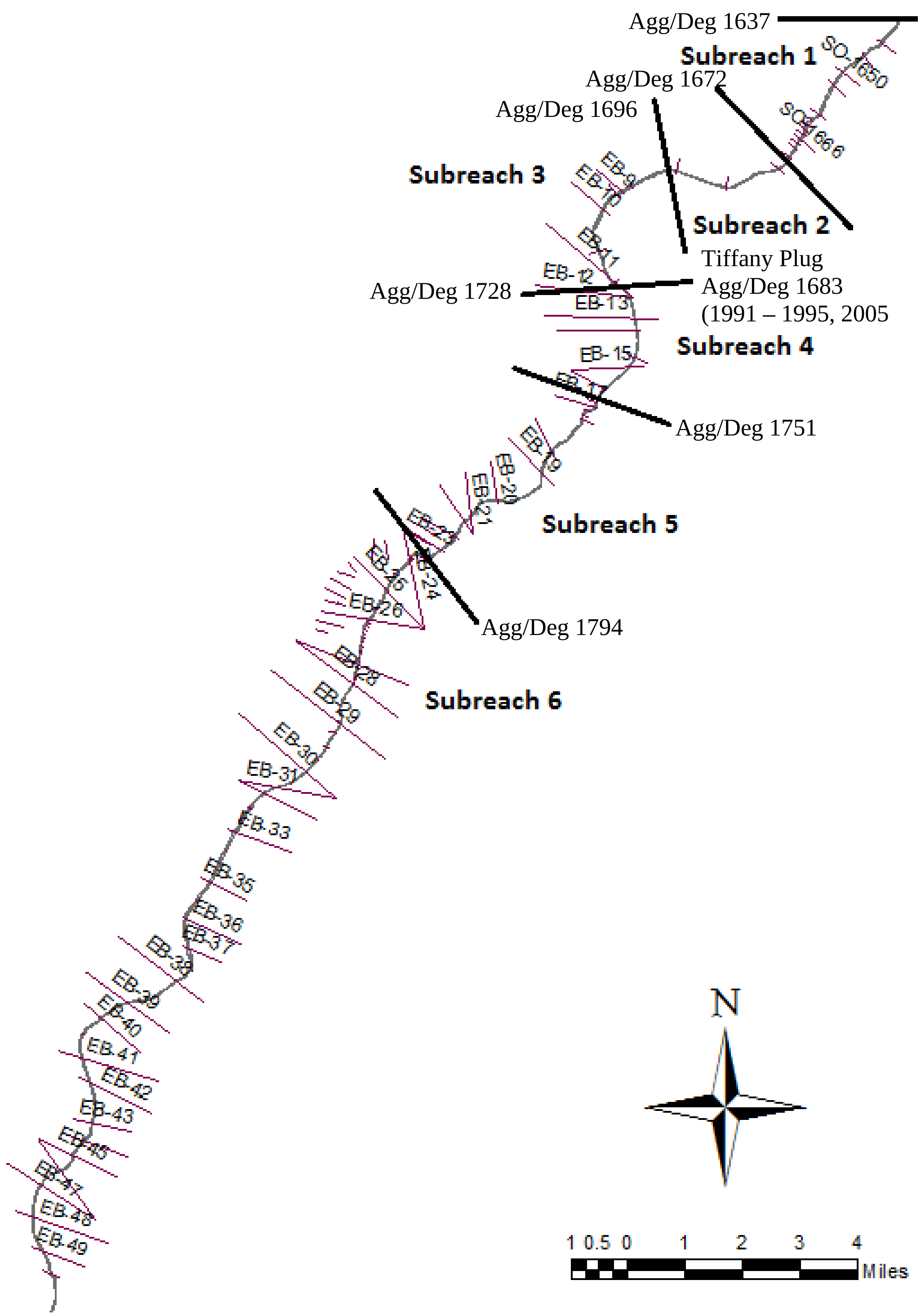

Figure 2.11 Subreach Definitions and Range Line Locations (2008 GIS Elephant Butte Reach Delineation Shown)

2.3.2 Discharge Data

Mean daily discharge data was primarily used from two USGS gauges: the San Marcial gauge (08358400, primary gauge), located in the upstream end of the study reach, and the San Acacia gauge (08354900, secondary gauge), located approximately 44 miles upstream of the study reach. The gauge numbers and their dates of available discharge data are shown in Table *2-1*.

Table 2-1: Available Daily Discharge Data

USGS Gauging Station	USGS Gauge Number	Dates Available
RG at San Marcial	8358400	1949- current
RG at San Acacia	8354900	1958-current

The Elephant Butte Dam gauge (8361000), located approximately 34 miles downstream of the Elephant Butte Reach, measures regulated reservoir releases, and was therefore not useful in this study. The San Antonio gauge (8355490), located approximately 25 miles upstream of the Elephant Butte reach, only contains discharge data for recent years (2005 – Sep 2008), and therefore was not considered. An additional gauge is located at the Escondida Bridge, approximately 16 miles upstream of the Elephant Butte reach. However, this gauge only records real-time discharge and not the historical data needed for this study. Figure 2.12 shows the locations of the nearby gauges.

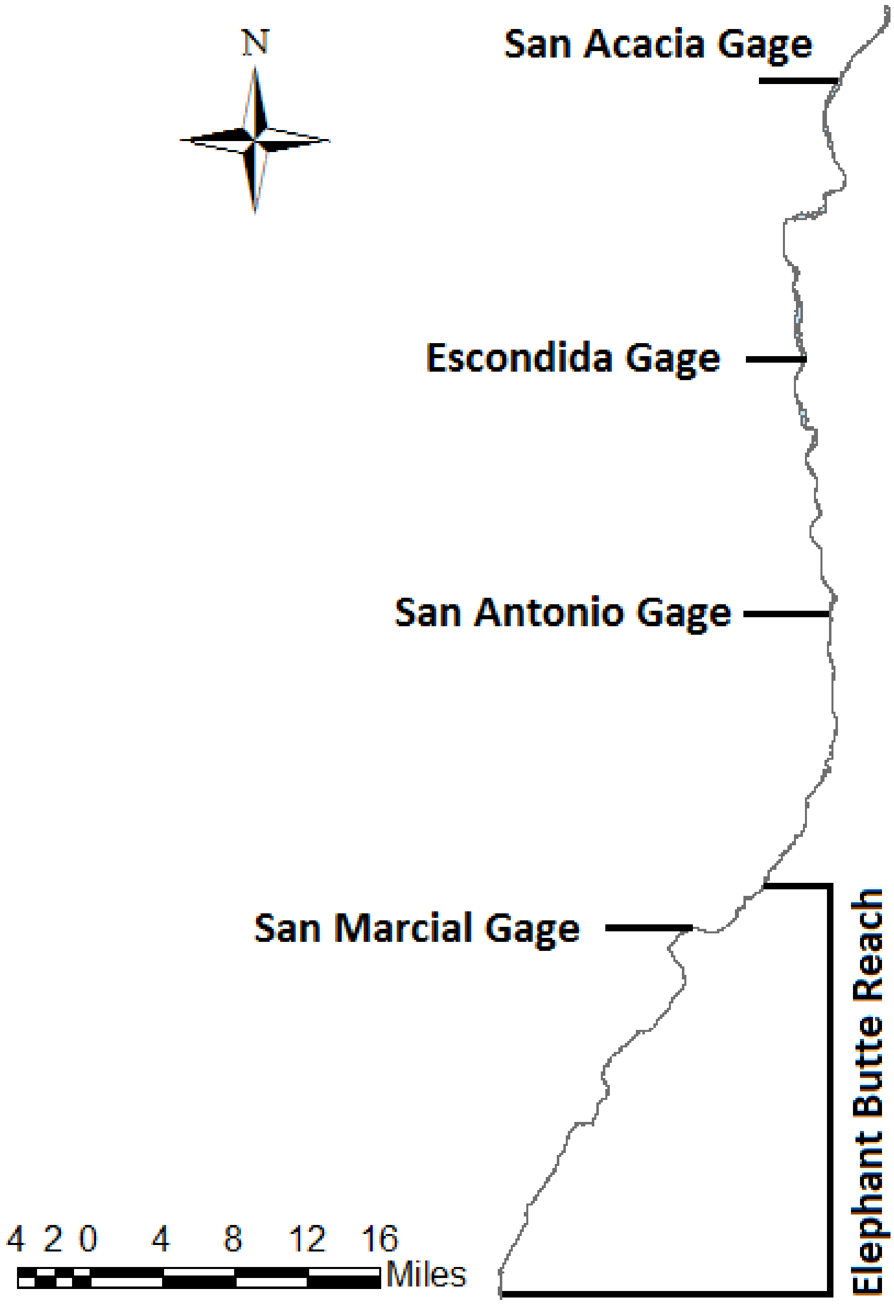

Figure 2.12 Location of Gauges

An example hydrograph for the San Acacia and San Marcial gauges for the year 1999 is shown in Figure 2.13. The hydrograph demonstrates that there are typically two distinct peaks on the Middle Rio Grande. The first peak occurs between mid-May until the end of June and the second peak occurs in August. As demonstrated in Figure 2.13, significant evapotranspiration losses from the river largely contribute to the typically lower discharge measurements at the San Marcial Gauge, compared to the San Acacia Gauge (Baird, D., Pers. Comm.). Additional daily discharge graphs from the years 1990-2010 are available in Appendix B.

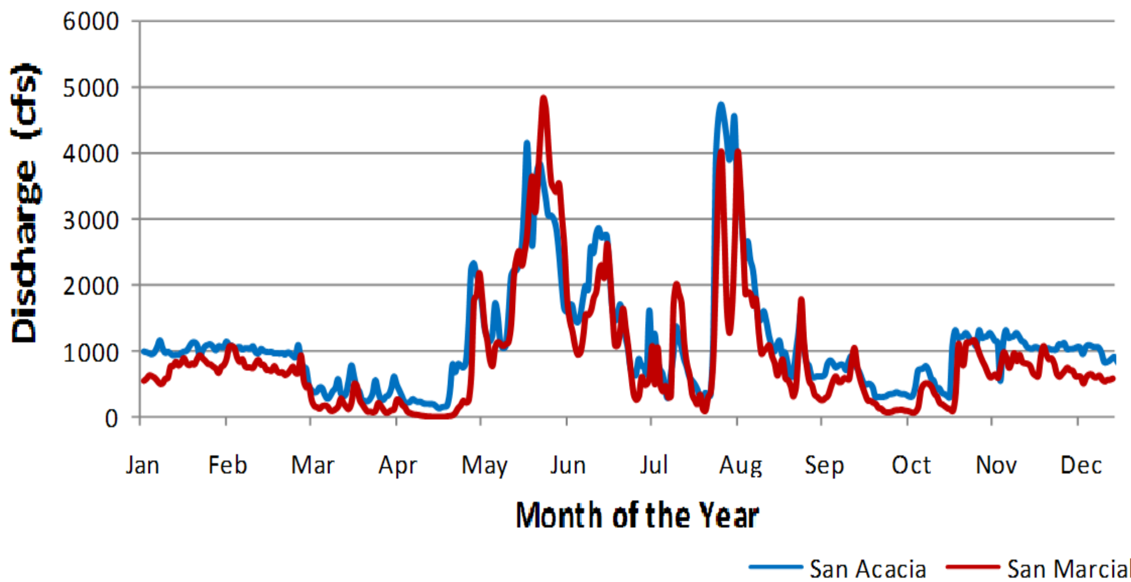

Figure 2.13: Daily Discharge of the Rio Grande in 1999

The annual peak flow information for the San Acacia and San Marcial gauges was obtained from the USGS website. Figure 2.14 displays a comparison of the peak flows at the San Acacia Gauge and the San Marcial Gauge.

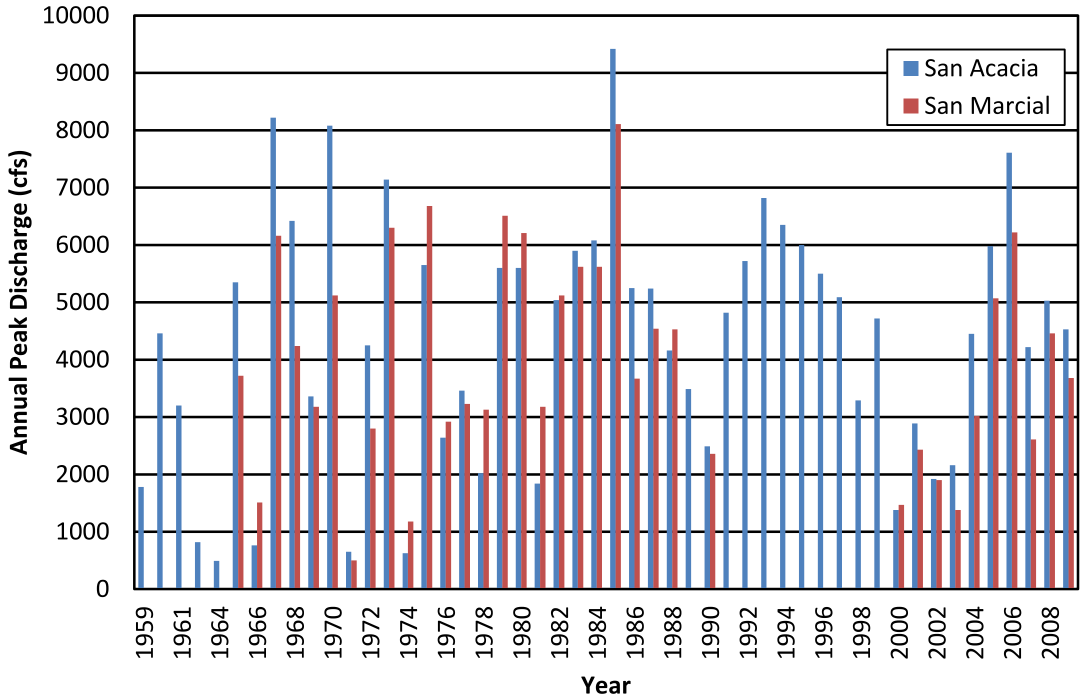

Figure 2.14 Comparison of Annual Peak Flows at San Acacia and San Marcial Gauges

2.3.3 Bed Material

Bed material data was collected by Reclamation from 1986-2007 at SO- and EB-range lines. The dates and locations of the collected bed material data are provided in Appendix C. Additional bed material data was also obtained from the USGS gauging stations at San Acacia, located approximately 44 miles upstream of Elephant Butte Reach, and San Marcial, located within the Elephant Butte Reach (http://nwis.waterdata.usgs.gov). The dates and locations of the data recorded are provided in Appendix D.

2.3.4 Suspended Sediment Data

As part of this study, the suspended sediment data was used from the Escondida Reach Report (Larsen et al. 2007). This was used since no new sediment data is available on the USGS website for the San Acacia and San Marcial guages. Daily suspended sediment data was used for this analysis. Figure *2.15* shows the annual suspended sediment load at each gauge. Continuous suspended sediment data was not always available for all parameters at each gauge. A blank year indicates that complete sediment data was not available for that year.

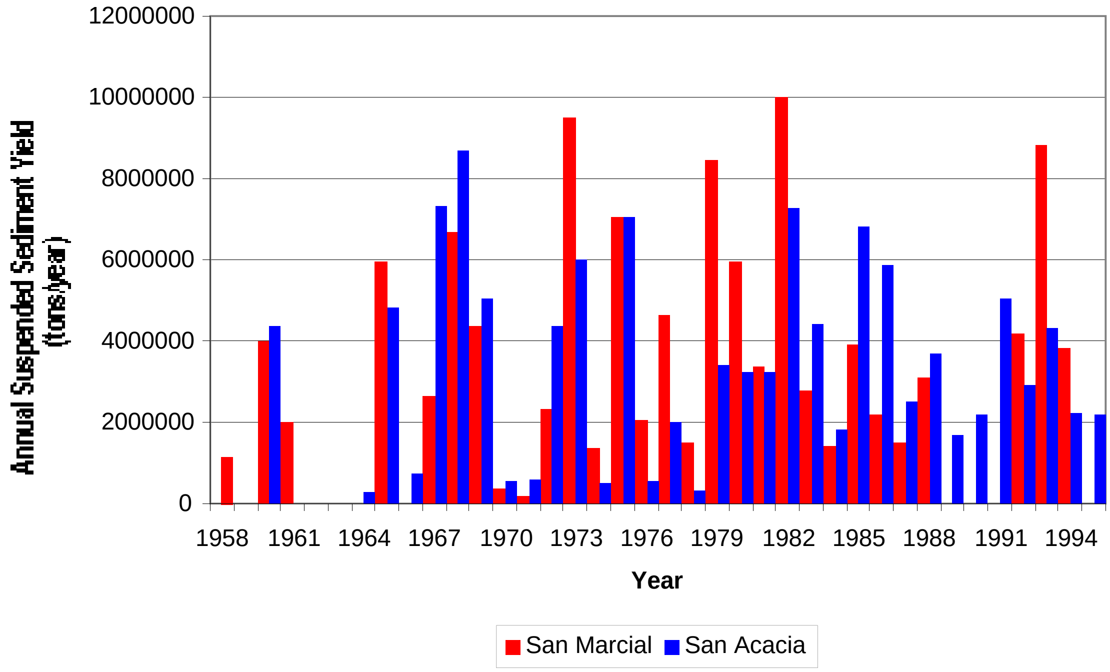

Figure 2.15: Annual Suspended Sediment Yield at San Acacia and San Marcial Gauges

Table 2-2 gives the dates of continuous, available data at each gauge.

Table 2-2: Available Suspended Sediment Data

USGS GAUGING STATION	DATES
RG at San Marcial	Oct. 1956 - July 1962
	Sep. 1962 - Aug. 1966
	Oct. 1966 - Sep. 1989
	Oct. 1991 - Sep. 1995
RG at San Acacia	Jan 1959 - Sep. 1959
	Jan 1960 - Sep. 1961
	July 1961
	April 1962 - July 1962
	Aug 1962 - Sep. 1962
	March 1963 - Sep. 1996

SECTION 3: RESERVOIR LEVEL ANALYSIS

3.1.1 Reservoir Level Analysis

A reservoir level analysis was performed for the Elephant Butte Reservoir, located at the downstream end of the Elephant Butte Reach. Figure 3.1 shows the Elephant Butte Reservoir level time series. Elephant Butte Dam construction began in 1908 and was completed in 1916, with water storage operations beginning in January of 1915 (Reclamation, 2008). The maximum water surface elevation (WSE) of Elephant Butte Reservoir is 4407.0 ft. Since its inception, the WSE behind Elephant Butte Dam has varied more than 150 ft in elevation. The reservoir was not completely filled until 1942, at which point the reservoir level dropped about 150 ft between 1942 and 1954, due to a drought which lasted from about 1942 to about 1974 (Figure 1.2). The low flow conveyance channel (LFCC), which was built to hydraulically efficiently transport water to Elephant Butte Reservoir and runs the entire length of Elephant Butte Reach, was in operation by 1955 and operated until 1986. With the operation of the LFCC during the drought, the reservoir WSE averaged between El 4331 and El 4404. By about 1977 the reservoir began to fill again until it was full, or essentially full, from 1985 to 1999, at which point another drought impacted the reservoir level, which decreased to an average WSE of about 4340 ft in 2010.

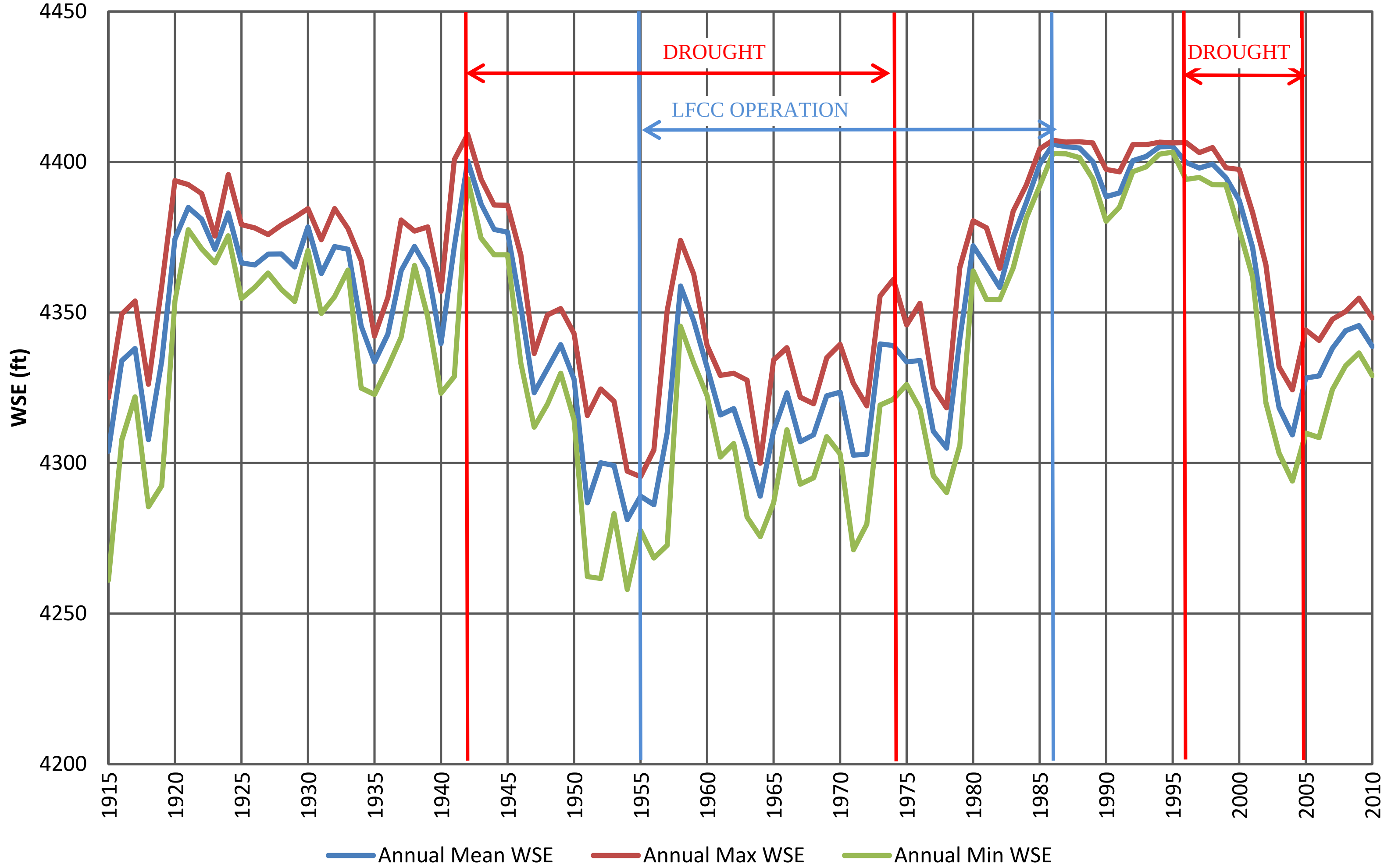

Figure 3.1 Elephant Butte Reservoir Level Time Series

Figure 3.2 shows the historical sediment survey longitudinal profile with reservoir sediment surveys completed in 1915, 1988, 1999, and 2007. Comparing the survey between 1915 and 1988, up to 50 ft of aggradation has occurred within Elephant Butte Reservoir. The decrease in longitudinal profile elevation from 1999 to 2007 can be attributed to the consolidation of the deposited sediment during the low reservoir levels in response to a second drought from 1999 to 2005.

In 1915, when the reservoir had just begun to fill, had the reservoir been at its maximum WSE, then the upstream extent of the reservoir would have reached RL 10 (or the upstream end of Subreach 3). By 2007, the upstream extent of the reservoir at its maximum WSE would have been about RL 20 (or the upstream end of Subreach 6). This means the maximum upstream extent of the reservoir would have shifted downstream approximately 6 miles. The level of the reservoir impacts Elephant Butte Reach, due to sediment deposition as a result of an increased base-level. The longitudinal profile of Elephant Butte Reach is base-level controlled; with an increase in base-level, the channel adjusts vertically by way of sediment deposition, resulting in channel aggradation.

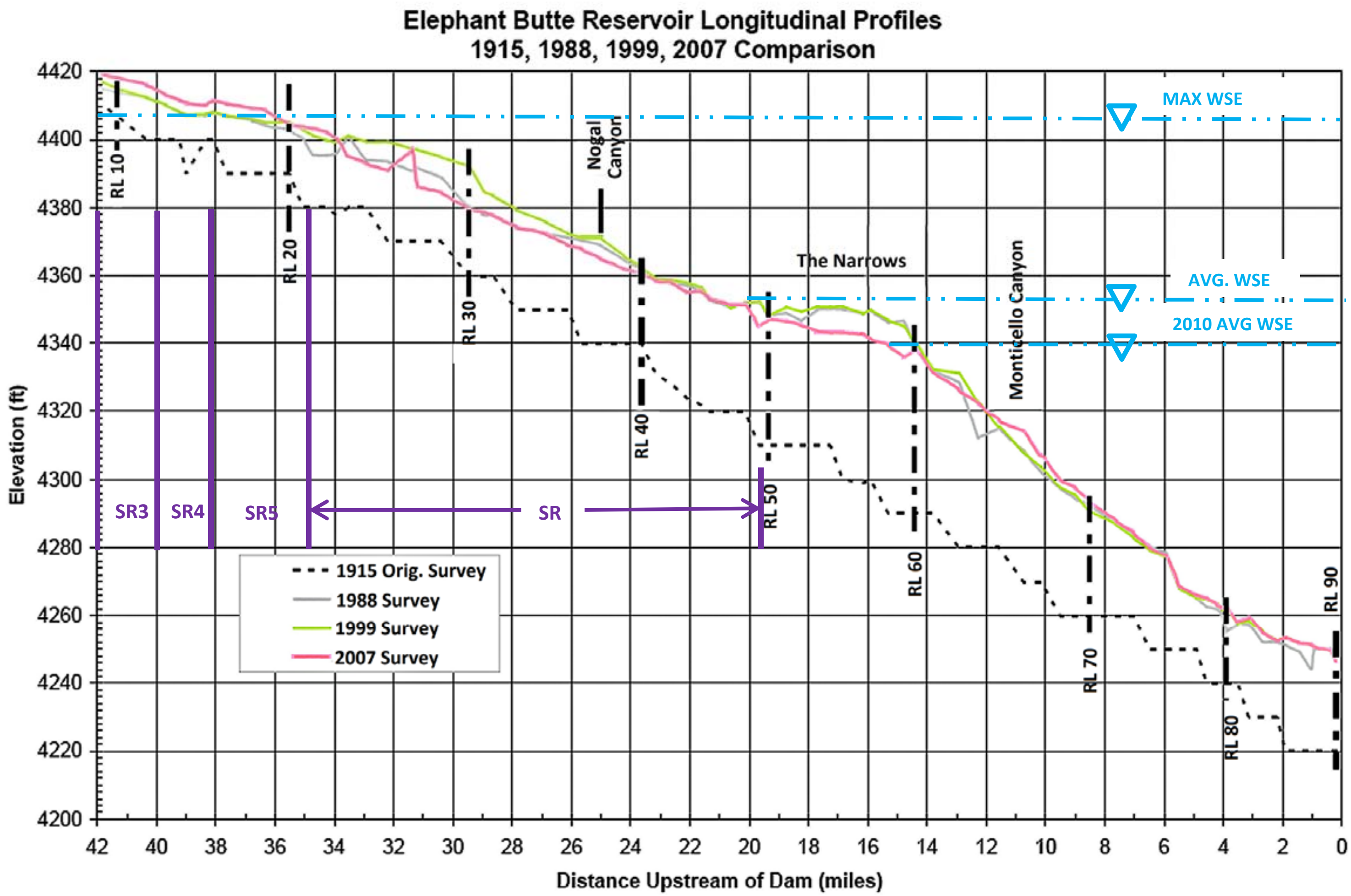

Figure 95 - Elephant Butte Reservoir Longitudinal Profiles

Figure 3.2 Elephant Butte Reservoir Historical Sediment Survey Longitudinal Profile (Reclamation, 2008)

SECTION 4: CHANNEL ANALYSIS

4.1 Channel Planform Analysis from Aerial Photographs

Using ArcGIS and aerial photographs supplied by Reclamation, the study reach's active channel was delineated for 1918, 1935, 1949, 1962, 1972, 1985, 1992, 2001, 2002, 2003, 2004, 2005, 2006, 2008 and 2010. These active channel delineations will be referred to as planforms for purposes of this report; the active channel corresponds to the area bounded by established vegetation. Aerial photographs were not available during 1985, and a delineation provided by Reclamation was used; the 2010 active channel was delineated using a Digital Elevation Model (DEM). See Appendix E for survey dates and additional information about the aerial photographs.

The active channel width was measured at each Agg/Deg line using the delineated planforms. A mean width value was then obtained for each subreach and for the overall reach using a weighted average method. Finally, the sinuosity was computed.

4.1.1 Channel Delineation

Figure 4.1 shows the channel planforms that were delineated in ArcGIS. Figure 4.2 through Figure 4.7 show magnified versions of Figure 4.1. Based on visual observations, the overall channel has narrowed and changed from a multithread channel to a primarily single-thread channel. Subreaches 1, 2, 5, and 6 have straightened and narrowed primarily between 1918 and 1962, and have remained relatively unchanged since then. The multithread characteristics of the river observed from 1928 to 1949 are not repeated after the recession of the reservoir from 2001 to 2003, because Reclamation regularly excavated pilot channels within Subreach 6 (Baird, D., Pers. Comm.).

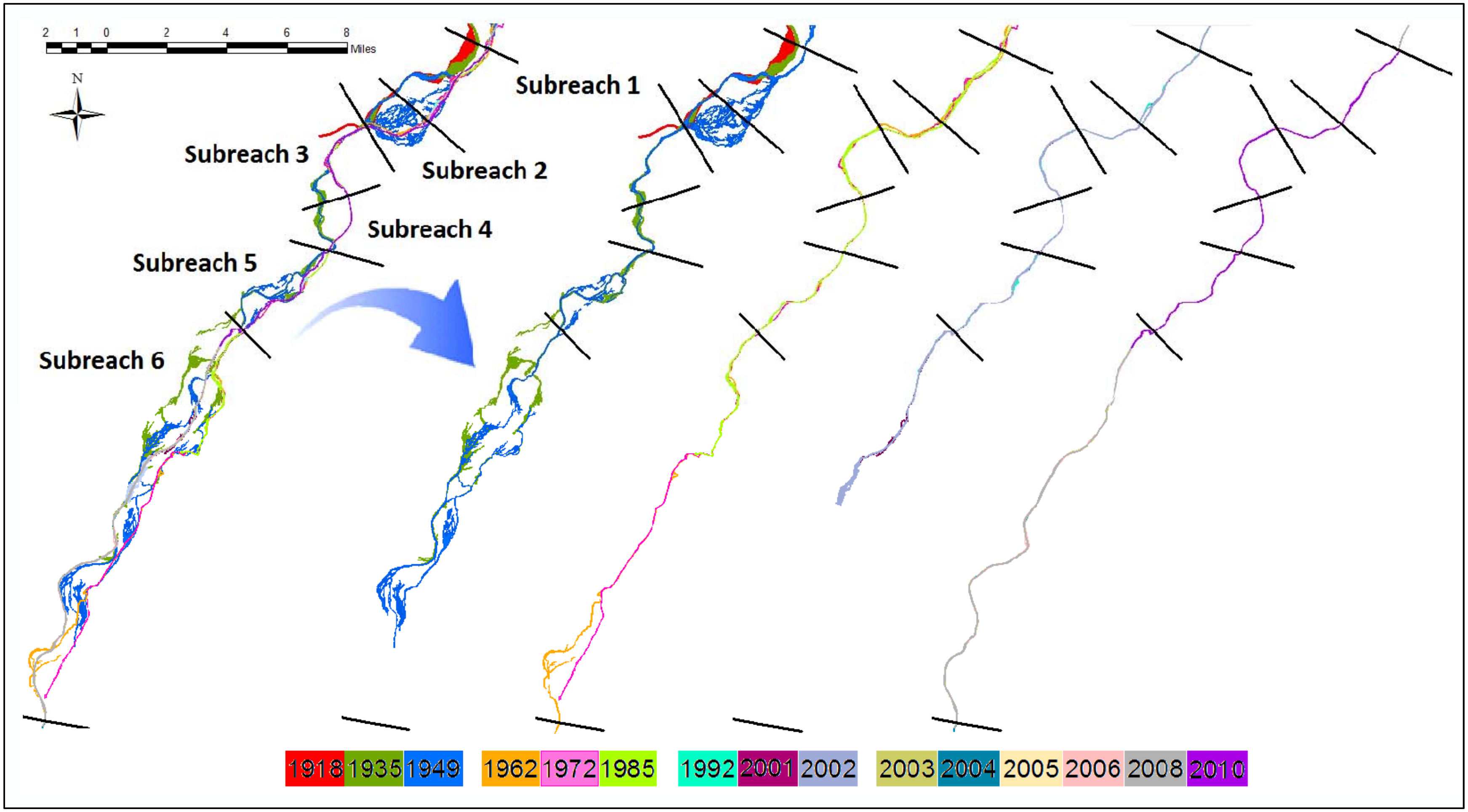

Figure 4.1 Channel Planforms from Aerial Photography

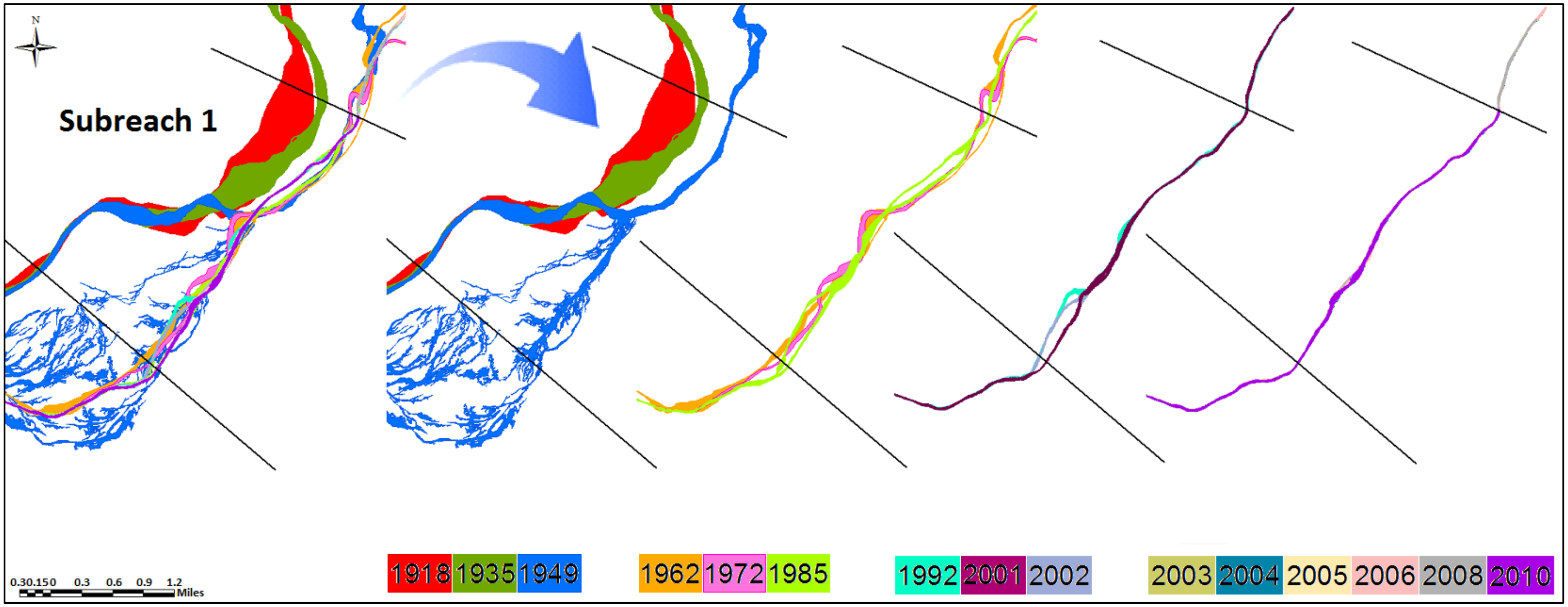

Figure 4.2 Subreach 1 Channel Planforms from Aerial Photography

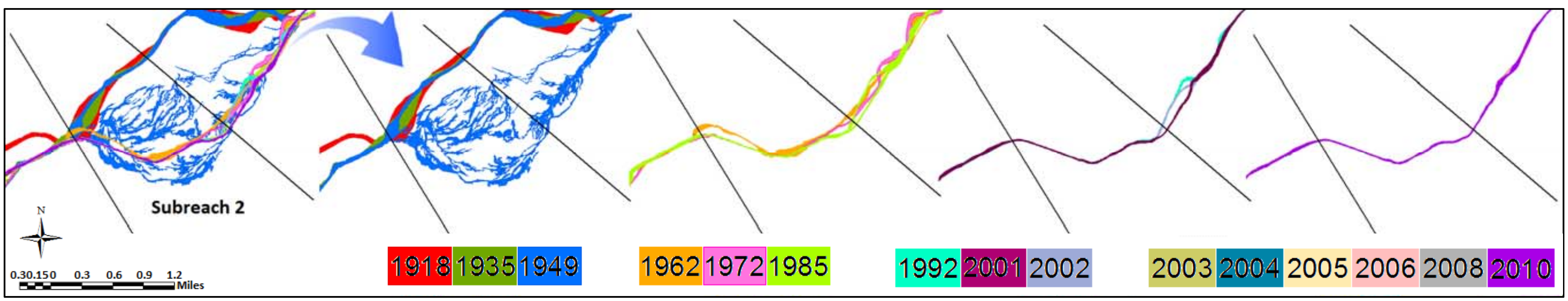

Figure 4.3 Subreach 2 Channel Planforms from Aerial Photography

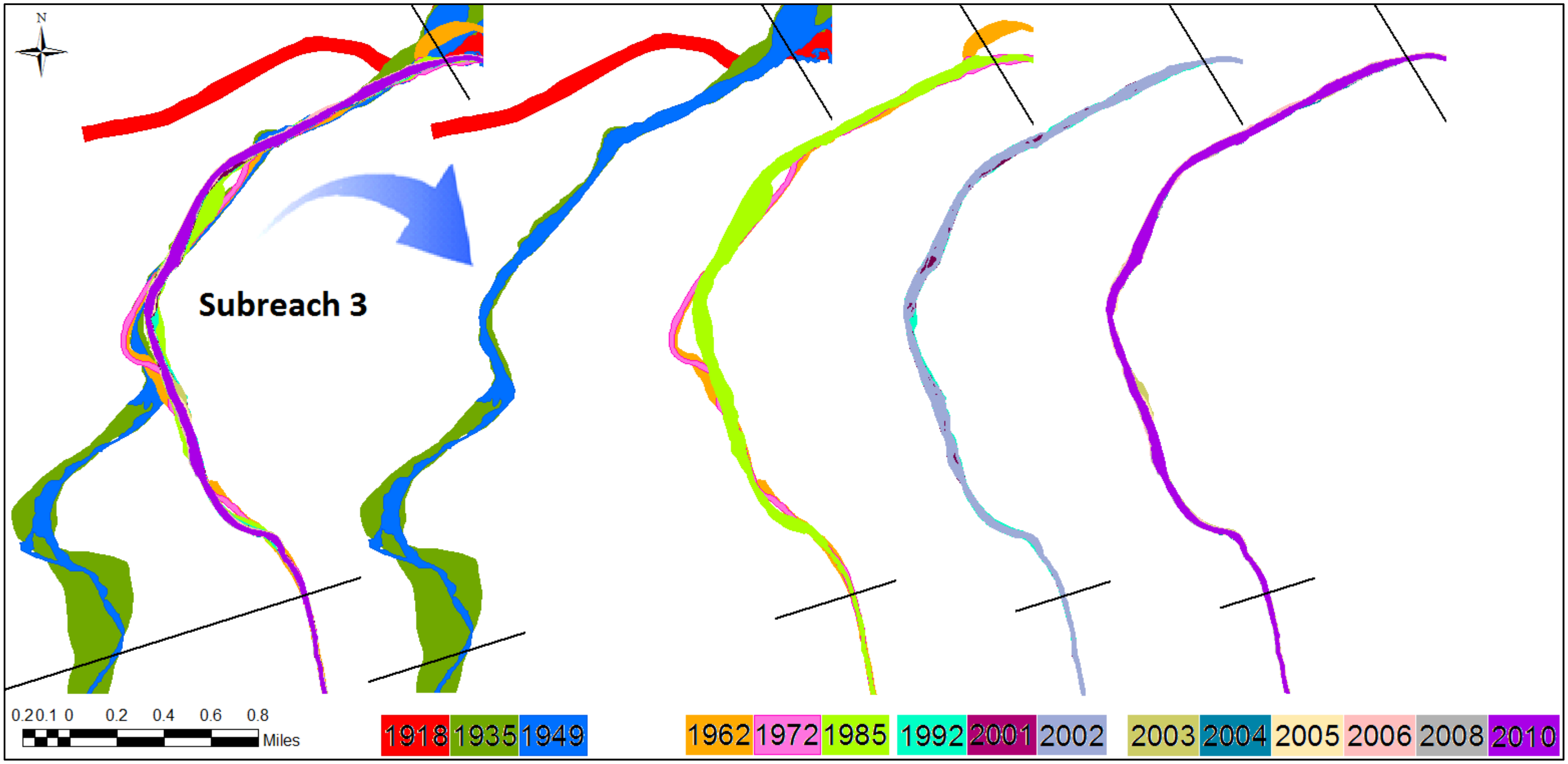

Figure 4.4 Subreach 3 Channel Planforms from Aerial Photography

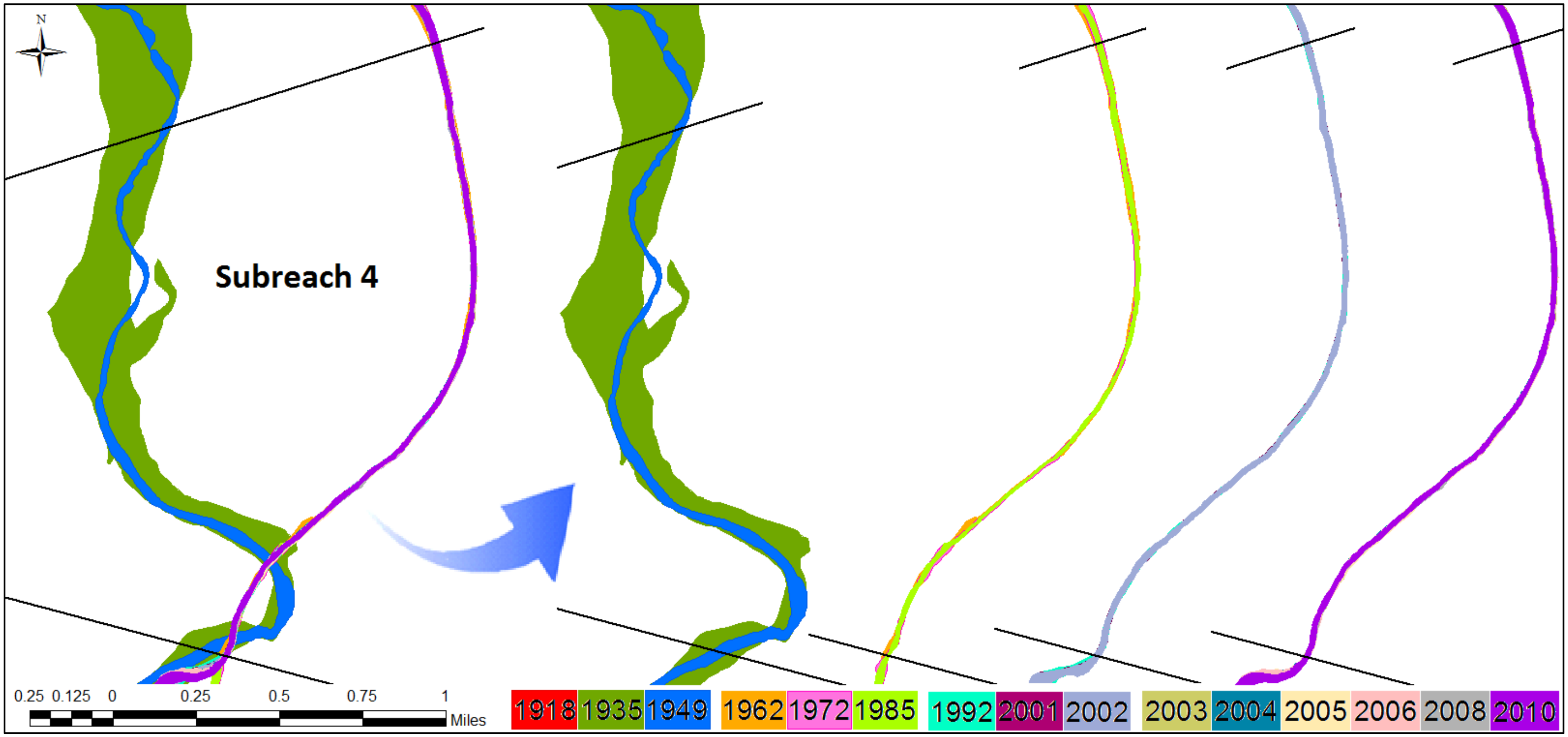

Figure 4.5 Subreach 4 Channel Planforms from Aerial Photography

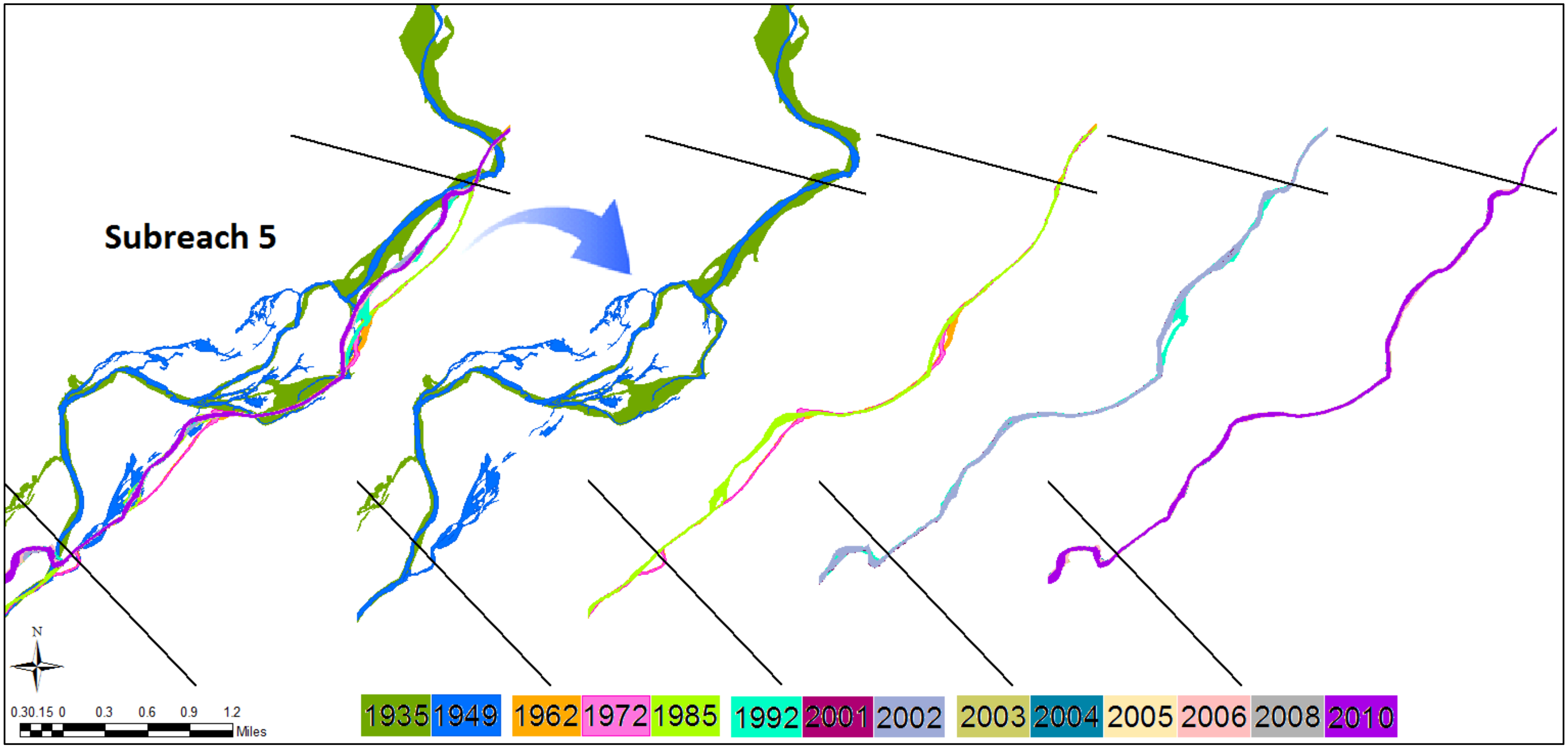

Figure 4.6 Subreach 5 Channel Planforms from Aerial Photography

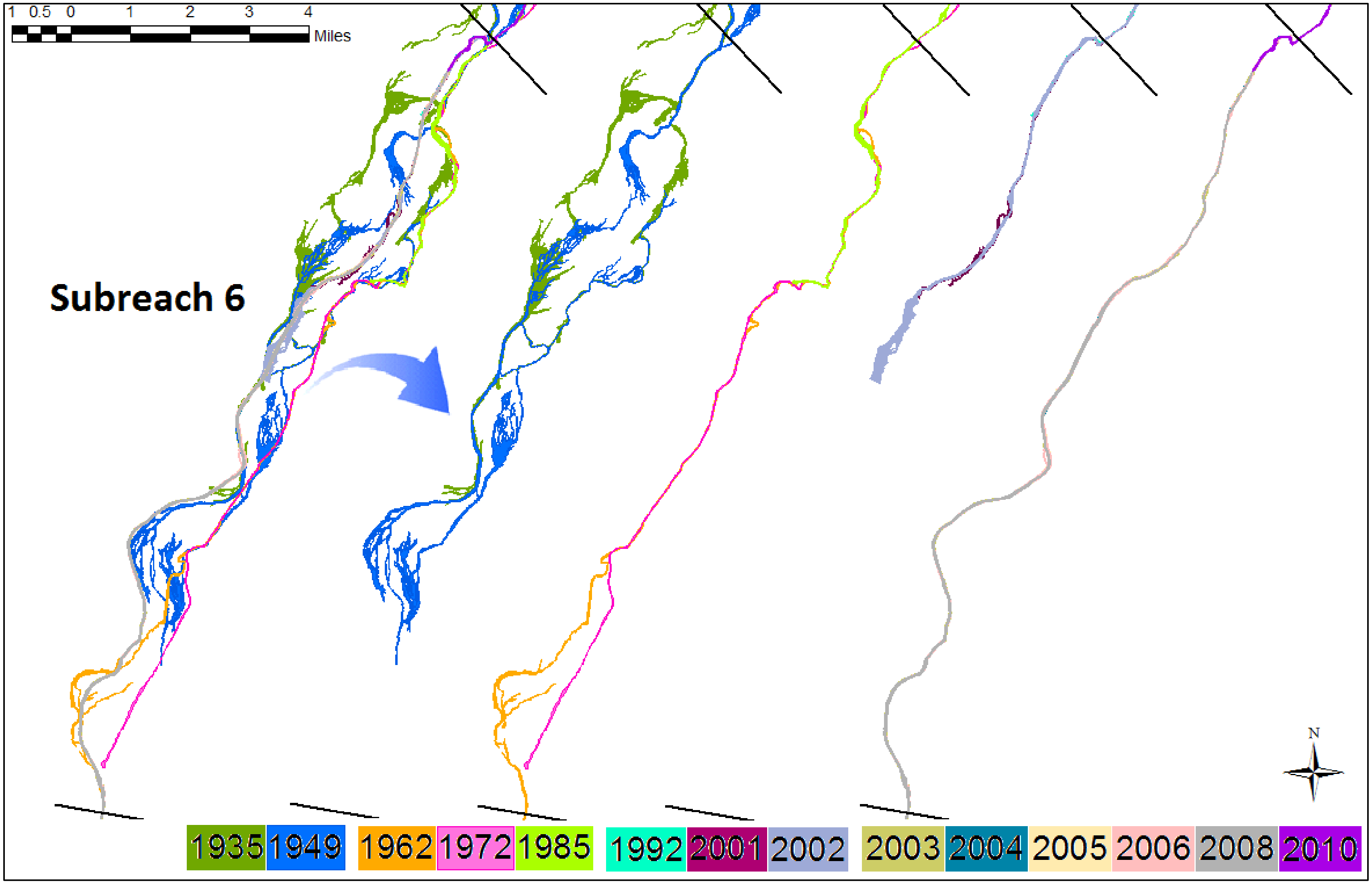

Figure 4.7 Subreach 6 Channel Planforms from Aerial Photography

Note that the difference between the first set of delineations, 1918-1949, is 31 years, the second set of delineations, 1962-1985, is 23 years, the third set of delineations, 1992-2002 is 10 years, and the fourth set of delineations, 2003-2010 is only 7 years. Based on a qualitative visual analysis, the first delineation comparison covers the longest time period and shows the most change and the last delineation comparison shows the shortest time period with the least change. Nevertheless, narrowing and straightening of the reach is observed over time.

4.1.2 Channel Widths from GIS

The active channel width corresponds to the non-vegetated channel. The active channel planforms were delineated from aerial photographs using this criterion, and widths were measured at every Agg/Deg line and/or Range line for which the river intersected. A distance-dependent, weighted average method was used to calculate the average width at each subreach and for the total reach.

In general, Figure 4.8 illustrates a decreasing trend in the width over time for all of the subreaches from 1935 to 1972. Subreaches 1 and 2 experienced an increase in average width in 1949 due to the existence of a multithread channel; Subreach 1 increased from about 940 ft to about 1100 ft, and Subreach 2 increased from about 700 ft to about 1700 ft. The decrease in channel width from 1935 to 1972 (on average, about 275 ft) may be attributed to lower than average discharges, a decrease in base-level, or a combination of the two. The lower than average discharges and decrease in base-level are both results of the drought, which lasted from 1942 to 1979. From 1935 to 2010, the channel width decreased according to the following second order polynomial equation:

$$y = 0.2353x^2 - 936.54x + 931904$$

Where, x is the year, and y is the average channel width (ft).

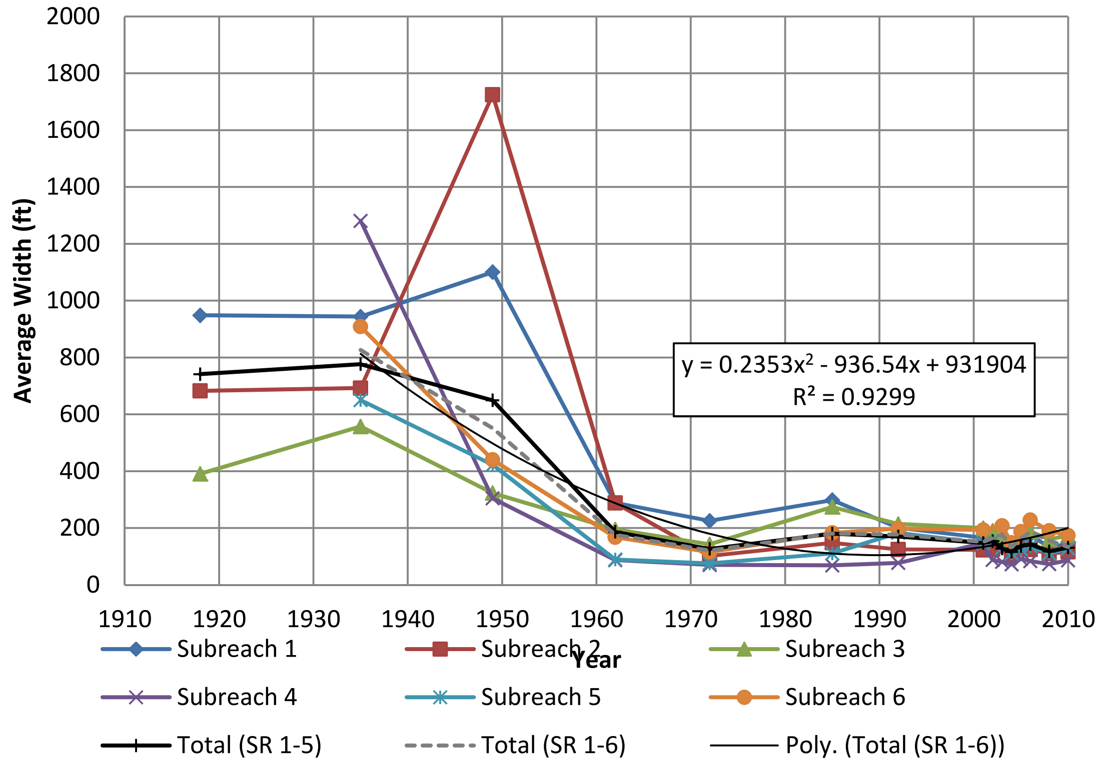

Figure 4.8 Channel Widths from GIS (1918 - 2010)

As seen in Figure 4.9, between 1972 and 1985, the average channel width increased, on average, about 60 ft and the base-level increased by up to 125 ft. Between 1985 and 2000, the base-level remained relatively unchanged, changing no more than 27 ft, and the average channel width, on average, changed no more than 30 ft. Between 2000 and 2004, the base-level decreased by up to 100 ft, and the average channel width increased 26 ft from 2001 to 2003 and decreased 45 ft from 2003 to 2004. The large decrease in channel width between 2003 and 2004 was due to mechanical excavation of narrow pilot channels by Reclamation (Baird, D. Pers. Comm.). The base-level increased by about 50 ft between 2004 and 2010, and the average channel width increased about 55 ft between 2004 and 2006, and decreased about 55 ft between 2006 and 2010. In general, based on this dataset, the channel width tends to increase with a rise in base-level, and decrease with a drop in base-level.

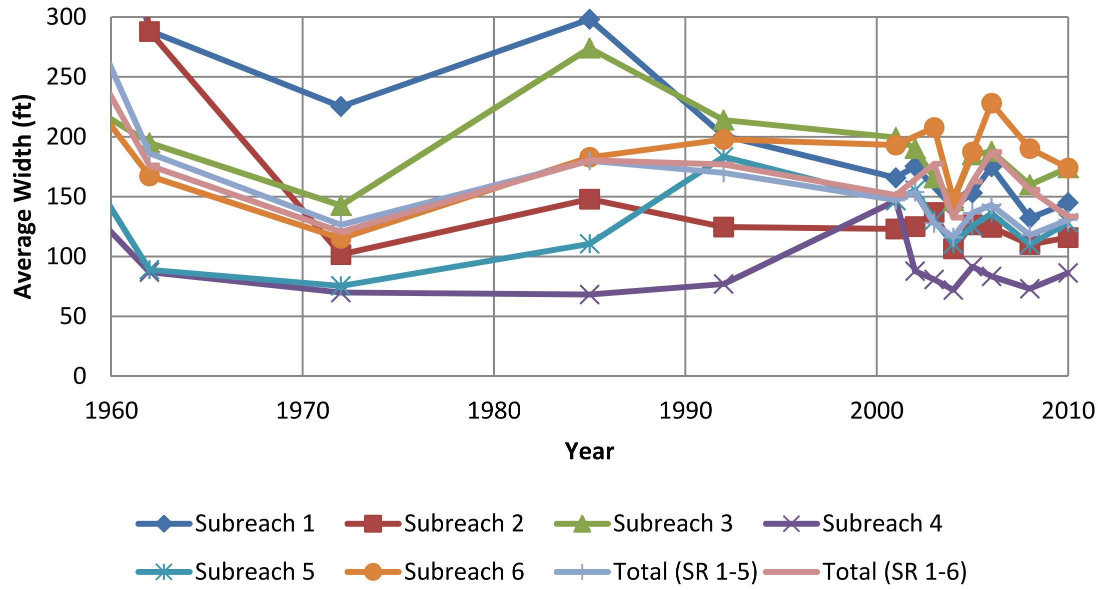

Figure 4.9 Channel Widths from GIS (1962 - 2010)

4.1.3 Sinuosity

Sinuosity of the entire Elephant Butte Reach, as well as the six subreaches, was computed using aerial photographs in ArcGIS. The sinuosity was determined by using the following equation:

$$S = \frac{Lc}{Lv}$$

Where S is the sinuosity, Lc is the length of the channel, and Lv is the length of the valley.

The length of the channel, and each of the six subreaches, was measured along the river thalweg, an estimated delineation from aerial photographs and channel delineations. The thalweg delineation was approximate and accuracy was, in some cases, further limited by the clarity and quality of the aerial photographs. The 1985 and 1918 planforms delineated by Reclamation were used to estimate the length of the channel and the length of the valley. For each year, the length of the valley was measured as the straight-line distance between the upstream and downstream extents of the reach and subreaches, as dictated by major geologic features, such as the Black Mesa. The channel length measurements are plotted in Figure 4.10 and presented in Table 4-1. The channel length decreased about 0.0126 miles/year between 1935 and 2010.

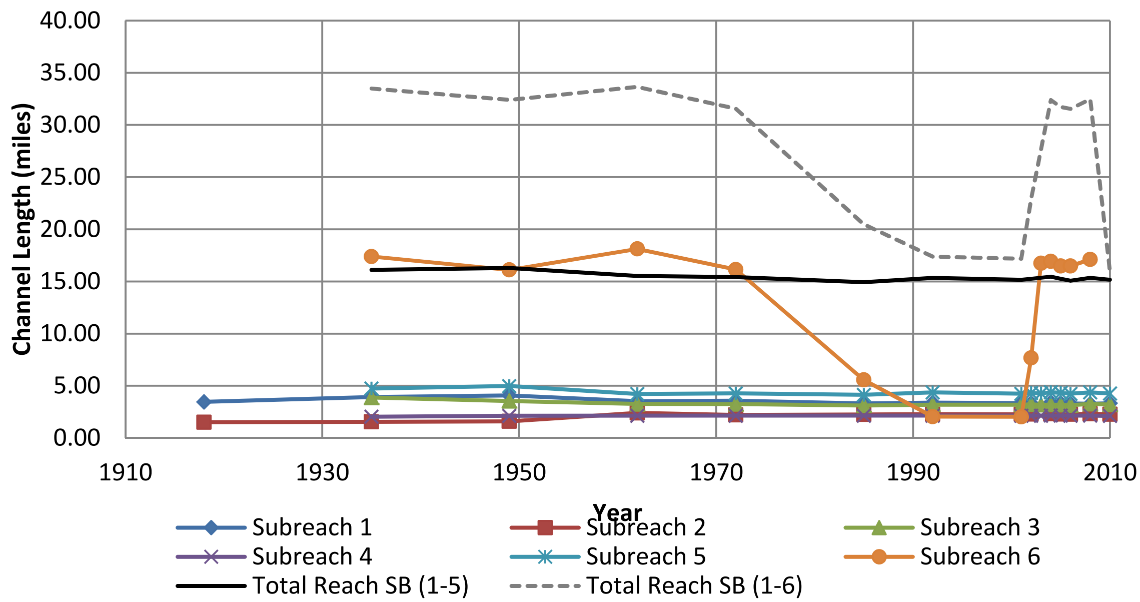

Figure 4.10 Subreach Lengths and Total Lengths as Measured From GIS Data

Table 4-1 Subreach Length and Total Length Values as Measured From GIS Data

Reach	Measured Lengths (mi)														
	1918	**1935**	**1949**	**1962**	**1972**	**1985**	**1992**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2008**	**2010**
Subreach 1	3.46	3.92	4.07	3.52	3.56	3.30	3.38	3.34	3.34		3.42	3.34	3.30	3.27	3.32
Subreach 2	1.51	1.54	1.59	2.39	2.21	2.25	2.27	2.26	2.28		2.31	2.28	2.27	2.31	2.27
Subreach 3	1.56	3.87	3.54	3.25	3.24	3.10	3.18	3.18	3.21	3.17	3.19	3.17	3.14	3.26	3.20
Subreach 4		2.04	2.12	2.14	2.13	2.13	2.13	2.13	2.13	2.13	2.15	2.15	2.13	2.14	2.11
Subreach 5		4.74	4.97	4.21	4.26	4.13	4.36	4.24	4.30	4.27	4.38	4.32	4.23	4.36	4.26
Subreach 6		17.39	16.11	18.12	16.14	5.56	2.04	2.03	7.67	16.73	16.93	16.48	16.48	17.11	0.79
Total Reach SR (1-5)	**6.52**	**16.10**	**16.29**	**15.52**	**15.41**	**14.92**	**15.33**	**15.15**	**15.26**	**9.57**	**15.45**	**15.25**	**15.07**	**15.35**	**15.16**
Total Reach SR (1-6)	***6.52***	***33.48***	***32.40***	***33.64***	***31.55***	***20.48***	***17.37***	***17.18***	***22.93***	***26.31***	***32.38***	***31.73***	***31.55***	***32.46***	**15.96**
Agg/Deg Start	1637	1637	1637	1637	1637	1637	1637	1637	1637	1692	1637	1637	1637	1637	1637
Agg/Deg End	1708	1962	1948	1962	1958	1849	1811	1811	1875	1962	1962	1960	1960	1962	1962

Figure 4.11 shows the sinuosity for the Elephant Butte Reach and each of the subreaches, values are presented in Table 4-2. From 1918 to 1935 sinuosity increased for the entire channel; though the overall sinuosity remains low, less than 1.3, Subreach 1 is more sinuous than Subreach 2 by about 15 percent. There is not enough planform delineated in Subreach 3 in 1918 to be considered representative of the entire subreach, so this portion was disregarded. No planform data exists below Subreach 3 in 1918, so sinuosity data is unavailable. From 1935 to 1949, the sinuosity for the entire channel, and for each subreach, decreased by less than 6 percent, except Subreach 5, which increased about by about 4 percent. Subreach 2 remained less sinuous, by about 15 percent on average and up to 20 percent, than the remaining Subreaches, which ranged in sinuosity from 1.18 to 1.29. From 1949 to 1962, the sinuosity of Subreaches 1, 3, 4, and 5 decreased between 10 and 20 percent, while Subreaches 2 and 6 increased between 5 and 10 percent. From 1962 to 2010 sinuosity tends to increase and decrease repetitively between a range of 1.0 and 1.15 for Subreaches 1 through 5, while Subreach 6 tends to have a higher sinuosity than the other subreaches from 1962 to 2010 and ranges from 1.12 to 1.24. The higher sinuosities observed in Subreach 6 in the mid-2000s is because Reclamation mechanically introduced a sinuous channel to Subreach 6 by excavating a pilot channel after the lowering of Elephant Butte Reservoir (Baird, D., Pers. Comm.). In general, it can be said that this channel has experienced relatively low sinuosity (less than 1.25) since 1962. From 1935 to 2010, the channel sinuosity can be described using the following second order polynomial:

$$y = 6E\text{-}05x^2 - 0.2196x + 219.57$$

Where, x is year, and y is channel sinuosity (ft/ft).

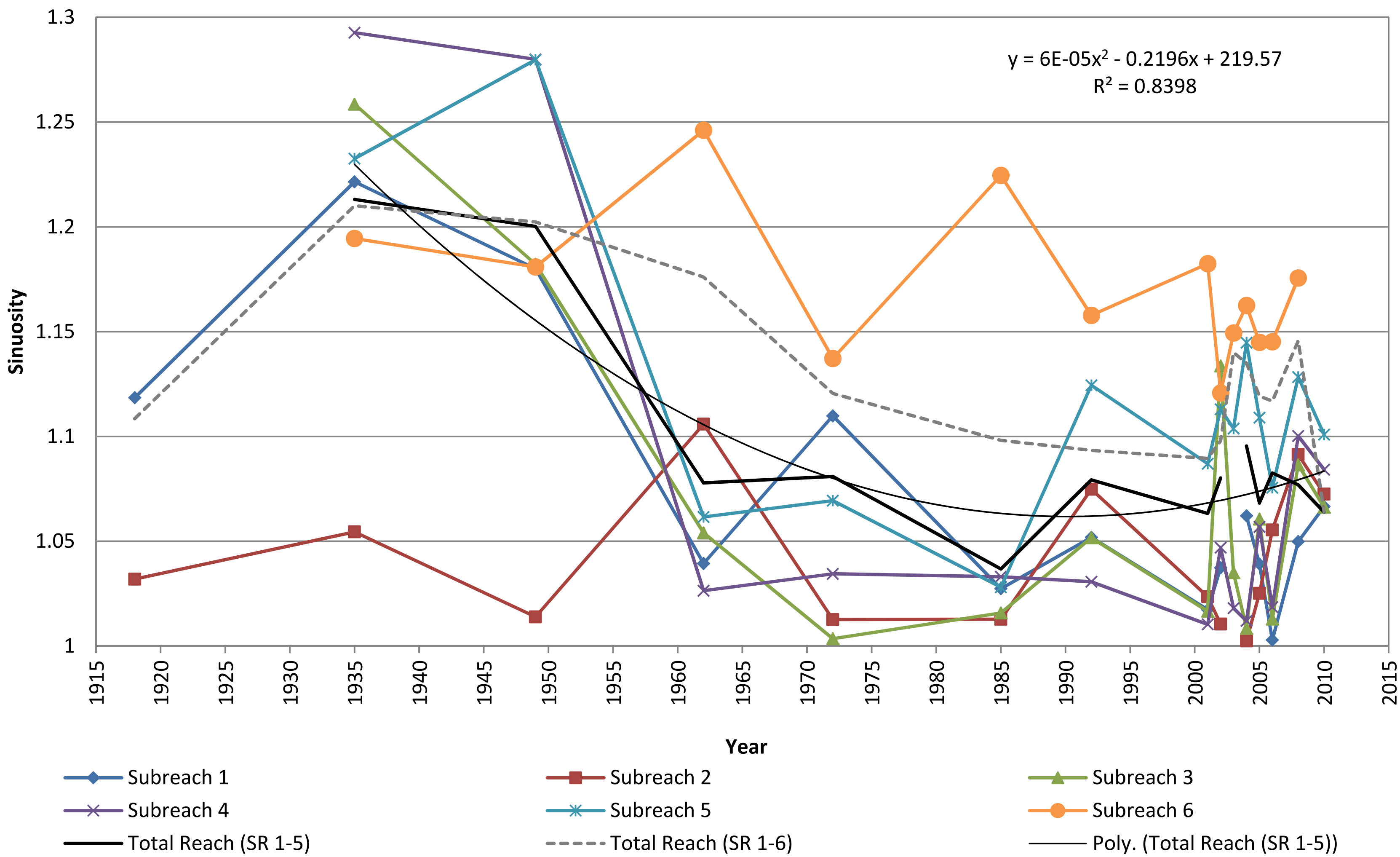

Figure 4.11 Temporal Sinuosity Trends

Table 4-2 Sinuosity Values

Reach	**Year**														
	1918	**1935**	**1949**	**1962**	**1972**	**1985**	**1992**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2008**	**2010**
Subreach 1	1.118	1.222	1.180	1.039	1.110	1.027	1.052	1.017	1.037		1.062	1.039	1.003	1.050	1.067
Subreach 2	1.032	1.054	1.014	1.106	1.013	1.013	1.075	1.024	1.010		1.002	1.025	1.055	1.091	1.073
Subreach 3	1.049	1.259	1.182	1.054	1.004	1.016	1.052	1.017	1.134	1.035	1.008	1.061	1.013	1.086	1.066
Subreach 4	--	1.293	1.280	1.026	1.034	1.033	1.031	1.010	1.047	1.018	1.012	1.057	1.019	1.100	1.084
Subreach 5	--	1.233	1.280	1.062	1.069	1.028	1.124	1.087	1.113	1.104	1.145	1.109	1.076	1.128	1.101
Subreach 6	--	1.194	1.181	1.246	1.137	1.225	1.158	1.182	1.121	1.149	1.162	1.145	1.145	1.176	
Total Reach (SR 1-5)	**--**	**1.213**	**1.200**	**1.078**	**1.081**	**1.037**	**1.079**	**1.063**	**1.080**		**1.095**	**1.068**	**1.083**	**1.077**	**1.064**
Total Reach (SR 1-6)	**1.108**	**1.210**	**1.202**	**1.176**	**1.121**	**1.098**	**1.093**	**1.089**	**1.098**	**1.140**	**1.135**	**1.119**	**1.117**	**1.146**	**1.064**
Agg/Deg Start	1637	1637	1637	1637	1637	1637	1637	1637	1637	1692	1637	1637	1637	1637	1637
Agg/Deg End	1708	1962	1948	1962	1958	1849	1811	1811	1875	1962	1962	1960	1960	1962	1794

4.2 Aggradation and Degradation from Agg/Deg Surveys

4.2.1 Channel Thalweg Profile from Agg/Deg Surveys

The channel thalweg profile from the Agg/Deg survey data was utilized to demonstrate how the minimum elevation and slope of the reach has changed over time, as shown in Figure 4.12. The average bed slope for each subreach and for the entire reach was determined by first plotting the thalweg profile versus downstream distance, as measured along the estimated thalweg in GIS, and fitting a linear regression trendline to each subreach. The slope of the linear regression line was considered the average bed slope of the respective subreach. A linear regression trendline was also fit to the total reach thalweg profile, from which the slope of the regression trendline was considered the average bed slope of the total reach. This method was used for 1962, 1972, 1992, and 2002. The average bed slope for each subreach and for the entire reach is shown in Figure 4.13.

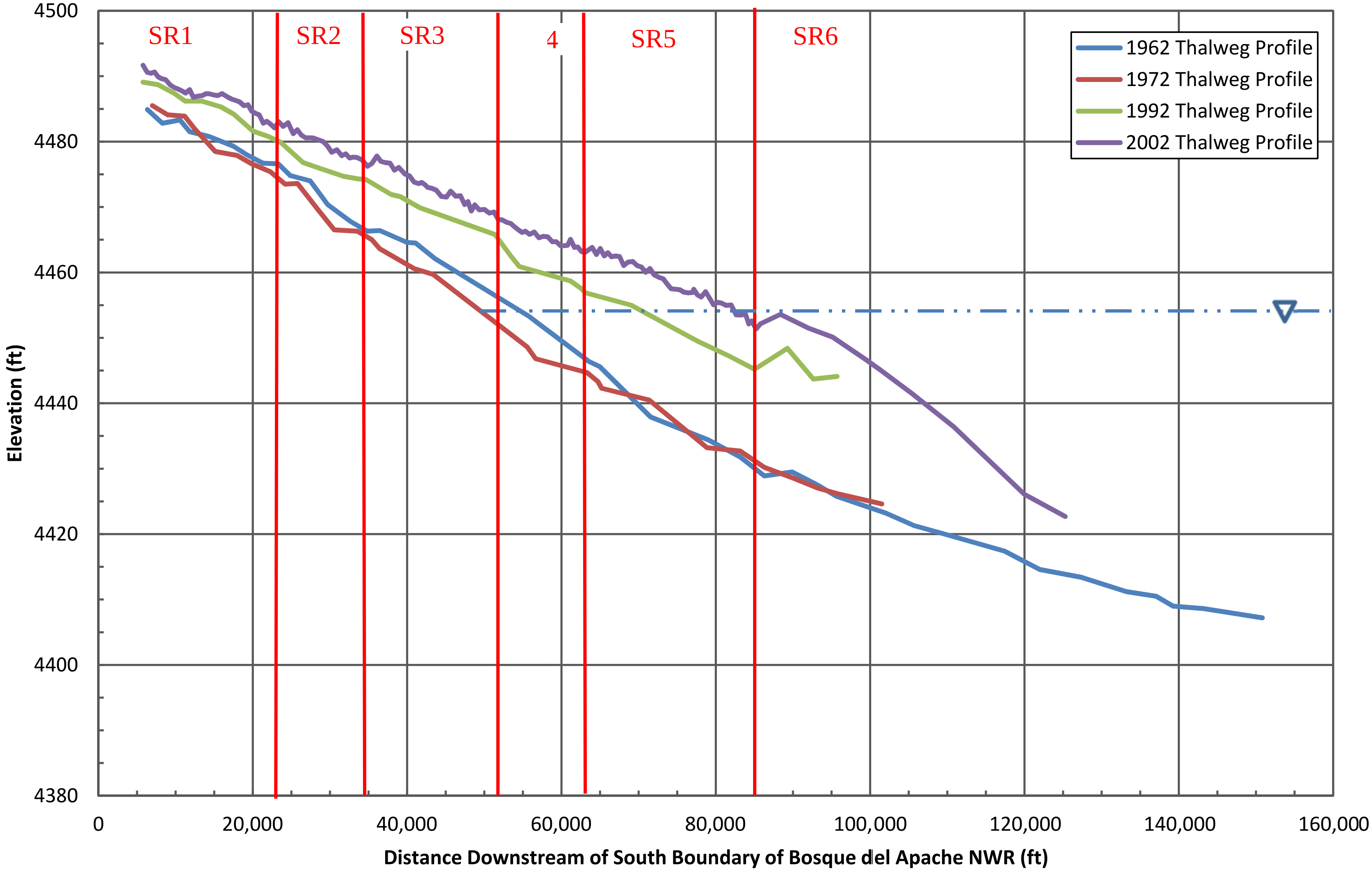

Figure 4.12 Thalweg Elevation Profile From Agg/Deg Surveys

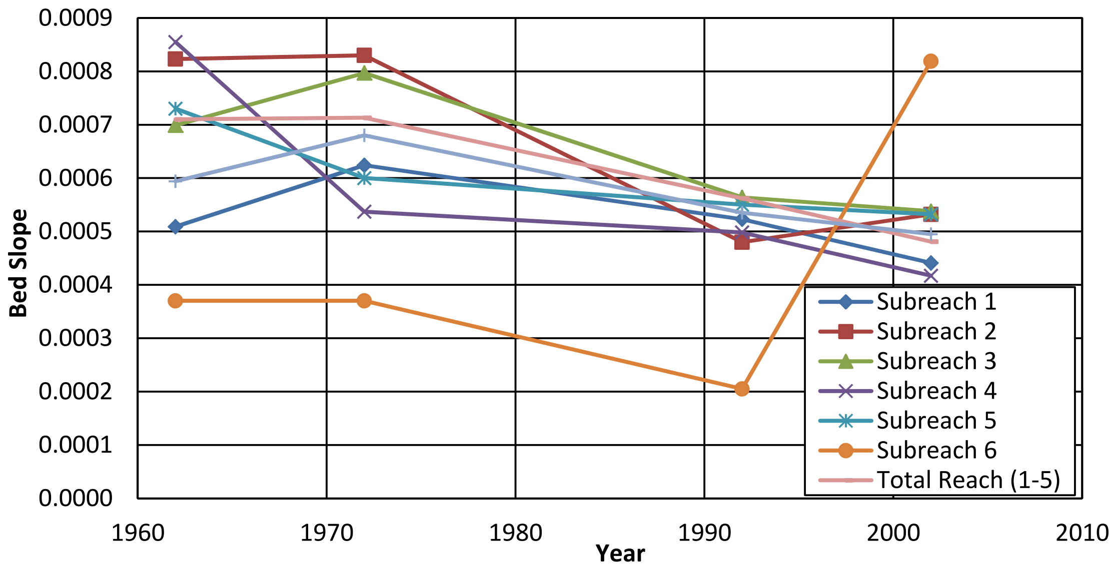

Figure 4.13 Bed Slope from Agg/Deg Surveys

Between the years 1962 and 1972, the bed slope increased between 15 and 30 percent for Subreaches 1, 2, and 3; bed slope decreased 40 and 20 percent for Subreaches 4 and 5, respectively. From 1972 to 1992, bed slope decreased between 10 and 45 percent for all subreaches. From 1992 to 2002, Subreach 2 increased 10 percent and Subreach 6 increased fourfold; all other subreaches decrease between 3 and 15 percent. The overall decrease in bed slope along the entire reach suggests aggradation has occurred between 1962 and 2002. The decrease in bed slope from 1972 to 1992 in Subreach 6 could be caused by the increased Elephant Butte Reservoir level (base-level), which increased by about 130 ft. The fourfold increase in bed slope from 1992 to 2002 in Subreach 6 could be due to the drop base-level, which dropped about 85 feet between 1992 and 2002. The longitudinal profile of Elephant Butte Reach is base-level controlled; with an increase in base-level, the channel adjusts vertically by way of sediment deposition, resulting in channel aggradation and a decrease in channel slope. It is important to note, however, that these trends could also be due to the lack of data in Subreach 6, especially in 1972 and 1992, which could skew the calculated bed slope value to be inaccurate. Table 4-3 shows the average values of the channel slope for each subreach and the overall reach.

Table 4-3 Average Bed Slope from Agg/Deg Surveys

Subreach	Agg/Deg Lines	1962	1972	1992	2002
1	1637 - 1672	0.000509	0.000675	0.000523	0.000441
2	1672 - 1696	0.000823	0.000830	0.000480	0.000532
3	1696 - 1728	0.000699	0.000797	0.000564	0.000538
4	1728 - 1751	0.000855	0.000537	0.000498	0.000417
5	1751 - 1794	0.000730	0.000600	0.000550	0.000532
6	1794 - 1875	0.000370	0.000370	0.000205	0.000819
Total (1-6)	1637 - 1875	0.000594	0.000684	0.000535	0.000495
Total (1-5)	1637 - 1794	0.000710	0.000720	0.000562	0.000481

4.2.2 Change in Channel Thalweg Elevation from Agg/Deg Surveys

A weighted average of the change in thalweg elevation was computed for the entire reach, as well as each subreach, for each year of available Agg/Deg survey data. The average change in thalweg elevation was then compared between years to determine the change in elevation over time. Figure 4.14 shows the average change in thalweg elevation for each subreach, and the overall reach over time; the tabulated values are displayed in Table 4-4. The results show that the average change in the channel thalweg elevation decreased between 0.7 and 3.5 ft from 1962 to 1972 for all subreaches except Subreaches 5 and 6; Subreaches 5 and 6 increased in elevation by about 0.2 to 0.4 ft. The average change in channel thalweg elevation has been increasing since 1972. An increase in channel thalweg elevation indicates aggradation, whereas a decrease indicates degradation. The entire reach has been aggrading since 1972.

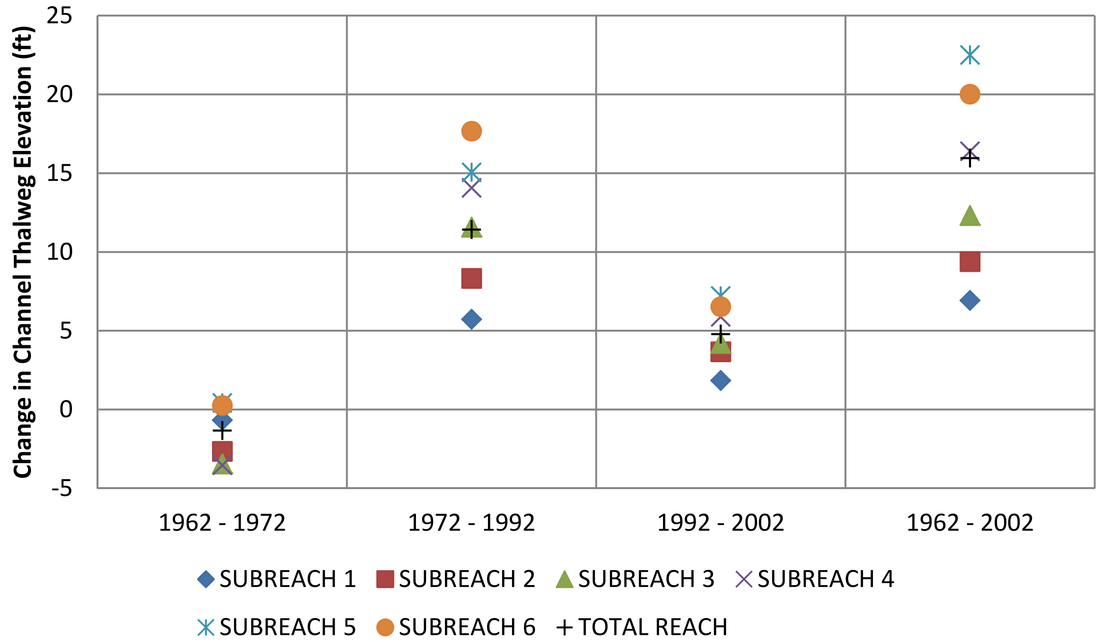

Figure 4.14 Change in Channel Thalweg Elevation from Agg/Deg Surveys

Table 4-4 Change in Channel Thalweg Elevation Values from Agg/Deg Surveys

	Δ Channel Thalweg Elevation (ft)			
Weighted Average	**1962 - 1972**	**1972 - 1992**	**1992 - 2002**	**1962 - 2002**
U/S OF EB REACH	0.79	3.36	1.76	5.91
SUBREACH 1	-0.67	5.73	1.85	6.93
SUBREACH 2	-2.65	8.33	3.67	9.39
SUBREACH 3	-3.45	11.57	4.20	12.31
SUBREACH 4	-3.53	14.07	5.88	16.39
SUBREACH 5	0.43	15.06	7.21	22.50
SUBREACH 6	0.26	17.68	6.53	20.01
TOTAL REACH	-1.33	11.42	4.79	15.95

Analyses were done using the Agg/Deg data to show the change in thalweg elevation at each Agg/Deg line (see Figure 4.15 to view the changes from 1962-1972, Figure 4.16 for 1972-1992, Figure 4.17 for 1992-2002, and Figure 4.18 for 1962-2002). Recall that Agg/Deg data does not have surveys available at every Agg/Deg line during the years 1962, 1972, and 1992, therefore the plots only show the Agg/Deg lines for which data exists. Table 4-5 shows the average, maximum and minimum changes in channel thalweg elevation with their respective Agg/Deg line for each group of years.

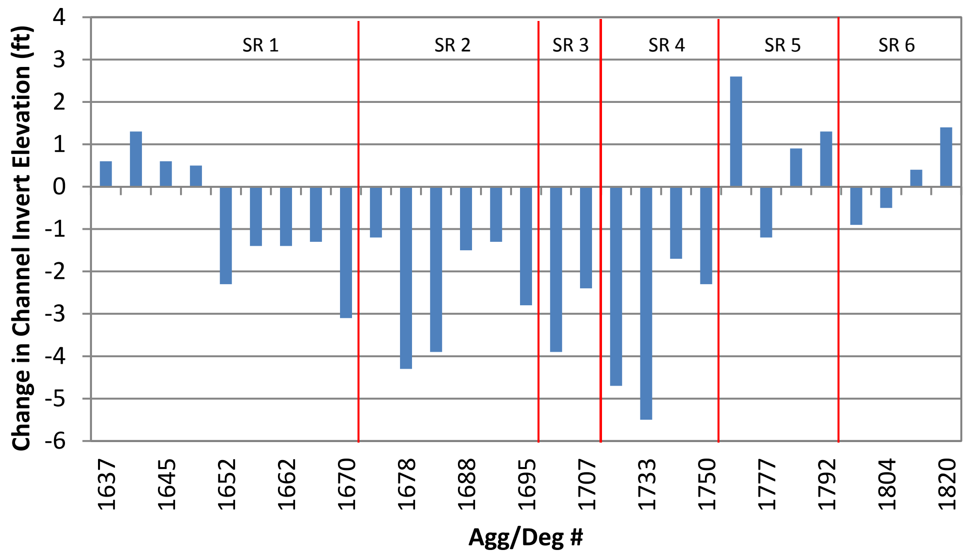

Figure 4.15 Change in Channel Thalweg Elevation (1962 – 1972) Based on Agg/Deg Surveys

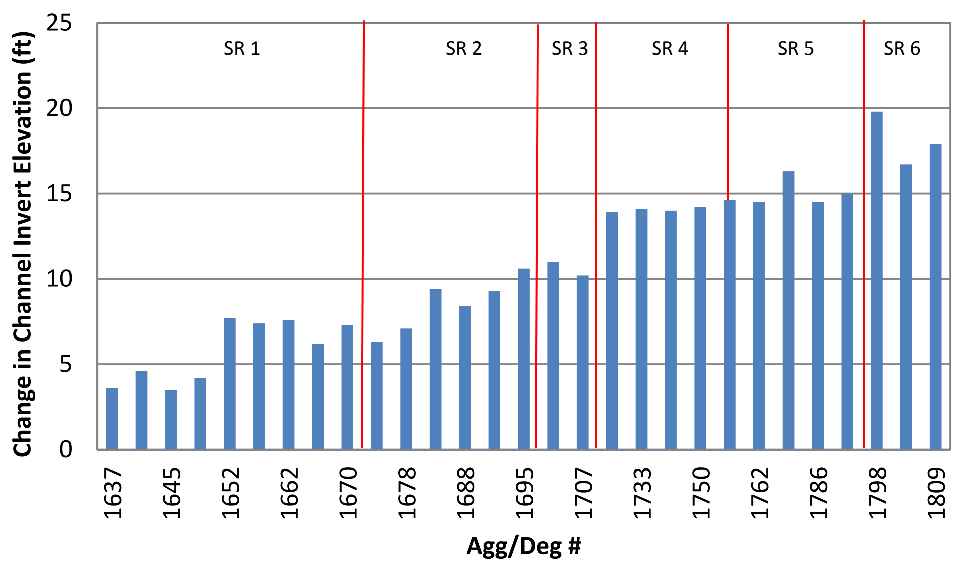

Figure 4.16 Change in Channel Thalweg Elevation (1972 – 1992) Based on Agg/Deg Surveys

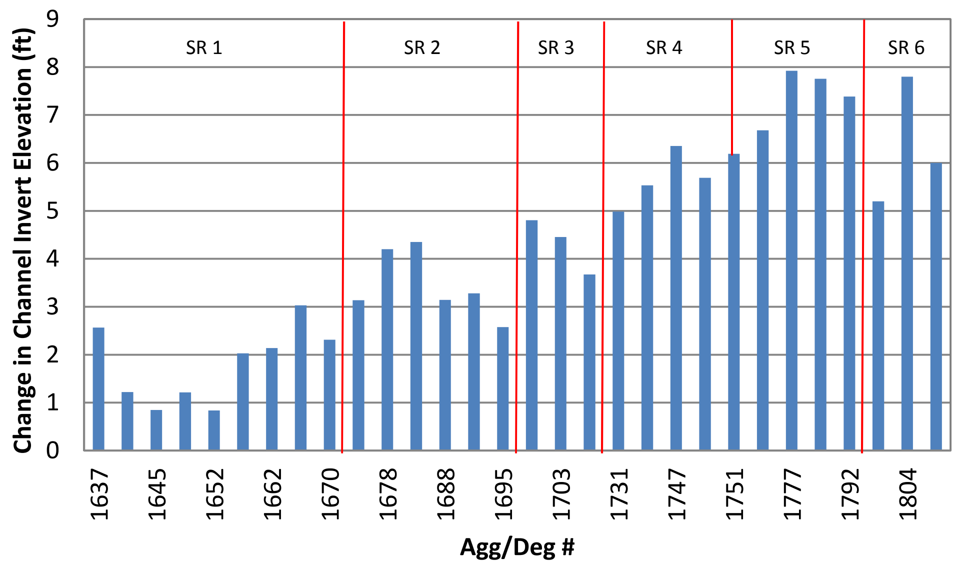

Figure 4.17 Change in Channel Thalweg Elevation from 1992 – 2002 Based on Agg/Deg Surveys

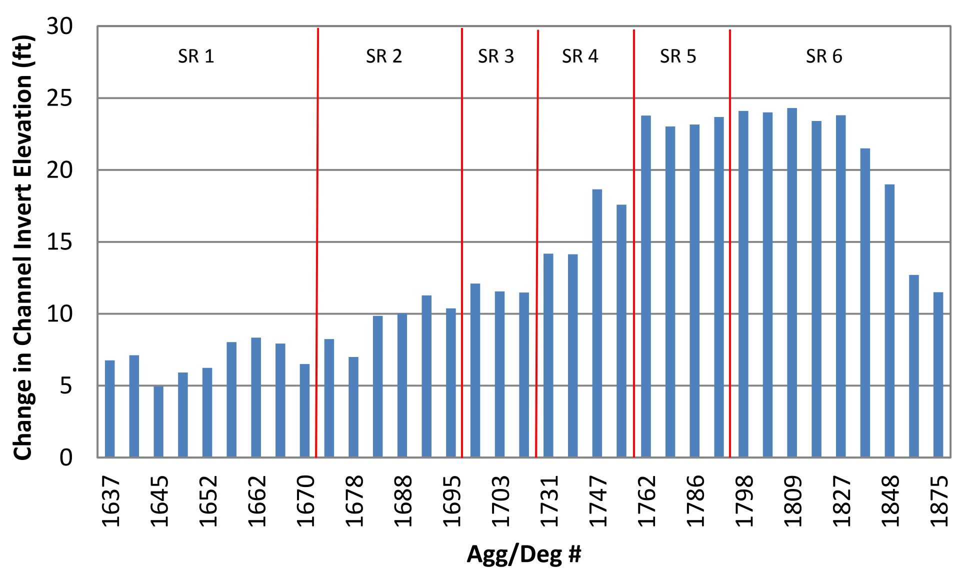

Figure 4.18 Change in Channel Thalweg Elevation from 1962 – 2002 Based on Agg/Deg Surveys

Table 4-5 Average, Maximum and Minimum Change in Channel Thalweg Elevation Based on Agg/Deg Surveys

	Year:	1962 - 1972		1972 - 1992		1992 - 2002		1962 - 2002	
		Δ Thalweg El (ft)	Agg/Deg #	Δ Thalweg El (ft)	Agg/Deg #	Δ Thalweg El (ft)	Agg/Deg #	Δ Thalweg El (ft)	Agg/Deg #
Subreach 1	Max	1.30	1641	7.70	1652	3.14	1673.0	8.34	1662
	Min	-3.10	1670	3.50	1645	0.84	1652.0	4.95	1645
	Average	**-0.67**		**5.73**		**1.85**		**6.93**	
Subreach 2	Max	-1.30	1692	10.60	1695	4.35	1683.0	11.28	1692
	Min	-4.30	1678	7.10	1678	2.58	1695.0	7.00	1678
	Average	**-2.65**		**8.33**		**3.67**		**9.39**	
Subreach 3	Max	-2.40	1707	13.90	1731	4.99	1731.0	14.19	1731
	Min	-4.70	1731	10.20	1707	3.68	1707.0	11.47	1707
	Average	**-3.45**		**11.57**		**4.20**		**12.31**	
Subreach 4	Max	-1.70	1747	14.60	1751	6.36	1747.0	18.66	1747
	Min	-5.50	1733	14.00	1747	5.53	1733.0	14.13	1733
	Average	**-3.53**		**14.07**		**5.88**		**16.39**	
Subreach 5	Max	2.60	1762	16.30	1777	7.92	1777.0	23.78	1762
	Min	-1.20	1777	14.50	1762	6.68	1762.0	23.02	1777
	Average	**0.43**		**15.06**		**7.21**		**22.50**	
Subreach 6	Max	1.40	1820	19.80	1798.00	7.80	1804.0	24.30	1809
	Min	-0.90	1798	16.70	1804	5.20	1798.0	11.50	1875
	Average	**0.26**		**17.68**		**6.53**		**20.01**	
Total Reach	Max	2.60	1762	19.80	1798	7.92	1777.0	24.30	1809
	Min	-5.50	1733	3.50	1645	0.84	1652.0	4.95	1645
	Average	**-1.33**		**11.42**		**4.79**		**15.95**	

From 1962 to 1972 degradation occurred in all subreaches. The upstream half of Subreach 1 aggraded from 1962 to 1972, along with five sections in Subreach 5 and Subreach 6. Since 1972, the channel has been aggrading along all subreaches. From 1962 to 2002, a maximum aggradation of 24.30 feet has occurred at Agg/Deg 1809, at the downstream end of the reach, with a minimum aggradation of 4.95 ft at Agg/Deg 1645, at the upstream end of the reach. From Figure 4.18, it is clear that aggradation increases in the downstream direction. Within Subreach 6, however, there tends to be a decrease in aggradation in the downstream direction. The overall aggradation of the reach is due to the increase in base-level between 1972 and 1985, at which point the base-level changed less than 30 ft between 1985 and 2000. Between 1992 and 2002, aggradation continued in the upstream portions of the reach, still in response to the increase in base-level between 1972 and 1985. However, the downstream portion of Subreach 6 (Agg/Deg 1827 to Agg/Deg 1875) did not aggrade as much as the upstream portion of Subreach 6, because of the drop in base-level of about 80 ft between 2000 and 2002.

Figure 4.19 shows the change in the thalweg elevation at selected Agg/Deg lines from 1962 – 1992. Only Agg/Deg lines with sufficient years of sample data were plotted. It can be inferred from this plot that as the reservoir level increases, the channel thalweg elevation increases at each Agg/Deg line, and that the increase in channel thalweg elevation is more pronounced in the downstream direction, closer to the reservoir.

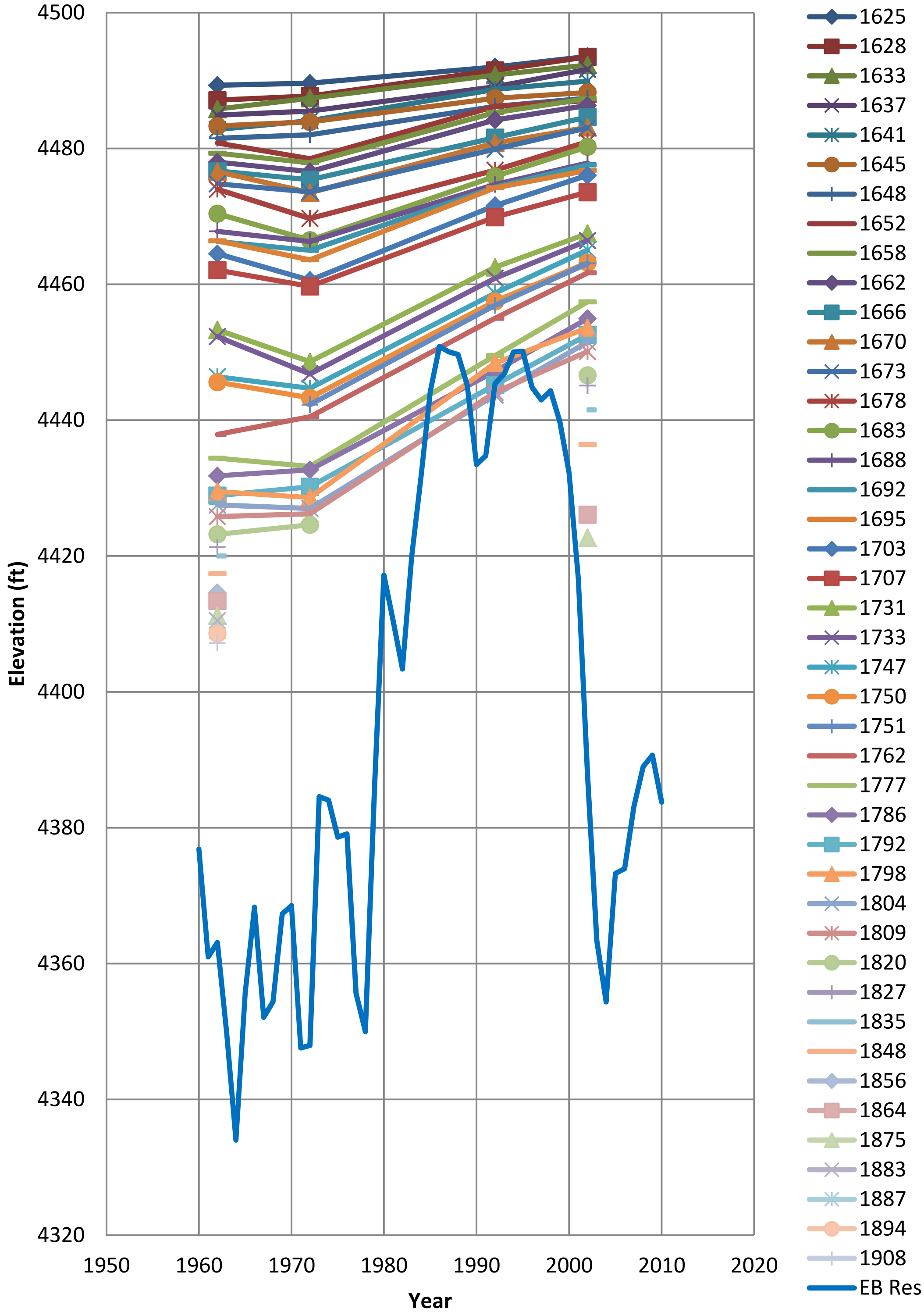

Figure 4.19 Temporal Trend in Thalweg Elevation at Agg/Deg Lines

Figure 4.20 shows the rate of aggradation between 1972 and 1992 at each Agg/Deg line for which there is data. A second order polynomial trendline was fit to the data. For an increase in base-level (Reservoir WSE) of up to 13.4 ft/yr, the following second order polynomial describes the rate of aggradation from 1972 to 1992 for the Elephant Butte Reach:

$$\text{Rate of Aggradation} = -0.0014x^2 + 0.0649x + 0.1832$$

Where, x is the distance in miles downstream of Agg/Deg 1637 (or the upstream end of Elephant Butte Reach).

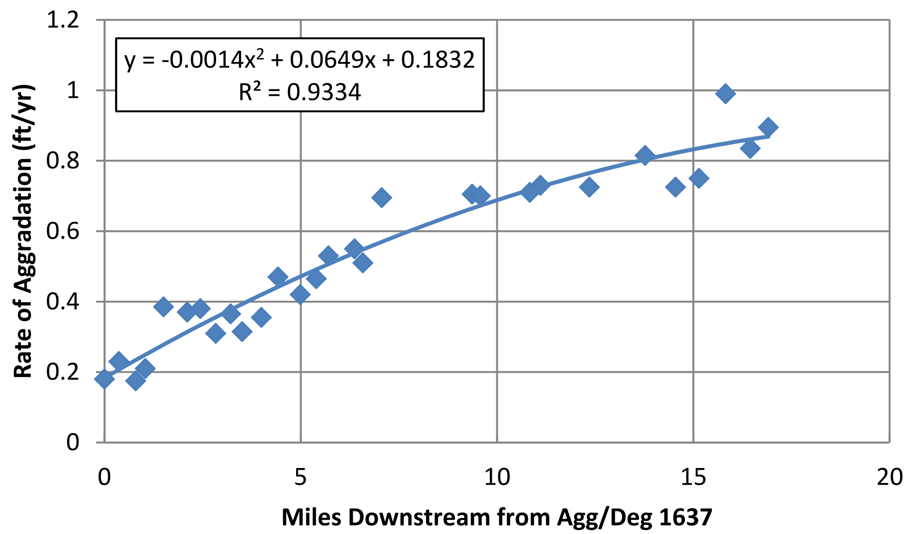

Figure 4.20 Rate of Channel Aggradation between 1972 and 1992

4.3 Aggradation and Degradation from Range Line Surveys

4.3.1 Channel Thalweg Profile from Range Line Surveys

Figure 4.21 shows the thalweg elevation profile of the entire reach. Only years with enough range line survey data were plotted. Not all years are presented, because the lines on the plot would be too dense to see trends if all the years were plotted, so certain years were chosen to represent changes. The thalweg elevation profile shows a general trend of varying aggradation and degradation over time. One of the most notable trends from this plot is the flattening of the channel slope from 2004 to 2009 in the downstream half of the reach, which is due to the aggradation induced by a rise in base-level from 2004 to 2009. Also noteworthy is the significant aggradation in 2005 upstream of EB-10 (Agg/Deg 1707). The Tiffany Plug formed in 2005 at SO-1683 (Agg/Deg 1683), just upstream of EB-10, which can be seen in the profile. In 1995, severe degradation can be seen downstream of SO-1683 (Agg/Deg 1683), and virtually no change at SO-1683, even though a sediment plug had formed upstream of SO-1683 in 1995. This is likely explained by the timing of the survey, which seems to have occurred after the sediment plug was mechanically removed by Reclamation.

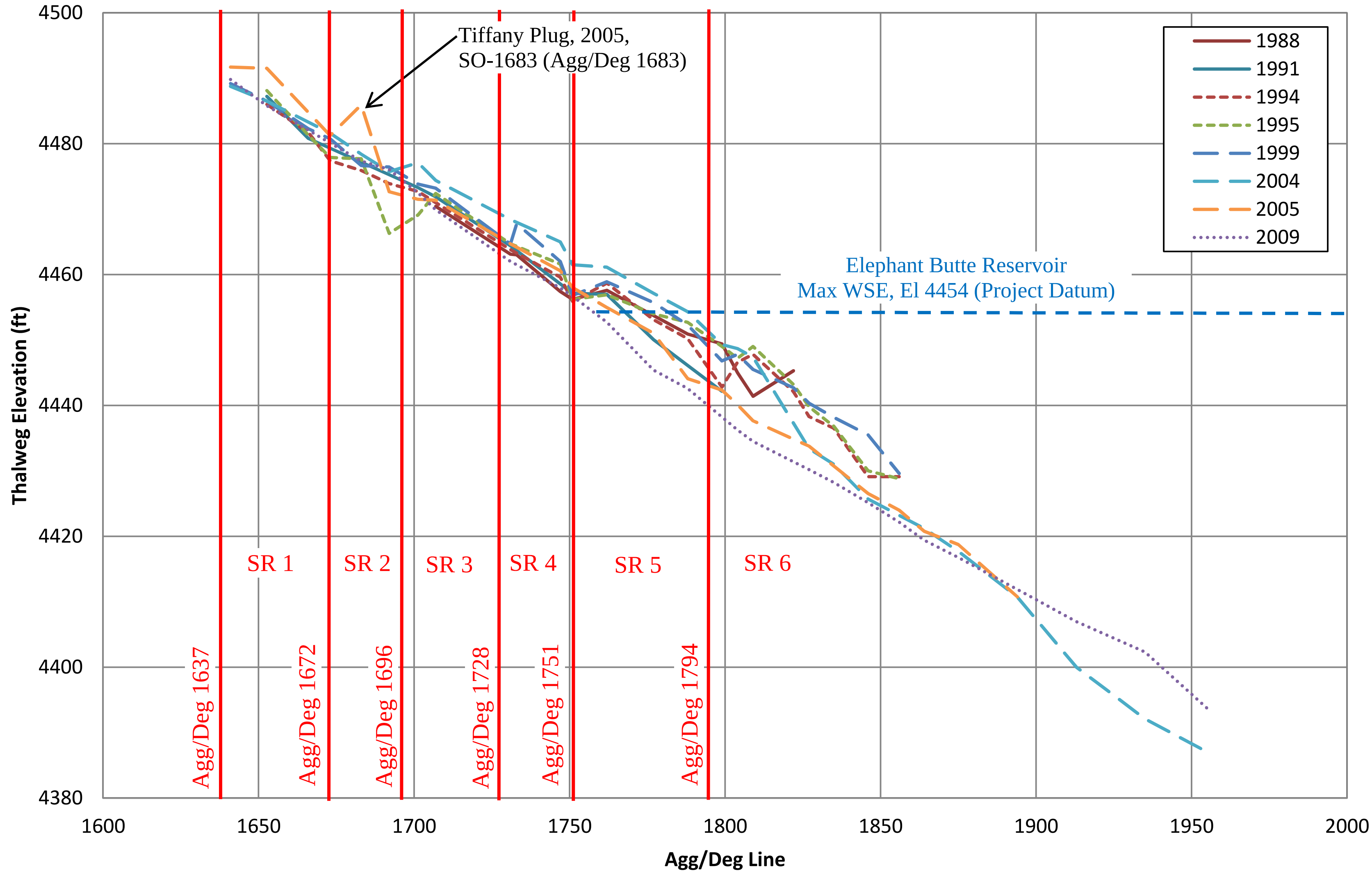

Figure 4.21 Thalweg Elevation Profile From Range Line Survey Data

The channel thalweg profile from the range line survey data was utilized to demonstrate how the minimum elevation and slope of the reach has changed over time. The average bed slope for each subreach was determined by first plotting the thalweg profile versus river mile, and then fitting a linear regression trendline to each subreach. The slope of the linear regression line was considered the average bed slope of the respective subreach. This method was used for all years for which range line survey data was available. The average channel thalweg slopes for each Subreach 1 through Subreach 6 are presented in Figure 4.22 through Figure 4.27, respectively. Table 4-6 presents the values of the average channel thalweg slopes for each subreach.

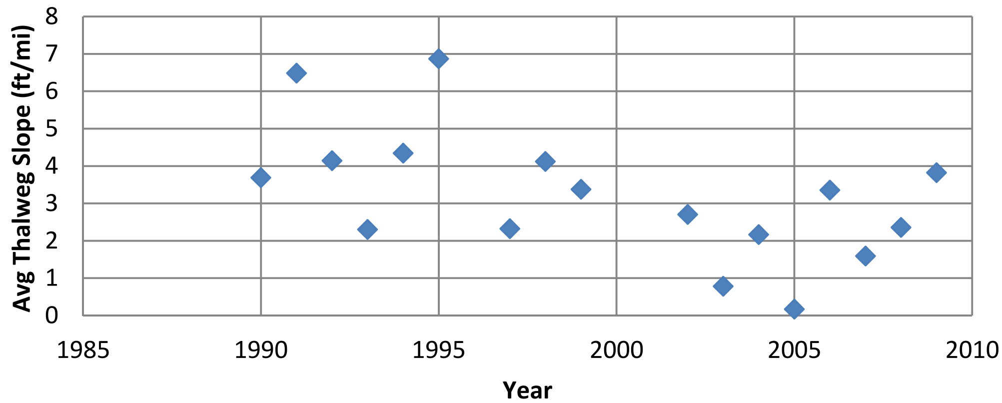

Figure 4.22 Subreach 1 Average Channel Thalweg Slope: Temporal Trend

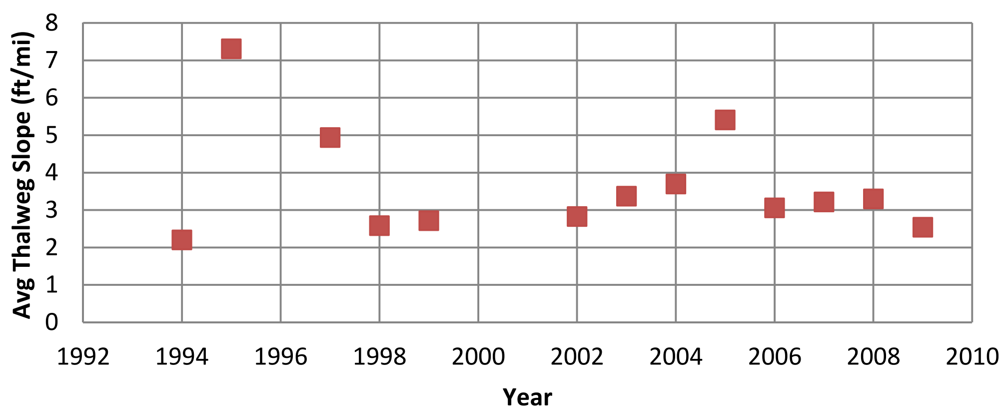

Figure 4.23 Subreach 2 Average Channel Thalweg Slope: Temporal Trend

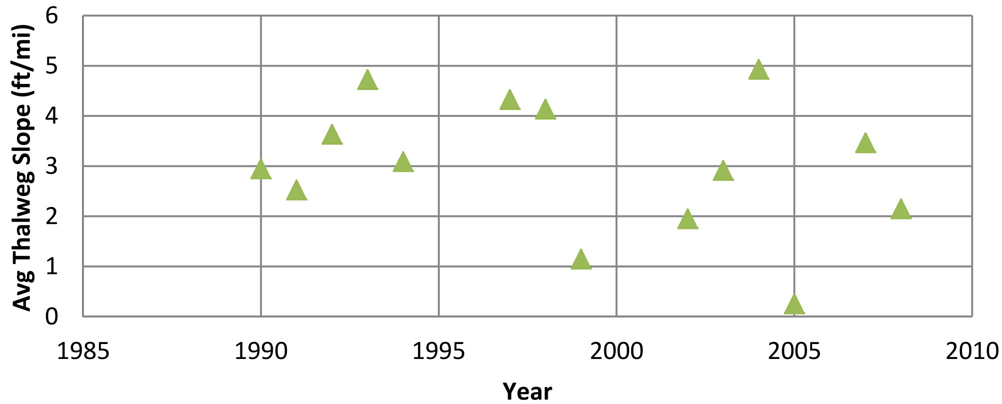

Figure 4.24 Subreach 3 Average Channel Thalweg Slope: Temporal Trend

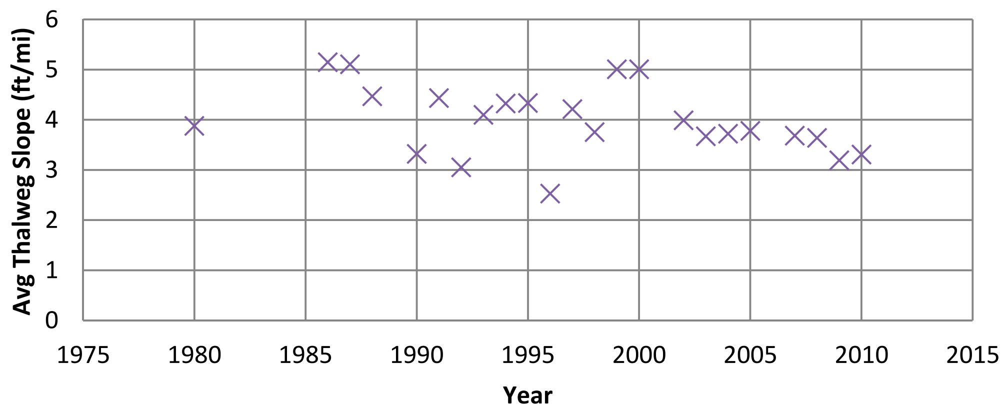

Figure 4.25 Subreach 4 Average Channel Thalweg Slope: Temporal Trend

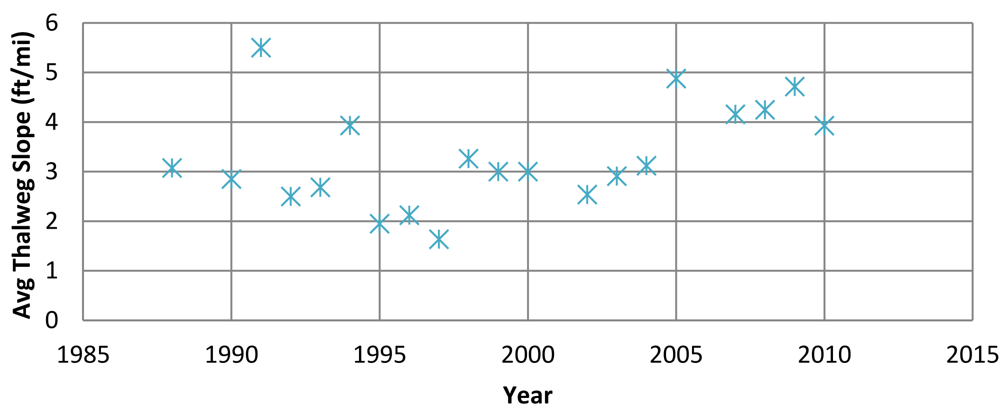

Figure 4.26 Subreach 5 Average Channel Thalweg Slope: Temporal Trend

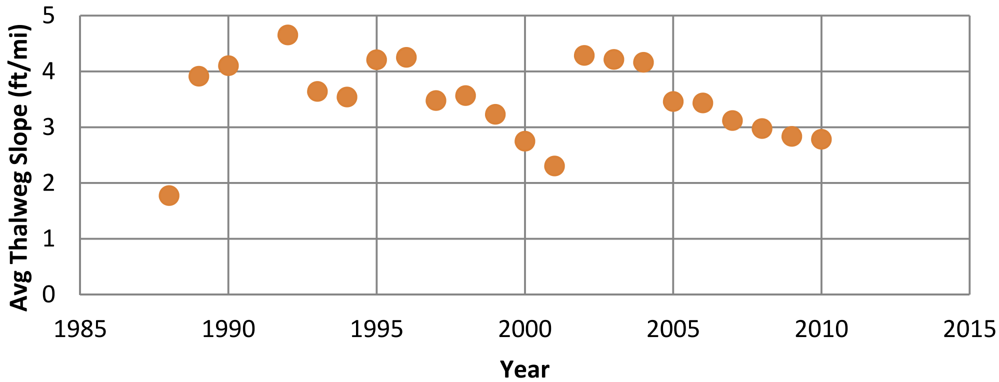

Figure 4.27 Subreach 6 Average Channel Thalweg Slope: Temporal Trend

Table 4-6 Average Channel Thalweg Slopes for Subreaches 1 through 6

Channel Thalweg Slope (ft/mi)						
Year	**SR 1**	**SR 2**	**SR 3**	**SR 4**	**SR 5**	**SR 6**
2010	----	----	----	3.3058	3.9285	2.7865
2009	3.819	2.5421	14.345	3.191	4.7156	2.8378
2008	2.3551	3.2975	2.1491	3.6395	4.2458	2.9771
2007	1.5905	3.215	3.4676	3.6845	4.1554	3.1211
2006	3.3542	3.0568	----	----	----	3.4361
2005	0.1714	5.4088	0.2545	3.7804	4.8768	3.4627
2004	2.1619	3.6974	4.9293	3.7213	3.1183	4.1643
2003	0.7829	3.3695	2.9158	3.6717	2.9102	4.2159
2002	2.7047	2.8284	1.9506	3.99	2.5376	4.2891
2001	----	----	----	----	----	2.3077
2000	----	----	----	5.0078	2.9984	2.7499
1999	3.3741	2.7141	1.147	5.0078	2.9984	3.2324
1998	4.1195	2.5813	4.1364	3.7546	3.2622	3.567
1997	2.3206	4.9367	4.3273	4.2125	1.6368	3.4796
1996	----	----	----	2.5278	2.1193	4.2534
1995	6.8687	7.3103	-6	4.3334	1.949	4.2116
1994	4.3434	2.2019	3.0909	4.3229	3.9316	3.5435
1993	2.303	----	4.7273	4.0989	2.6817	3.6434
1992	4.1414	----	3.6364	3.053	2.5	4.6557
1991	6.4848	----	2.5273	4.4329	5.5	----
1990	3.6869	----	2.9455	3.3211	2.8516	4.1049
1989	----	----	----	----	----	3.9154
1988	----	----	----	4.4677	3.0734	1.7771
1987	----	----	----	5.1043	----	----
1986	----	----	----	5.1482	----	----
1980	----	----	----	3.8767	----	----

Subreaches 1 through 5 don't appear to have a trend relating average channel thalweg slope to time. Subreach 6, however, has a decreasing trend from 1995 to 2001 and again from 2002 to 2010. From 1995 to 2001, the channel slope decreases at a rate of 0.32 ft/mi/yr; from 2002 to 2010, the channel slope decreases at a rate of 0.21 ft/mi/yr. From 1995 to 2001, the base-level drops about 35 ft, while Subreach 6's slope decreases. From 2001-2004, the base-level drops another 60 ft, and from 2004 to 2009, the base-level increases about 35 ft, all while the channel slope decreases. Therefore, the channel slope is not dependent on the base-level changes within the same time-frame. Rather, the channel slope decrease from 1995 to 2001 is due to the increase in base-level from 1982 to 1986, or from the increase in base-level from 1990 to 1995. And, the channel slope decrease from 2001 to 2010 is due to the increase in base-level from 2004 to 2009. The sudden jump in channel slope from 2.3 ft/mile, in 2001, to 4.3 ft/mile, in 2002, is likely a result of the decrease in base-level between 1995 and 2004, during which the base-level dropped by about 100 ft.

Cross-sections were plotted at select range lines for all years of available data and are presented in Appendix F. Figure 4.28 through Figure 4.36 show representative cross-sections of Elephant Butte Reach. SO-1683, Figure 4.29, is located in Subreach 2. From 2004 to 2005 the channel aggraded by about 8 ft and then degraded by about 8 ft from 2005 to 2006. This is the location of the Tiffany Sediment Plug in 2005. The sediment plug was removed by excavating a pilot channel, which accounts for the decrease in bed elevation from 2005 to 2006. EB-41, Figure 4.36, is located in Subreach 6. When the reservoir was full from 1985 to 2000, this range line was inundated by the reservoir, which is why there is only data available beginning in 2004.

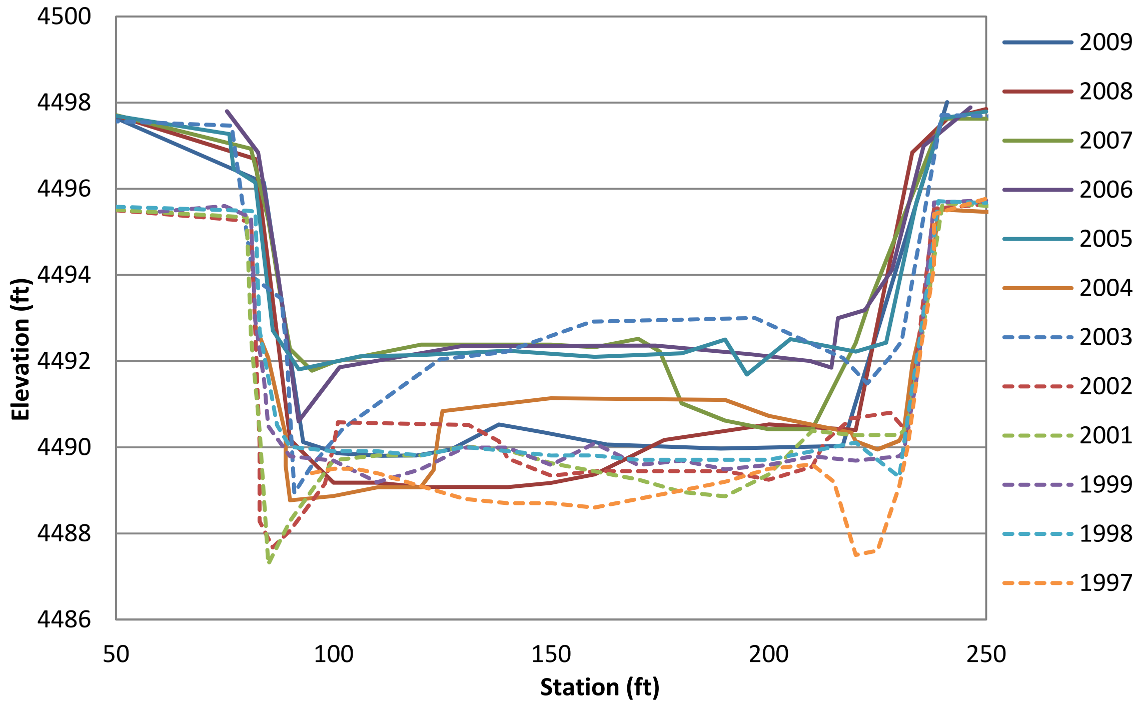

Figure 4.28 Subreach 1: SO-1641 Surveyed Cross-Sections

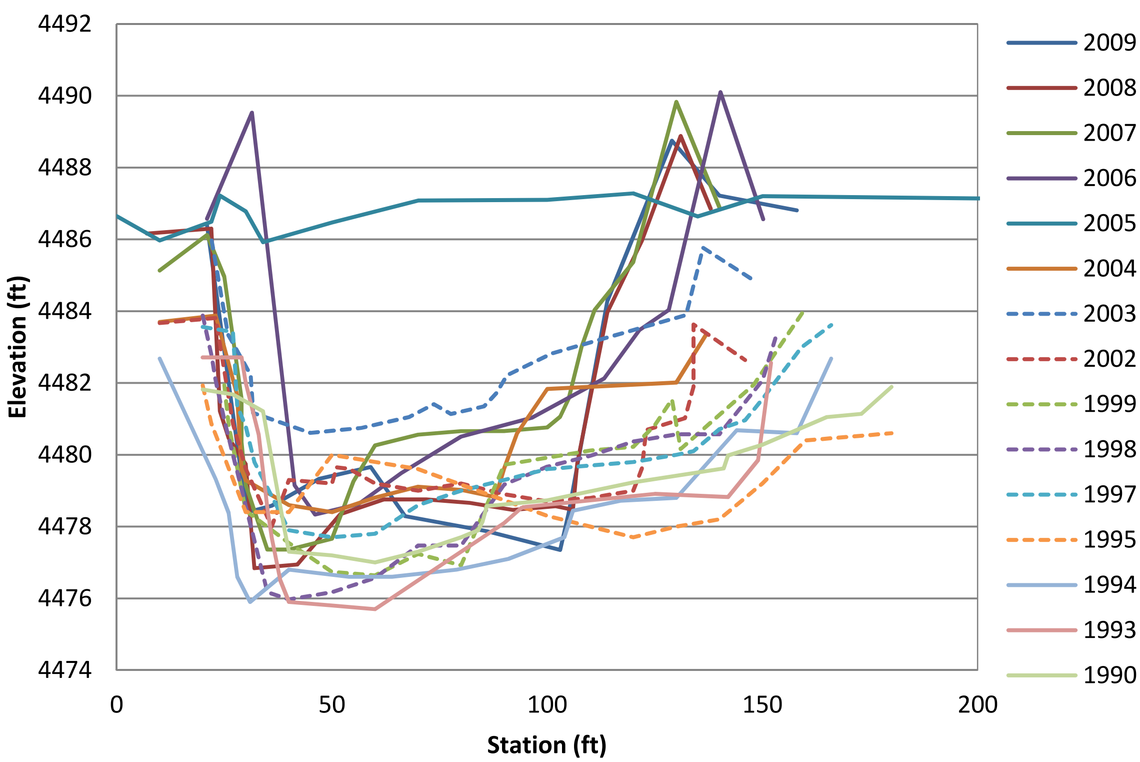

Figure 4.29 Subreach 2: SO-1683 Surveyed Cross-Sections

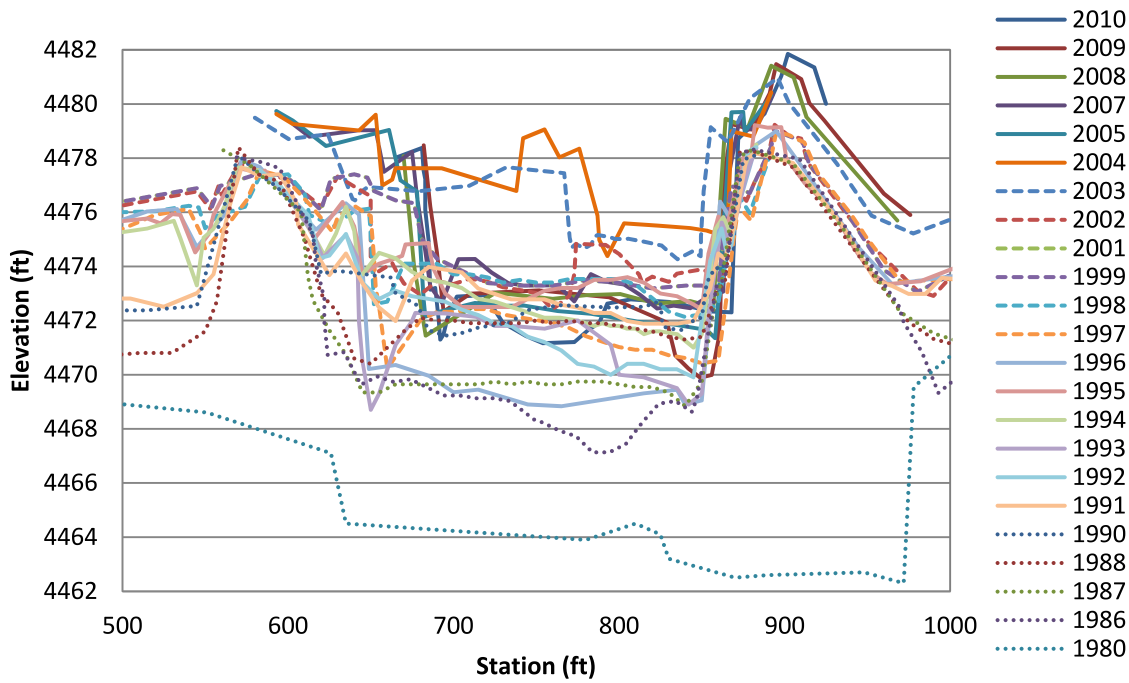

Figure 4.30 Subreach 3: EB-10 Surveyed Cross-Sections

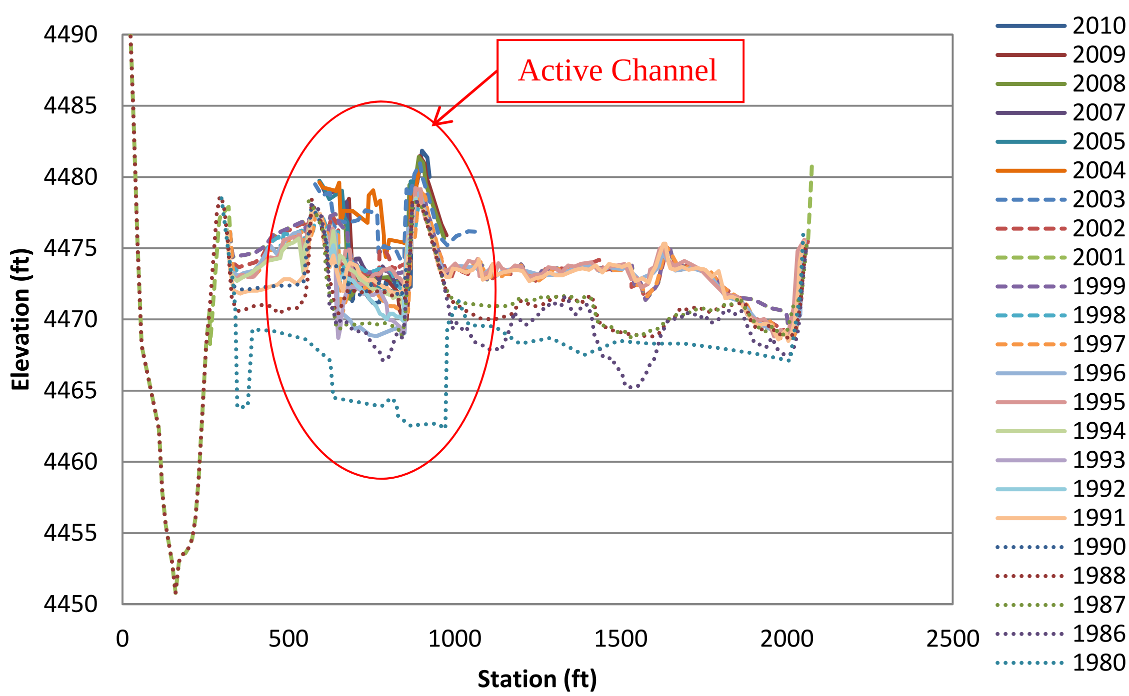

Figure 4.31 Subreach 3: EB-10 (w/Floodplain) Surveyed Cross-Sections

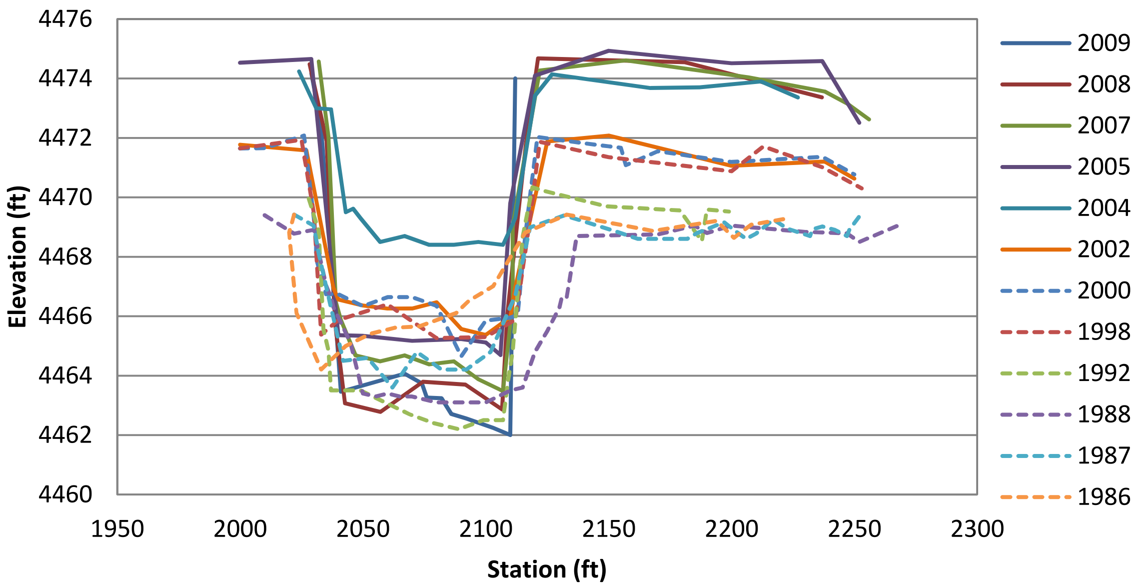

Figure 4.32 Subreach 4: EB-13 Surveyed Cross-Sections

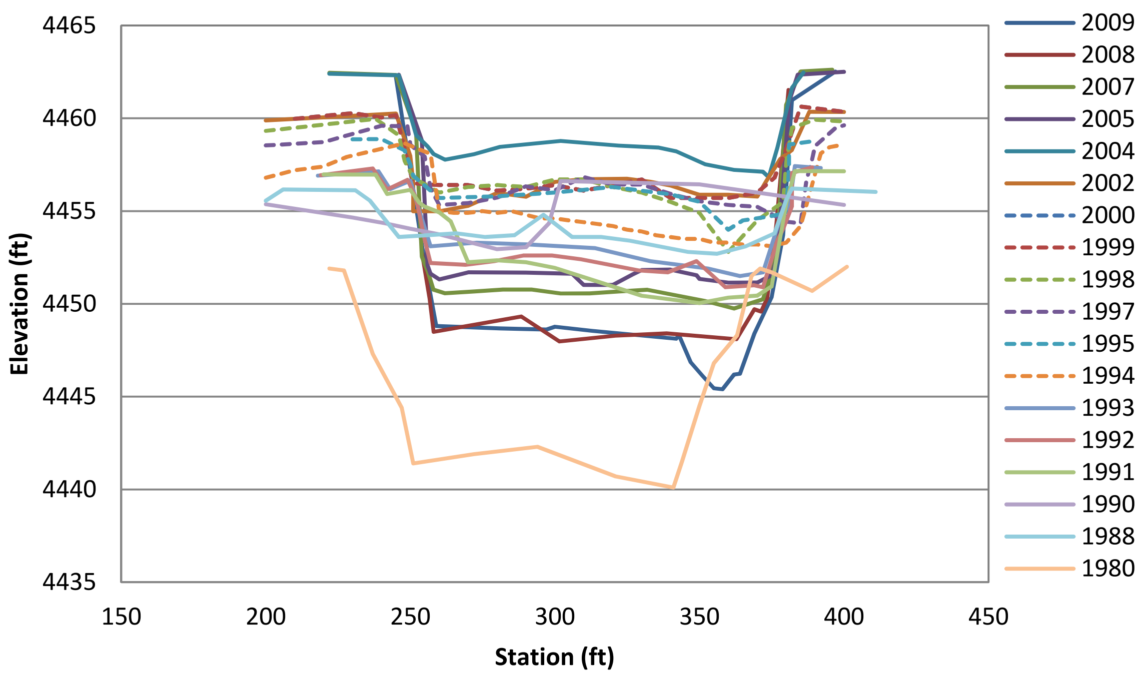

Figure 4.33 Subreach 5: EB-20 Surveyed Cross-Sections

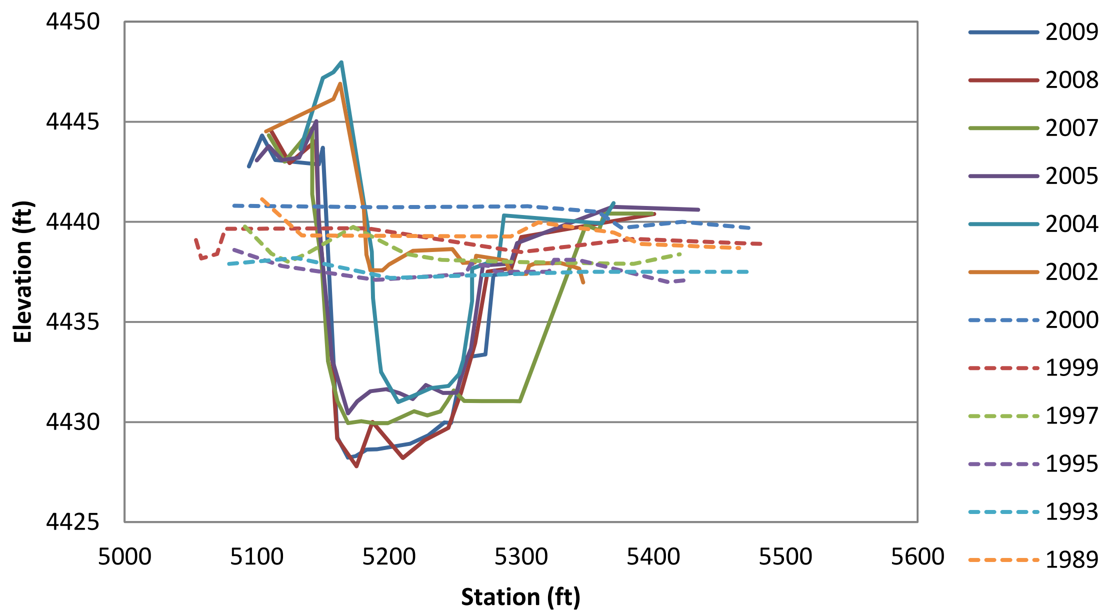

Figure 4.34 Subreach 6: EB-29 Surveyed Cross-Sections

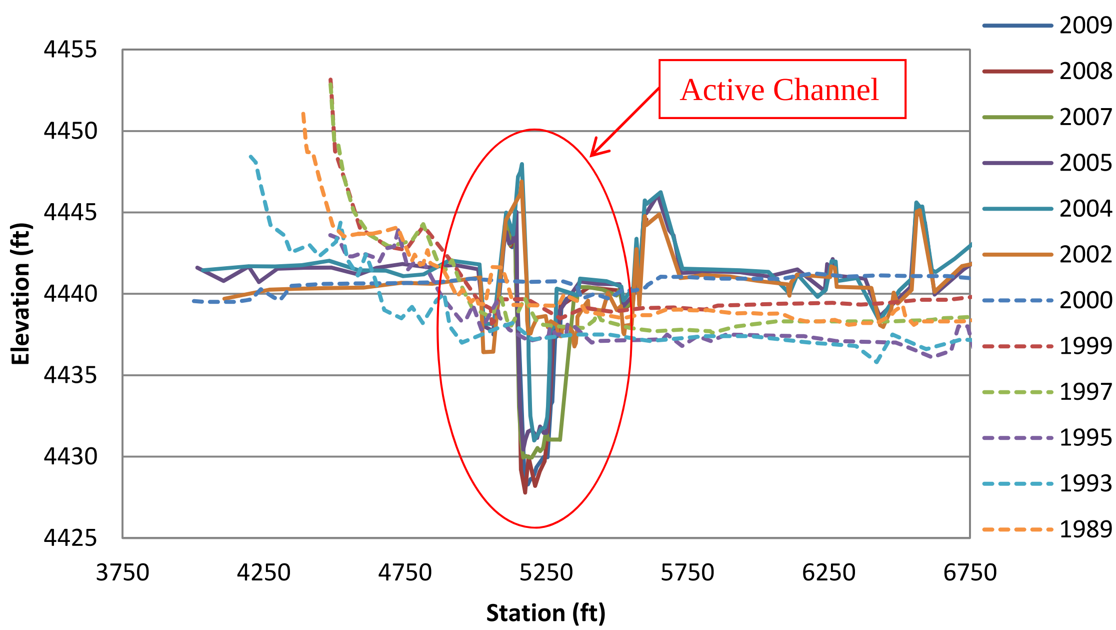

Figure 4.35 Subreach 6: EB-29 (w/Floodplain) Surveyed Cross-Sections

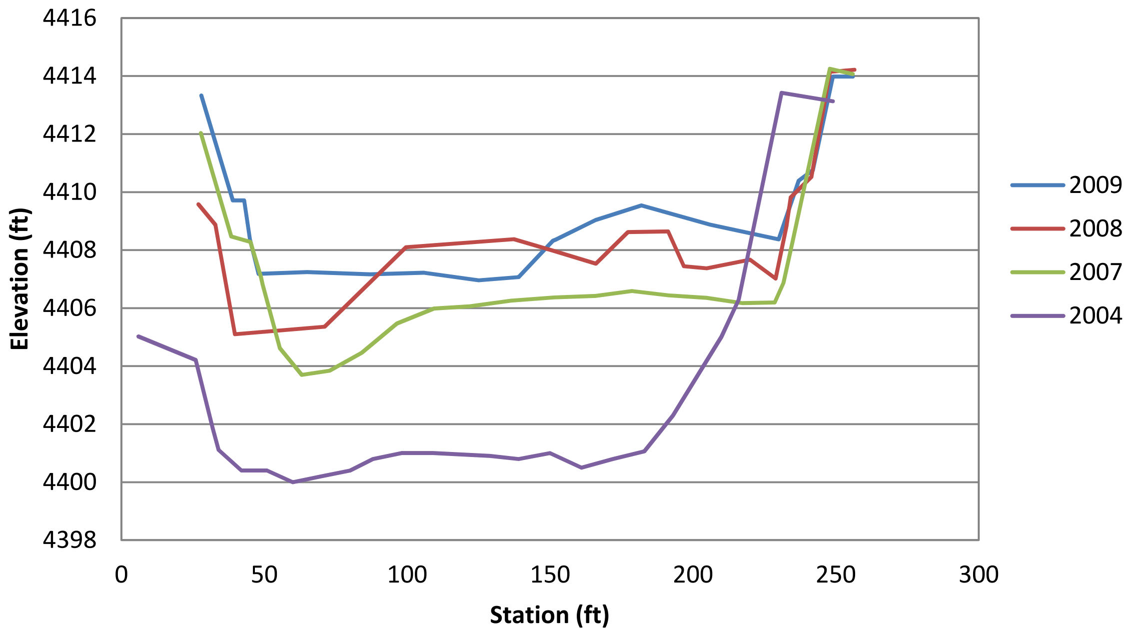

Figure 4.36 Subreach 6: EB-41 Surveyed Cross-Sections

4.3.2 Change in Thalweg and Average Bed Elevation from Range Line Surveys

As seen in Figure 4.28 through Figure 4.36 aggradation and degradation occur across the entire channel bed, not just the thalweg. Therefore, the following analyses focus on the change in thalweg elevation temporally and spatially. Figure 4.37 shows the change in the thalweg elevation at selected range lines from 1980-2010. Only range lines with sufficient years of sample data were plotted.

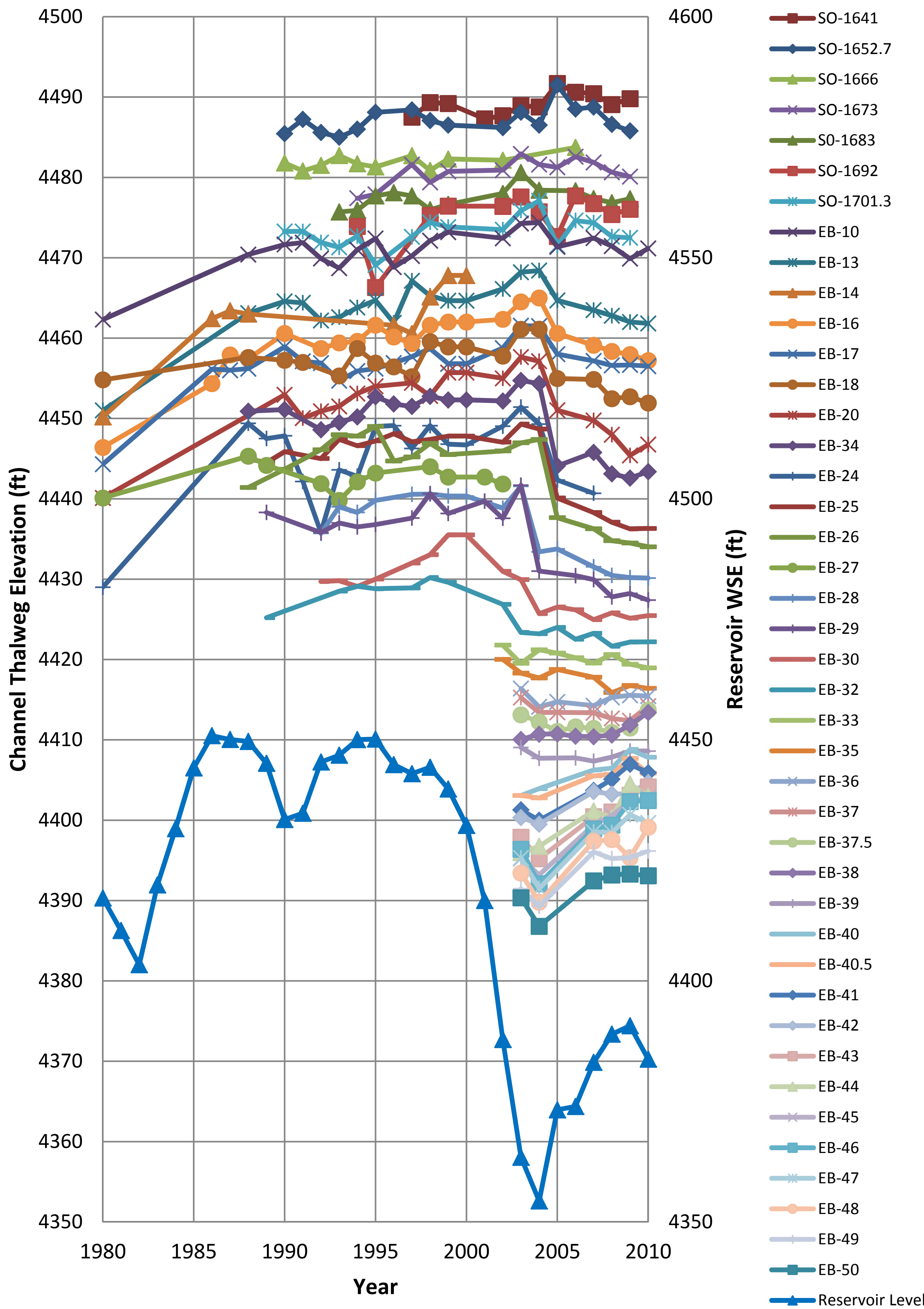

Figure 4.37 Change in Thalweg Elevation at Range Lines (1980 – 2010)

From 1980 to 1988, aggradation occurred at all range lines for which there is data. From 1988 to 1994, the thalweg elevation alternated between increasing and decreasing elevation, typically changing no more than 3 ft in either direction. From 1994 to 1995, mostly aggradation occurs, up to 6.2 ft, near the upstream reservoir extent; degradation occurs just downstream of the 1995 Tiffany Sediment Plug at SO-1692 and SO-1701.3, 7.6 ft and 3.6 ft, respectively. From 1995 to 2002, the change in channel thalweg elevation varies between aggradation and degradation. From 2002 to 2003, aggradation occurs from SO-1641 to EB-29, ranging between 1 ft and 4 ft; degradation occurs downstream of EB-29, up to 3.5 ft. From 2003 to 2004, the channel degraded from SO-1641 to SO-1692, and from EB-20 to EB-50 by up to 10.7 ft; the channel aggraded from SO-1701.3 to EB-18 by up to 1 ft. From 2004 to 2007, aggradation occurred from SO-1641 to SO-1692, up to 2.3 ft, and from EB-40 to EB-50, up to 7.6 ft; degradation occurred from SO-1701.3 to EB-39, up to 11 ft. From 2007 to 2008, degradation occurred from SO-1641 to EB-37.5, up to 2.7 ft; aggradation occurred from EB-38 to EB-50, up to 1.4 ft. From 2008 to 2009, the channel degraded from SO-1641 to EB-37, up to 2.6 ft; the channel aggraded from EB-37.5 to EB-50, up to 4.2 ft. From 2009 to 2010, the channel varied between aggradation and degradation, ranging between -1.8 ft and 2.2 ft in elevation change.

A few notable changes occurred at EB-24. From 1990 to 1992 the thalweg elevation decreased by about 12 ft, from 1992 to 1993 the thalweg elevation increased by about 7.8 ft, and from 1994 to 1995, the thalweg elevation increased another 6.2 ft. These changes are in direct response to the change in reservoir WSE, as the shape of the thalweg elevation over time mimics the shape of the change in WSE over time, as seen in Figure 4.37.

Table 4-7 shows the calculated values of change in thalweg elevation between selected year sets at each range line for which there is data. The table is color-coded such that cells highlighted with light red fill indicate degradation between the year set, while cells highlighted with light green fill indicate aggradation, or in the case of the reservoir level change, the colors indicate a drop in level and rise in level, respectively. A Cell highlighted with blue fill and white text, or a cell under the area of the pink outline, indicates the cross-section was inundated by the reservoir during the latter of the two years associated with the year set. If the text within a cell reads "----", then data was not available at that range line during at least one of the two years associated with the year set. A cell within the area of a red outline indicates the cell is associated with a "wave" of degradation, while a cell within the area of a green outline indicates the cell is associated with a "wave" of aggradation. If a cell is between the area of a red and green outline, then the cell is considered a transitional area.

Four "waves" were analyzed from this dataset. The first wave is a wave of degradation and is the result of a decrease in average reservoir level (base-level) from 2009 to 2010 of about 7 ft. The second wave is a wave of aggradation and is the result of an increase in average base-level from 2004 to 2009 of about 35 ft. The third wave is a wave of degradation and is the result of a decrease in average base-level from 1995 to 2004 of about 105 ft. The fourth and final wave analyzed, is a wave of aggradation and is the result of an increase in average base-level from 1990 to 1995. No other waves were analyzed in detail, due to the lack of available data between 1980 and 1990.

Table 4-7 Change in Thalweg Elevation Between Select Year Sets

	2009-2010	2008-2009	2007-2008	2004-2007	2003-2004	2002-2003	1999-2002	1998-1999	1997-1998	1995-1997	1994-1995	1993-1994	1992-1993	1991-1992	1990-1991	1990-1992	1988-1990	1980-1988
SO-1641	----	0.73	-1.35	1.65	-0.17	1.26	-1.52	-0.12	1.81	----	----	----	----	----	----	----	----	----
SO-1652.7	----	-0.81	-2.15	2.25	-1.62	1.92	-0.30	-0.57	-1.33	0.30	2.10	1.00	-0.60	-1.62	1.77	0.15	----	----
SO-1666	----	----	----	----	----	----	-0.16	1.43	-1.84	1.40	-0.40	-1.02	1.22	0.70	-1.00	-0.30	----	----
SO-1673	----	-0.55	-1.22	0.26	-1.32	2.02	0.15	1.37	-2.22	3.70	0.50	----	----	----	----	----	----	----
SO-1683	----	0.51	-0.52	-1.04	-2.21	2.61	1.36	0.67	-1.73	0.00	1.80	0.20	----	----	----	----	----	----
SO-1692	----	0.66	-1.35	1.02	-1.84	1.16	-0.03	1.16	----	----	-7.60	----	----	----	----	----	----	----
SO-1701.3	----	-0.15	-1.72	-2.74	1.22	2.38	-0.33	-0.58	1.80	3.50	-3.60	1.40	-0.60	-1.37	0.00	-1.37	----	----
EB-10	1.27	-1.56	-0.99	-1.94	0.12	1.85	-0.77	1.06	1.91	-2.18	1.40	2.30	-1.20	-1.98	0.23	-1.75	1.25	8.10
EB-13	-0.18	-0.78	-0.70	-4.92	0.20	2.09	1.46	-0.61	-1.87	2.43	0.90	1.20	0.40	-2.19	-0.18	-2.37	1.47	12.10
EB-14	----	----	----	----	----	----	----	2.68	4.54	----	----	----	----	----	----	----	----	12.80
EB-16	-0.75	-0.39	-0.76	-5.89	0.49	2.17	0.34	0.40	2.28	-2.28	2.00	0.20	0.70	----	----	-1.88	3.18	11.00
EB-17	-0.15	0.06	-0.56	-4.33	-0.06	2.79	1.96	-1.90	1.01	1.49	0.30	1.20	-2.20	-0.22	-1.78	-2.00	2.70	11.90
EB-18	-0.79	0.25	-2.39	-6.27	0.02	3.35	-1.15	-0.67	4.37	-1.70	-1.80	3.40	----	----	-0.27	----	-0.36	2.80
EB-20	1.35	-2.58	-1.77	-7.37	-0.52	2.65	-0.71	2.90	-1.63	0.43	0.90	1.60	0.60	0.86	-2.91	-2.05	----	----
EB-34	0.80	-0.53	-2.66	-8.56	-0.40	2.56	-0.13	-0.45	1.26	-1.21	2.50	0.70	0.90	----	----	-2.50	0.20	----
EB-24	----	----	----	-8.62	-2.11	2.38	2.23	-2.30	2.84	-2.74	6.20	-0.80	7.80	-6.36	-5.68	-12.04	-1.56	20.40
EB-25	0.05	-0.83	-1.20	-10.40	-0.62	2.26	-0.76	0.40	0.30	-0.10	0.60	-0.80	2.40	----	----	-0.86	0.86	----
EB-26	-0.47	-0.29	-1.48	-11.13	0.44	1.01	0.45	-1.40	1.70	-3.80	1.20	-0.17	1.87	----	----	2.43	2.27	----
EB-27	----	----	----	----	----	----	-0.86	-1.30	----	----	1.10	2.30	-2.10	----	----	----	----	5.20
EB-28	-0.06	-0.27	-1.07	-1.86	-8.15	2.72	-1.51	-0.26	0.05	0.75	1.50	-0.70	3.30	----	----	----	----	----
EB-29	-0.83	0.43	-2.15	-1.06	-10.69	4.12	-0.60	-2.47	3.04	0.80	0.30	-0.50	1.20	----	----	----	----	----
EB-30	0.32	-0.66	0.85	-0.75	-4.24	-1.03	-4.53	2.47	1.03	2.00	0.90	-0.70	0.10	----	----	----	----	----

Table 4-7 Change in Thalweg Elevation Between Select Years (Part 2)

	2009-2010	2008-2009	2007-2008	2004-2007	2003-2004	2002-2003	1999-2002	1998-1999	1997-1998	1995-1997	1994-1995	1993-1994	1992-1993	1991-1992	1990-1991	1990-1992	1988-1990	1980-1988
EB-32	0.02	0.53	-1.62	0.06	-0.17	-3.49	-2.74	-0.60	1.30	0.10	-0.30	0.60	----	----	----	----	----	----
EB-33	-0.46	-1.21	1.07	-1.65	1.69	-2.27	----	----	----	----	----	----	----	----	----	----	----	----
EB-35	-0.36	0.88	-1.91	0.09	-0.60	-1.71	----	----	----	----	----	----	----	----	----	----	----	----
EB-36	-0.10	0.26	1.03	0.15	-2.28	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-37	1.80	-0.28	-0.71	-0.03	-1.86	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-37.5	2.22	0.53	-0.49	-0.80	-0.89	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-38	1.54	1.27	0.20	-0.30	0.65	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-39	0.00	0.74	0.52	-0.36	-1.36	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-40	-0.98	2.31	0.25	2.32	0.85	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-40.5	-1.84	1.98	0.17	2.75	-0.30	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-41	-1.05	1.86	1.40	3.70	-1.29	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-42	1.42	0.05	-0.32	4.06	-0.83	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-43	1.04	2.06	0.60	5.24	-2.68	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-44	-1.54	4.22	-0.86	4.41	0.79	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-45	0.48	1.75	1.18	6.20	-2.02	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-46	0.13	2.93	0.46	6.83	-4.28	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-47	-1.02	2.23	-0.06	7.01	-3.80	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-48	3.79	-2.25	0.19	7.59	-3.62	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-49	0.82	0.12	-0.82	6.74	-2.17	----	----	----	----	----	----	----	----	----	----	----	----	----
EB-50	-0.21	0.11	0.74	5.65	-3.55	----	----	----	----	----	----	----	----	----	----	----	----	----
Res	-6.91	1.73	5.85	28.75	-9.07	-24.43	-51.95	-4.51	1.33	-7.17	0.12	3.23	1.41	10.64	1.29	11.94	-16.20	32.49

The change in thalweg and mean channel bed elevation were evaluated using the range line survey data. First, the minimum channel elevation (thalweg) was calculated for each range line at different surveyed years. Then, the change in Thalweg elevation was compared between years at each range line where data was available. A second, similar analysis was done by calculating the change in the average channel bed elevations for which a weighted average was used to calculate the mean bed elevation for each range line at different surveyed years.

Because data was not available each year for every range line, different ranges of years had to be used to calculate the change in elevation. This is indicated by the different colors of bars in Figure 4.38 for the change in average bed elevation analysis, and Figure 4.39 for the change in thalweg elevation analysis. The orange bars show a change in elevation for range lines between 1988 and 1990; the turquoise bars show a change in elevation between 1990 and 1995; the purple bars show a change in elevation from 1995 to 2003; the green bars show a change in elevation between 2003 and 2004; and the red bars show a change in elevation from 2004 to 2009; and blue bars show a change in elevation from 2009 to 2010. Note that each set of bars has a different time increment; this is because the selected years contain data for most of the range lines, and the year sets represent an overall aggrading or degrading trend.

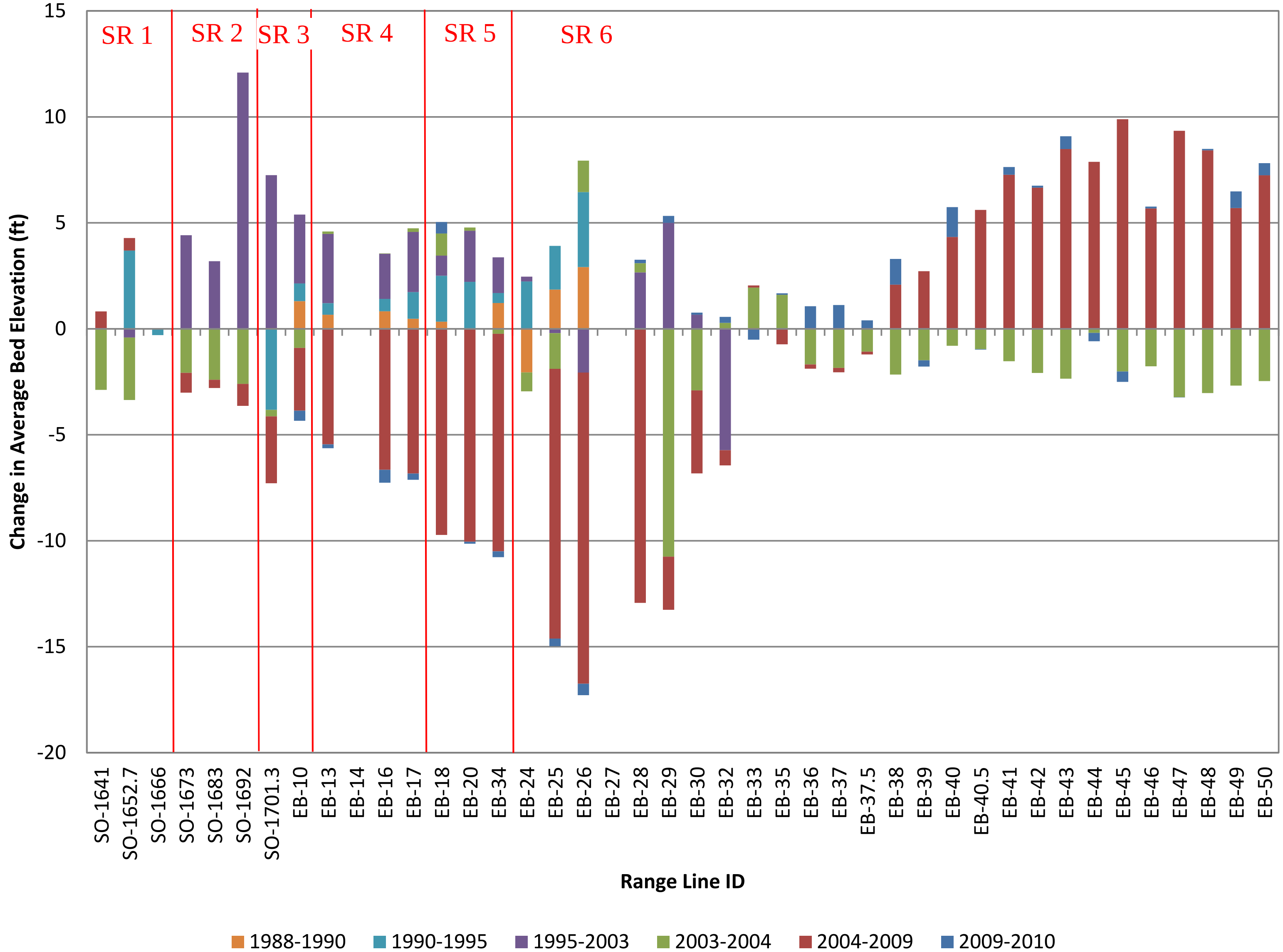

Figure 4.38 Change in Average Channel Bed Elevation at Range Lines (1988-2010)

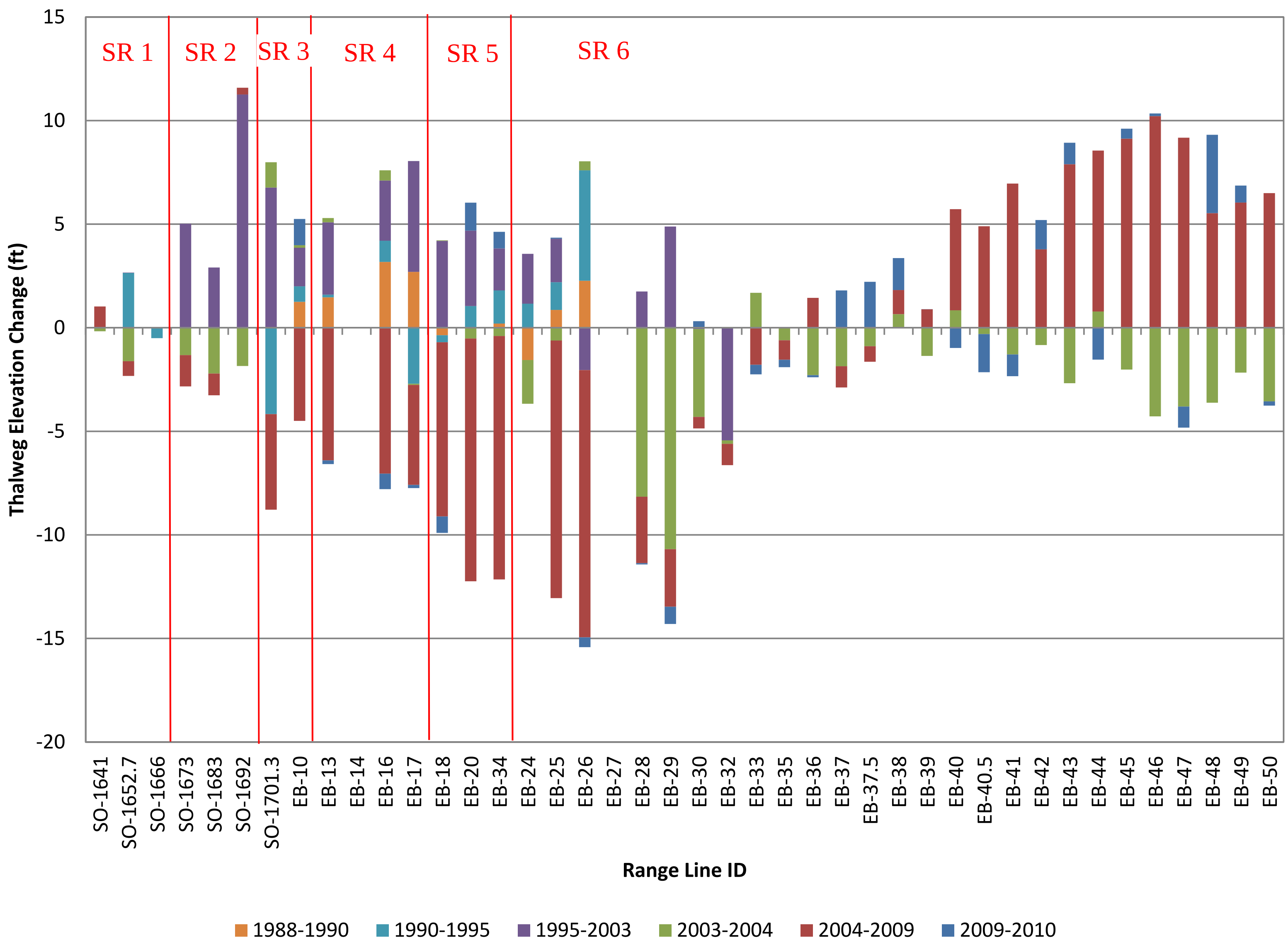

Figure 4.39 Change in Channel Thalweg Elevations at Range Lines (1988-2010)

The following observations are based specifically on the change in thalweg elevation; however, the general trends observed are similar for the change in average bed elevation. From 1988 to 1990, primarily aggradation occurred, up to 3.2 ft. From 1990 to 1995, which includes the first instances in which the Tiffany Plug formed, there is aggradation and degradation observed, depending on the range line; there does not appear to be a hinge point spatially separating aggradation and degradation. From 1995 to 2003, after the second Tiffany Plug, there is mostly aggradation between SO-1673 and EB-29, up to 11.3 ft. From 2003 to 2004, there is degradation the majority of the reach, up to 10.7 ft. From 2004 to 2009, degradation is observed from SO-1652.7 to EB-37.5, at which point aggradation is observed from EB-38 to EB-50. From 2009 to 2010, the channel alternates between aggradation and degradation along the reach profile, with the greatest magnitude of aggradation, 3.8 ft, occurring at EB-48.

4.3.3 Rate of Aggradation/Degradation from Range Line Surveys

From 2003 to 2004, shown in Figure 4.40 and Figure 4.41, degradation is observed along the entire reach, except for at five range lines. The wave of degradation between EB-13 and EB-50 (Wave 3) is in response to the drop in base-level (Reservoir WSE) by about 100 ft between 1995 and 2004. Figure 4.41 shows the magnitude of degradation from 2003 to 2004 at River Miles, which is represented by the following second order polynomial equation:

$$y = -0.1601x^2 + 16.209x - 410.5$$

Where, y is the magnitude of degradation and x is the longitudinal location along the reach in River Miles (RM, as defined by Reclamation, where measurements begin at the downstream end of the Middle Rio Grande River); this equation is appropriate for RM 45.21 to RM 57.75.

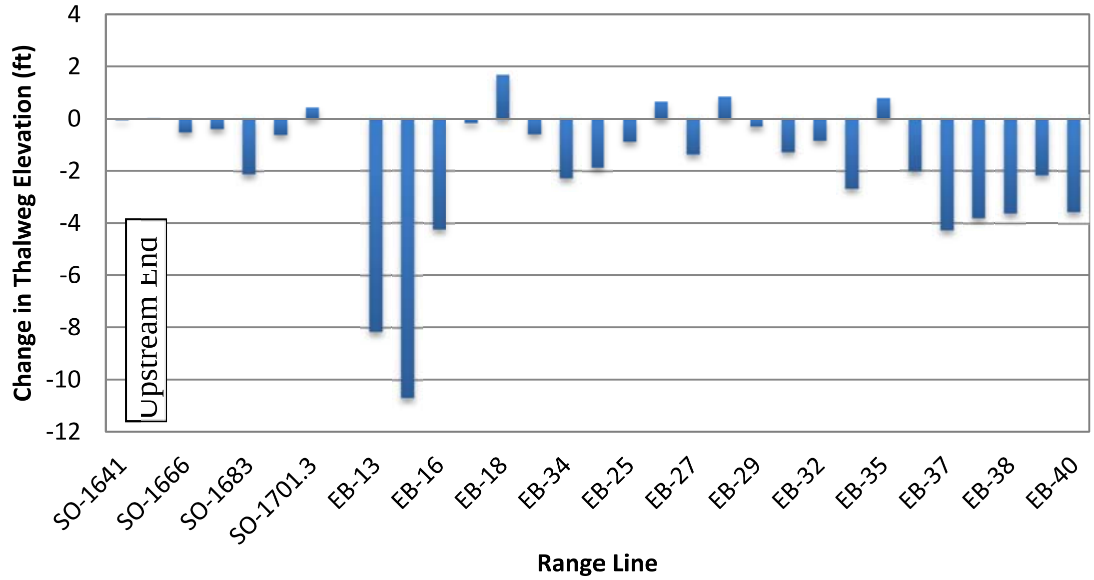

Figure 4.40 Magnitude of Aggradation and Degradation at Range Lines (2003-2004)

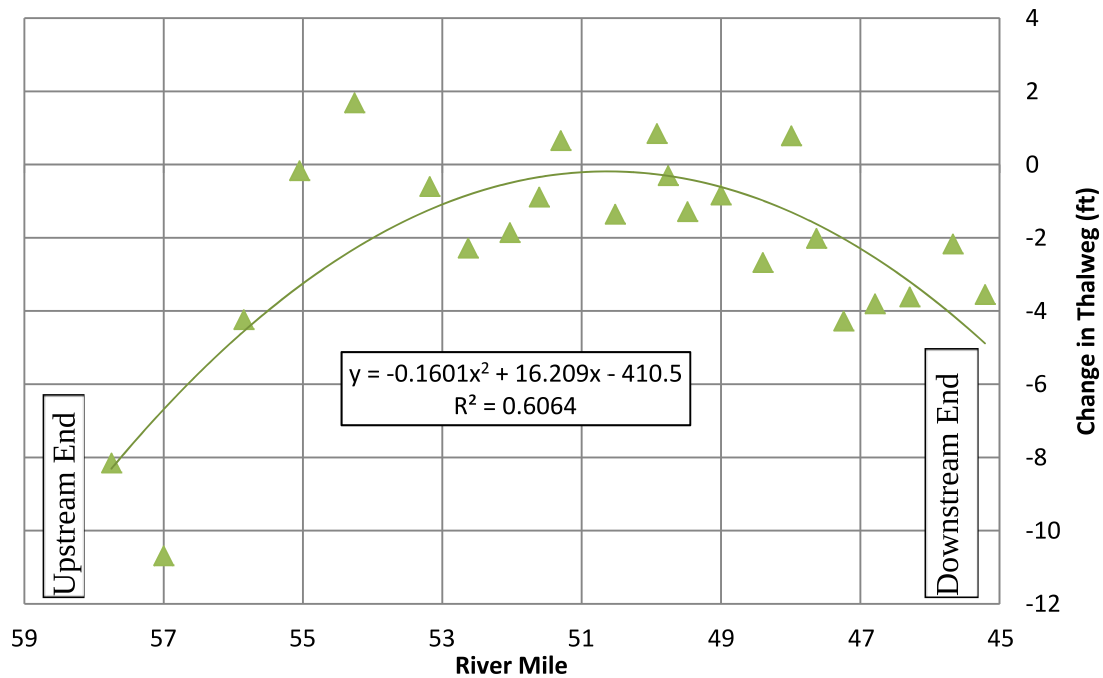

Figure 4.41 Magnitude of Aggradation and Degradation at River Miles (2003-2004)

From 2004 to 2005, all of the thalweg elevations decreased between SO-line 1683 and EB-26; the decrease becomes more pronounced in the downstream direction between these range lines, as seen in Figure 4.42 and Figure 4.43. From 2004 to 2005, SO-lines 1641, 1652.7, and 1683 increased. The wave of degradation between SO-1683 and EB-26 (Wave 3) is in response to the drop in base-level (Reservoir WSE) by about 100 ft between 1995 and 2004. Figure 4.42 shows the magnitude of degradation from 2004 to 2005 at River Miles, which is represented by the following linear equation:

$$y = 0.8233x - 58.29$$

Where, y is the magnitude of degradation and x is the longitudinal location along the reach in River Miles; this equation is appropriate for RM 59.34 to RM 73.59.

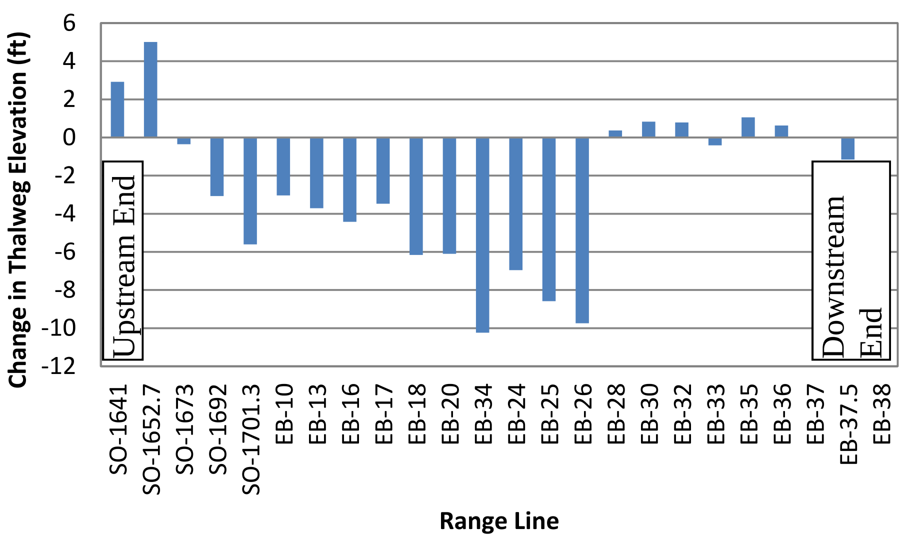

Figure 4.42 Magnitude of Aggradation and Degradation at Range Lines (2004-2005)

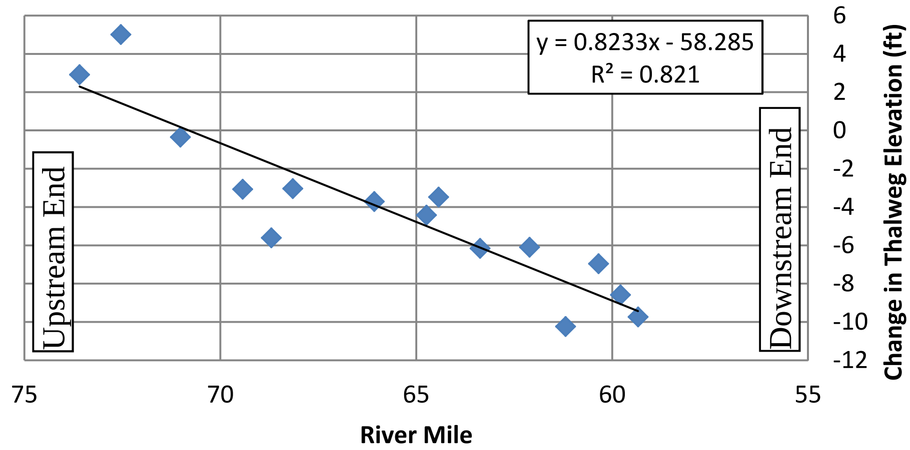

Figure 4.43 Magnitude of Aggradation and Degradation at River Miles (2004 to 2005)

From 2004 to 2009, shown in Figure 4.44, degradation is observed from SO-1652.7 to EB-37.5, at which point aggradation is observed from EB-38 to EB-50. These two trends represent two distinct waves of thalweg elevation changes in response to base-level changes, Wave 3 and Wave 2, respectively.

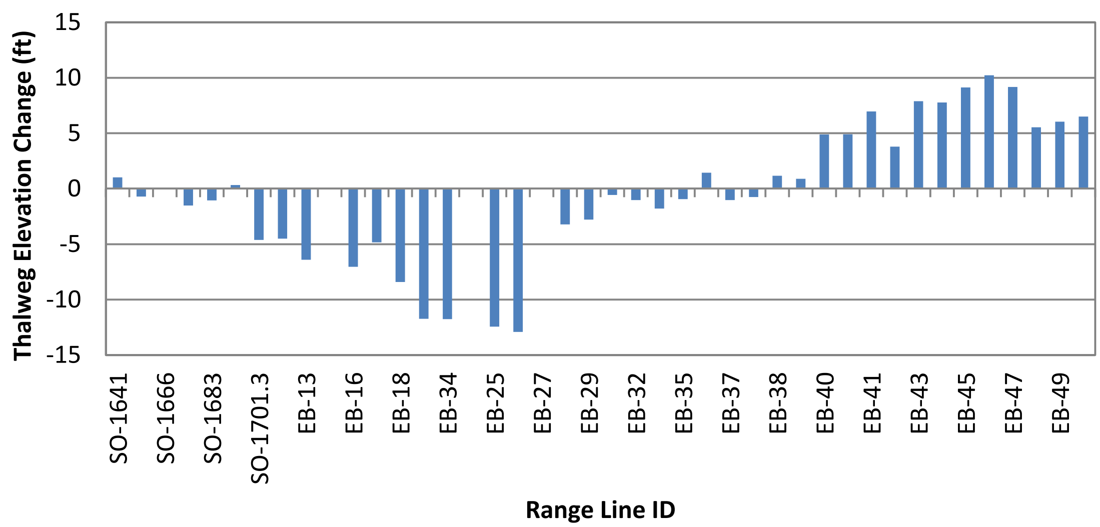

Figure 4.44 Change in Thalweg Elevation from 2004 to 2009

The wave of degradation between SO-1701.3 and EB-26 (Wave 3) is in response to the decrease in base-level by about 100 ft between 1995 and 2004. Figure 4.45 shows the magnitude of degradation from 2004 to 2009, which is represented by the following second order polynomial equation:

$$y = -0.0226x^2 + 4.0x - 171.53$$

Where, y is the magnitude of degradation and x is the longitudinal location along the reach in River Miles; this equation is appropriate for RM 45.21 to RM 52.03.

The wave of aggradation between EB-38 and EB-50 (Wave 2) is in response to the reservoir WSE increase of about 35 ft between 2004 and 2009. Figure 4.46 shows the magnitude of aggradation from 2004 to 2009, which is represented by the following second order polynomial equation between RM 59.34 and RM 73.59:

$$y = -0.4355x^2 + 41.11x - 962.27$$

Where, y is the magnitude of degradation and x is the longitudinal location along the reach in River Miles.

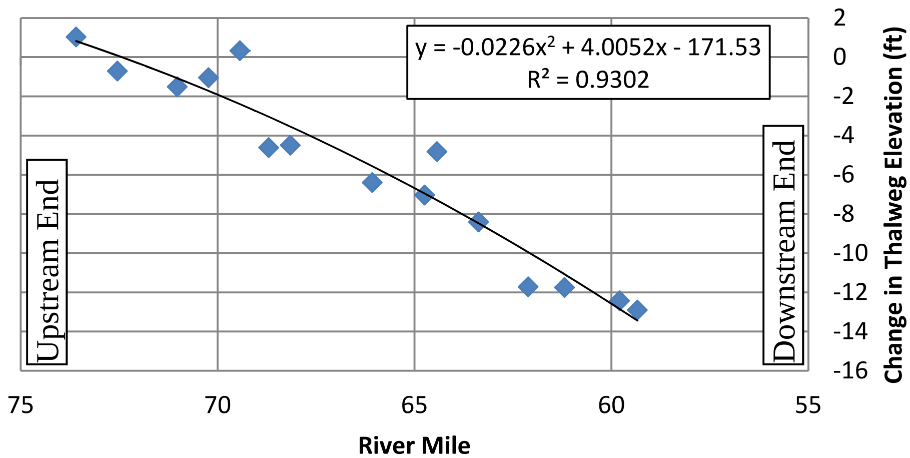

Figure 4.45 Magnitude of Degradation from 2004 to 2009

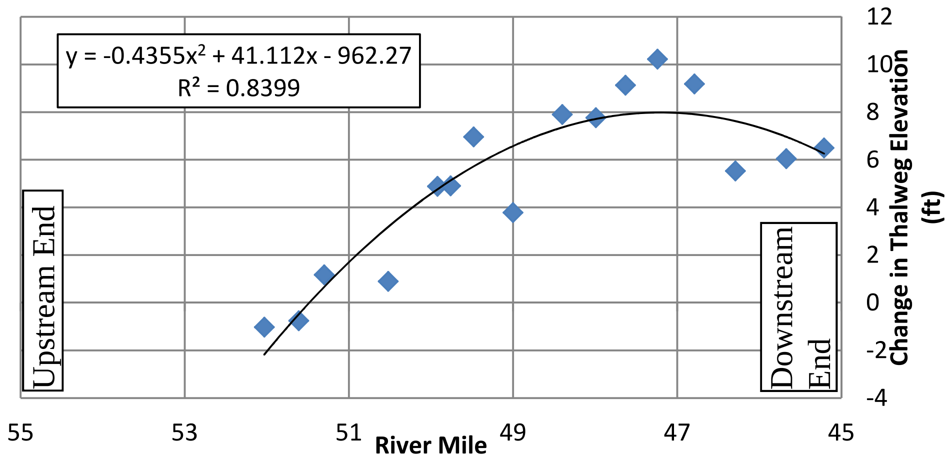

Figure 4.46 Magnitude of Aggradation from 2004-2009

Appendix G presents plots of the change in thalweg elevation between selected year sets versus river mile, along with trendlines associated with “waves” of aggradation and “waves” of degradation.

4.3.4 Rate of Wave Propagation Upstream from Range Line Surveys

Wave 1, resulting from the decrease in base-level from 2009 to 2010, is represented by range line EB-50. EB-50 decreased approximately 0.2 ft between 2009 and 2010. The rate of wave propagation upstream was determined by first plotting the river mile of the upstream extent of the reservoir during the first year of the wave. Then, the river mile of the upstream-most affected range line cross-section was determined and plotted versus the latter year of the year set. If a wave continued beyond one year set, then this step was repeated for each year set that the wave propagated and for which data existed. The upstream extent of the reservoir was determined by interpolating (or extrapolating) the average channel thalweg slope during the first year of the wave to the average elevation of the reservoir; where the channel slope and reservoir elevation intersected, the river mile was calculated. Figure 4.47 shows the reservoir water surface elevation change from 2009 to 2010, which induces Wave 1 degradation. Figure 4.48 shows the rate of Wave 1 propagation upstream as a result of the decrease in WSE (base-level) from 2009 to 2010. The wave propagated upstream at a rate of 1.46 miles/year with a decrease in base-level of 6.9 ft/year, and the upstream extent of the reservoir receded 2.71 miles/year.

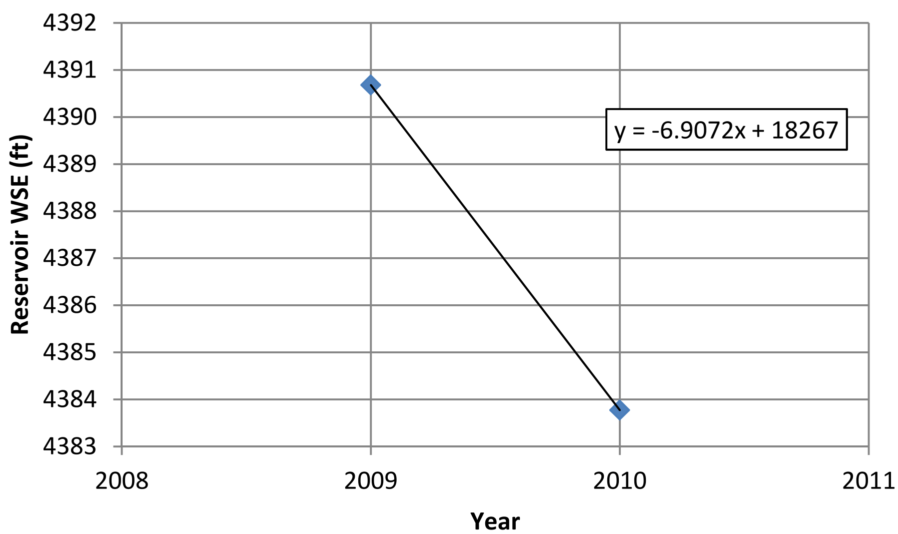

Figure 4.47 Reservoir Water Surface Elevation Change from 2009-2010 Resulting in Wave 1 Channel Degradation

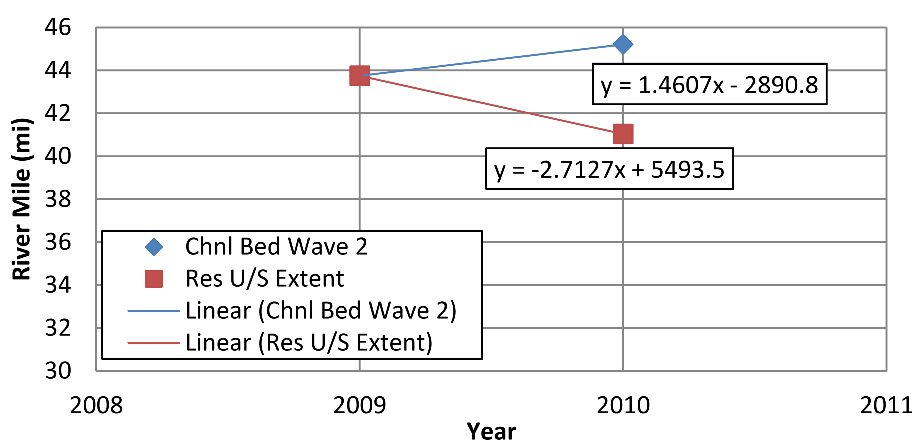

Figure 4.48 Rate of Wave 1 Propagation Upstream

Wave 2 resulted from an increase in base-level from 2004 to 2009. Figure 4.49 shows the reservoir water surface elevation change from 2004 to 2009, which induced

Wave 2 aggradation. Figure 4.50 shows the rate of Wave 2 propagation upstream as a result of the increase in WSE (base-level) from 2004 to 2009. With an increase in base-level of 6.8 ft/year, Wave 2 propagated upstream according to the following second order polynomial:

$$y = -0.5522x^2 + 2219.1x - 2E{+}06$$

Where, y is the upstream-most River Mile at which aggradation occurs as a result of an increase in base-level of 6.8 ft/year, and x is the year at which River Mile y begins to aggrade. The upstream extent of the reservoir progressed upstream at a rate of 1.36 miles/year.

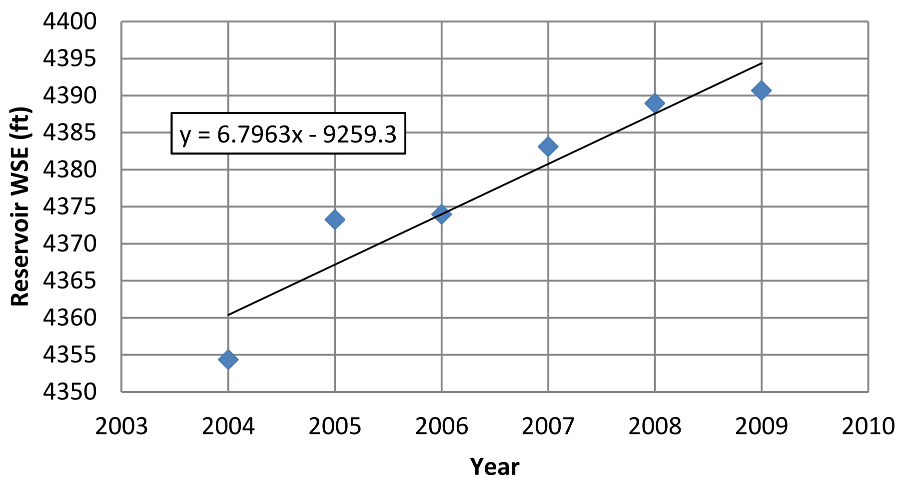

Figure 4.49 Reservoir Water Surface Elevation Change from 2004-2009 Resulting in Wave 2 Channel Aggradation

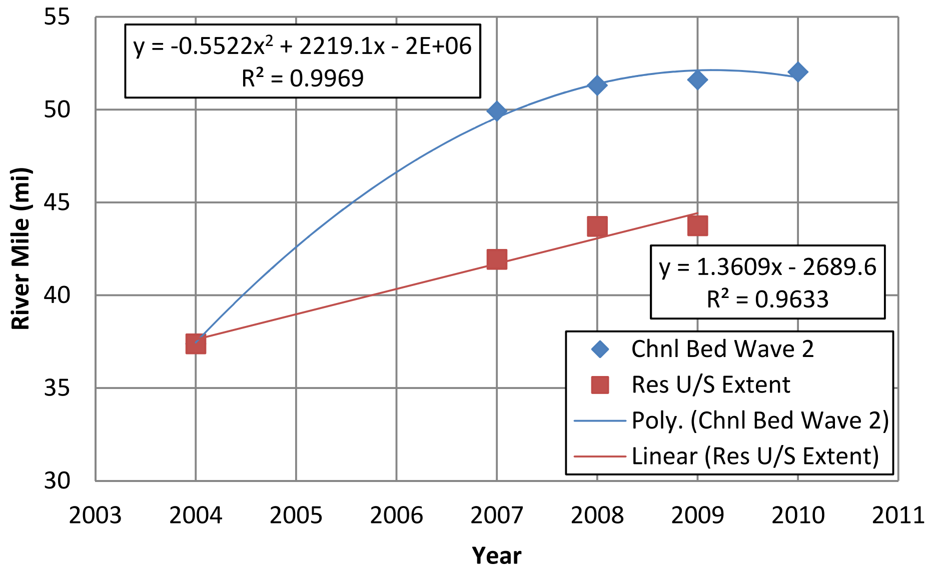

Figure 4.50 Rate of Wave 2 Propagation Upstream

Wave 3 resulted from a decrease in base-level from 1997 to 2004. Figure 4.51 shows the reservoir water surface elevation change from 1997 to 2004, which induced Wave 3 degradation. Figure 4.52 shows the rate of Wave 3 propagation upstream as a result of the decrease in WSE (base-level) from 1997 to 2004. With a decrease in base-level of 14.2 ft/year, Wave 3 propagated upstream according to the following second order polynomial:

$$y = 0.0692x^2 - 276.2x + 275686$$

Where, y is the upstream-most River Mile at which degradation occurs as a result of a decrease in base-level of 14.2 ft/year, and x is the year at which River Mile y begins to degrade. The upstream extent of the reservoir receded at a rate of 2.9 miles/year.

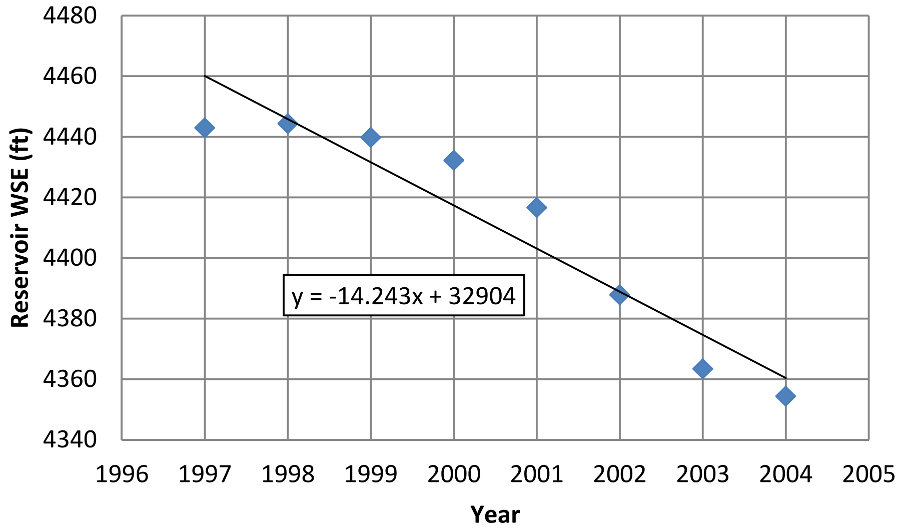

Figure 4.51 Reservoir Water Surface Elevation Change from 1997-2004 Resulting in Wave 3 Channel Degradation

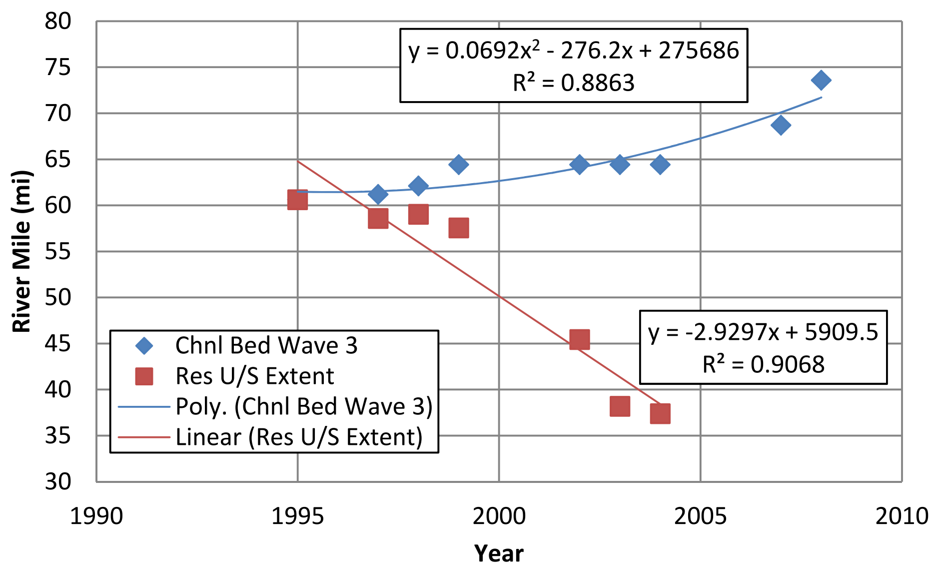

Figure 4.52 Rate of Wave 3 Propagation Upstream

Wave 4 resulted from an increase in base-level from 1990 to 1995. Figure 4.53 shows the reservoir water surface elevation change from 1990 to 1995, which induced Wave 4 aggradation. Figure 4.54 shows the rate of Wave 4 propagation upstream as a result of the increase in WSE (base-level) from 1990 to 1995. With an increase in base-level of 3.7 ft/year, Wave 4 propagated upstream according to the following second order polynomial:

$$y = -0.1222x^2 + 489.03x - 489299$$

Where, y is the upstream-most River Mile at which aggradation occurs as a result of an increase in base-level of 3.7 ft/year, and x is the year at which River Mile y begins to aggrade. The upstream extent of the reservoir progressed upstream at a rate of 1.07 miles/year.

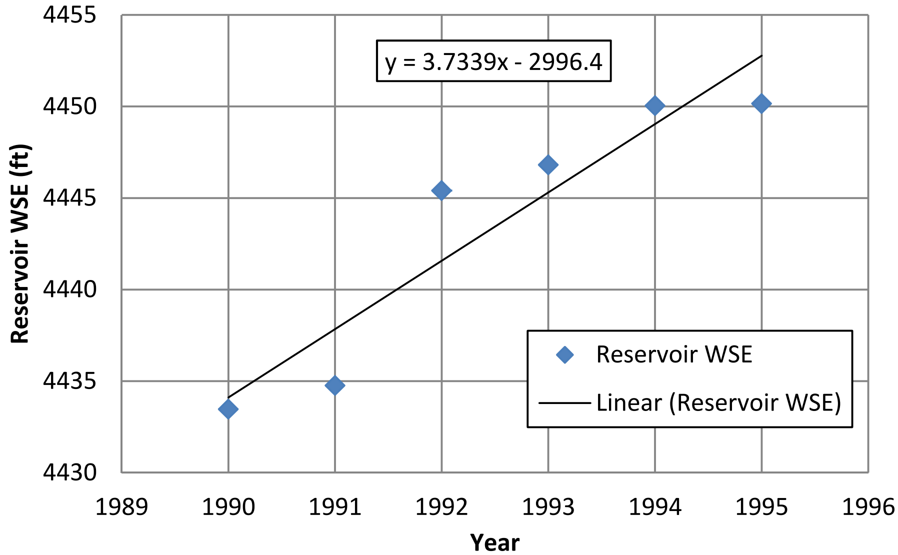

Figure 4.53 Reservoir Water Surface Elevation Change from 1990-1995 Resulting in Wave 4 Channel Aggradation

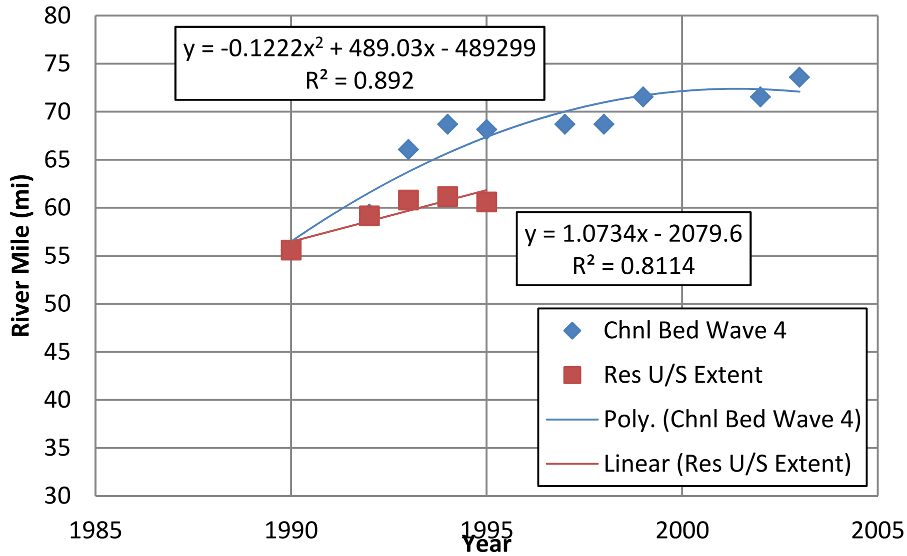

Figure 4.54 Rate of Wave 4 Propagation Upstream

4.4 Bed Material Analysis

4.4.1 Grain Size Distributions

Bed material surveys taken at SO- and EB- range lines by Reclamation were used to create grain size distribution curves for each subreach. Also, San Acacia and San Marcial gauges' bed material grain size distributions were plotted to study the trend of the bed material grain size about 44 miles upstream of the study reach and within the study reach.

Since complete temporal sequences of data related to each range line were not available, those with the most complete set of data were chosen to represent each subreach (see Table 4-8).

Table 4-8 Representative Range Lines for Each Subreach

Subreach	Range Line
1	SO-1641
2	SO-1683
3	EB-10
4	EB-13
5	EB-18
6	EB-24

Multiple samples were collected at a given range line and for a given year. In many cases, stations along the range line cross-section at which samples were collected were provided. Where stations were provided, the sample locations were compared to the surveyed range line cross-sections, which were presented in Section 4.3. If the samples collected were from the floodplain within the cross-section, then the sample was not included in this analysis, as bed material only is of interest. If sample locations were not provided, then it was assumed that the sample was a bed material sample, because the data provided was defined by Reclamation as bed material sample data. The grain size distributions of all the collected bed material samples at a given station and in a given year were plotted. A representative grain size distribution was selected for each range line and for each year, from which the average mean grain size was computed. This same procedure was applied to the San Acacia and San Marcial gauge data. For example, Figure 4.55 shows different grain size distributions for range line EB-10 in 1992. The most representative distribution chosen for that year is highlighted in yellow.

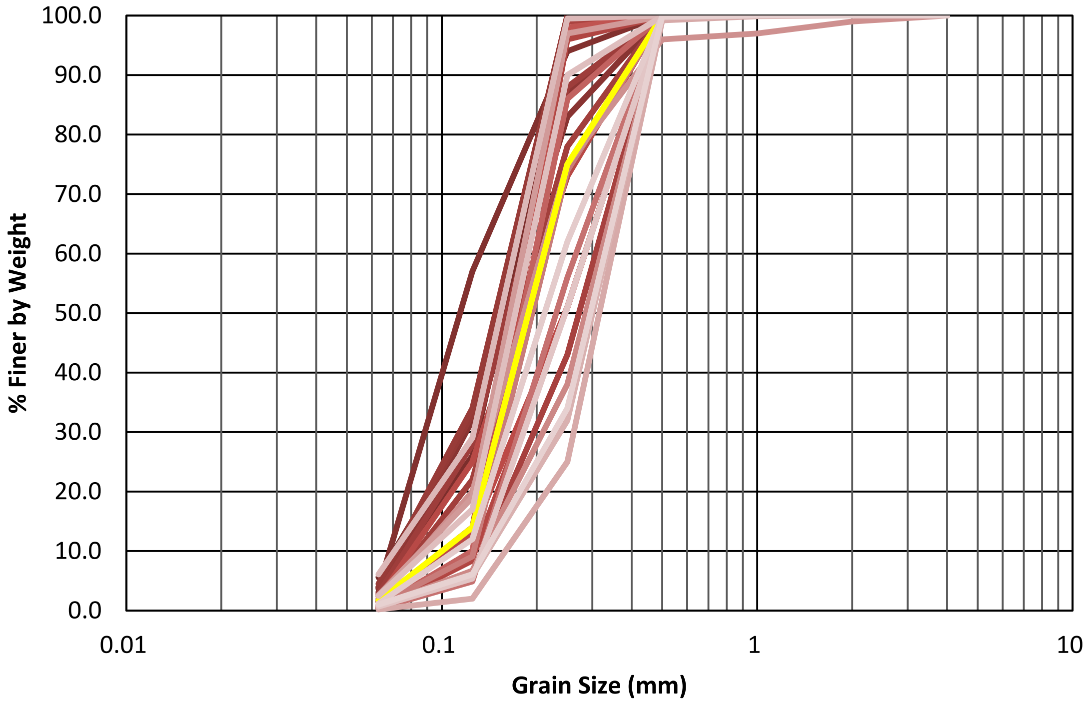

Figure 4.55 EB-10 1992 Bed Material Grain Size Distributions

Figure 4.56 through Figure 4.63 show the compilation of representative grain size distributions for each year at the San Acacia gauge, at the San Marcial gauge, and at each subreach. Select bed material grain size distribution plots are provided in Appendix H.

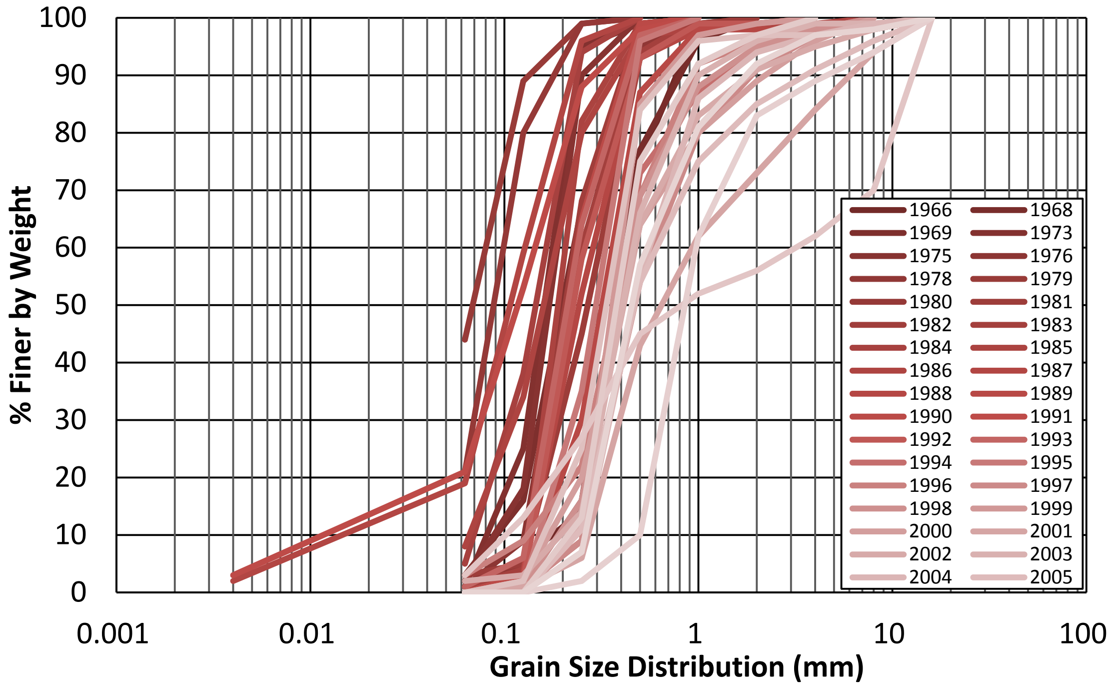

Figure 4.56 San Acacia Gauge: Annual Bed Material Grain Size Distributions

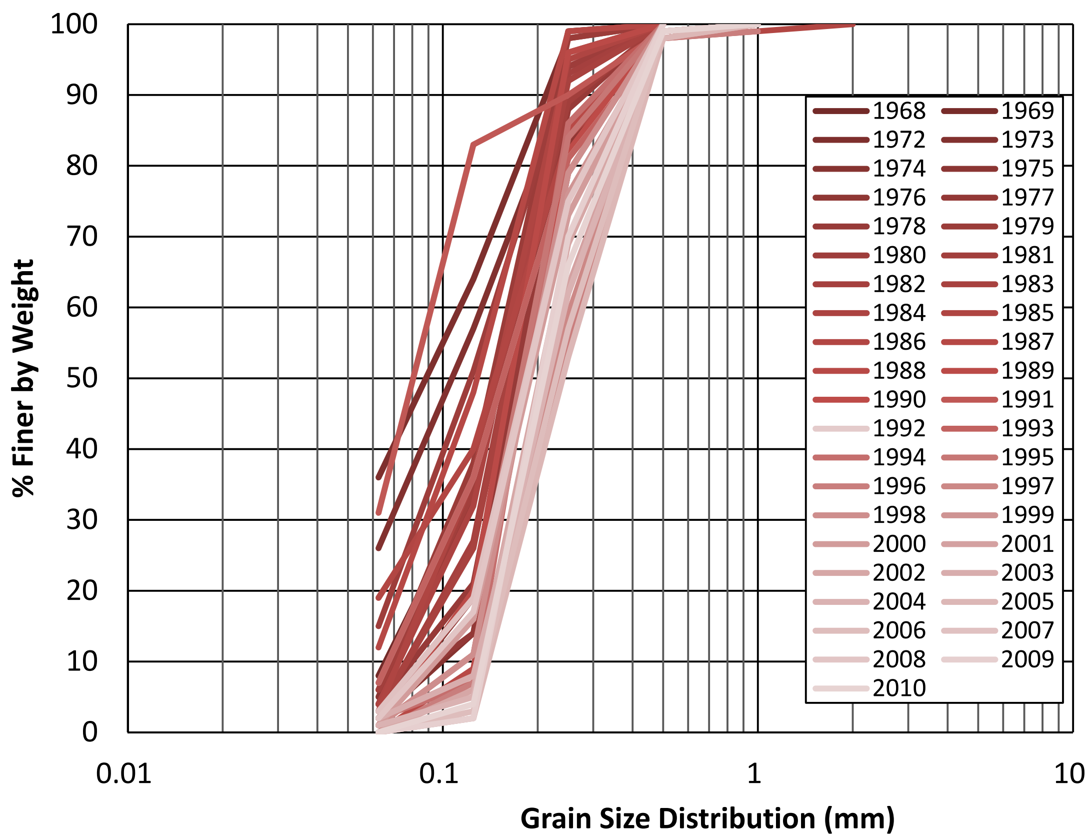

Figure 4.57 San Marcial Gauge: Annual Bed Material Grain Size Distributions

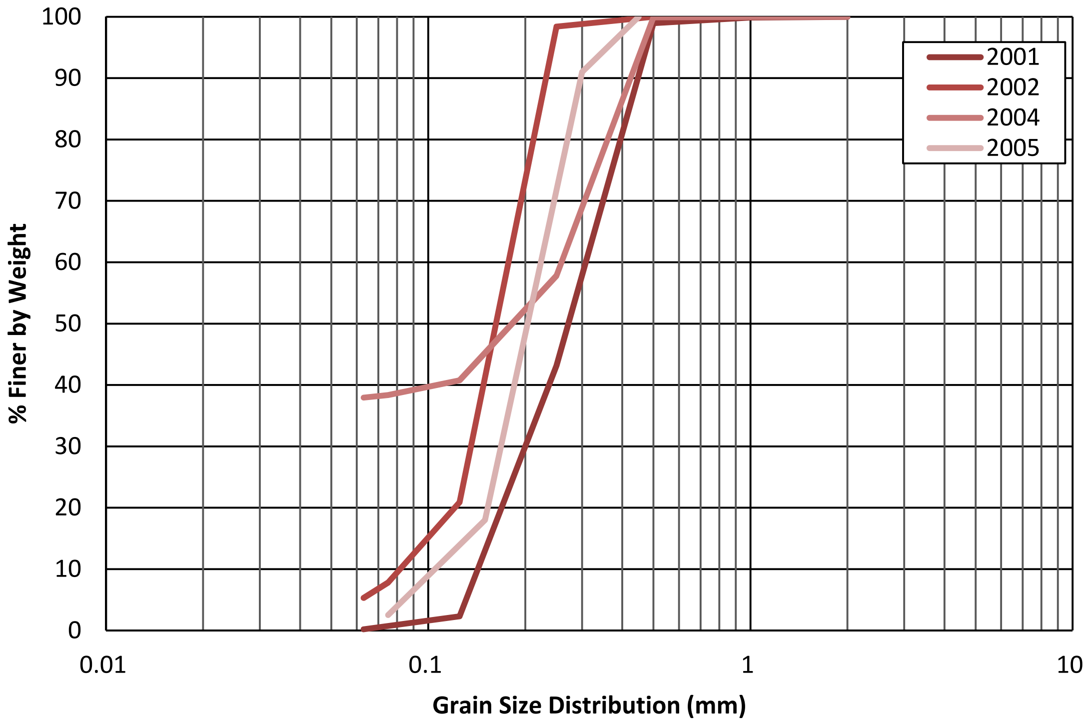

Figure 4.58 Subreach 1 (SO-1641): Annual Bed Material Grain Size Distributions

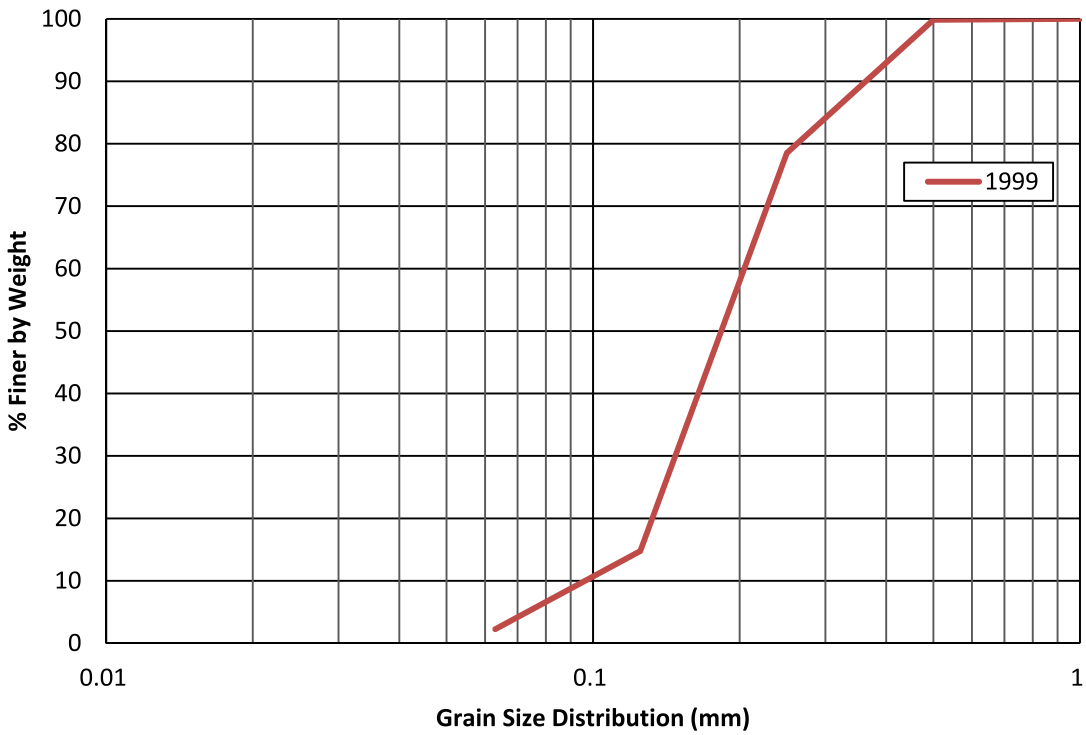

Figure 4.59 Subreach 2 (SO-1683): Annual Bed Material Grain Size Distributions

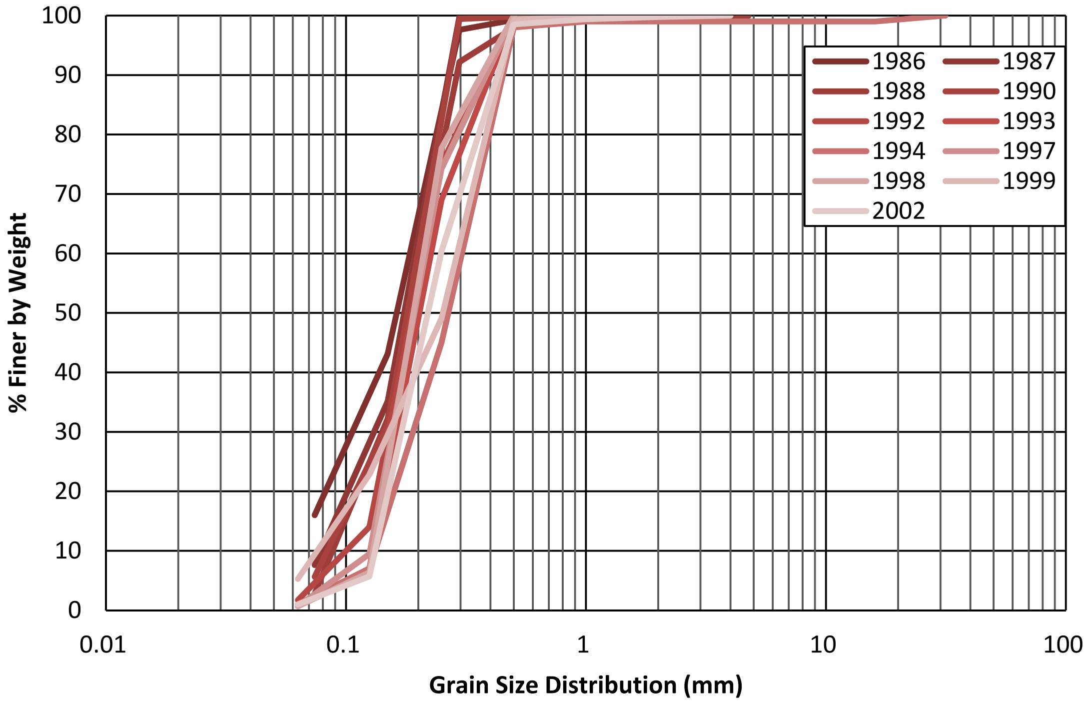

Figure 4.60 Subreach 3 (EB-10): Annual Bed Material Grain Size Distributions

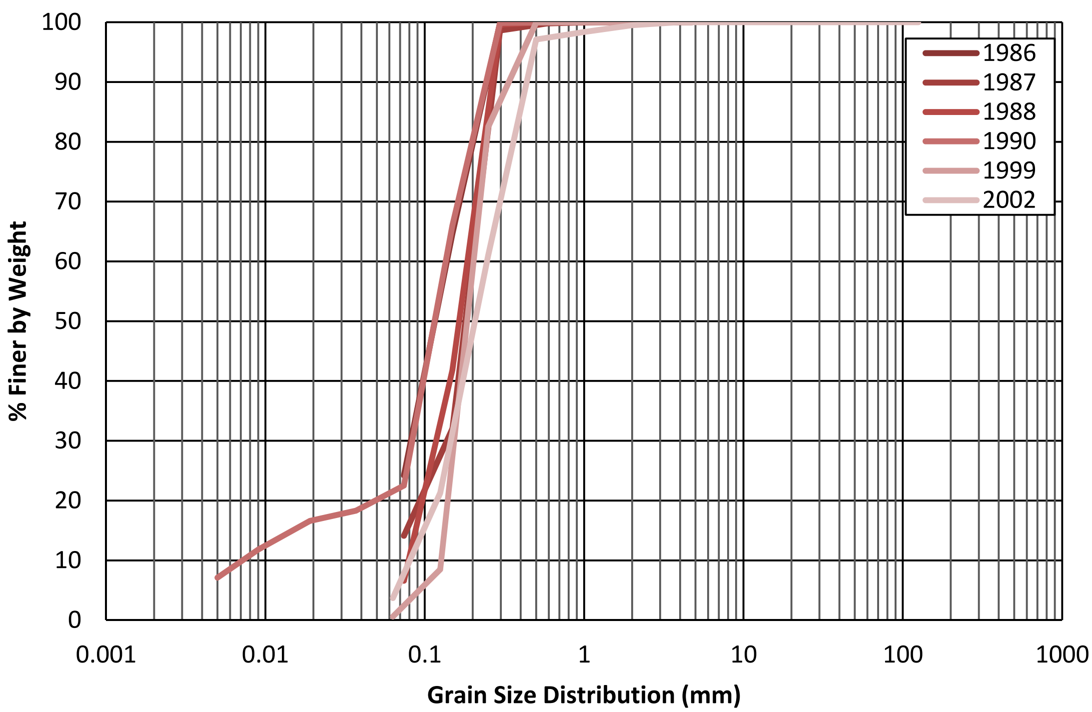

Figure 4.61 Subreach 4 (EB-13): Annual Bed Material Grain Size Distributions

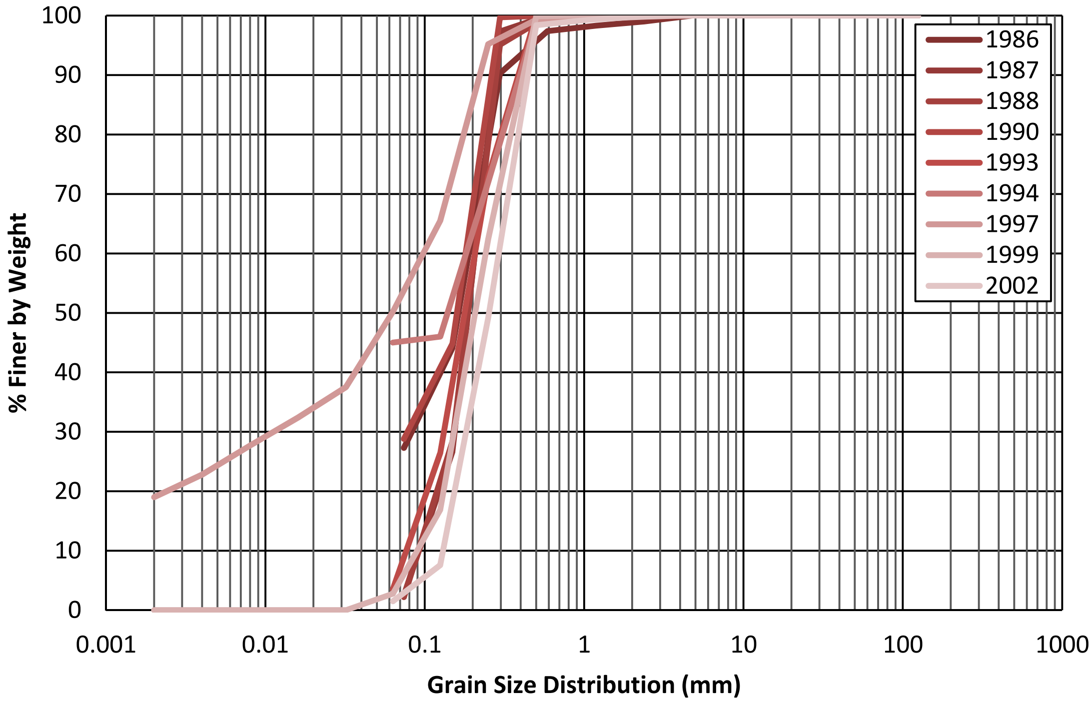

Figure 4.62 Subreach 5 (EB-18): Annual Bed Material Grain Size Distributions

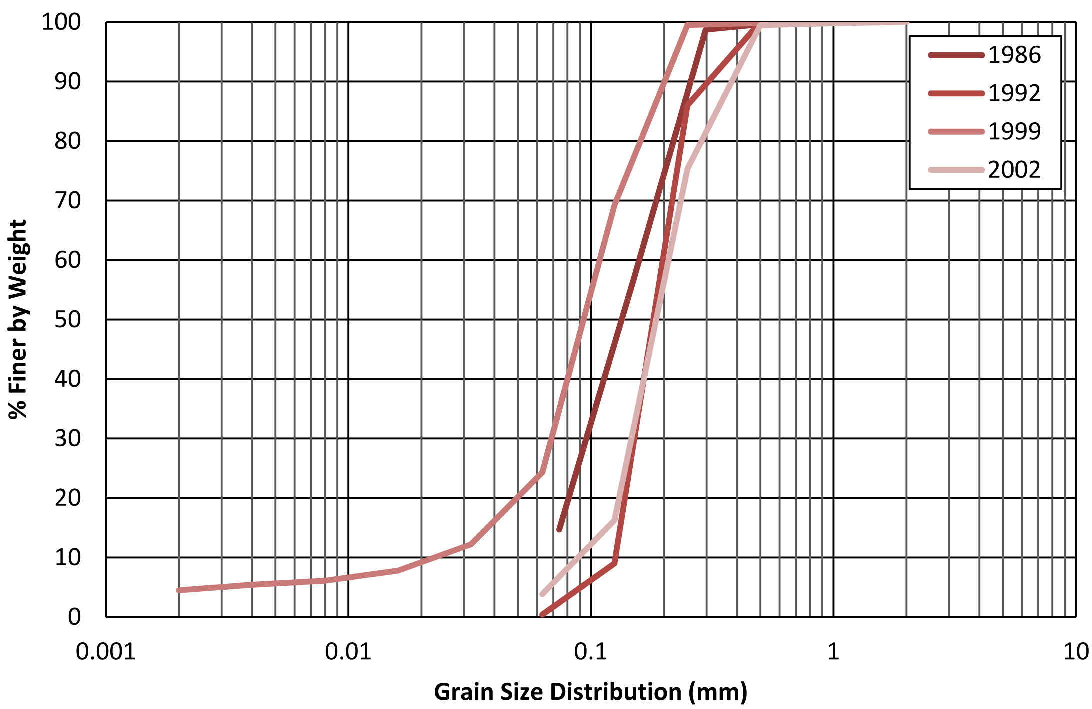

Figure 4.63 Subreach 6 (EB-24): Annual Bed Material Grain Size Distributions

The San Acacia and San Marcial grain size distribution plots show that the bed material has become slightly coarser over time as indicated by the grain size distribution curves moving to the right with time. Note that the San Acacia gauge is 44 miles upstream of this study reach and is not representative of this study reach, while the San Marcial gauge is located at the upstream end of this study reach, and therefore represents this study reach very well. The grain size distributions of each subreach have experienced minimal changes throughout the years. It should be noted that in the case of San Acacia and San Marcial gauges, the sequences of data ranges from 1967 to 2008, while Subreaches 3, 4, 5, and 6 data range from 1986 to 2002; Subreach 1 only ranges from 2001 to 2005; and Subreach 2 only has data from 1999.

4.4.2 Median Grain Size

Figure 4.64 shows the change over time of the average median bed material grain size in each subreach and at the San Acacia and San Marcial gauges, located 44 miles upstream of the study reach and within the study reach, respectively. Figure 4.65 shows the average median bed material grain size trends for each subreach from 1986 to 2005.

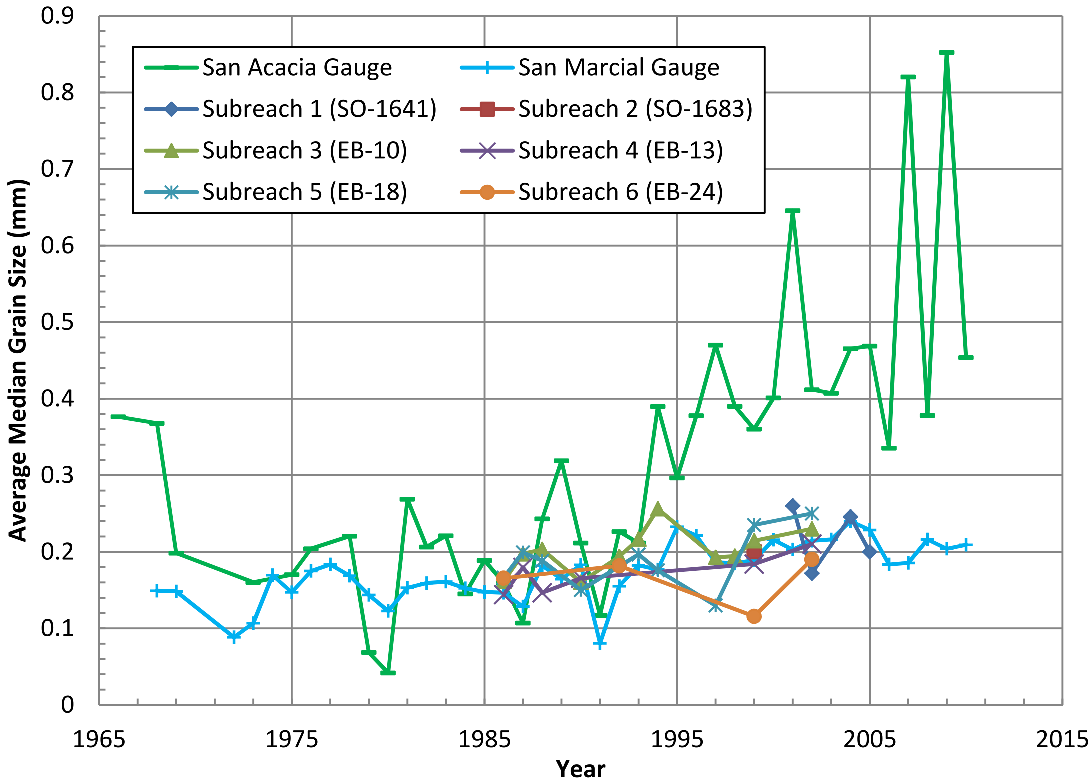

Figure 4.64 Average Median Bed Material Grain Size Temporal Trends

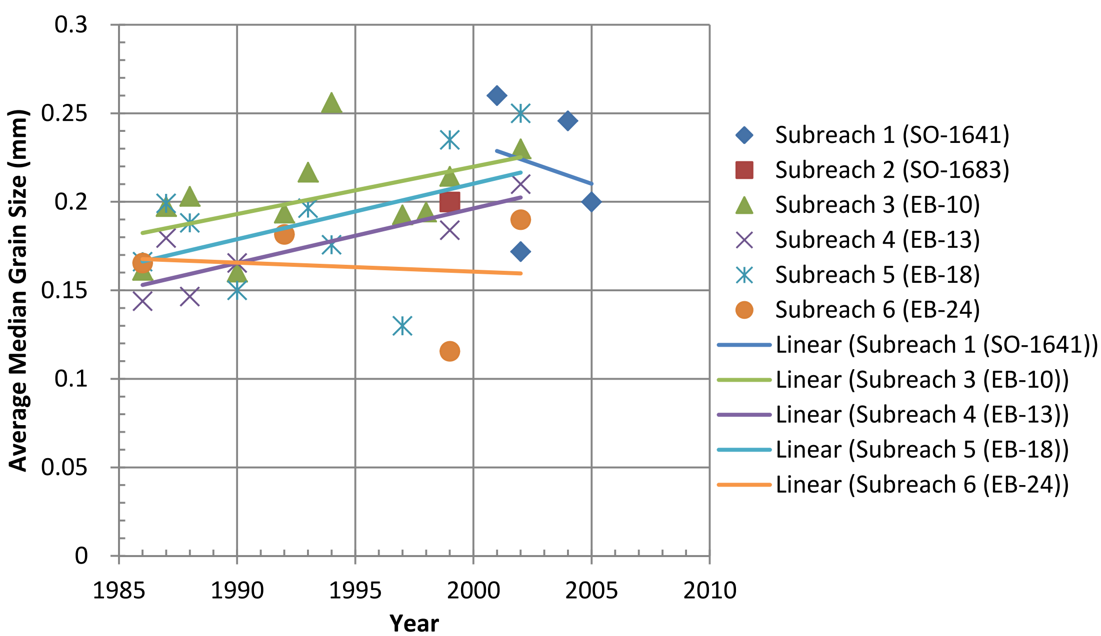

Figure 4.65 Average Median Bed Material Grain Size: Subreach Temporal Trends

Overall, mean grain sizes of the study reach range between 0.11 and 0.26 mm, corresponding to very fine to medium sand (Julien 2002). In general, the bed material at the San Marcial gauge has become coarser since the 1960s by about 0.002 mm/year (from a minimum of 0.08 mm in 1991 to a maximum of 0.24 mm in 2004). The bed material at the San Acacia gauge has become coarser by about 0.009 mm/year (from a minimum of 0.04 mm in 1980 to a maximum of 0.85 mm in 2009), which is about five times faster than the bed material coarsening rate at the San Marcial gauge. Note that the rates of bed material coarsening were determined using the entire datasets for each respective gauge that are presented in Figure 4.64.

Figure 4.65 shows that the average median grain size in Subreach 1 has become finer at a rate of 0.0046 mm/year between 2001 and 2005; Subreach 2 has no temporal trend, because the only data available for Subreach 2 is from 1999; the average median grain size within Subreach 3 coarsened at a rate of 0.0027 mm/year between 1986 and 2002; the average median grain size within Subreach 4 coarsened at a rate of 0.0031 mm/year between 1986 and 2002; the average median grain size within Subreach 5 coarsened at a rate of 0.0031 mm/year between 1986 and 2002; the average median grain size within Subreach 6 became finer at a rate of 0.0005 mm/year between 1986 and 2002.

All average median grain sizes are within the very fine to fine sand range, except for the averages in Subreach 1 in 2001 and in Subreach 3 in 1994, which are in the low end of the medium sand classification (0.26 mm). So, though there has been overall coarsening of the bed material within this study reach, it is less than 0.003 mm/year, and is still generally classified as very fine to fine sand. Figure 4.65 also shows that while the median bed material size has coarsened with time, it tends to get finer in the downstream direction.

4.5 Suspended Sediment Data

Suspended sediment data was used from the Escondida Reach Report (Larsen et al. 2007). Single and double mass curves developed in the Escondida Reach Report (Larsen et al. 2007) are presented below. Trends in water discharge, suspended sediment discharge, and suspended sediment concentration are shown in Figure 4.66, Figure 4.67, and Figure 4.68, respectively.

The single mass curve for water discharge, Figure 4.66, shows similar trends at the San Marcial and San Acacia gauges. Both curves show breaks around 1979 and 2000. In about 1979, the discharge increased from about 600 cfs to over 2000 cfs. Table 4-9, also from the Escondida Reach Report (Larsen et al. 2007), is presented below and shows the average discharge for each period displayed on the graph.

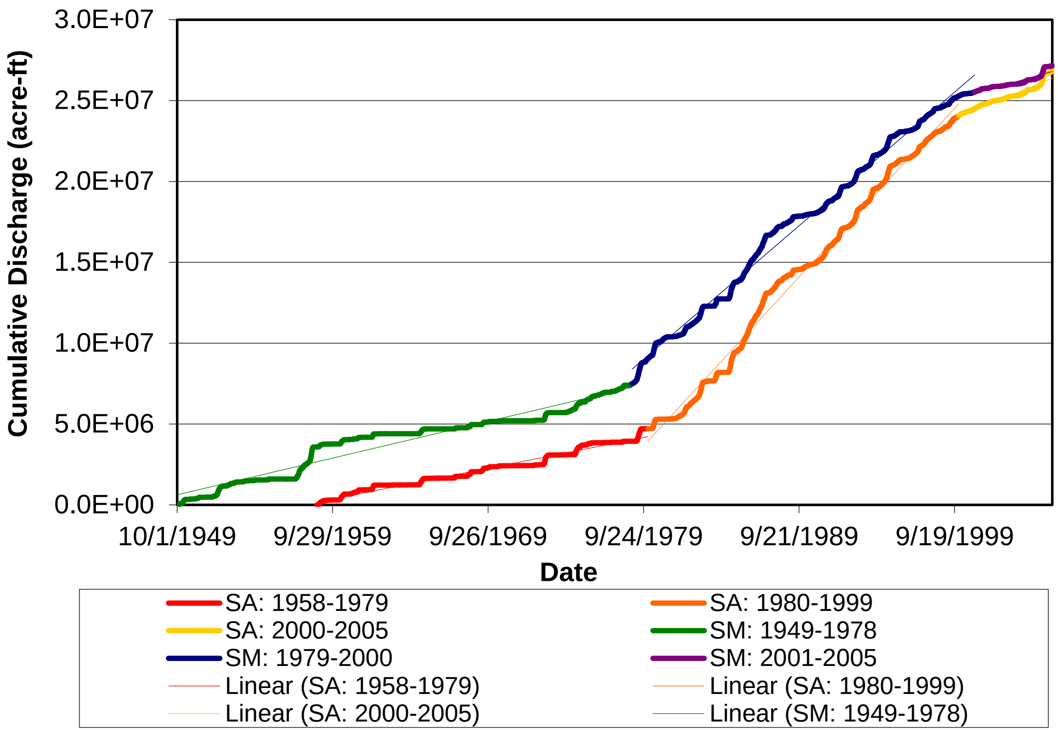

Figure 4.66 Water Discharge Single Mass Curve (Larsen et al. 2007)

Table 4-9 Water Discharge (Larsen et al. 2007)

Gauge	Years	acre-ft/day	R^2 value
San Acacia	1958-1979	522	0.98
	1980-1999	2856	0.99
	2000-2005	1055	0.93
San Marcial	1949-1978	621	0.94
	1979-2000	2263	0.99
	2001-2005	740	0.84

Figure 4.67 shows the single mass curve for suspended sediment discharge at the San Acacia and San Marcial Gauges. The San Marcial gauge has a much higher suspended sediment discharge than the San Acacia gauge from 1956 until about 1968. From 1968 to 1991, the two gauges both have a suspended sediment discharge of about 10,000 tons/day. From 1991 to 1996, the San Marcial gauge again shows a much higher suspended sediment discharge. Table 4-10 shows the average suspended sediment discharge for the periods shown on the graph.

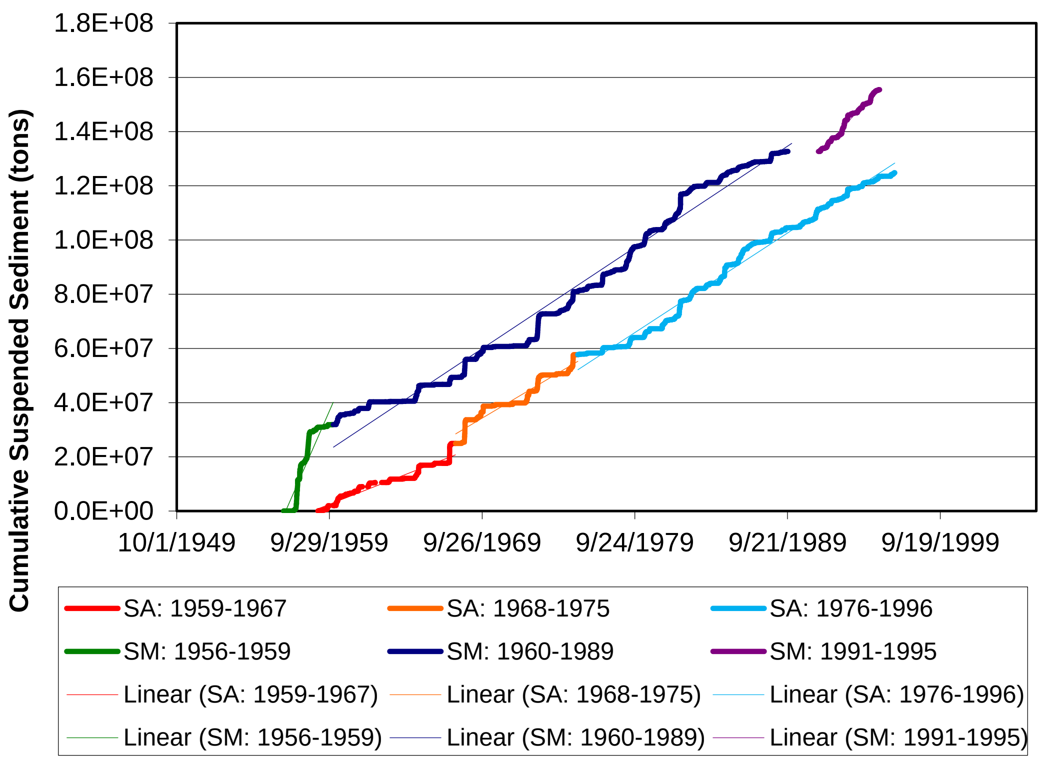

Figure 4.67 Suspended Sediment Discharge Single Mass Curve (Larsen et al. 2007)

Table 4-10 Suspended Sediment Discharge (Larsen et al. 2007)

Gauge	Years	tons/day	R^2 value
San Acacia	1959-1967	6062	0.94
	1968-1975	9172	0.92
	1976-1996	10066	0.99
San Marcial	1956-1959	35276	0.88
	1960-1989	10232	0.98
	1991-1995	16707	0.98

Double mass curves were developed at each gauge to show the changes in suspended sediment concentration over time, as seen in Figure 4.68.

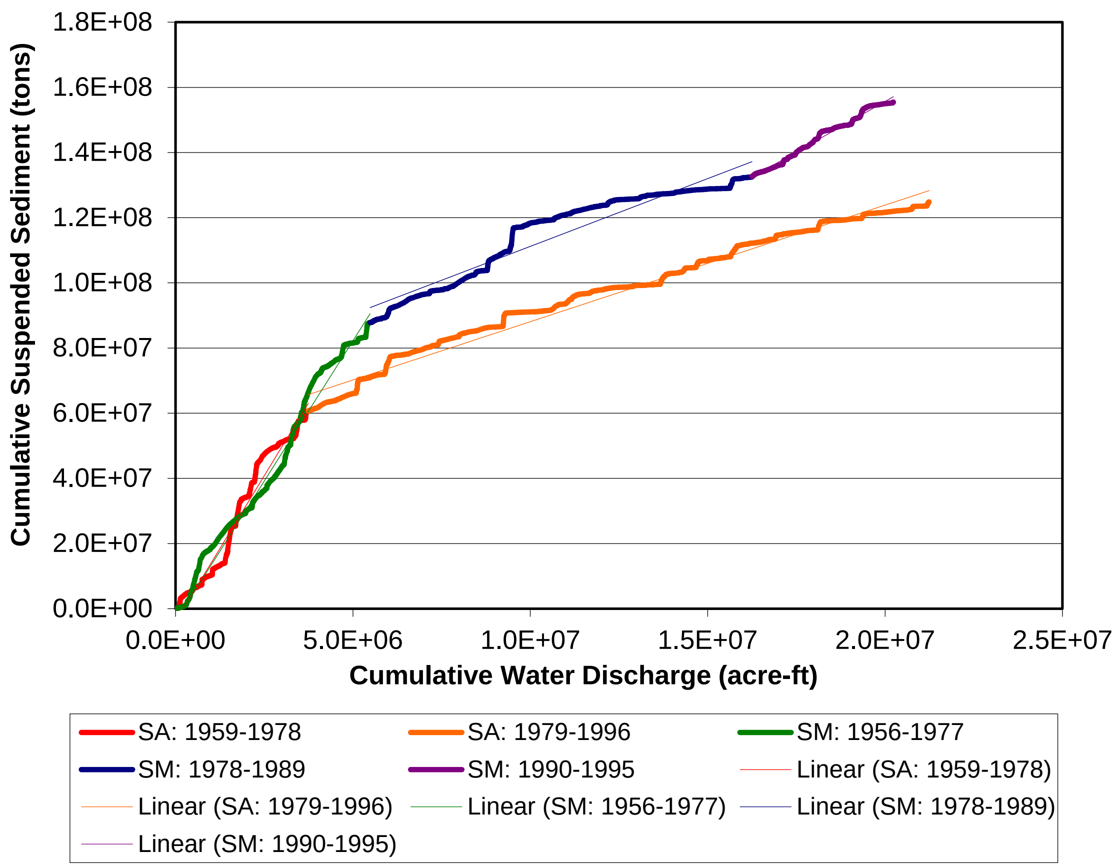

Figure 4.68 Suspended Sediment Concentration Double Mass Curves (Larsen et al. 2007)

From 1959 to 1978, the two curves are very similar, with an average suspended sediment concentration of about 13,000 mg/L. Around 1978, both curves break, and the suspended sediment concentration drops to about 3,000 mg/L. The concentration at the San Acacia gauge remains at about 3,000 mg/L through the end of the available data. The San Marcial gauge, however, shows an increase in suspended sediment concentration from 3,000 mg/L to 4,500 mg/L around 1990. Table 4-11 shows the average concentration as well as the R^2 values for each segment of the graph.

Table 4-11 Suspended Sediment Concentration (Larsen et al. 2007)

Gauge	Years	tons/acre-ft	mg/L	R^2 value
San Acacia	1959-1978	17.9	13165	0.97
	1979-1996	3.58	2633	0.98
San Marcial	1956-1977	17.21	12657	0.97
	1978-1989	4.16	3060	0.92
	1990-1995	6.2	4560	0.98

From 1960 to 1989 at the San Marcial gauge, and from 1959 to 1996 at the San Acacia gauge, the suspended sediment discharge consistently averaged between about 9,000 and 10,000 tons/day, as seen in Figure 4.67. Around 1980, the water discharge at the San Acacia and San Marcial gauges increased four to five times the average water discharge from 1949 to 1980. From 1942 to 1979, New Mexico experienced a state-wide drought (Paulson et al 1988). The decrease in suspended sediment concentration in 1979 was due to the increase in water discharge following the nearly 40 year drought, and was not due to a change in suspended sediment discharge.

SECTION 5: SUMMARY AND CONCLUSIONS

The Elephant Butte Reach spans about 30 miles, beginning from the South Boundary of the Bosque del Apache National Wildlife Refuge (River Mile 73.9) to the "narrows" of the Elephant Butte Reservoir (River Mile 44.65), in central New Mexico. Further understanding of the historical and spatial changes within Elephant Butte Reach, along with a better understanding of the influences of Elephant Butte Reservoir levels on channel aggradation/degradation is essential for improvement in future river management practices along the Middle Rio Grande. The objectives addressed in this study included the following:

6. Quantified temporal changes in channel widths and sinuosity from 1935 to 2010.
7. Quantified change in channel slope temporally.
8. Quantified rate of aggradation/degradation in response to a change in base-level (i.e., change in reservoir water surface elevation).
9. Quantified aggradation/degradation wave propagation upstream.
10. Quantified spatial and temporal trends in bed material grain size.

The average channel width and channel sinuosity for Elephant Butte Reach have decreased since 1918. From 1935 to 2010, the average channel width decreased according to the following equation:

$$\text{Avg. Chnl Width} = 0.2353x^2 - 936.54x + 931904$$

Where, x is the year. Since 1962, the average channel width has ranged between 50 ft and 300 ft. From 1935 to 2010, channel sinuosity has decreased according to the following equation:

$$\text{Channel Sinuosity} = 6E\text{-}05x^2 - 0.2196x + 219.57$$

Where, x is the year. Since 1962, channel sinuosity has remained lower than 1.25.

The channel slope since 1962 has primarily decreased. From 1962 to 2002, based on Agg/Deg-line survey data, the average channel slope (Subreaches 1 through 5) decreased about 0.03 ft/mile/year. Within Subreach 6, based on range line survey data, the channel slope decreased 0.32 ft/mile/year from 1995 to 2001 as a result of an increase in base-level of about 20 ft from 1990 to 1995; from 2002 to 2010, the channel slope decreased 0.21 ft/mile/year as a result of an increase in base-level of about 35 ft from 2004 to 2009; from 2001 to 2002, the channel slope increased from 2.3 ft/ft to 4.3 ft/ft in one year as a result of a decrease in base-level of about 100 ft from 1995 to 2004.

The rate of aggradation/degradation along the reach varied between different year sets. Based on Agg/Deg-line survey data, from 1972 to 1992, the base-level increased 13.4 ft/year, and the channel aggraded in response as described by the following equation:

$$\text{Rate of Aggradation} = -0.0014x^2 + 0.0649x + 0.1832$$

Where, x is the distance (in miles) downstream of Agg/Deg 1637 (or the upstream end of Elephant Butte Reach).

Between 1995 and 2004, the base-level dropped 100 ft (11.1 ft/year). The following equations describe the rate of degradation for year sets 2003-2004, 2004-2005, and 2004-2009, respectively:

$$\text{(2003-2004) Rate of Degradation} = -0.1601x^2+16.209x - 410.5$$

$$\text{(2004-2005) Rate of Degradation} = 0.8233x - 58.29$$

$$\text{(2004-2009) Rate of Degradation} = -0.0226x^2 + 4.0x - 171.53$$

Where, x is the River Mile (as defined by Reclamation). From 2004 to 2009, the channel aggraded in response to an increase in base-level of about 35 ft between 2004 and 2009 (7 ft/yr), as follows (where x is the River Mile):

(2004-2009) Rate of Aggradation = $-0.4355x^2 + 41.11x - 962.27$

Wave 1 propagated upstream at a rate of 1.46 miles/year with a decrease in base-level of 6.9 ft/year. Wave 2 propagated upstream following a rise in base-level of 6.8 ft/year between 2004 and 2009, as follows:

$y = -0.5522x^2 + 2219.1x - 2*10^6$

Wave 3 propagated upstream following a drop in base-level of 14.2 ft/year between 1997 and 2004, as follows:

$y = 0.0692x^2 - 276.2x + 275686$

Wave 4 propagated upstream following a rise in base-level of 3.7 ft/year between 1990 and 1995, as follows:

$y = -0.1222x^2 + 489.03x - 489299$

Where, x is year and y is river mile.

The average median grain size in Subreach 1 has become finer at a rate of 0.0046 mm/year between 2001 and 2005; Subreach 2 only has data available in 1999; between 1986 and 2002, the average median grain size within Subreach 3, 4, and 5 coarsened at a rate of 0.0027 mm/year, 0.0031 mm/year, and 0.0031 mm/year respectively; the average median grain size within Subreach 6 became finer at a rate of 0.0005 mm/year between 1986 and 2002. There has been overall coarsening of the bed material within this study reach at a rate of less than 0.003 mm/year. Lastly, the median bed material size gets finer in the downstream direction, and is generally classified as very fine to fine sand.

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APPENDICES

APPENDIX A: RANGE LINE SURVEY DATES

Table A.1 Range Line Survey Dates

Range Line	Year																								
	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
SO-1638.8																									x	
SO-1641													x	x	x		x	x	x	x	x	x	x	x	x	
SO-1643.1																									x	
SO-1644.8																									x	
SO-1645						x		x	x				x	x	x			x				x		x		
SO-1646.9																									x	
SO-1649.1																									x	
SO-1650													x	x	x							x		x		
SO-1650.7																									x	
SO-1652.7						x	x	x	x				x	x	x			x		x	x	x	x	x	x	
SO-1656.1																									x	
SO-1657.7																									x	
SO-1660													x	x	x				x	x	x	x	x	x	x	
SO-1662							x						x	x	x			x				x		x	x	
SO-1663							x						x	x	x			x	x	x	x	x	x	x	x	
SO-1664							x						x	x	x			x				x		x		
SO-1665							x						x	x	x				x	x	x	x	x	x	x	
SO-1666						x	x	x	x	x	x		x	x	x			x				x		x		
SO-1667													x	x	x							x		x	x	
SO-1668							x						x	x	x			x				x		x		
SO-1668.4																									x	
SO-1670							x						x	x	x			x	x	x	x	x	x	x	x	
SO-1671.5																									x	
SO-1673										x	x		x	x	x			x	x	x	x	x	x	x	x	
SO-1674.8																									x	
SO-1676.4																									x	
SO-1679.4																									x	
SO-1680.8																									x	
SO-1683						x		x		x	x	x	x	x	x			x	x	x	x	x	x	x	x	

Range Line Survey Dates (Continued)

Range	Year																									
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
SO-1684.7																									x	
SO-1686.4																									x	
SO-1689.9																									x	
SO-1692										x	x			x	x			x	x	x	x	x	x	x	x	
SO-1694.9																									x	
SO-1696.7																									x	
SO-1698.9																									x	
SO-1701.3						x		x	x	x	x		x	x	x			x	x	x	x	x	x	x	x	
EB-5		x	x	x	x																					
EB-9	x			x											x	x										
EB-9.2														x	x											
EB-9.4																								x	x	x
EB-9.5																								x	x	x
EB-10	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
EB-10.1																								x	x	x
EB-10.2																								x	x	x
EB-10.3																								x	x	x
EB-10.45																								x	x	x
EB-10.5														x	x											
EB-10.7																								x	x	x
EB-10.9																								x	x	x
EB-11				x											x	x										
EB-11.1																								x	x	x
EB-11.5																								x	x	x
EB-11.9																								x	x	x
EB-12				x										x	x	x						x		x		
EB-12X								x				x	x					x								
EB-12.4																								x	x	x
EB-12.7																								x	x	x

Range Line Survey Dates (Continued)

Range	Year																									
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-13	x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x
EB-13.9																								x	x	x
EB-14	x	x	x	x									x	x	x	x						x		x		
EB-14.3																								x	x	x
EB-14.5																								x	x	x
EB-14.7																								x	x	x
EB-15				x										x	x	x						x		x		
EB-15.1																								x	x	x
EB-15.4																								x	x	x
EB-15.7																								x	x	x
EB-15X								x				x	x					x								
EB-16	x	x	x	x		x		x	x	x	x		x	x	x	x		x	x	x	x		x	x	x	x
EB-16.5																								x	x	x
EB-17	x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x
EB-17.1																							x			
EB-17.2																							x			
EB-17.3																							x			
EB-17.35																								x	x	x
EB-17.4																							x			
EB-17.5																							x			
EB-17.6																							x			
EB-17.7																							x	x	x	x
EB-17.8																								x	x	x
EB-17.85																								x	x	x
EB-17.9																								x	x	x
FC-1754															x											
EB-18	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
EB-18.5																								x	x	x
EB-18.9																								x	x	x

Range Line Survey Dates (Continued)

Range	Year																									
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-19				x						x					x	x						x		x		
EB-19.1																								x	x	x
EB-19.3																								x	x	x
EB-19.5																								x	x	x
EB-19.7																								x	x	x
EB-19.8																								x	x	x
EB-20	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
EB-20.3																								x	x	x
EB-20.7																								x	x	x
EB-21				x											x	x								x	x	x
EB-22				x											x	x		x				x		x		
EB-22.2																								x	x	x
EB-22.6																								x	x	x
EB-23				x											x	x						x				
EB-23.05																								x	x	x
EB-23.1																										
EB-23.2																								x	x	x
EB-23.3																										
EB-23.4																							x	x	x	x
EB-23.5A																										
EB-23.5B																							x			
EB-23.6A																								x	x	x
EB-23.6B																							x			
EB-23.8																								x	x	x
EB-23.9																							x			
EB-23.9A																							x			
EB-24	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
EB-24-A								x	x	x	x	x	x	x									x	x	x	x
EB-24.3																								x	x	x

Range Line Survey Dates (Continued)

Range	Year																								
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-24.4																										
EB-24.5																							x			
EB-24.6																								x	x	x
EB-24.8																										
EB-24.9																								x	x	x
EB-24B																										
EB-25	x			x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
EB-25.2																										
EB-25.3																								x	x	x
EB-25.4																										
EB-25.5																								x	x	
EB-25.6																								x		
EB-25.8																										
EB-25.9																										
EB-26				x		x		x	x	x	x	x	x	x	x		x	x	x	x	x		x		x	x
EB-26.3								x																		
EB-26.6								x																		
EB-26.7																										
EB-26A																										
EB-26B																										
EB-26C																										
EB-26D																								x	x	x
EB-26E																										
EB-26F																								x	x	x
EB-26G																										
EB-26H																										
EB-26I																								x	x	x
EB-26J																										
EB-26K																										

Range Line Survey Dates (Continued)

Range	Year																									
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-27	x			x	x			x	x	x	x		x	x	x	x	x	x				x				
EB-27.3																								x	x	x
EB-27.6																								x	x	x
EB-27A																										
EB-27B																										
EB-27C																										
EB-27D																										
EB-27E																										
EB-28								x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x
EB-28 TCH																										
EB-28.3																								x	x	x
EB-28.5																								x	x	x
EB-28.7																								x	x	x
EB-28A																										
EB-29					x			x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x
EB-29 TCH																										
EB-29.1																								x	x	x
EB-29.2																		x								
EB-29.3																								x	x	x
EB-29.5																		x	x	x	x		x	x	x	x
EB-29.7																								x	x	x
EB-29.8																		x						x	x	x
EB-30								x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
EB-30.3																								x	x	x
EB-30.5																		x								
EB-30.6																								x	x	x
EB-31																	x	x	x	x	x		x	x	x	x
EB-32					x				x	x	x		x	x	x			x	x	x	x	x	x	x	x	x
EB-32.1																								x	x	x

Range Line Survey Dates (Continued)

Range Line	Year																									
	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-32.3																	x		x	x	x	x	x	x	x	x
EB-32.5																								x	x	x
EB-32.7																	x		x	x	x	x	x	x	x	x
EB-33																	x	x	x	x	x	x	x	x	x	x
EB-33.3																	x							x	x	x
EB-33.6																								x	x	x
EB-33.65																								x	x	x
EB-33.7																	x							x	x	x
EB-33.8																									x	x
EB-34				x		x		x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x
EB-34.5																								x	x	x
EB-34.8																								x		
EB-35																	x		x	x	x		x	x	x	x
EB-35.2																								x	x	x
EB-35.5																								x	x	x
EB-35.8																								x	x	x
EB-36																			x	x	x		x	x	x	x
EB-36.3																								x	x	x
EB-36.6																								x	x	x
EB-37																			x	x	x		x	x	x	x
EB-37.2																								x	x	x
EB-37.5																			x	x	x	x	x	x	x	x
EB-37.7																								x	x	x
EB-38																			x	x	x	x	x	x	x	x
EB-38.1																						x	x	x	x	x
EB-38.15																						x				
EB-38.2																						x	x	x	x	x
EB-38.3																						x	x	x	x	x
EB-38.4																						x				

Range Line Survey Dates (Continued)

Range	Year																									
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-38.6																							x	x	x	x
EB-39																			x	x		x	x	x	x	x
EB-39.1																						x				
EB-39.3																							x	x	x	x
EB-39.6																							x	x	x	x
EB-40																			x	x			x	x	x	x
EB-40.2																							x	x	x	x
EB-40.4																							x	x	x	x
EB-40.5																			x	x			x	x	x	x
EB-40.7																							x	x	x	x
EB-40.9																							x	x	x	x
EB-41																			x	x			x	x	x	x
EB-41.4																							x	x	x	x
EB-41.8																							x	x	x	x
EB-42																			x	x			x	x	x	x
EB-42.3																							x	x	x	x
EB-42.5																							x	x	x	x
EB-42.8																							x	x	x	x
EB-43																			x	x			x	x	x	x
EB-43.6																							x	x	x	x
EB-44																			x	x			x	x	x	x
EB-44.6																							x	x	x	x
EB-45																			x	x			x	x	x	x
EB-45.6																							x	x	x	x
EB-46																			x	x			x	x	x	x
EB-46.4																							x	x	x	x
EB-47																			x	x			x	x	x	x
EB-47.3																							x	x	x	x
EB-47.7																							x	x	x	x

Range Line Survey Dates (Continued)

Range	Year																								
Line	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-48																			x	x			x	x	x	x
EB-48.3																							x	x	x	x
EB-48.5																							x	x	x	x
EB-48.7																							x	x	x	x
EB-49																			x	x			x	x	x	x
EB-49.5																							x	x	x	x
EB-49.7																							x	x	x	x
EB-50																			x	x			x	x	x	x
EB-50.3																							x	x		
EB-50.7																							x	x		
EB-51																							x	x		
EB-51.3																							x	x		
EB-51.7																							x	x		
EB-52																							x	x		
EB-52.4																							x	x		
EB-52.7																							x	x		
EB-53																							x	x		
EB-53.3																							x	x		
EB-53.7																							x	x		
EB-54																							x	x		
EB-54.4																							x	x		
EB-54.7																							x	x		
EB-55																							x	x		
EB-55.3																							x	x		
EB-55.7																							x	x		
EB-56																							x	x		
EB-56.4																							x	x		
EB-56.7																							x	x		
EB-57																							x	x		

Range Line Survey Dates (Continued)

Range Line	Year																									
	80	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10
EB-57.3																							x	x		
EB-57.5																							x	x		
EB-57.8																							x	x		
EB-58																							x	x		
EB-58.4																							x	x		
EB-58.6																							x	x		
EB-59																							x	x		
EB-59.5																							x	x		
EB-60																							x	x		

APPENDIX B: DAILY DISCHARGE HYDROGRAPHS

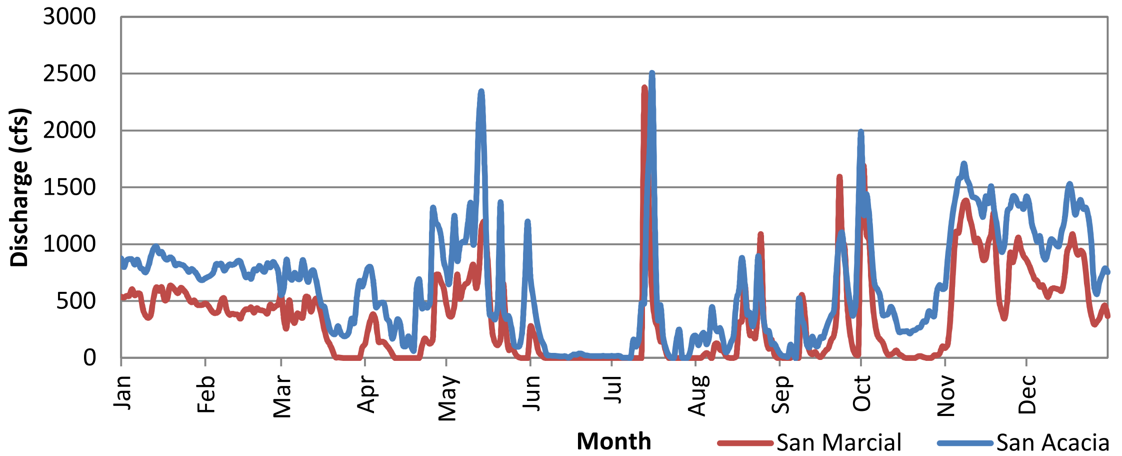

Figure B.1 1990 Daily Discharge Data

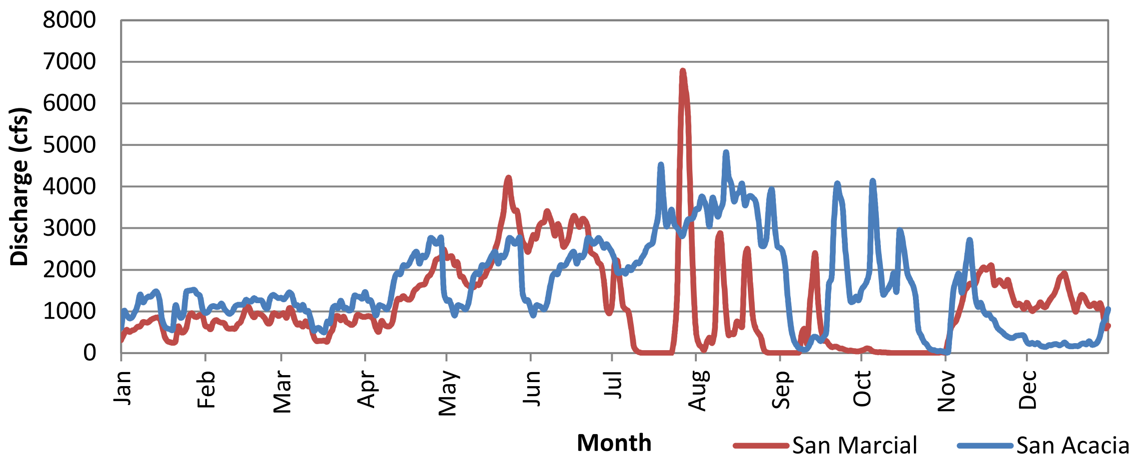

Figure B.2 1991 Daily Discharge Data

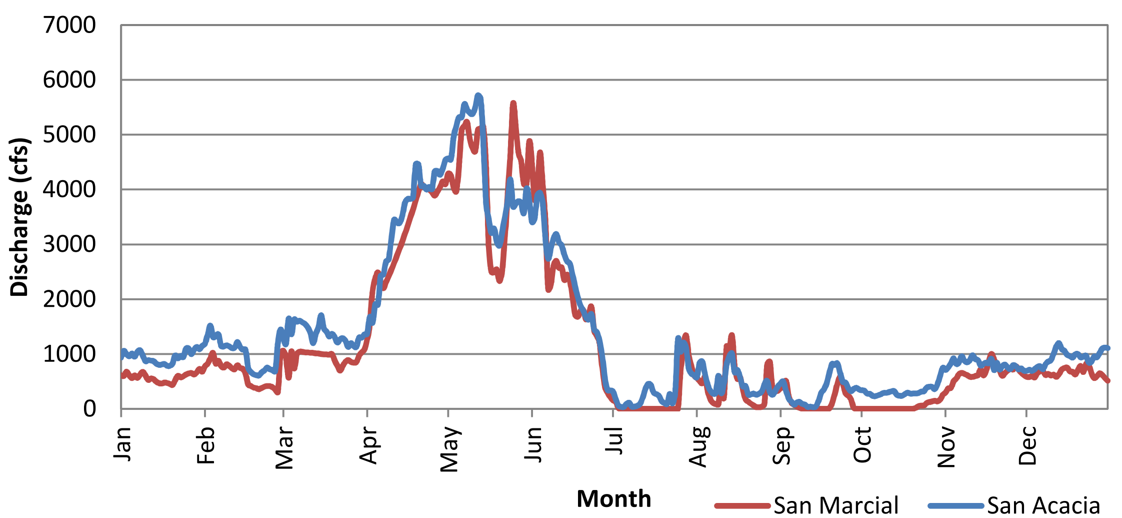

Figure B.3 1992 Daily Discharge Data

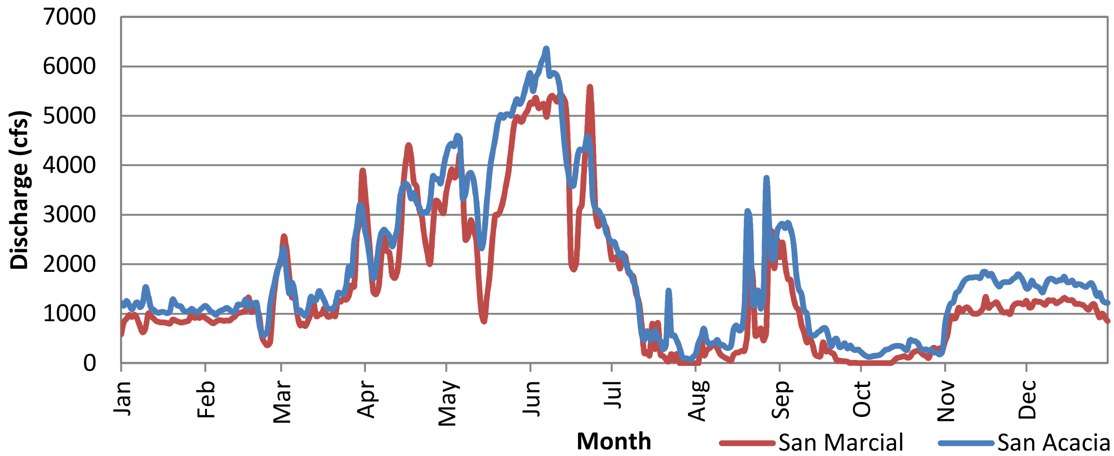

Figure B.4 1993 Daily Discharge Data

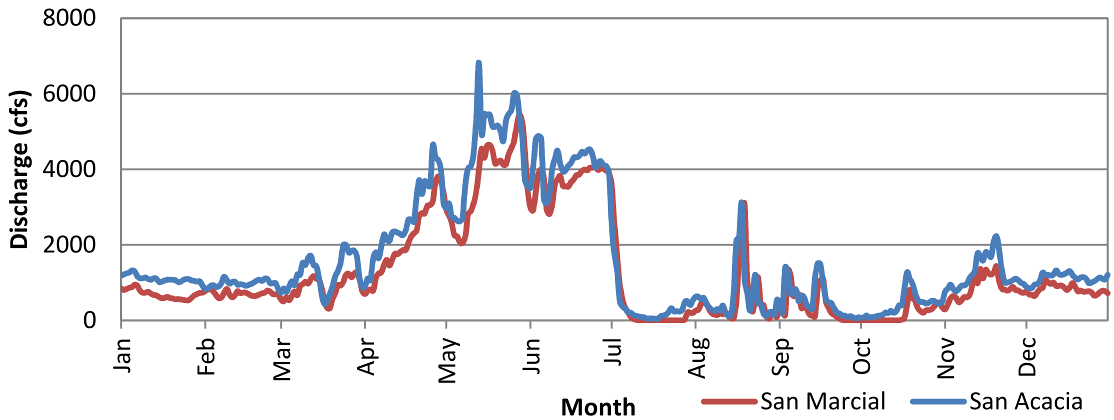

Figure B.5 1994 Daily Discharge Data

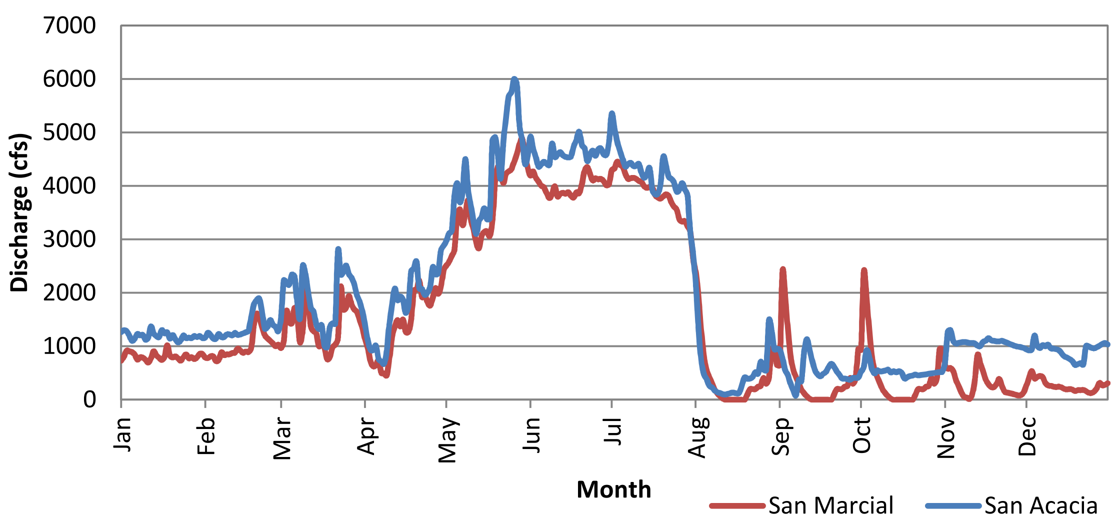

Figure B.6 1995 Daily Discharge Data

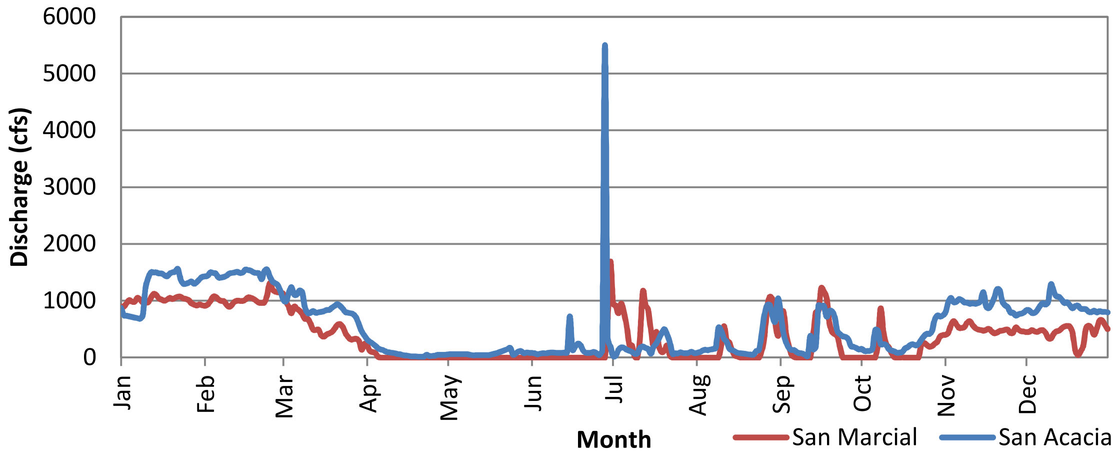

Figure B.7 1996 Daily Discharge Data

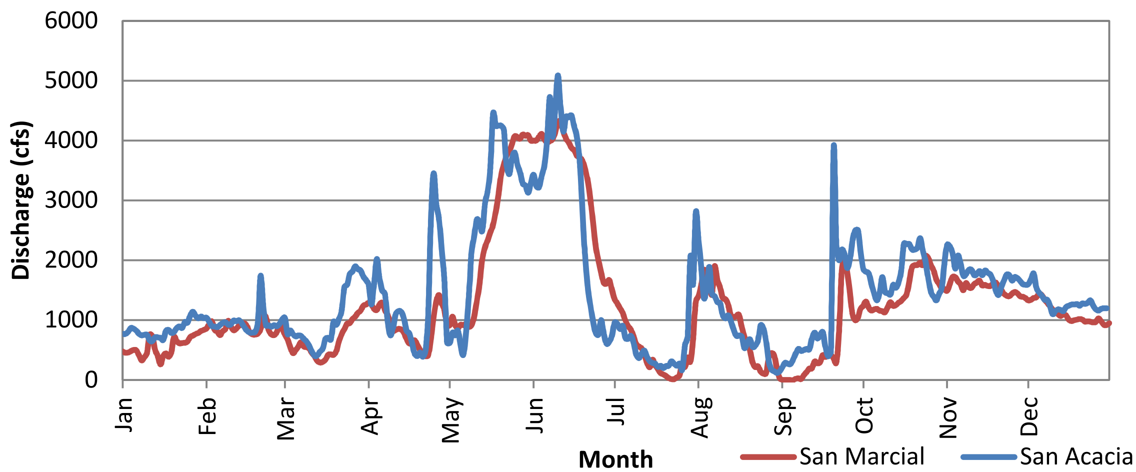

Figure B.8 1997 Daily Discharge Data

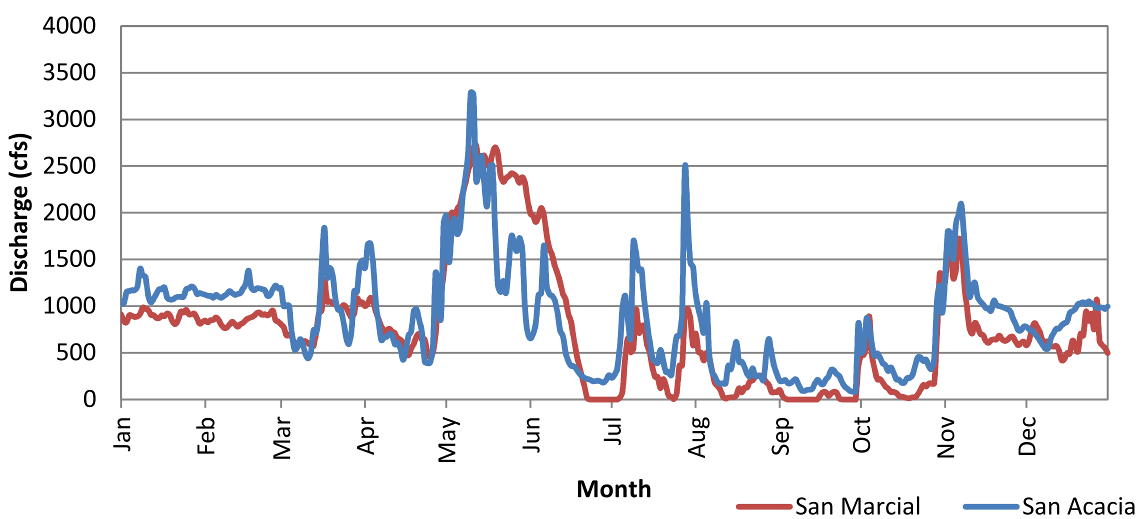

Figure B.9 1998 Daily Discharge Data

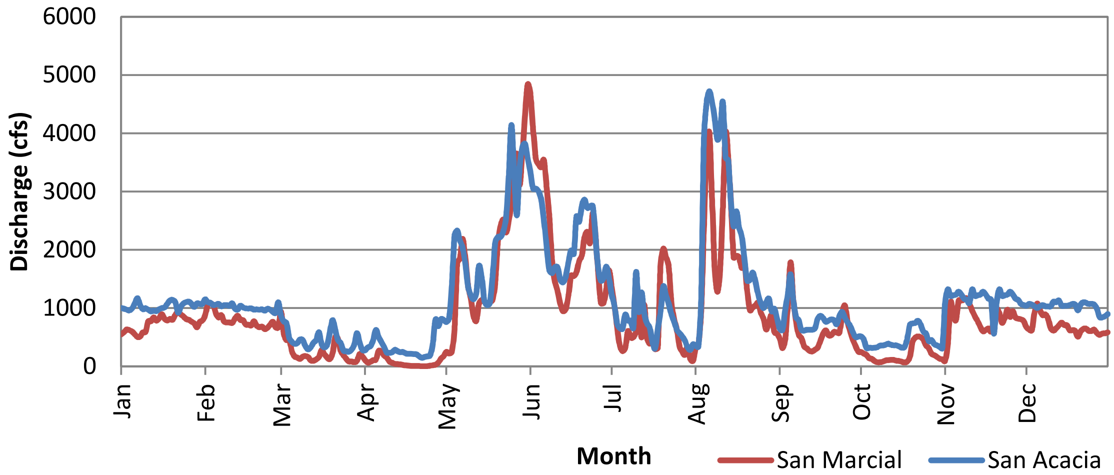

Figure B.10 1999 Daily Discharge Data

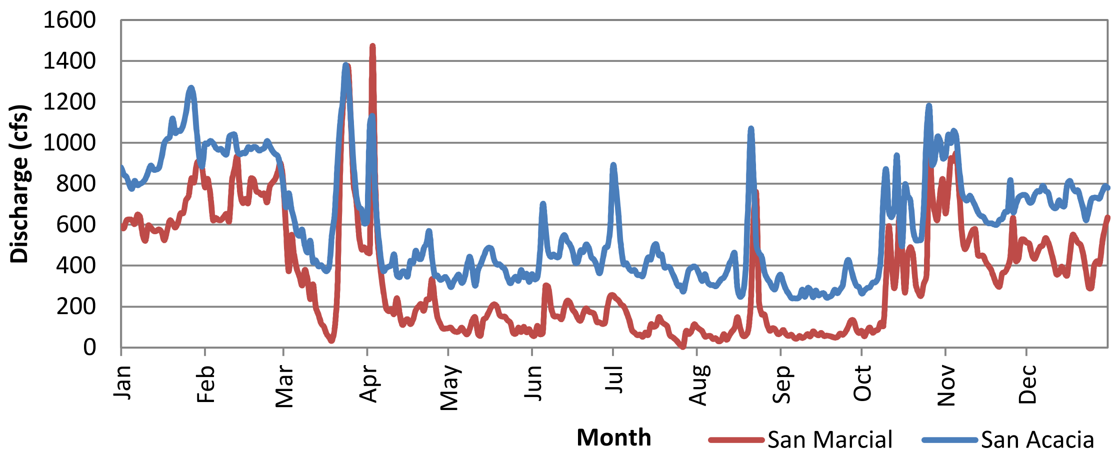

Figure B.11 2000 Daily Discharge Data

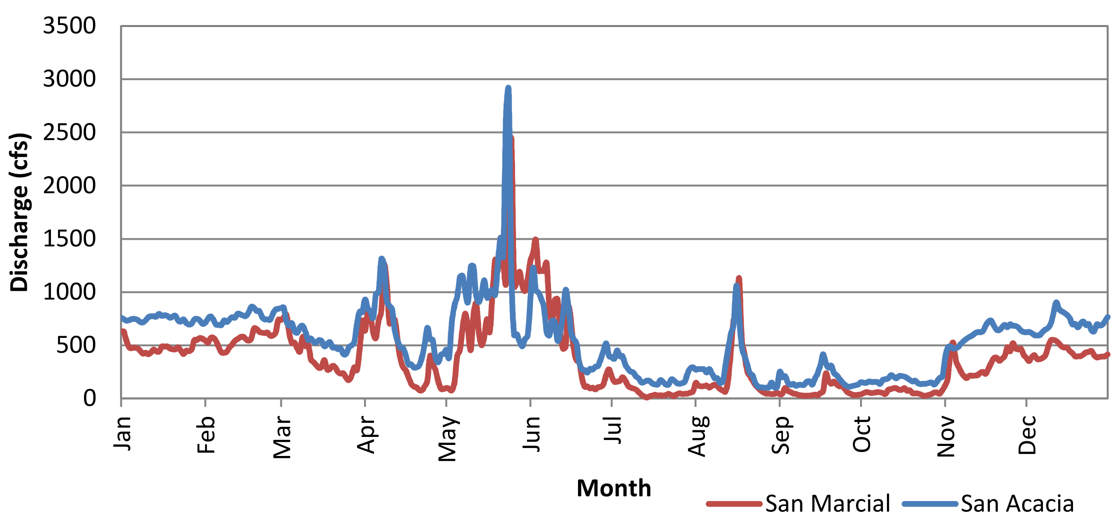

Figure B.12 2001 Daily Discharge Data

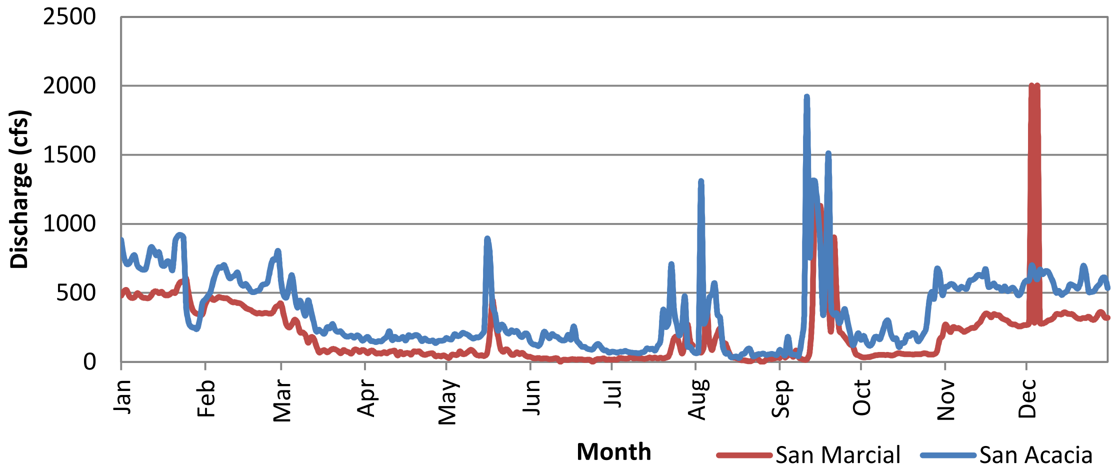

Figure B.13 2002 Daily Discharge Data

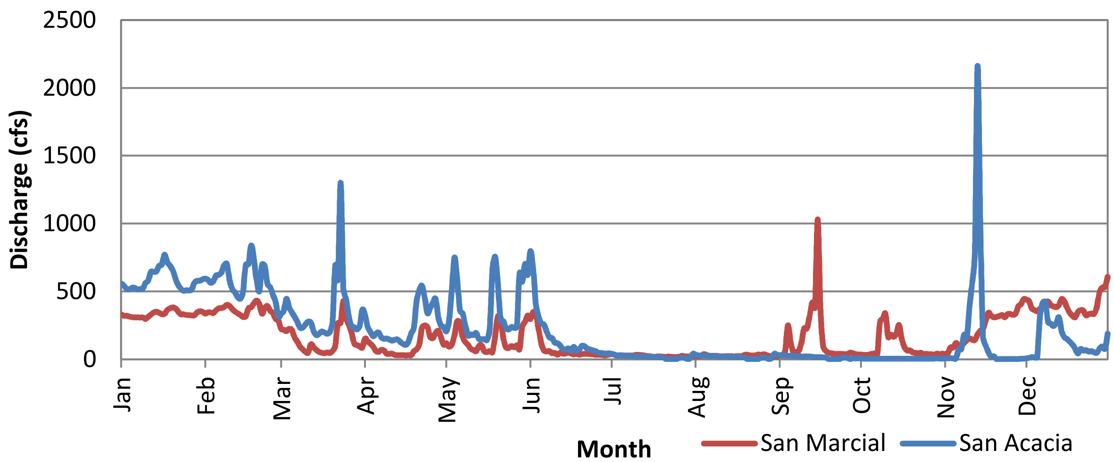

Figure B.14 2003 Daily Discharge Data

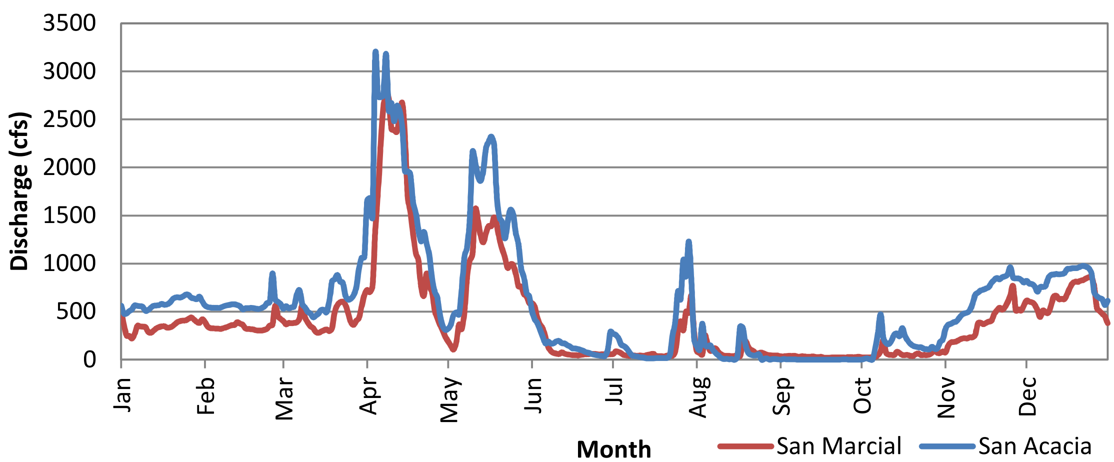

Figure B. 15 2004 Daily Discharge Data

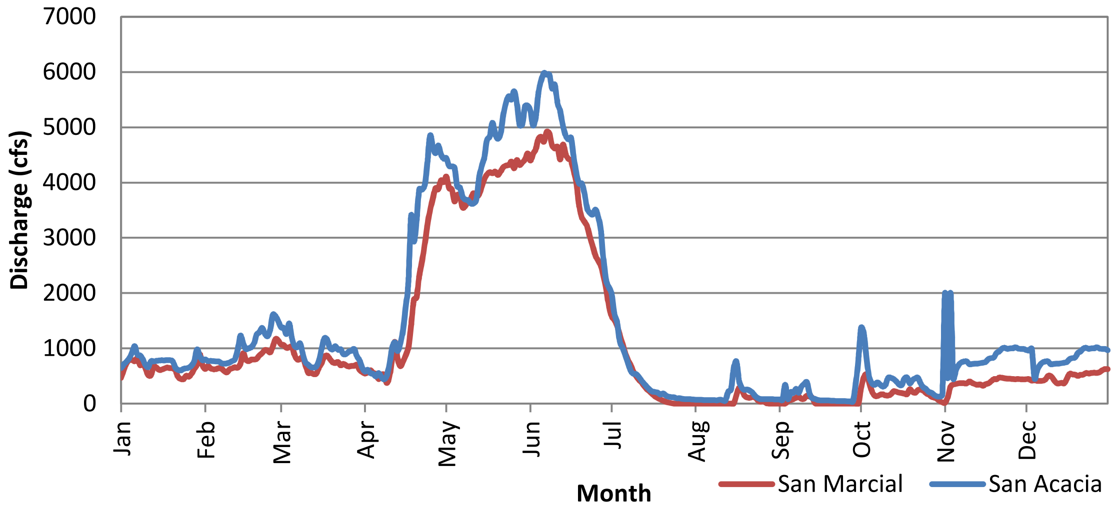

Figure B.16 2005 Daily Discharge Data

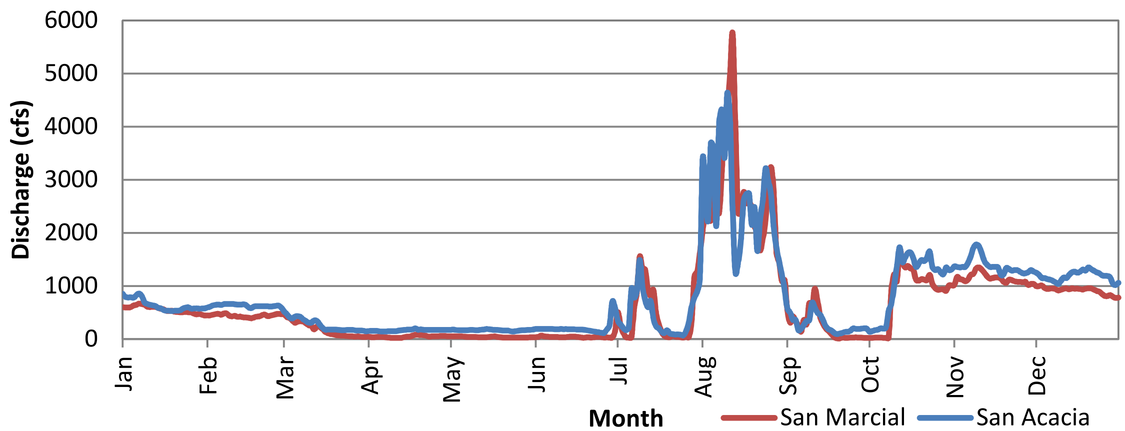

Figure B.17 2006 Daily Discharge Data

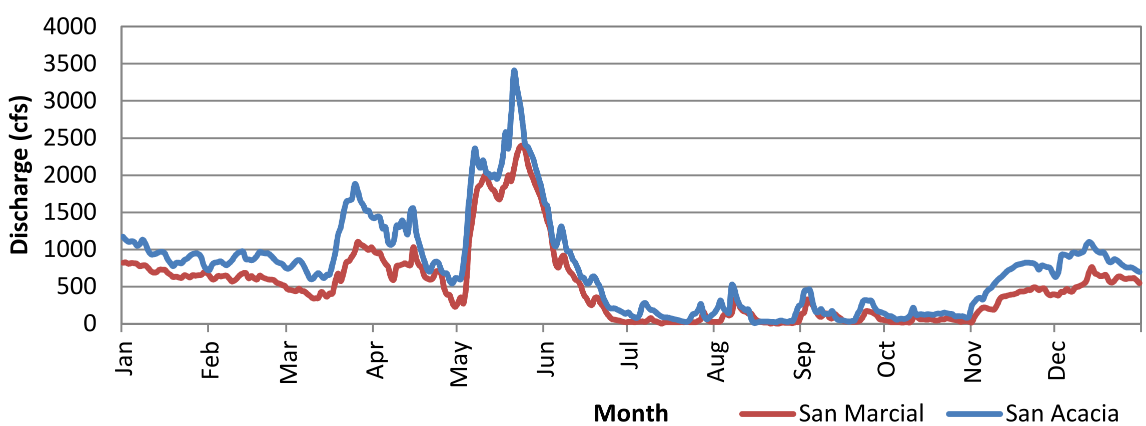

Figure B.18 2007 Daily Discharge Data

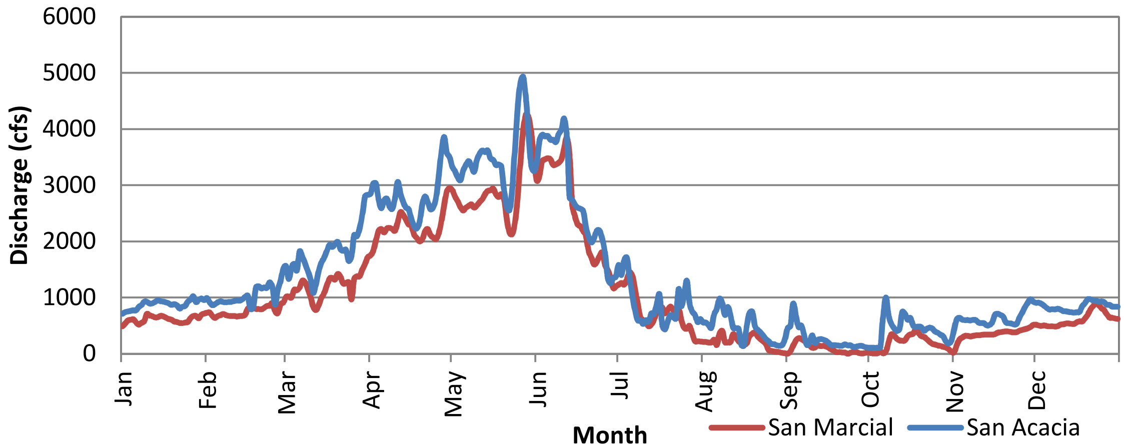

Figure B.19 2008 Daily Discharge Data

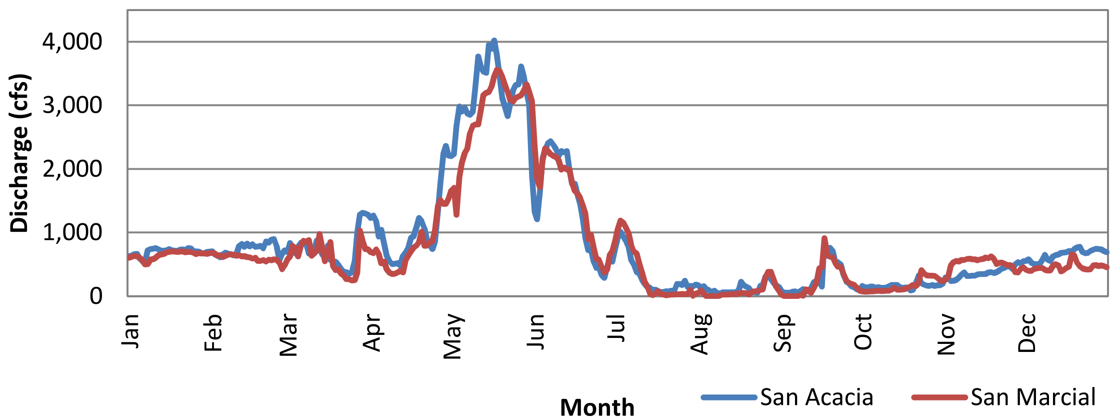

Figure B.20 2009 Daily Discharge Data

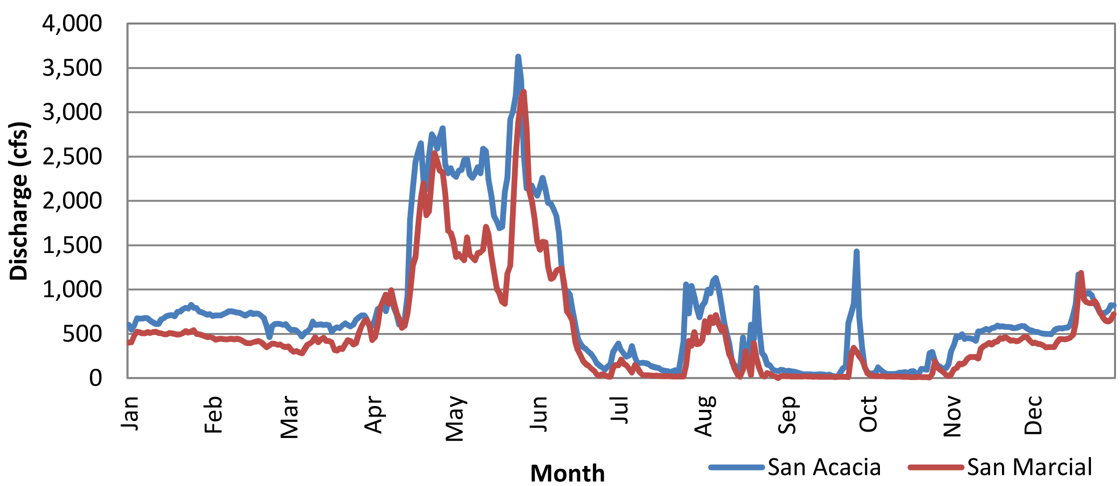

Figure B.21 2010 Daily Discharge Data

APPENDIX C: DATES AND LOCATIONS OF BED MATERIAL SAMPLES

Table C.1 Available Bed Material Data at Range Lines

	Year															
Range Line	**86**	**87**	**88**	**90**	**92**	**93**	**94**	**96**	**97**	**98**	**99**	**01**	**02**	**04**	**05**	**07**
SO-1641												X	X	X	X	
SO-1652.7									X		X					
SO-1660											X					
SO-1665																X
SO-1666								X	X		X					
SO-1670											X					
SO-1683											X					
SO-1701.3								X	X		X					
EB-5	X	X	X													
EB-10	X	X	X	X	X	X	X		X	X	X		X			
EB-13	X	X	X	X							X		X			
EB-14	X	X	X													
EB-16	X	X	X	X												
EB-17	X															X
FC-1754						X										
EB-18	X	X	X	X		X	X		X		X		X			
EB-20	X	X	X	X		X	X		X		X		X			
EB-34				X							X		X			
EB-24	X				X						X		X			
EB-24A					X	X	X		X	X						
EB-25				X	X											
EB-26					X											
EB-26.6					X											
EB-27					X											
EB-28					X											
EB-29					X											
EB-29.5																X
EB-30					X											
EB-36																X

APPENDIX D: DATES AND LOCATIONS OF USGS GAUGE BED MATERIAL SAMPLES

Table D.1: Available Bed Material Data at USGS gauging stations: San Acacia and San Marcial

Year	Gauging station		Year	Gauging station	
	San Acacia	San Marcial		San Acacia	San Marcial
1966	x		**1988**	x	x
1967			**1989**	x	x
1968	x	x	**1990**	x	x
1969	x	x	**1991**	x	x
1970			**1992**	x	x
1971			**1993**	x	x
1972		x	**1994**	x	x
1973	x	x	**1995**	x	x
1974		x	**1996**	x	x
1975	x	x	**1997**	x	x
1976	x	x	**1998**	x	x
1977		x	**1999**	x	x
1978	x	x	**2001**	x	x
1979	x	x	**2002**	x	x
1980	x	x	**2003**	x	x
1981	x	x	**2004**	x	x
1982	x	x	**2005**	x	x
1983	x	x	**2006**	x	x
1984	x	x	**2007**	x	x
1985	x	x	**2008**	x	x
1986	x	x	**2009**	x	x
1987	x	x	**2010**	x	x

APPENDIX E: AERIAL PHOTOGRAPH SURVEY DATES AND INFORMATION

Table E.1 Aerial Photo Survey Dates and Information

	Mean Daily Discharge			
Date	**San Acacia**	**San Marcial**	**Scale**	**Notes (1918-2002:from Novak 2006 2005: from ArcGIS metadata)**
1918	No Data	No Data	1:12,000	Hand-drafted linens (39 sheets). USBR Albuquerque Area Office. Surveyed in 1918. Published in 1922.
1935	No Data	No Data	1:8,00	Black and white photography. USBR Albuquerque Area Office. Flown in 1935. Published in 1936.
1949	No Data	No Data	1:5,000	Photo-mosaic. J-Ammann Photogrammetric Engineers, San Antonio, TX. USBR Albuquerque Area Office.
March 1962	25 cfs	0 cfs	1:4,800	Photo-mosaic. Abram Aerial Survey Corp, Lansing, MI. USBR Albuquerque Area Office.
April 1972	4 cfs	0 cfs	1:4,800	Photo-mosaic. Limbaugh Engineers, Inc., Albuquerque, NM. USBR Albuquerque Area Office.
March 1985	1900 cfs	1320 cfs	1:4,800	Orthophoto. M&I Consulting Engineers, Fort Collins, CO. Aero-Metric Engineering, Sheboygan, MN. USBR Albuquerque Area Office.
February 1992	1020 cfs	630 cfs	1:4,800	Ratio-rectified photo-mosaic. Koogle and Poules Engineering, Albuquerque, NM. USBR Albuquerque Area Office.
February 2001	770 cfs	560 cfs	1:4,800	Ratio-rectified photo-mosaic. Pacific Western Technologies, Ltd., Albuquerque, NM. USBR Albuquerque Area Office.
March 2002	310 cfs	150 cfs	1:4,800	Digital ortho-imagery. Pacific Western Technologies, Ltd., Albuquerque, NM. USBR Albuquerque Area Office.
December 2003	628 cfs	439 cfs	1:28,800	Digital ortho-imagery. USBR Albuquerque Area Office.
Winter 2004	Date Unknown	Date Unknown	1:4,800	Digital ortho-rectified imagery. USBR Albuquerque Area Office.
April 2005	2270 cfs	1680 cfs	1:4,800	Digital ortho-rectified imagery. Aero-Metric, Inc., Fort Collins, CO. USBR Albuquerque Area Office.
January 2006	Date Unknown	Date Unknown	1:4,800	Digital ortho-rectified imagery. Aero-Metric, Inc., Fort Collins, CO. USBR Albuquerque Area Office.
June 2008	3990 cfs	3460	1:45,720	Digital ortho-rectified imagery. USBR Albuquerque Area Office.
2010	Date Unknown	Date Unknown		LiDAR Optec 3100 EA LiDAR 3m. Aero-Metric, Inc., Fort Collins, CO. USBR Albuquerque Area Office.

APPENDIX F: RANGE LINE CROSS-SECTION PLOTS

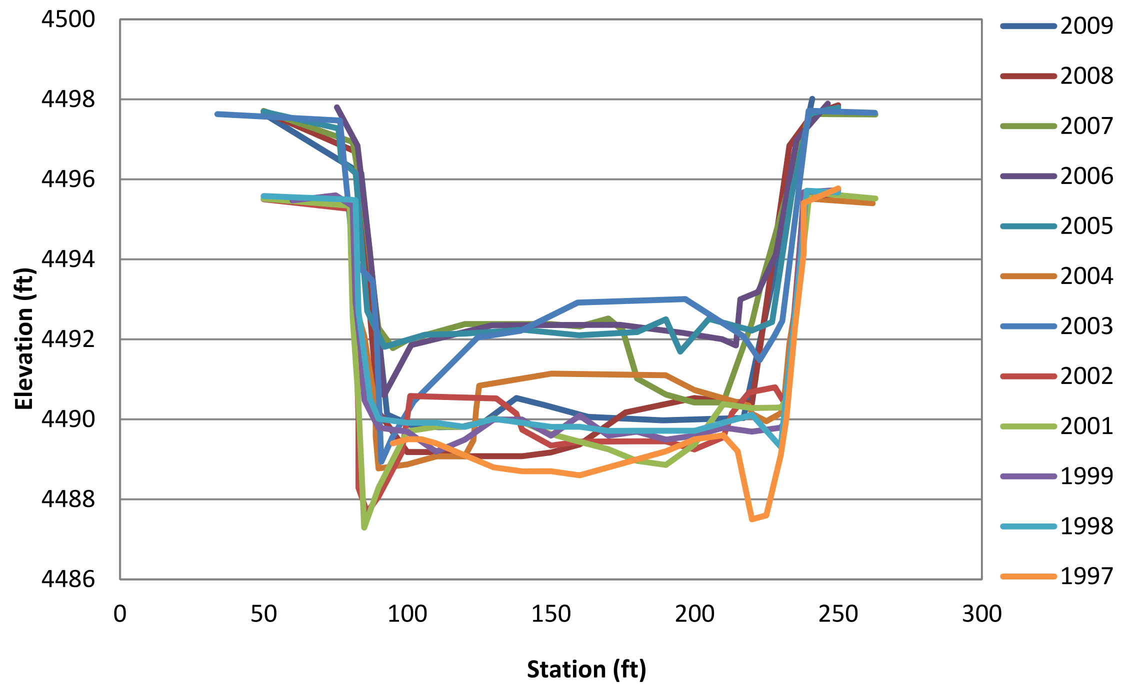

Figure F.1 SO-1641 Cross-Section

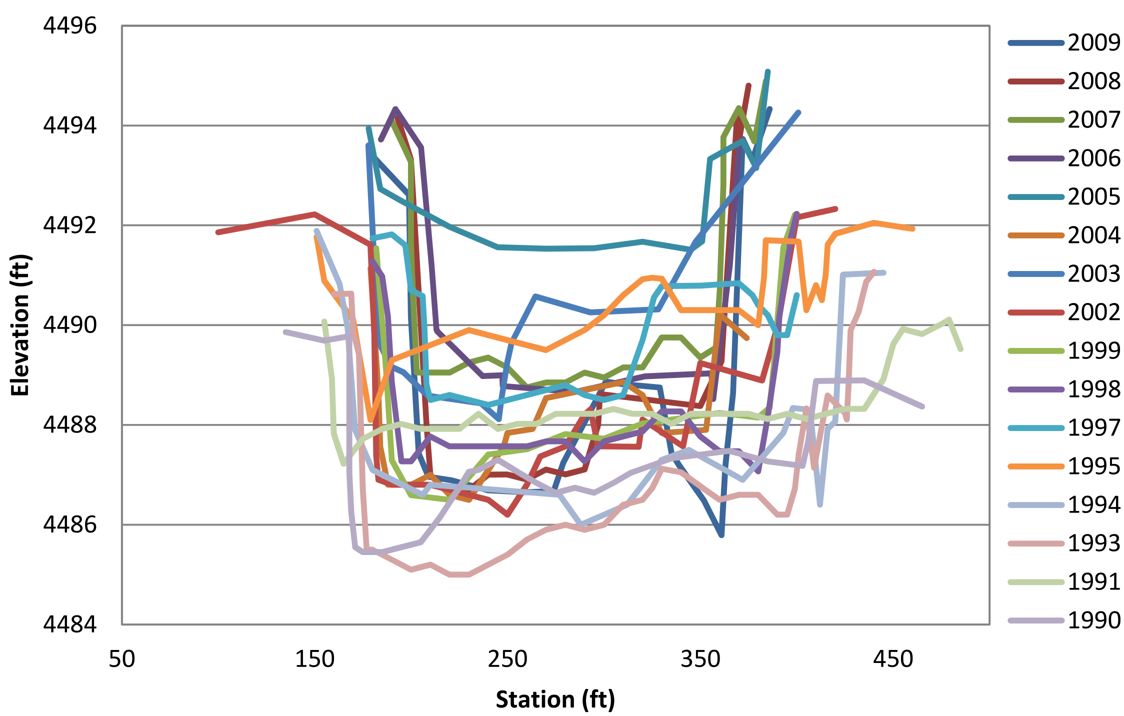

Figure F.2 SO-1652.7 Cross-Section

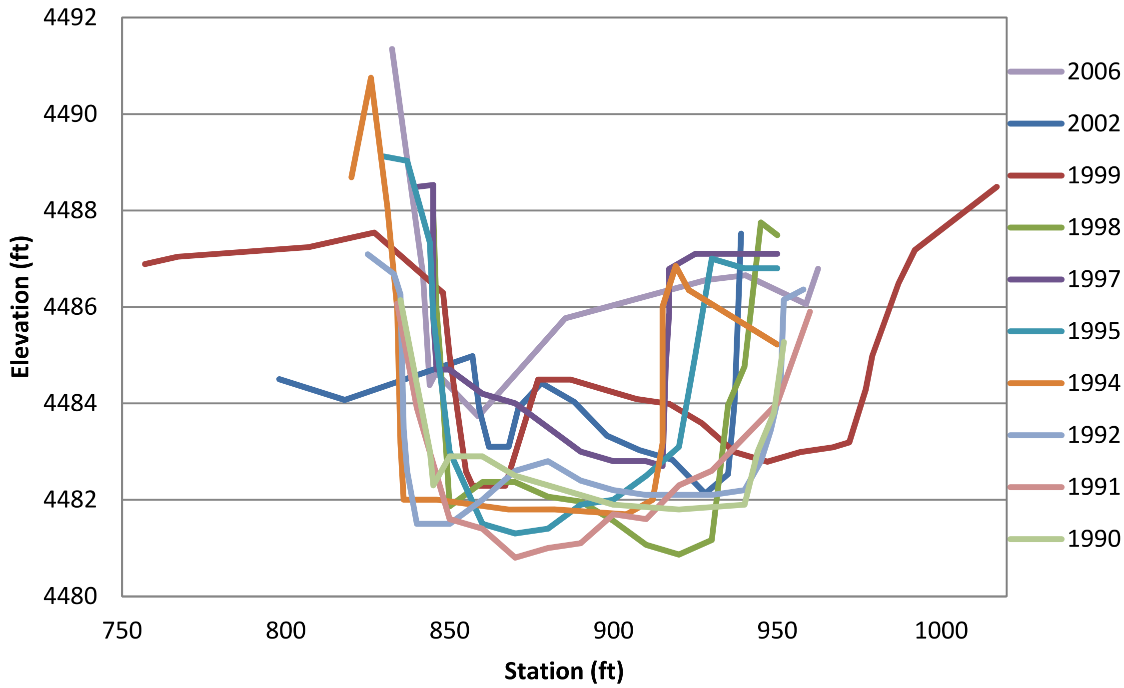

Figure F.3 SO-1666 Cross-Section

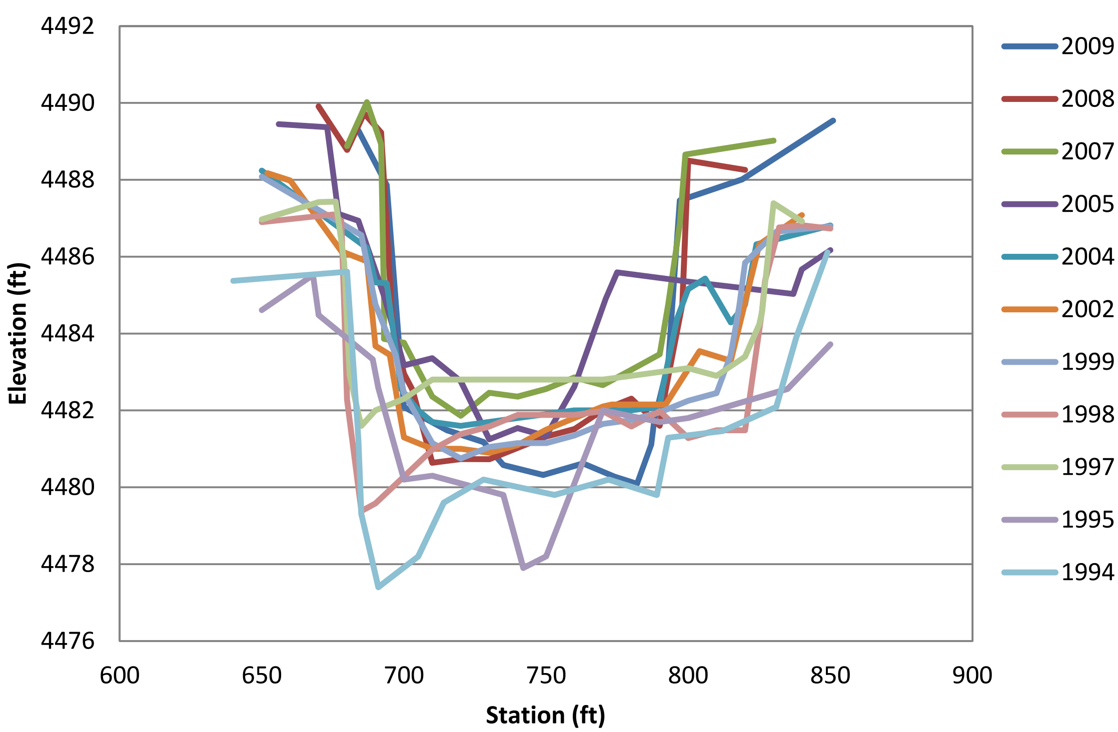

Figure F.4 SO-1673 Cross-Section

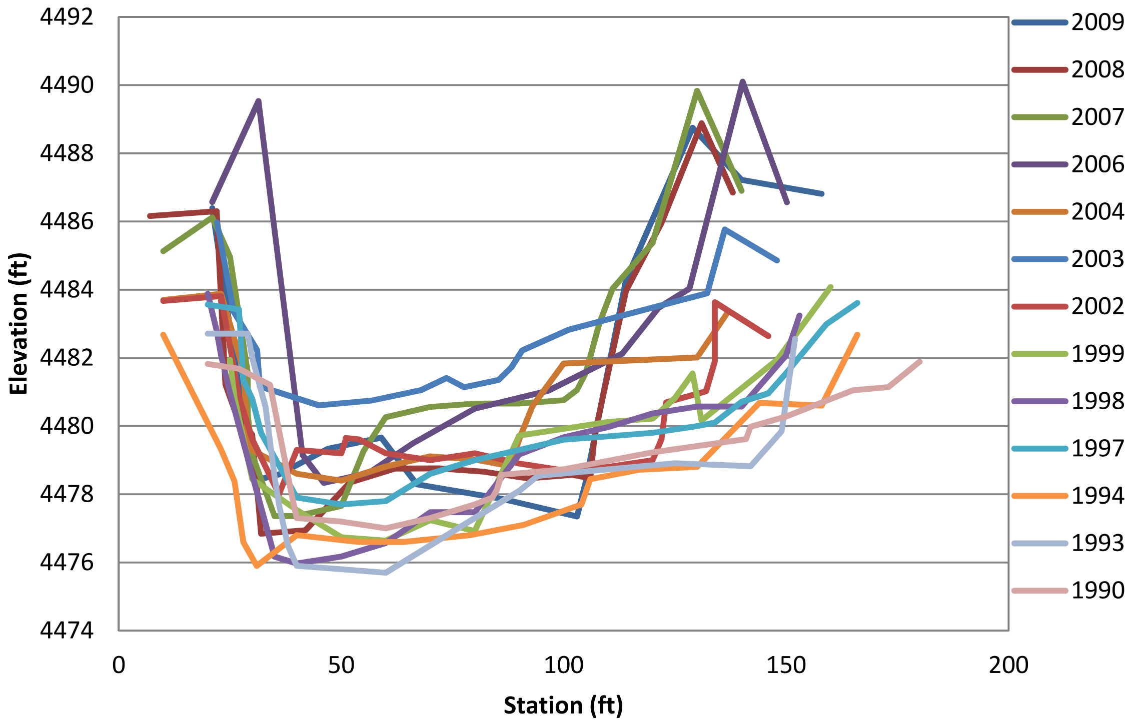

Figure F.5 SO-1683 Cross-Section

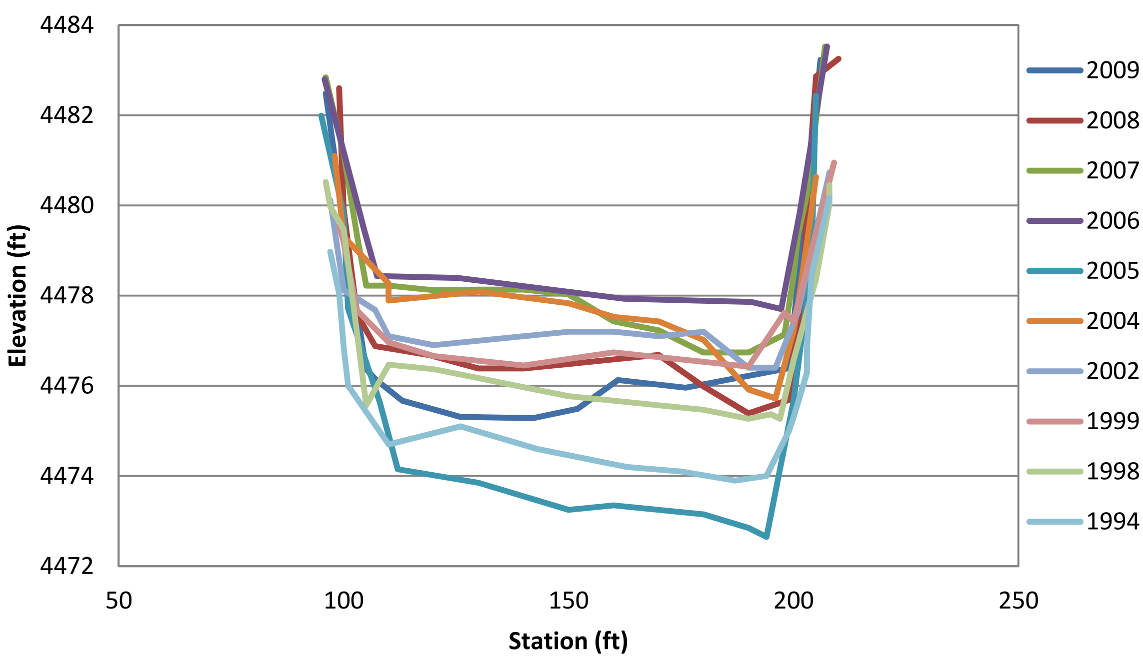

Figure F.6 SO-1692 Cross-Section

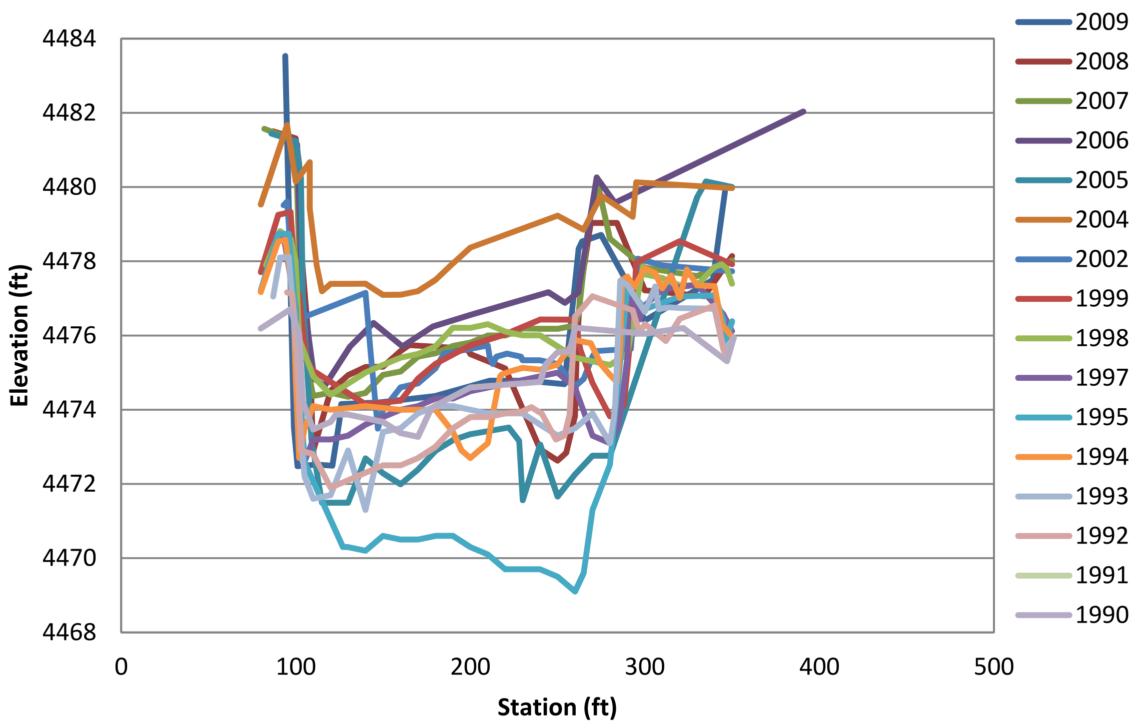

Figure F.7 SO-1701.3 Cross-Section

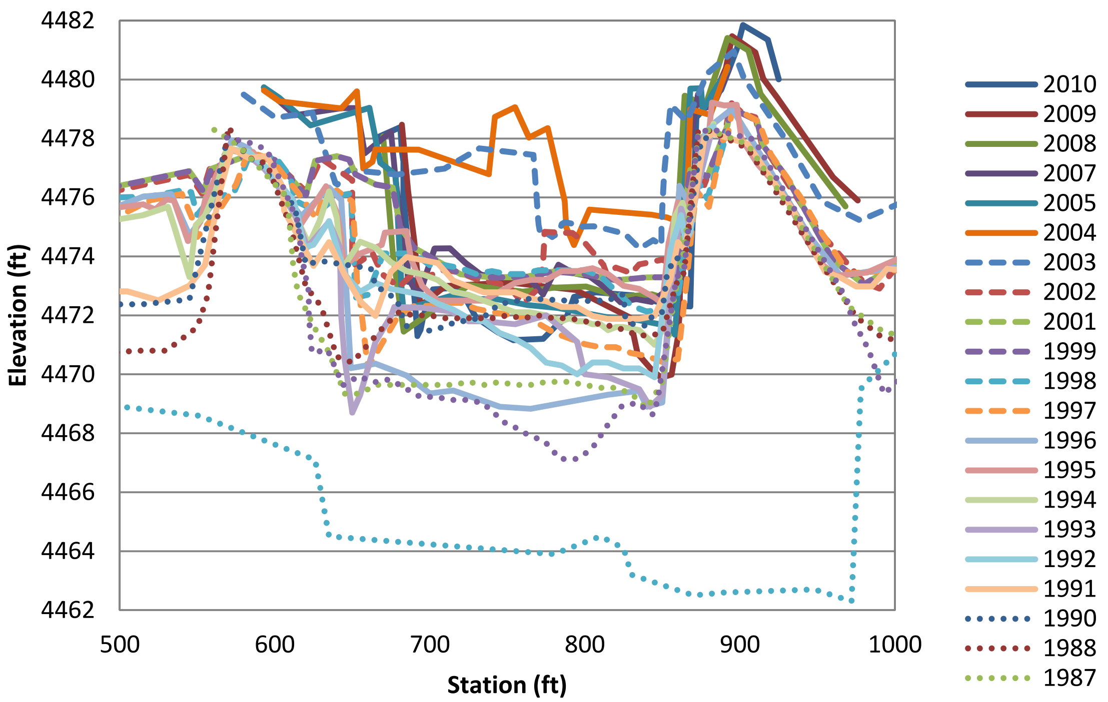

Figure F.8 EB-10 Cross-Section

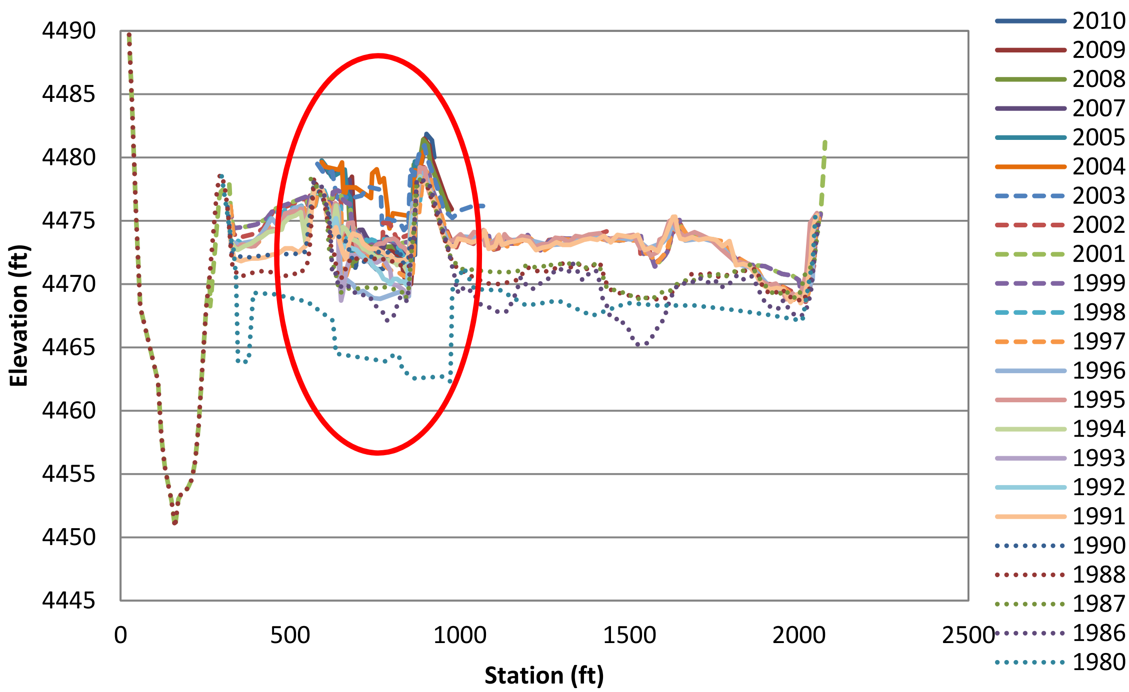

Figure F.9 EB-10 (w/Floodplain) Cross-Section

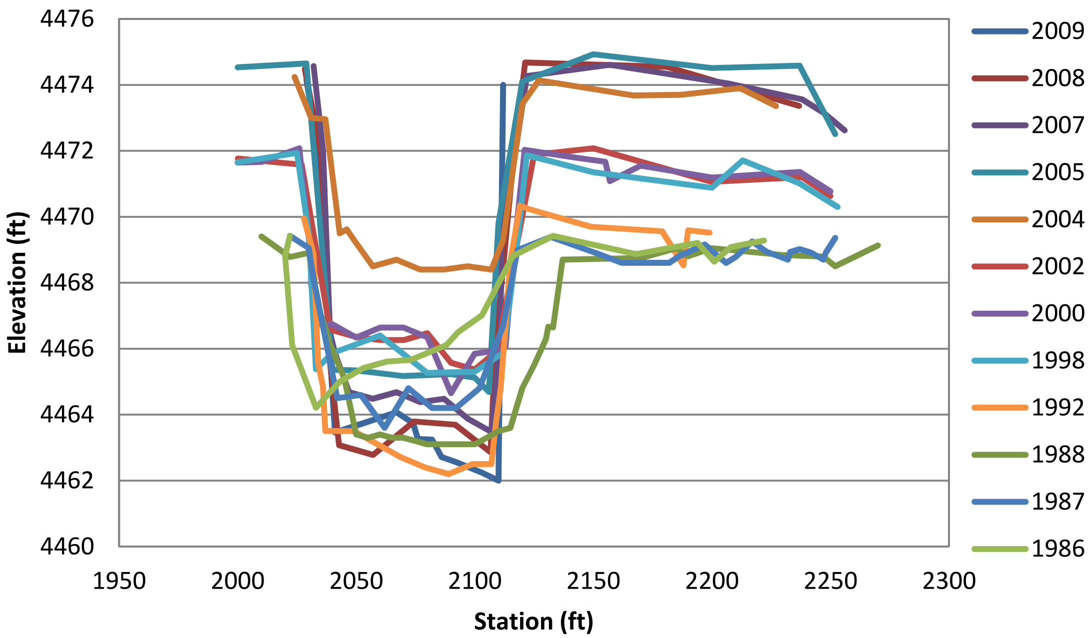

Figure F.10 EB-13 Cross-Section

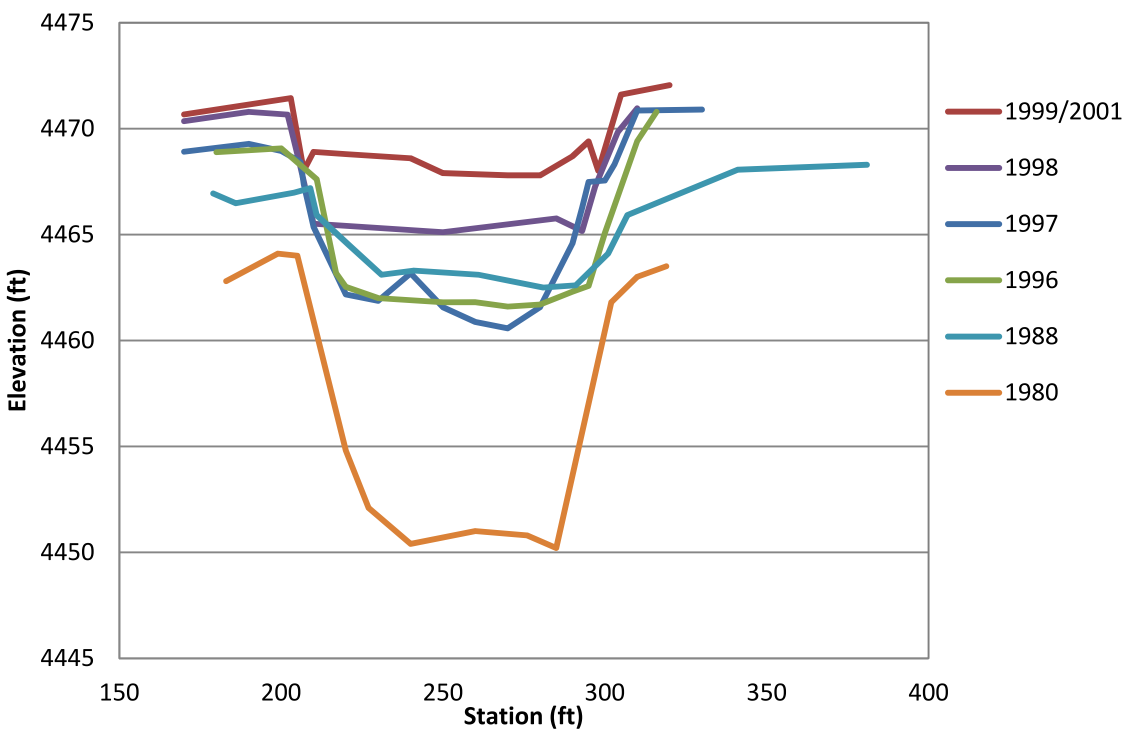

Figure F.11 EB-14 Cross-Section

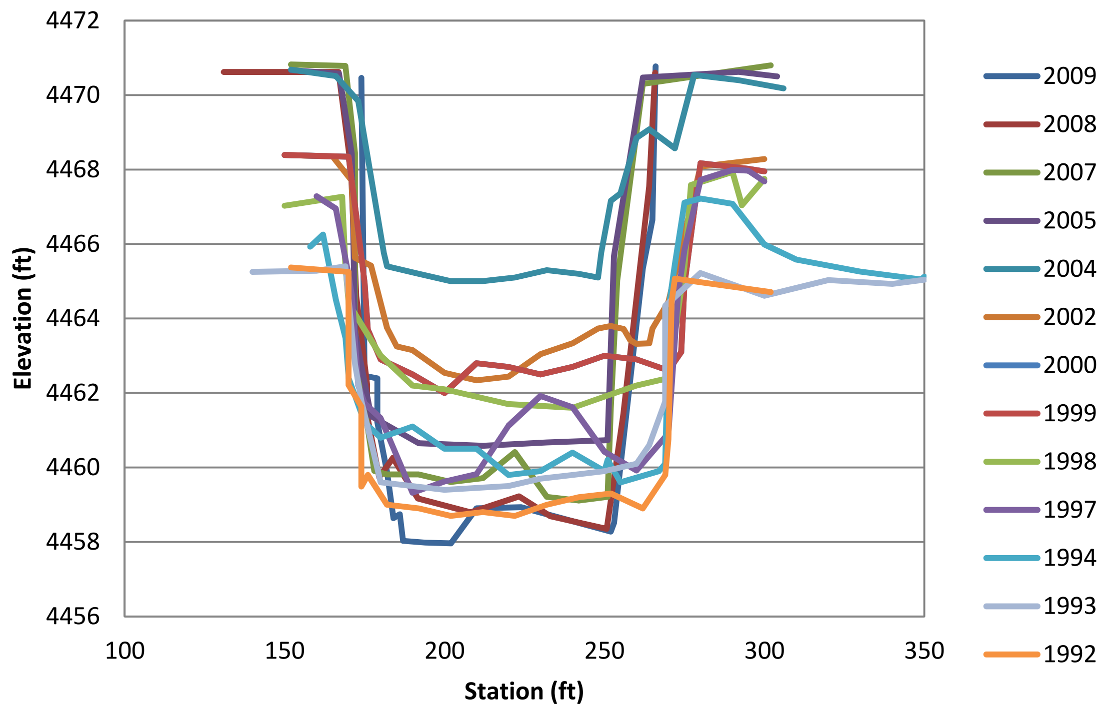

Figure F.12 EB-16 Cross-Section

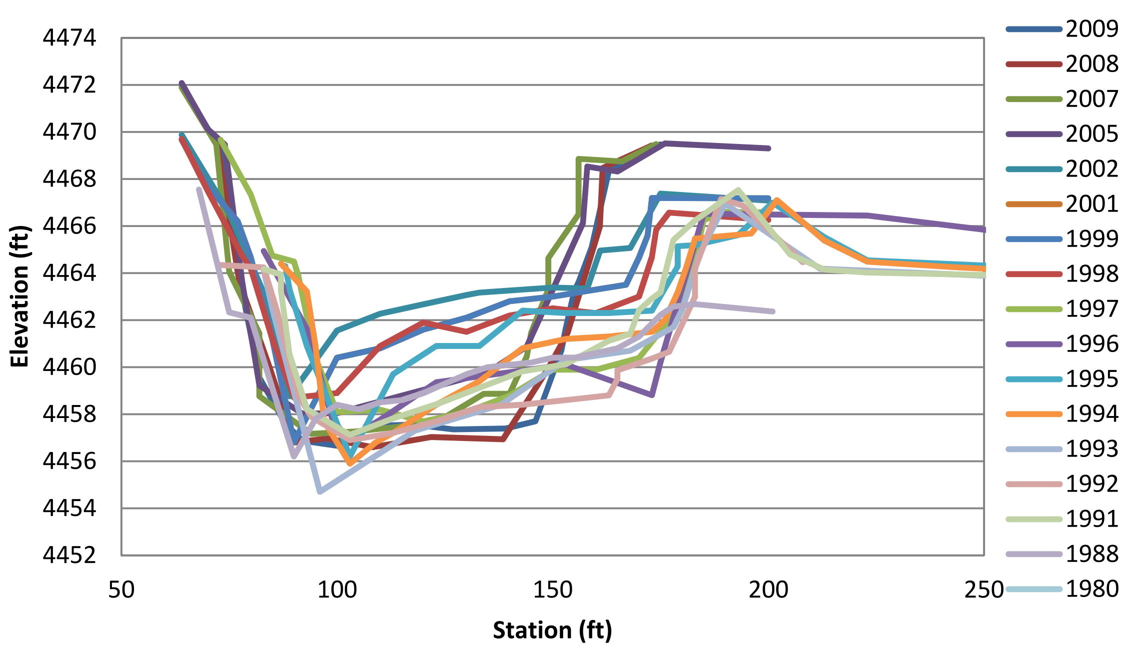

Figure F.13 EB-17 Cross-Section

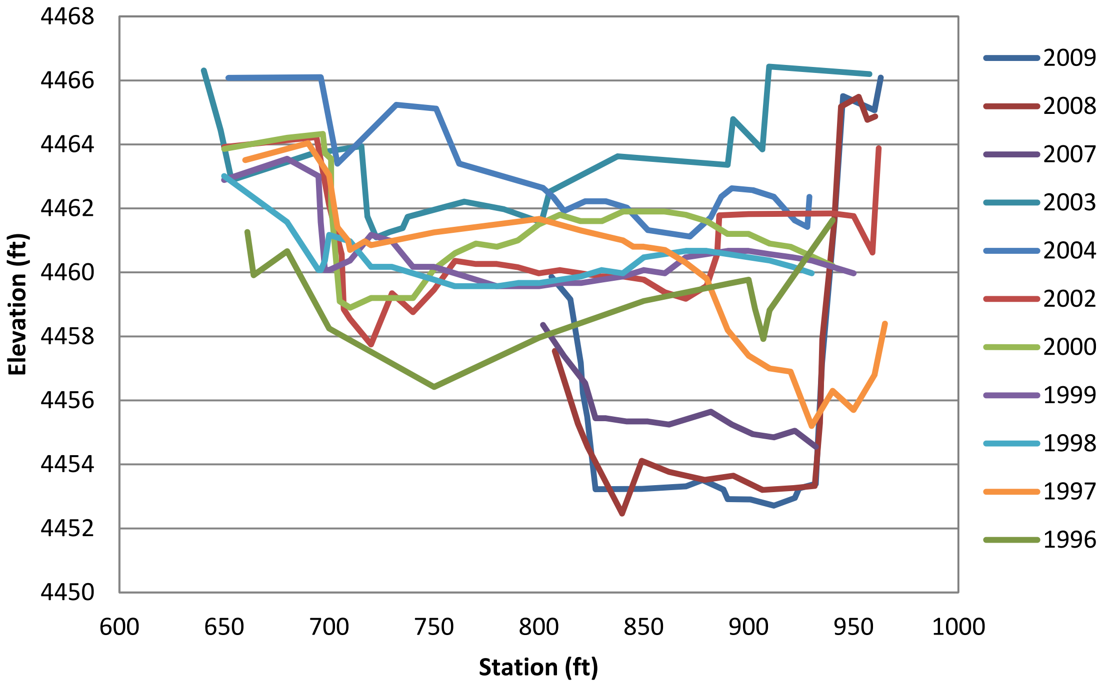

Figure F.14 EB-18 Cross-Section

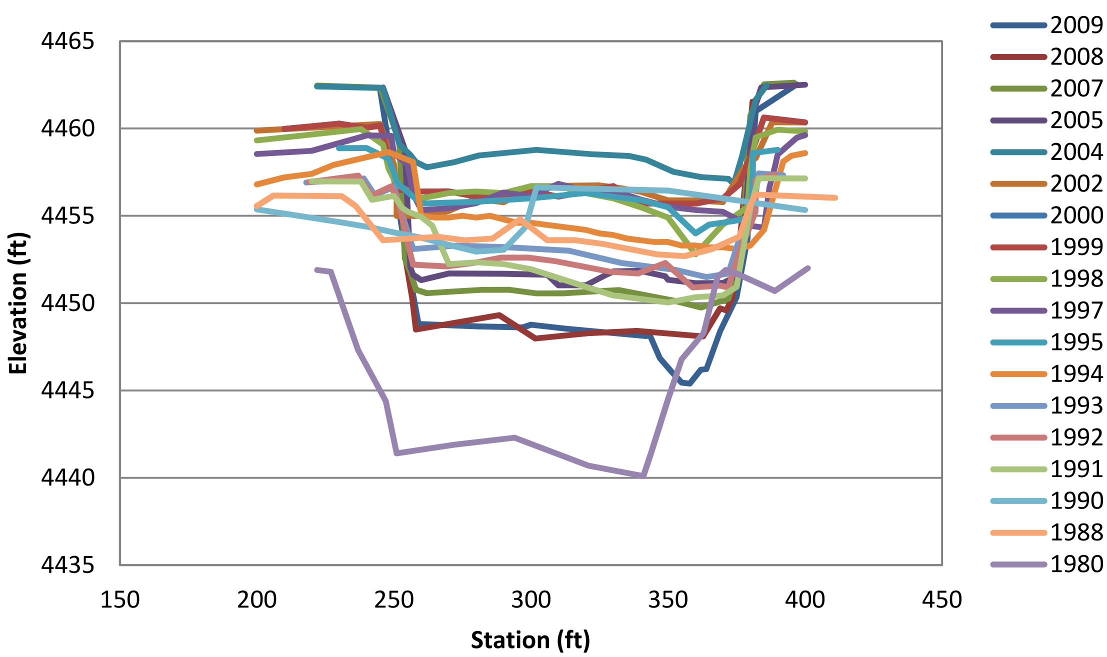

Figure F.15 EB-20 Cross-Section

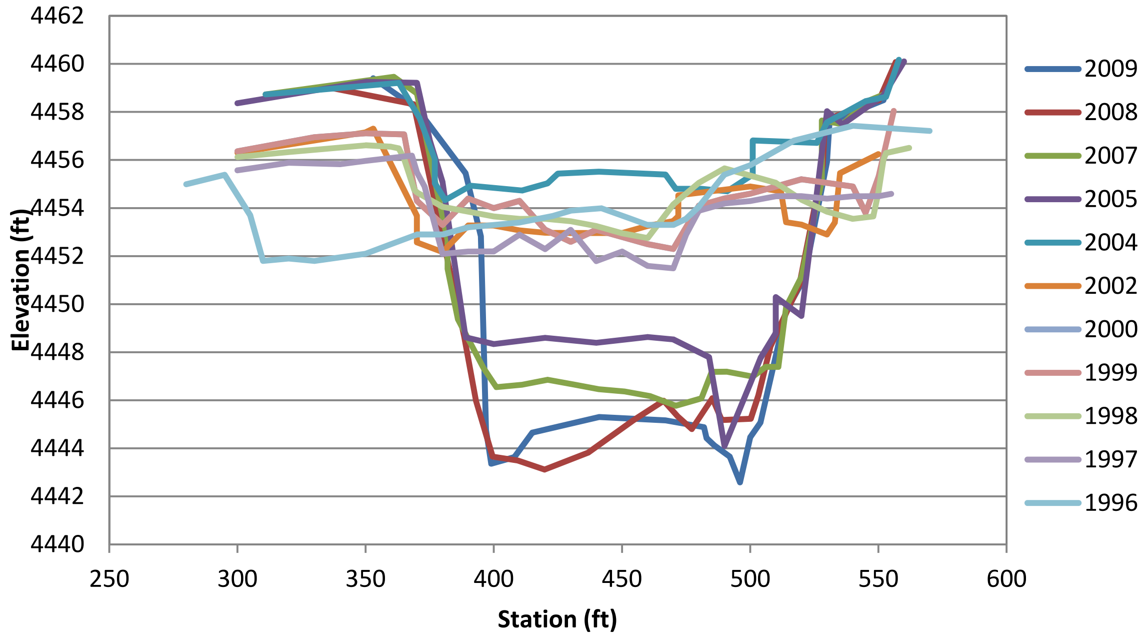

Figure F.16 EB-34 Cross-Section

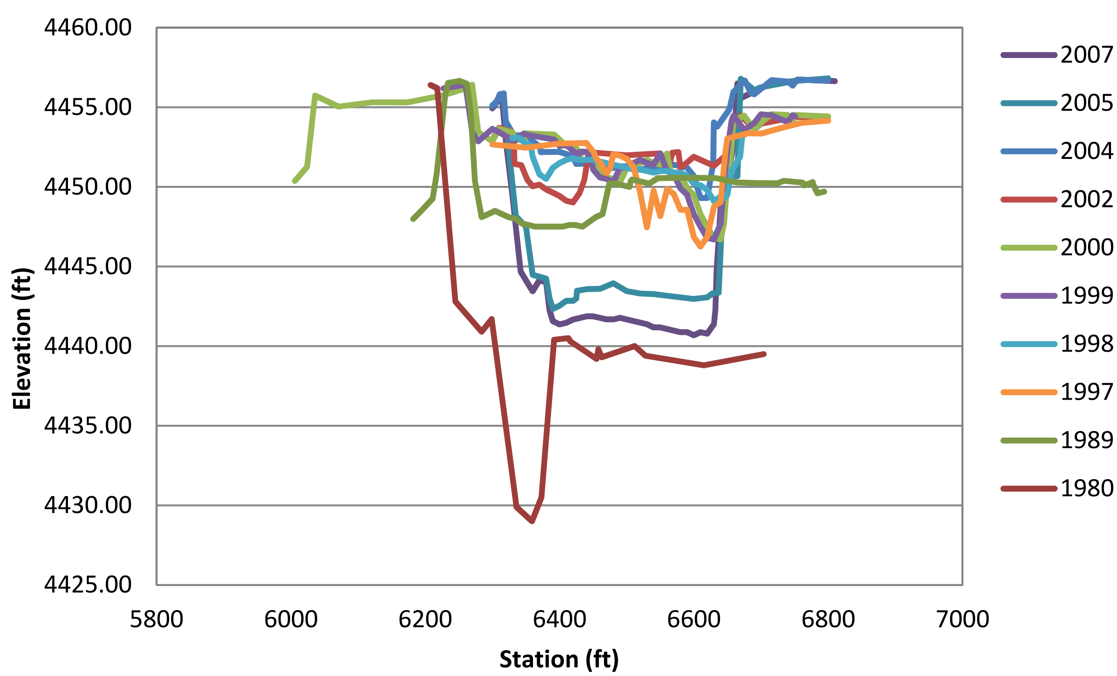

Figure F.17 EB-24 Cross-Section

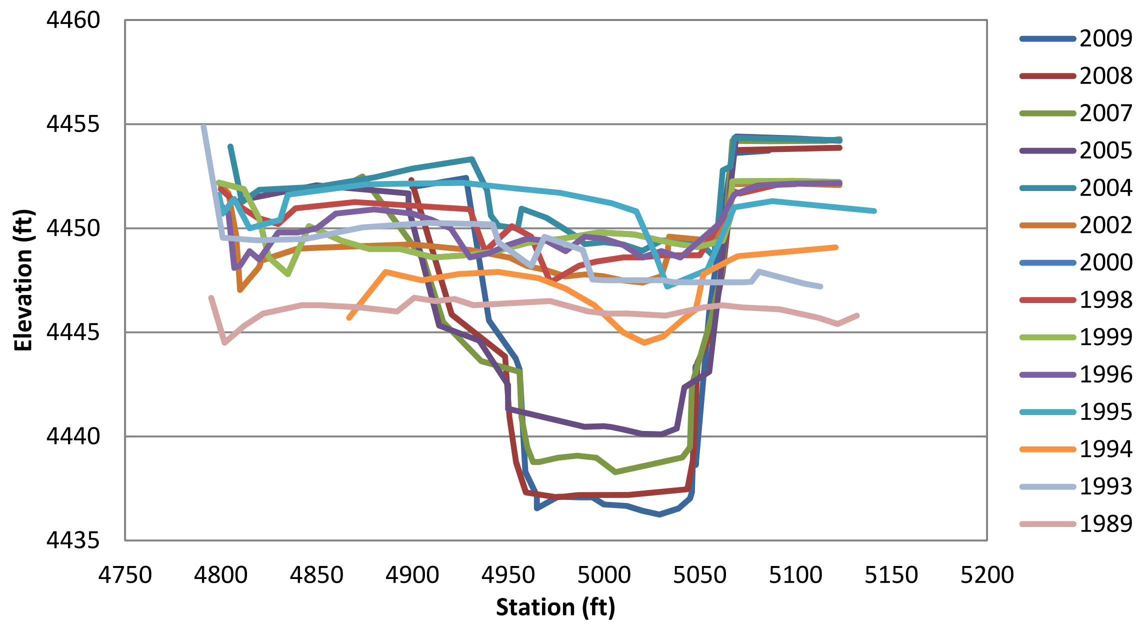

Figure F.18 EB-25 Cross-Section

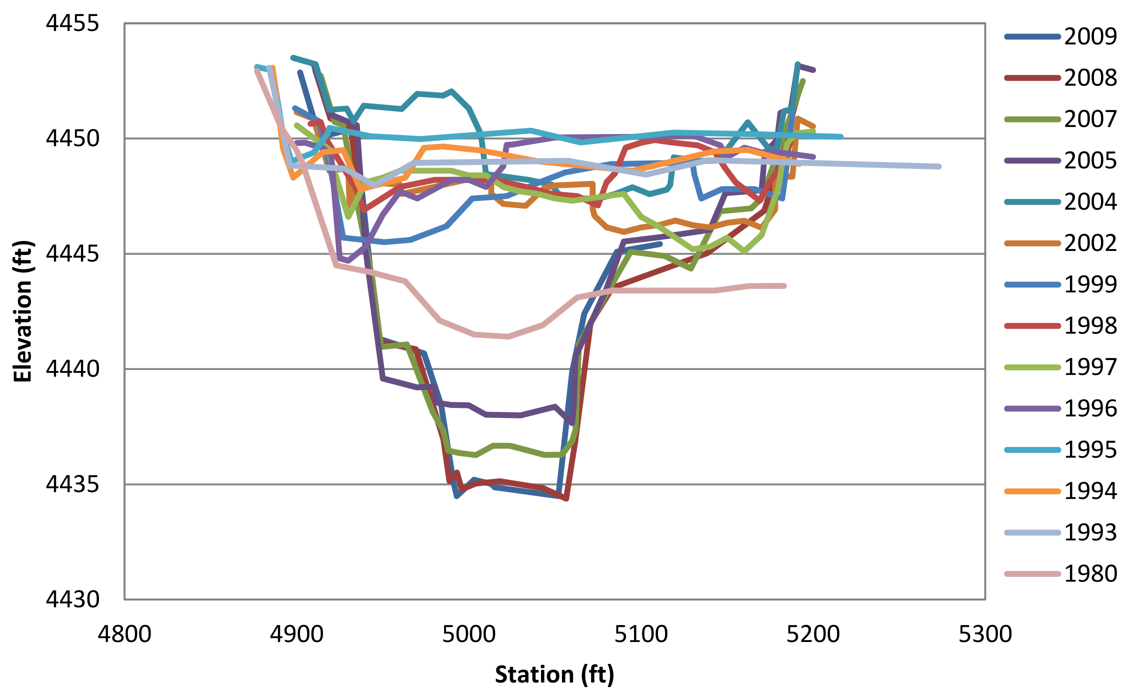

Figure F.19 EB-26 Cross-Section

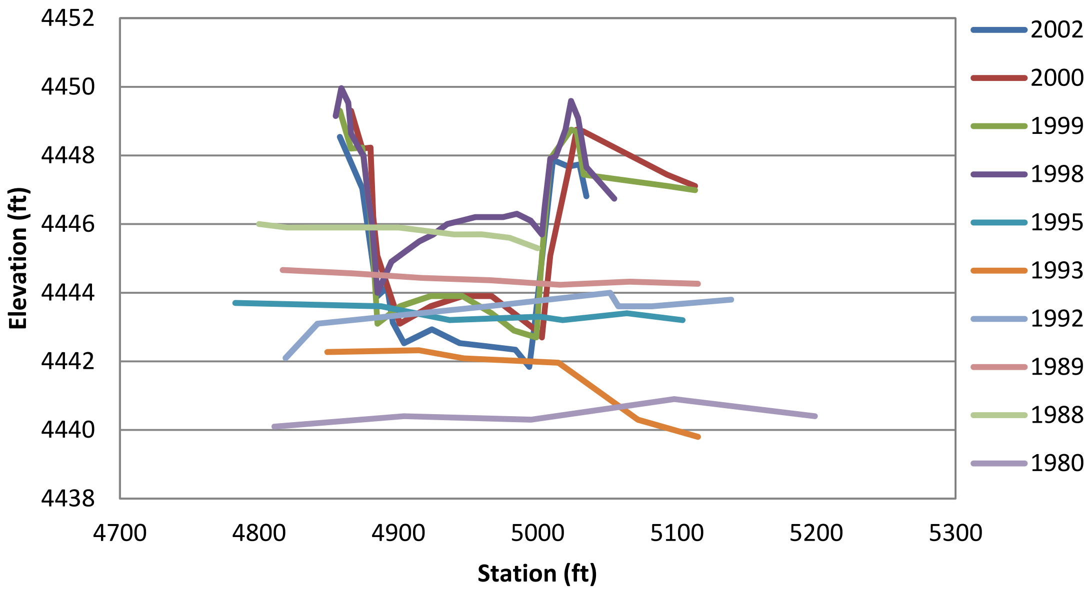

Figure F.20 EB-27 Cross-Section

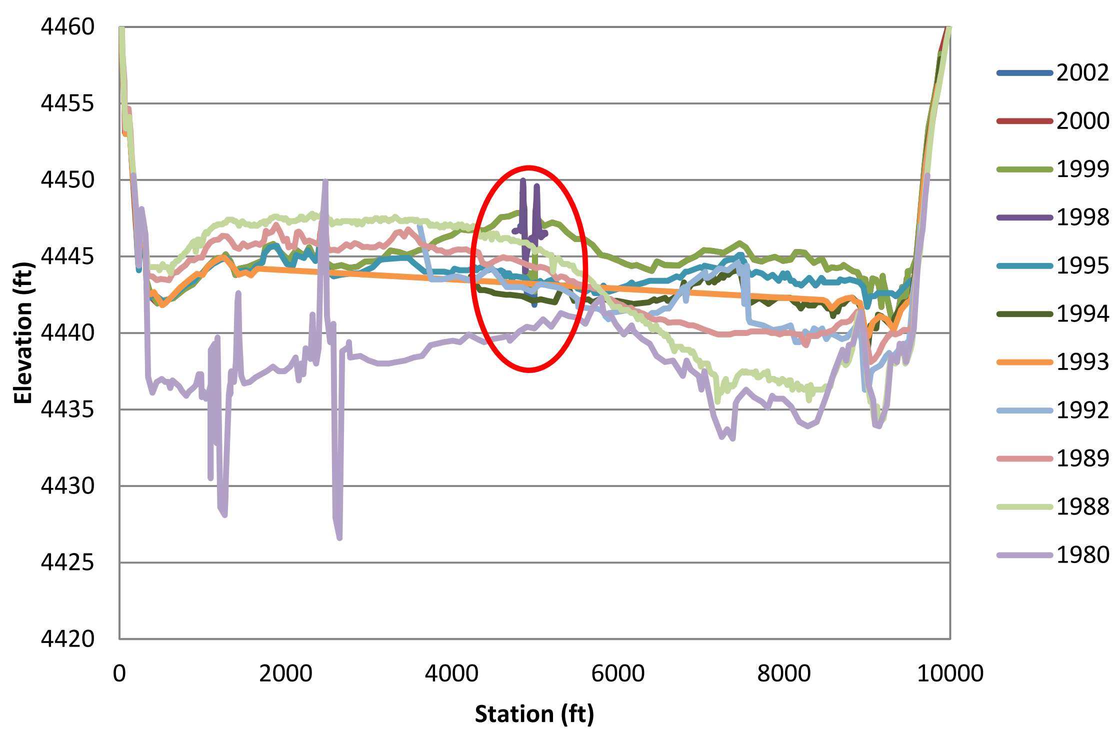

Figure F.21 EB-27 (w/Floodplain) Cross-Section

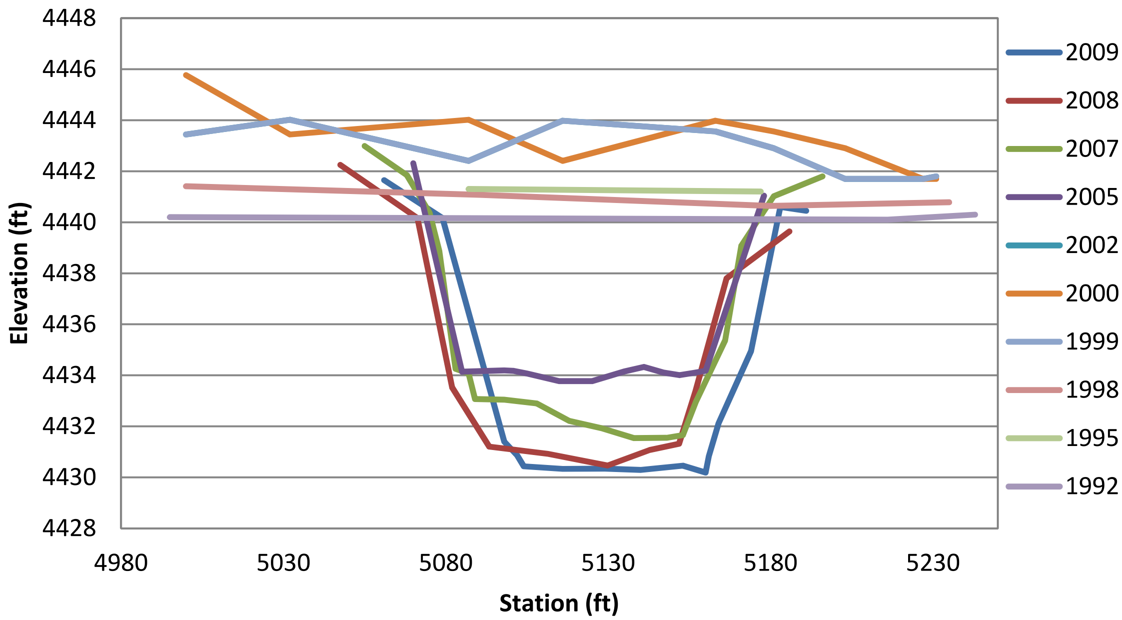

Figure F.22 EB-28 Cross-Section

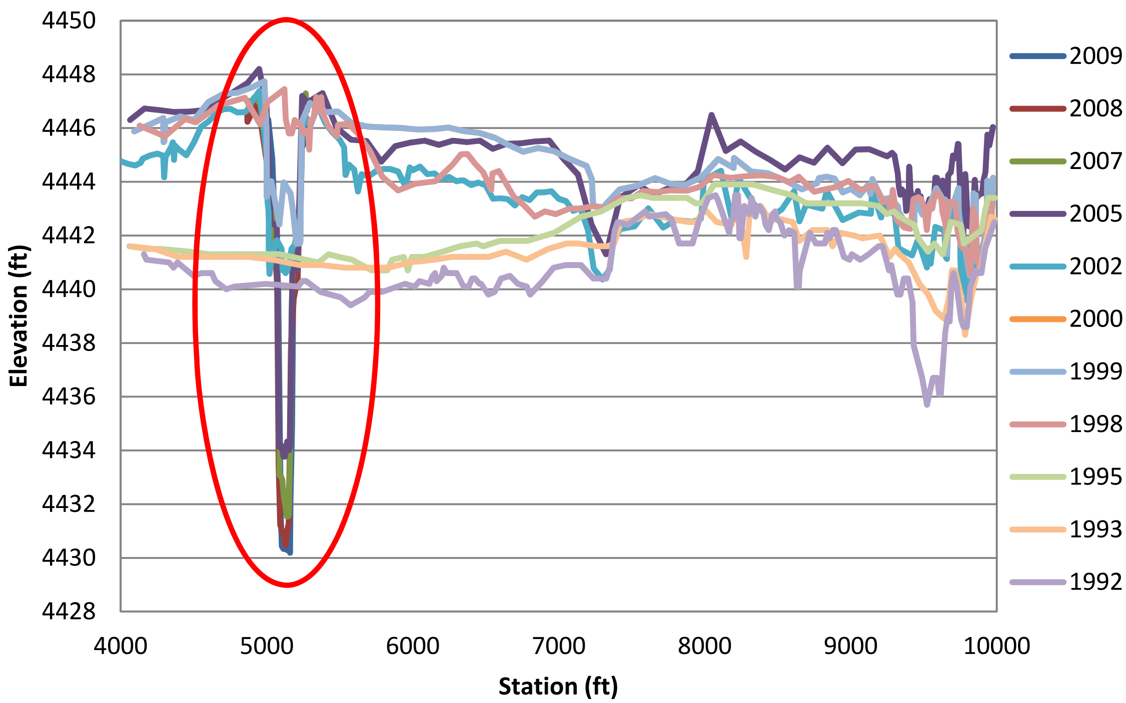

Figure F.23 EB-28 (w/Floodplain) Cross-Section

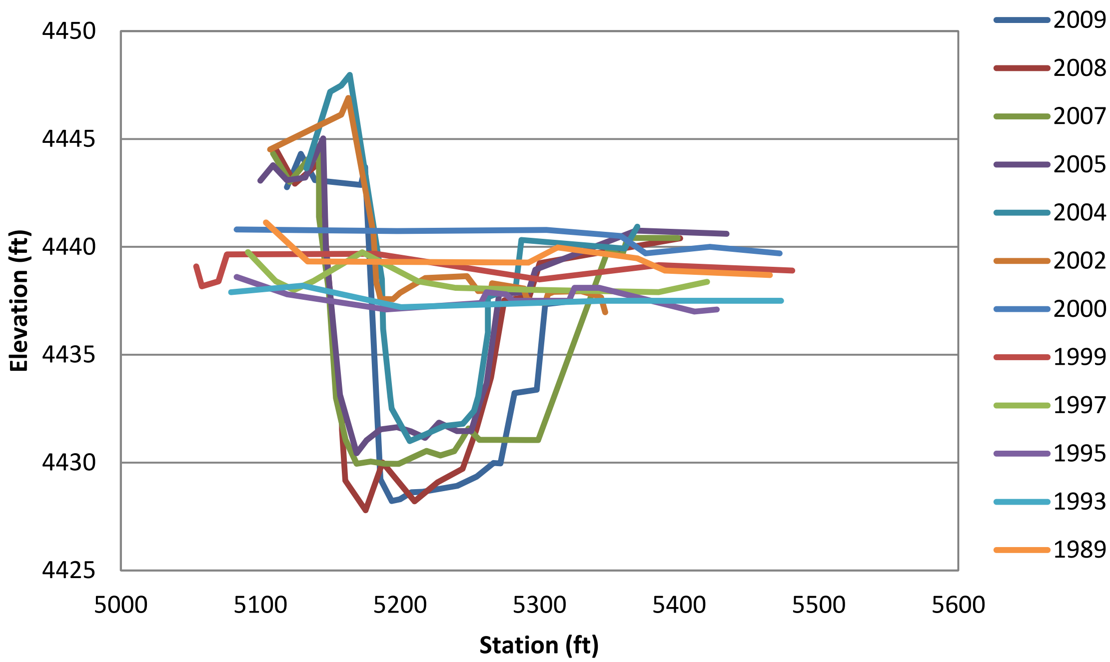

Figure F.24 EB-29 Cross-Section

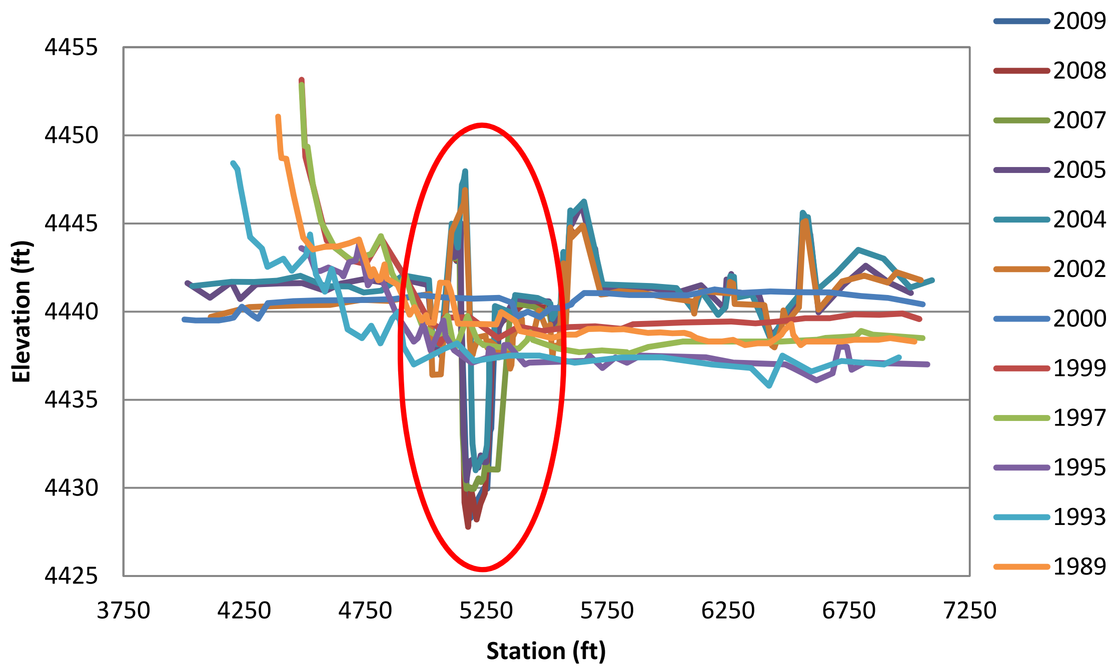

Figure F.25 EB-29 (w/Floodplain) Cross-Section

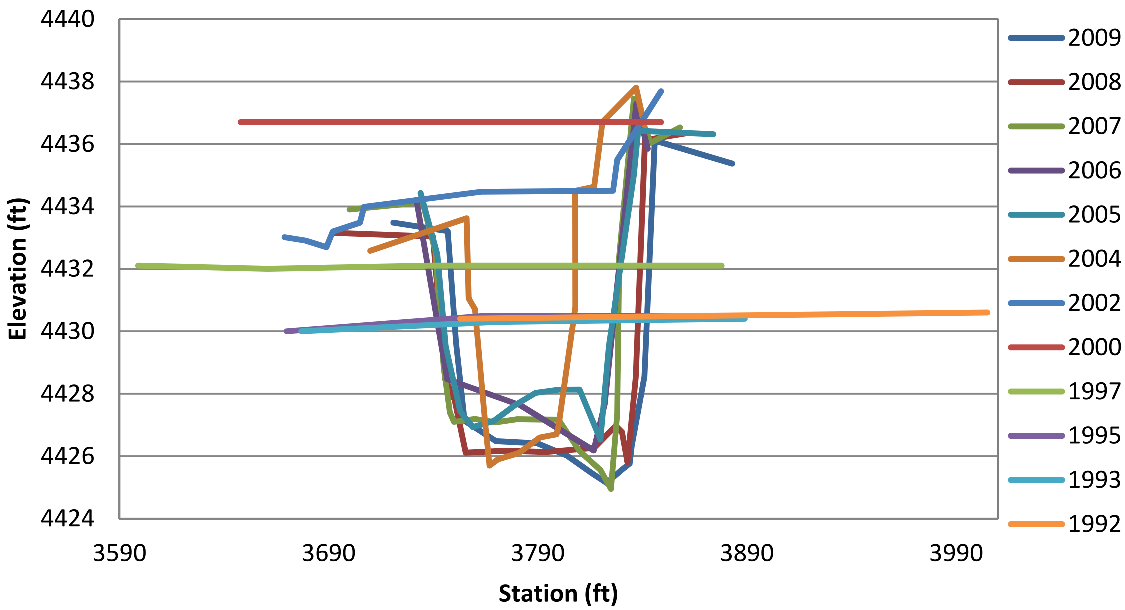

Figure F.26 EB-30 Cross-Section

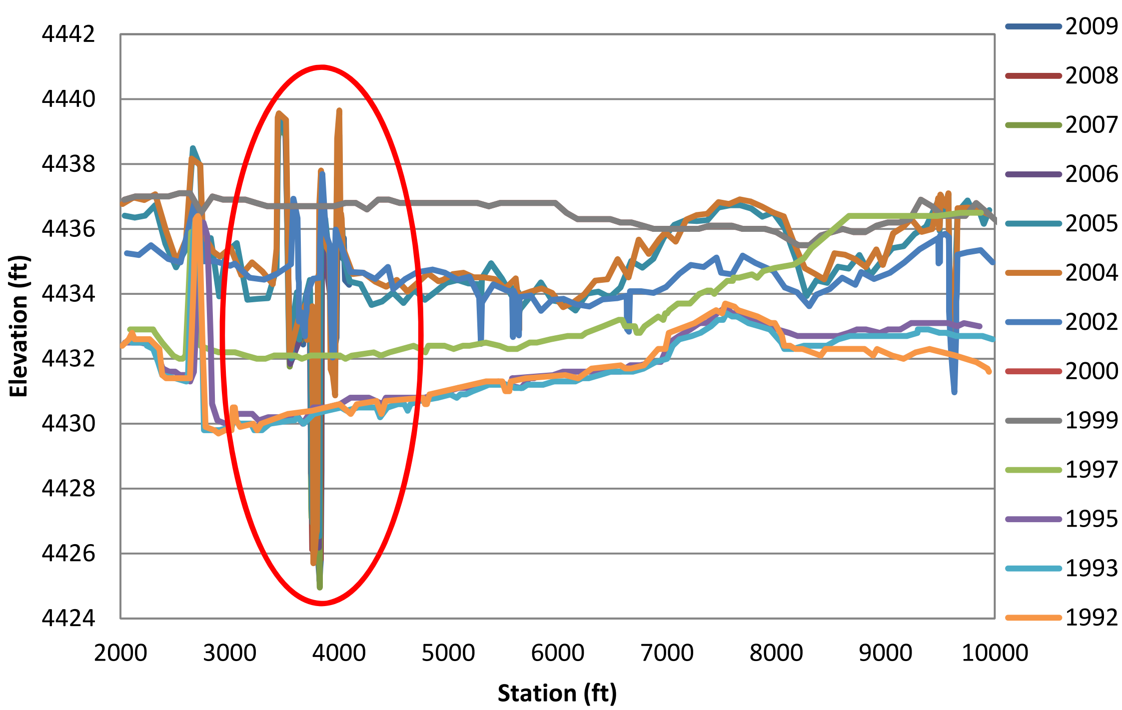

Figure F.27 EB-30 (w/Floodplain) Cross-Section

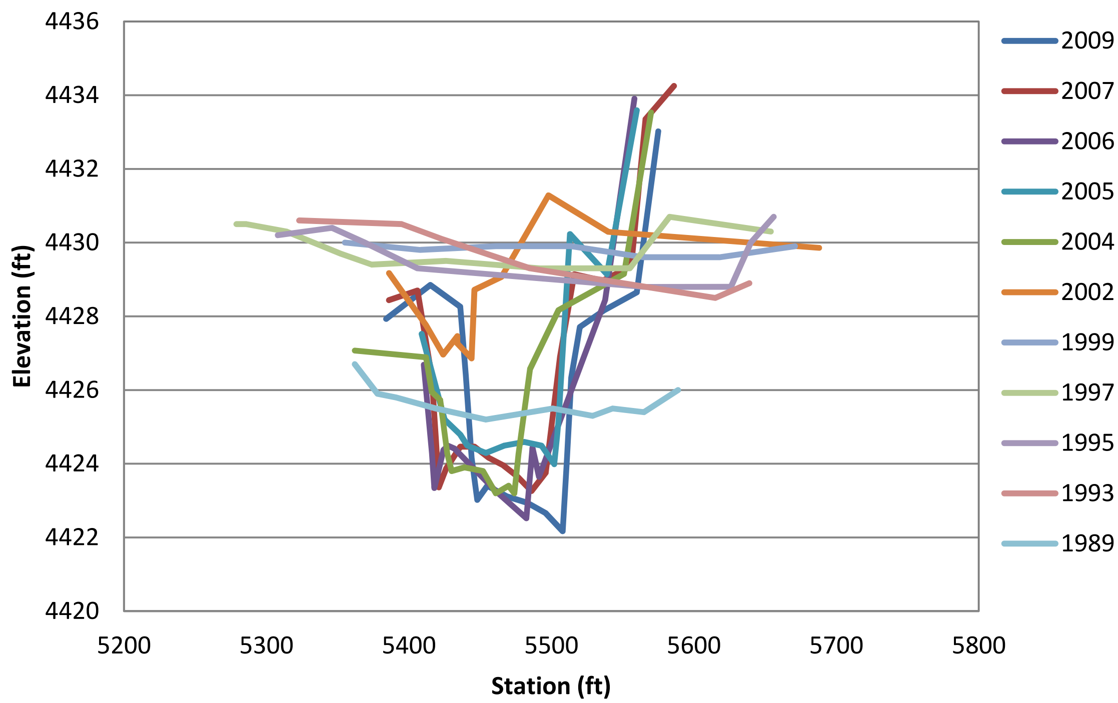

Figure F.28 EB-32 Cross-Section

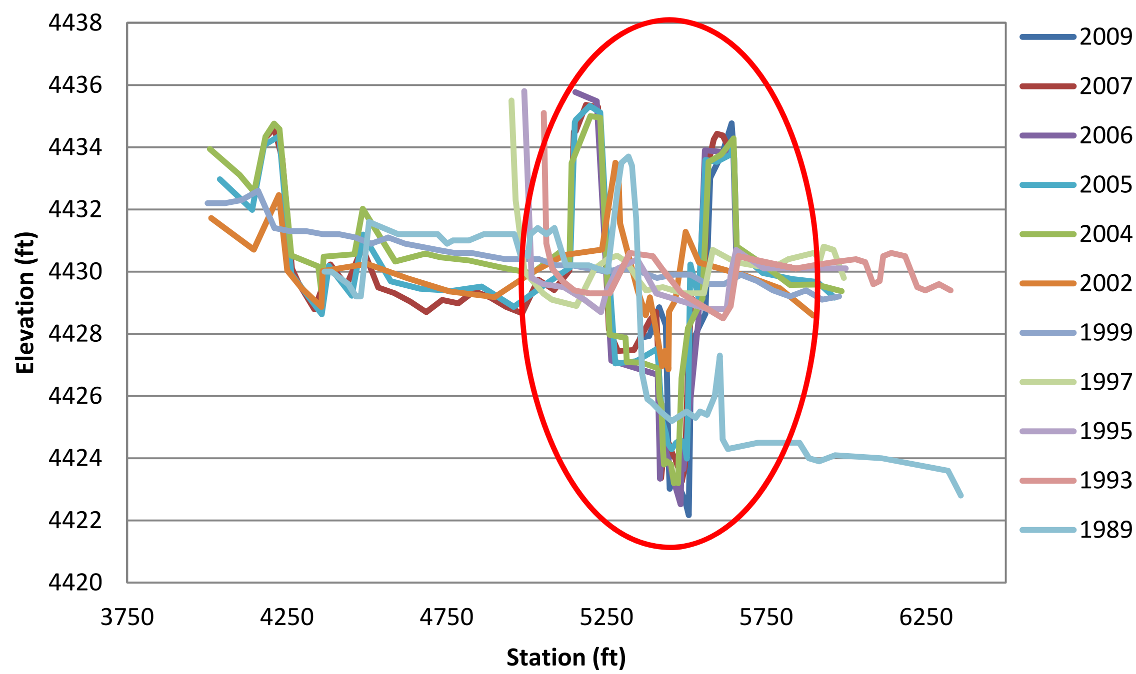

Figure F.29 EB-32 (w/Floodplain) Cross-Section

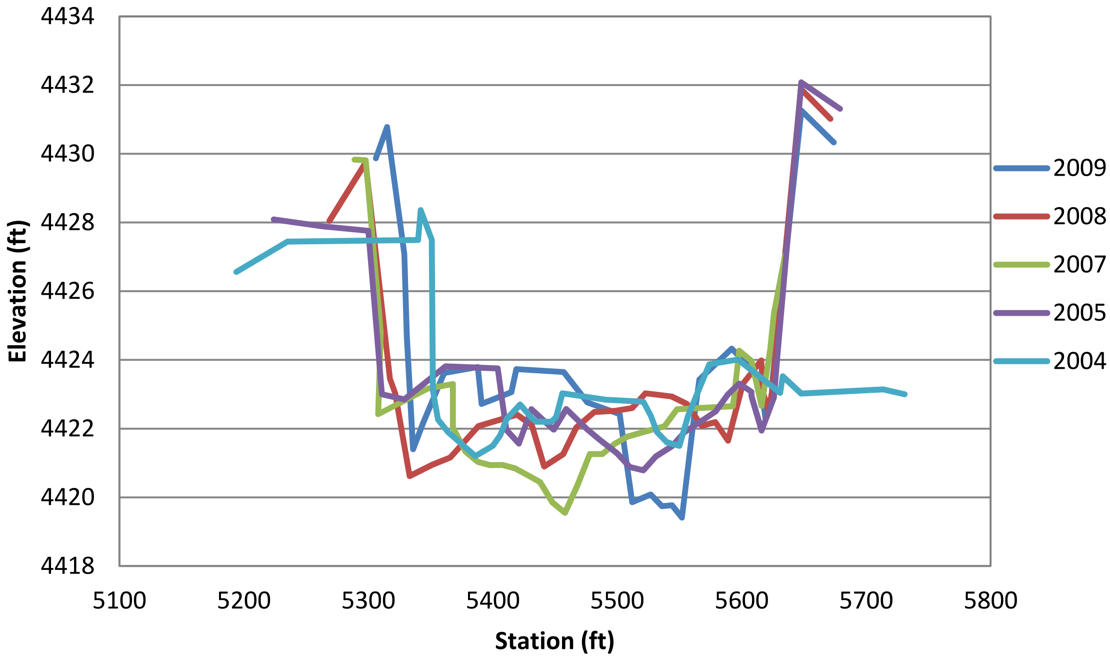

Figure F.30 EB-33 Cross-Section

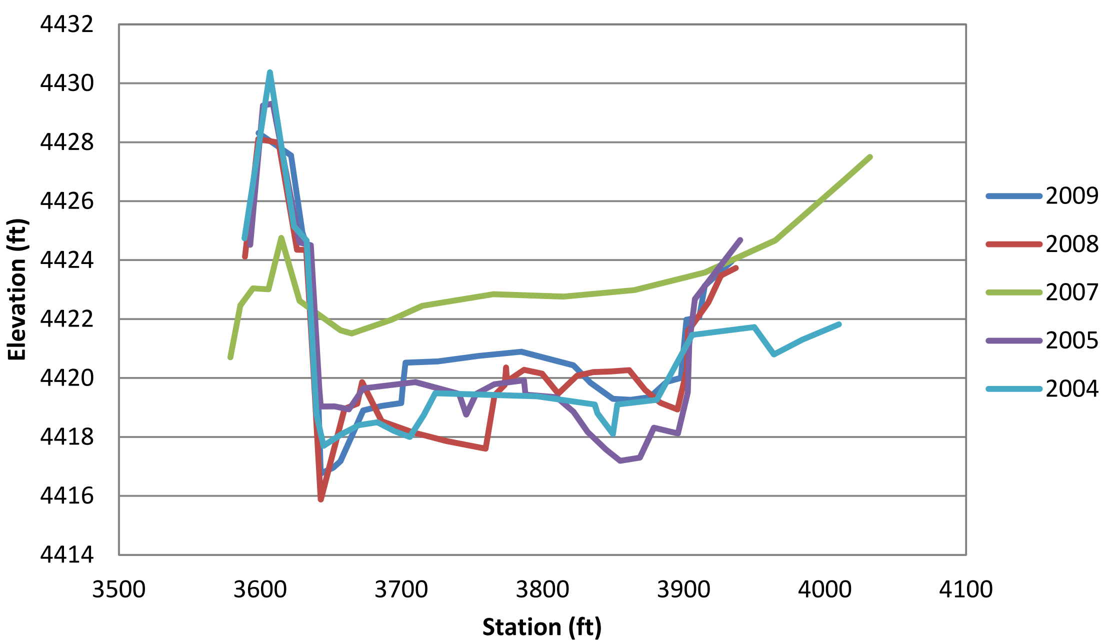

Figure F.31 EB-35 Cross-Section

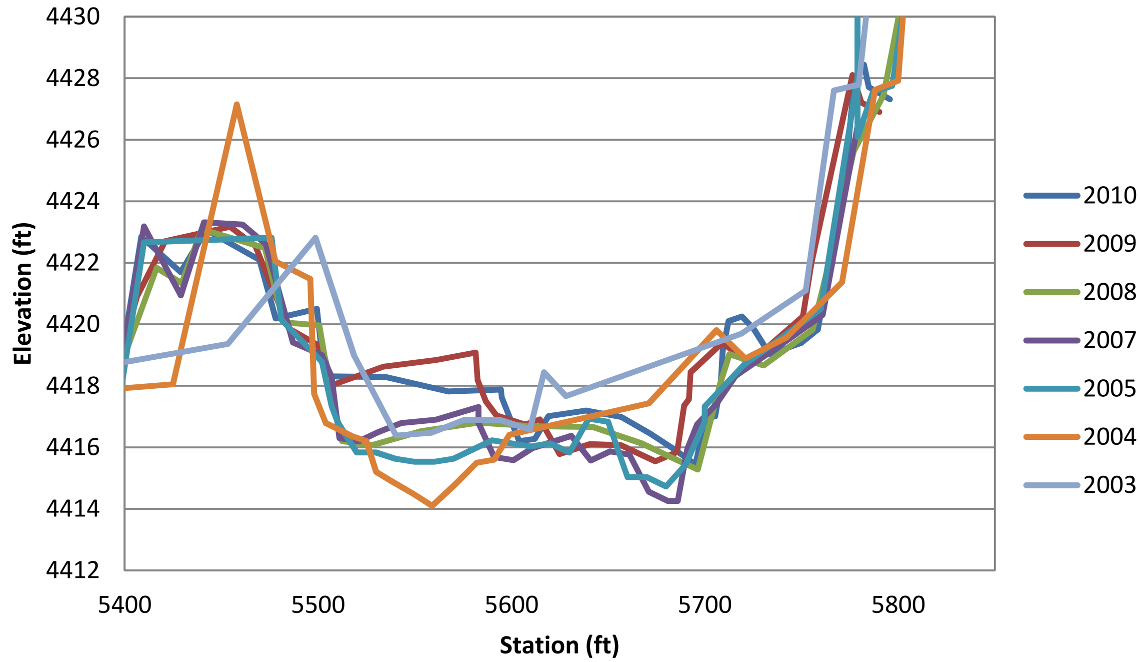

Figure F.32 EB-36 Cross-Section

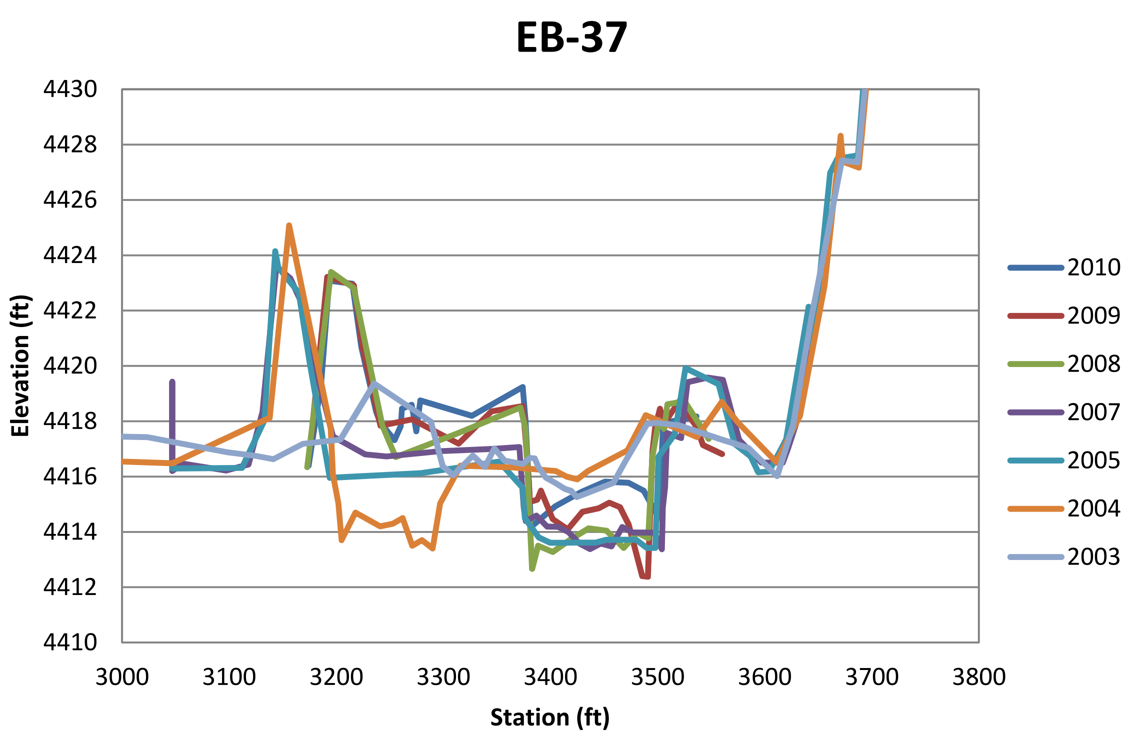

Figure F.33 EB-37 Cross-Section

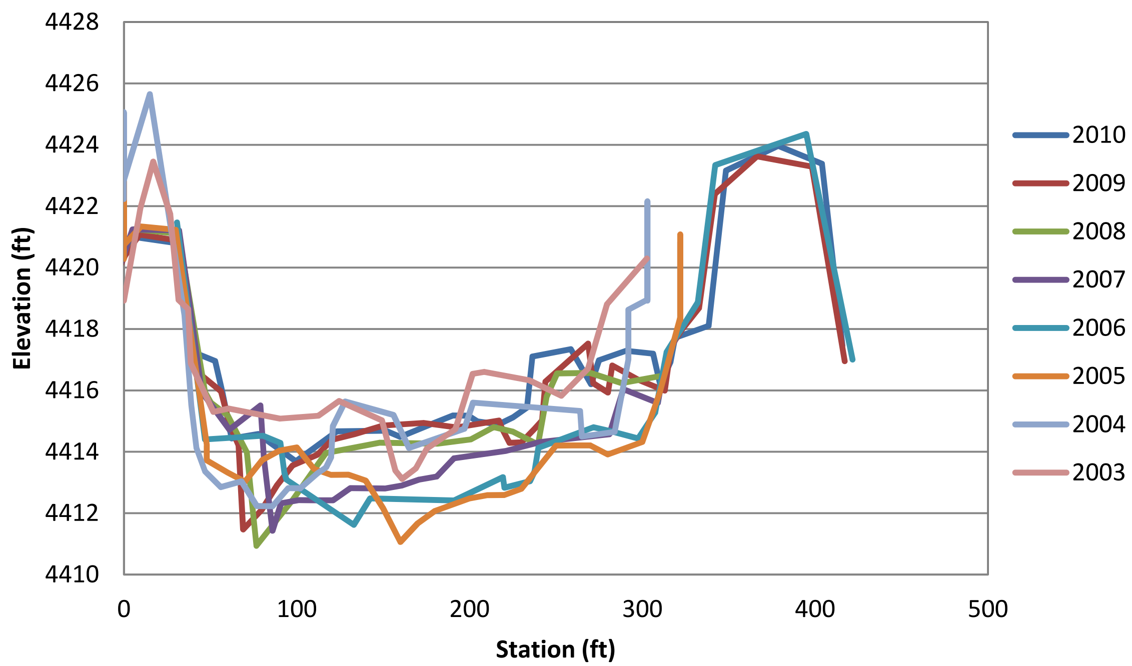

Figure F.34 EB-37.5 Cross-Section

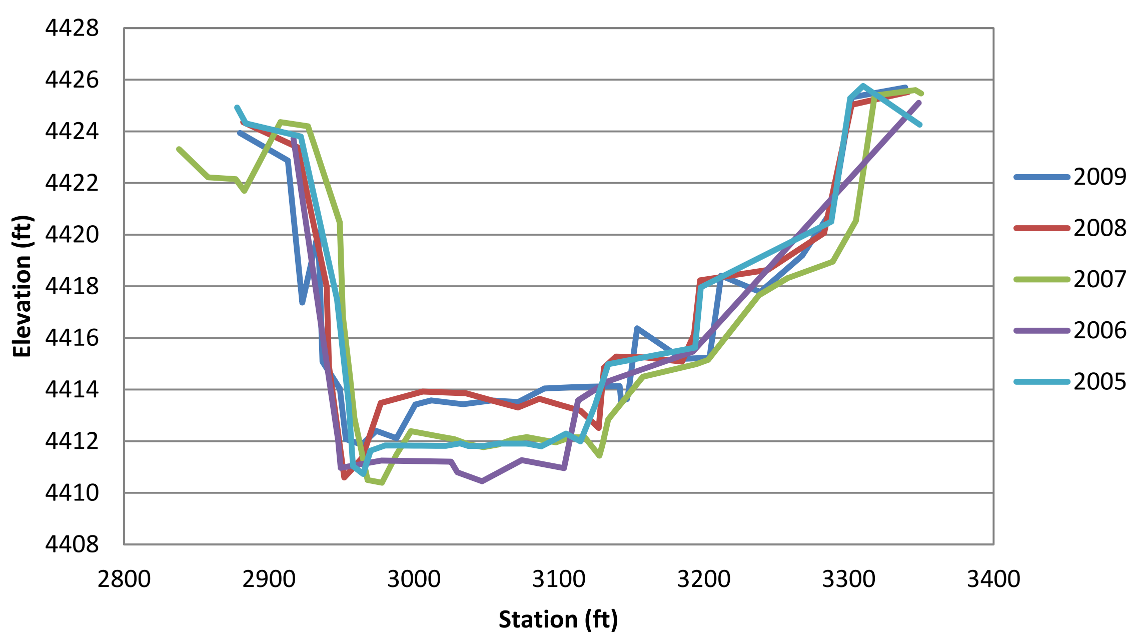

Figure F.35 EB-38 Cross-Section

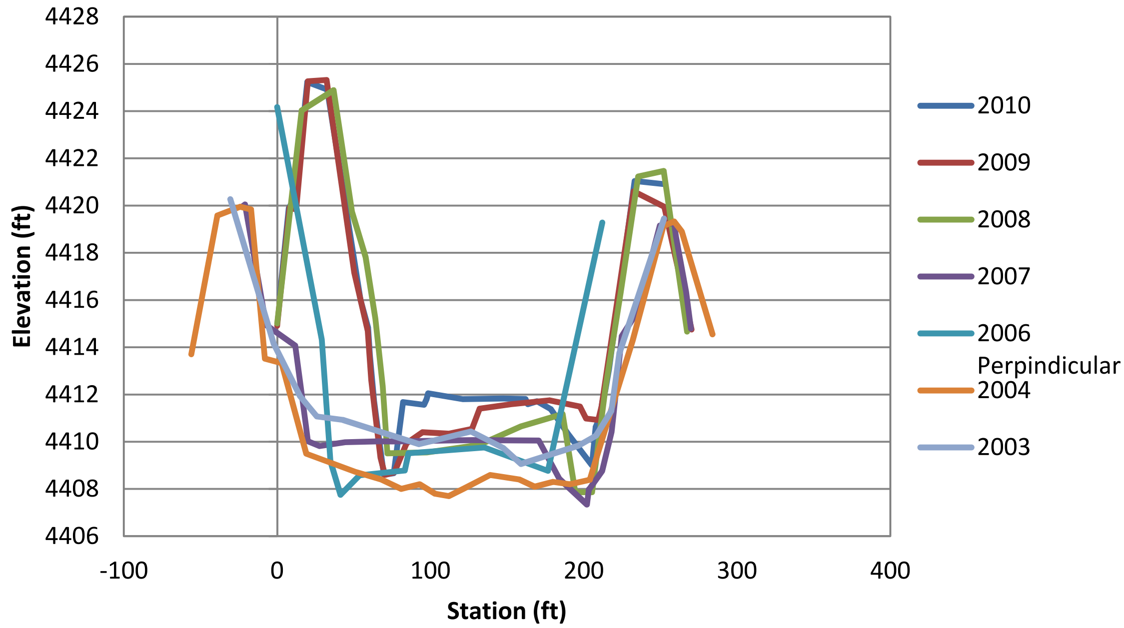

Figure F.36 EB-39 Cross-Section

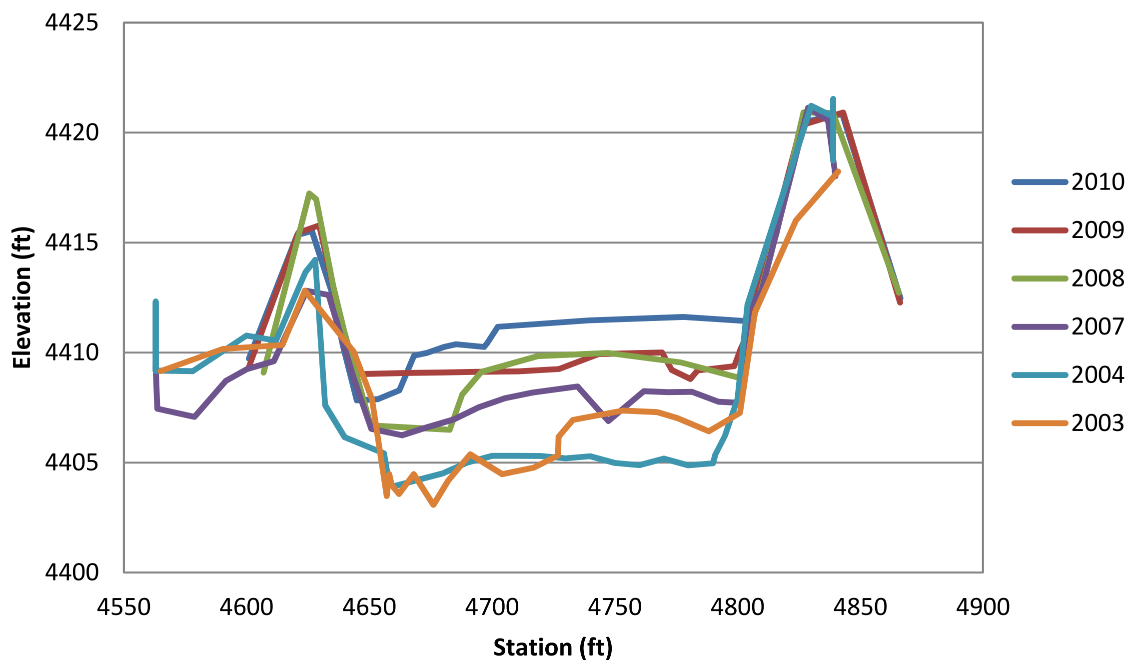

Figure F.37 EB-40 Cross-Section

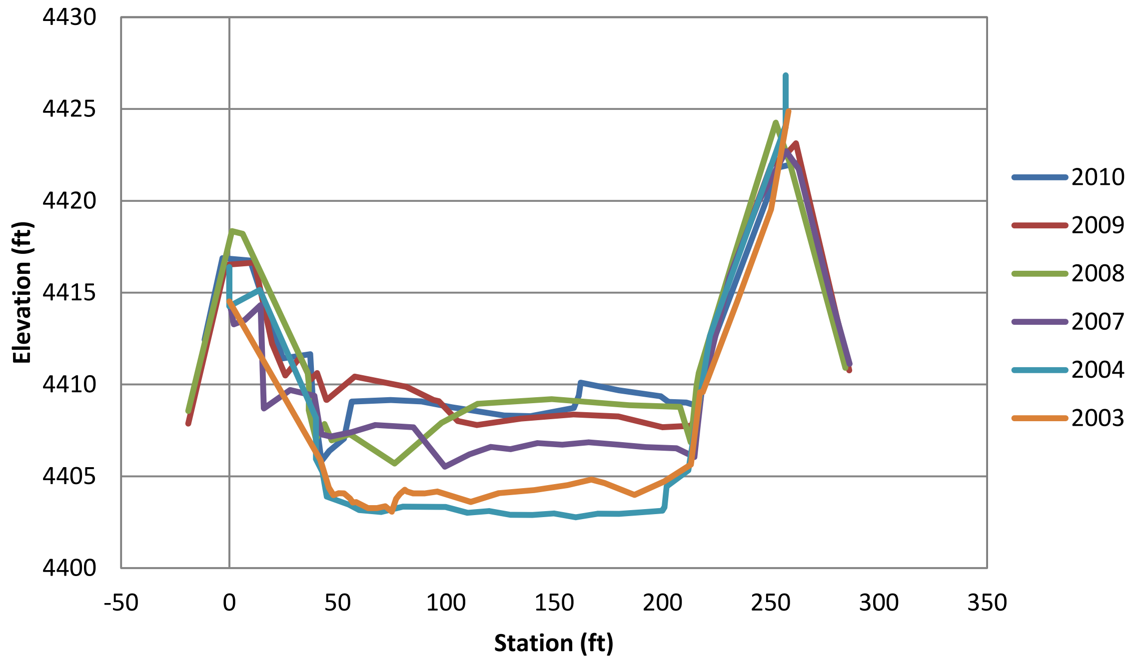

Figure F.38 EB-40.5 Cross-Section

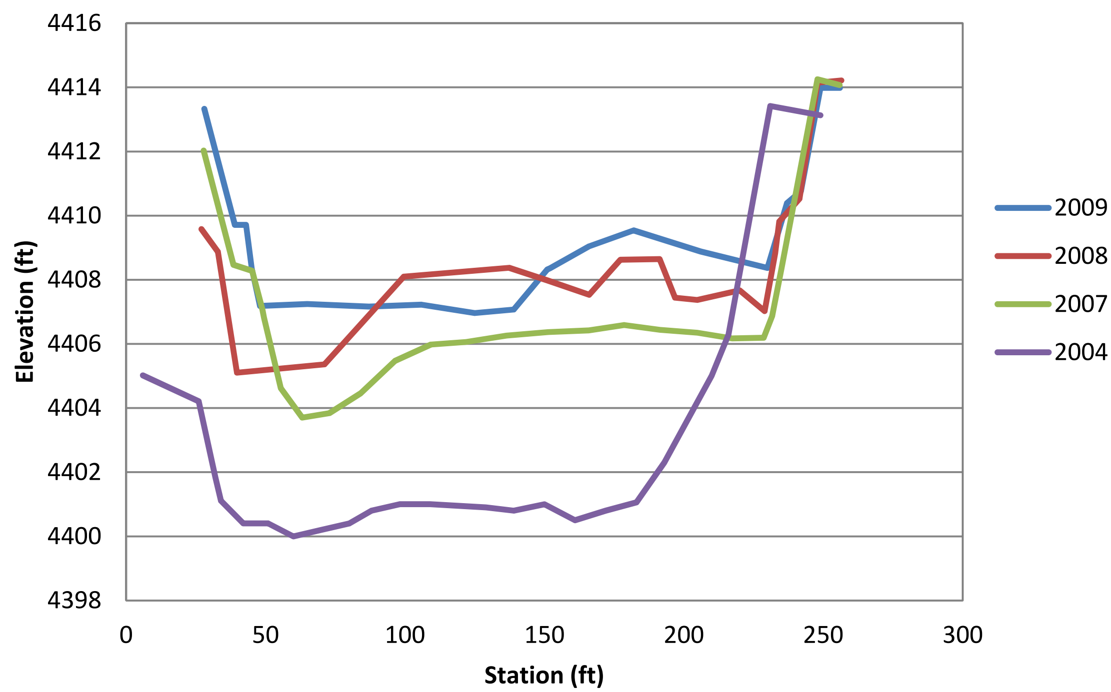

Figure F.39 EB-41 Cross-Section

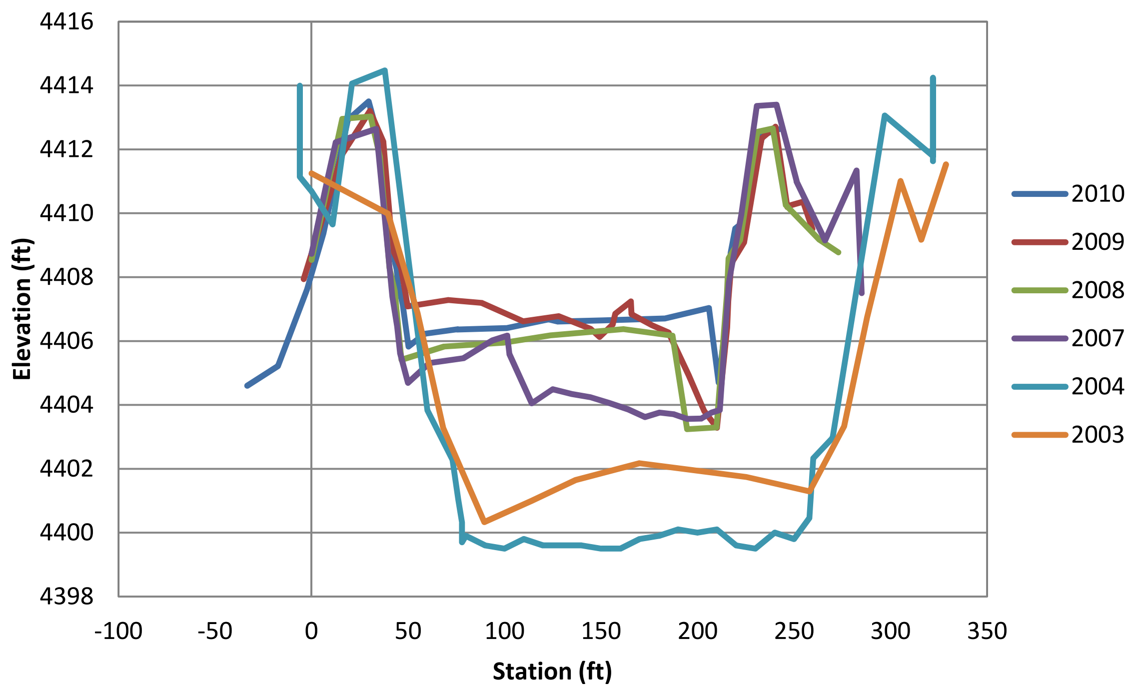

Figure F.40 EB-42 Cross-Section

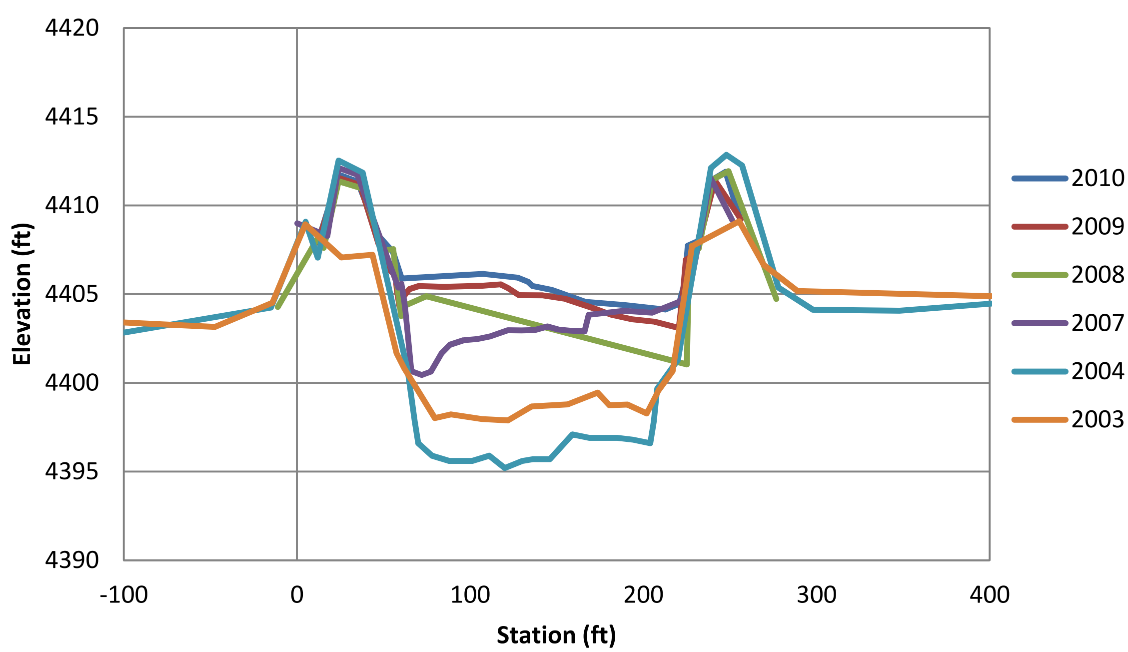

Figure F.41 EB-43 Cross-Section

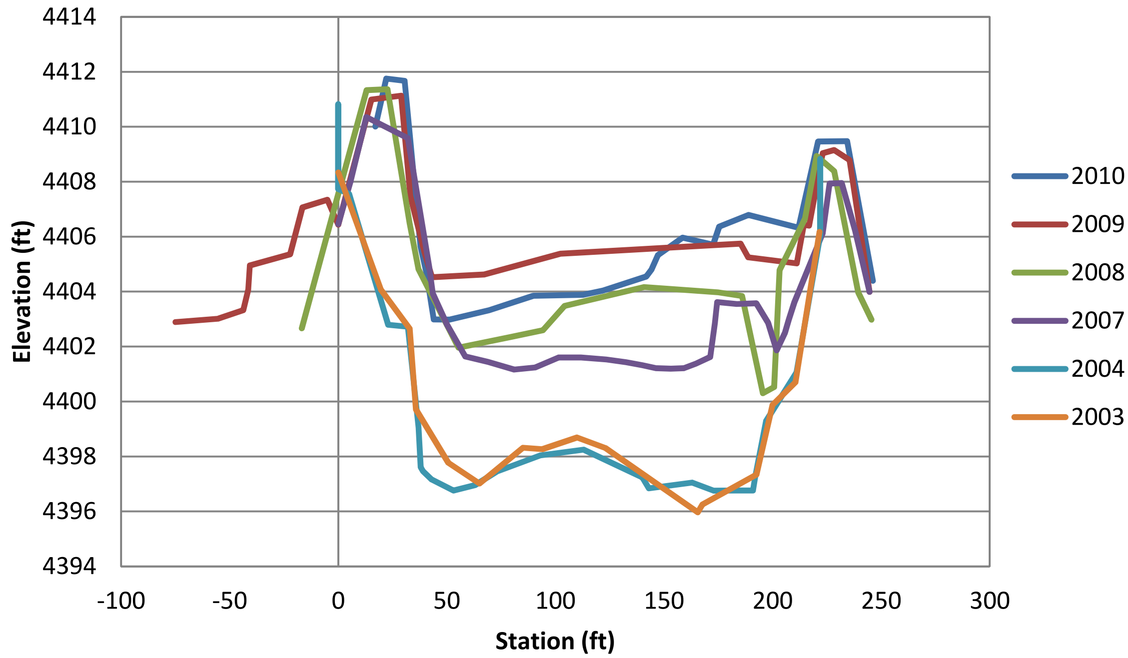

Figure F.42 EB-44 Cross-Section

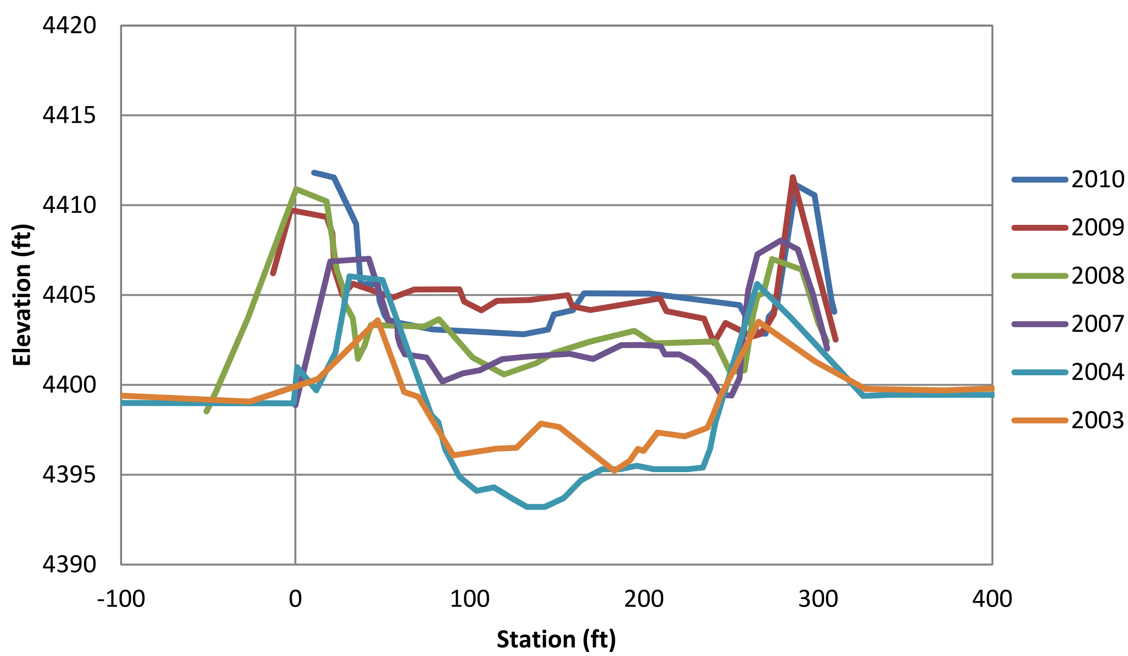

Figure F.43 EB-45 Cross-Section

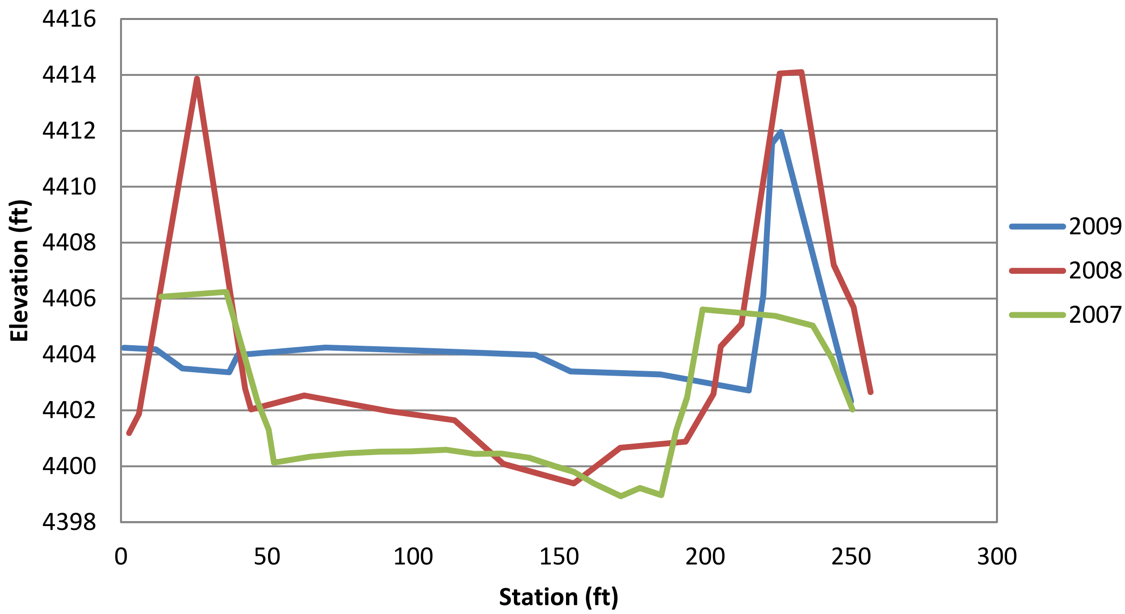

Figure F.44 EB-46 Cross-Section

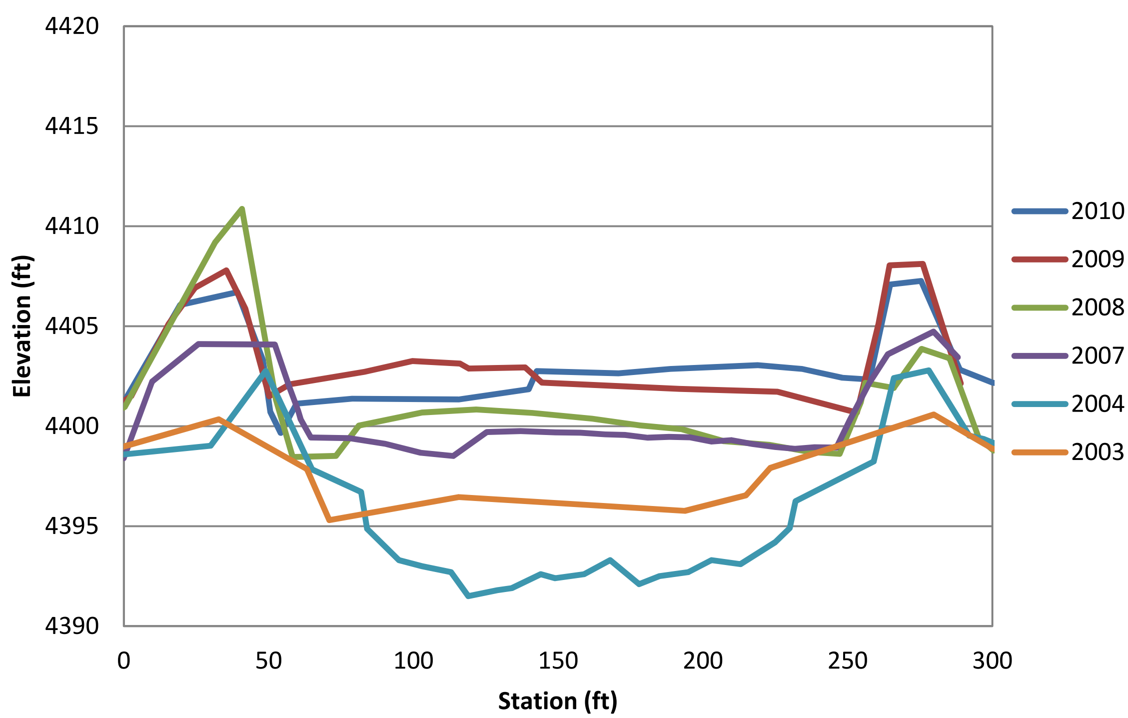

Figure F.45 EB-47 Cross-Section

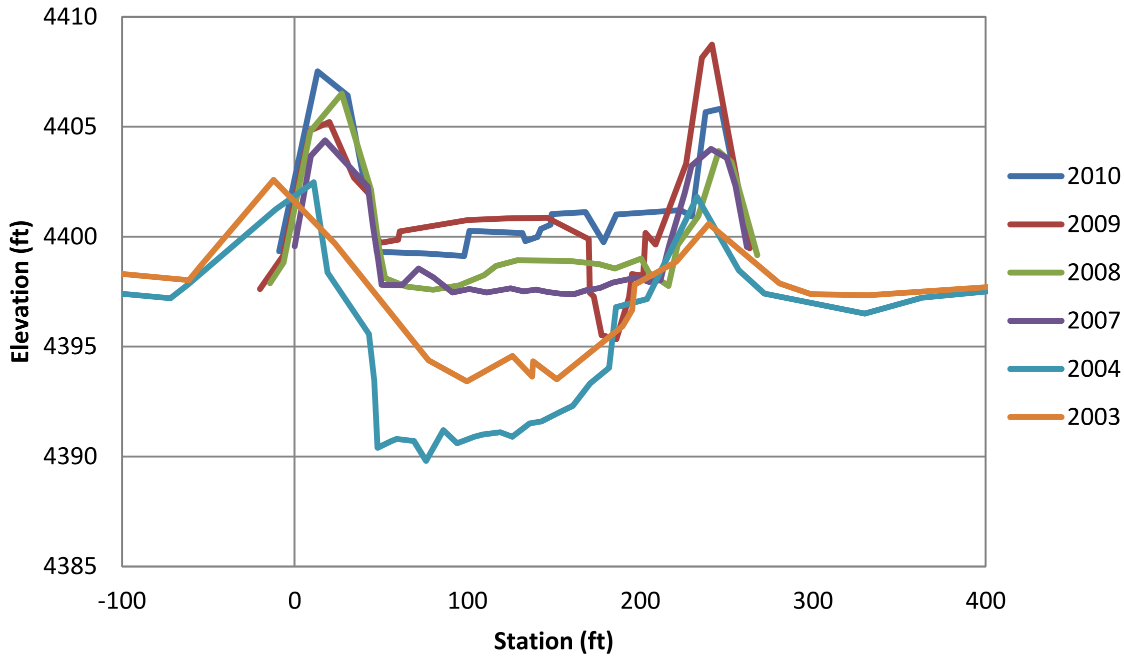

Figure F.46 EB-48 Cross-Section

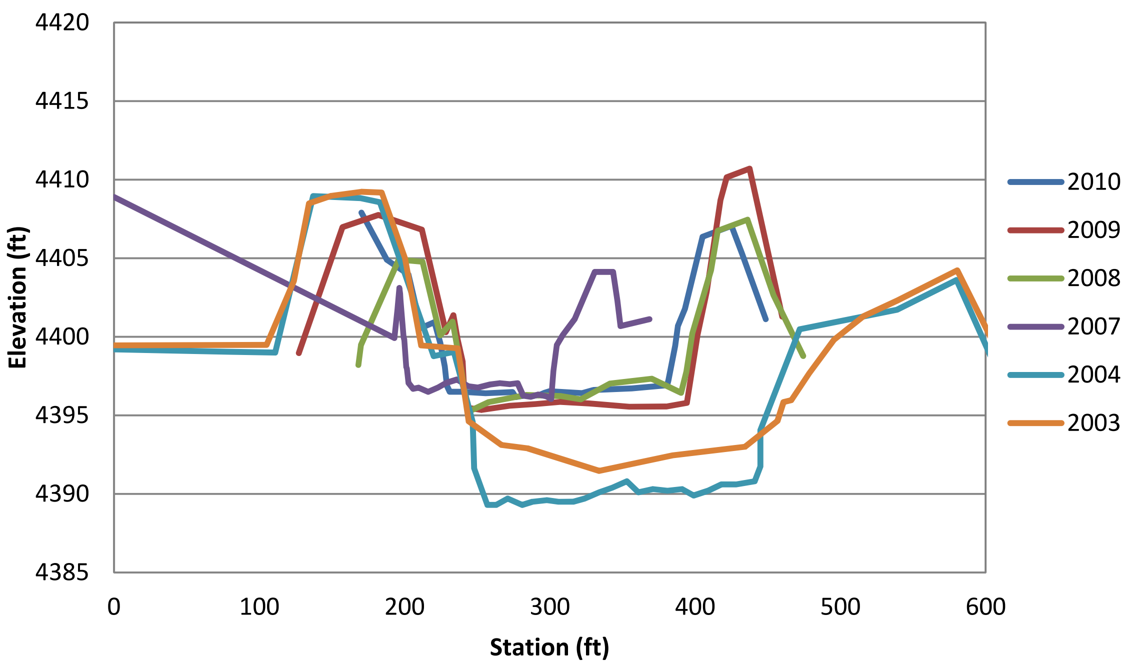

Figure F.47 EB-49 Cross-Section

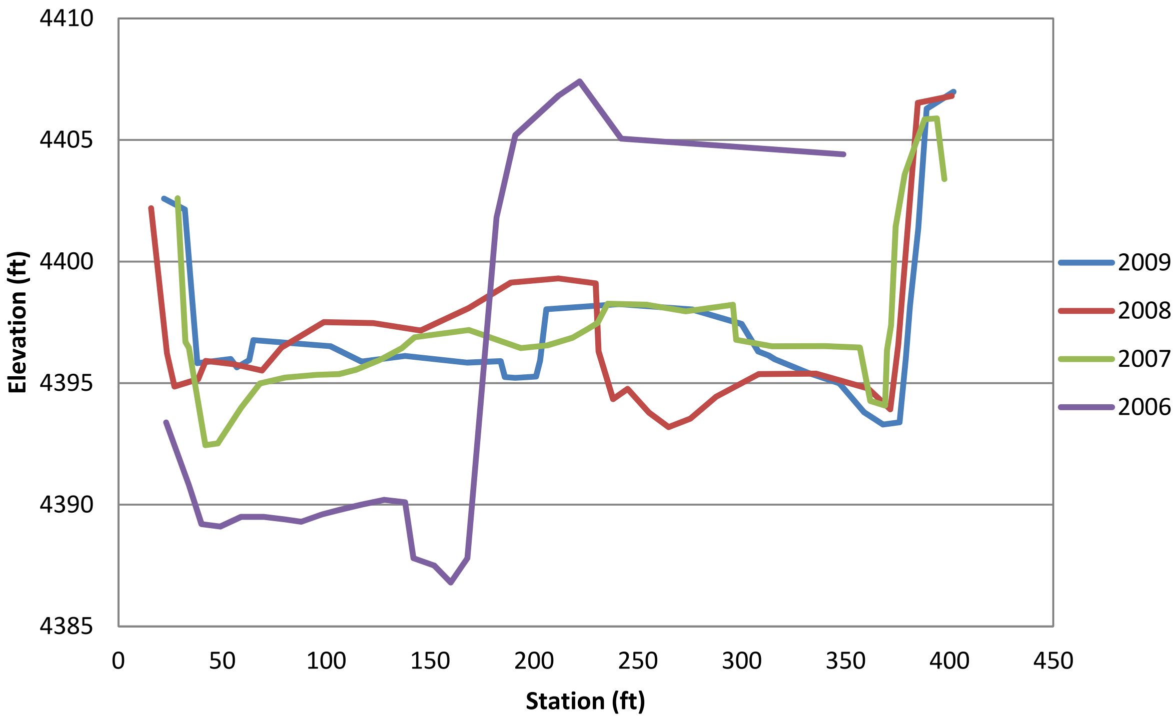

Figure F.48 EB-50 Cross-Section

APPENDIX G: CHANGE IN THALWEG ELEVATION VS. RIVER MILE PLOTS

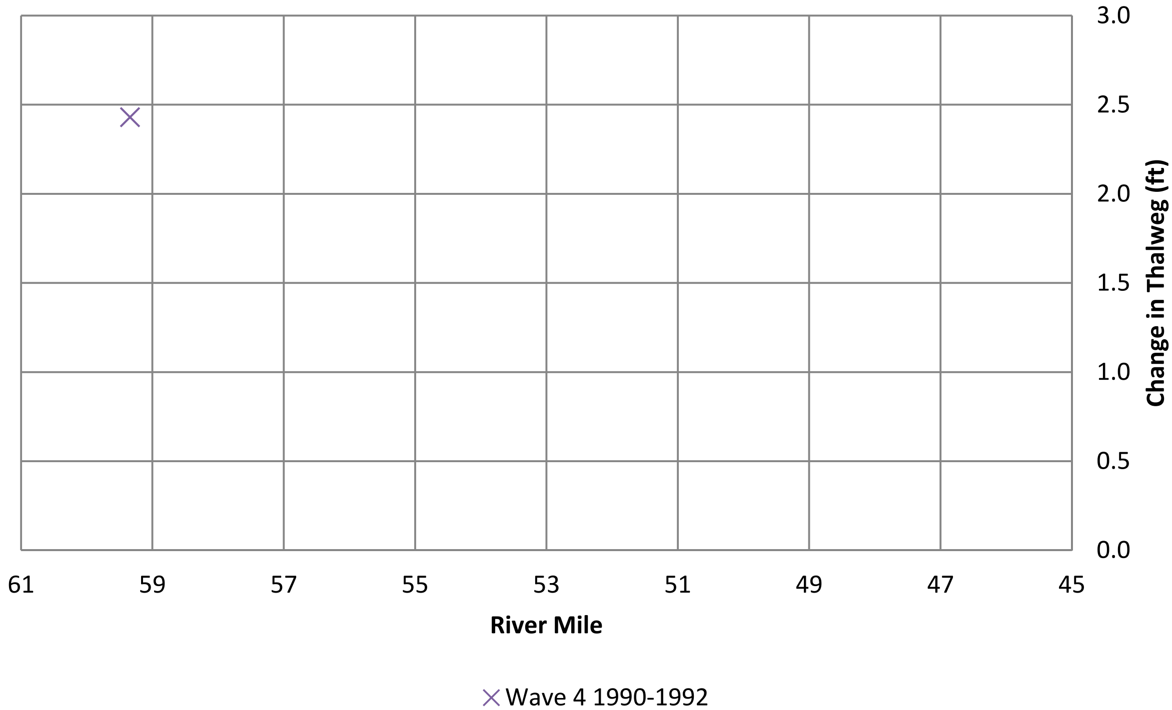

Figure G.1 1990-1992 Thalweg Change

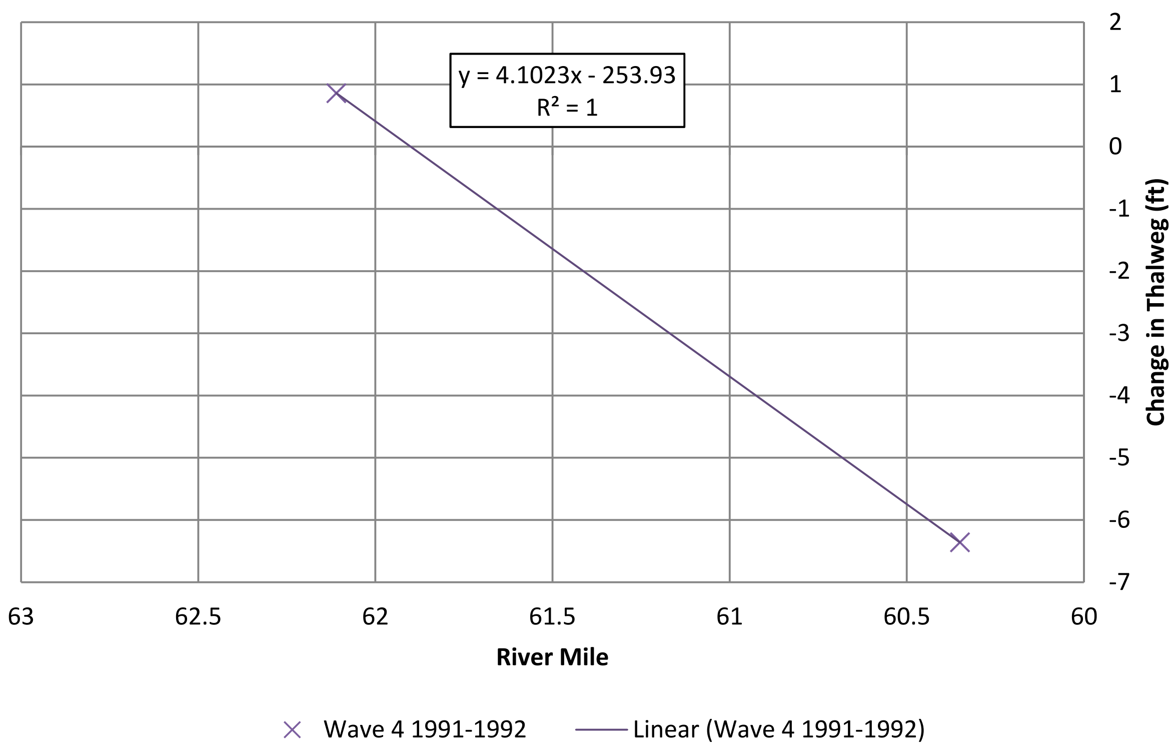

Figure G.2 1991-1992 Thalweg Change

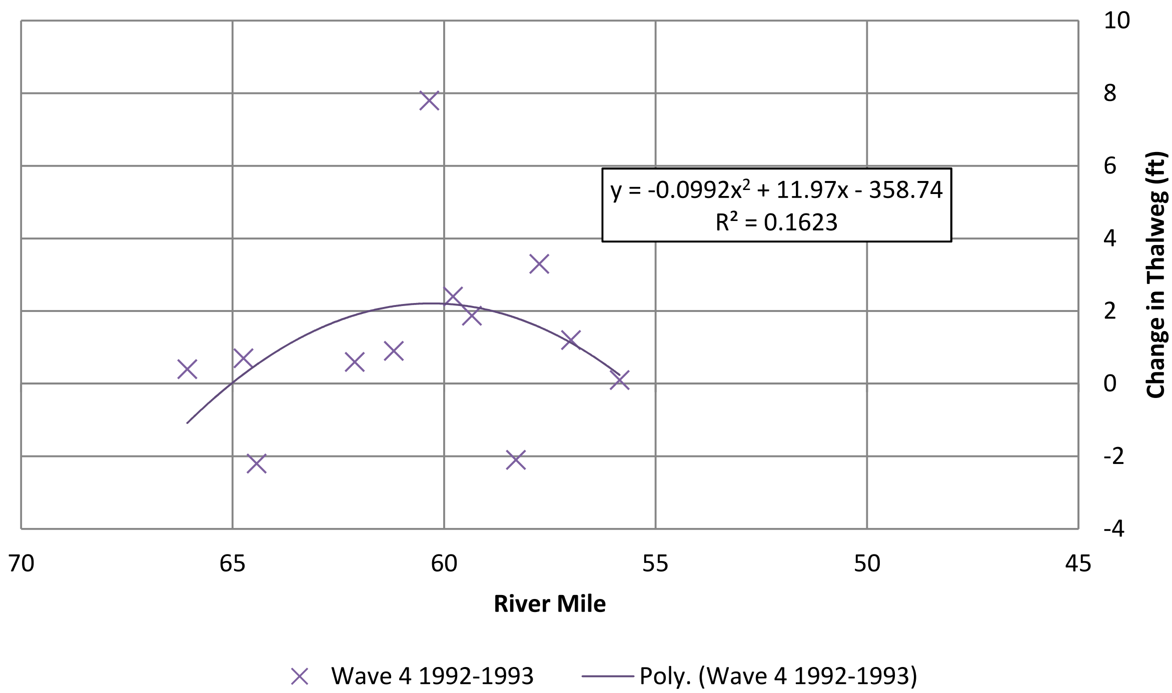

Figure G.3 1992-1993 Thalweg Change

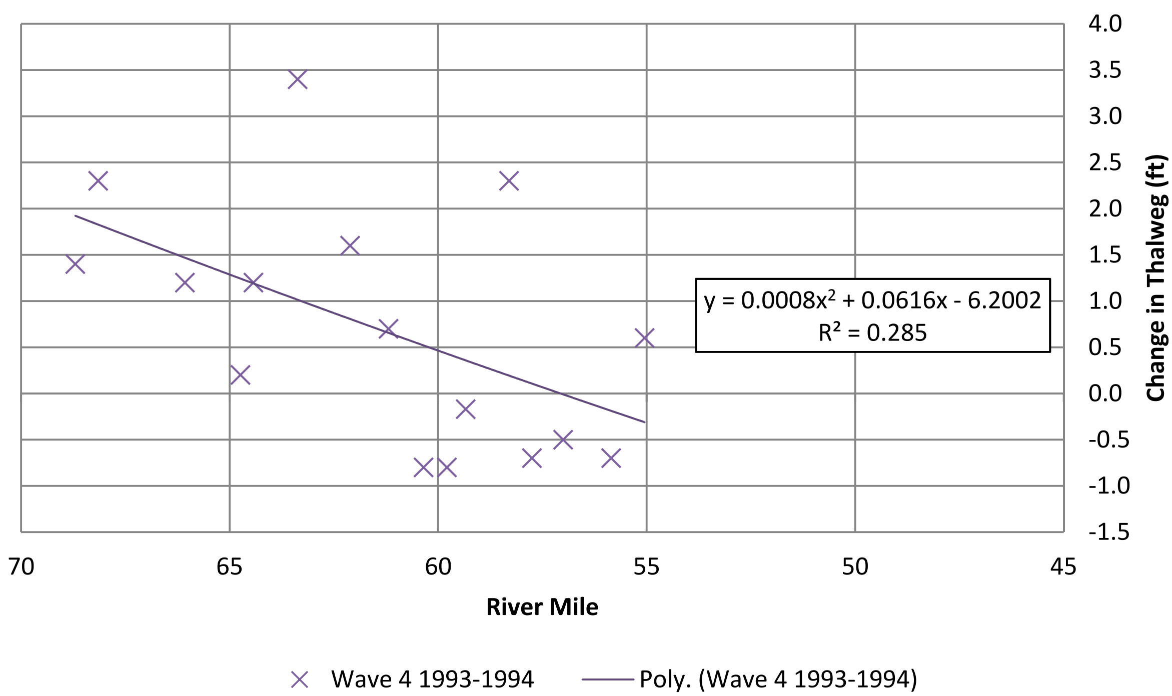

Figure G.4 1993-1994 Thalweg Change

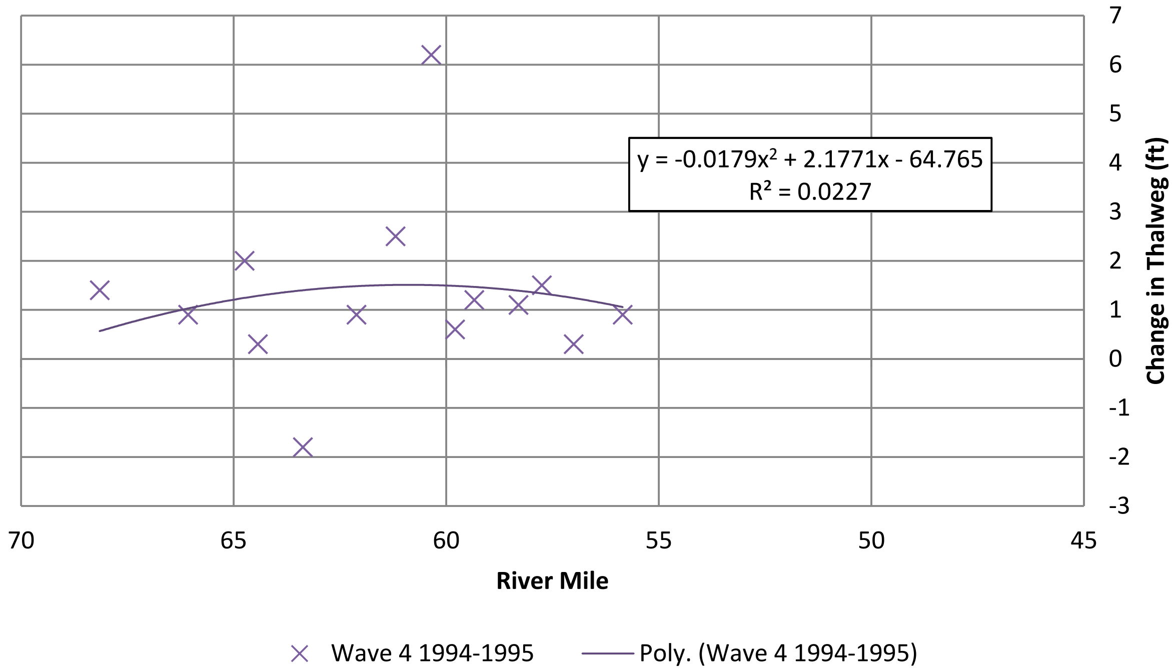

Figure G.5 1994-1995 Thalweg Change

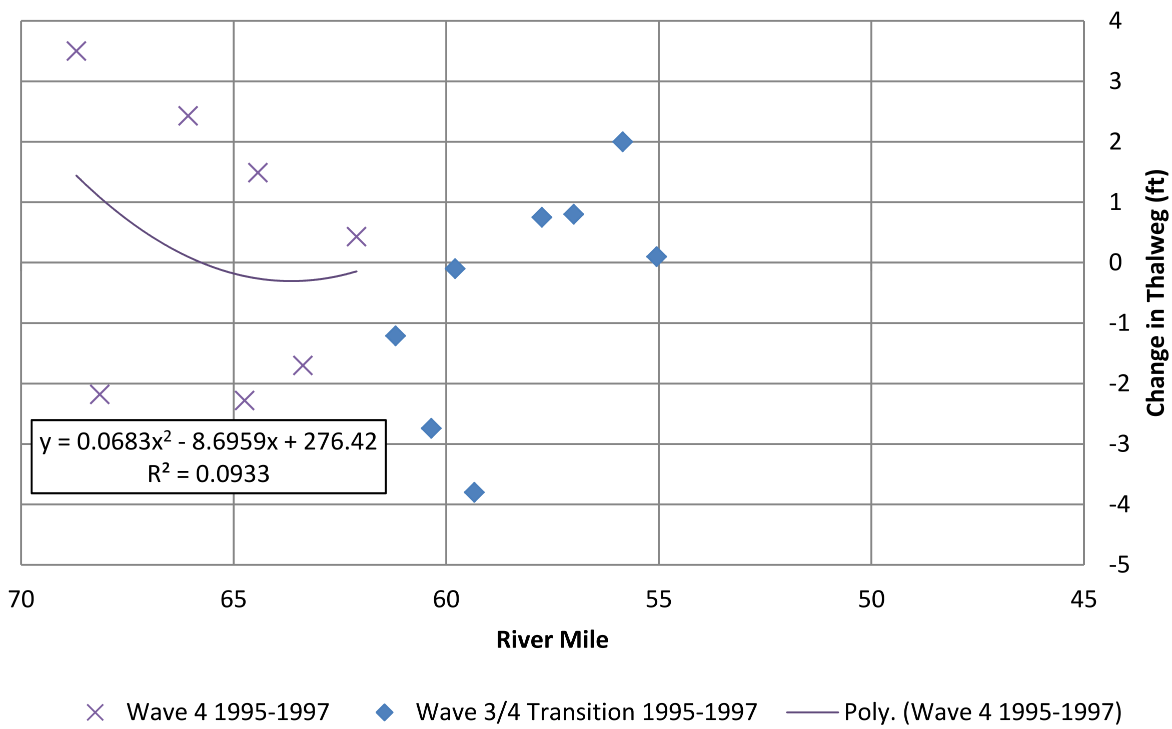

Figure G.6 1995-1997 Thalweg Change

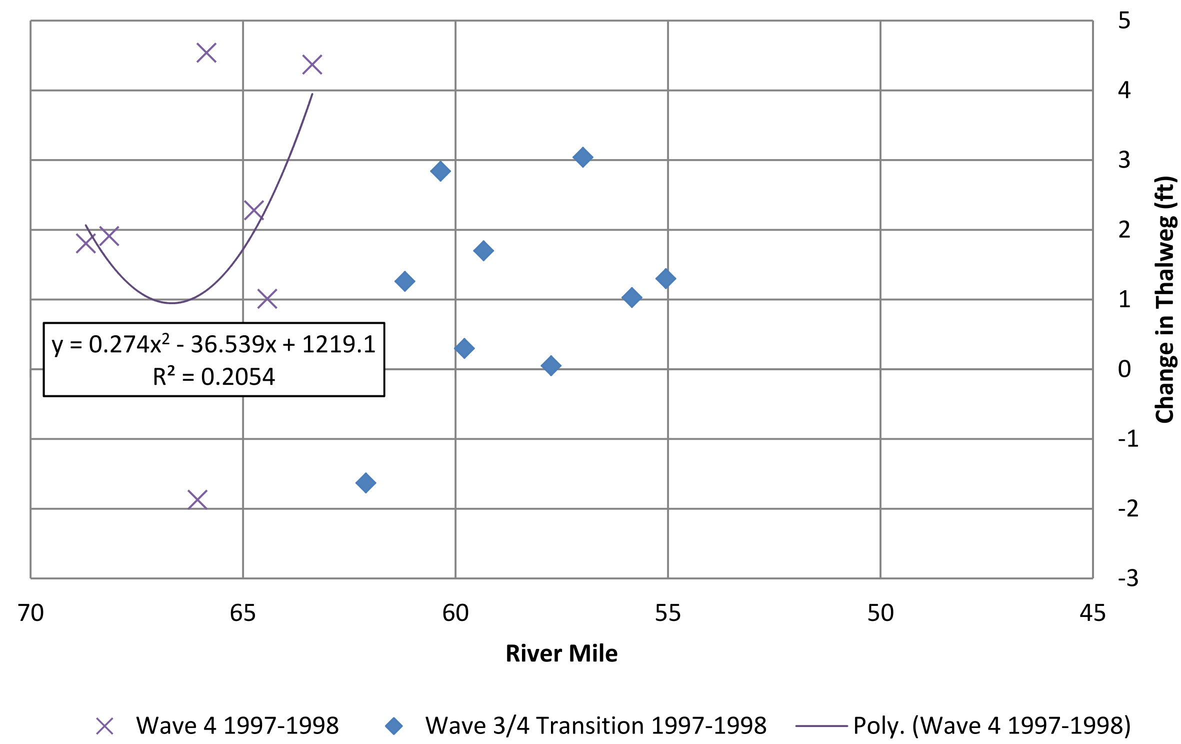

Figure G.7 1997-1998 Thalweg Change

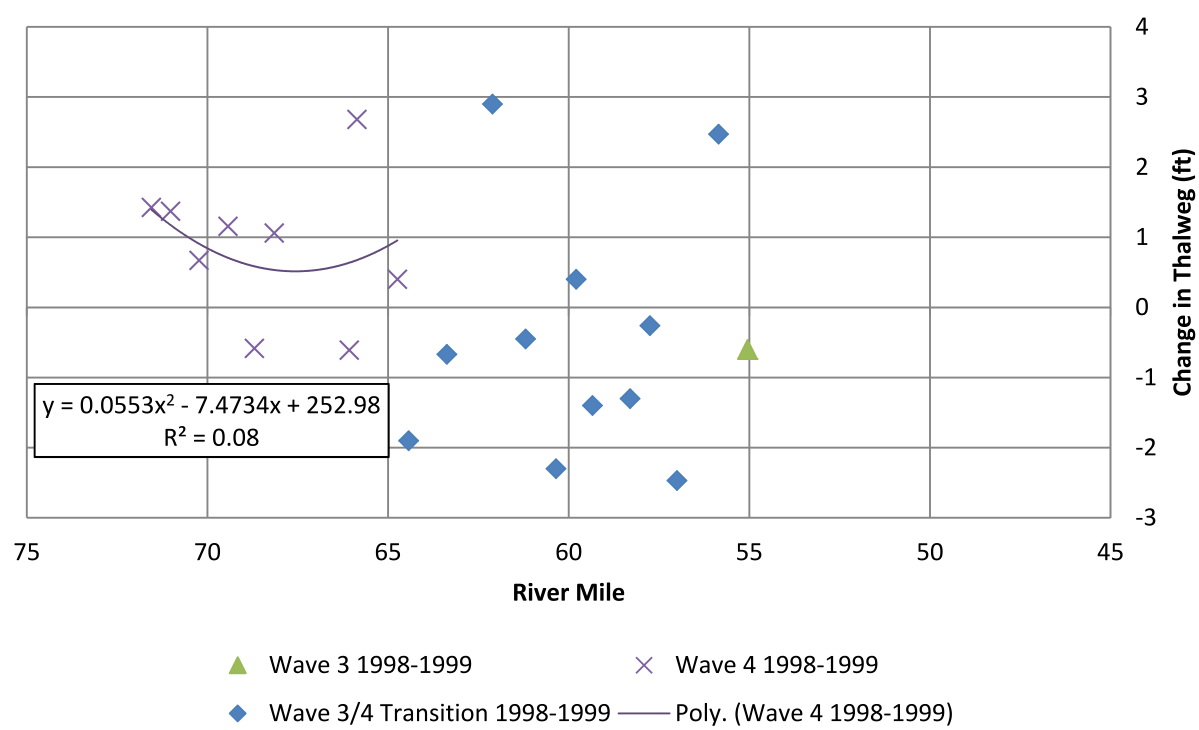

Figure G.8 1998-1999 Thalweg Change

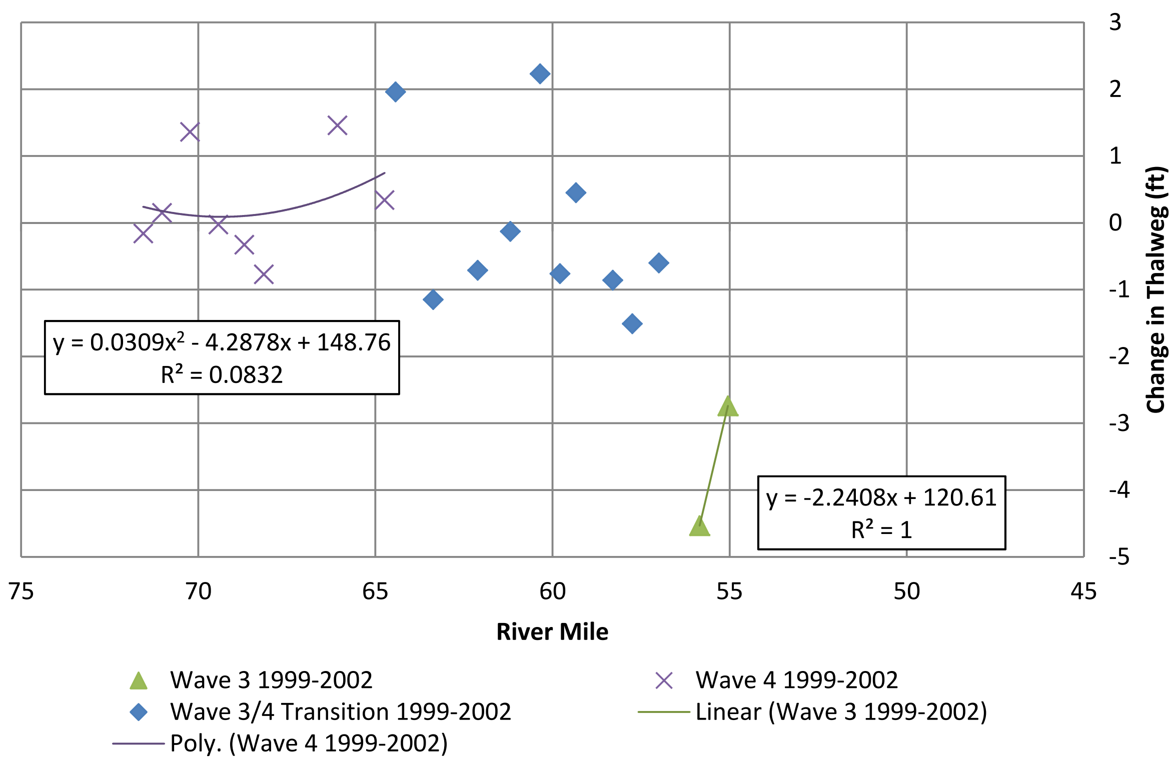

Figure G.9 1999-2002 Thalweg Change

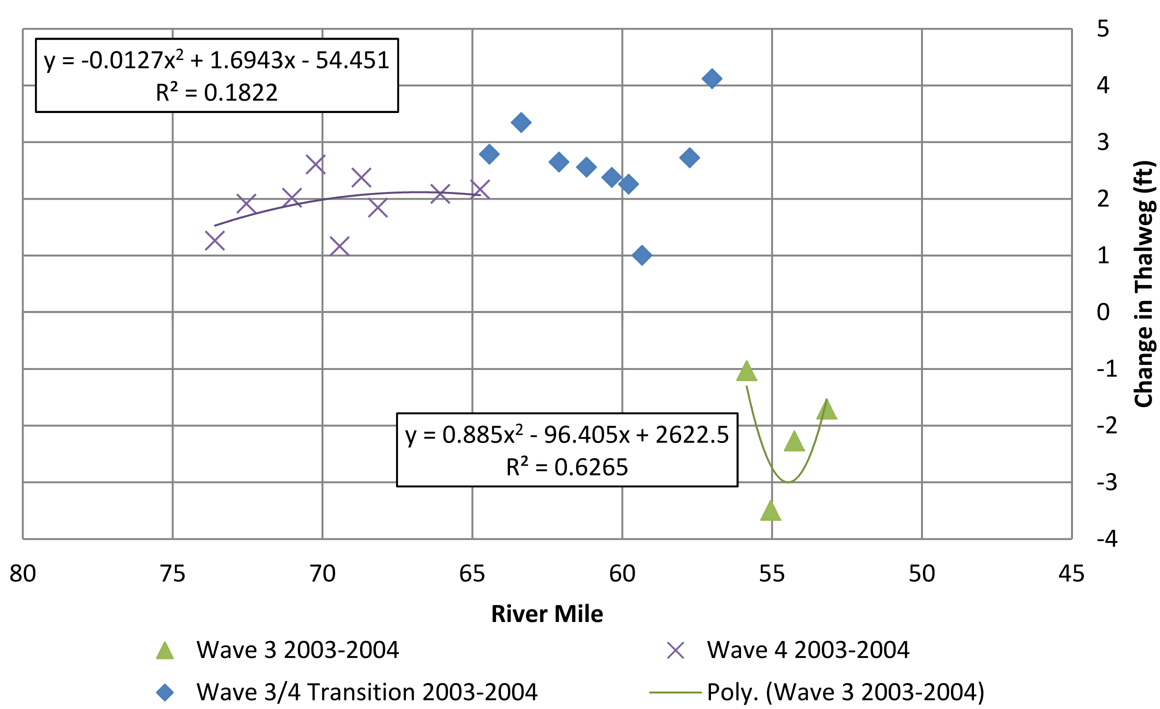

Figure G.10 2002-2003 Thalweg Change

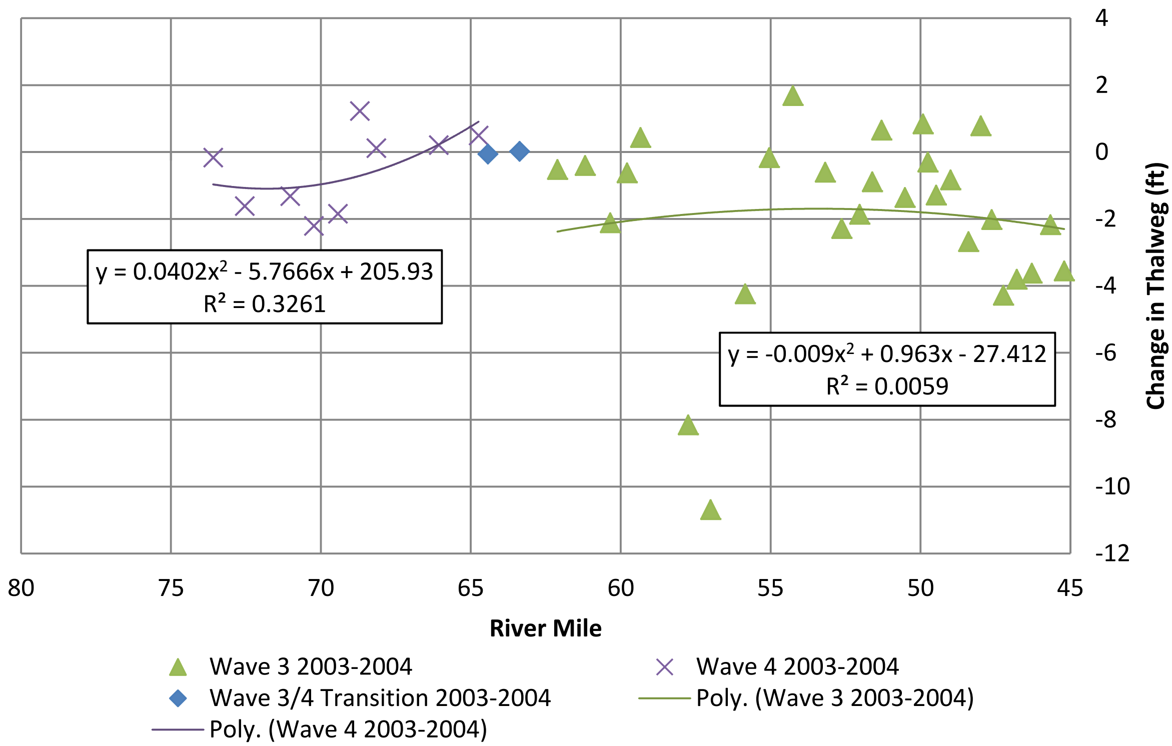

Figure G.11 2003-2004 Thalweg Change

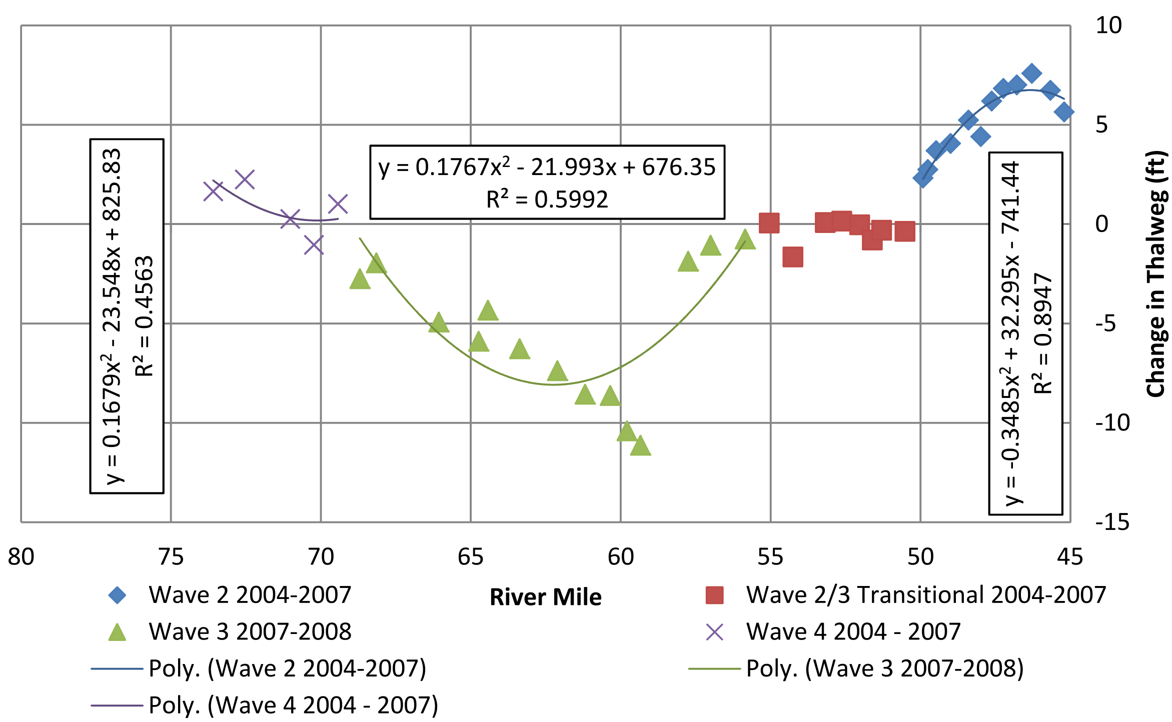

Figure G. 12 2004-2007 Thalweg Change

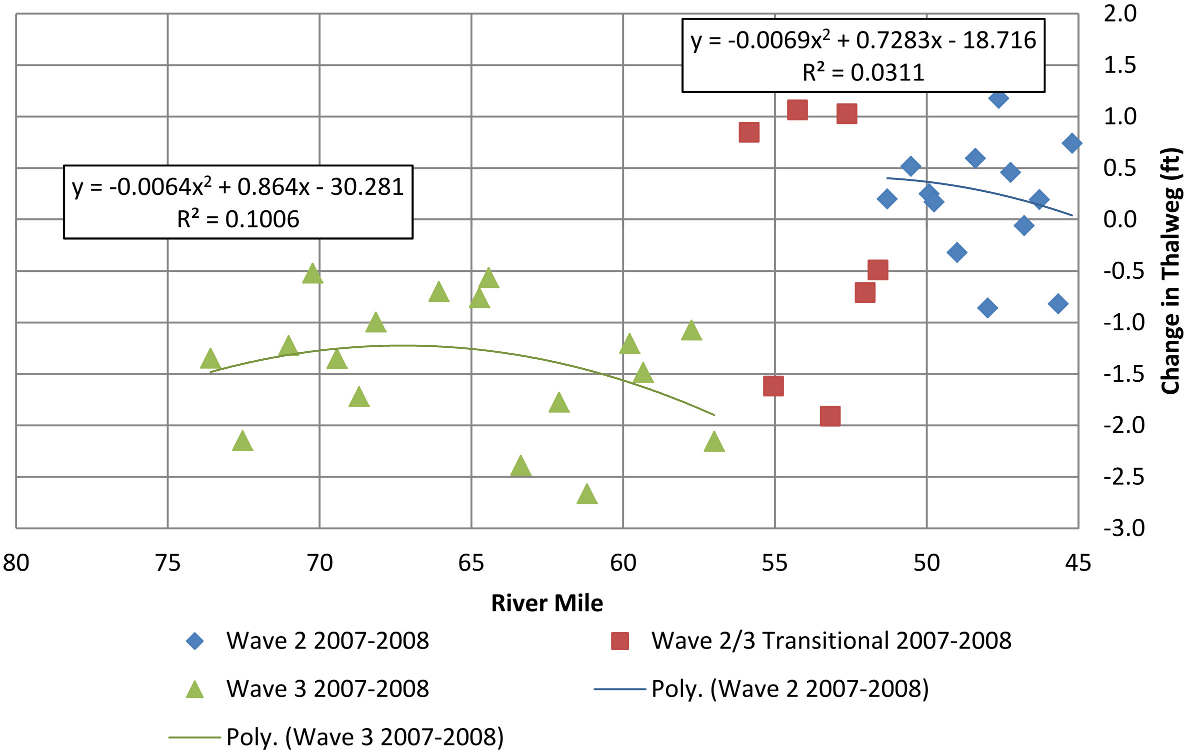

Figure G.13 2007-2008 Thalweg Change

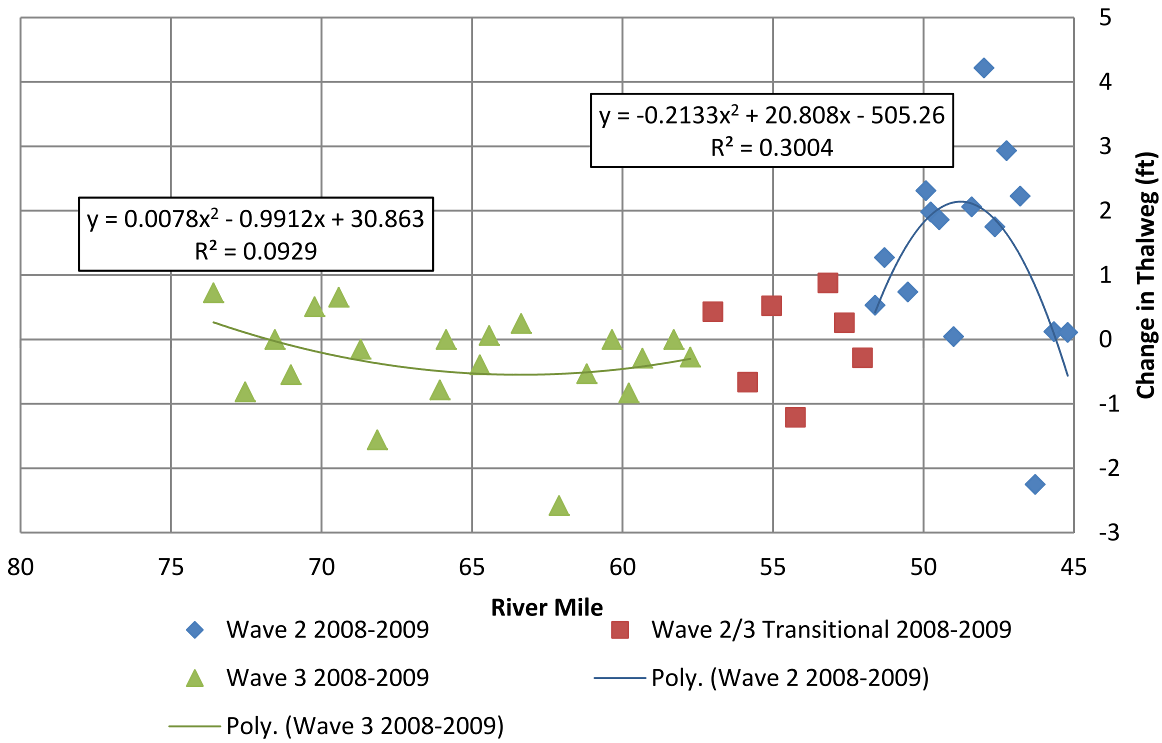

Figure G.14 2008-2009 Thalweg Change

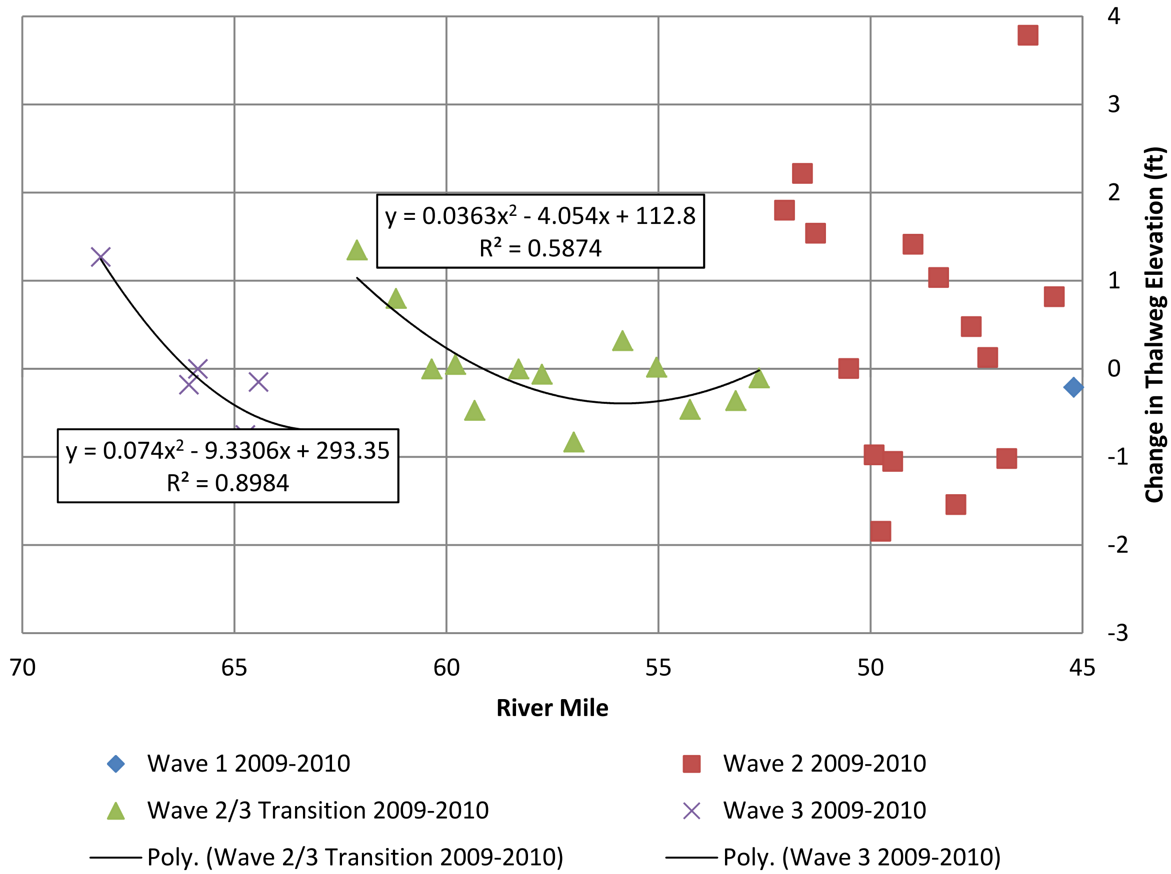

Figure G.15 2009-2010 Thalweg Change

APPENDIX H: BED MATERIAL GRAIN SIZE DISTRIBUTION PLOTS

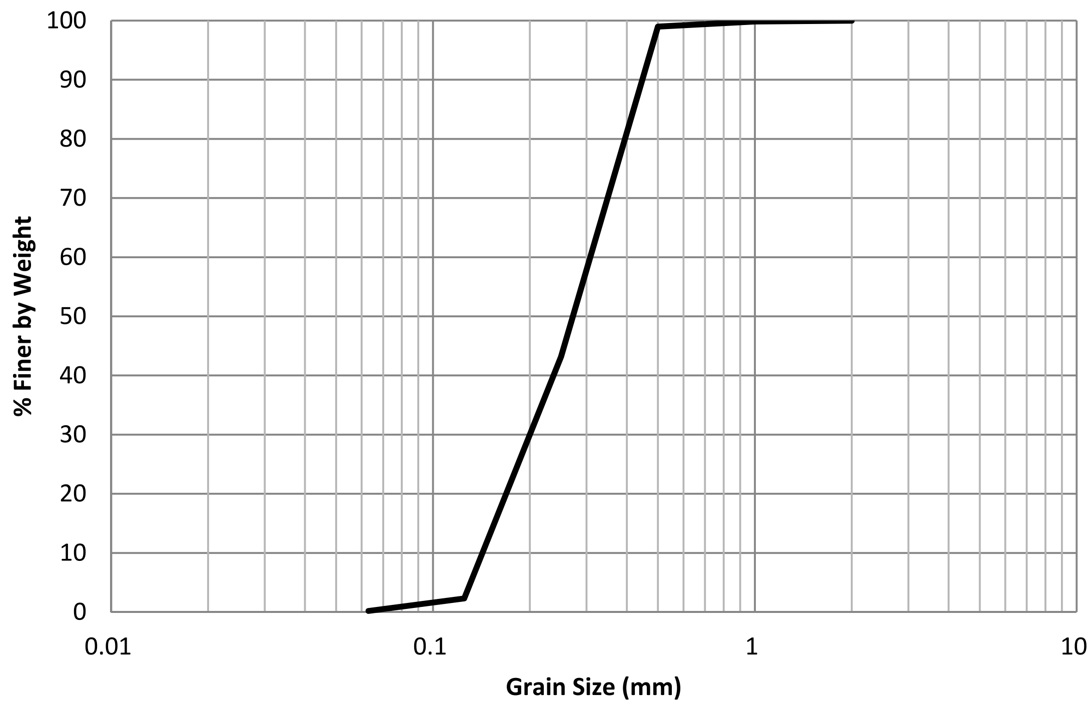

Figure H.1 SO-1641 2001 Grain Size Distribution

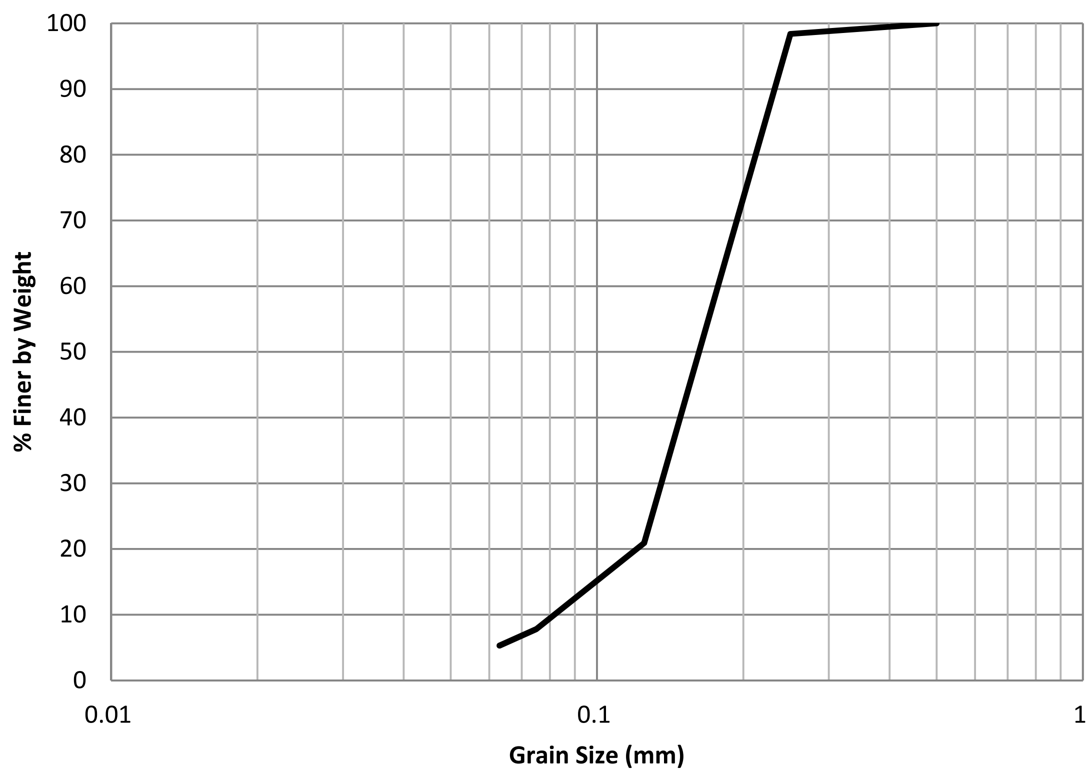

Figure H.2 SO-1641 2002 Grain Size Distribution

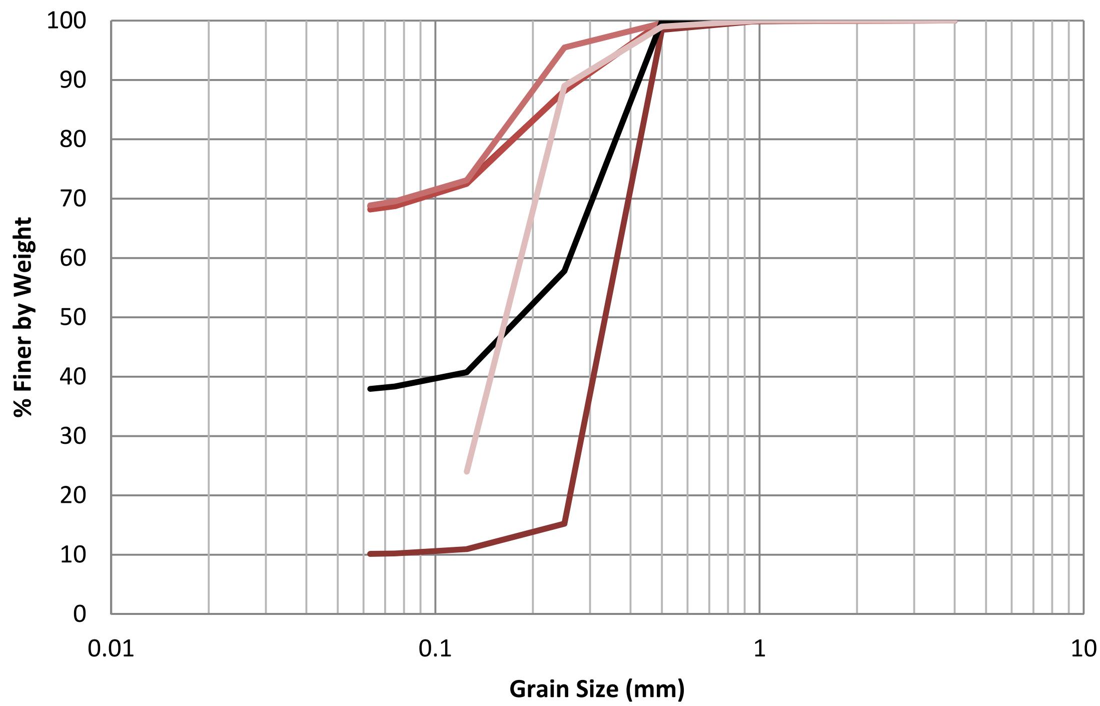

Figure H.3 SO-1641 2004 Grain Size Distribution

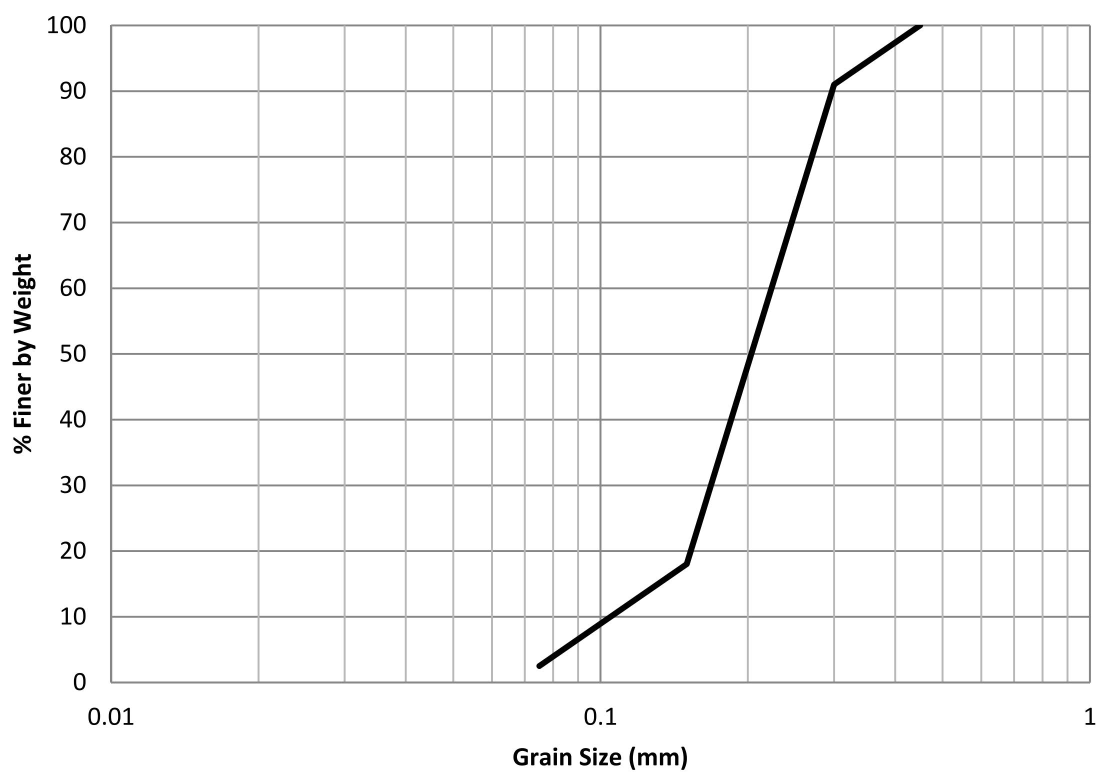

Figure H.4 SO-1641 2005 Grain Size Distribution

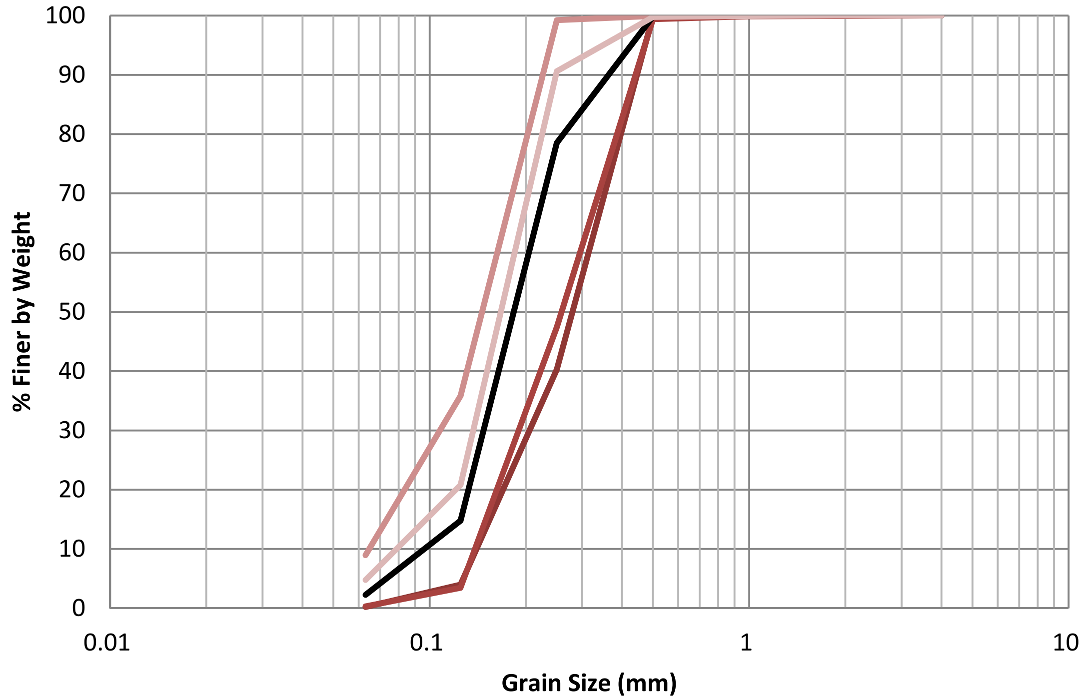

Figure H.5 SO-1683 1999 Grain Size Distribution

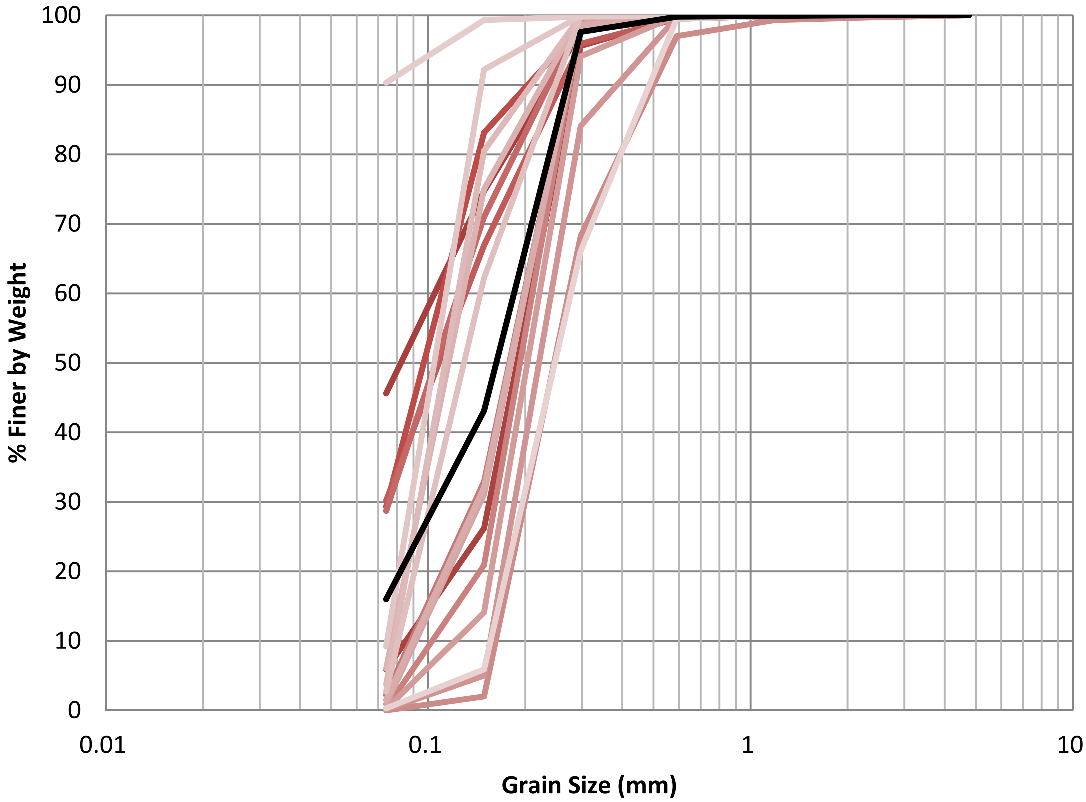

Figure H.6 EB-10 1986 Grain Size Distribution

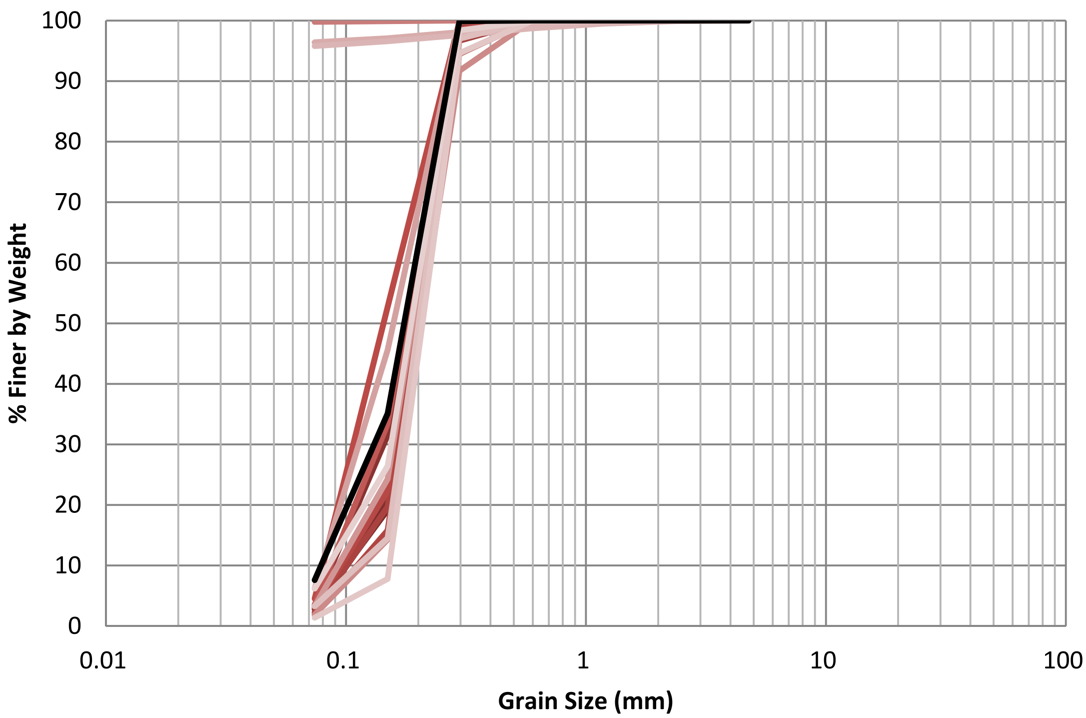

Figure H.7 EB-10 1987 Grain Size Distribution

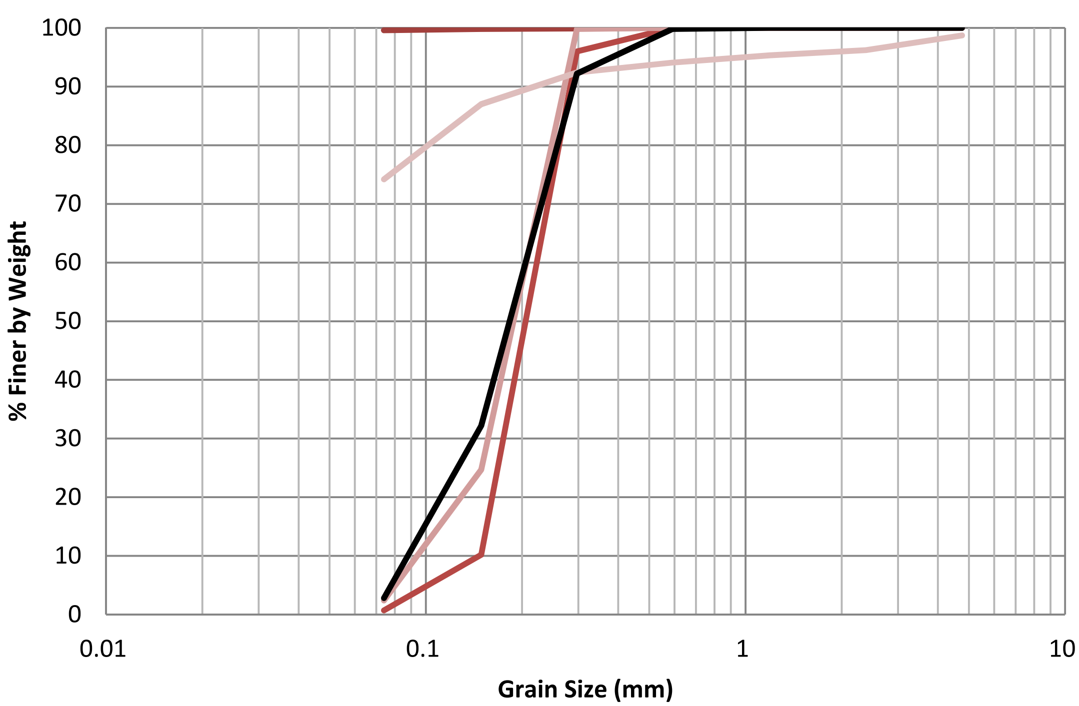

Figure H.8 EB-10 1988 Grain Size Distribution

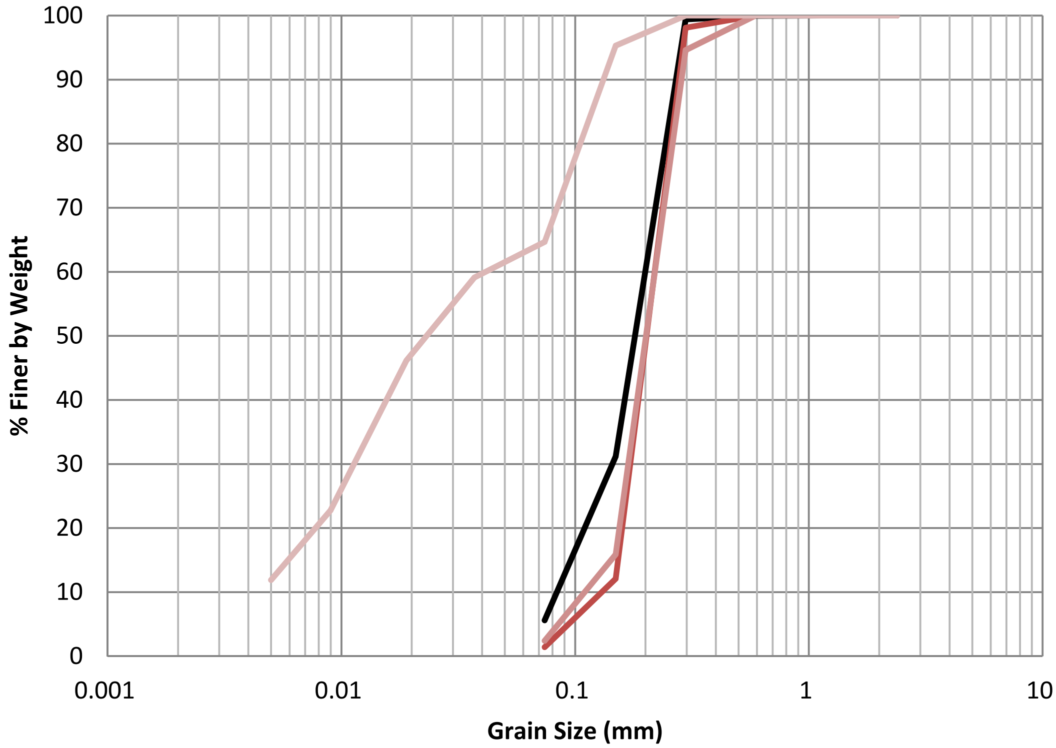

Figure H.9 EB-10 1990 Grain Size Distribution

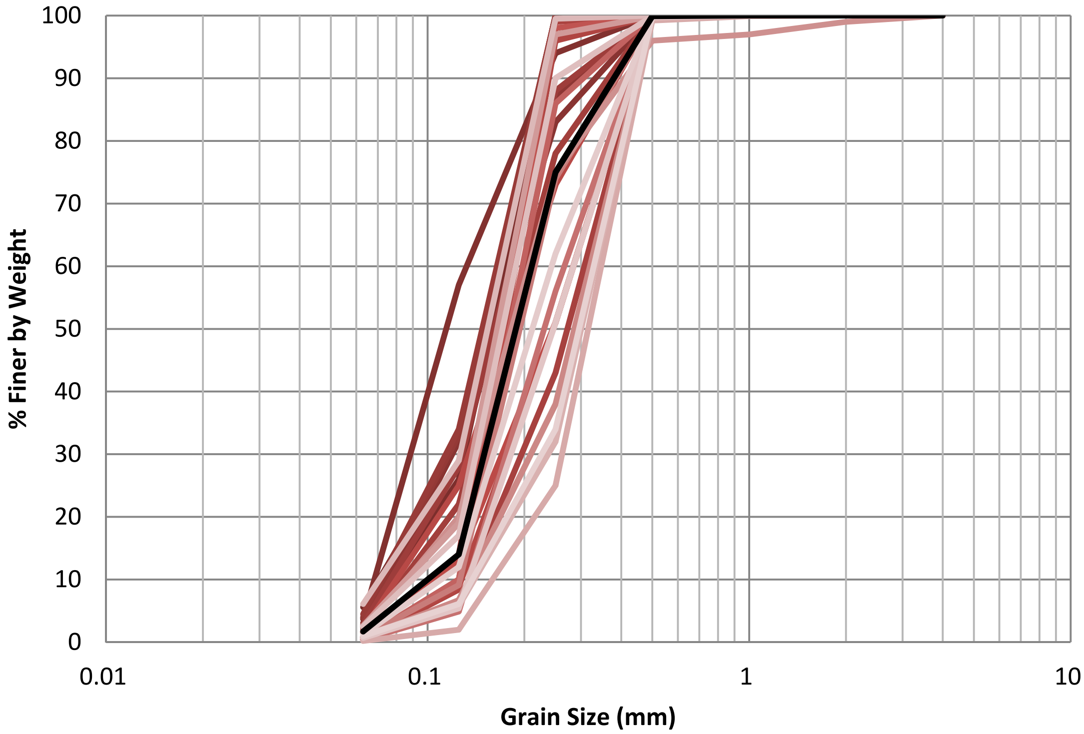

Figure H.10 EB-10 1992 Grain Size Distribution

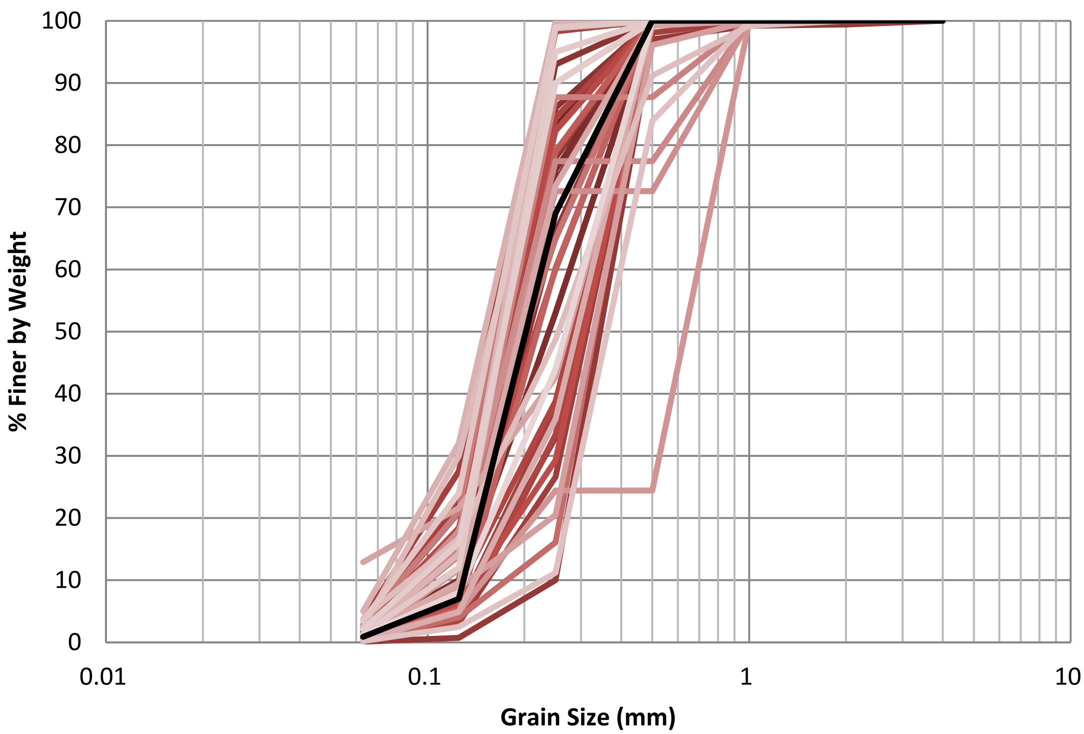

Figure H.11 EB-10 1993 Grain Size Distribution

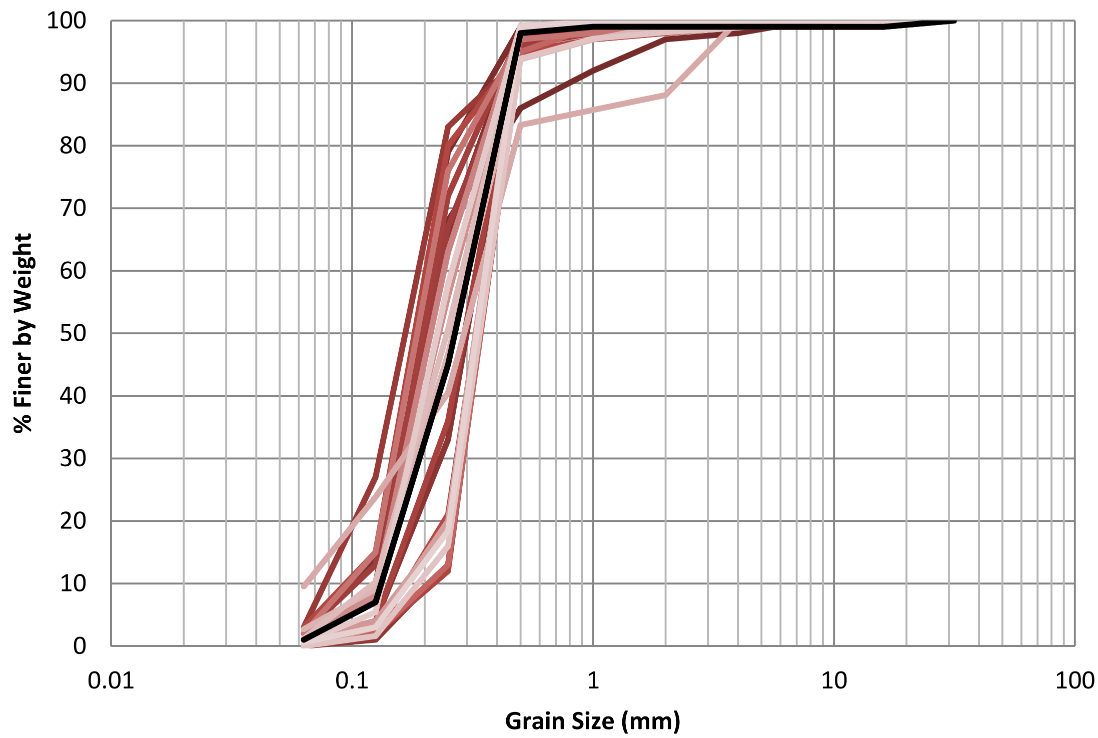

Figure H.12 EB-10 1994 Grain Size Distribution

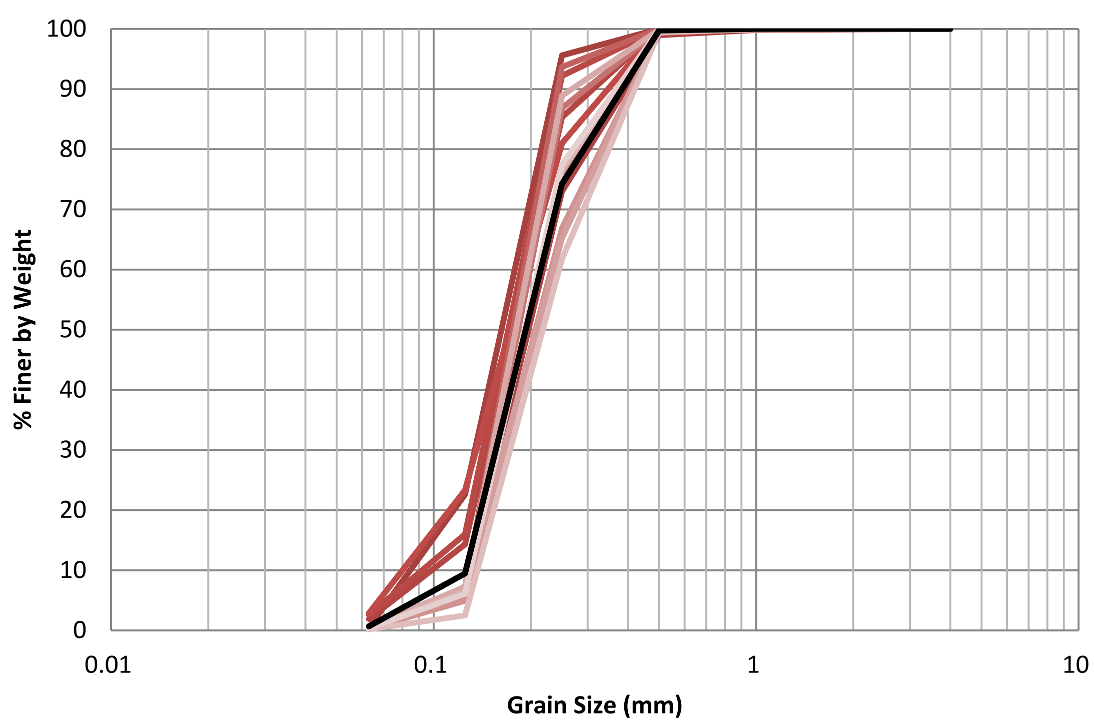

Figure H. 13 EB-10 1997 Grain Size Distribution

Figure H.14 EB-10 1998 Grain Size Distribution

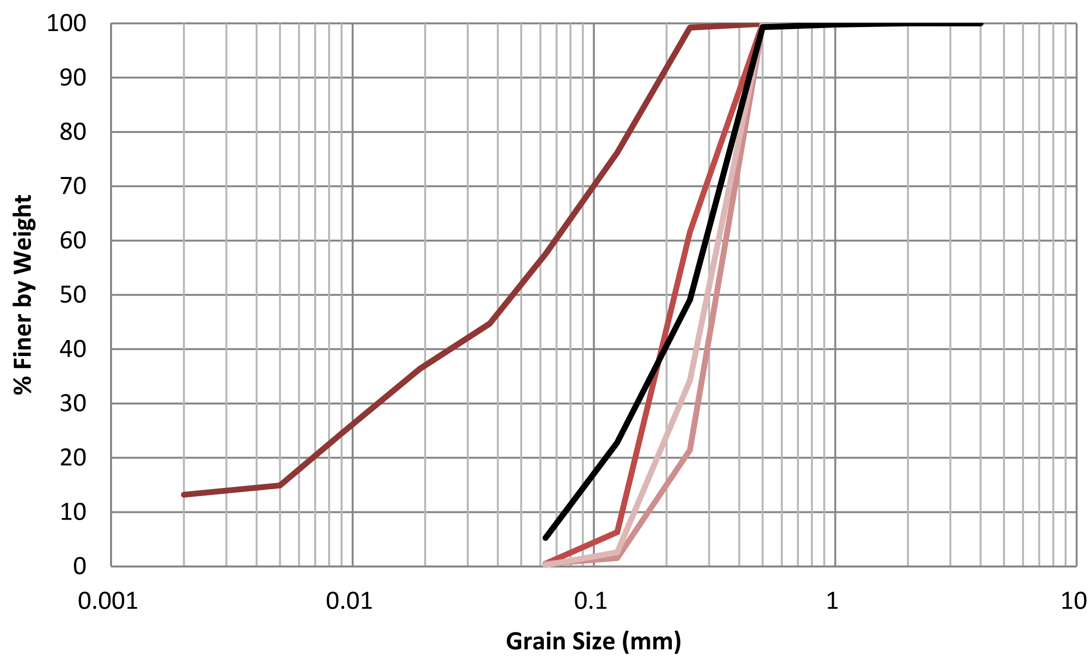

Figure H.15 EB-10 1999 Grain Size Distribution

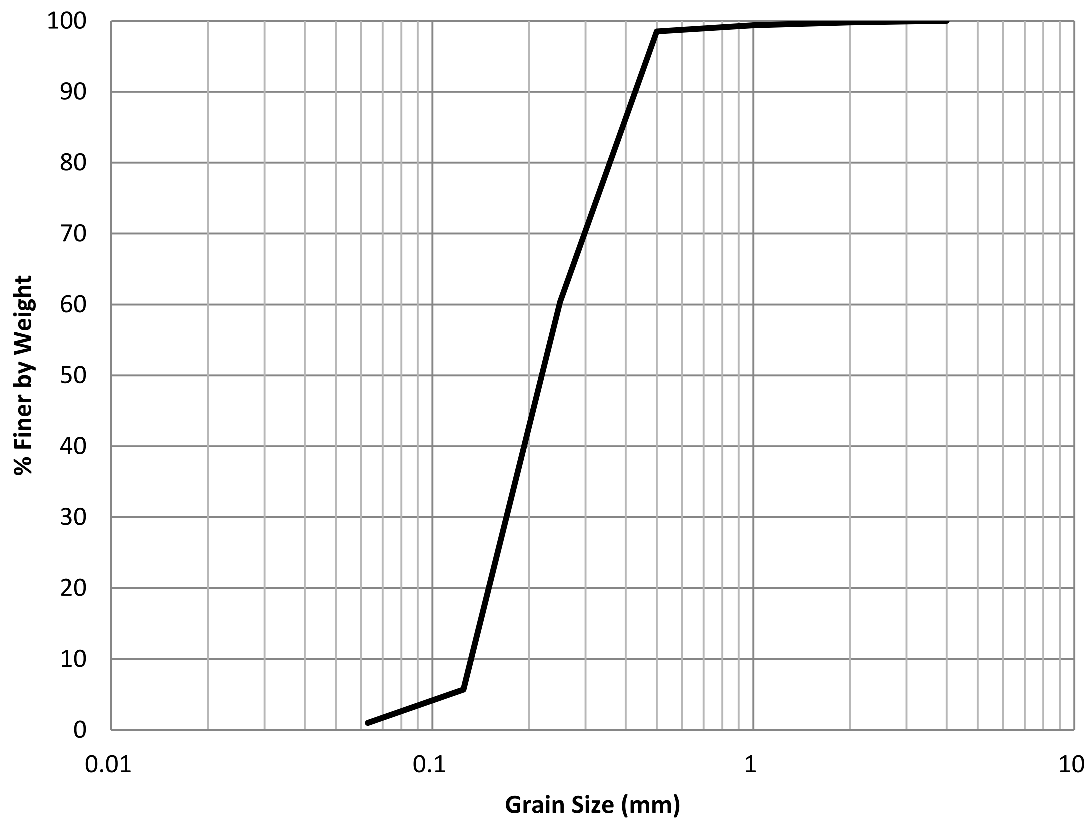

Figure H.16 EB-10 2002 Grain Size Distribution

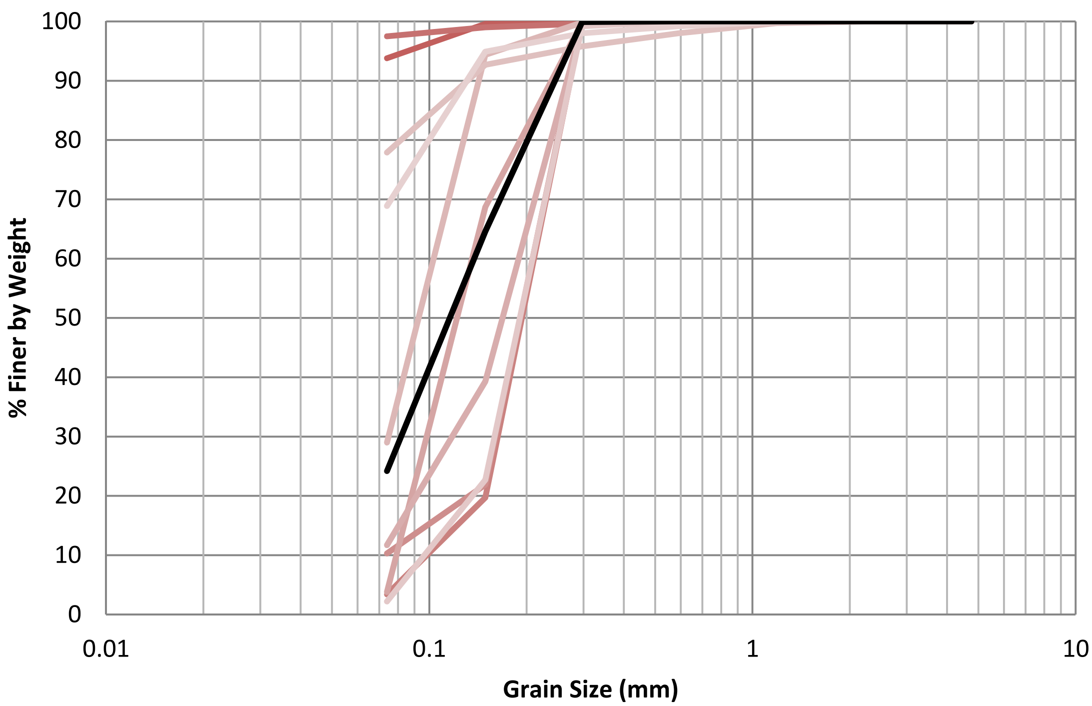

Figure H.17 EB-13 1986 Grain Size Distribution

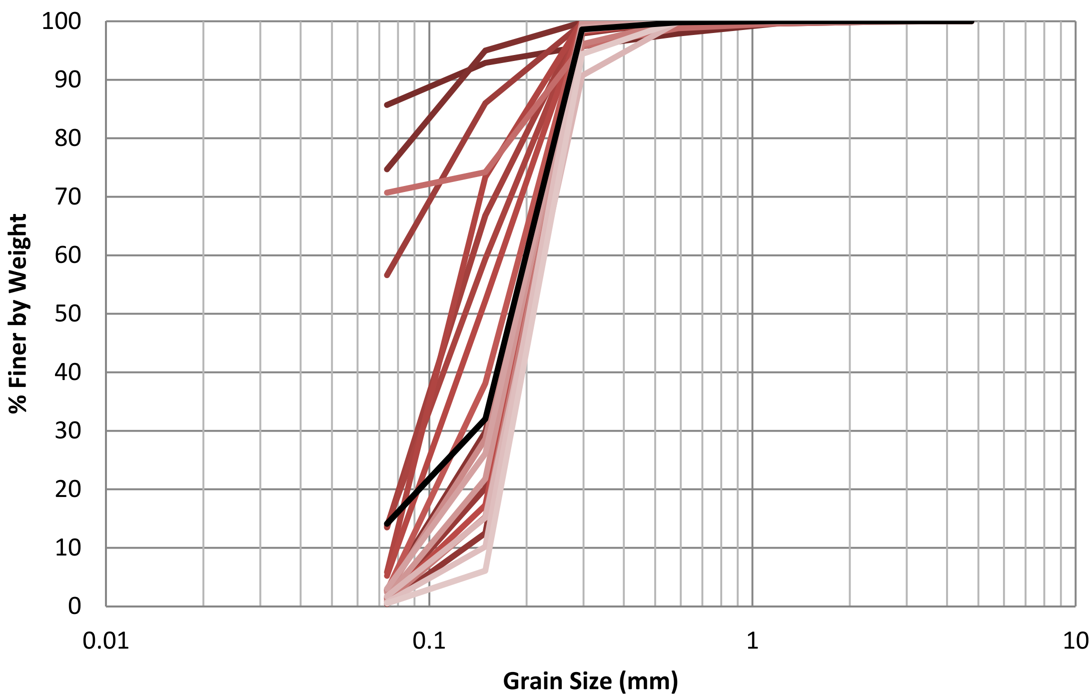

Figure H.18 EB-13 1987 Grain Size Distribution

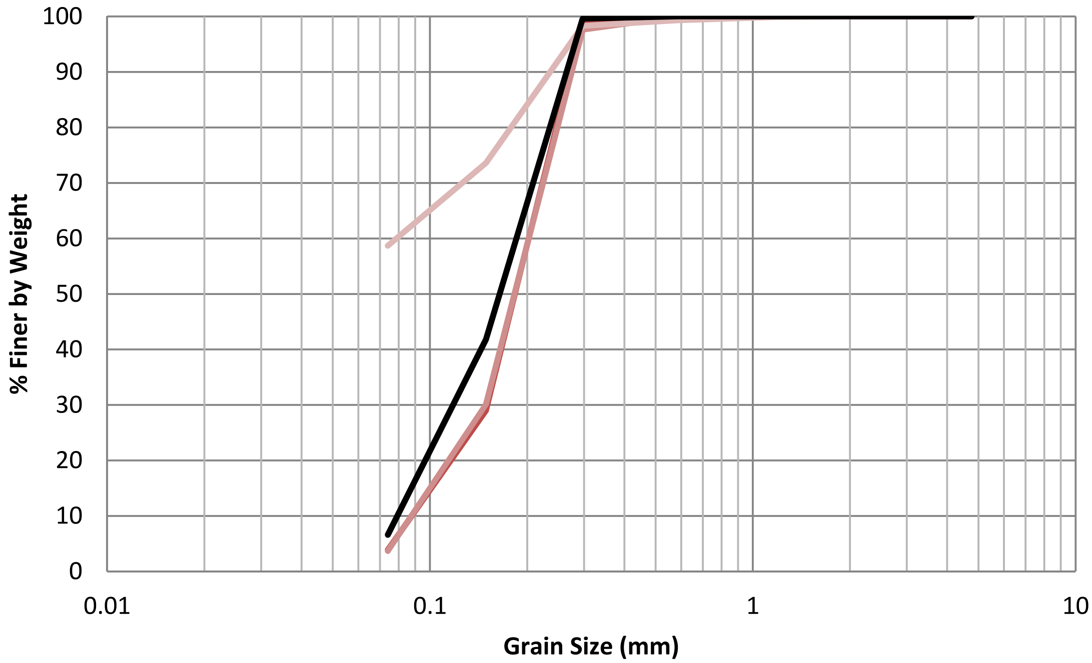

Figure H.19 EB-13 1988 Grain Size Distribution

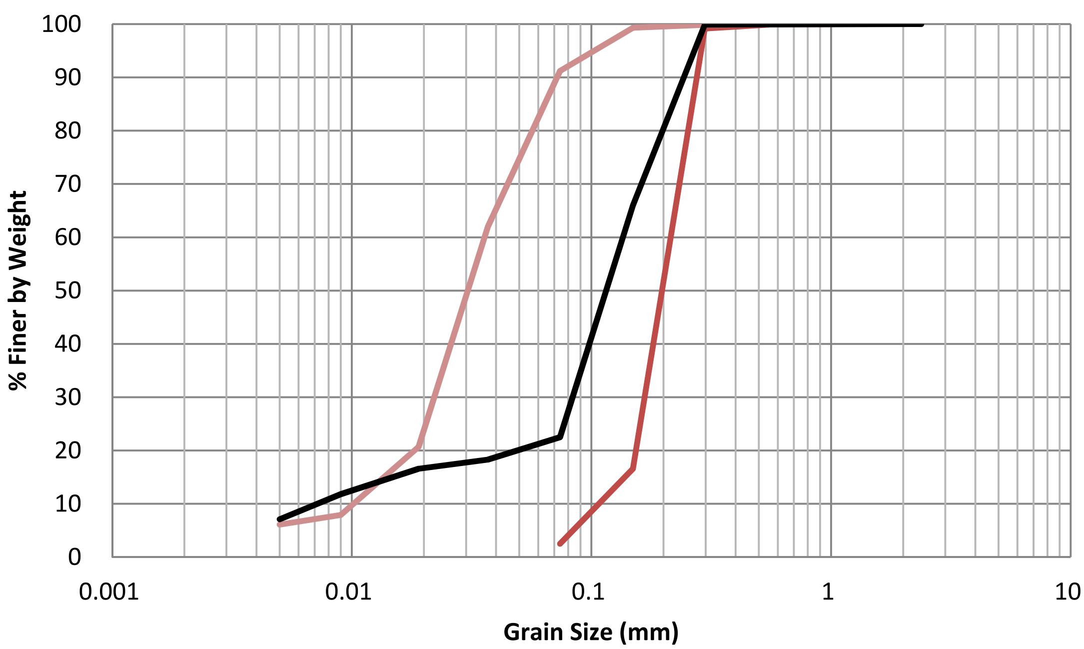

Figure H.20 EB-13 1990 Grain Size Distribution

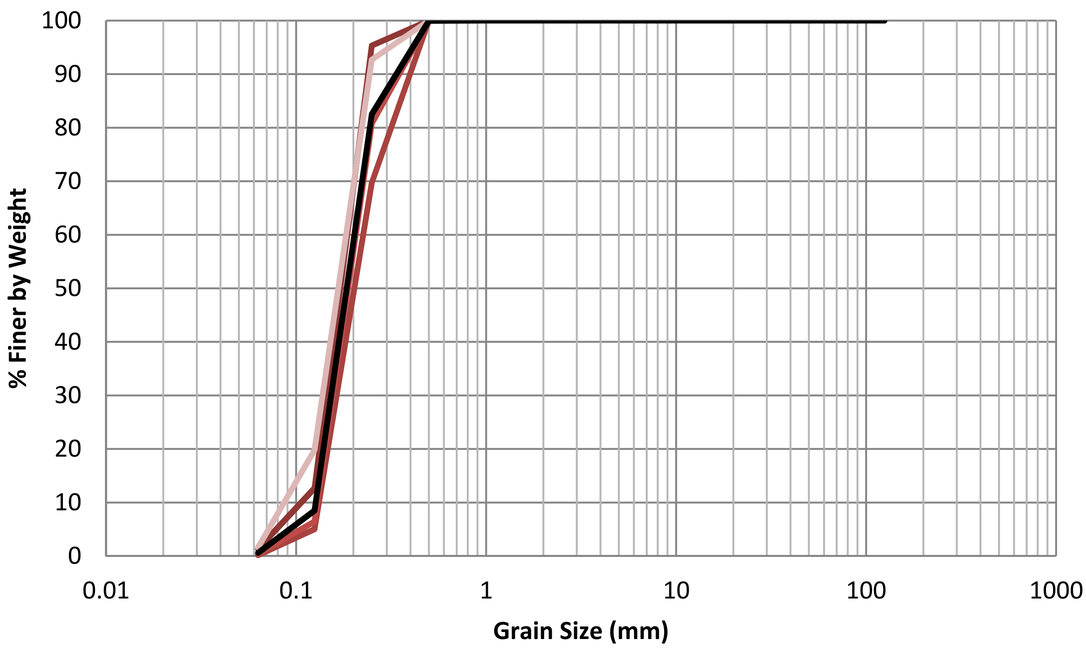

Figure H.21 EB-13 1999 Grain Size Distribution

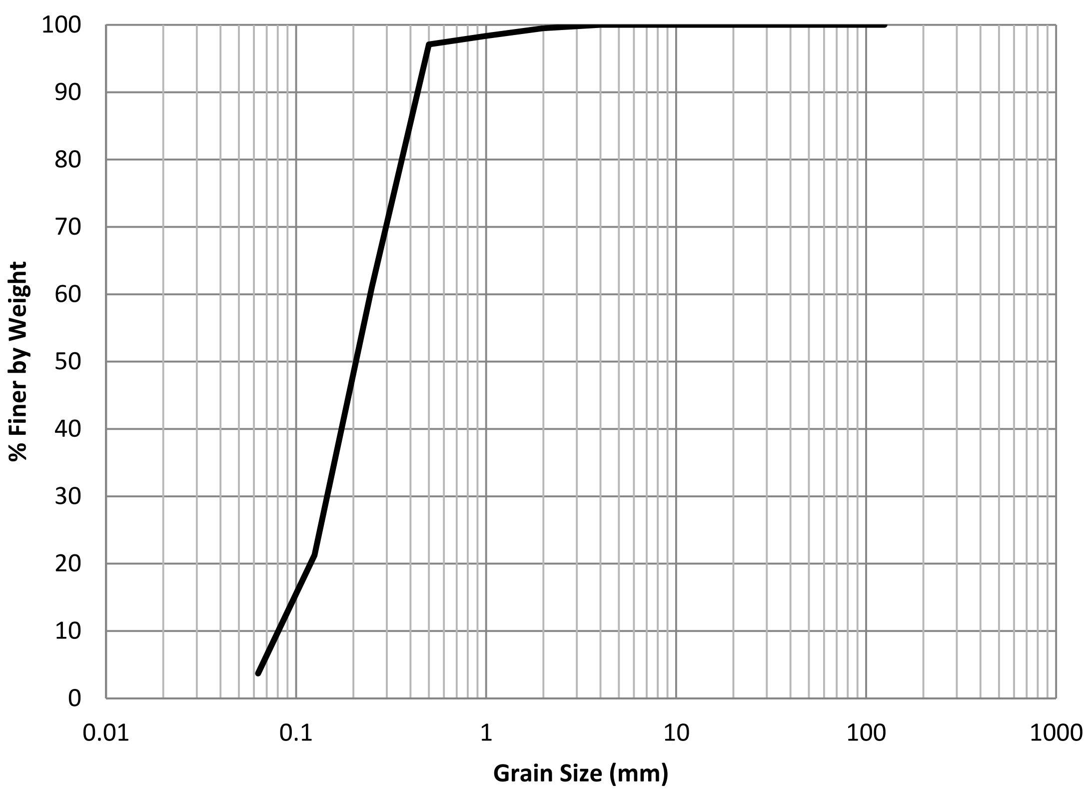

Figure H.22 EB-13 2002 Grain Size Distribution

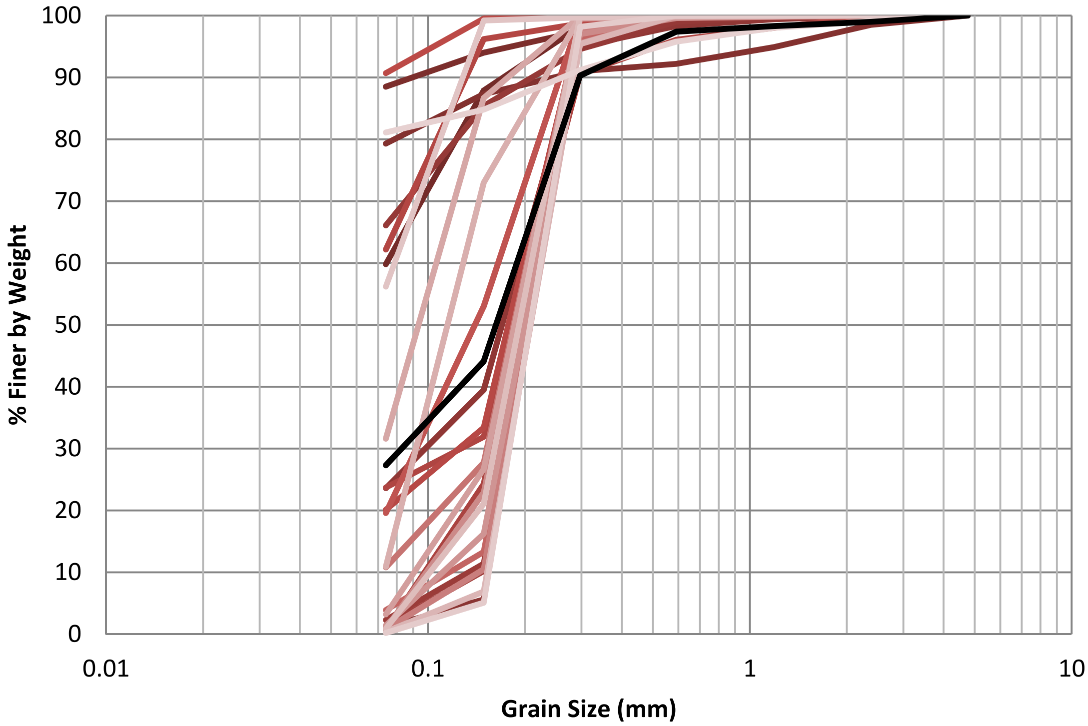

Figure H.23 EB-18 1986 Grain Size Distribution

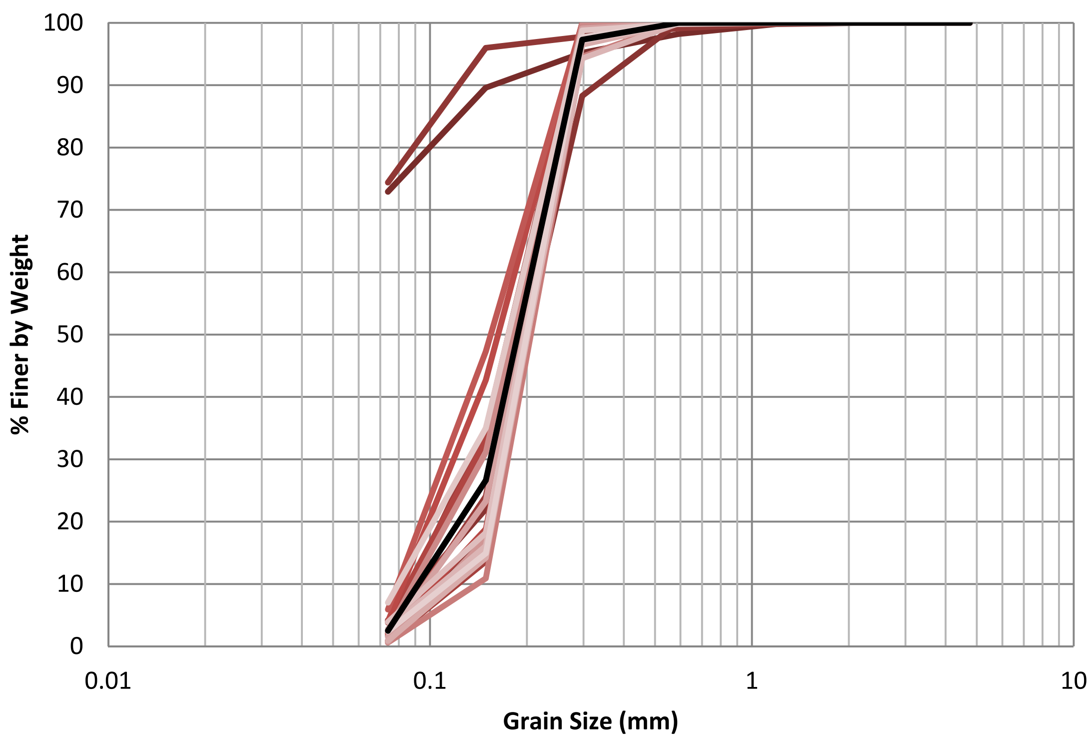

Figure H.24 EB-18 1987 Grain Size Distribution

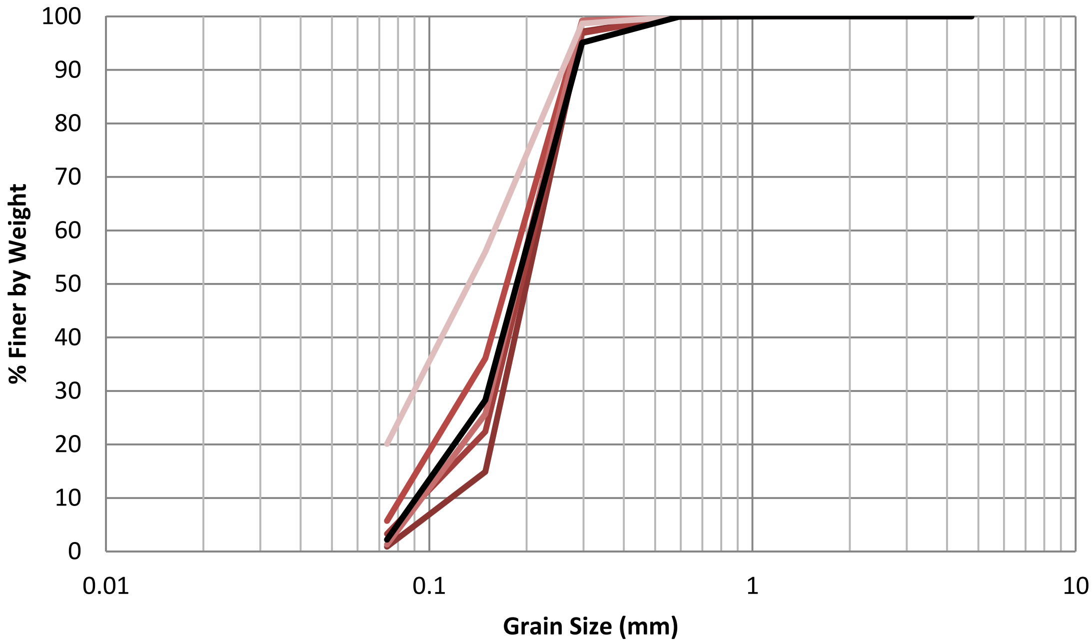

Figure H.25 EB-18 1988 Grain Size Distribution

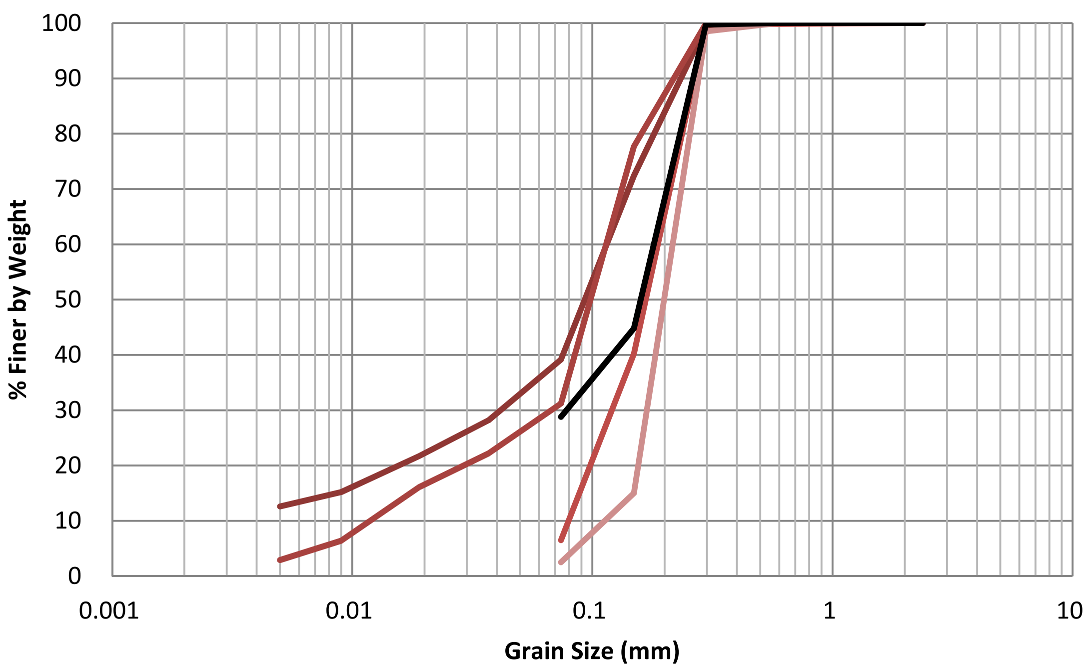

Figure H.26 EB-18 1990 Grain Size Distribution

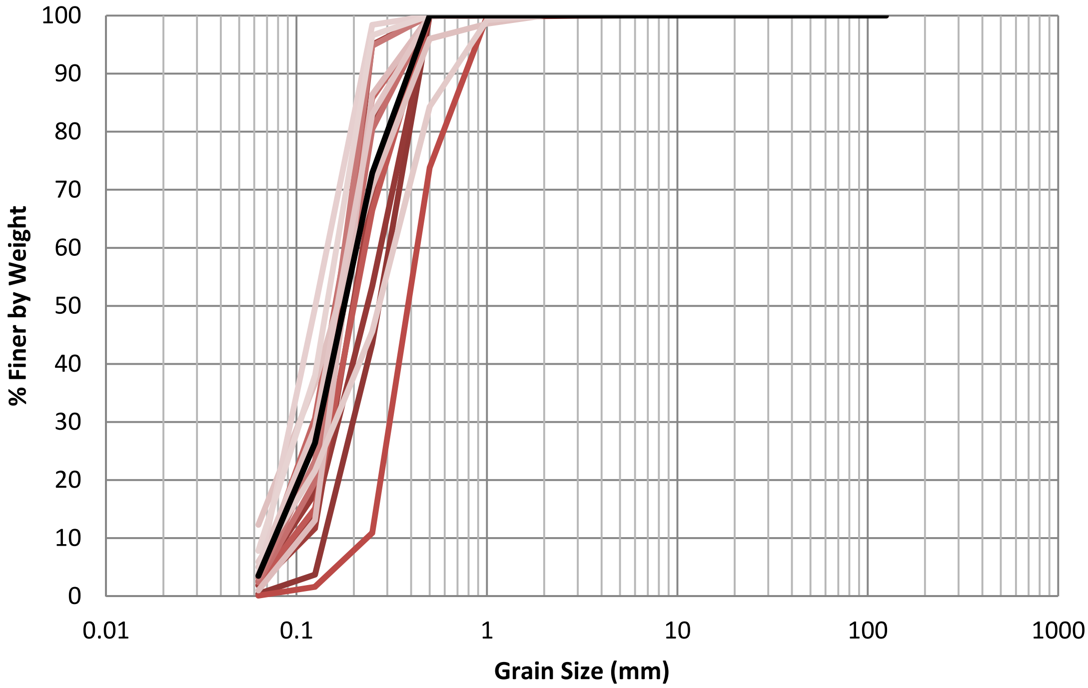

Figure H.27 EB-18 1993 Grain Size Distribution

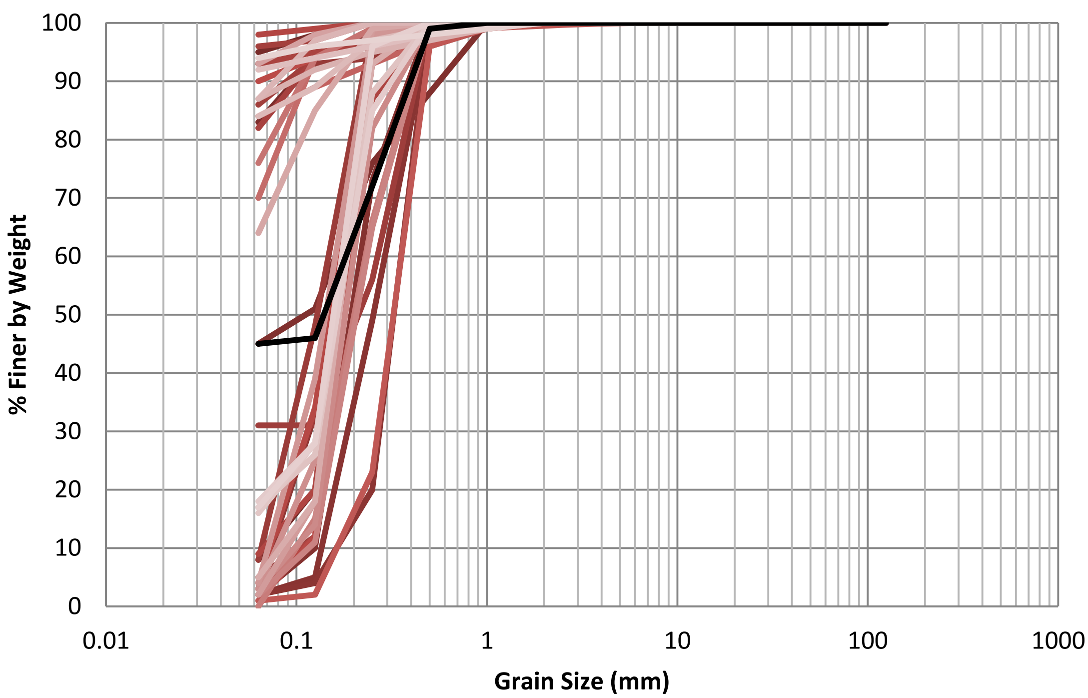

Figure H.28 EB-18 1994 Grain Size Distribution

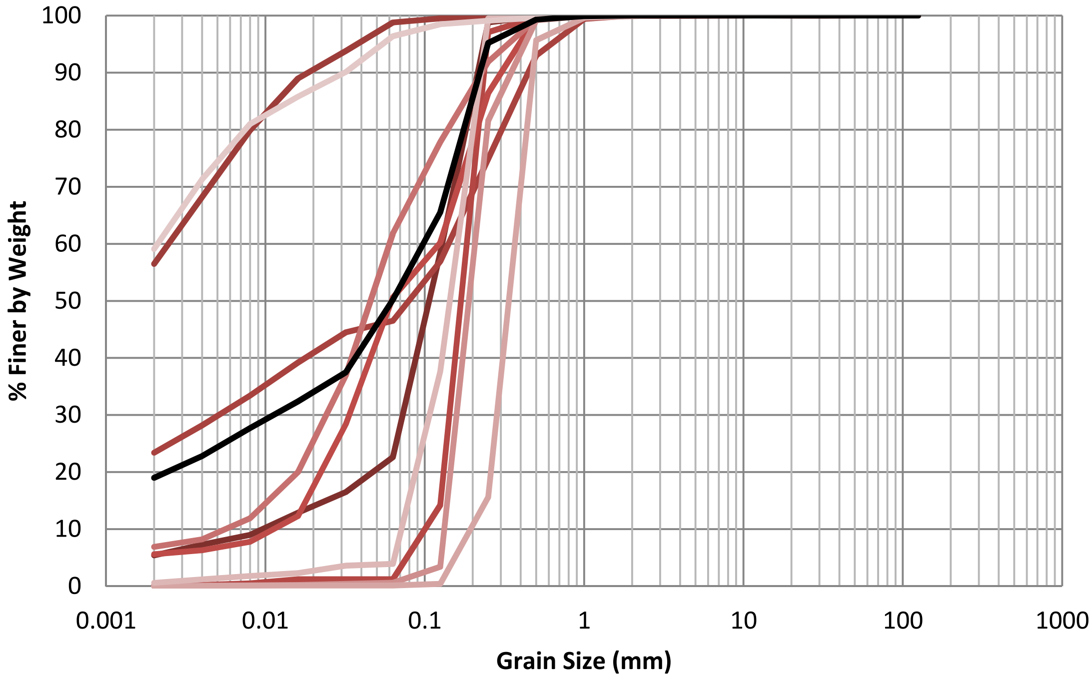

Figure H.29 EB-18 1997 Grain Size Distribution

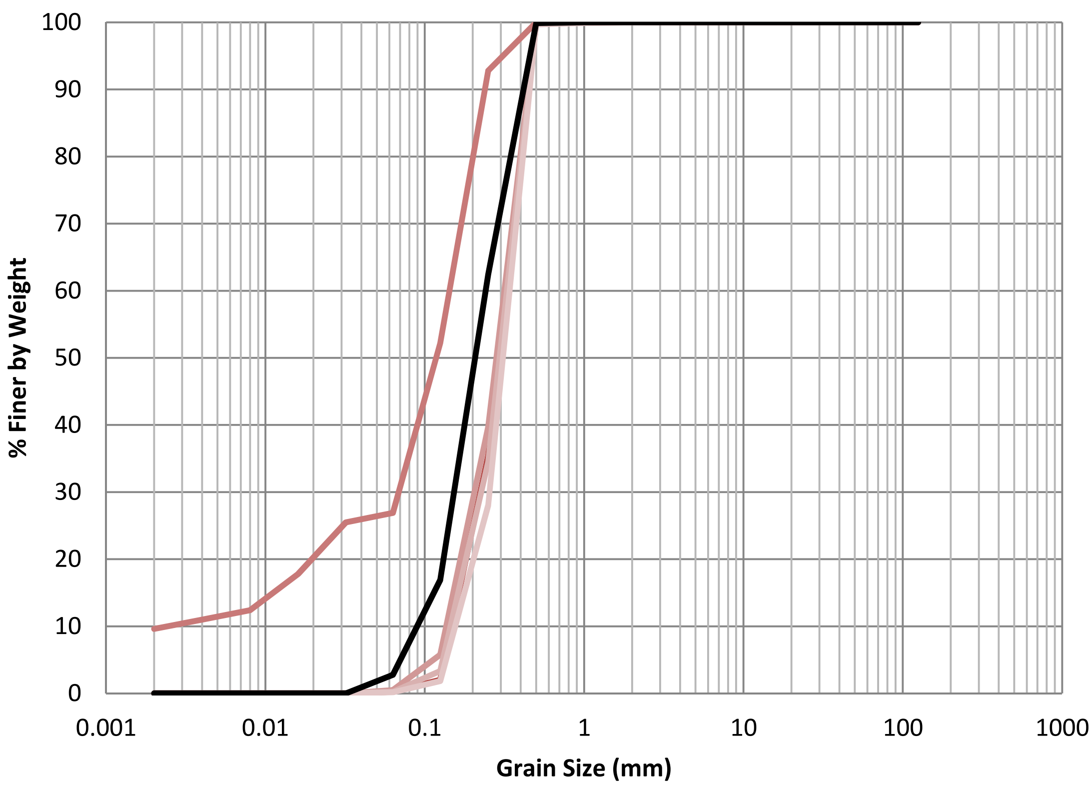

Figure H.30 EB-18 1999 Grain Size Distribution

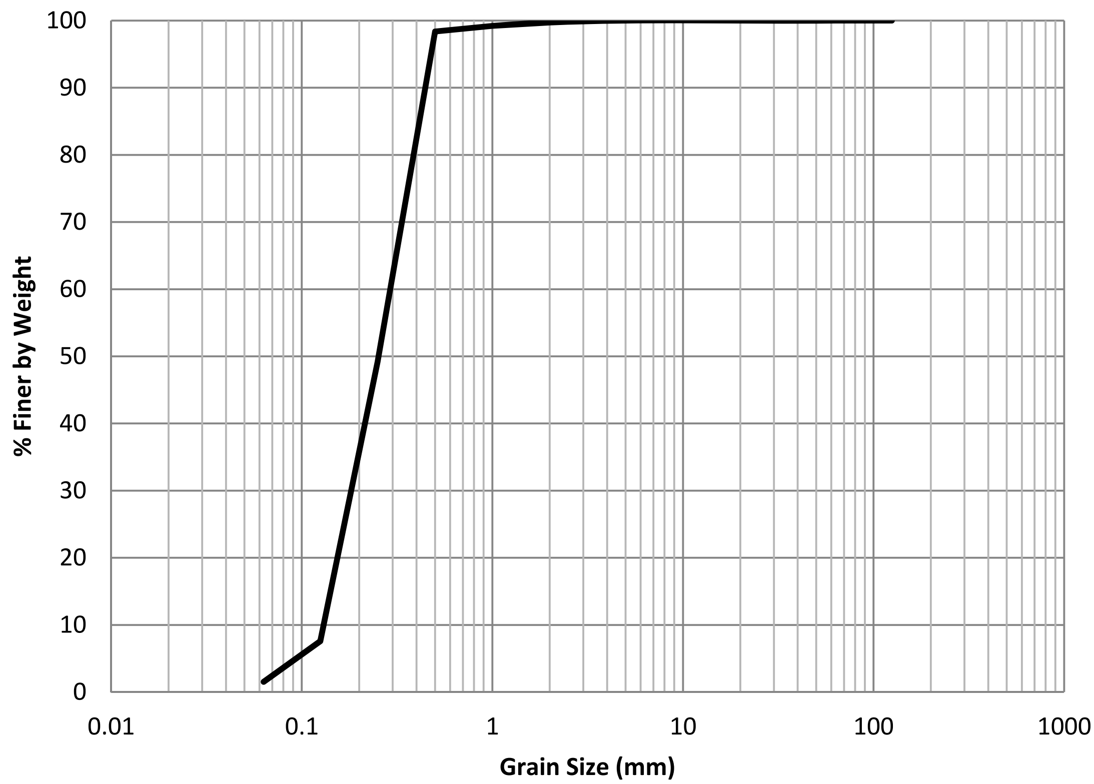

Figure H.31 EB-18 2002 Grain Size Distribution

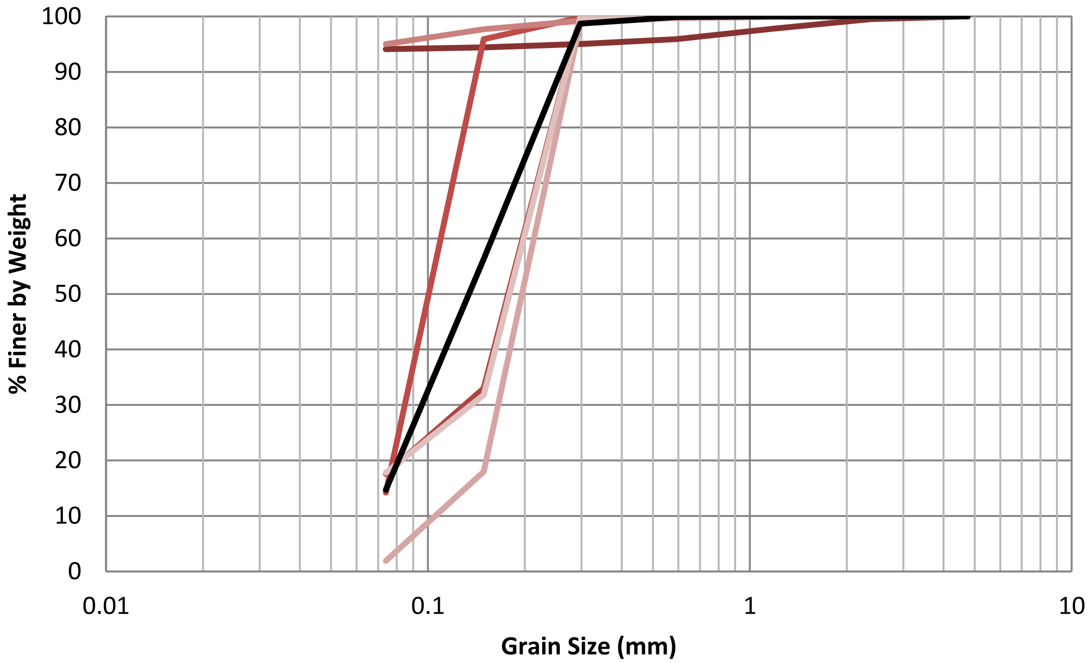

Figure H.32 EB-24 1986 Grain Size Distribution

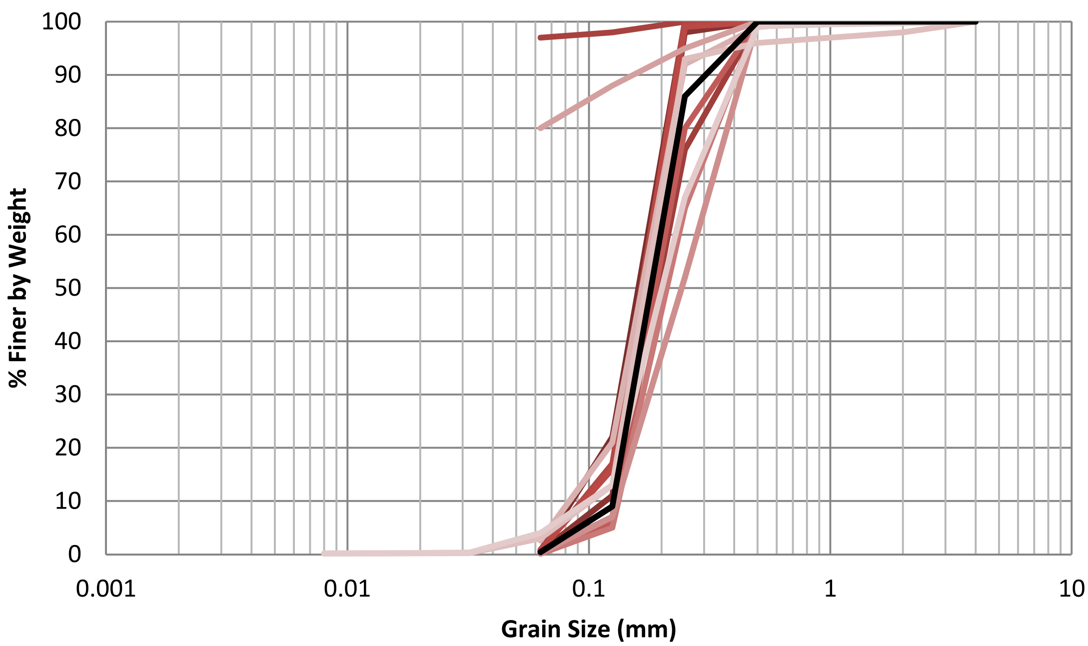

Figure H.33 EB-24 1992 Grain Size Distribution

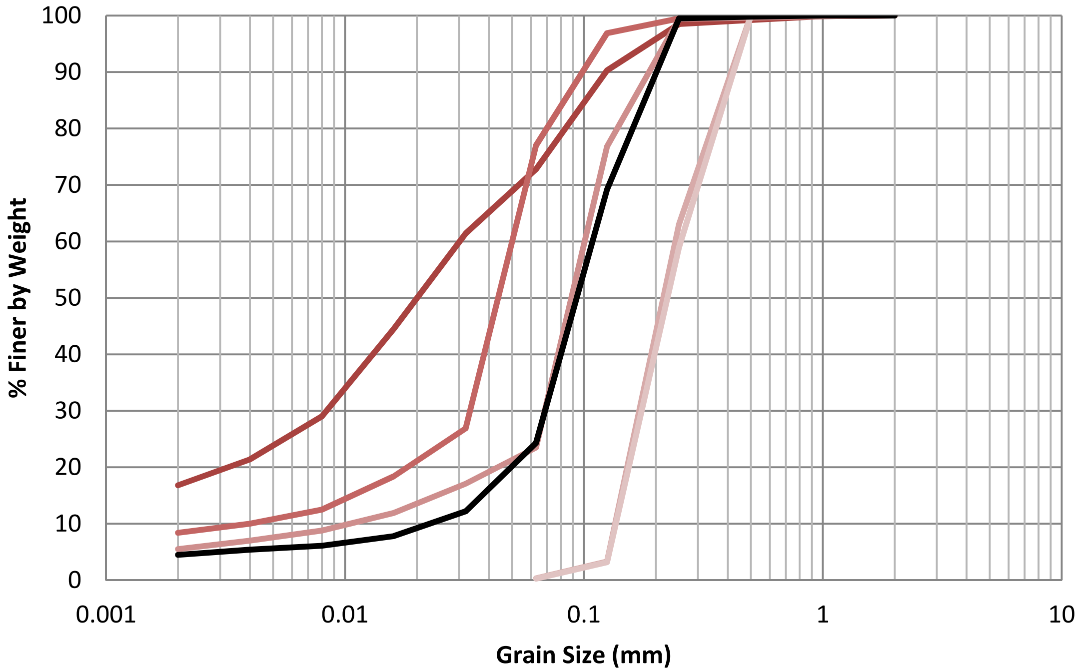

Figure H.34 EB-24 1999 Grain Size Distribution

Figure H.35 EB-24 2002 Grain Size Distribution