Baseline Report
Rio Grande-Caballo Dam to American Dam FLO-2D Modeling, New Mexico and Texas




Prepared for: **United States Section International Boundary and Water Commission (USIBWC)**
Under IBM 92-21, Task IWO #31

Prepared by:
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September 4, 2007

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1. INTRODUCTION

The United States Section of the International Boundary and Water Commission (USIBWC) is evaluating the long-term river management alternatives for the Rio Grande Canalization Project (RGCP), a narrow river corridor that extends 105 miles from Percha Dam at River Mile (RM) 105.4 in Sierra County, New Mexico to American Dam at RM 0 in El Paso, Texas (USIBWC, 2004; **Figure 1.1**). The RGCP reach is contained within the Lower Bioregion (Caballo Dam, NM to Candelaria, TX) geomorphic subreach of the Rio Grande (Fullerton and Batts, 2003). The Albuquerque District of the U.S. Army Corps of Engineers (Corps) is conducting this evaluation for the USIBWC under Authority of the Economy in Government Act (31 USC 1535), and the USIBWC will use the information to support the management evaluation for the RGCP.

1.1. Project Objectives

The Corps and USIBWC objective for the this study is to investigate river channel/overbank connectivity to identify and evaluate sites where it would be feasible to produce enhanced cover and aquatic diversity and restore healthy riparian function to enhance natural riverine processes and improved terrestrial wildlife habitat, while protecting existing infrastructure. Habitat improvements to meet the project objectives were previously identified at 20 locations within the RGCP (Table 2-9, USIBWC, 2004). The suggested habitat improvements at these locations included native vegetation plantings, bank shave-downs for riparian vegetation, opening up of former meanders and modifications of dredging practices at the mouths of the tributary arroyos (USIBWC, 2004). In addition to further evaluation of the previously identified sites, a key goal of this study is to assist the project sponsors and stakeholders in reassessing the restoration potential along the entire 105-mile project reach to identify other feasible sites and determine the most suitable restoration actions at these sites.

1.2. Scope of Work

The primary goal of this baseline conditions investigation was to modify an existing FLO-2D hydraulic model (Tetra Tech, 2004) to assess overbank flow potential, sediment-transport and geomorphologic processes within the RGCP reach, and to develop a description of baseline geomorphic conditions within the reach. Specific tasks that were completed for the baseline study included:

1. Meetings with various branches of the Corps, USIBWC, Elephant Butte Irrigation District (EBID), Environmental Defense (ED), World Wildlife Fund (WWF), and other agencies as appropriate to obtain existing studies, hydraulic models (HEC-RAS, FLO-2D), and flood studies for the Rio Grande reach from Caballo Dam to American Dam.

2. Compilation of the Rio Grande geomorphology data to include applicable studies and reports that investigated the Rio Grande and its tributaries within the project reach.

3. A site visit to meet with Stakeholders and gain familiarity with the reach, including the various dams and diversion operations.

4. Review of available GIS databases and mapping to identify survey information and mapping available to support hydraulic modeling and analyses, and to recommend additional survey/mapping requirements, as necessary.

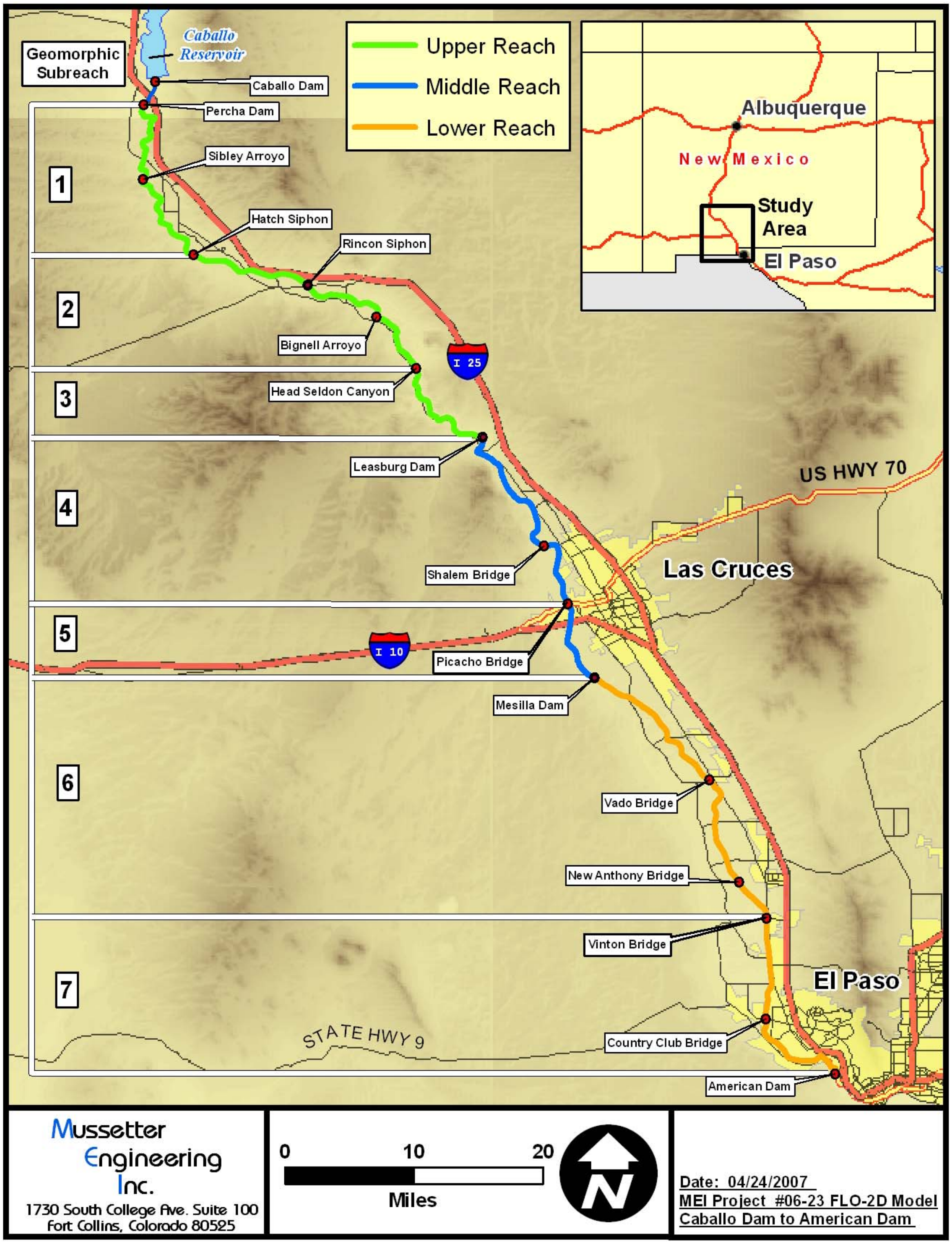


Figure 1.1. Map showing the location of the Rio Grande Canalization Project.

5. Obtain from the Corps and USIBWC river profile, cross section, flow, sediment data and aerial photographs to update the information for this reach of the Rio Grande as a basis for more detailed hydraulic analyses.

6. An evaluation of hydraulic, sediment-transport and geomorphic impacts and trends to define baseline conditions for the project reach. Of particular importance are potential impacts on hydraulic structures and bridges throughout the study reach and the impact of any proposed Rio Grande gradient control or other proposed features on the 100-year water-surface elevation, and other events as appropriate. The following efforts were included in this evaluation:

    a. Identification of subreaches based on geomorphology, hydraulic and biologic considerations, including substrate, channel width/depth ratio, bankfull discharge, vegetation communities, and other channel morphology parameters. This required some additional field time to review substrate conditions at various arroyo confluences.

    b. Conduct data compilation of the Rio Grande geomorphology affecting this reach and develop existing conditions descriptions including aggradation/degradation trends, sediment size distribution and composition.

7. Updating of the 2-dimensional hydraulic model using the existing URGWOM FLO-2D model for the Rio Grande from Caballo Dam to American Dam to include the channel/overbank from levee to levee.

8. Modeling of existing conditions flows to establish baseline conditions including an assessment of potential overbank flow and sedimentation effects at existing locations. This effort included a frequency analysis based on the Caballo Dam, Leasburg gage, and the Courchesne (El Paso) gage data and determination of the hydrograph shape and timing for the FLO-2D model inputs. The following target flows were included in the modeling effort:

    a. Average annual Spring hydrograph (about 2,350 cfs in the upper reach, and about 1,400 cfs in the lower reach)
    b. Average annual irrigation flows (2,500 cfs)
    c. Bankfull discharge (2,500 to 3,500 cfs)
    d. 10-year storm event
    e. 100-year storm event

9. Development of this existing conditions baseline report (including a description of existing conditions, a summary explanation of the model development, hydrologic and hydraulic assumptions and results from the sediment-transport analysis to evaluate short-term trends).

1.3. Authorization

This study, and the resulting baseline report, have been conducted for the Corps and USIBWC by Mussetter Engineering, Inc. (MEI) and Riada Engineering, Inc. (REI). The Corps project manager was Mr. Steve Boberg, P.E., and Dr. Bob Mussetter, P.E. was the MEI project manager. Dr. Jim O'Brien of REI conducted the FLO-2D modeling. MEI staff who contributed to this report included Dr. Mike Harvey, P.G., Messrs. Dai Thomas, P.E. (CO), Stuart Trabant, P.E. (CO), and Chad Morris, P.E. (CO).

2. GEOMORPHOLOGY

2.1. Background

The geomorphic character of the present-day Rio Grande in the project reach is significantly controlled by human activities that have occurred for over a century, culminating with the construction and continued operation of the RGCP. Information on the characteristics of the reach prior to 20th century is very sparse; thus, a specific detailed description is not possible. Because of the importance of the RGCP in meeting water delivery obligations and protecting public safety, specific habitat restoration activities resulting from this project must be designed and implemented in a manner that is consistent within the overall constraints of the RGCP. There are, however, certain physical attributes of the historic Rio Grande that could potentially be restored within the constraints of the RGCP that would improve riparian and instream habitat without jeopardizing the effectiveness of the RGCP. Based on these factors, the following discussion presents the available, relevant information regarding the historic Rio Grande in the project reach, and the effects of the RGCP and other upstream water development projects on the dynamic behavior of the reach.

2.2. Pre-Canalization Conditions

Based on the limited available mapping, the Rio Grande through the Mesilla and upper El Paso Valleys appears to have had a primarily single-thread, meandering channel prior to significant human impacts. Historical channel alignments compiled by USIBWC (2004) indicate that the sinuosity (i.e., ratio of river length to downvalley distance) of the 12 mile-long reach from about 0.7 miles upstream from the Picacho Bridge near Las Cruces to about 2.3 miles downstream from the Santo Tomas Bridge downstream from Las Cruces was about 2.1 in the mid-1800s compared to only about 1.1 under current conditions (Figure 4.6, USIBWC, 2004). During the early part of the 20th Century, the stream channel width was highly variable, and the channel planform appears to have varied from multi-channel, braided to single-thread channel, highly sinuosity, meandering. According to USIBWC (2004), major reductions in stream length due to channel straightening to improve water delivery and flood control occurred before 1907. The greatest man-made changes in river sinuosity occurred in the El Paso area, and included the Vinton cutoff between about the New Anthony and Country Club Bridges that relocated the river from the east side of the valley to the west side and reduced the sinuosity from about 1.7 to 1.05 (Figure 4-6, USIBWC, 2004). Extensive upstream water development in Colorado and New Mexico that was in place prior to completion of the RGCP in 1943 significantly reduced the water supply and sediment loads to the RGCP reach (MEI, 2002). Elephant Butte Dam, completed in 1916, and Caballo Dam, completed in 1939, were particularly significant in this regard, leading to channel degradation and coarsening of the bed material downstream from Caballo Dam (Fullerton and Batts, 2003). Additionally Percha, Leasburg, Mesilla and American Diversion Dams were constructed on the Rio Grande between 1912 and 1919.

2.3. Canalization Project

The RGCP, that extends from Percha Dam downstream to American Dam, was constructed between 1938 and 1943 under the authority of an Act of Congress approved June 4, 1936 (49 Stat. 1463), to facilitate compliance with the 1906 Convention between the United States and Mexico, and to properly regulate and control, to the fullest extent possible, the water supply for use of the two countries as provided by the treaty (USIBWC, 2004). The 1936 Act authorized the construction, operation and maintenance of the RGCP in agreement with the Engineering Record Plan of December 14, 1935 (Baker, 1943 cited in USIBWC, 2004).

Major elements of the plan included acquisition of Right of Way (ROW) for the river channel and adjoining floodways (8,332 acres), improvement of the alignment and efficiency of the river channel conveyance for water delivery, and flood-control measures that extended through the Rincon and Mesilla Valleys of New Mexico and El Paso Valley in Texas. As part of the RGCP, a deeper main channel was dredged to facilitate water delivery for irrigation. Hydraulic capacity of the dredged channel ranged from 2,500 to 3,000 cfs in the Upper Rincon Valley, to less than 2,000 cfs in the Lower Mesilla Valley (USIBWC, 2001). In general, the dredged channel followed the alignment of the existing channel in most locations (5-percent reduction in channel length), resulting in a small increase in the average river bed slope from 0.00073 (3.85 ft/mi) to 0.00074 (3.9 ft/mi). Canalization included riprapping the channel banks to prevent lateral migration of the channel.

Flood protection levees, designed to provide a 100-year level of flood protection, were placed along two-thirds of the length of the RGCP (57 miles along the west side of the channel and 74 miles along the east side), where the channel was not confined by hillslopes or canyon walls (e.g., Selden Canyon). The width between the levees north of Mesilla Dam ranged from 750 to 800 feet, and it was a constant 600 feet downstream of Mesilla Dam. A number of NRCS sediment/flood-control dams were built between 1969 and 1975 on tributary arroyos to control flooding and sediment delivery to the RGCP from about 300 square miles of drainage basin downstream of Percha Dam. The NRCS dams in Broad Canyon, Green Canyon, Arroyo Cuervo and Berrenda/Jaralosa Arroyo control approximately one third of the drainage area between Percha and Leasburg Dams, and reduce the flood peak frequency by an estimated 40 percent (USACE, 1996). A number of potential deficiencies in the RGCP were reported by the Corps (USACE, 1996) based on HEC-2 modeling of a 100-year storm event, and the levee system's capability to contain the simulated water levels. A recent evaluation of the project levees by USIBWC (2007) determined that the design freeboard would be encroached during the 100-year flood (i.e., the water surface would be within 3 feet of the levee crest) along 37 miles of levee in Dona Ana County and 12 miles of levee in El Paso County. The USIBWC (2007) study found that levee overtopping would occur during the 100-year event at several locations along the reach, with a total length of about 1 mile in Dona Ana County and about 2 miles in El Paso County. As a result of this study, USIBWC plans to raise the levees in the affected area.

The USIBWC has been responsible for maintaining the flood-control and water delivery capabilities of the RGCP since its completion in 1943. To accomplish these missions, the USIBWC performs Operation and Maintenance (O&M) activities consisting of: sediment removal from the channel and the lower ends of the tributary arroyos; leveling of the floodway; vegetation management along the channel banks, floodway and levees; replacement of channel bank riprap; care of the NRCS dams on the arroyos; and maintenance of infrastructure such as levee roads, bridges and the gates at the American Diversion Dam (USIBWC, 2004). Since construction of the tributary arroyo dams in the mid 1970s, dredging of the main channel in the RGCP reach has been conducted infrequently (USIBWC, 2004). Environmental measures, including limited planting of cottonwood trees, selective mowing to retain native vegetation and control salt cedar, test areas of limited mowing, and installation of in-channel structures (vortex weirs and rock groins) to diversify aquatic habitat, have been included in the O&M program.

2.4. Subreach Delineation

For purposes of evaluating and discussing restoration potential, the overall study reach was divided into three primary subreaches: Upper (above Leasburg Dam), Middle (Leasburg Dam to Leasburg Dam to Mesilla Dam) and Lower (Mesilla Dam to American Dam) (Figure 1.1). Because these primary subreaches do not provide sufficient resolution for the more detailed geomorphic and sediment transport analyses, the study reach was further subdivided using the seven River Management Units (RMU) that were previously identified for the RGCP by USIBWC (2004) as a guide (**Table 2.1**). The major geographic subreach boundaries (Rincon Valley, Selden Canyon and Mesilla Valley), coincide with geologic structure and lithologic boundaries (Seager et al., 1975; Mack, 1997) which influence the volume and caliber of the arroyo sediment supply to the RGCP. As will be discussed in subsequent sections of this report, the seven RMU's were further subdivided into a total of 13 subreaches, with the subdivisions internal to the RMU's being defined by existing vertical or lateral controls (e.g., siphon crossings, large tributaries, key bridges).

Table 2.1. Subreach boundaries for the RGCP (modified from USIBWC, 2004).

Subreach No.	Subreach Name	Upstream Boundary (RM and Station)	Downstream Boundary (RM and Station)	Subreach Length (mi)	Upstream Location	Downstream Location
1	Upper Rincon	105.4 5576+00	92 4768+00	13.4	Percha Diversion Dam	Hatch Siphon
2	Lower Rincon	92 4768+00	72 3730+00	20	Hatch Siphon	Head of Selden Canyon
3	Selden Canyon	72 3730+00	63 3280+00	9	Head of Selden Canyon	Leasburg Diversion Dam
4	Upper Mesilla	63 3280+00	46.5 2416+00	16.5	Leasburg Diversion Dam	Picacho Bridge
5	Las Cruces	46.5 2416+00	40 2076+00	6.5	Picacho Bridge	Mesilla Diversion Dam
6	Lower Mesilla	40 2076+00	16 832+00	24	Mesilla Diversion Dam	Vinton Bridge
7	El Paso	16 832+00	0 0+00	16	Vinton Bridge	American Diversion Dam

2.5. Geology and Geomorphology of the RGCP

The geologic and geomorphic settings of the RGCP govern both the hydrology and sediment supply to the Rio Grande, and thus are briefly discussed in the following sections. Photographs that were taken during the field reconnaissance of the RGCP in February 2007 by Drs. Bob Mussetter and Mike Harvey illustrating the geologic and geomorphic characteristics of the RGCP reach are included in **Appendix A**.

2.5.1. Geologic Setting

The Rio Grande Valley between Caballo Dam and El Paso, Texas is located within the Mexican Highlands Section of the Basin and Range Physiographic Province. Within the Basin and Range Section, the topography is expressed as isolated, generally north-south-trending, fault-block mountain ranges that rise above the surrounding desert plains (Kues, 1992). The Rio Grande Rift, through which the Rio Grande flows, is composed of a series of interconnected grabens that have subsided and have been filled with thousands of feet of Tertiary-age and Quaternary-age sediments. Baselevel lowering, as a result of incision of the Rio Grande that commenced about 900,000 years ago (Kues, 1992), has resulted in erosion of the upper parts of the basin fill sediments (Santa Fe Group), and these sediments are an important modern source of the sediments delivered by the tributary arroyos to the RGCP. The major fault-block mountains that bound the RGCP are shown on **Figure 2.1**. Important sediment source areas for the RGCP are the Caballo Mountains, the Rincon Hills, Sierra de las Uvas and Robledo Mountains.

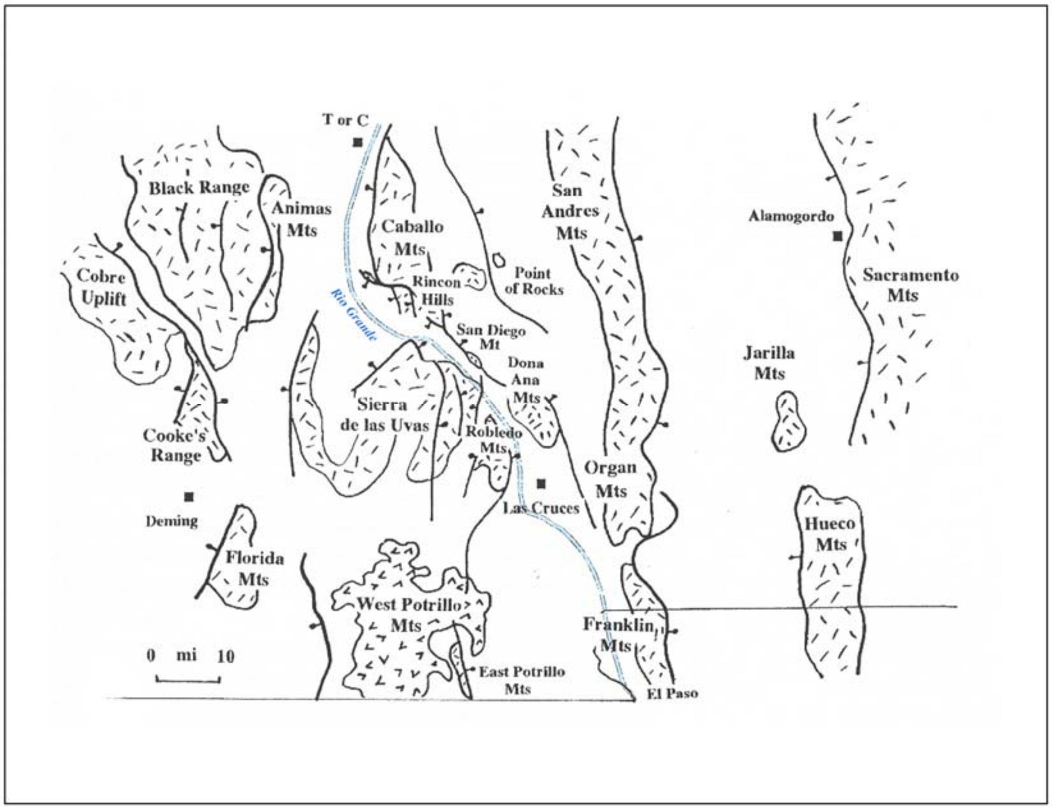


Figure 2.1. Location of the major fault blocks of the southern Rio Grande rift. Heavy lines with ball and stick represent normal faults, with ball on the downthrown side (modified from Mack, 1997).

The geology of the lower Rio Grande region within the State of New Mexico is shown in **Figure 2.2**. Within the Rincon Valley subreaches (Upper and Lower Rincon), the headwaters of the west side arroyos primarily drain areas that are underlain by the Lower Pleistocene-age Upper Santa Fe Group (Camp Rice Fm.) that is composed of unconsolidated to poorly consolidated, erodible, and relatively fine-grained basin-fill sediments. The downstream portions of the arroyos traverse areas underlain by the Lower Santa Fe Group that include conglomeratic sediments with interbedded basalts that produce coarser-grained sediments. Paleozoic interbedded shales, sandstones and limestones underlie the southern portion of the Caballo Mountains and Rincon Hills (Figure 2.1) on the east side of the Upper Rincon Valley, but the

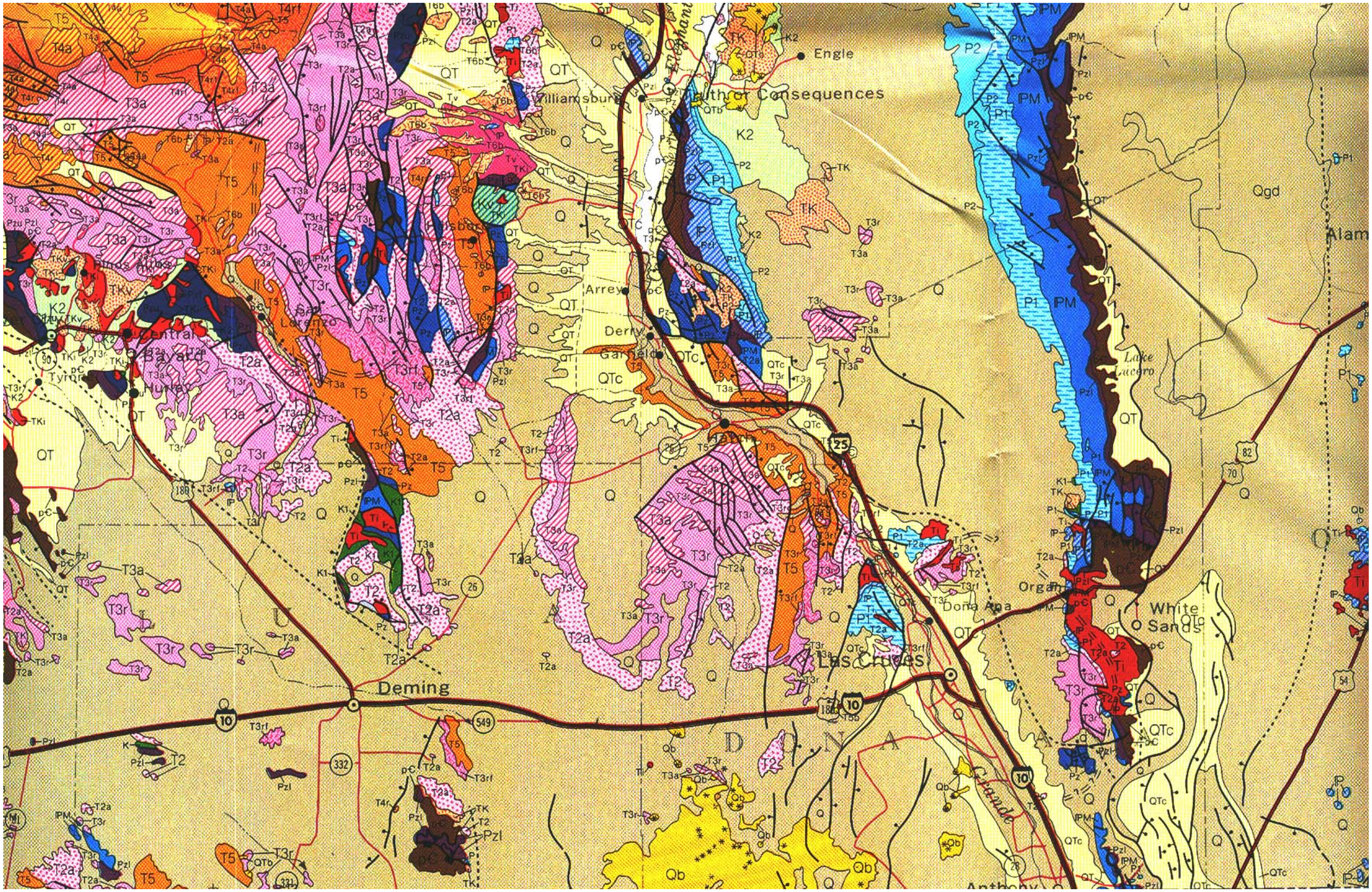
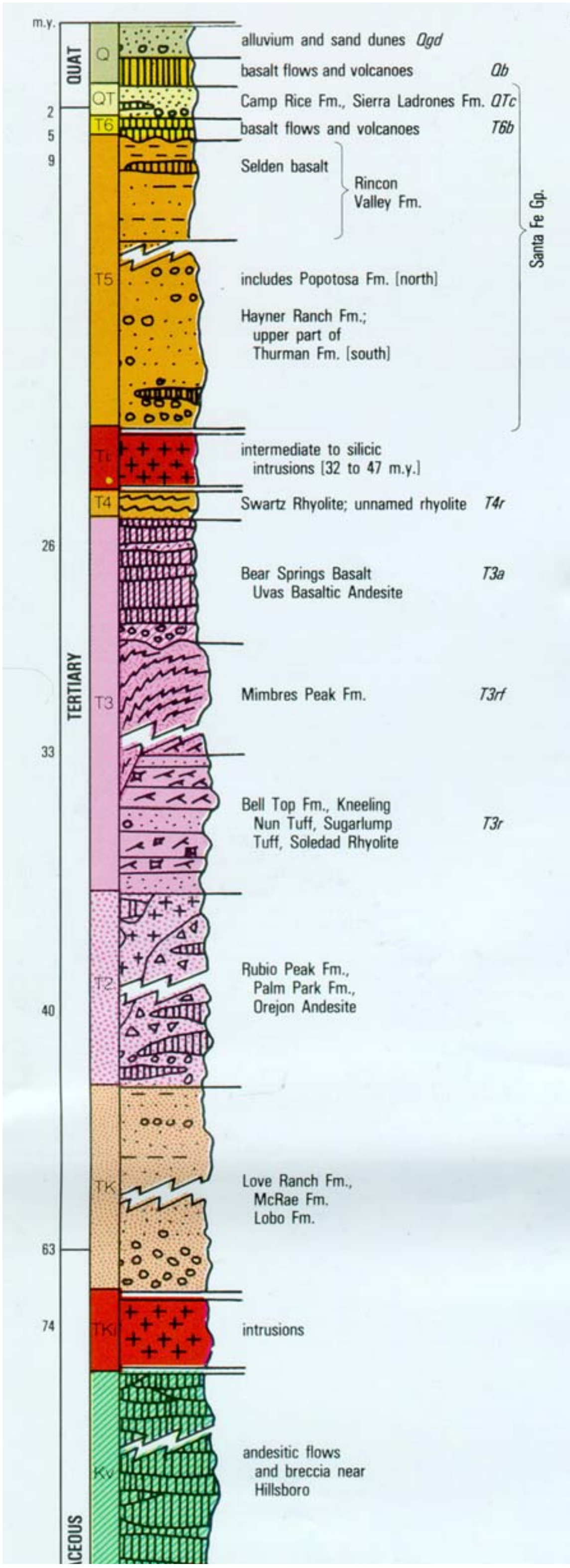


Figure 2.2a. Geologic map of south-central New Mexico that encompasses the RGCP reach of the Rio Grande (from New Mexico Geological Society, 1996).

SOUTH CENTRAL



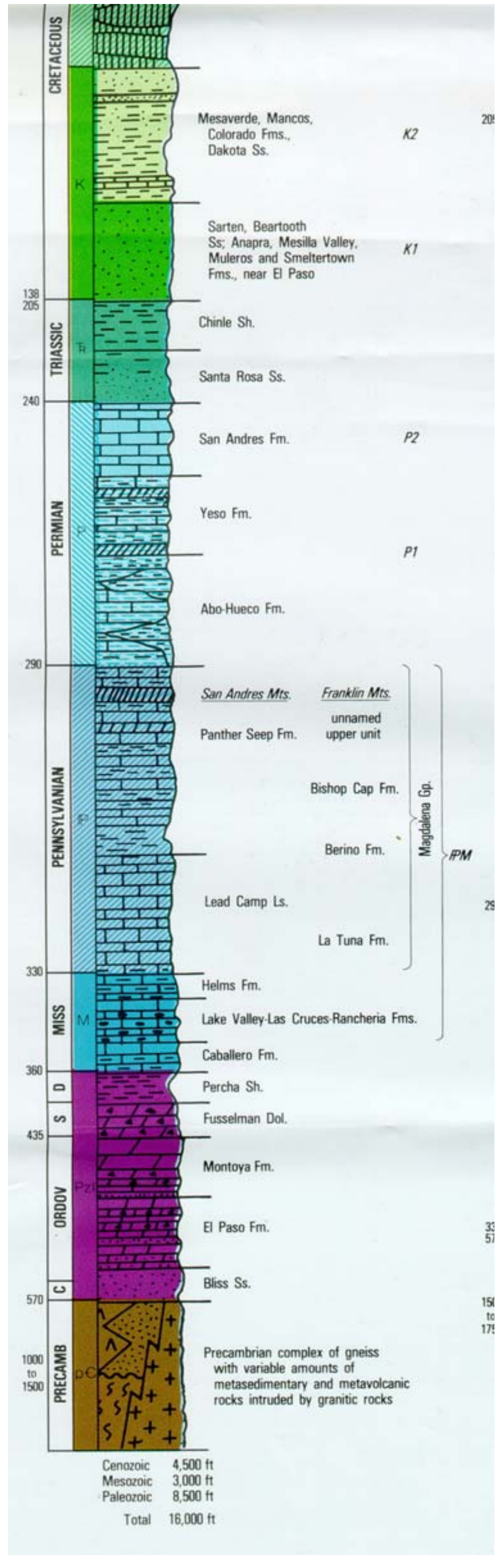


Figure 2.2b. Stratigraphic column that accompanies the geologic map of south-central New Mexico shown on Figure 2.2a (from New Mexico Geological Society, 1996).

tributary arroyos to the RGCP also traverse the Camp Rice Fm. basin fill sediments. The headwaters of the more southerly tributaries in the lower Rincon Valley on the west side of the Rio Grande are located within the Sierra de las Uvas Mountains (Figure 2.1) that are underlain by Tertiary-age basaltic andesites and volcaniclastic sedimentary units (Scholle, 2003) that produce coarse-grained sediments that are ultimately delivered to the RGCP by the tributary arroyos. Selden Canyon has formed where the Rio Grande cuts through the eastern portion of the Sierra de las Uvas Mountains. The canyon is bounded by the Tertiary-age basaltic andesites and volcaniclastic sedimentary units and the Lower Santa Fe Group sediments, all of which tend to produce coarse-grained sediments. The Robledo Mountains, that form the headwaters of the tributary arroyos in the Upper Mesilla Valley subreach of the RGCP, are composed of Tertiary-age intrusives and Permian-age interbedded sandstones, shales and limestones of the Abo-Hueco Fm. The Las Cruces, Lower Mesilla and El Paso subreaches of the RGCP are bounded by the Upper Santa Fe Group that consists of poorly consolidated, fine-grained, basin fill sediments of the Mesilla bolson (Hawley, 1981).

2.5.2. Geomorphic Setting

The geomorphic setting of the Rio Grande within the RGCP is typical for a desert river, where the bulk of the flow is derived from snowmelt runoff in the upper elevation headwaters, and the bulk of the sediment is delivered from lower elevation, ephemeral flow tributaries (Graf, 1988). Where the groundwater table is well below the streambed, significant downstream losses of flow can occur due to infiltration into the bed, which in turn reduces the ability of the river to transport sediments, and tends to cause aggradation and channel braiding. Based on a review of the historical aerial photographs of the Rio Grande in the RGCP reach, this process may have been occurring in the reach prior to construction of the Canalization Project. At the present time, the groundwater table is relatively shallow along much of the reach; thus, this may not be an important factor under current conditions. In general, delivery of sediment from the lower elevation tributaries is dependent on spatially restricted summer thunderstorms, or Monsoon-type flows, that occur when the flows in the mainstem tend to be low. The asynchronous delivery of water and sediment to the lower reaches of desert rivers causes the smaller drainage area tributaries to have a disproportionate influence on the local dynamics of the mainstem river (Graf, 1988). The steeper, ephemeral flow tributaries where high-concentration flows, and in some cases, even mud and debris flows, can occur (Webb et al., 1988; Costa, 1988), deliver a wide range of sediment sizes (depending on the availability of sizes) to the mainstem, the coarser fraction of which the mainstem is incapable of remobilizing. The coarse lag deposits in canyon sections create rapids (Graf, 1979; Miller, 1994; Hammack and Wohl, 1996), and in alluvial sections they cause the mainstem to migrate laterally away from the margins of the tributary alluvial fans (Graf, 1988).

Storage in, and release of, flows from Elephant Butte and Caballo Reservoirs, and diversion of the released flows at the Percha, Leasburg and Mesilla Diversion Dams have altered the flow pattern within the RGCP (**Table 2.2**), and have, therefore, also altered the relationship between the mainstem and the tributary arroyos. The higher irrigation flows during the summer thunderstorm-monsoon period are capable of remobilizing some of the sediment delivered by the tributary arroyos (sands and smaller gravels) (**Figure A.1**), but they are not capable of remobilizing the coarser sediments (cobbles and small boulders) that form lag deposits and coarse grained fans within, and marginal to, the Rio Grande channel (**Figure A.2**). Where the opposing banks to the tributary arroyos have been armored, the tributary fans behave more like canyon constrictions, and relatively coarse grained riffles form in the Rio Grande channel (**Figure A.3**). These constrictions cause upstream backwater and sediment deposition within the channel (**Figure A.4**). The hydraulic forces caused by the tributary constrictions can also cause damage and destruction of in-place revetments (**Figure A.5**). Where the opposing banks of the river have not been armored, the channel migrates laterally away from the tributary fans, and can threaten the RGCP levees (**Figure A.6**). Aggradation of the Rio Grande downstream of the individual tributary arroyos can also cause bank erosion (**Figure A.7**), but USIBWC O&M activities since completion of the RGCP have resulted in a significant portion of the banks of the Rio Grande being armored, especially in Subreaches 4, 5, 6 and 7. Additionally, the mouths of a number of the arroyos have been relocated by the USIBWC to reduce the confluent angle with the Rio Grande with the intention of reducing the hydraulic stress on the bank armor on the opposing banks.

Table 2.2. Reference flows for the RGCP subreaches (USIBWC, 2004).

Subreach	Typical Irrigation Season Flows (cfs)	Canalization Reach Design Flow (cfs)
1. Upper Rincon	1,150	2,350
2. Lower Rincon	1,200	2,350
3. Selden Canyon	1,200	2,350
4. Upper Mesilla	1,000	1,900
5. Las Cruces	1,000	1,900
6. Lower Mesilla	650	1,600
7. El Paso	650	1,600

Thalweg profiles of the RGCP reach of the Rio Grande were developed from pre-canalization profiles, and the 1943 design profile that were provided by the USIBWC, and from cross sections surveyed by Tetra Tech in 2004 (**Figure 2.3**). Channel degradation downstream of Caballo Dam has been reported by Fullerton and Batts (2003). Review of the 1943 design plans indicates that there was some straightening of the channel during the canalization project (about 5-percent reduction in channel length over the 150 miles of the RGCP), but the major change was an increase in depth (Figure 2.3). The greatest changes in channel depth occurred between Percha Dam and the Rincon Siphon in Subreaches 1 and 2. The channel depth also increased by 2 to 4 feet in Subreach 6 (Lower Mesilla). Comparison of the 1943 and 2004 profiles indicates that the channel has generally degraded since 1943, except in Subreach 7 (El Paso) where there has been up to 2 feet of aggradation (Figure 2.3). Between Percha Dam and the Hatch Siphon in Subreach 1, there has been up to about 6 feet of degradation. Immediately downstream of the Hatch Siphon at the head of Subreach 2 and downstream of the Rincon Siphon there has been between 9 and 10 feet of degradation. Less than 2 feet of degradation has occurred in the Salem Bridge-Hatch portion of Subreach 2 where vegetated mid-channel bars are present in the channel. In the lower portion of Subreach 2, there has been up to 2 feet of aggradation, primarily in the reach upstream of Bignell Arroyo. No 1943 data were available for the Selden Canyon reach (Subreach 3), but field observations suggest that the canyon may in fact be somewhat aggradational. Downstream of Leasburg Diversion Dam there has been between 2 and 4 feet of degradation in Subreach 4. The Las Cruces reach (Subreach 5) has experienced about 2 feet of degradation. Downstream of the Mesilla Diversion Dam in Subreach 6, degradation ranges from about 6 feet nearer to the dam to negligible at the Vinton Bridge. Up to 2 feet of aggradation has occurred in Subreach 7.

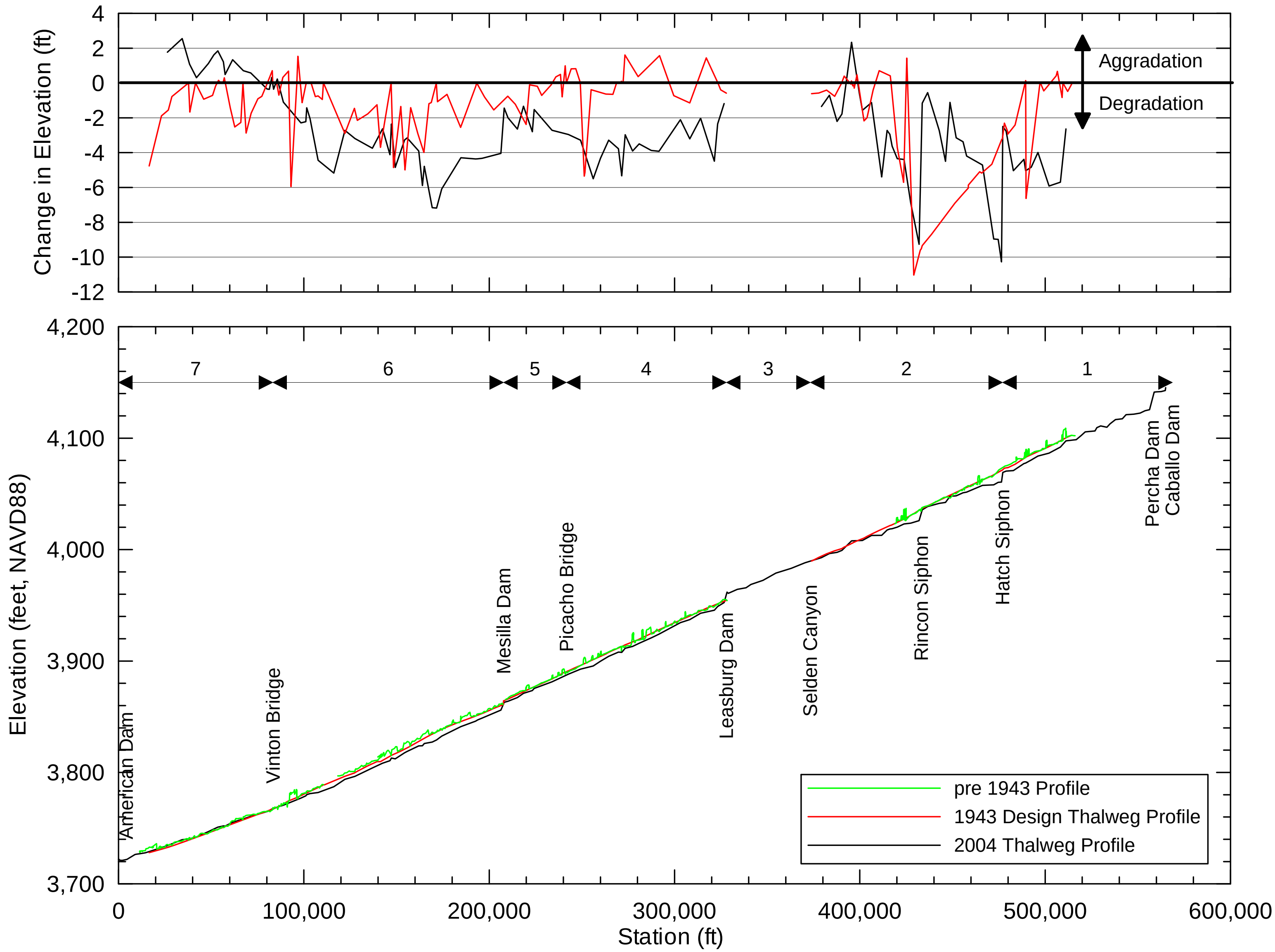


Figure 2.3. Pre-canalization, 1943 design and 2004 thalweg profiles of the RGCP. Also shown are the changes in elevation between the pre-canalization and 1943 profiles (green line) and between the 1943 profile and the 2004 profile (red line).

2.5.3. Sedimentology of the RGCP

A number of bed material samples, representing material in the Rio Grande delivered to its present location from upstream reaches or supplied to the RGCP by the arroyos, have been collected over the past decade. Prior to this investigation, samples of bed material were collected by Resource Technology Inc. (RTI) in 1996 (three samples) and by Tetra Tech in June 2004 (six samples). In February 2007, MEI collected 14 bulk samples of sediment from the bed of the Rio Grande and at the mouths of tributary arroyos, and conducted pebble counts (Wolman, 1954) of the coarse surface bed material at two locations in the Rio Grande and one location at the mouth of Tierra Blanca Arroyo. The bulk samples were analyzed by Raba Kistner Consultant (SW), Inc. at their soils laboratory in El Paso, Texas. The MEI samples tended to be coarser than samples collected by either RTI or Tetra Tech, except in the lower subreaches (4 through 7) where the bed material is composed of sand. The coarser MEI upstream samples are probably due to the occurrence of the extensive tributary events in 2006. The locations of the various samples are shown on **Figure 2.4**. **Tables 2.3 and 2.4** summarize the sediment gradation data from all three sources. Gradation curves for the three MEI pebble counts are provided in **Figure 2.5** and gradation curves for the MEI bulk samples are provided in **Figure 2.6**.

In Subreach 1, downstream of the Arrey Highway Bridge, the surface of the sampled low relief bar is armored with sediment that has median (D_{50}) size of 45 mm (**Figures A.10 and A.11**). The D_{50} of the underlying sediments in the bar (SS-1) is 15.6 mm (**Figure A.12**). Tipton Arroyo delivered a significant volume of sediment to the RGCP in 2006, and the mouth of the arroyo and the channel of the Rio Grande were excavated and reconstructed by USIBWC (**Figure A.13**). Sample S-1, that has D_{50} of 3.5 mm, was collected from the reworked arroyo deposits that had been moved to the opposing bank (**Figure A.14**).

Table 2.3. Summary of MEI February 2007 sediment sampling data.

Sample Number	Station	Subreach	D_{50} (mm)	D_{84} (mm)
WC1	551,000	1	45.0	72.7
WC2	527,546	1	62.9	108.3
WC3	519,017	1	47.0	76.1
SS1	551,000	1	15.6	41.2
S1	549,033	1	3.5	11.09
S2	527,546	1	16.0	42.6
S3	525,798	1	3.8	15.8
S4	521,537	1	0.14	10.1
SS2	519,017	1	21.4	44.7
S4#2	478,991	1	2.2	9.9
S5	461,886	2	0.34	1. 7
S6	437,858	2	0.44	1. 5
S7	400,061	2	0.33	1.
S8	401,345	2	0.92	13.1
S9	85,778	4	0.40	1.2
S10	224,479	5	0.33	1.1
S11	212,419	5	0.29	0.71

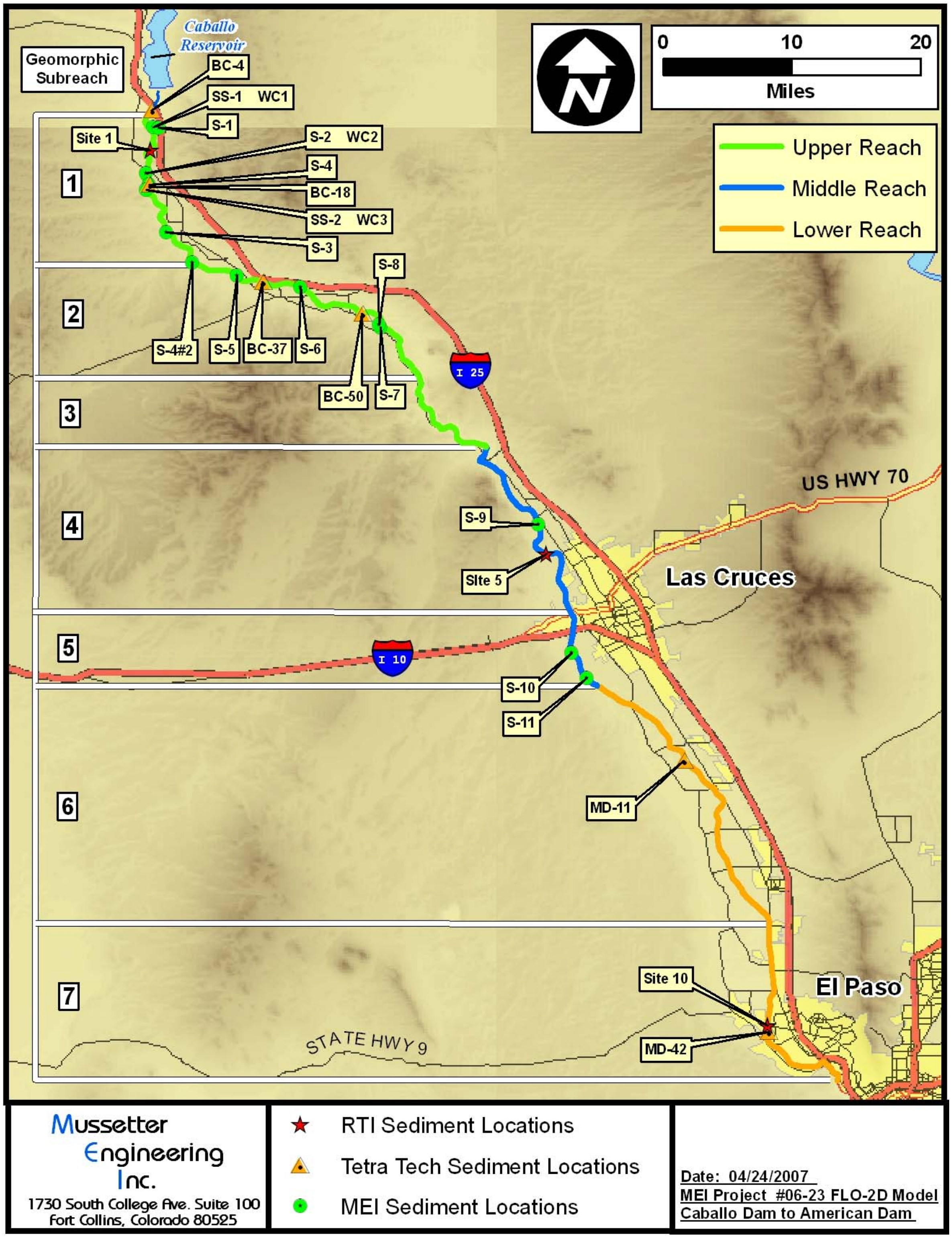


Figure 2.4. Map of the RGCP showing the locations of sediment samples collected by RTI in 1996, Tetra Tech in 2004 and MEI in 2007.

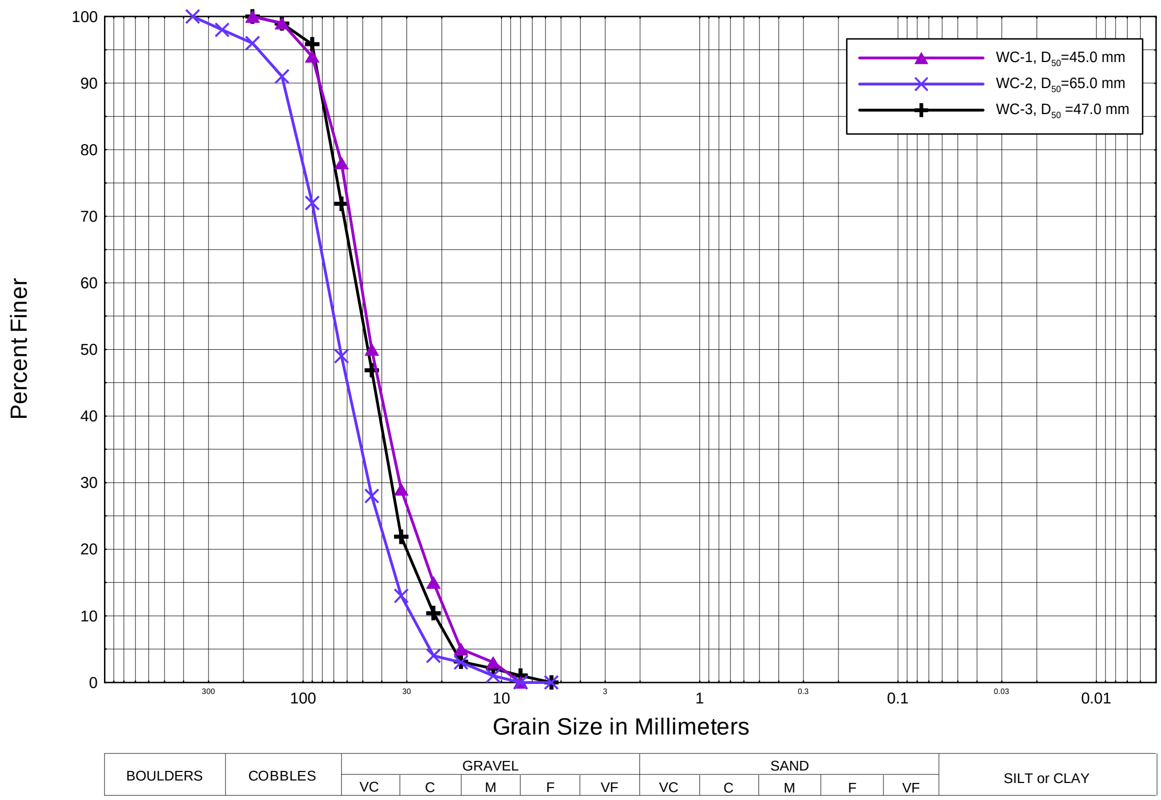


Figure 2.5. Sediment gradation curves developed from pebble counts of the bed material in the Rio Grande (WC1, WC3) and the mouth of Tierra Blanca Arroyo (WC2). Refer to Table 2.3 and Figure 2.4 for locations of the samples.

Table 2.4. Summary of Tetra Tech and RTI sediment samples.				
Tetra Tech Sediment Samples (2004)				
Sample Number	Station	Subreach	D_{50} (mm)	D_{84} (mm)
BC-4	560,204	1	0.13	0.26
BC-18	521,599	1	0.67	17.2
BC-37	451,863	2	4.3	30.5
BC-50	411,505	2	7.9	17.7
MD-11	161,900	6	0.32	0.57
MD-42	38,595	7	0.27	0.39
RTI Sediment Samples (1996)				
Sample Number	Station	Reach	D_{50} (mm)	D_{84} (mm)
Site 1	538,460	1	5.5	14.5
Site 5	271,030	5	0.4	1.1
Site 10	41,320	7	0.3	0.4

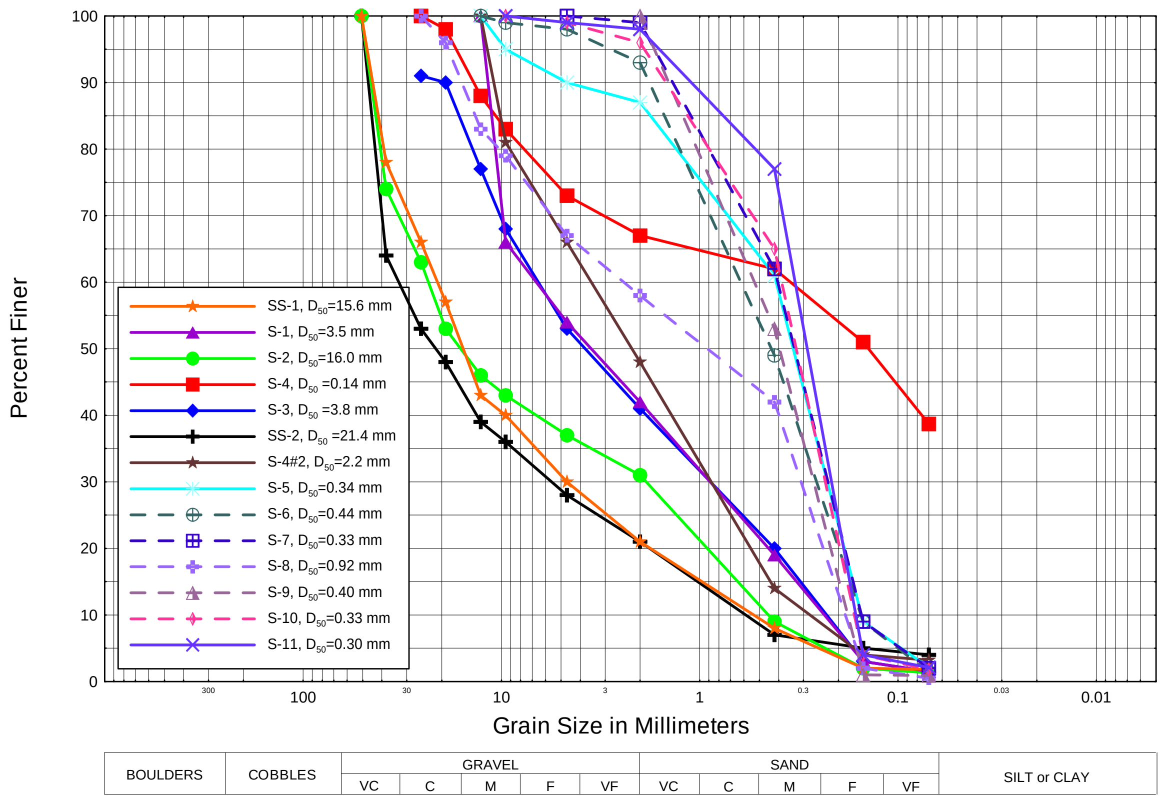


Figure 2.6. Sediment gradation curves developed from samples of the bed material of the Rio Grande collected by MEI in 2007 (refer to Table 2.3 and Figure 2.4 for sample locations).

Tierra Blanca Arroyo delivered a large volume of material to the RGCP during 2006 that severely constricted the channel of the Rio Grande (**Figure A.15**). The upstream portion of the fan was reworked and coarsened by the summer irrigation flows, and the coarser sediments were sampled with a pebble count (WC-2) (**Figure A.16**) that had a D_{50} of 65 mm. The un-reworked portion of the fan was also bulk sampled (S-2) and had a D_{50} of 16 mm (**Figure A.17**). Sample S-3 was collected from a mid-channel bar in a locally aggraded reach located about 0.4 miles downstream of the mouth of the arroyo (**Figure A.18**), and the D_{50} was 4 mm (**Figure A.19**).

A low-relief alternate bar was sampled at the Sibley Point Bar site (**Figure A.20**). The bar surface was covered with freshwater mussel shells (**Figure A.21**) that were removed from the sample (S-4) before the gradation analysis was conducted. The D_{50} of the sample was 0.14 mm.

Downstream of Yeso Arroyo, the surface sediments on a low-elevation gravel bar (**Figure A.22**) were sampled with a pebble count (WC-3) (**Figure A.23**), and the subsurface sediments were bulk sampled (SS-2) (**Figure A.24**). The D_{50} of the surface sediments was 47 mm, and that of the subsurface sediments was 21.4 mm.

At the upstream end of the backwater pool from the Hatch Siphon, a subaqueous bed material sample was collected (S4#2) (**Figure A.25**). The D_{50} of the bed-material sediments was 2.2 mm.

In Subreach 2, about 0.75 miles downstream of the Salem Bridge, a low relief, mid-channel gravel bar that was located in a split flow reach of the river (**Figure A.26**) was bulk sampled (S-5). The D_{50} of the bar materials is 0.34 mm (**Figure A.27**). A subaqueous sample was collected from the bed of the river in the aggraded reach at the Remnant Bosque site upstream of the Rincon Siphon (**Figure A.28**). The D_{50} of the bed material was 0.44 mm (S-6). Samples of the bed material were collected downstream (S-7) and upstream (S-8) of the very large tributary fan at Bignell Arroyo. The D_{50} of the two samples were 0.33 and 0.92 mm, respectively.

In Subreach 4, a bed-material sample was collected at the Mile 54 Cut (S-9), and the D_{50} was 0.4 mm (**Figure A.29**). In Subreach 5, a bed-material sample (S-10) was collected in an alternate bar reach about 150 feet upstream of the Mesilla Bridge (**Figure A.30**). The D_{50} of the bar materials is 0.33 mm (**Figure A.31**). Sample S-11 was collected from a sandy alternate bar about 2.1 miles downstream of the Mesilla Bridge in a reach where a number of west side arroyos are delivering primarily sand-sized sediment derived from the Upper Santa Fe Group to the river (**Figure A.32**). The D_{50} of the bar materials is 0.29 mm (**Figure A.33**).

A longitudinal profile of the D_{50} and D_{84} values from the RTI, Tetra Tech and MEI samples shows that the bed material is coarsest in Subreaches 1 and 2 where there has been the most degradation and bed armoring (Subreach 1), and where there are a large number of tributary arroyos that deliver sediment from the west side of the valley where the Lower Santa Fe Group and Tertiary volcaniclastic sedimentary units are sediment sources (**Figure 2.7**). In Subreaches 4 to 7, the bed material is sand, and there is little variation in the bed-material gradations.

2.6. USIBWC Sediment Operation and Maintenance Activities

To compensate for the historically reduced peak flows and annual flow volume from upstream (USIBWC, 2004) that have reduced sediment-transport capacity in the Rio Grande within the RGCP, USIWBC has historically removed sediment from upstream of diversion dams, at various locations along the river and from the mouths of the tributary arroyos (**Figures A.8 and A.9**). Construction of the four NRCS flood/sediment detention dams on Broad Canyon, Green Canyon, Arroyo Cuervo and Berrenda Arroyo within Subreaches 1, 2 and 3 in the mid-1970s reduced the required frequency of sediment removal (USIBWC, 2004).

Based on USIBWC O&M records for the 1994-1995 to 2006-2007 non-irrigation seasons, approximately 141,000 cubic yards of sediment have been removed from upstream of American and Mesilla Diversion Dams (about 12,000 cubic yards/year) (**Table 2.5**). About 27,000 cubic yards of sediment has been removed from the mouths of the tributary arroyos and relocated across the channel to prevent further erosion of the opposite river bank (Table 2.3), and about 25,000 cubic yards have been removed from the Rio Grande channel, primarily between Hatch and the Salem Bridge (Table 2.5). Disposal practices for the excavated sediment are variable and included off-site removal, disposal within the floodway between the levees, and in-channel relocation and bank reconstruction.

Table 2.5. Summary of sediment excavation in the RGCP between 1994 and 2006 (based on USIBWC records).

Sediment Removal Category	Volume of Sediment Removed	
	(yd^3)	(ac-ft)
Diversion Dams	141,000	87
Tributary Mouth Sediment Relocation	27,000	17
In-Channel Removal	>25,000	16

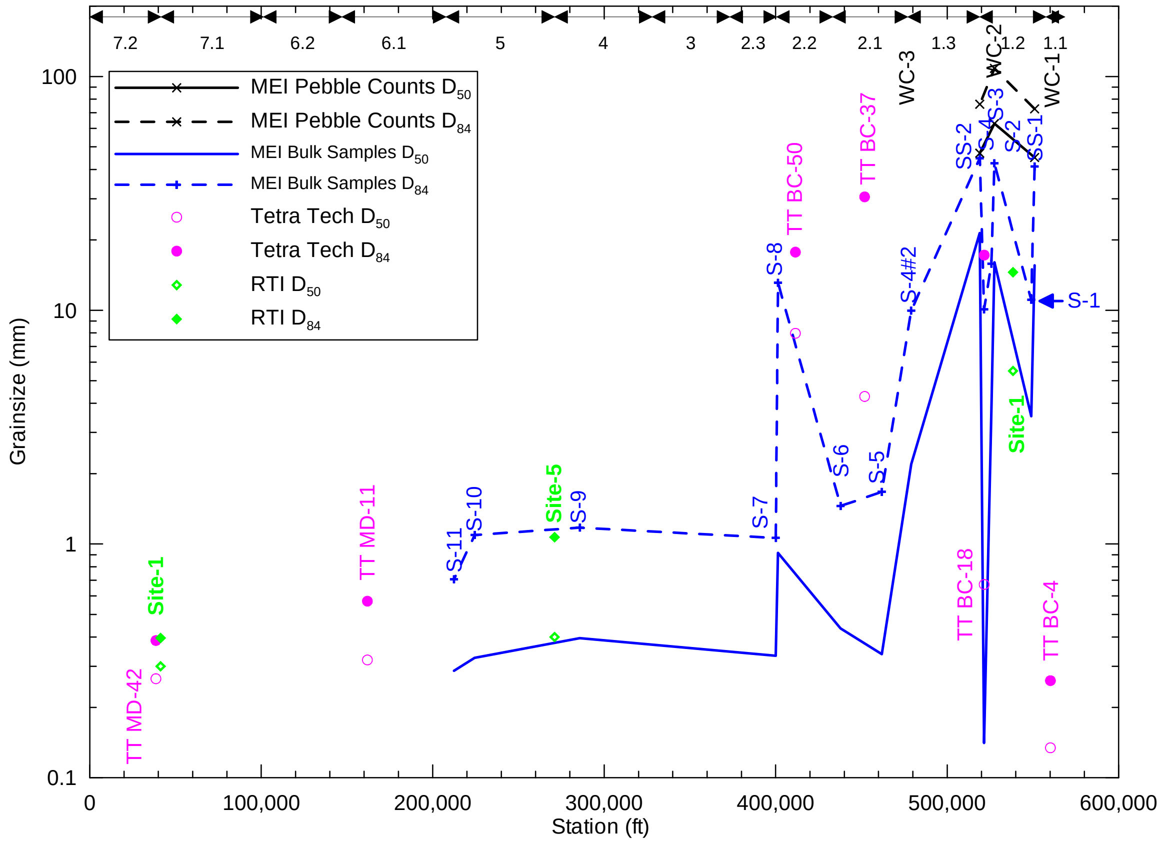


Figure 2.7. Longitudinal profile of D_{50} and D_{84} sediment sizes collected by MEI, Tetra Tech, and RTI.

During the 2006 monsoon season, a considerable amount of sediment was deposited at the mouths of most of the uncontrolled tributaries in Subreaches 1 and 2. The USIBWC 5-year maintenance plan for the RGCP (FY 2006-2010) calls for removal or relocation of about 386,000 cubic yards of sediment from within the main channel and mouths of the major arroyos. Of the arroyos that were identified for sediment removal in the 5-year plan, work had been completed at Trujillo, Placitas and Tipton Arroyos (about 55,000 cubic yards of sediment were removed or relocated) as of May 2007. Large, vegetated islands have formed in the Rio Grande in the Salem Bridge to Hatch reach, and these are being monitored by IBWC for adverse impacts on flow conveyance through the bridges. If deemed necessary, removal of these islands would require excavation of about 65,000 cubic yards.

2.7. Subreach Descriptions

The seven River Management Unit subreaches and their boundaries in the RGCP reach of the Rio Grande are summarized in Table 2.1. General descriptions of the subreach characteristics as observed in February 2007 are provided in the following sections, and photographs of particular features are provided in Appendix A. Channel dimensions are based on the FLO-2D model output.

2.7.1. Subreach 1 (Upper Rincon)

Subreach 1 extends from Percha Dam (**Figure A.34**) to the Hatch Siphon (**Figure A.35**), a distance of 13.4 miles. The channel has degraded between 4 and 6 feet since 1943 (Figure 2.3), and the bed material has coarsened as a result (**Figure A.36**). The bed slope in the subreach is 0.00083 (4.4 ft/mi), and the bankfull capacity of the channel (**Figure A.37**) varies from 3,500 cfs to greater than 6,000 cfs. At a flow of 5,000 cfs in the subreach, the average channel top width is about 180 feet, the average hydraulic depth is 6.2 feet, and the average velocity is 4 fps. The distance between the levees in the subreach varies from 750 to 800 feet.

During the 2006 monsoon season tributary flow events, Tipton and Holguin Arroyos on the east side of the river, and Trujillo, Montoya, Tierra Blanca, Sibley and Jaralosa Arroyos on the west side, all delivered significant quantities of sediment to the RGCP. USIBWC has removed sediment from the channel and reconstructed the opposing banks at Tipton and Trujillo Arroyos (**Figures** A.13, **A.38**), and has regraded the mouth of Trujillo Arroyo (**Figure A.39**). The damage to the existing bank protection on the east bank of the river opposite the Montoya and Tierra Blanca fans has not been repaired (**Figures A.40, A.41**), and no sediment has been removed from Holguin (Figure A.1), Sibley (**Figure A.42**), or Jaralosa Arroyos (**Figure A.43**), or their fans. The NRCS flood control and sediment detention dams on Green and Cuervo Arroyos (**Figure A.44**) significantly reduced the amount of sediment delivered to the RGCP. The dam on Berrenda Arroyo also significantly reduced the contributing drainage area to the Jaralosa fan.

2.7.2. Subreach 2 (Lower Rincon)

Subreach 2 extends from the Hatch Siphon to the head of Selden Canyon, a distance of 20 miles. Immediately downstream of the Hatch Siphon, the channel has degraded about 10 feet since 1943 (Figure 2.3). For the remainder of the upper part of the subreach, the degradation reduces from about 6 feet in the upstream end to about 1 foot upstream of the Rincon Siphon (Figure A.28). Downstream of the Rincon Siphon, there has been about 9 feet of degradation (**Figure A. 45**), but the degradation diminishes in the downstream direction to about 2 feet. Upstream of Bignell Arroyo there has been about 2 feet of aggradation since 1943 (**Figure A.46**). Depending on the location within the subreach the bed material varies from sand to gravel. The bed slope in the subreach is 0.00074 (3.9 ft/mi), and the bankfull capacity of the channel varies from 3,500 to 4,500 cfs. At a flow of 4,000 cfs in the subreach, the average channel top width is about 270 feet, the average hydraulic depth is 4.4 feet, and the average velocity is 3 fps. The distance between the levees in the subreach varies from 750 to 800 feet.

During the 2006 monsoon season tributary flow events, four small tributaries, as well as Garcia and Rincon Arroyos on the east side of the river, delivered significant quantities of sediment to the RGCP. USIBWC has removed sediment from the river, reconstructed the opposite bank and excavated the mouth of the Thurman I Arroyo at Sta 4524+00 (Figures A.8 and A.9). At Hershey Arroyo, sediment of relocated from the arroyo mouth to the opposite riverbank in February 2006 to prevent further erosion. The remainder of the east-side arroyos has not been modified by USIBWC. On the west side of the river, a number of very large arroyos that drain areas underlain by the Lower Santa Fe Group and the Tertiary-age volcaniclastic sedimentary units delivered a significant amount of sediment to the RGCP during the 2006 events. On the west side, with the exception of Placitas Arroyo, where the lower reaches of the arroyo channels were excavated and the channel of the Rio Grande was excavated and the east bank reconstructed (**Figures A.47 and A.48**), USIBWC has not modified the channel of the Rio Grande or the lower reaches of the arroyos. A very coarse grained fan has virtually blocked the Rio Grande channel at the Angostura Arroyo fan (Figure A.2). At Reed Arroyo (**Figure A.49**) and Bignell Arroyo (**Figure A.50**) the coarse tributary fans have displaced the Rio Grande towards the east and the RGCP levee. Hersey Arroyo and Rock Canyon Arroyo, both west side tributaries to the Rio Grande in the lower part of Subreach 2, also delivered large volumes of sediment to the river in 2006.

2.7.3. Subreach 3 (Selden Canyon)

Subreach 3 extends from the head of Selden Canyon to Leasburg Diversion Dam, a distance of 9 miles. There are no comparative thalweg data for this subreach, but under low-flow conditions the bed of the channel is braided and appears to be mildly aggradational (**Figure A.51**). The bed slope in the subreach is 0.00066 (3.5 ft/mi), and the bankfull capacity of the channel varies from 3,500 to 4,500 cfs. At a flow of 4,000 cfs in the subreach, the average channel top width is about 230 feet, the average hydraulic depth is 4.7 feet, and the average velocity is 3.2 fps. There are no RGCP levees in the subreach. A large number of arroyos on both the east and west side of the river deliver sediment to the Rio Grande in this subreach. The NRCS flood control and sediment detention dam on Broad Canyon Arroyo significantly reduced the amount of sediment delivered to the river during the 2006 floods. Because of the presence of Highway 185 on the west side of the river through the canyon, many of the west side arroyos have been channelized in the vicinity of the highway.

2.7.4. Subreach 4 (Upper Mesilla)

Subreach 4 extends from Leasburg Diversion Dam to the Picacho Bridge, a distance of 16.5 miles. The comparative thalweg data (Figure 2.3) indicate that there has been about 4 feet of degradation in this subreach since 1943 (**Figure A.52**). The bed slope in the subreach is 0.00077 (4.1 ft/mi), and the bankfull capacity of the channel is about 4,500 cfs. At a flow of 4,000 cfs in the subreach, the average channel top width is about 275 feet, the average hydraulic depth is 3.8 feet, and the average velocity is 3.3 fps. The bed material in the subreach is sand and under low-flow conditions the bed of the channel is braided. A considerable percentage of both banks within the subreach is revetted. The distance between the levees in the subreach varies from 750 to 800 feet.

A large number of arroyos that drain the Robledo Mountains on the west side of the river deliver sediment to the Rio Grande from Leasburg Dam to the Shalem Bridge (Sta 2710+00). Between the Shalem Bridge and the Picacho Bridge there is little sediment delivery to the Rio Grande, other than from the drains.

2.7.5. Subreach 5 (Las Cruces)

Subreach 5 extends from the Picacho Bridge to the Mesilla Diversion Dam, a distance of 6.5 miles. The comparative thalweg data (Figure 2.3) indicate that there has been 2 to 3 feet of degradation in this subreach since 1943 (Figure A.30). The bed slope in the subreach is 0.00074 (3.9 ft/mi), and the bankfull capacity of the channel is about 4,500 cfs. At a flow of 4,000 cfs in the subreach, the average channel top width is about 356 feet, the average hydraulic depth is 3.3 feet, and the average velocity is 2.9 fps. The bed material in the subreach is sand and under low-flow conditions the bed of the channel is braided. The distance between the levees in the subreach varies from 750 to 800 feet. A considerable percentage of both banks within the subreach is revetted. A number of west side arroyos that drain the Upper Santa Fe Group deliver sediment to the Rio Grande between Sta 2160+00 and the Mesilla Diversion Dam (Figure A.32).

2.7.6. Subreach 6 (Lower Mesilla)

Subreach 6 extends from the Mesilla Diversion Dam to the Vinton Bridge, a distance of 24 miles. The comparative thalweg data (Figure 2.3) indicate that there has been up to 8 feet of degradation downstream of the Mesilla Diversion Dam, but the amount of degradation diminishes in the downstream direction to about 1 foot. The bed slope in the subreach is 0.00074 (3.9 ft/mi), and the bankfull capacity of the channel is about 3,000 cfs. At a flow of 3,000 cfs in the subreach, the average channel top width is about 245 feet, the average hydraulic depth is 3.3 feet, and the average velocity is 3 fps. The bed material in the subreach is sand and under low-flow conditions the bed of the channel is braided (**Figure A.53**). The distance between the levees in the subreach is 600 feet. A considerable percentage of both banks within the subreach is revetted. There are no significant sources of sediment delivery to the Rio Grande within the subreach.

2.7.7. Subreach 7 (El Paso)

Subreach 7 extends from the Vinton Bridge to the American Diversion Dam, a distance of 16 miles. The comparative thalweg data (Figure 2.3) indicate that there has been up to 2 feet of aggradation since 1943. The bed slope in the subreach is 0.00056 (3 ft/mi), and the bankfull capacity of the channel is about 2,500 cfs. At a flow of 2,000 cfs in the subreach, the average channel top width is about 240 feet, the average hydraulic depth is 2.8 feet, and the average velocity is 2.5 fps. The bed material in the subreach is sand and under low-flow conditions the bed of the channel is braided. The distance between the levees in the subreach is 600 feet. A considerable percentage of both banks within the subreach is revetted. There are no significant sources of sediment delivery to the Rio Grande within the subreach.

3. HYDROLOGY

The available gage records were used to assess the hydrologic characteristics of the study reach for purposes of calibrating the hydraulic (FLO-2D) model to known storm events and developing mean-daily flow-duration and flood-frequency curves that can be used in evaluating potential restoration actions. Flow data have been collected over various periods-of-record at eight mainstem gages and several diversion dams, wasteways, canals and return-flow drains within the study reach (**Figure 3.1**). The available data from these gages were obtained from a variety of sources, including the USGS, EBID, and Dr. Phil King at New Mexico State University (NMSU), with the bulk of the data for the non-mainstem gages being provided by NMSU. These data include a complete record of mean daily flows for the post-Caballo Dam period (WY1938 through WY2006) for the below Caballo Dam and El Paso gages at the up- and downstream ends of the reach obtained from U.S. Geological Survey (USGS). The data for the other mainstem gages, obtained from NMSU, EBID, and USIBWC include various periods-of-record ranging from 7 to 29 years in length, with no data being collected prior to WY1975. Data for the non-mainstem gages, obtained primarily from NMSU, also include various periods-of-record, with the earliest data beginning in WY1975. A review of the non-mainstem gage data indicates that, at most of these locations, the recorded discharges were quite small. Because channel stability and potential restoration actions that are being contemplated for this project are not significantly affect by low flows, and because a thorough analysis of the flow distribution during low flow periods is complex and beyond the scope of this study, only gages with flows exceeding 10 cfs were considered in the hydrology analysis (Figure 3.1, **Table 3.1**). These gages include the three primary diversions (Arrey Canal at Percha Dam, Leasburg Heading, and Eastside Canal at Mesilla), the Percha Private Lateral, and drain inflows at Spillway #5 on the Hatch Main Canal and the Garfield Drain.

In addition to the analysis of the available gage data, a discussion of the historic and anticipated future maximum flow releases from Caballo Dam that will control the longer-duration, snowmelt driven high flows is provided in the following sections of this chapter.

Table 3.1. Streamflow gaging stations and diversions along the project reach.

Location	Station (ft)	Source of Data	Period of Record Used	Number of Years
Rio Grande below Caballo	564,589	USGS	WY1938-2006	69
Percha Private Lateral	557,648	NMSU	WY79-98, WY01-02[1]	22
Arrey Canal	557,648	NMSU	WY75-98, WY01-02[1]	22
Spillway #5 Hatch Main	476,997	NMSU	WY79-84, WY93-03[1]	19
Garfield Drain	454,840	NMSU	WY82-92[1]	11
Haynor Bridge	390,118	NMSU	WY01-03[1]	2
Rio Grande above Leasburg Dam	327,946	NMSU	WY75-83[1]	29
Leasburg Heading	327,946	NMSU	WY75-95, WY97-03[1]	26
Rio Grande below Leasburg Dam	317,457	NMSU, EBID	WY75-87, WY97-01[1]	18
Rio Grande at Picacho Bridge	236,204	NMSU, EBID	WY91-99, WY01-05[1]	14
Eastside Canal (at Mesilla Dam)	207,746	NMSU, EBID	WY75-99, WY01-03[1]	28
Rio Grande at Vado Bridge	147,061	EBID	WY85-95[1]	10
Rio Grande at Anthony Bridge	101,247	NMSU	WY86-89, WY01-03[1]	7
Rio Grande at El Paso Bridge	8,810	USGS, USIBWC	WY1938-2006	69

[1]Incomplete Records

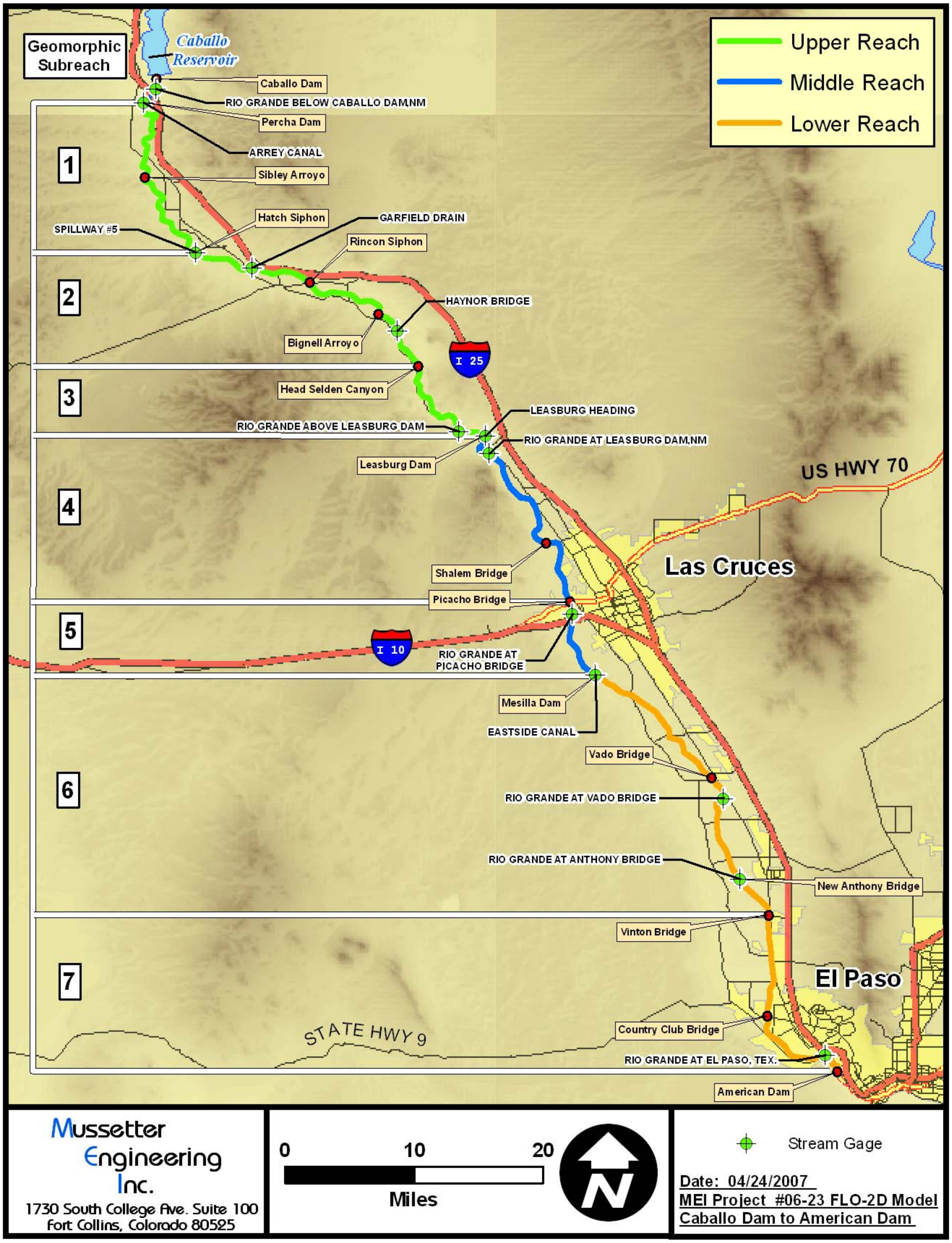


Figure 3.1. Map of project reach showing the location of stream gages, major diversions, and subreach boundaries used in the channel-stability analysis.

3.1. Project Operations

The flows analyzed for this study represent possible restoration flows that are within the range of operational releases from the Caballo Dam outlet works that has a maximum release capacity of 5,000 cfs. This maximum release can, however, only occur when the reservoir reaches the maximum water-surface elevation of 4,182 feet, which is not likely to occur under the current operational regime. As a result a peak discharge from Caballo Dam of 5,000 cfs is highly unlikely (USIBWC, 2004; Tetra Tech, 2005; **Appendix B.1**).

Caballo Dam is typically operated during the spring and summer at flows less than the channel capacity. Average monthly flows downstream from Caballo Dam range from 2,350 cfs in the upper Leasburg reach to 1,600 cfs in the lower Las Cruces reach. The conveyance capacity of the RGCP reach ranges from about 2,500 to 3,000 cfs in the Upper Rincon Valley to less than 2,000 cfs in the Lower Mesilla and El Paso Valleys.

Due to the flood control provided by Caballo Dam, large infrequent flood flows are caused primarily by tributary inflows downstream from the dam. The 24-hour general storm over the entire basin was shown to produce the highest peak discharge and largest storm volume (Tetra Tech, 2004). Based on discussions between USIBWC, the Corps of Engineers and Tetra Tech in 2004, it was decided that the project design flood event would consist of the tributary design storm flood inflows to the Rio Grande with a constant release of 2,350 cfs from Caballo Dam. For purposes of evaluating potential floodplain inundation over the entire possible range of flow releases from Caballo Dam that would result in some overbank flooding, a series of nine potential restoration flows (i.e., Caballo Dam releases) ranging between 2,350 and 5,000 cfs were evaluated (Appendix B).

3.2. Analysis of Historic Flow Data

3.2.1. Mean Daily Flows

The available mean daily flow records listed in Table 3.1 were used to develop mean daily flow hydrographs and flow duration curves for each of the 13 subreaches that were used in the geomorphic and channel stability analysis. This was accomplished by estimating the flows for the missing periods of record from WY1975 to WY2006 at each of the diversions and drains that were considered in the analysis, and then using a combination of algebraic calculations and the MOVE.1 record extension technique (Hirsh, 1982) to estimate the flows in ungaged subreaches and fill-in the missing records at the mainstem gages with incomplete records. [1]

The records for the diversions and drains were completed using a representative annual hydrograph that was developed by applying a smoothing function to the average annual hydrograph computed from the available data (**Figures 3.2 through 3.4**). Based on the available data, approximately 94,800 ac-ft of flow is diverted annually to the Arrey Canal at Percha Dam, and peak diversions of approximately 240 cfs occur during May, June and July (Figure 3.2). At Leasburg Dam, approximately 153,000 ac-ft of flow is diverted annually to the

[1] MOVE.1 is an analytical technique for extending the short record of a site (or filling in missing data) using values from a base gaging station that has a longer period of record and has similar hydrologic characteristics to the short-record station at which the record is to be extended. A relationship is then developed between the pairs of measured flows during the concurrent period of record at the base and short-record stations (Hirsh, 1982). A Box-Cox transform (Hirsh, 1982) is also applied to the data to improve the relationship between the long and short records. The extended record is then computed by applying the resulting relationship to each of the base station flows in the non-concurrent record.

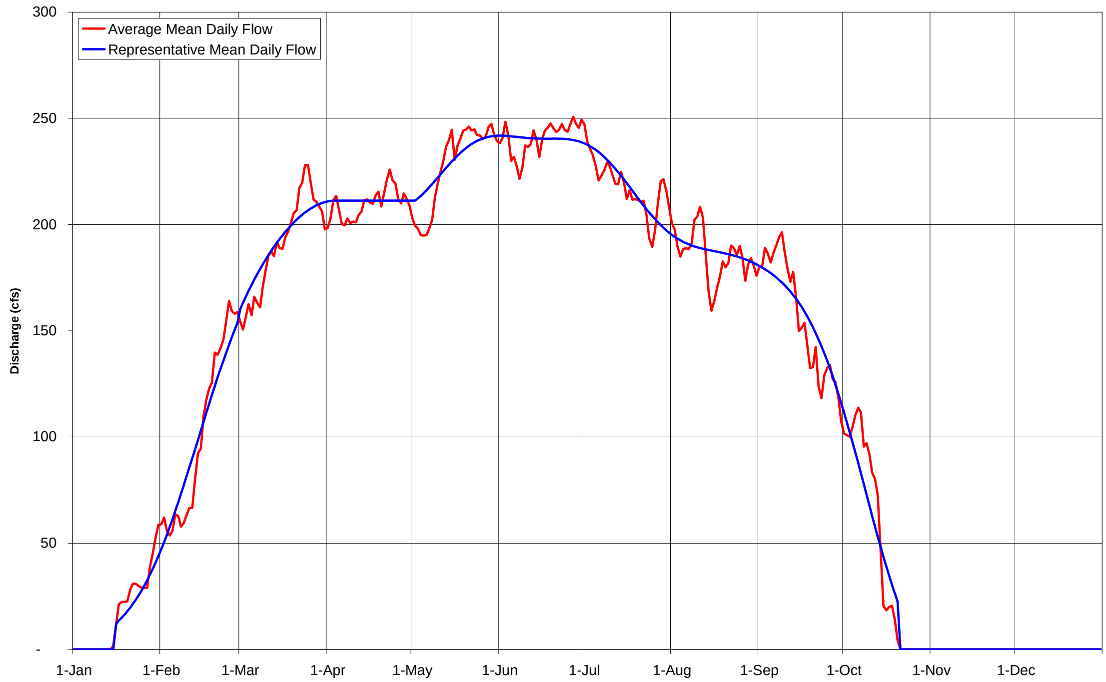


Figure 3.2. Recorded average and representative mean daily flows for the Arrey Canal diversion.

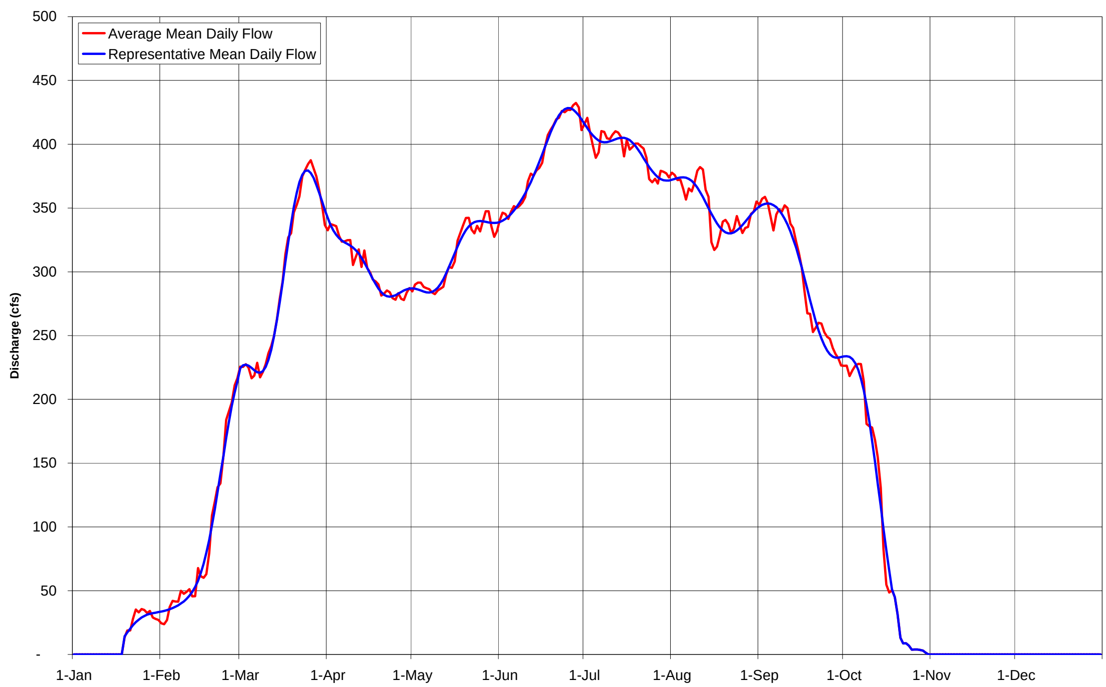


Figure 3.3. Recorded average and representative mean daily flows for the Leasburg Canal diversion.

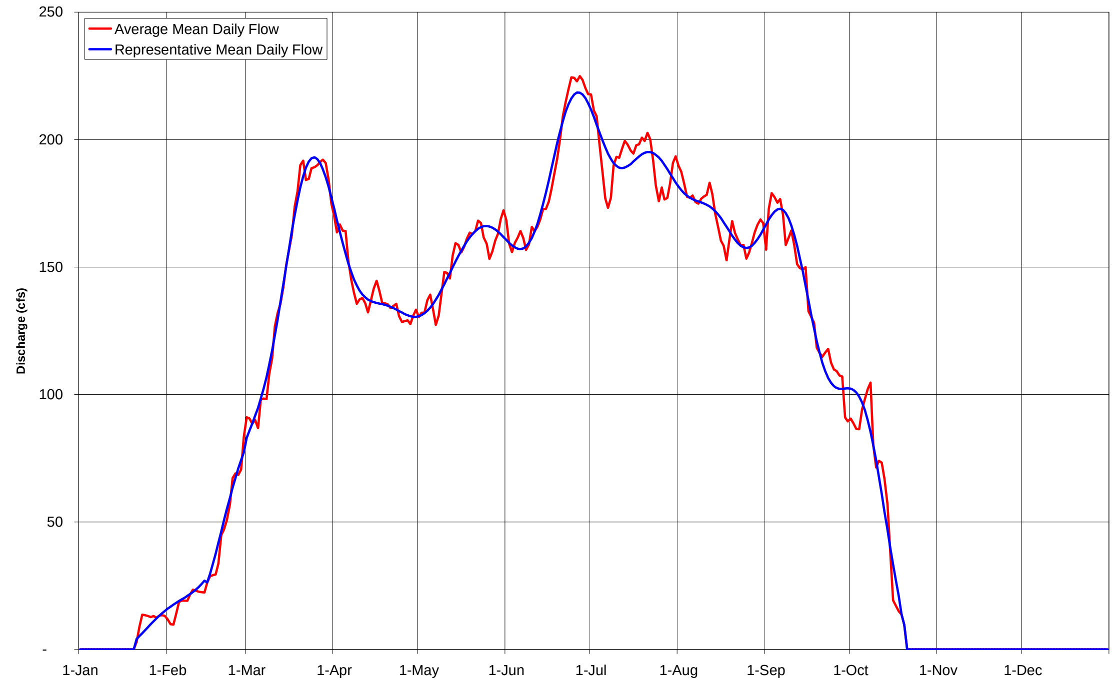


Figure 3.4. Recorded average and representative mean daily flows for the Eastside Canal diversion.

Leasburg Canal and diversions are typically greater than 250 cfs from mid-March to mid-October (Figure 3.3). At Mesilla Dam, approximately 72,000 ac-ft of flow is diverted annually to the Eastside Canal, and flow diversions are typically greater than 100 cfs from mid-March to mid-October (Figure 3.4).

The incomplete records for the mainstem gages were filled-in in sequence working from upstream to downstream by subtracting the diversions and adding the drains to the upstream mainstem flows, where appropriate, or by estimating the flow from an adjacent gage using the MOVE.1 technique (**Table 3.2**). The MOVE.1 and Box-Cox transform relationship that was used to complete the flow record at the Anthony gage using recorded flows at the El Paso gage is shown in **Figure 3.5**. This relationship is typical of those used at the other locations.

Based on the complete record of measured flows for the post-Caballo Dam period (WY1939 through WY2006), the annual flow volume at the Caballo Gage ranged from 206,170 ac-ft (WY1964) to 1,750,570 ac-ft (WY1942), and averaged about 669,300 acre-feet (**Figure 3.6**). The annual flow volume at the El Paso gage during this period ranged from 59,010 ac-ft (WY1956) to a maximum of 1,513,940 ac-ft (WY1942) and averaged 398,340 ac-ft. For comparison, the annual volume passing the Caballo gage during the period of analysis used in this study from WY1975 through WY2006 ranged from 356,190 ac-ft (1978) to 1,691,990 ac-ft, and averaged 718,350 ac-ft, approximately 7 percent higher than the complete period of record. At the El Paso gage, the annual volume during the period from WY1975 through WY2006 ranged from 156,050 ac-ft (1978) to 1,413,560 ac-ft (1987), and averaged 430,640 ac-ft, about 8 percent higher than the complete period of record.

Table 3.2. Subreaches defined for the channel-stability analyses and method used to estimate flows within each subreach.

Subreach[1]	Feature at Upstream End	Upstream Station (ft)	Length (ft)	Length (mi)	Gages Used to Calculate Reach Mean Daily Flow Values
1.1	Caballo Dam	568,640	10,992	2.1	Rio Grande below Caballo
1.2	Percha Dam	557,648	38,613	7.3	Rio Grande below Caballo - Percha Private Lateral - Arrey Canal
1.3	Sibley Arroyo	519,035	42,035	8.0	Rio Grande below Caballo - Percha Private Lateral - Arrey Canal
2.1	Hatch Siphon	477,000	43,812	8.3	Reach 1.3 - Spillway #5 Hatch Main + Garfield Drain
2.2	Rincon Siphon	433,188	32,688	6.2	Rio Grande at Haynor Bridge (MOVE.1 extension with Reach 2.1 values)
2.3	Bignell Arroyo	400,500	27,200	5.2	Rio Grande at Haynor Bridge (MOVE.1 extension with Reach 2.1 values)
3	Head Selden Canyon	373,300	45,354	8.6	Rio Grande above Leasburg Dam (MOVE.1 extension with Haynor Gage values)
4	Leasburg Dam	327,946	86,294	16.3	Rio Grande below Leasburg Dam (RG above Leasburg - Leasburg Heading values)
5	Picacho Bridge	241,652	33,906	6.4	Rio Grande at Picacho Bridge (MOVE.1 extension with RG below Leasburg values)
6.1	Mesilla Dam	207,746	60,685	11.5	Rio Grande at Vado Bridge (MOVE.1 extension with Anthony Gage values)
6.2	Vado Bridge	147,061	63,802	12.1	Rio Grande at Anthony Bridge (MOVE.1 extension with El Paso values)
7.1	Vinton Bridge	83,259	41,695	7.9	Rio Grande at Anthony Bridge (MOVE.1 extension with El Paso values)
7.2	Country Club Bridge	41,564	41,564	7.9	Rio Grande at El Paso
	American Dam	---			

[1]The first number in the subreach designation corresponds to the modified RMU designation from USIBWC (2004), and the second number represents a subdivision of the corresponding RMU.

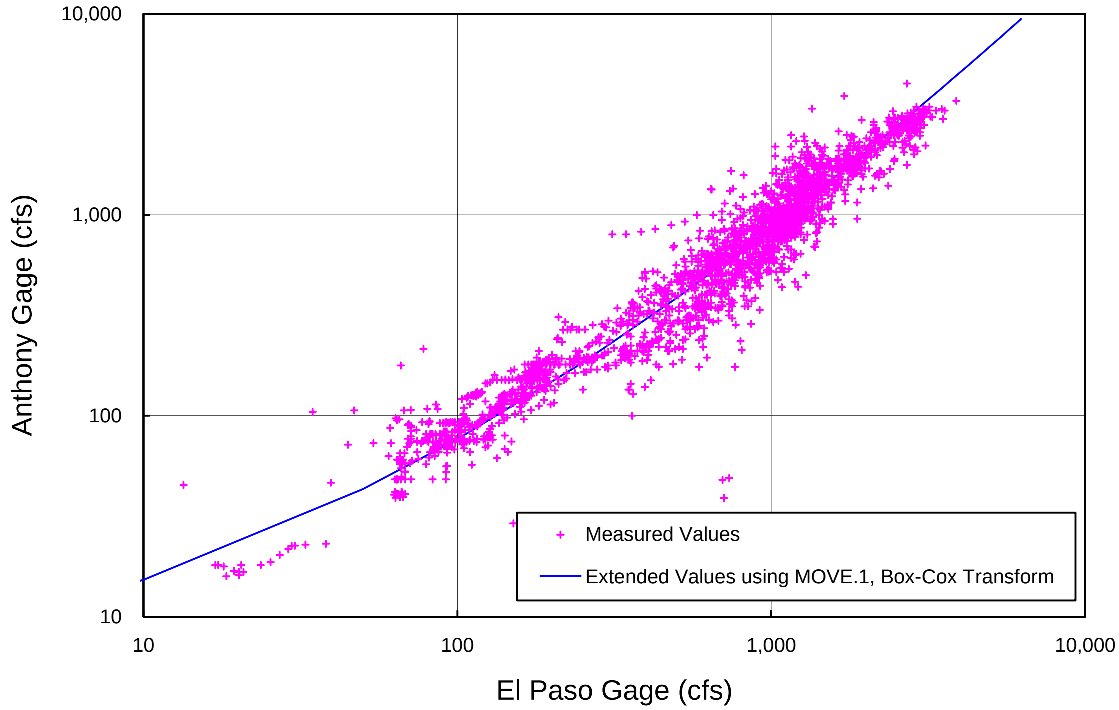


Figure 3.5. Extension of the Rio Grande at Anthony gage mean daily flow record using recorded flows at the El Paso gage with the MOVE.1 record extension and Box-Cox transform.

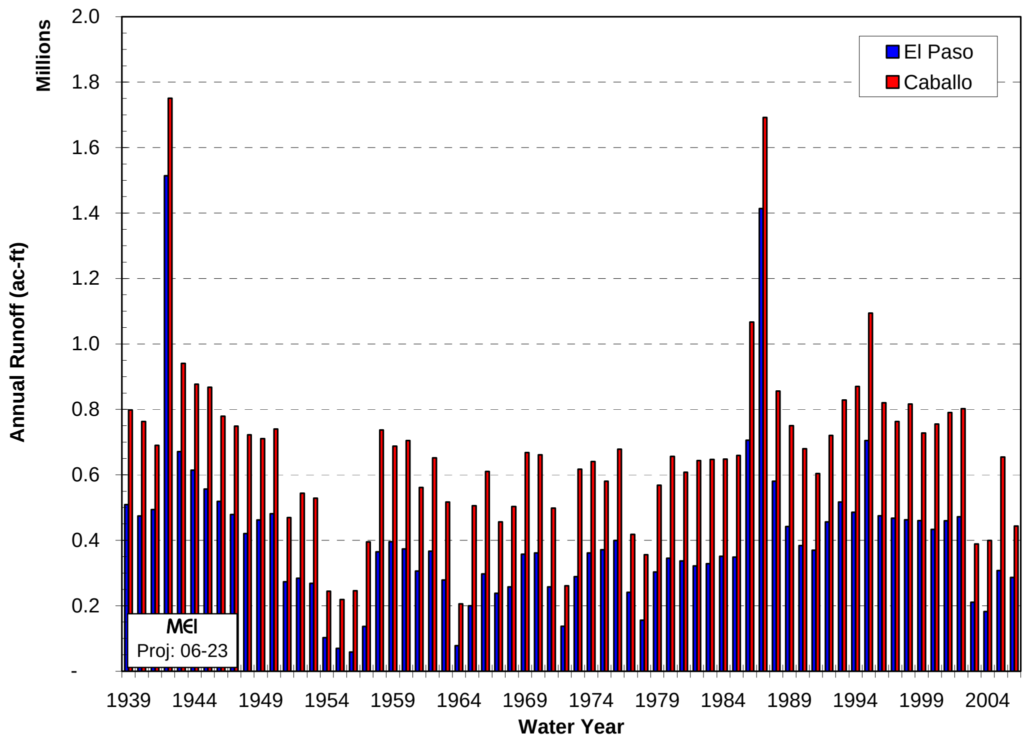


Figure 3.6. Annual flow volumes at the Rio Grande at Caballo gage (USGS Gage No. 08362500) and the Rio Grande at El Paso gage (USIBWC gage) for the period from WY1938 through WY2006.

Average annual hydrographs at the Caballo and El Paso gages indicate that the primary runoff period in the RGCP reach corresponds with the irrigation season that typically begins at the beginning of March and ends in mid- to late-September (**Figure 3.7**). These hydrographs also indicate that the highest mean daily flows usually occur between June and July, with a secondary peak in mid- to late-March at the beginning of the irrigation season. The mean daily flow duration curves indicate that releases from Caballo Dam exceeded 1,000 cfs about half the time during the period from WY1975 through WY2006, and were less than 10 cfs about 40 percent of the time (**Figure 3.8**). At the El Paso gage, mean daily flows exceeded 530 cfs about half the time, but they exceeded 10 cfs over 99 percent of the time, most likely due to groundwater inflow during the non-irrigation season.

Based on the estimated flow duration curves for the geomorphic subreaches used in the channel stability analysis, the flows for a given exceedence value greater than the 30 to 50 percent exceedence flows typically decrease in the downstream direction as water is diverted from the river, but the baseflows tend to increase in the downstream direction (**Figures 3.9 and 3.10**).

3.3. Flood-frequency Analysis

A flood frequency analysis was conducted using the available gage data to quantify the frequency of the highest flows that have occurred in the study reach. The purpose of the analysis was primarily to determine the magnitude of the frequently occurring flood flows that are most important for anticipated the restoration activities. Originally, it was intended that a peak flood-frequency analysis would be performed for each of the primary gages along the reach (i.e., Rio Grande below Caballo (USGS Gage No. 083625000), Rio Grande below Leasburg Dam (USIBWC Gage) and the Rio Grande at El Paso (USIBWC Gage) gages). In reviewing the available data, however, it was determined that the reported peak flows at both the below Caballo and Leasburg gages are actually mean daily values which are typically less than the instantaneous peak values. As a result, a valid peak flood frequency analysis could not be performed for these gages. A flood-frequency analysis was, however, conducted using the available peak flow data at the El Paso gage. Since restoration flows must have a reasonable duration to be effective, the frequency distribution of the maximum annual mean-daily flows was also evaluated for all three gages based on their plotting position using the Weibull formula.

Annual peak flow values are reported for 18 occurrences during the period from WY1938 to 2006 at the El Paso gage. A comparison of these values with the concurrent mean daily flow indicates that the peak flow was approximately 210-percent higher than the mean daily flow (**Figure 3.11**). Based on this relationship, peak flow values were estimated for the other 52 water-years when no peak flow was measured by multiplying the annual peak mean daily flow by 2.1. A flood frequency analysis was then conducted using the measured and computed peak flow values at the El Paso gage. The data were sorted to include only rainfall floods, based on the time of their occurrence. The analysis was carried out using the U.S. Army Corps of Engineers HEC-FFA computer program (USCOE, 1992), which is based on the industry-standard procedures described in Water Resources Council Bulletin 17B (WRC, 1981). This method involves fitting a record of annual instantaneous peak flows to a Log-Pearson Type III frequency distribution.

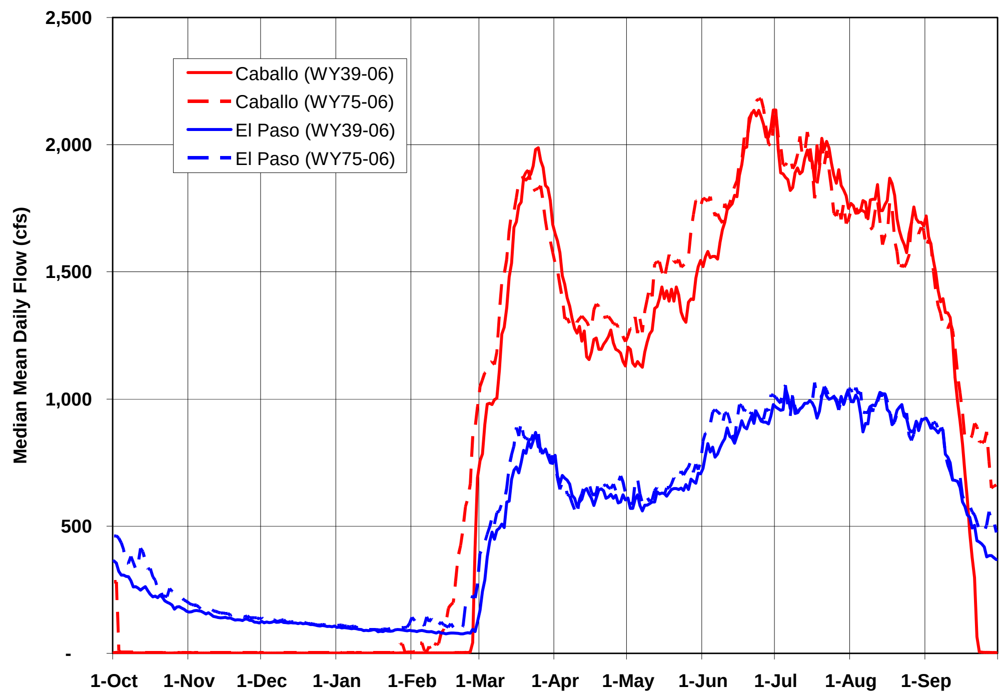
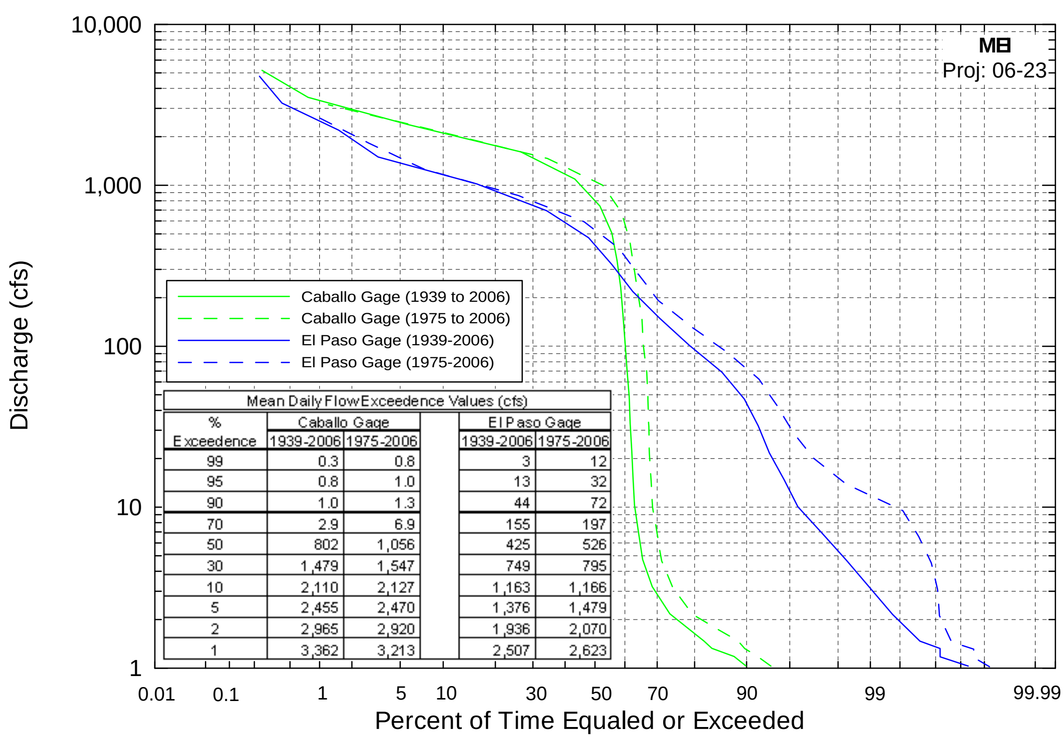


Figure 3.7. Median mean daily flows at Rio Grande at the Caballo gage (USGS Gage No. 08362500) and the Rio Grande at El Paso gage (USIBWC gage) for the periods from WY1938 through WY2006 and WY1975 through WY2006.



Mean Daily Flow Exceedence Values (cfs)

% Exceedence	Caballo Gage 1939-2006	Caballo Gage 1975-2006	El Paso Gage 1939-2006	El Paso Gage 1975-2006
99	0.3	0.8	3	12
95	0.8	1.0	13	32
90	1.0	1.3	44	72
70	2.9	6.9	155	197
50	802	1,056	425	526
30	1,479	1,547	749	795
10	2,110	2,127	1,163	1,166
5	2,455	2,470	1,376	1,479
2	2,965	2,920	1,936	2,070
1	3,362	3,213	2,507	2,623

Figure 3.8. Mean daily flow-duration curves for two periods (1938–2006 and 1975–2006) for the Caballo and El Paso gages.

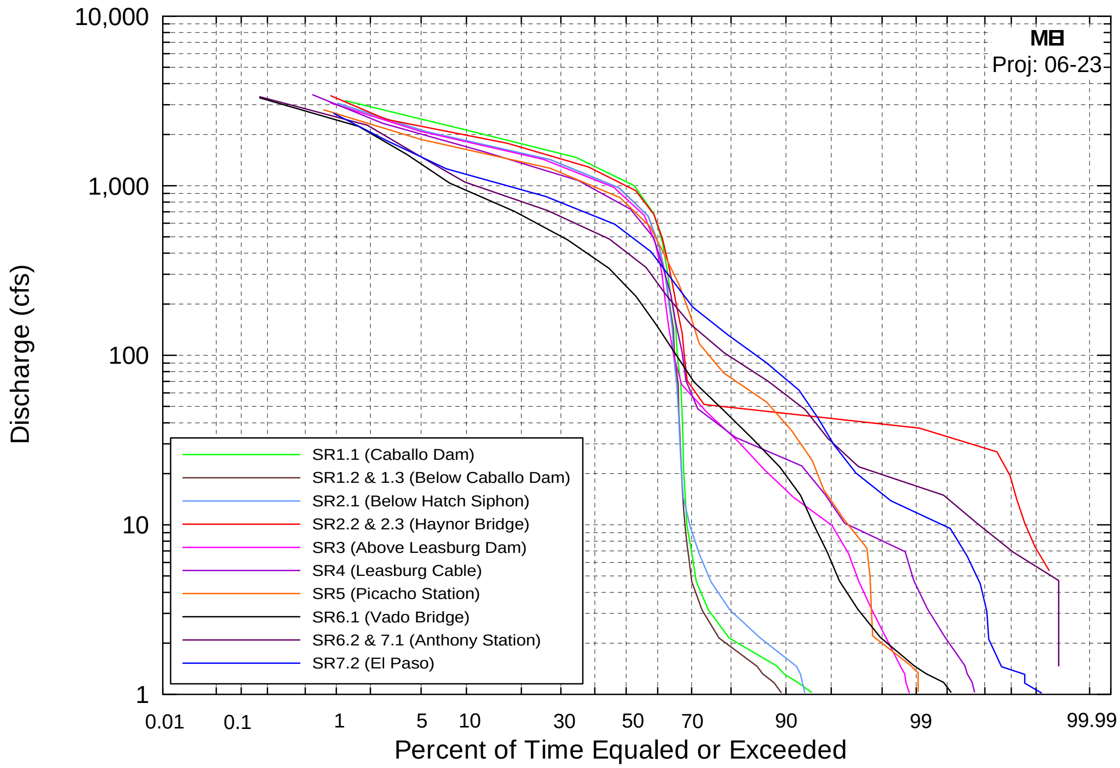


Figure 3.9. Mean daily flow-duration curves based on the 1975 to 2006 period of record for Subreaches 1.1 through 7.3.

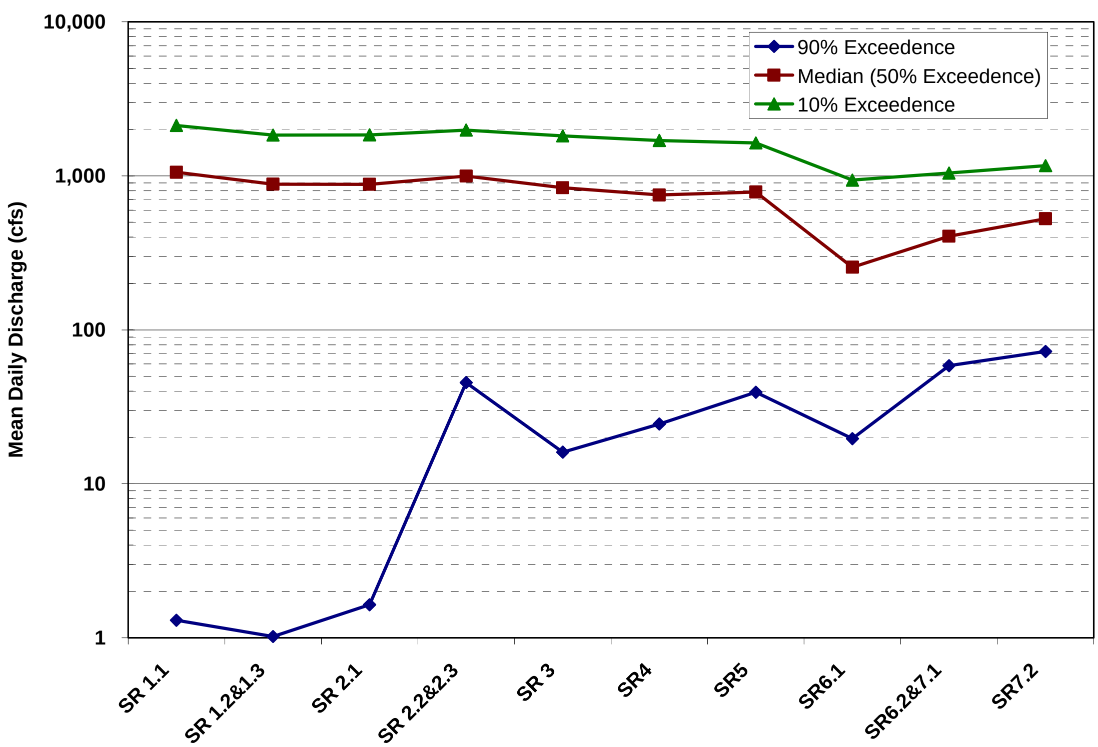


Figure 3.10. Variation in median (50% exceedence), 10% exceedence, and 90% exceedence flows along the study reach for the period from WY1975 through WY2006.

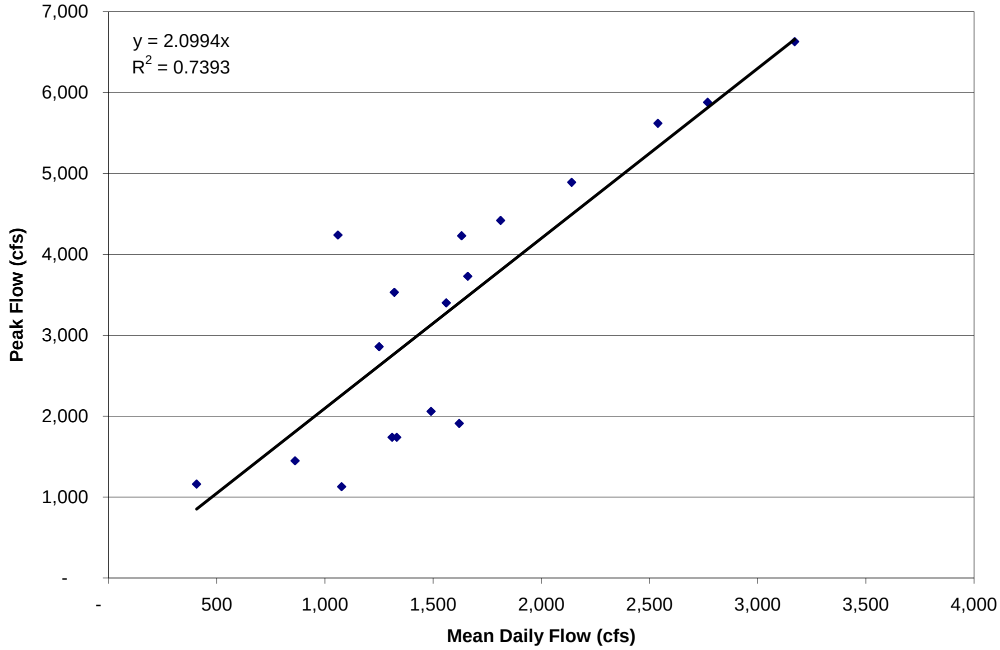


Figure 3.11. Comparison of the measured peak flows and concurrent mean daily flows at the Rio Grande at El Paso gage.

Based on the flood-frequency analysis, the 2, 5-, 10-, 20-, 50- and 100- year peak flow event discharges are approximately 4,040, 6,000, 7,270, 8,470, 9,980, and 11,100 cfs, respectively (**Figure 3.12**). The 100-year peak flow resulting from the flood frequency analysis is approximately 200 cfs higher than the peak flow of 10,990 cfs reported by Tetra Tech (2004) for this location based on FLO-2D routings of the tributary peak flows from a previous HEC-1 analysis that assumed a 24-hour general storm over the entire basin and a 2,350 cfs release from Caballo Dam (**Table 3.3**). The Tetra Tech (2004) routing resulted in peak flows of 15,150 cfs at the mouth of Arroyo Cuervo in the upstream portion of the study reach, with the flows generally attenuating in the downstream direction.

Comparison of the Weibull plotting positions of the annual maximum mean daily flows at the Leasburg, Caballo, and El Paso gages for the complete period of record from WY1938 through WY2006 indicates that peak discharges are similar at all three locations for the less frequent (5-year and greater) recurrence intervals, but they tend to decrease in the downstream direction at the smaller, more frequent recurrence intervals. This is probably a result of the limited overbank and in-channel storage capacity and relatively small effect of the flow diversions at higher discharges.

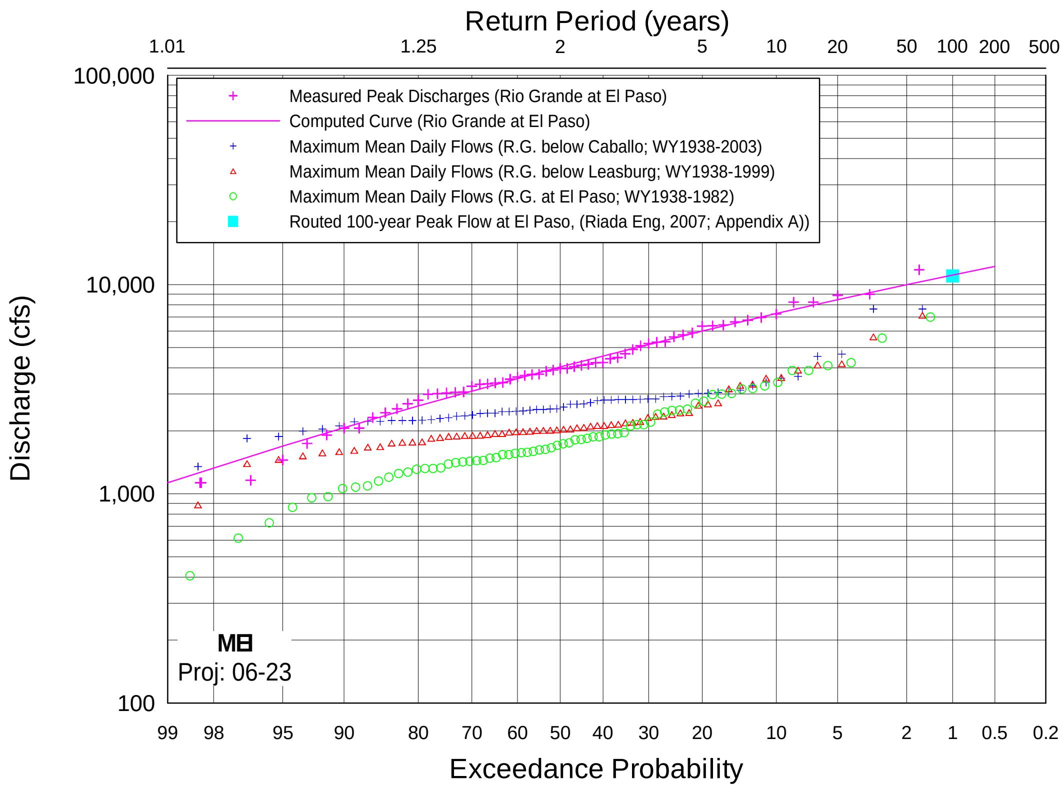


Figure 3.12. Computed flood-frequency curve for the Rio Grande at El Paso gage and maximum mean daily flows for the Rio Grande gages below Caballo, Leasburg, and at El Paso.

Table 3.3. 100-year 24-hour routed peak discharges between Caballo and American Dams.	
Location	Flood-routed (FLO-2D) Rio Grande Peak Discharge (cfs)
Caballo Dam Release	2,350
Trujillo Canyon	4,880
Montoya Arroyo	8,470
Green Canyon	11,600
Tierra Blanca Arroyo	10,430
Sibley Arroyo	12,970
Berrenda Arroyo	14,900
Arroyo Cuervo	15,150
Placitas Arroyo	14,690
Angostura Arroyo	14,300
Rincon Arroyo	14,070
Reed Arroyo	14,110
Broad Canyon	11,690
Faulkner Canyon	10,990
Leasburg Diversion Dam	12,060
Shalem Bridge	13,120
Dona Ana Dam	12,580
Picacho Dam	12,700
Mesilla Diversion Dam	12,870
Vinton, Texas	12,110
Nuway, Texas	13,130
Canutillo, Texas	13,090
Borderland, Texas	11,170
Courchesne Bridge	9,790
American Diversion Dam	10,990

4. TWO-DIMENSIONAL HYDRODYNAMIC MODELING

A FLO-2D model of the RGCP reach from Caballo Dam to American Dam (105 miles) was used to estimate hydraulic conditions in the project reach and to aid in evaluating the restoration opportunities. FLO-2D is a two-dimensional flood routing model that predicts flood-wave attenuation, floodplain inundation and spatially variable water-surface elevations. The FLO-2D model that was previously developed for the Upper Rio Grande Water Operations Review and EIS (URGWOPS) for this reach by Tetra Tech (2004) was applied to the RGCP by Riada Engineering, Inc. This model uses 250-foot square grid elements and was originally developed to predict the potential flood inundation associated with the 100-year design flood event. In this study, only discharges up to 5,000 cfs (approximately the 3.4-year peak flow return interval at the El Paso gage) are simulated with the FLO-2D model for the purpose of investigating riparian restoration opportunities.

Results from the FLO-2D model were used to evaluate overbank inundation areas at a range of discharges up to 5,000 cfs, and to provide main channel hydraulic information for use in the channel stability analysis.

4.1. Model Development

4.1.1. Topographic Data, River Cross Sections and Model Details

The FLO-2D model was developed from available topographic, orthographic and cross section data. In early 2005 a comprehensive digital mapping project was completed for a significant portion of Dona Ana County, New Mexico, and included color digital orthophotos, LIDAR digital terrain data and digital topographic mapping of the Rio Grande corridor. The project was administered by the Dona Ana County Flood Commission (DACFC). The mapping products were parsed into files that correspond with the Public Land Survey System (PLSS). For each land section, a digital orthophoto file, a Digital Terrain Model (DTM) file, and a contour file were prepared and referenced to the New Mexico State Plane Coordinate Grid System NAD 83 Central Zone. Coordinate files referenced U.S. survey feet and elevation data were referenced to the North American Vertical Datum 1988 (NAVD 88). The 1:12,000 scale aerial photography from the DACFC project was scanned and rectified at a resolution which produced 1 foot pixels in the final digital image files that show substantial detail of the floodplain features.

The mass point LIDAR data was edited and filtered to eliminate points that did not reflect “bare earth” ground points and to remove high and low outliers. The DTM points and images were imported to the FLO-2D Grid Developer System (GDS) and grid element elevations were interpolated and assigned. The final grid consists of 43,937 elements that are 250 feet square.

A total of 145 channel cross sections were surveyed in June and July, 2004 (Tetra Tech, 2004) in the project reach with an average spacing of about 2 per mile, with enhanced resolution in the vicinity of hydraulic structures. The cross sections were separated into three groups, including:

- Sixty-six “Below Caballo” (BC) lines between the Caballo Dam and Leasburg Diversion Dam.
- Twenty-five “Leasburg Dam” (LD) lines between Leasburg Dam and Mesilla Diversion Dam.
- Fifty-four “Mesilla Dam” (MD) lines between Mesilla Dam and American Diversion Dam in El Paso.

These cross sections were distributed and interpolated to 2,046 channel elements.

To complete the FLO-2D model, various floodplain details were added to the model including levees, hydraulic structures, and rates of infiltration and evaporation. The levees on both sides of the river constitute an important control for limiting overland flooding through most of the RGCP project reach, with approximately 74 miles on the east side and 57 miles on the west side of the river. The levees are typically set back from the active river channel by less than seven hundred feet. In the model, levees block grid element flow directions and are represented by a crest elevation that can be overtopped. Levee failure was not simulated under the assumption that levee stability would not be affected by the restoration project; however discontinuities created by wasteways, tributary arroyos and roadway/railroad embankments were included in the model.

A total of 27 bridges, 2 siphons and 4 diversion dams were modeled using stage-discharge rating tables that were developed from a HEC-RAS model that was developed from a series of HEC-2 models (RTI, 1996). Of the four diversion dams, only the Mesilla Diversion Dam was included in the original HEC-2 models because the models were divided into reaches around the other diversion dams. The individual HEC-2 models were combined into a single HEC-RAS model that incorporated the channel geometry in the vicinity of the structures. The HEC-RAS model was executed over a range of flows from 100 cfs to 30,000 cfs, and the results from the model were used to develop rating curves at the hydraulic structures that were then used in the FLO-2D model.

Channel and overland flow infiltration losses in the FLO-2D model were calculated using the Green-Ampt infiltration model. In the absence of spatially variable soil data, uniform infiltration parameters were assigned for the floodplain and channel.

Evaporation losses were computed using an open-water surface evaporation routine to account for losses associated with long-duration flood flows. Evaporation is computed based on a mean monthly total evaporation distributed daily on the basis of an assumed diurnal hourly variation, but does not include evapotranspiration from vegetation.

4.2. Model Calibration

The FLO-2D model was calibrated, to the extent possible, by comparing the computed and measured flood-routing characteristics of three recorded hydrograph events. The flood-routing characteristics include the hydrograph shape (volume), hydrograph timing and water-surface elevations. The flood hydrograph shape is primarily defined by inflow discharge, irrigation diversions, and system losses (infiltration and evaporation). Peak discharge or discharge spike timing (arrival) at various locations in the system is primarily a function of volume, but is also dependent on resistance to flow.

The initial calibration focused on measured water-surface elevation data from the 2004 channel cross section surveys, when the flows were relatively low. The calibration procedure involved adjusting the roughness (Manning's *n*-value) to minimize the difference between the surveyed and predicted water-surface elevations at the cross sections. The final calibration resulted in an average main-channel *n*-value of 0.029, and had differences in predicted and surveyed water surfaces that ranged from -0.45 to 0.49 feet with an average of 0.034 feet.

Recorded gage discharge hydrographs during the 2004 survey were compared with the computed FLO-2D hydrographs (**Figures 4.1 through 4.4**). The differences between the measured and predicted hydrographs are attributed primarily to irrigation drain return flows that

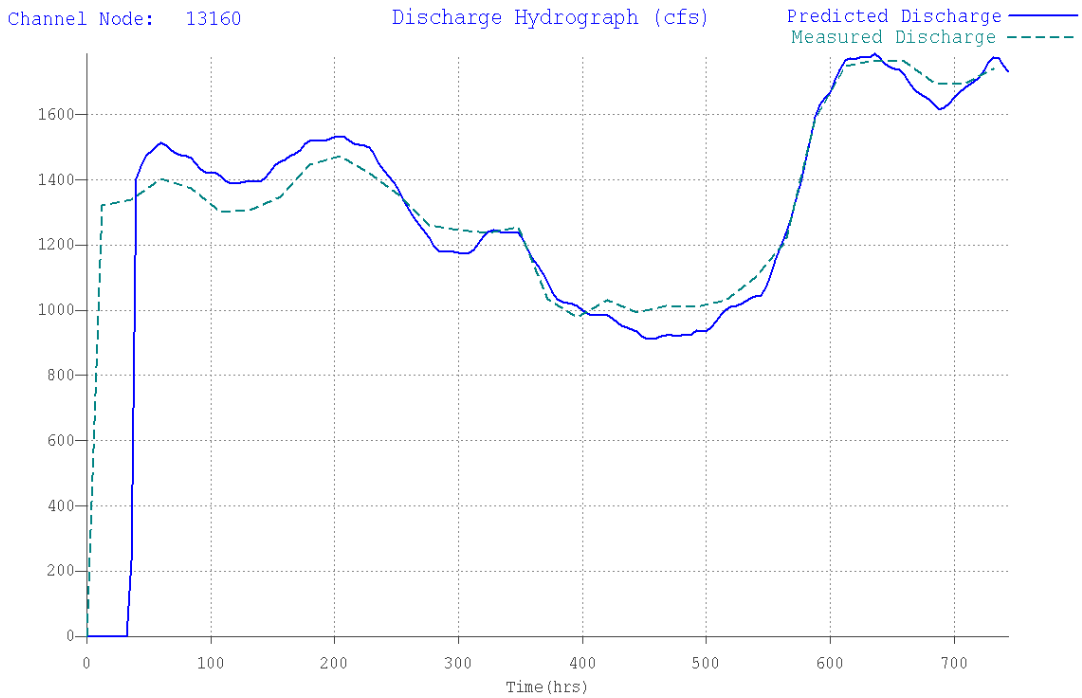


Figure 4.1. Measured and predicted hydrographs during June and July 2004 at the Haydon Gage (after Tetra Tech, Inc., 2004).

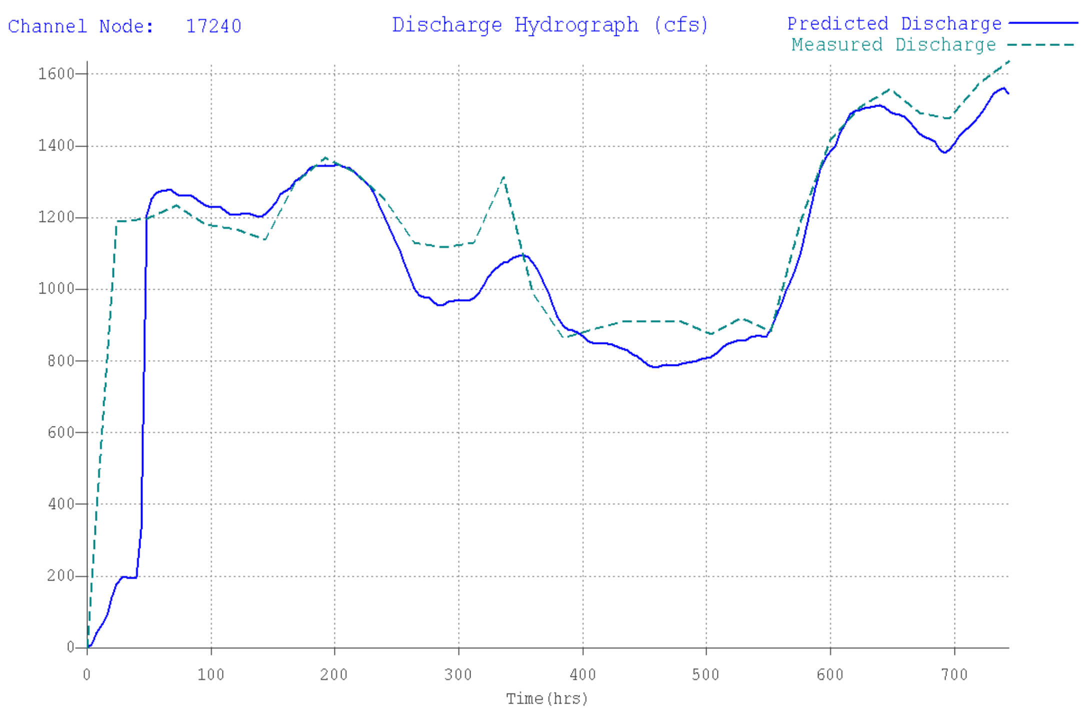


Figure 4.2. Measured and predicted hydrographs during June and July 2004 at the Leasburg Gage (after Tetra Tech, Inc., 2004).

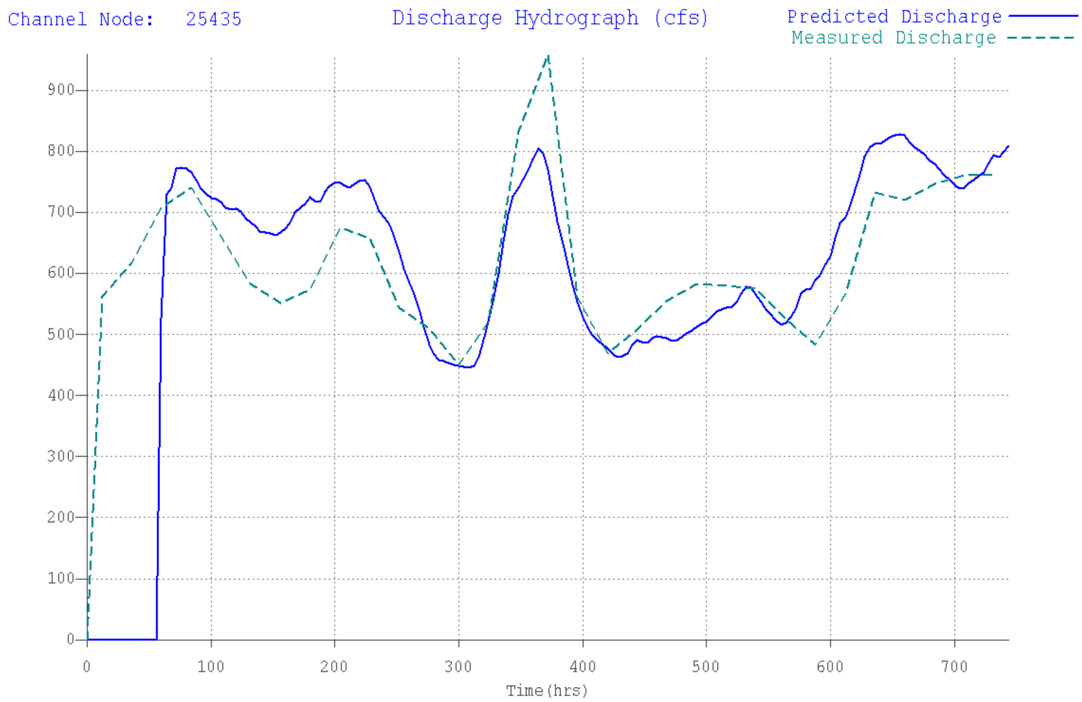


Figure 4.3. Measured and predicted hydrographs during June and July 2004 at the Mesilla Gage (after Tetra Tech, Inc., 2004).

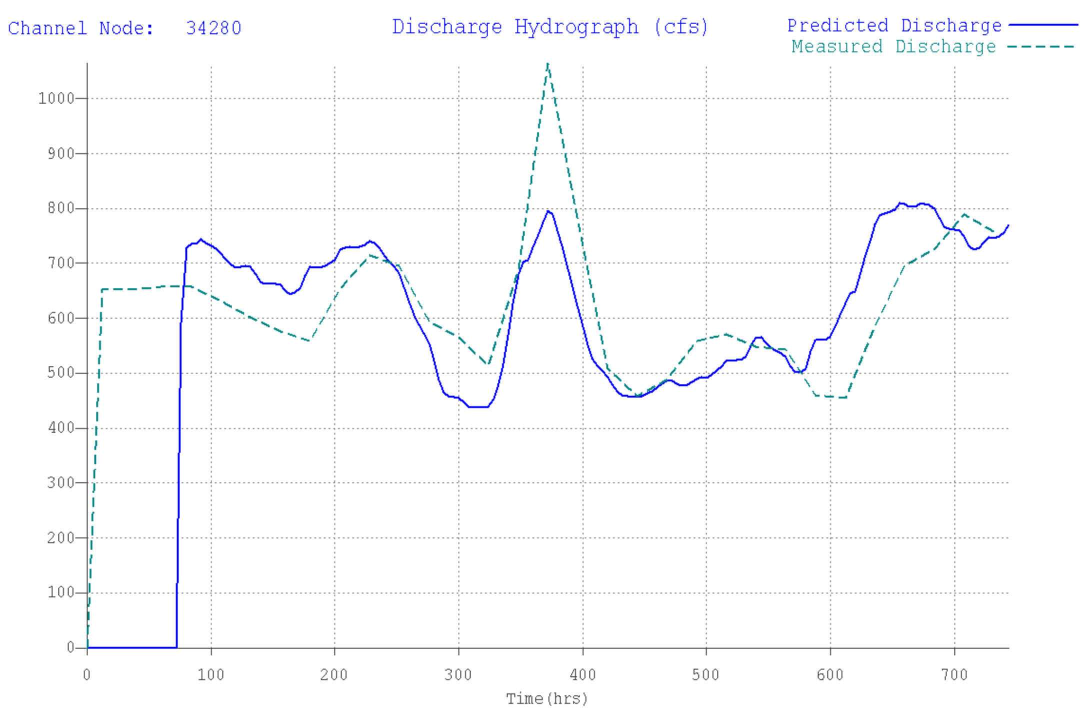


Figure 4.4. Measured and predicted hydrographs during June and July 2004 at the Anthony Gage (after Tetra Tech, Inc., 2004).

are not considered in the model. Considering the irrigation return flows that are not included in the model, the computed hydrographs match the measured data reasonable well. In addition, the model results reasonably predict the observed storm inflow spike that was recorded in the reach from Leasburg Dam to New Anthony Bridge (Figures 4.2 through 4.4).

The second calibration effort focused on the shape of the hydrograph at higher flows during July, 1995, when the Caballo Dam release ranged from 3,600 to 4,540 cfs. This 31-day period had a relatively complete record of irrigation diversions and return flows throughout the river system that was made available by EBID. Since the *n*-values were calibrated for the 2004 water-surface elevations, only minor *n*-value adjustments were made to the 1995 data set to account for potential variation in roughness with flow depth. To provide a better match of the predicted and measured hydrographs (**Figures 4.5 through 4.7**), the channel hydraulic conductivity was adjusted. Again, it should be noted that there are irrigation return flows that are either ungaged or not included in the database. (During this simulation, the cumulative return flow that is not accounted for is less than 200 to 300 cfs.)

A final calibration run was executed for a low-flow period with no overbank flows in July 1998 to verify the previously calibrated channel *n*-values and geometry. The results indicate a similar pattern as the previous calibration runs where the difference between measured and predicted discharge increased in the downstream direction (**Figures 4.8 through 4.11**) due to increased return flows. Considering the effects of the return flows that are either ungaged or not included in the model, the calibration results confirmed that the model replicates both the water-surface elevation and the hydrograph shape and timing as noted by correlation of the spikes and troughs in the discharge hydrographs (Tetra Tech, Inc., 2004).

The calibrated input files are essentially the same input files used in the 2004 flood hazard delineation study (Tetra Tech, 2004), except the data files were converted to FLO-2D Version 2007. The final FLO-2D model is provided on the DVD in **Appendix B.2**, that includes all input database files and a summary of the model output.

4.3. Model Results

To aid in assessing inundation potential along the reach, a series of steady-state releases from Caballo Dam from approximately bankfull flow (2,350 cfs) to the maximum Caballo Dam outlet releases (5,000 cfs) were simulated with the FLO-2D model. The simulations were executed under both with- and without-diversion conditions in increments of 250 to 500 cfs. No irrigation return flows were simulated.

4.3.1. Existing Conditions Restoration Flow Analysis

The relationship between the total predicted area of inundation along the reach and discharge over the range of modeled steady-state releases is presented in **Figure 4.12**. For the no-diversion scenario, there is essentially a linear increase of the area of inundation with discharge for the range of restoration flows from 2,350 to 5,000 cfs and an increase in the area of flooding for the 4,500- and 5,000-cfs flows. For the 2,350-cfs restoration flow with diversions, there is only about 1 acre of overbank flooding. Downstream from Mesilla Dam, the channel capacity is about 1,500 cfs. It should be noted that the accuracy of the FLO-2D model to predict very shallow and limited overbank flooding is dependent on the bank and floodplain grid element elevations, and therefore, the results are less accurate for shallow overbank flows.

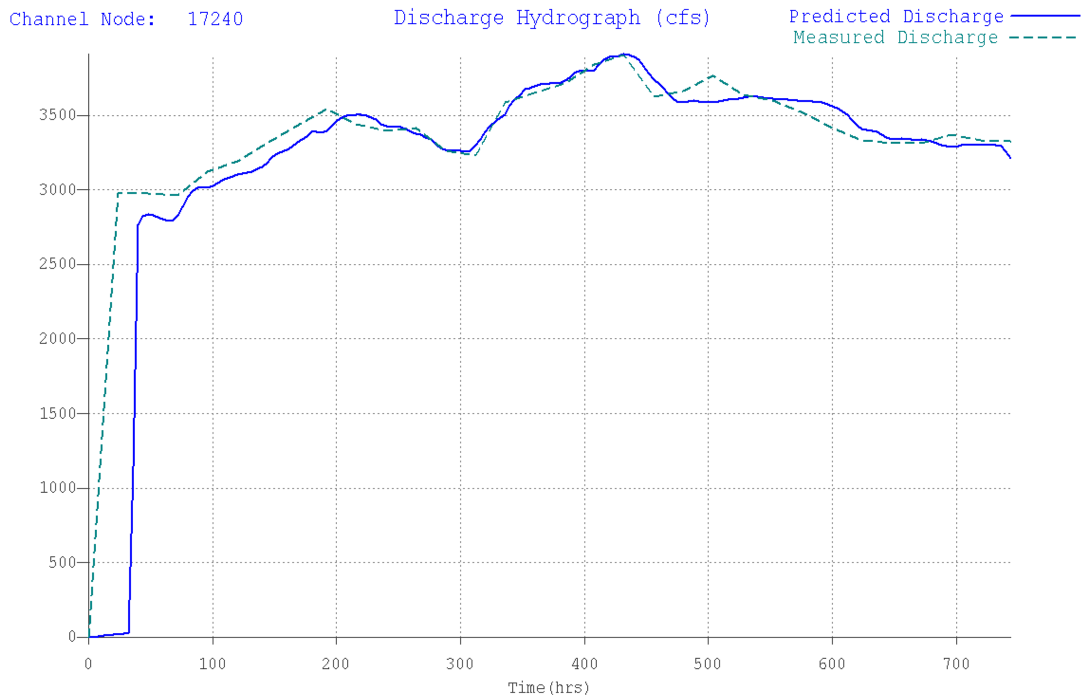


Figure 4.5. Measured and predicted hydrographs during July 1995 at the Leasburg Gage (after Tetra Tech, Inc., 2004).

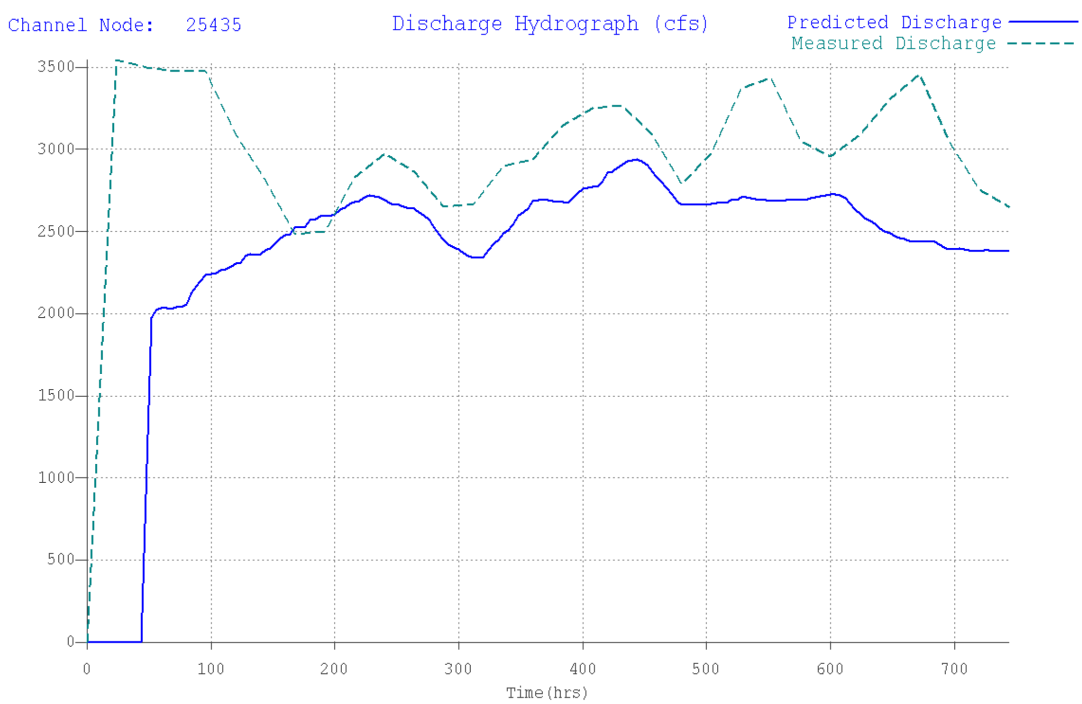


Figure 4.6. Measured and predicted hydrographs during July 1995 at the Mesilla Gage (after Tetra Tech, Inc., 2004).

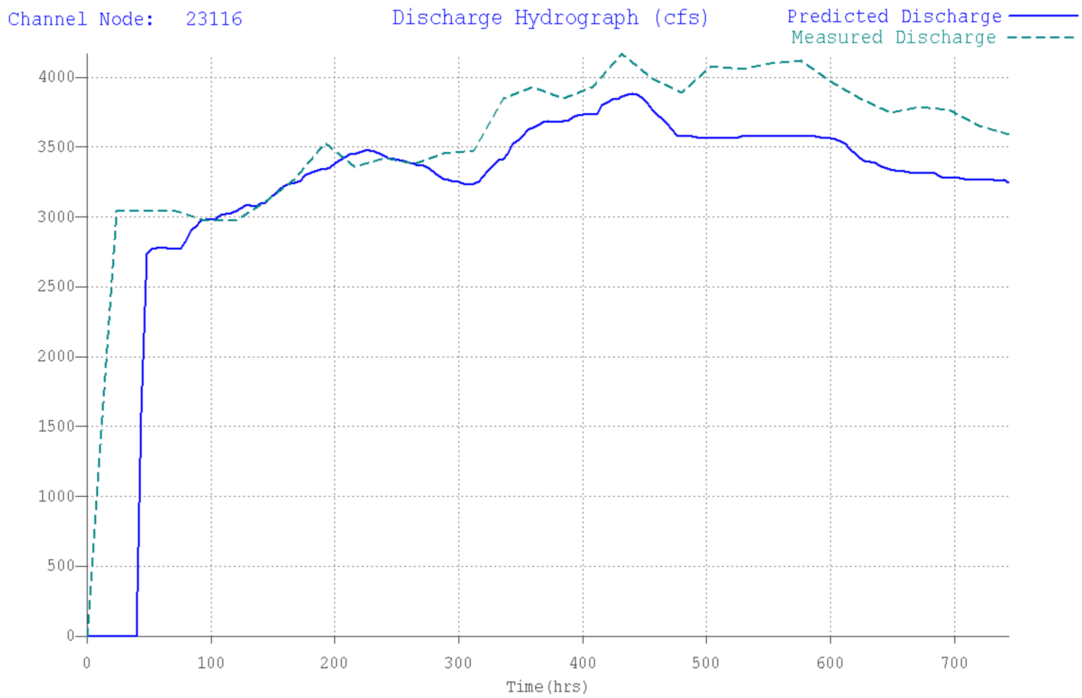


Figure 4.7. Measured and predicted hydrographs during July 1995 at the Picacho Gage (after Tetra Tech, Inc., 2004).

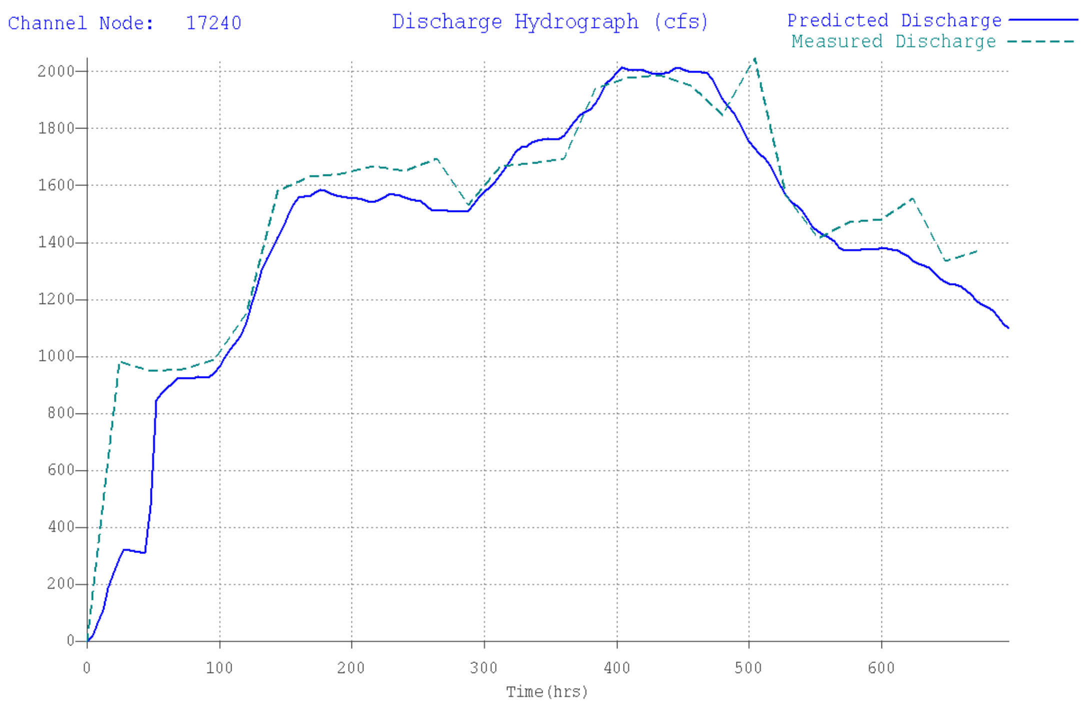


Figure 4.8. Measured and predicted hydrographs during July 1998 at the Leasburg Gage (after Tetra Tech, Inc., 2004).

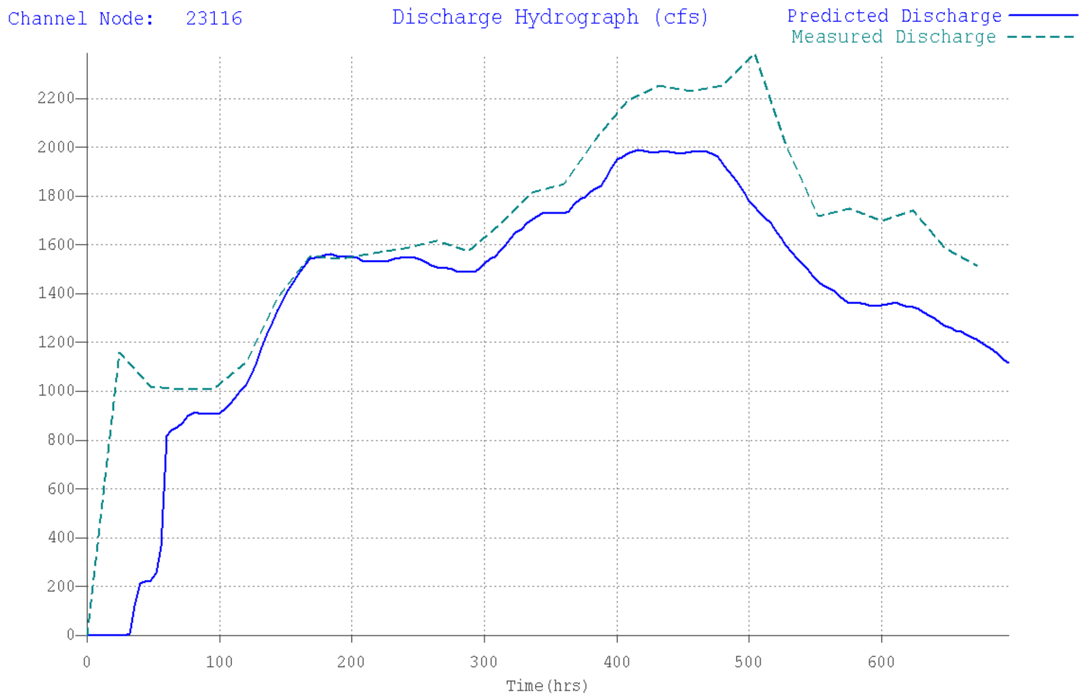


Figure 4.9. Measured and predicted hydrographs during July 1998 at the Picacho Gage (after Tetra Tech, Inc., 2004).

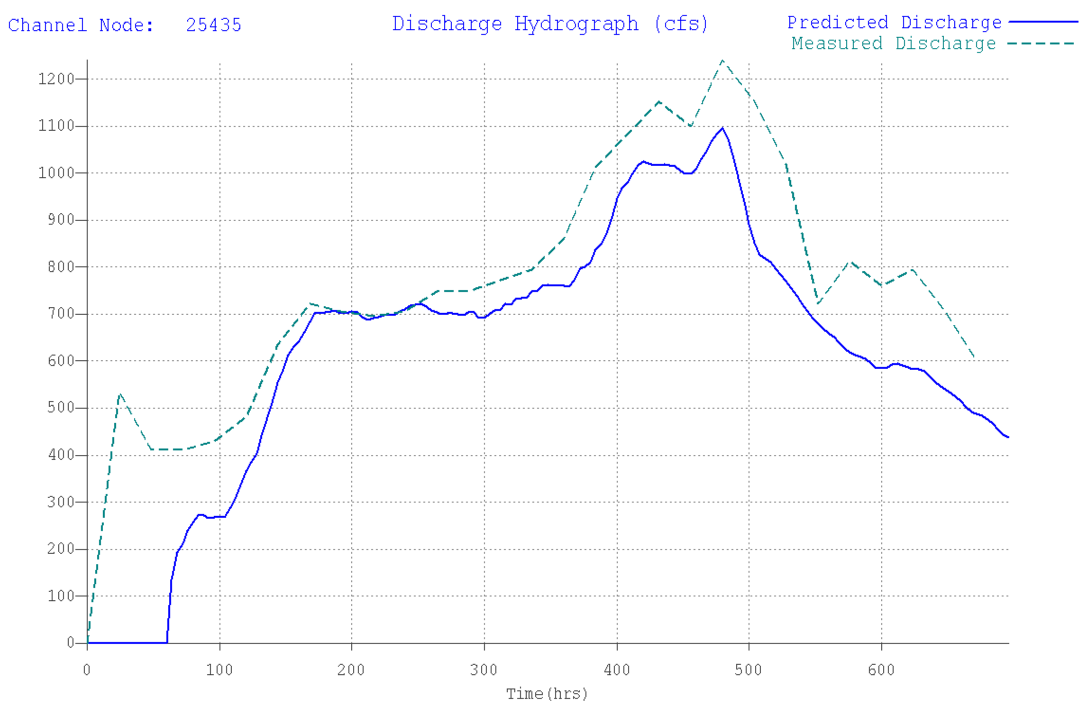


Figure 4.10. Measured and predicted hydrographs during July 1998 at the Mesilla Gage (after Tetra Tech, Inc., 2004).

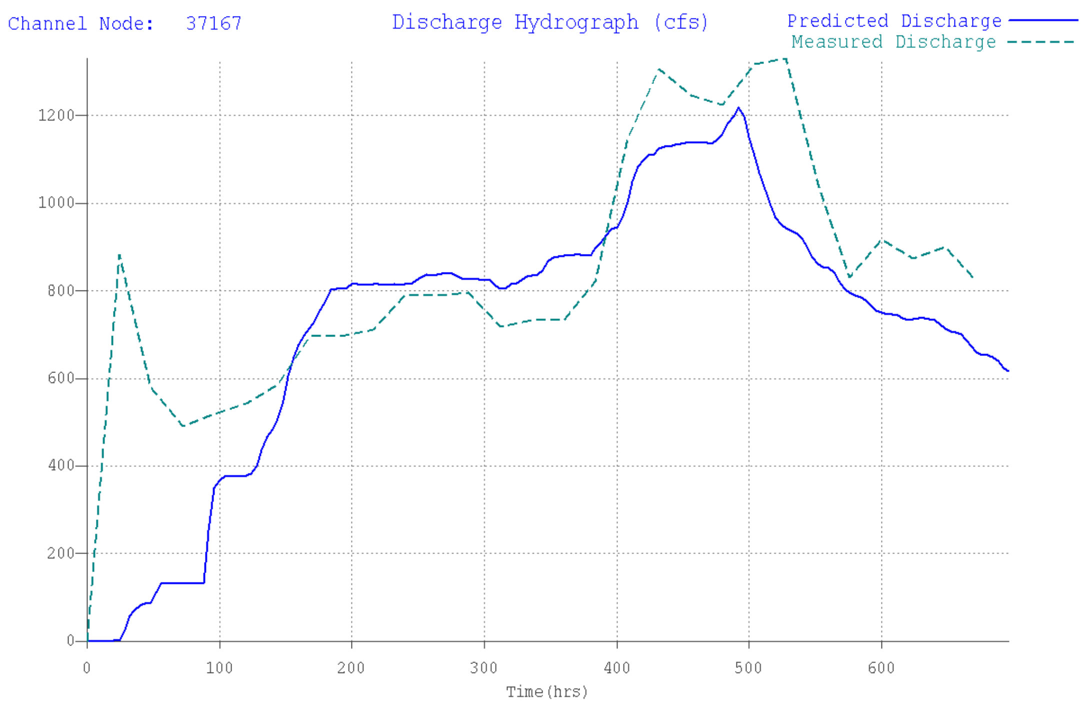


Figure 4.11. Measured and predicted hydrographs during July 1998 at the Canutillo Gage (after Tetra Tech, Inc., 2004).

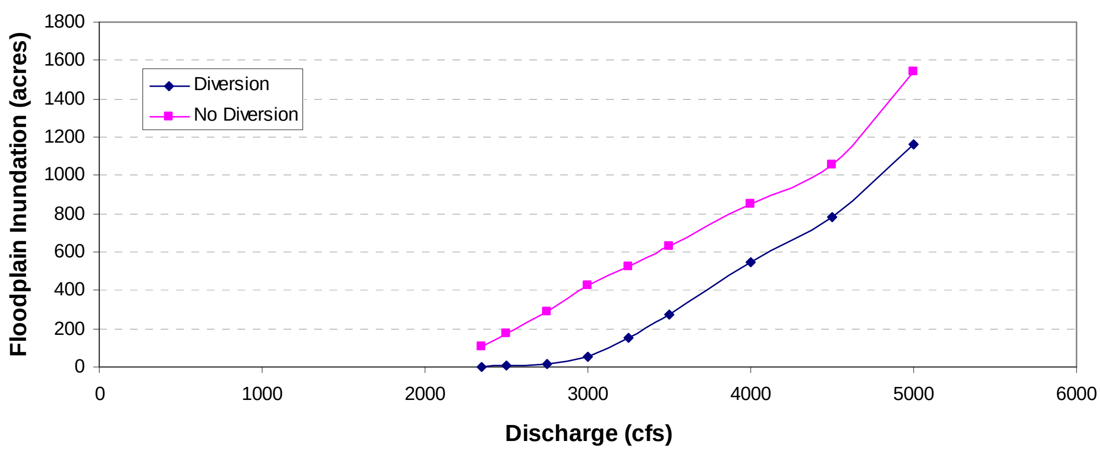


Figure 4.12. Predicted area of inundation for the range of potential restoration flows.

Overbank inundation mapping for restoration flows under diversion and no-diversion simulations are shown in Appendix B. The FLO-2D results for the lower range of discharges from 2,350 cfs to 3,000 cfs showed minimal flooding just north of El Paso and the railroad bridge (Subreach 7). There was very little flooding in Subreaches 4, 5 and 6 (Mesilla to Leasburg) and no flooding north of Leasburg (Subreach 3). For the mid-range of steady flows from 3,250 to 3,750 cfs, increased flooding was indicated in the El Paso reach (Subreach 7) while limited overbank flow occurs in Subreaches 1 through 6. For discharges greater than 4,000 cfs, flooding was predicted at locations throughout the entire RGCP reach, with the reach from Las Cruces to El Paso experiencing the most flooding (Subreaches 5 through 7), the reach from Leasburg to Las Cruces (Subreach 4) having moderate flooding and the subreach from Caballo to Leasburg showing minimal flooding (Subreaches 1, 2 and 3). This pattern was consistent for all of the higher flows. Flooding was most significant for the 5,000-cfs discharge for both diversion and no- diversion simulations. Little difference is indicated between the diversion and no-diversion flooding simulations at 4,500 and 5,000 cfs.

4.3.2. Reach-averaged Hydraulic Conditions

To evaluate the channel hydraulic characteristics over a broad range of flows and to provide input to the sediment-transport calculations, a stepped hydrograph under no-diversion conditions was simulated using the FLO-2D model for a range of flows from 10 to 6,000 cfs, with the discharge increasing in 250 cfs increments up to 3,000 and 500 cfs increments from 3,000 to 6,000 cfs. The step lengths of 120 hours were used to allow the model to reach steady-state conditions during each discharge period. This range of discharges encompasses the range of flow observed in the flow-duration curves.

To facilitate the sediment continuity analysis that is discussed in the next chapter, the one-dimensional hydraulic results for the main channel (e.g., flow velocity, depth, topwidth, and energy slope) were taken from the model output for the stepped hydrograph and used to develop reach-averaged hydraulic conditions for each of the identified subreaches (**Table 4.1**). The seven geomorphic subreaches described in Chapter 2 were further subdivided for purposes of the sediment-continuity and channel-stability analysis to account for the effect of the existing siphons on hydraulic and sediment-transport conditions and to provide reasonable reach lengths (**Figure 4.13**). Results from the analysis indicate that the subreach-averaged main channel hydraulic depth ranges from 2.3 to 3.9 feet at 2,000 cfs, and from about 3.8 to 6.4 feet at 5,000 cfs. The lowest depths occur in the relatively wide and shallow portion of the reach near Las Cruces (Subreach 5), and the largest depths occur in the constricted reach between Percha Dam and Sibley Arroyo (Subreach 1.3). Little variability in average main channel velocity occurs among the subreaches, with values ranging from 2.1 to 2.7 fps at 2,000 cfs and from 3.1 and 4.1 fps at 5,000 cfs. Average main channel topwidths range from about 150 to 300 feet at 2,000 cfs, and from about 180 to 330 feet at 5,000 cfs. Average main channel top widths generally increase with increasing drainage area upstream from Las Cruces (Subreaches 1 through 5), with the most narrow topwidths occurring in the incised areas of Subreach 1.2 and the largest topwidths occurring in Subreach 5, likely due to historic bank erosion associated with aggradation upstream from Mesilla Dam. Downstream from Mesilla Dam, channel topwidth tends to be somewhat narrower.

Table 4.1. Subreach-averaged hydraulic conditions in the project reach.

Subreach	Discharge (cfs)					
	500	1,000	2,000	3,000	4,000	5,000
Velocity (ft/s)						
1.1	1.3	1.6	2.1	2.6	3.0	3.3
1.2	1.5	1.9	2.8	3.2	3.7	4.0
1.3	1.5	1.9	2.8	3.2	3.7	4.1
2.1	1.1	1.4	2.1	2.4	2.8	3.1
2.2	1.3	1.5	2.1	2.4	2.8	3.1
2.3	1.3	1.6	2.4	2.8	3.2	3.6
3	1.4	1.7	2.6	2.9	3.4	3.7
4	1.4	1.7	2.5	2.9	3.3	3.6
5	1.2	1.5	2.2	2.5	2.9	3.2
6	1.5	1.9	2.7	3.1	3.5	3.8
7.1	1.4	1.8	2.6	2.9	3.3	3.5
7.2	1.4	1.7	2.6	2.9	3.4	3.7
7.3	1.3	1.6	2.4	2.7	3.1	3.5
Hydraulic Depth (ft)						
1.1	2.3	3.3	5.0	5.6	6.5	7.2
1.2	2.0	2.6	4.2	4.9	5.7	6.4
1.3	1.6	2.2	3.7	4.4	5.2	5.9
2.1	1.4	1.9	3.1	3.7	4.4	5.0
2.2	1.6	2.0	3.1	3.7	4.4	5.0
2.3	1.3	1.7	2.9	3.5	4.2	4.8
3	1.5	2.0	3.3	3.9	4.6	5.2
4	1.2	1.6	2.7	3.2	3.8	4.3
5	1.0	1.4	2.3	2.8	3.3	3.8
6	1.3	1.7	2.8	3.3	3.9	4.3
7.1	1.3	1.8	2.9	3.3	3.8	4.2
7.2	1.3	1.8	2.8	3.3	3.9	4.4
7.3	1.4	1.9	2.9	3.5	4.2	4.8
Top Width Channel (ft)						
1.1	130	143	166	173	181	188
1.2	131	139	151	157	168	175
1.3	157	162	170	174	178	183
2.1	237	247	266	273	279	284
2.2	186	224	269	276	282	288
2.3	216	236	247	250	255	260
3	172	187	203	211	222	231
4	221	236	251	258	267	277
5	260	282	304	313	325	334
6	180	195	225	238	252	272
7.1	178	198	226	249	275	305
7.2	192	204	234	253	262	264
7.3	181	202	238	250	255	255
Energy Slope (ft/ft)						
1.1	0.00026	0.00023	0.00024	0.00031	0.00034	0.00036
1.2	0.00042	0.00044	0.00050	0.00053	0.00057	0.00059
1.3	0.00048	0.00049	0.00055	0.00057	0.00060	0.00063
2.1	0.00033	0.00035	0.00041	0.00043	0.00046	0.00048
2.2	0.00040	0.00039	0.00044	0.00046	0.00048	0.00050
2.3	0.00056	0.00058	0.00063	0.00066	0.00070	0.00073
3	0.00051	0.00052	0.00058	0.00061	0.00064	0.00067
4	0.00060	0.00060	0.00066	0.00069	0.00072	0.00075
5	0.00053	0.00053	0.00058	0.00061	0.00064	0.00066
6	0.00053	0.00054	0.00059	0.00061	0.00064	0.00068
7.1	0.00052	0.00053	0.00058	0.00062	0.00065	0.00067
7.2	0.00046	0.00048	0.00057	0.00060	0.00062	0.00065
7.3	0.00041	0.00042	0.00048	0.00049	0.00051	0.00052

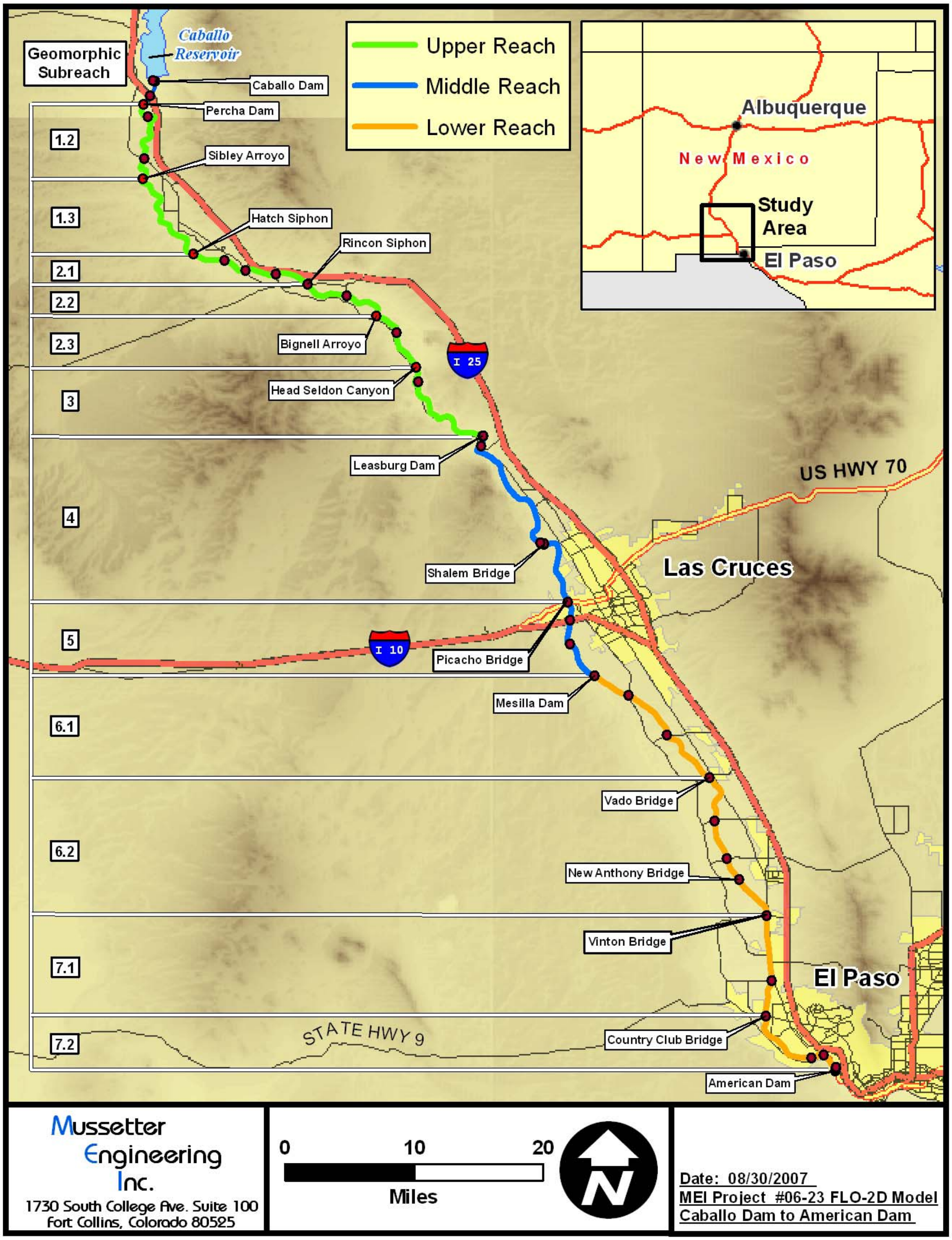


Figure 4.13. Map of the project reach showing the subreaches used in the sediment-continuity and channel-stability analysis.

5. SEDIMENT-CONTINUITY ANALYSIS

A baseline sediment-continuity analysis was performed to evaluate the potential for aggradation or degradation with the present channel configuration and reservoir operations. In general, the analysis was conducted by estimating the annual bed-material transport capacity of each consecutive subreach, and comparing the resulting transport capacity with the supply from the upstream river and tributaries within the reach. The transport capacity was estimated by developing bed-material transport capacity rating curves for each subreach using Yang's (Sand) sediment-transport equation (Yang, 1973) and integrating the rating curves over the applicable mean daily flow-duration curves to obtain a transported volume. Where the transport capacity of a particular subreach exceeds the supply, the channel will respond by either degrading (i.e., channel downcutting) or coarsening its bed material, and where the supply exceeds the capacity, the channel will respond by aggrading or fining its bed material. It should be noted, however, that significant amounts of downcutting or aggradation can also lead to lateral instability. No sediment supply was provided to the head of the study reach due to the trapping of sediment in Caballo Reservoir.

5.1. Subreach-averaged Hydraulics

The transport capacity estimates were made based on the subreach-averaged hydraulic conditions for Subreaches 1.1 through 7.3, as discussed in Chapter 4.3.2 (Table 4.1).

5.2. Representative Bed-material Gradations

The available bed material data (Table 2.3) were used to develop representative bed material gradations for use in the analysis. The representative gradation for Subreaches 1.1 to 1.3 was developed by averaging Pebble Counts 1 through 3. The resulting gradation has a D_{50} and D_{84} of 51 and 85 mm, respectively (**Figure 5.1**). Due to the similarity in bed material characteristics, a single representative gradation was developed for the remainder of the study reach (i.e., Subreaches 2.1 through 7.2) by averaging the 7 MEI bulk samples (S-5 to S-11), two Tetra Tech samples (MD-11, MD-42), and two RTI Samples (Loc-5 and Loc-10). This gradation has a D_{50} and D_{84} of 0.36 and 1.48 mm, respectively (Figure 2.6).

5.3. Flow-duration Curves

Mean daily flow duration curves were developed for each of the subreaches based on the hydrology analysis presented in Chapter 3. For the sediment transport analysis, the mean daily flow-duration curves for all the subreaches were based on the 32-year period of record from WY1975 to WY2006 (Figure 3.9).

5.4. Incipient-motion Analysis

An incipient-motion analysis was performed to evaluate the range of flows required to move the relatively coarse bed material in Subreaches 1.2 and 1.3. The analysis was performed by comparing the effective shear stress on the channel bed with the shear stress that is required to move the surface particles. The shear stress required for bed mobilization was estimated from the Shields (1936) relation, given by:

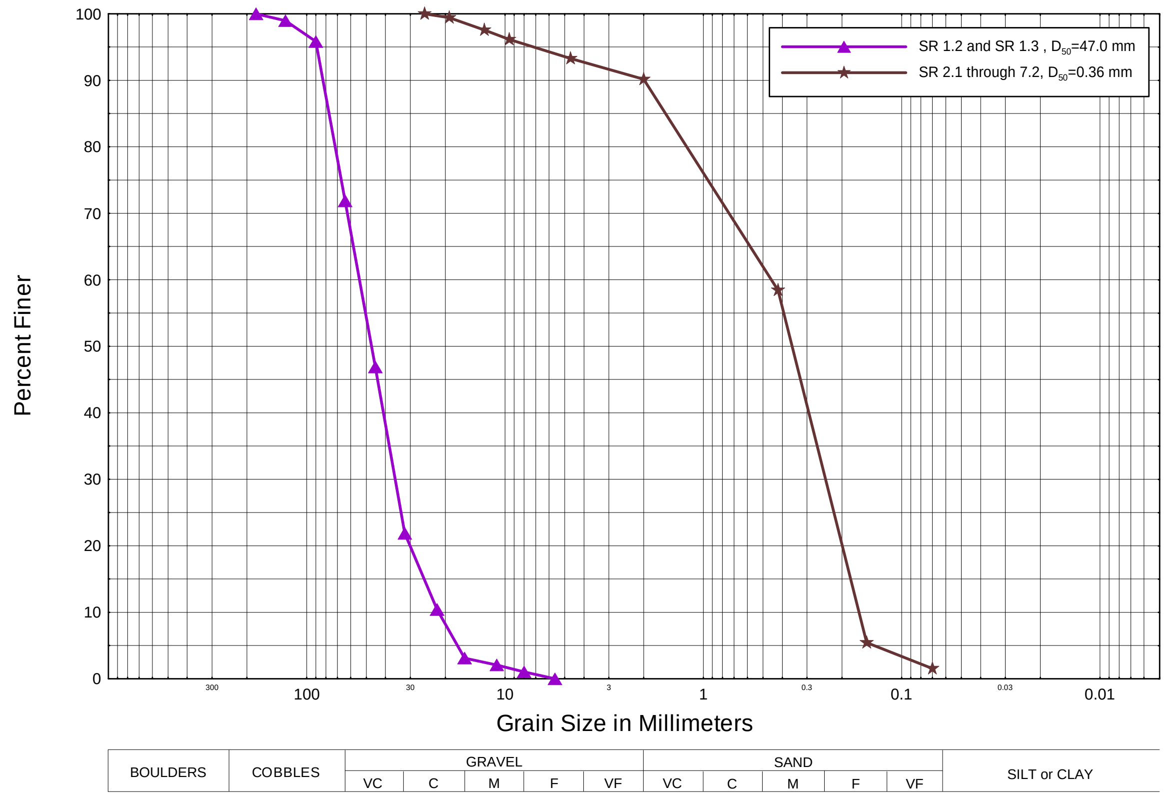


Figure 5.1. Representative bed-material gradation curves for the subreaches used in the sediment-continuity analysis.

$$\tau_c = \tau_{*c}(\gamma_s - \gamma)D_{50} \tag{5.1}$$

where τ_c = critical shear stress for particle motion,
τ_{*c} = dimensionless critical shear stress (often referred to as the Shields parameter),
γ_s = unit weight of sediment (~165 lb/ft^3),
γ = unit weight of water (62.4 lb/ft^3), and
D_{50} = median particle size of the bed material.

In gravel-bed streams, when the critical shear stress for the median particle size is exceeded, the bed is mobilized and all sizes up to about 5 times the median size can be transported by the flow (Parker et al., 1982; Andrews, 1984).

Reported values for the Shields parameter range from 0.03 (Neill, 1968; Andrews, 1984) to 0.06 (Shields, 1936). A value of 0.047 is commonly used in engineering practice, based on the point at which the Meyer-Peter, Müller (MPM) bed-load equation indicates no transport (MPM, 1948). More recent evaluations of the MPM data and other data (Parker et al., 1982; Andrews, 1984) indicates that true incipient motion occurs at a value of about 0.03 in gravel- and cobble-bed streams. Neill (1968) concluded that a dimensionless shear value of 0.03 corresponds to true incipient motion of the bed-material matrix while 0.047 corresponds to a low, but measurable transport rate. A value of 0.03 was used in this analysis.

In performing an incipient-motion analysis, the bed shear stress due to grain resistance (τ') is used rather than the total shear stress, because it is a better descriptor of the near-bed hydraulic conditions that are responsible for sediment movement. The grain shear stress is computed from the following relation:

$$\tau' = \gamma Y' S \tag{5.2}$$

where Y' = the portion of the total hydraulic stress associated with grain resistance (Einstein, 1950), and
S = the energy slope at the cross section.

The value of Y' is computed by iteratively solving the semi-logarithmic velocity profile equation:

$$\frac{V}{V_*'} = 6.25 + 5.75 \log \frac{Y'}{K_S} \tag{5.3}$$

where V = mean velocity at the cross section,
K_s = characteristic roughness of the bed, and
V_*' = shear velocity due to grain resistance given by:

$$V_*' = \sqrt{gY'S} \tag{5.4}$$

The characteristic roughness height of the bed (K_s) was assumed to be 3.5 D_{84} (Hey, 1979). Normalized grain shear stress (ϕ') is the ratio of the grain shear stress (τ') to the critical shear stress for particle mobilization (τ_c). When ϕ' is equal to 1 the bed material begins to mobilize (point of incipient motion), and substantial sediment transport occurs when $\phi'>1.5$ (Mussetter et al., 2001). The concept of equi-mobility, as advanced by Parker and Andrews (Parker et al., 1982; Andrews, 1984), shows that at $\phi'>1.5$ all material up to about 5 times the median size can be transported by the flow.

The incipient motion analysis was conducted using the subreach-averaged hydraulics for the range of flows from 10 cfs to 6,000 cfs, and the representative bed material gradation that has a median grain size of 51.7 mm (Figure 5.1). The analysis indicates that the coarse surface layer in Subreaches 1.2 and 1.3 between Percha Dam and the Hatch Siphon is generally immobile over the range of flows that could reasonably occur in the reach (**Figure 5.2**).

5.5. Sediment-transport Capacity

To compute annual bed-material transport volumes, sediment-transport capacity rating curves were developed for each of the subreaches using the subreach-averaged hydraulics, the representative subreach bed-material gradations, and appropriate sediment-transport formulae. The sediment-rating curves were also used with the flow-duration data to estimate the effective (channel forming) discharge (Biedenharn et al., 2001).

5.5.1. Selection of Sediment-Transport Formulae

The sediment-transport formulae used to compute the bed-material transport capacity sediment rating curves for the individual subreaches were selected based on the range of bed material sizes, hydraulic characteristics within the study reach, and previous experience with similar channels.

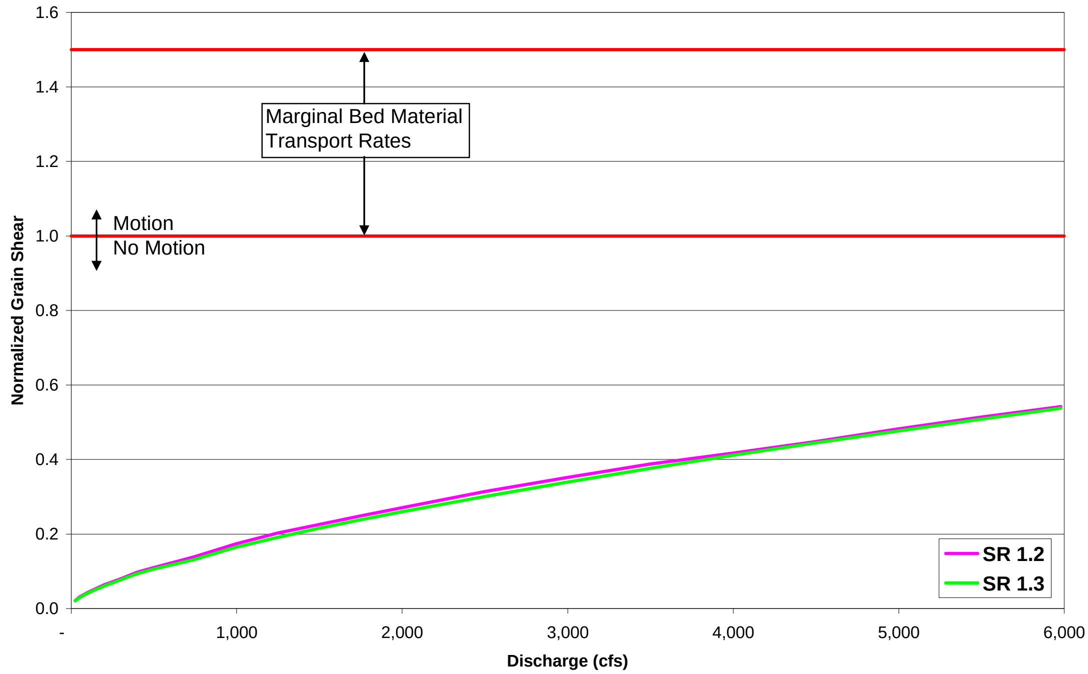


Figure 5.2. Variation in normalized grain shear stress with discharge in Subreaches 1.2 and 1.3.

As discussed above, the incipient motion analysis indicated that no significant sediment transport occurs at discharges less than 6,000 cfs in Subreach 1. As a result, no sediment-transport calculations were conducted for these subreaches.

Measured bed-material transport data are not available for the study reach. In a previous study for the URGWOPS EIS, MEI (2004) evaluated a range of possible transport equations that were developed for conditions similar to those in the project reach, and determined that the Yang (sand) equation (Yang, 1973) produced results that were the most consistent with the available measured data at the Rio Grande gages between Cochiti Dam and Elephant Butte Reservoir. Based on this conclusion and the general similarity of conditions, the Yang (Sand) sediment-transport equation was also selected for use in estimating the sediment-transport rating curves for Subreaches 2 through 7 of the present study reach.

The Yang (sand) equation relates the concentration of the bed material discharge to the rate of energy dissipation in the flow using dimensional analysis and the unit stream power concept. The basic form of Yang's equation is:

$$log\ C_S = M + N\ log\ \frac{VS}{\omega} \tag{5.5}$$

where C_s = total bed material concentration in ppm
V = flow velocity
S = slope
ω = fall velocity of sediment
M, N = dimensionless parameters related to the flow

The values of M and N were determined by regression analysis of field and laboratory data with particles sizes (d_s) ranging from 0.9 to 7.01 mm, water depths ranging from 0.037 to 49.9 feet , and water-surface slopes ranging from 0.000043 to 0.0031.

The dimensionless relationships for total sediment concentration are:

$$\log C_S = 5.435 \quad 0.286 \log \frac{\omega d_S}{v} \quad 0.457 \log \frac{V_*}{\omega} + \quad 1.799 \quad 0.409 \log \frac{\omega d_S}{v} \quad 0.314 \log \frac{V_*}{\omega} \quad * \log \quad \frac{VS}{\omega} \quad \frac{VcS}{\omega} \tag{5.6}$$

where ν = kinematic viscosity
V_* = shear velocity given by:

$$V_* = \sqrt{gRS} \tag{5.7}$$

where g = acceleration due to gravity
R = hydraulic depth of the main channel

In the above equations, the dimensionless critical velocity (V_c) is given by:

$$\frac{Vc}{\omega} = \frac{2.5}{\log\left(\frac{V_* d_s}{\nu}\right) - 0.06} + 0.66 \qquad \text{for } 1.2 < \frac{V_* d_S}{v} < 70 \tag{5.8}$$

and

$$\frac{Vc}{\omega} = 2.5 \qquad \text{for } \frac{V_* d_s}{\nu} \geq 70 \tag{5.9}$$

The sand equation is applicable for sizes up to 2 mm.

5.5.2. Sediment Transport Capacity Rating Curves

Subreach-averaged hydraulic data and the representative subreach gradations were used as input to the Yang equation to develop sediment-transport capacity rating curves for Subreaches 2.1 through 7.2 (**Figure 5.3**). The resulting rating curves indicate that Subreach 2.1 has the lowest transport capacity and Subreach 6.2 typically has the highest transport capacity over the range of flows that were evaluated. Since the same representative sediment gradation was applied to the entire reach, the sediment-transport rates reflect differences in the reach-averaged hydraulic conditions. Generally, low transport rates occur in the subreaches where the channel is wider, the velocities are lower and the gradients are flatter.

5.6. Tributary Bed-material Contributions

Tributary bed-material contributions along the project reach were estimated from results of a tributary sediment yield analysis conducted by Tetra Tech (2004). In performing their analysis, Tetra Tech (2004) re-evaluated a previous study performed by Resource Technology, Inc (RTI) in 1996 for the Corps of Engineers in which they quantified the sediment yield from twenty major arroyo basins between Percha Diversion Dam and American Diversion Dam and used the results to develop predictive equations for a range of flood-frequency recurrence intervals to estimate the sediment loading from the remaining tributary basins in the 922-square mile watershed.

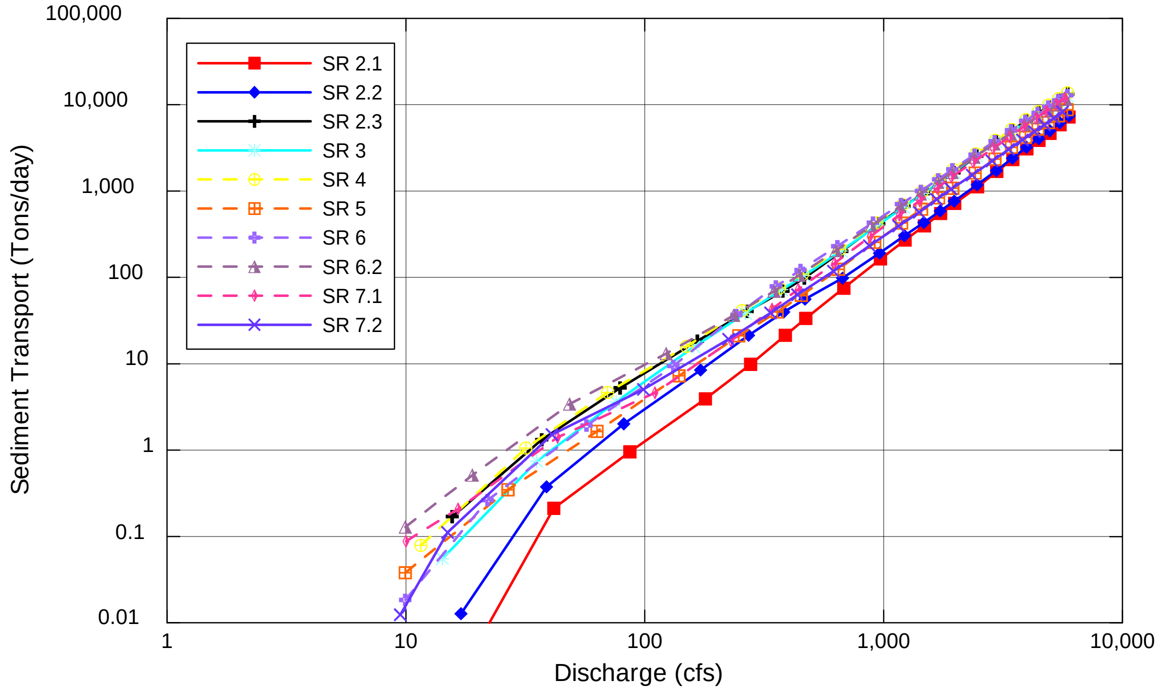


Figure 5.3. Sediment-transport rating curves for Subreaches 2.1 through 7.2.

Tetra Tech (2004) concluded that the RTI (1996) analysis overestimated the average annual sediment load and recomputed the average annual total sediment yield to the study reach by making appropriate adjustments to the RTI (1996) results. Review of the available aerial photography and topography indicated that several drainage basins listed in the Tetra Tech (2004) and RTI (1996) reports are not directly connected, and therefore, do not contribute to the sediment supply to the river. These tributaries were not included in the present analysis. A summary of the mean annual total sediment load to the RGCP reach from the remaining tributaries is provided in **Table 5.1**.

The total sediment yield estimates in Table 5.1 include both the fine sediment (i.e., wash) load and the bed material load (i.e., sand and coarser sediment). Because the fine sediment (i.e. wash) load does not contribute substantially to the aggradation/degradation and lateral erosion behavior of the mainstem, it was necessary to estimate the component of the total sediment yield that is made up of bed material-sized sediment. Because of the manner in which they adjusted the RTI (1996) results, Tetra Tech (2004) did not provide information on the relative amount of bed material load in the total load. RTI (1996) does provide information on the relative amount of bed material load, but because of the flaws in the analysis that were identified by Tetra Tech (2004), these results are not believed to be reliable. Previous analyses by MEI (2004 and 2007) of tributaries in the San Acacia Reach upstream from Elephant Butte Reservoir and the Rectification Reach downstream from El Paso indicate that the amount of bed material in the total load varies significantly depending on the specific characteristics of the individual tributary, but the overall average for the tributaries from those studies is about 35 percent on an average annual basis. Based on this information, the bed material component of the annual total sediment yield from the tributaries to the RGCP was assumed to also be 35 percent.

Table 5.1. Summary of mean annual tributary total sediment yield and mean annual tributary bed-material yield (Modified from Tetra Tech, 2004).

Subreach	Watershed Name	Station (ft)	Basin Drainage Area (mi^2)	Mean Annual Sediment Yield (ac-ft)	Mean Annual Sediment Yield per Unit Area ($af/mi^2/yr$)	Mean Annual Bed-Material Yield (ac-ft)[1]
1.2	Trujillo Canyon	544,233	52.90	14.70	0.28	5.15
1.2	Montoya Arroyo	536,802	23.00	6.93	0.30	2.43
1.2	Holguin Arroyo (Misc 2)	532,192	2.20	1.29	0.59	0.45
1.2	Tierra Blanca Creek	527,819	68.20	18.95	0.28	6.63
1.2	Green Canyon	527,650	35.60	10.13	0.28	3.55
1.3	Sibley Arroyo	519,017	27.20	7.99	0.29	2.80
1.3	Berrenda Creek	511,366	87.40	24.54	0.28	8.59
1.3	Jaralosa Arroyo	511,366	6.80	2.76	0.41	0.97
1.3	Yeso Arroyo (Misc 3?)	496,887	9.50	3.49	0.37	1.22
1.3	Arroyo Cuervo	489,213	126.20	36.69	0.29	12.84
2.1	Misc. 4	452,650	14.50	4.79	0.33	1.68
2.1	Placitas Arroyo	448,310	34.60	9.87	0.29	3.45
2.1	Misc. 5	433,290	11.80	4.10	0.35	1.44
2.2	Angostura Arroyo	423,313	8.90	3.33	0.37	1.17
2.2	Rincon Arroyo	415,461	124.70	36.20	0.29	12.67
2.2	Reed Arroyo	412,627	9.60	3.52	0.37	1.23
3	Misc 6 (includes Bignell Arroyo)	359,161	43.50	12.19	0.28	4.27
3	Lytten Canyon	358,944	0.96	0.74	0.77	0.26
3	Buckle Bar Canyon	355,816	2.12	1.26	0.59	0.44
3	Foster Canyon	338,815	11.00	3.89	0.35	1.36
3	Faulkner Canyon	334,082	25.00	7.43	0.30	2.60
3	Misc.7	329,750	10.38	3.73	0.36	1.31
4	Subarea 15	308,124	3.40	1.72	0.51	0.60
4	Subarea 16	295,082	3.80	1.86	0.49	0.65
4	Subarea 17	285,835	4.92	2.21	0.45	0.77
4	Subarea 18	283,730	2.80	1.51	0.54	0.53
4	Subarea 19	277,203	2.60	1.44	0.55	0.50
4	Subarea 20	272,356	3.00	1.58	0.53	0.55
5	Subarea 23	212,732	0.87	0.69	0.79	0.24
6.1	Subarea 24	207,767	4.20	1.98	0.47	0.69
7.1	Subarea 101	84,790	2.90	1.55	0.53	0.54
7.1	Subarea 102	82,317	6.53	2.68	0.41	0.94
7.1	Subarea 103	80,697	5.35	2.34	0.44	0.82
7.1	Subarea 104	77,585	3.54	1.77	0.50	0.62
7.1	Subarea 105	75,289	0.98	0.75	0.77	0.26
7.1	Subarea 106A	67,181	1.95	1.19	0.61	0.42
7.1	Subarea 106B	67,181	7.40	2.92	0.39	1.02
7.1	Subarea 106C	67,181	8.15	3.13	0.38	1.10
7.2	Subarea 207	27,957	1.50	1.00	0.67	0.35
7.2	Subarea 206	23,786	0.60	0.53	0.88	0.19

[1]35 percent of total sediment yield.

5.7. Effective Discharge

The concept of effective discharge, as advanced by Wolman and Miller (1960), related the frequency and magnitude of various discharges to their ability to do geomorphic work by transporting sediment. They concluded that events of moderate magnitude and frequency transported the most sediment over the long-term, and that these flows were the most effective in forming and maintaining the planform and geometry of the channel. Andrews (1980) defined the effective discharge as "*the increment of discharge that transports the largest fraction of the annual sediment load over a period of years.*"

Alluvial rivers adjust their shape in response to flows that transport sediment, and numerous authors have attempted to relate the effective discharge to the concepts of dominant discharge, channel-forming discharge and bankfull discharge, and it is often assumed that these discharges are roughly equivalent and correspond to approximately the mean annual flood peak (Benson and Thomas, 1966; Pickup, 1976; Pickup and Werner, 1976; Andrews, 1980, 1986; Nolan et al., 1987; Andrews and Nankervis, 1995). Quantification of the range of flows that transport the most sediment provides useful information to assess the current state of adjustment of the channel, and to evaluate the potential effects of increased discharge and sediment delivery to channel behavior. Although various investigators have used only the suspended-sediment load and the total sediment load to compute the effective discharge, the bed-material load should generally be used when evaluating the linkage between sediment loads and channel size because it is the bed-material load that has the most influence on the morphology of the channel (Schumm, 1963; Biedenharn et al., 2000).

Following recommendations by Biedenharn et al. (2000), the effective discharge in each subreach was computed by dividing the range of flows into 25 to 30 arithmetic classes and then computing the total quantity of bed-material load transported by the flows within each class. An example of the effective discharge histogram is shown in **Figure 5.4**. The effective discharge was not calculated in Subreach 1 since the incipient motion analysis indicates that the bed material in this subreach is rarely mobilized.

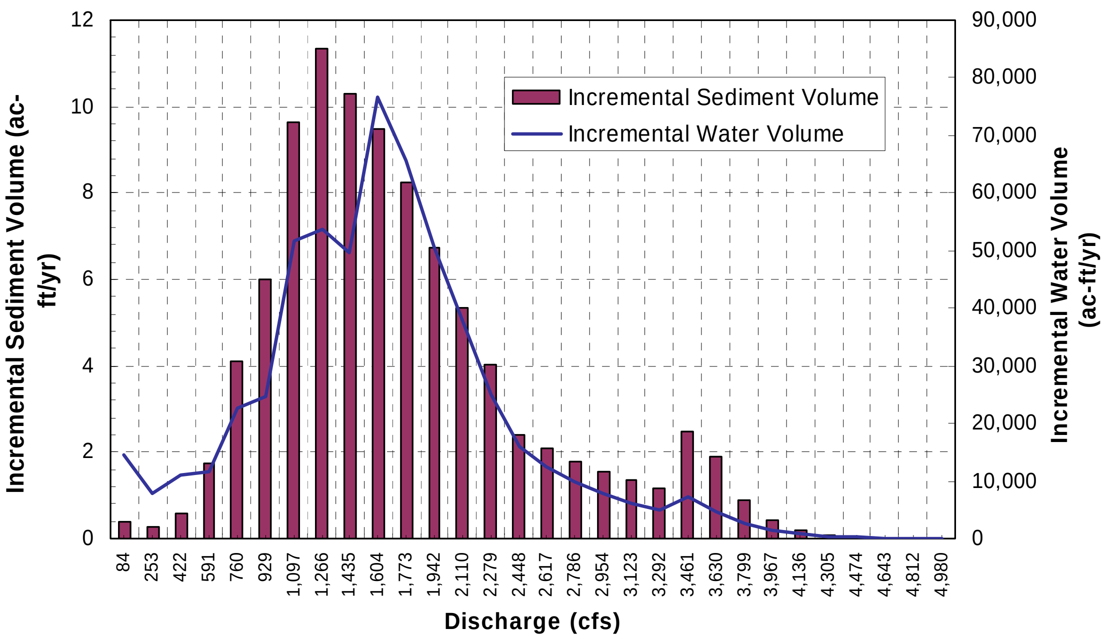


Figure 5.4. Example of effective discharge histogram for Subreach 4 (Leasburg Diversion Dam to Picacho Bridge).

The results of this analysis indicate that the effective discharge is significantly less than the channel capacity throughout the reach, ranging from about 820 cfs (13-percent exceedence on the mean daily flow-duration curve) in Subreaches 6 and 7 to about 1,780 cfs (exceedence percentage of about 17) in Subreaches 2.2, 2.3 and 3 (**Figure 5.5**). The analysis also shows a general trend of decreasing effective discharge in the downstream direction due to the effects of the diversions and other flow losses that occur in the project reach.

5.8. Sediment-Continuity Analysis Results

The long-term aggradation/degradation tendencies along the study reach were evaluated by comparing the average annual bed material load in each subreach with the upstream and tributary supply (**Figure 5.6**). As noted above, the bed-material load in Subreaches 1.2 and 1.3 were assumed to be negligible because the surface bed material is typically not mobilized in the range of flows that could reasonably occur in the reach. It should be noted, however, that the sand-sized sediment delivered from the tributaries would be transported as a veneer over the existing bed material at approximately the same rate at which it is supplied. The average annual bed-material load between Subreaches 2.1 and 7.2 varies between 35 and 106 ac-ft, with an average of 65 ac-ft over the entire study reach (**Figure 5.7**). The highest transport capacities along the RGCP reach typically occur in Subreaches 2.3, 3 and 4 between Bignell Arroyo and the Picacho Bridge due to the relatively steep gradients.

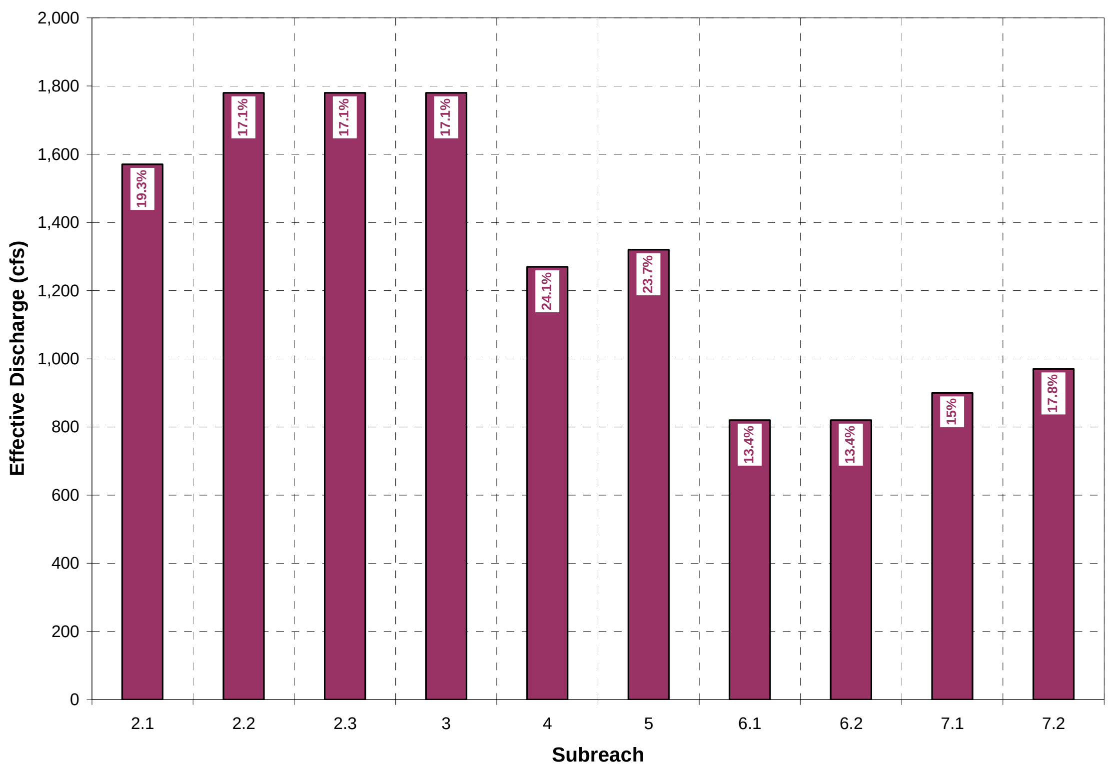


Figure 5.5. Results from the effective discharge analysis. The mean daily flow exceedence percentage associated with the computed effective discharge is also shown.

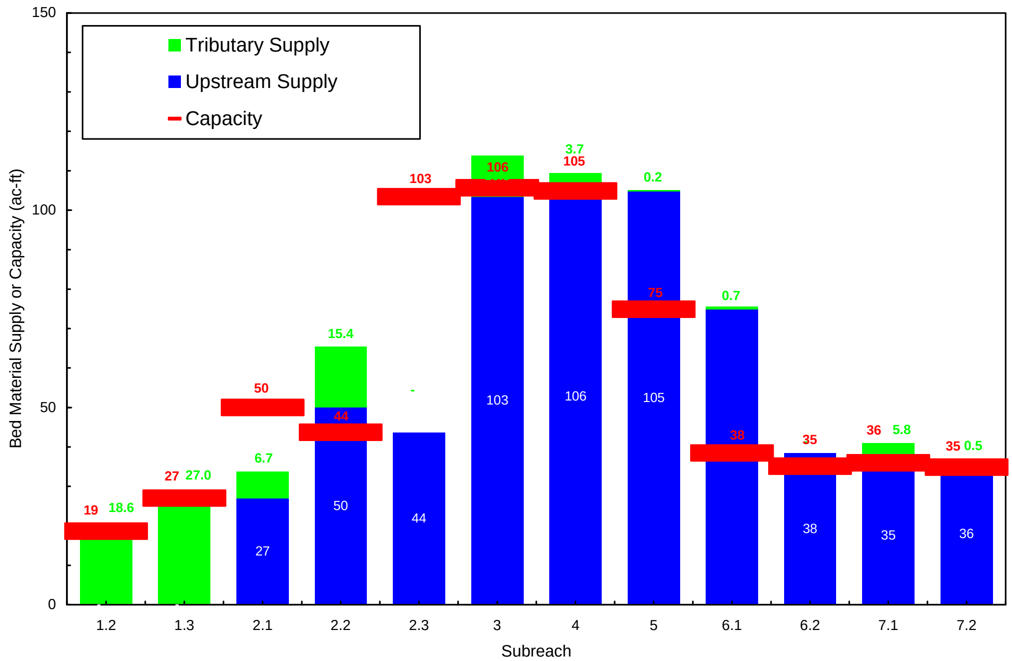


Figure 5.6. Comparison of supply and bed-material transport capacity for each subreach.

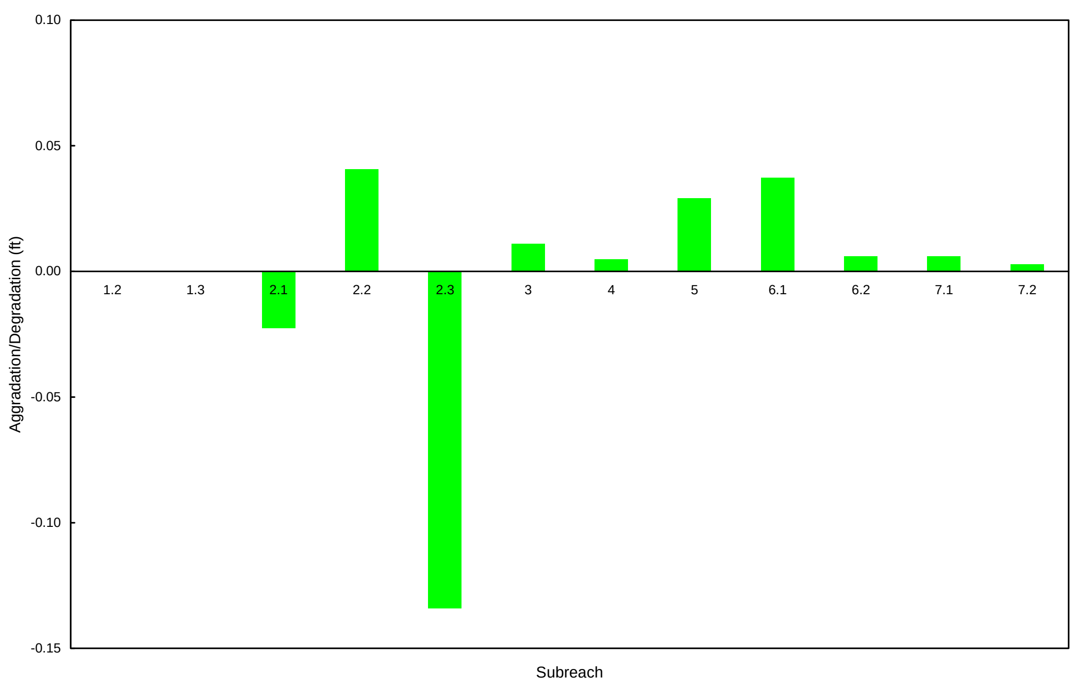


Figure 5.7. Computed aggradation/degradation depths for each subreach for the annual flow-duration curve.

Based on sediment samples collected by RTI (1996) at the mouths of five of the tributaries that deliver sediment to Subreach 1, the sediment derived from these tributaries is typically significantly finer than the bed material in the mainstem (D_{50} ranging from 1.9 mm to 10.4 mm, compared to about 51 mm in the mainstem; **Table 5.2**). The mainstem discharge required to mobilize this material ranges from only about 70 cfs at Jaralosa Arroyo to about 1,540 cfs at Green Canyon. Since discharges in this range occur relatively frequently, most of the sediment entering the channel from these tributaries will be mobilized and transported through Subreach 1, preventing significant, long-term channel aggradation. For purposes of this analysis, it was, therefore, assumed that the transport capacity of Subreaches, 1.2 and 1.3 is the same as the bed material supply from the local tributaries.

Table 5.2. Summary of grain-size parameters of tributary sediment sample and critical discharge to mobilized sediments.

Subreach	Arroyo	D_{50} (mm)	D_{84} (mm)	Critical Discharge (cfs)
1.2	Montoya Arroyo	2.8	12.4	310
1.2	Tierra Blanca Creek	2.2	11.4	210
1.2	Green Canyon	10.4	39.2	1,540
1.3	Sibley Arroyo	4.6	24.9	370
1.3	Jaralosa Arroyo	1.9	16.1	70

The approximate change in bed elevation (i.e., aggradation/degradation potential) associated with the computed differences in volume in the other subreaches was estimated by dividing the difference between bed material supply and capacity of the subreach by the approximate surface area of the channel bed, based on the product of the subreach length and channel topwidth (Tables 3.2 and 4.1). In evaluating this information, it is important to note that the actual changes will not occur uniformly throughout the reach or across the channel at any given location, nor will they continue progressively for a long period of time because the bed material, channel geometry and gradient will adjust to compensate for imbalances between the sediment supply and transport capacity. In spite of this limitation, the analysis provides a reasonable basis for assessing the long-term aggradation/degradation trends along the study reach.

Based on the results of this analysis, Subreach 2.1 is net degradational (about -0.02 feet per year) due to the high transport capacity compared to the upstream sediment supply (34 ac-ft supply versus 50 ac-ft transport capacity) (Figure 5.7). This subreach is located below the Hatch Siphon, where approximately 10 feet of degradation has occurred since completion of the Canalization project in the early-1940s (Figure 2.3). The degradation rate indicated by the continuity analysis is less than the historical rate, which is reasonable since the channel has undergone substantial adjustment during the period and is likely approaching equilibrium with the existing upstream sediment supply. Subreach 2.2 is slightly aggradational (0.04 feet per year), with an average annual sediment-transport capacity of about 44 ac-ft, compared to the combined supply of approximately 65 ac-ft from Subreach 2.1 and local tributaries. The aggradational trend of Subreach 2.2 is consistent with aggradation observed within the subreach. Subreach 2.3 is net degradational (-0.13 feet per year) due to the high sediment-transport capacity (103 ac-ft) and little or no tributary supply to the reach. This subreach is located within the steeper and confined section between Bignell Arroyo and Selden Canyon. Compared to the degradation rates in the other subreaches (e.g. 2.1), it appears that the computed rate in Subreach 2.3 may be unreasonably high. It is possible that the bed material in this relatively inaccessible reach is coarser than the gradation that was used in the analysis, but sufficient data are not available to confirm this. Reaches 3 to 7.2 are approximately in balance with the upstream sediment supply, with a small aggradational trend in Subreaches 5 and 6.1 (0.03 and 0.04 feet per year, respectively). The aggradational trend in Subreaches 5 and 6.1 represent an accumulation of 67 ac-ft of sediment per year over the approximately 20-mile combined length of the two subreaches. This result is also consistent with observed trends in the reach. As discussed in Section 2.6, USIBWC has excavated and removed sediment from this reach on numerous occasions since construction of the Canalization Project.

As previously discussed, the river has likely responded to the sediment imbalance by altering the bed-material gradation (generally coarsening in degradational areas and fining in aggradational areas). As a result these estimates represent an upper limit, and the actual amount of aggradation/degradation that will occur in the future will likely be smaller than is indicated by the results obtained in this analysis.

6. IMPLICATIONS FOR RESTORATION POTENTIAL

From the results of the geomorphic, hydrologic, hydraulic and sediment transport analyses that were conducted to define the baseline conditions in the RGCP, two primary questions related to the habitat restoration potential within the RGCP can be considered:

1. What is the overall habitat restoration potential for the RGCP?
2. Is it necessary to remove sediment from the main channel and tributaries through maintenance dredging activities, and if it is not removed, what are the implications for downstream conveyance of flows and maintenance of the in-channel and channel-margin infrastructure?

6.1. Restoration Potential

Measures to meet some of the habitat improvement objectives were previously identified at 20 locations within the RGCP (Table 2-9, USIBWC, 2004). These measures included native vegetation plantings, bank shave-downs for riparian vegetation, opening up of former meanders and modifications of dredging practices at the mouths of the tributary arroyos. The FLO-2D model results were used to assess the flow levels that would be required for overbank inundation along the entire reach, including the previously identified sites. As described in Chapter 4 and Appendix B, under existing conditions, the amount of area inundated over the entire reach ranges from negligible at Caballo releases up to about 3,000 cfs and increasing linearly to about 1,200 acres at 5,000 cfs, if water is being diverted at the typical rates. With no diversion operating, the amount of inundation increases from about 100 ac at 2,350 cfs to nearly 1,600 acres at 5,000 cfs. Most of the modeled inundation under these scenarios occurs in the downstream portion of the RGCP.

To provide a preliminary basis for assessing the feasibility of restoring riparian and overbank habitat at the 20 previously identified sites, water-surface profiles over a range of flows from 1,500 cfs to 5,000 cfs were compared with the overbank profiles. For purposes of presenting the result, the 20 sites were subdivided into those at which overbank flooding will occur at flows between 3,500 and 5,000 cfs (**Table 6.1**), and those that currently would not experience overbank flooding in this range of flows (**Table 6.2**). Additionally, a review of available groundwater information was conducted to determine whether the water table is sufficiently shallow to support riparian vegetation. Shallow groundwater elevations are controlled by the drain elevations within the Mesilla Valley, and are typically 8 to 10 feet below the existing ground surface at most locations (SSPA, 1987).

Some overbank flows occur at seven of the identified restoration sites (Table 6.1). Bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs (**Figure 6.1**), and mapping of the overbank inundation at a flow of 5,000 cfs (**Figure 6.2**) at the Trujillo Arroyo site show the existing extent and depths of inundation. Additional shave-downs would be required at this site to extend the area and increase the frequency of inundation. Similar figures (**Figures 6.3 and 6.4**) show the water-surface profiles and inundation areas for the Montoya Arroyo site. Additional shave-downs would also be required at the site to open the abandoned meander, extending the area and increasing the frequency of inundation. Overbank inundation is quite extensive at the Holguin Arroyo site (**Figures 6.5 and 6.6)**. At Crow Canyon, some overbank inundation occurs at 5,000 cfs (**Figures 6.7 and 6.8**). Inundation is quite extensive in both the left and right overbanks at the Remnant Bosque site at 5,000 cfs (**Figures 6.9 and 6.10**). Very little overbank flow occurs at 5,000 cfs at the Bignell Arroyo site (**Figures 6.11 and 6.12**). Bank lowering of about 1 foot would be required to provide significant overbank flow at 5,000 cfs at this location. Under existing conditions, very little overbank area is inundated at 5,000 cfs at the Picacho and NMGF sites at RM 41 (**Figures 6.13 and 6.14**). Significant inundation depth and frequency at these locations would require at least 1 foot of excavation of the right overbank area and more than 2 feet of excavation of the left overbank area.

Table 6.1. Point Project Restoration Sites and Measures where some overtopping occurs under baseline conditions (modified from USIBWC, 2004).

Site	Location RM and Station	Point Project Measures	Area (ac)	Overtopping Flow (cfs)
Trujillo Arroyo	103 5441+70	Bank Shave-down (102B)	26.5	5,000
Montoya Arroyo	102 5367+60	Bank Shave-down (102B) Open Former Meander (102C) Native Vegetation Planting (102A)	24.7 2.8 2.8	3,500–5,000
Holguin Arroyo	101 5321+60	Bank Shave-down (101B) Native Vegetation Planting (101A)	12.5 6	3,500–5,000
Crow Canyon	92 4847+00	Bank Shave-down (92B) Open Former Meander (92C)	17.9 84.6	5,000
Remnant Bosque	83 4381+00	Bank Shave-down (83B) Native Vegetation Planting (83A)	17.9 16.2	3,500–5,000
Bignell Arroyo	76 4008+00	Bank Shave-down (76B) Native Vegetation Planting (76A)	16.3 10.3	5,000
Mile 41, Picacho and NMGF	41 2181+00	Native Vegetation Planting (41A)	71.3	5,000

Table 6.2. Point Project Restoration Sites and Measures where no overtopping occurs under baseline conditions (modified from USIBWC, 2004).				
Site	Location RM and Station	Point Project Measures	Area (ac)	Approximate Cut Down to Get Overtopping at 5,000 cfs (ft)
Mile 105 Oxbow Restoration	105 5534+00	Open Former Meander (105C) Native Vegetation Planting (105A)	6.6	3-4
Tipton Arroyo	104 5490+10	Bank Shave-down (104B) Native Vegetation Planting (104A)	3.4 2.52	2-3
Green-Tierra Blanca Arroyo	99 5217+00	Native Vegetation Planting (99A)	5.05	1-2
Sibley Point Bar	98 5113+00	Bank Shave-down (98B)	4.1	2-3
Jaralosa Arroyo	97 5017+00	Open Former Meander (97B)	28	3-4
Jaralosa South	95 5015+00	Open Former Meander (95C) Native Vegetation Planting (95A)	5.1	3-4
Yeso Arroyo	94 4966+00	Bank Shave-down (94B) Native Vegetation Planting (94A)	3.9 11.5	4-5
Mile 54 Channel Cut	54 2858+70	Open Former Meander (54C) Native Vegetation Planting (54A)	19.6	1-2
Miles 49 & 48 Spillways	49/48 2519+70	Native Vegetation Planting (49A)	15.9	1-2
Clark Lateral	42 2238+80	Native Vegetation Planting (42A)	15.4	1-2

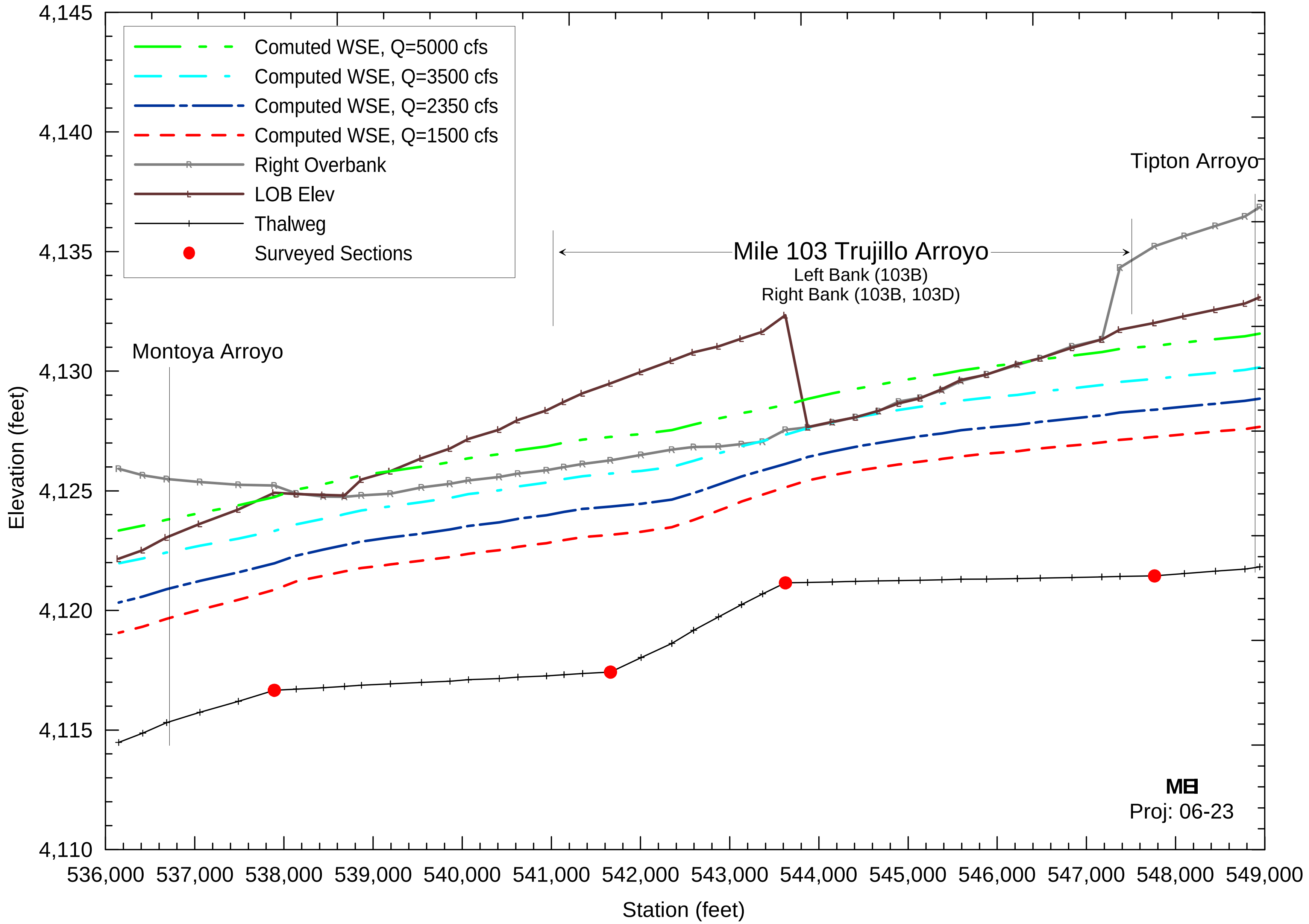


Figure 6.1. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Trujillo Arroyo site.

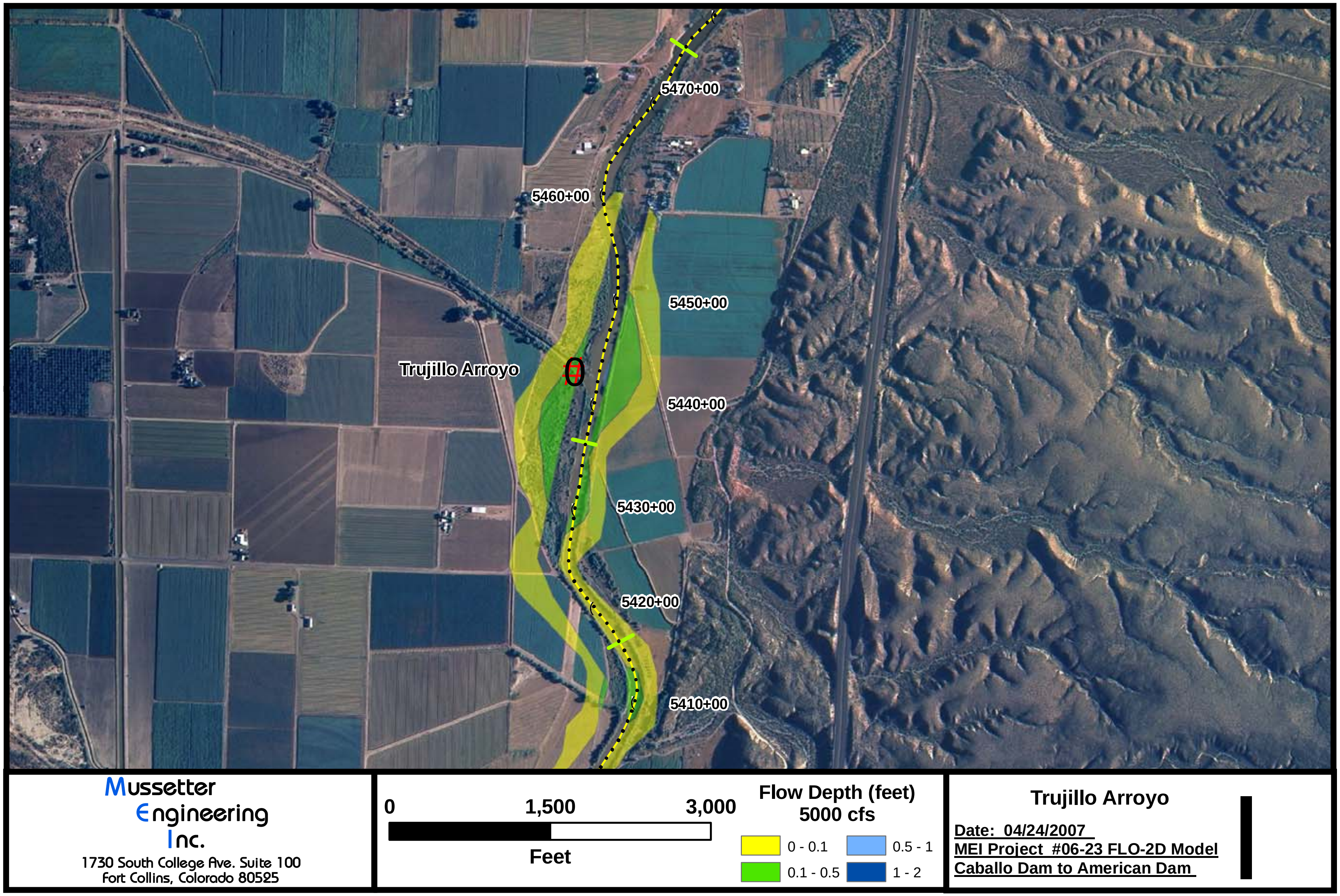


Figure 6.2. Overbank inundation areas at a flow of 5,000 cfs at the Trujillo Arroyo site.

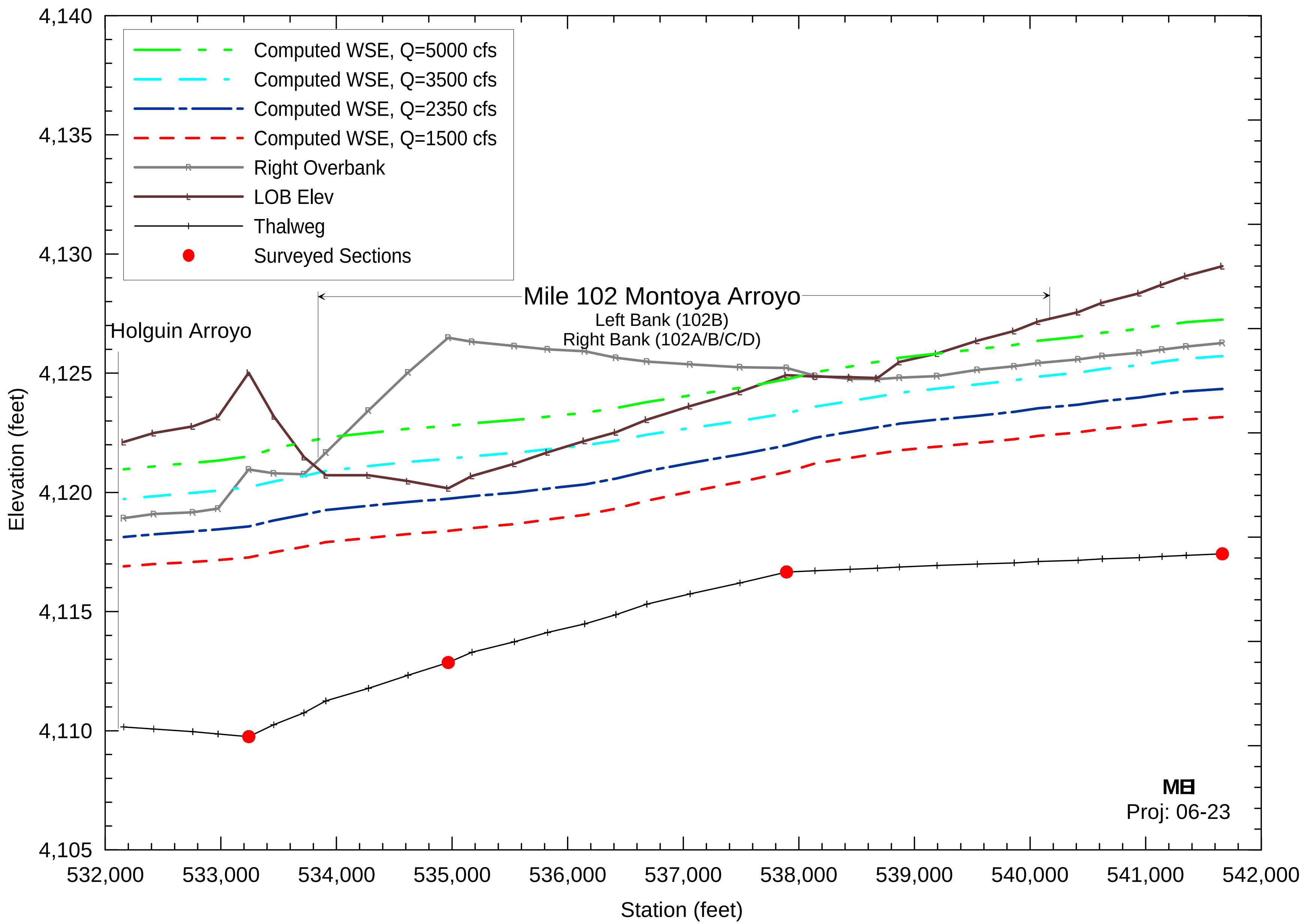


Figure 6.3. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Montoya Arroyo site.

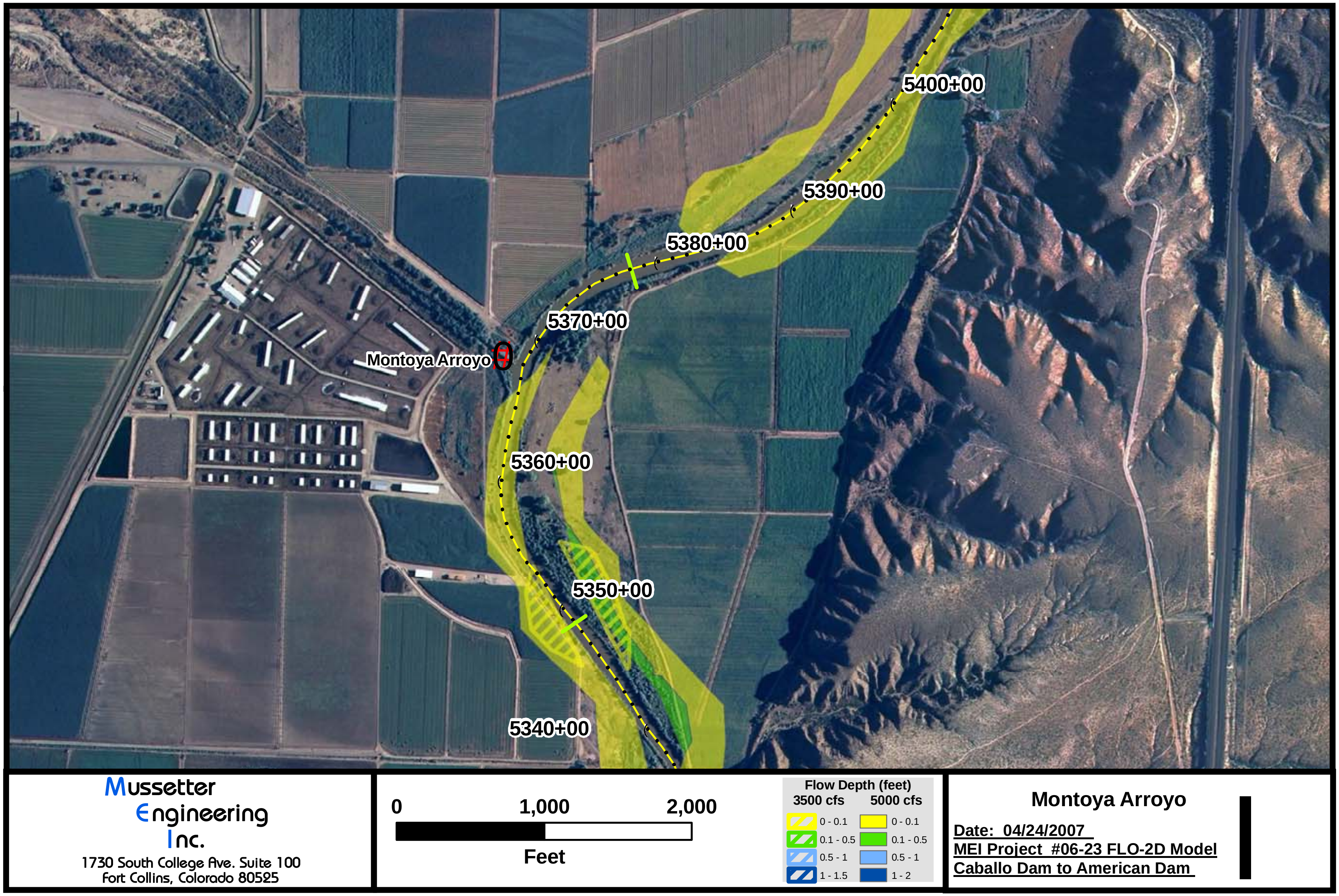


Figure 6.4. Overbank inundation areas at flows of 3,500 and 5,000 cfs at the Montoya Arroyo site.

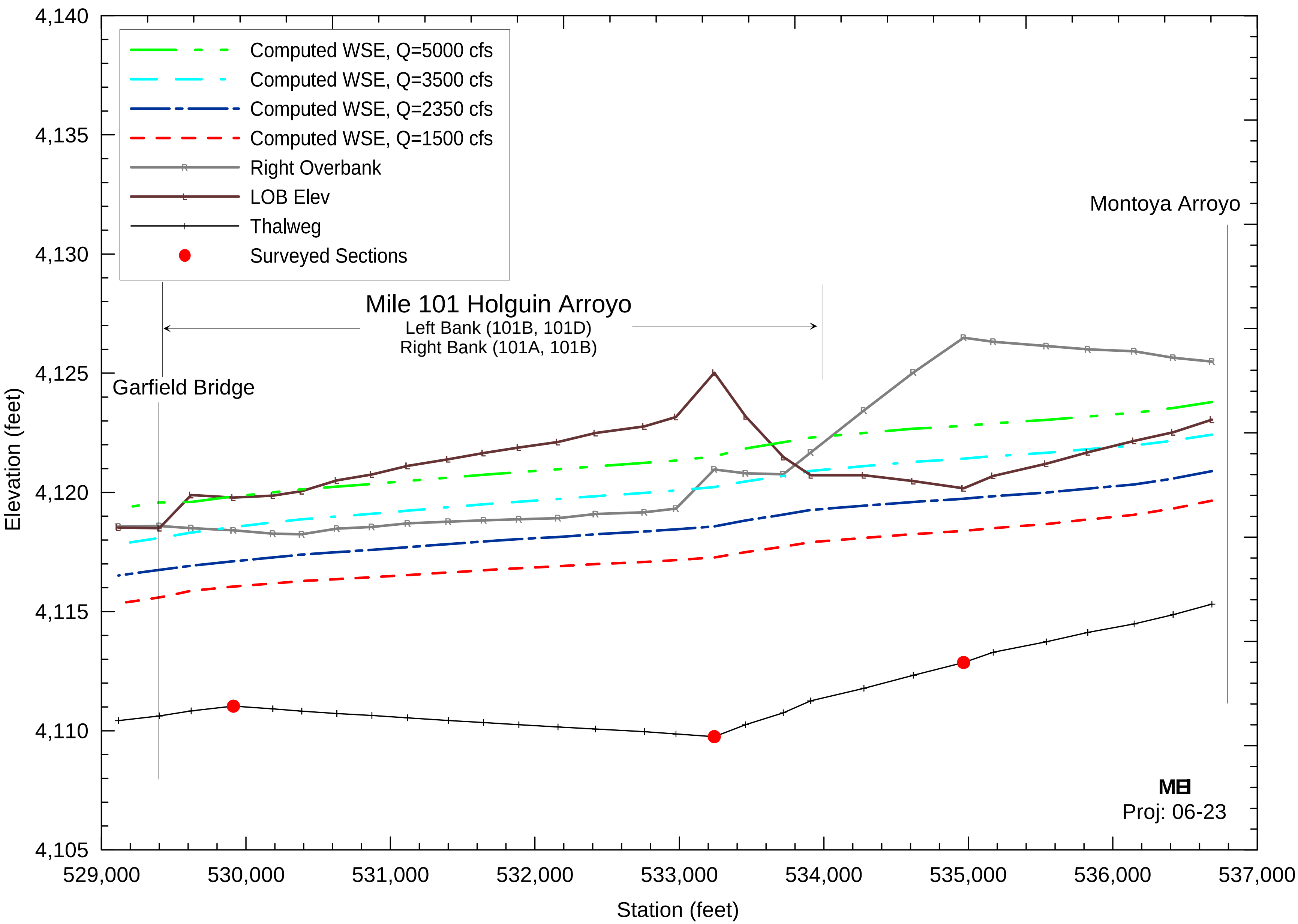


Figure 6.5. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Holguin Arroyo site.

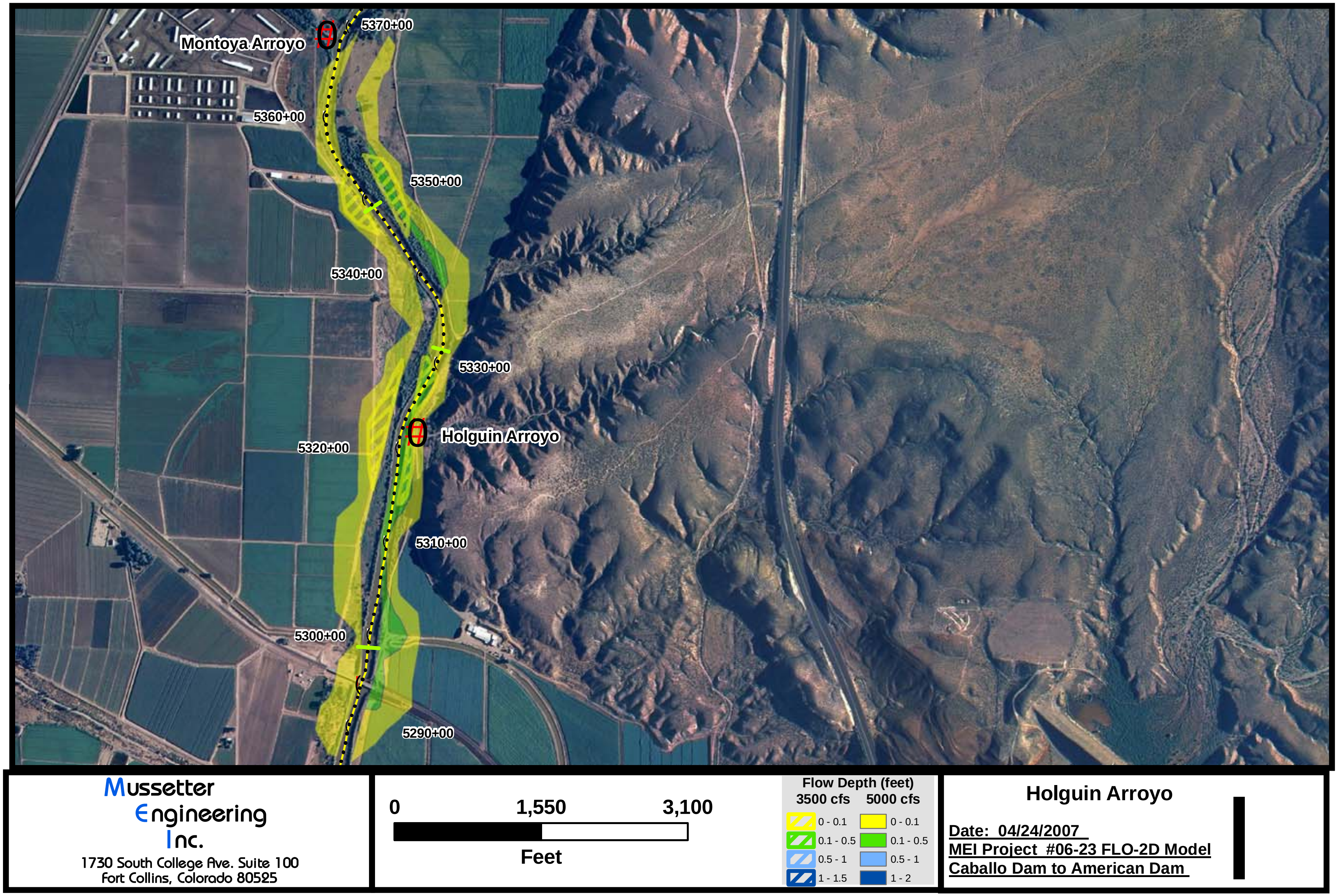


Figure 6.6. Overbank inundation areas at flows of 3,500 and 5,000 cfs at the Holguin Arroyo site.

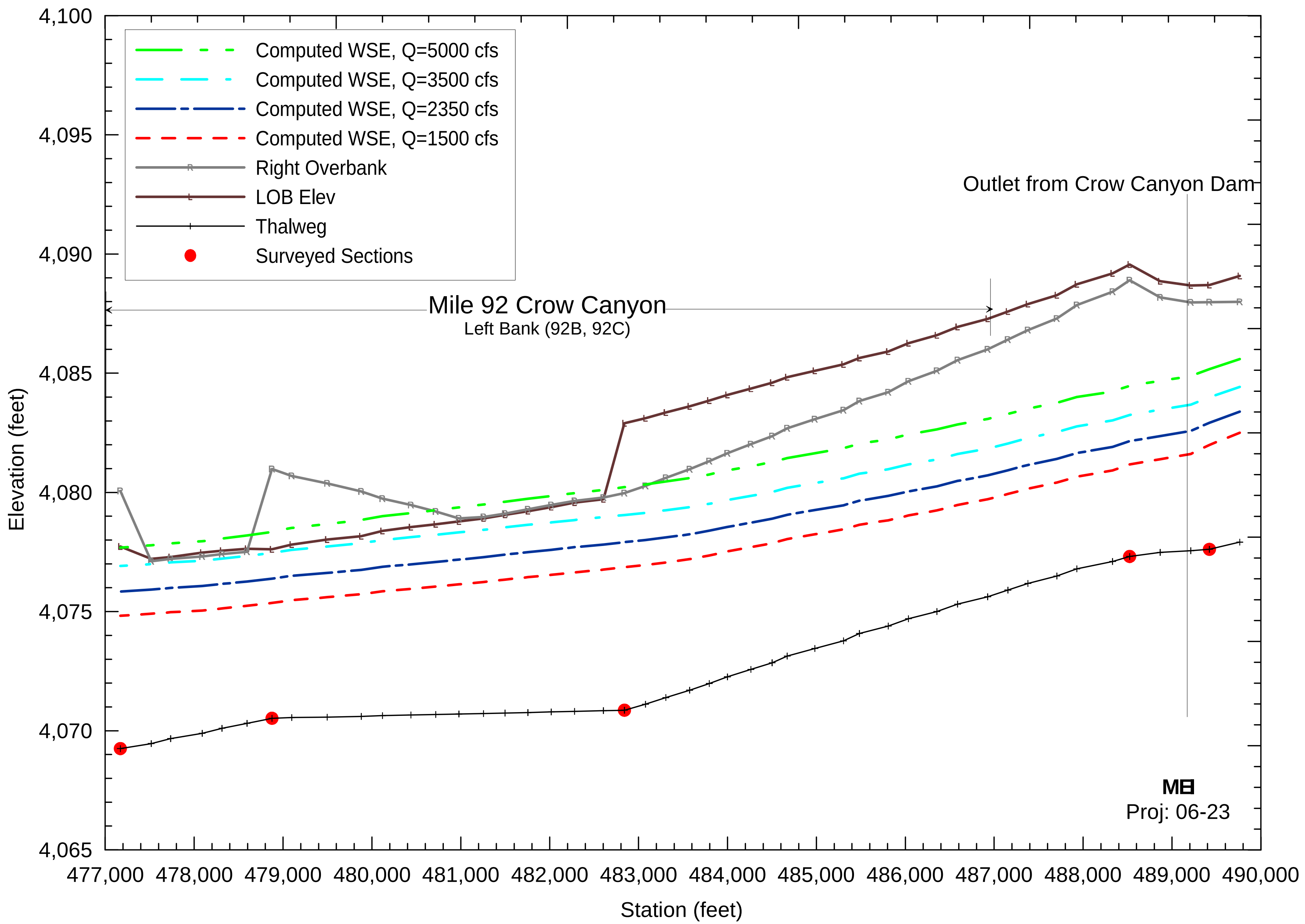


Figure 6.7. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Crow Canyon site.

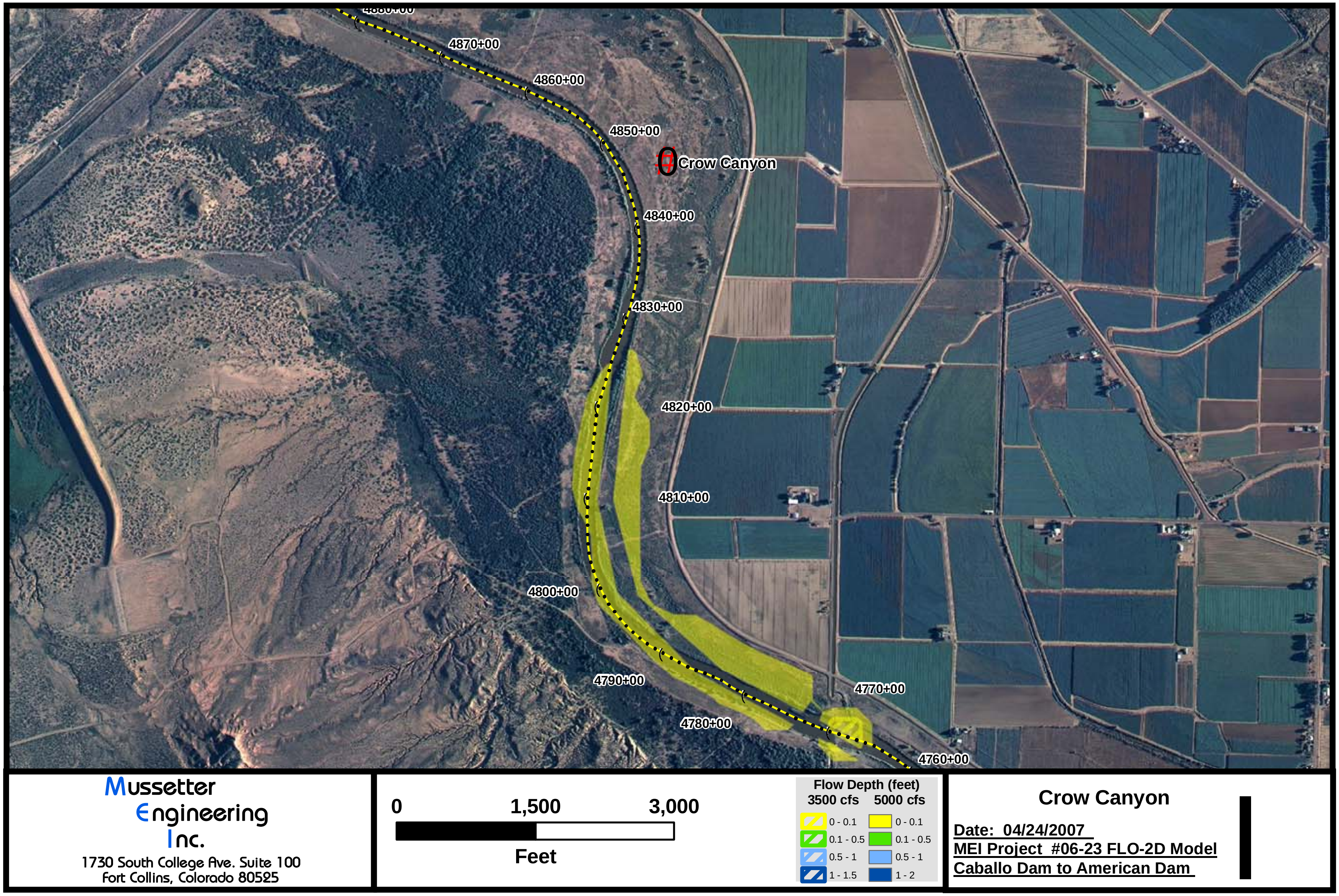


Figure 6.8. Overbank inundation areas at flows of 3,500 and 5,000 cfs at the Crow Canyon site.

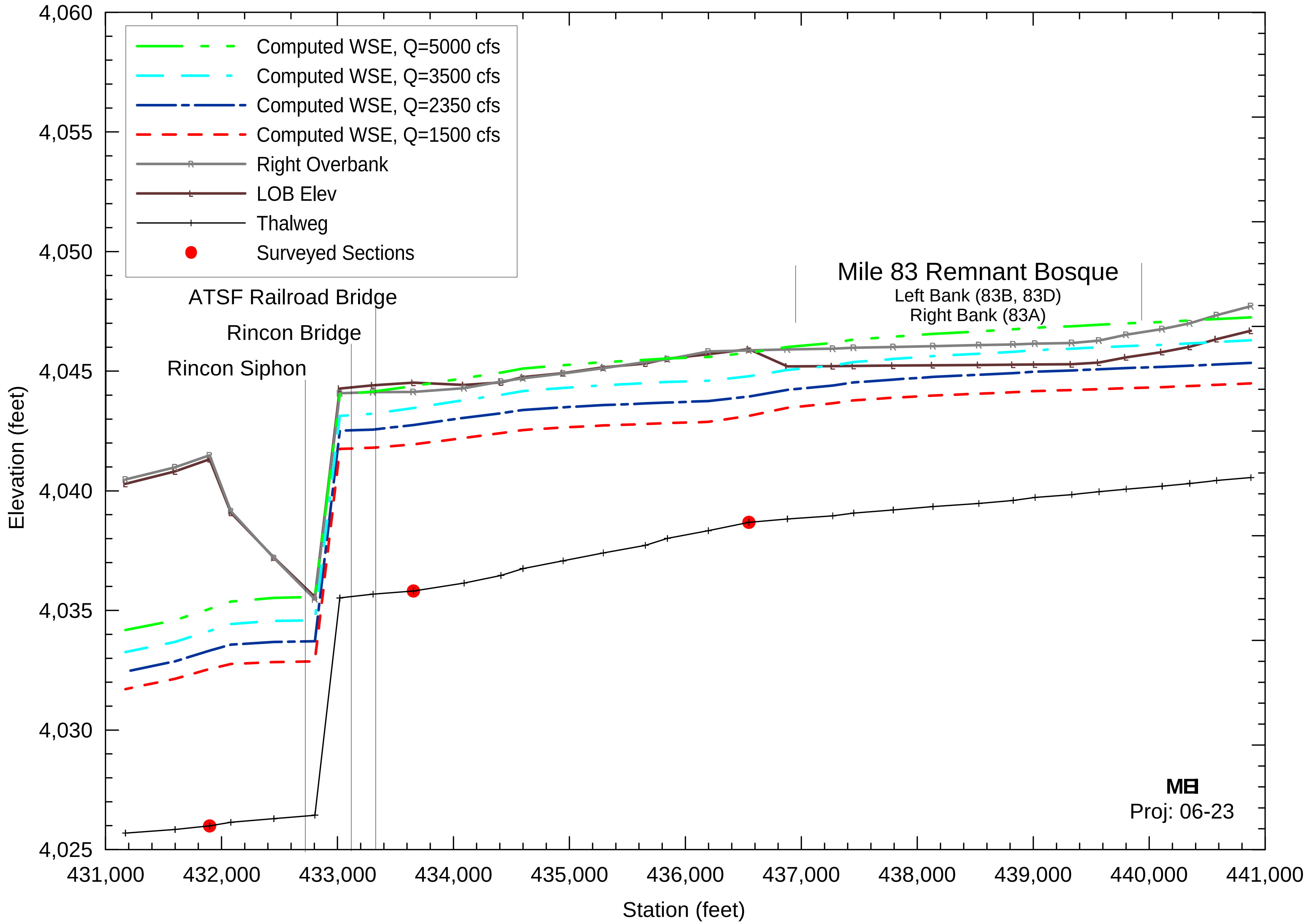


Figure 6.9. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Remnant Bosque site.

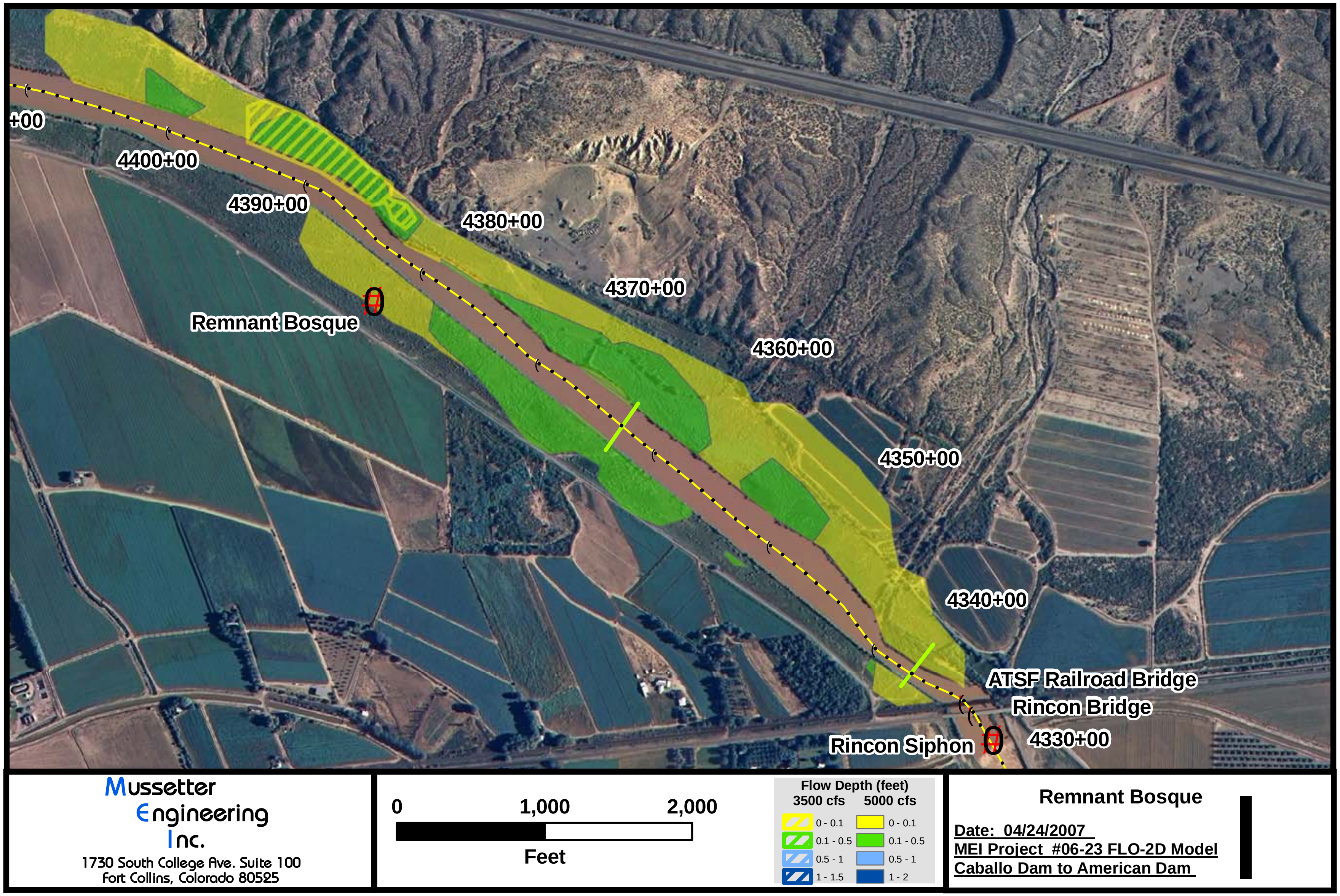


Figure 6.10. Overbank inundation areas at flows of 3,500 and 5,000 cfs at the Remnant Bosque site.

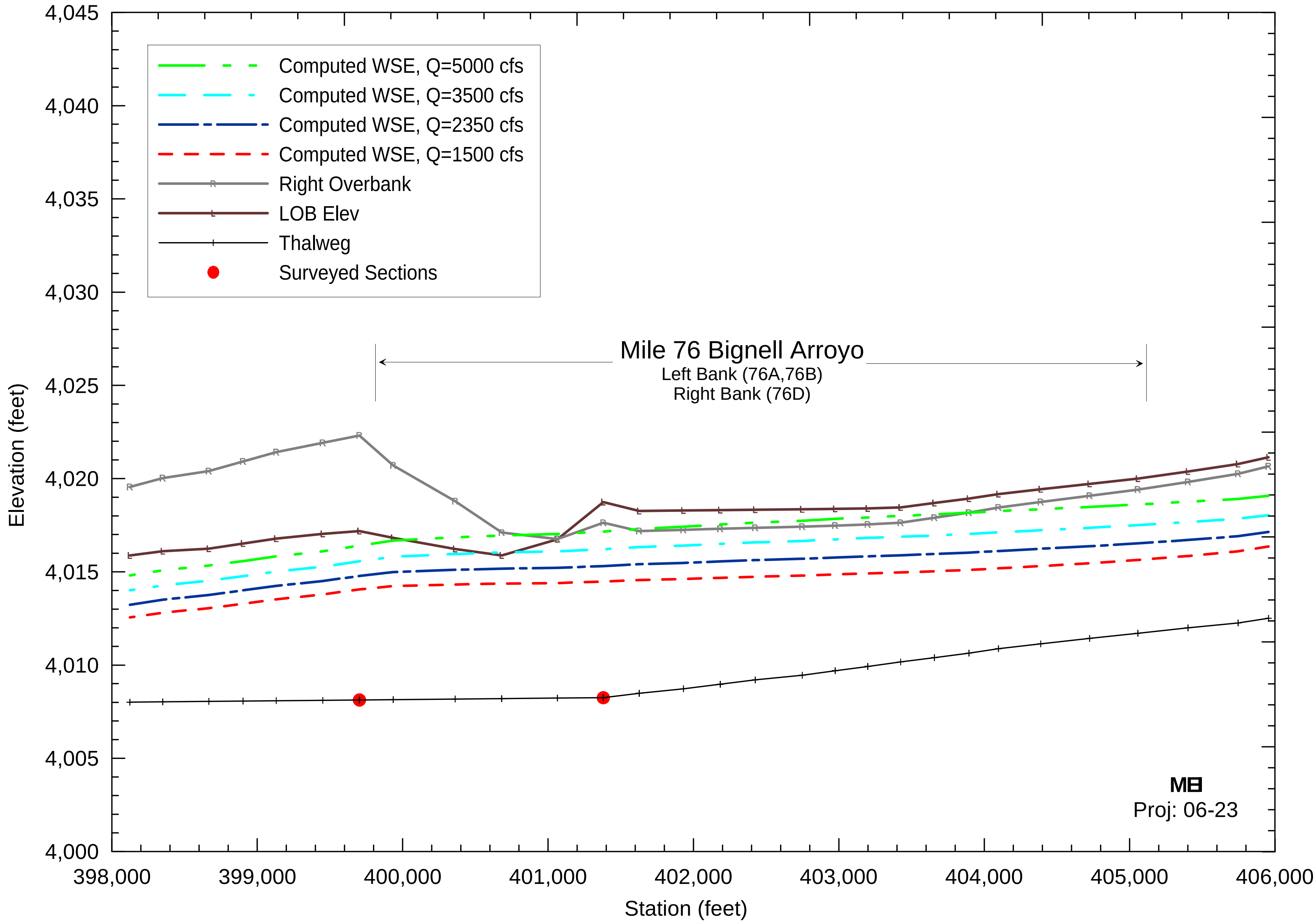


Figure 6.11. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Bignell Arroyo site.

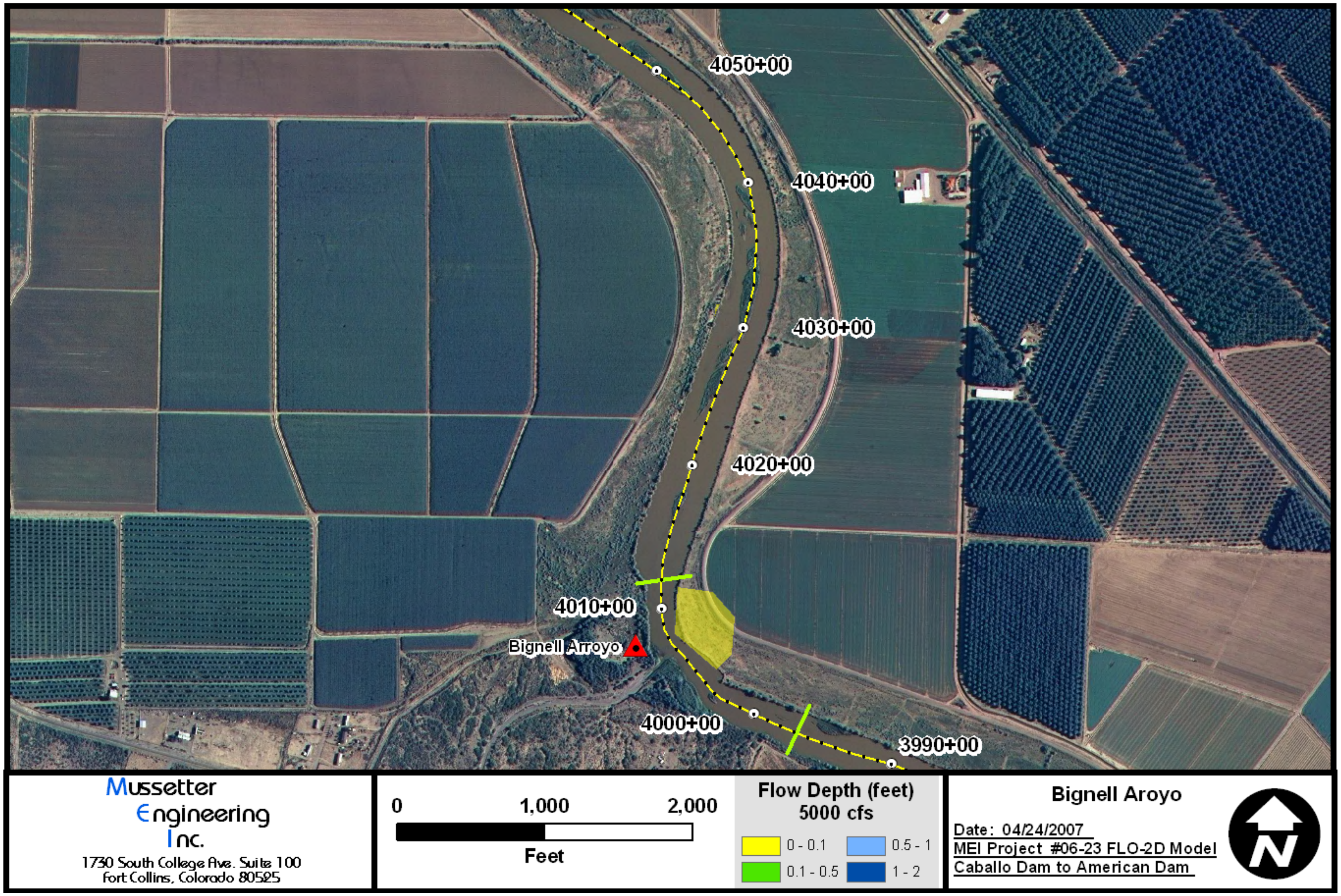


Figure 6.12. Overbank inundation areas at a flow of 5,000 cfs at the Bignell Arroyo site. No overbank inundation occurs at 3,500 cfs.

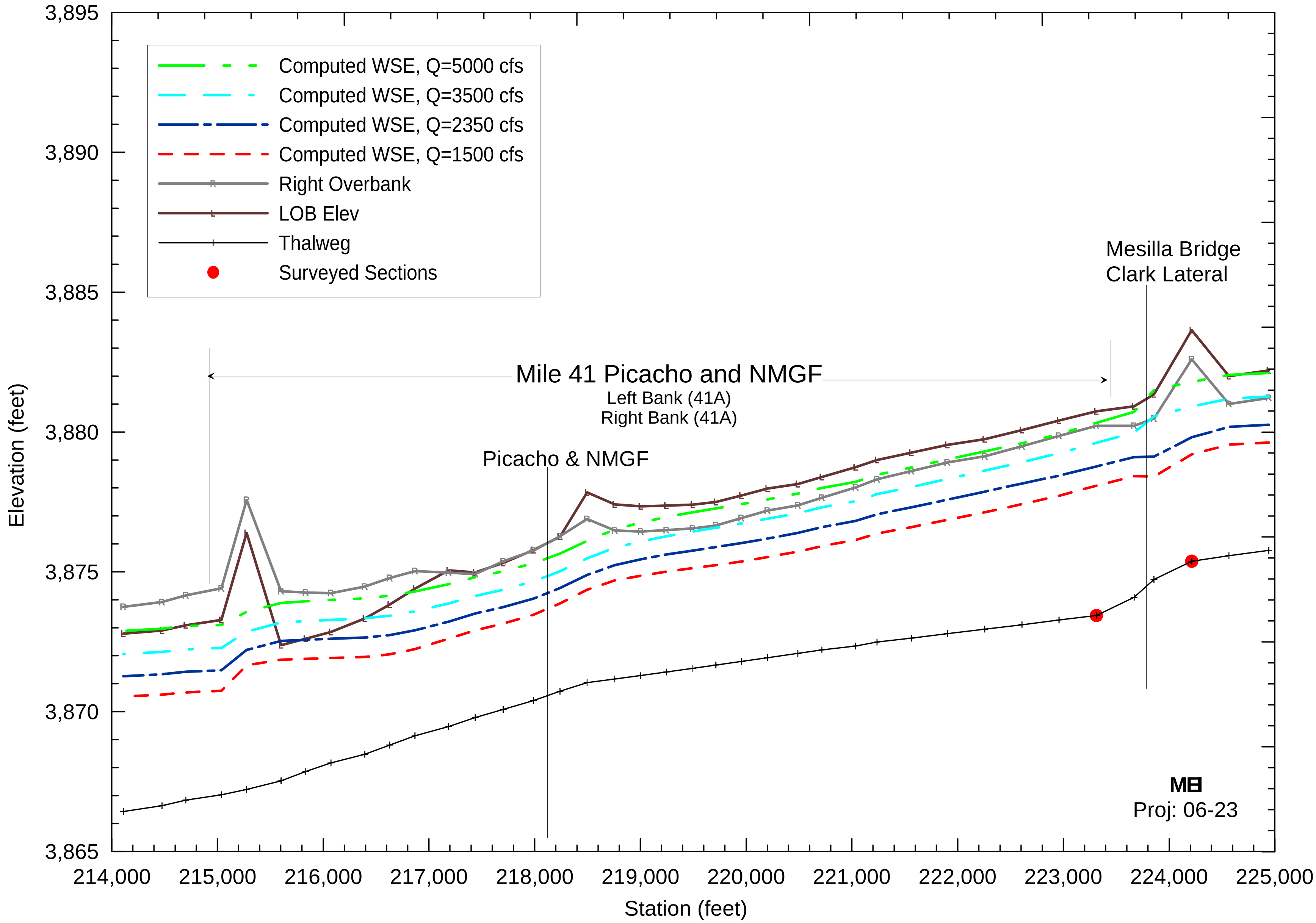


Figure 6.13. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Mile 41 Picacho and NMGF site.

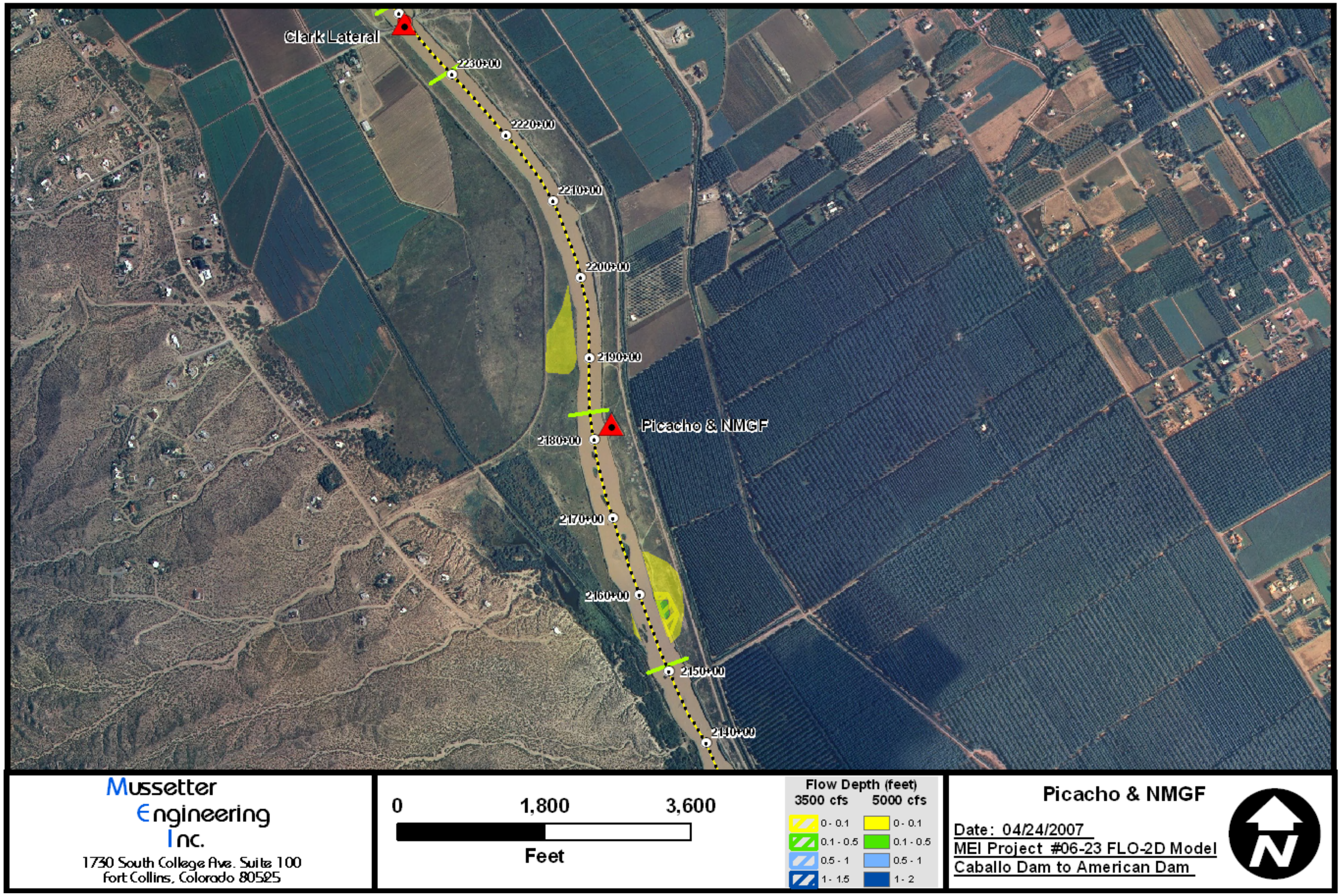


Figure 6.14. Overbank inundation areas at flows of 3,500 and 5,000 cfs at the Mile 41 Picacho and NMGF site.

Under current conditions, several of the previously identified restoration sites experience no overbank inundation at discharges up to 5,000 cfs (Table 6.2). At the RM 105 Oxbow site, opening up of the former meander would require between 3 and 4 feet of bank lowering to achieve a reasonable frequency of inundation (**Figure 6.15**). At the Tipton Arroyo site, inundation of the point bar will require 2 to 3 feet of bank excavation (**Figure 6.16**). Excavation of 3 to 4 feet of the left overbank will be required to inundate the Green-Tierra Blanca Arroyo site with a reasonable frequency (**Figure 6.17**). At the Sibley Point Bar site, the right overbank area will have to be lowered about 3 to 4 feet for relatively frequent inundation to occur (**Figure 6.18**). At the Jaralosa Arroyo site, inundation of the right overbank area with a reasonable frequency will require 3 to 4 feet of excavation (**Figure 6.19**). At the Jaralosa South site, inundation of the right overbank area with a reasonable frequency will require 3 to 4 feet of excavation (**Figure 6.20**). At the Yeso Arroyo site, 4 to 5 feet of excavation will be required to achieve a reasonable frequency of overbank flows on both the left and right overbanks (**Figure 6.21**). One to two feet of excavation will be required to achieve reasonably frequent overbank flooding on the right overbank area at the Mile 54 Channel Cut site (**Figure 6.22**). At the Mile 49 and 48 Spillway sites, lowering of the overbanks by 1 to 2 feet will provide a reasonable frequency of inundation (**Figure 6.23**). Similarly, 1 to 2 feet of bank lowering will provide a reasonable frequency of inundation in the left overbank at the Clark Lateral site above the Mesilla Bridge (**Figure 6.24**).

At a number of the arroyo confluences, primarily in Subreaches 1 and 2, modification of current dredging practices to create embayments for in-channel habitat was previously identified as a Point Project measure (USIBWC, 2004). The amount of habitat created at the embayments will depend on the amount of dredging, but the constructed embayments may be short-lived features since they create flow expansion zones on the channel margins where sediments are likely to be deposited. Since this may be an effective measure for creating temporary habitat improvements, this approach should be further investigated in the next phase of this study.

6.2. Sediment Removal from the River and Tributaries

Comparison of the 1943 design thalweg profile of the RGCP with the thalweg profile developed from the 2004 Tetra Tech survey (Figure 2.3) suggests that, since 1943, the channel has degraded at most locations downstream of Percha Dam. The exceptions to this general observation occur upstream from Bignell Arroyo at the boundary between Subreaches 2.2 and 2.3, and in Subreaches 7.1 and 7.2, which appear to have experienced up to 2 feet of aggradation since 1943. Localized aggradation is also occurring upstream from the Rincon Siphon. The results of the sediment continuity analysis (Figure 5.7) suggest that most of the subreaches are either armored (Subreaches 1.2 and 1.3), are nearly in balance or locally degradational (Subreach 2.1), or slightly aggradational (Subreaches 2.2 and 3 through 7.2). In combination, the profile and sediment continuity data suggest that there may be more hydraulic capacity in the RGCP than was initially designed, and extensive removal of sediment from the river may, therefore, not be necessary to maintain conveyance capacity, at least in portions of the reach. Review of the USIBWC O&M records (Table 2.5) indicates that most of the in-channel sediment removal since 1994 has occurred in the backwater area upstream from the American and Mesilla Diversion Dams. Construction of the NRCS sediment and flood detention structures in tributaries that are primarily located in the Upper reach has significantly reduced the sediment supply and need to remove sediment from the river (USIBWC, 2004)

Tributary sediment delivery events, such as those that occurred during the 2006 monsoon season, have significant local impacts on the mainstem Rio Grande, primarily in the portions of the RGCP upstream from Selden Canyon. Channel blockage by coarse-grained tributary fans causes upstream backwater and can cause overbank flows that result in flow conveyance losses. Where the river bank opposite the fans are already armored, there is a potential for damage to the bank protection, and depending on the proximity to the levees, potential for threats to the integrity of the levee system or other channel margin infrastructure such as bridges and siphons. Where the opposing banks are not currently armored, deposition of coarse grained tributary fans leads to lateral migration of the river, which can also threaten local infrastructure. While this condition creates O&M challenges, it may also provide some unique restoration opportunities by providing vertical control that could increase upstream overbank inundation and/or allowing lateral adjustment in the river that can rejuvenate in-channel and overbank habitat. These opportunities should be explored further in the next phase of this study to determine whether reasonable gains in habitat quality can be achieved while protecting local infrastructure.

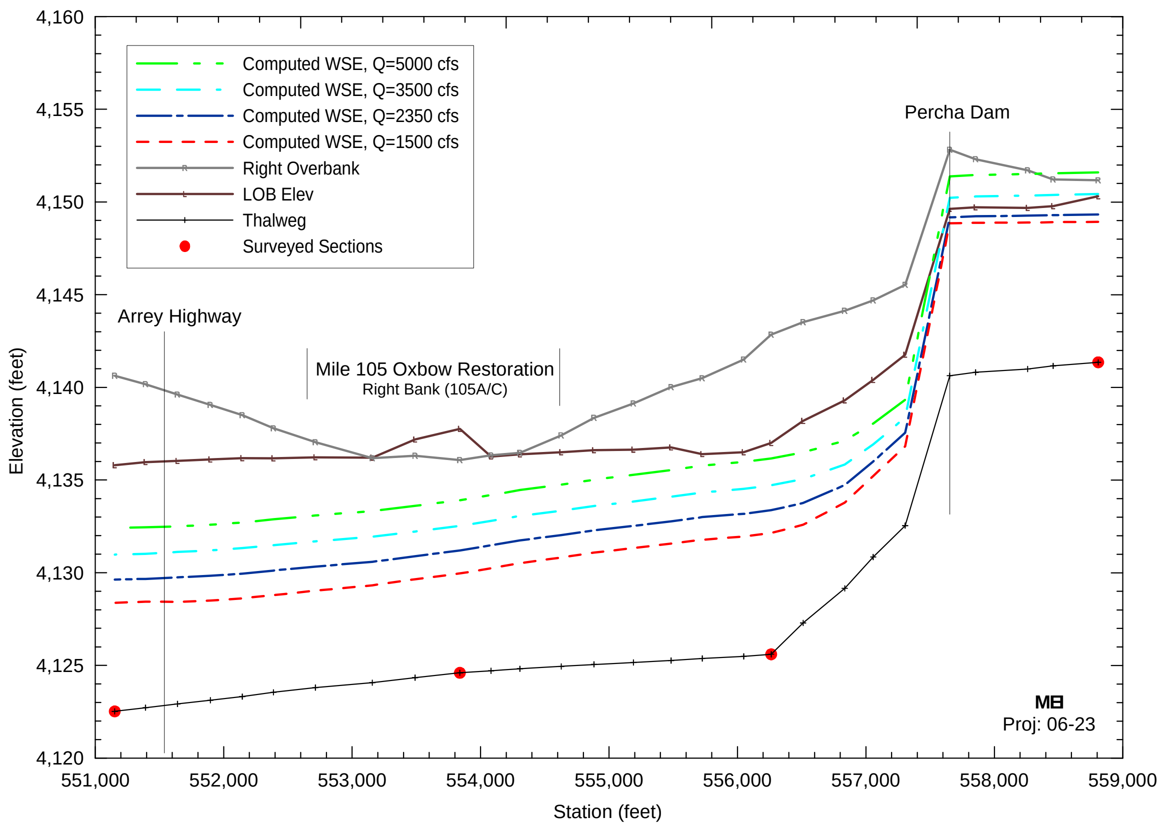


Figure 6.15. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Mile 105 Oxbow site.

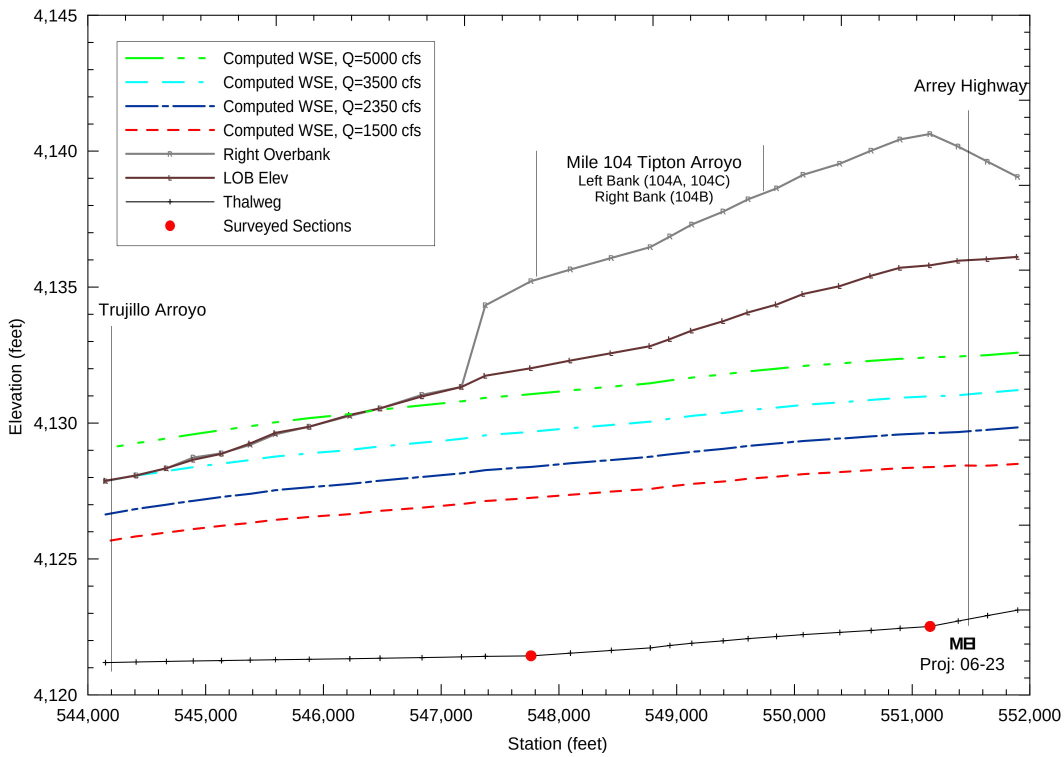


Figure 6.16. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Tipton Arroyo site.

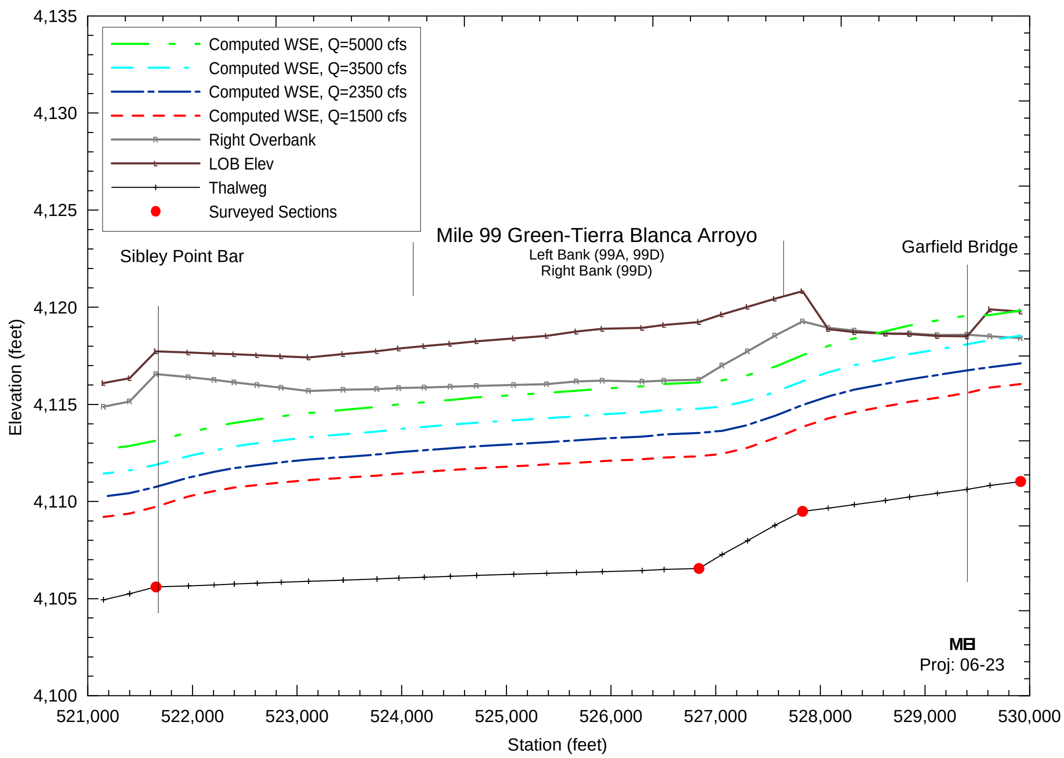


Figure 6.17. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Green-Tierra Blanca Arroyo site.

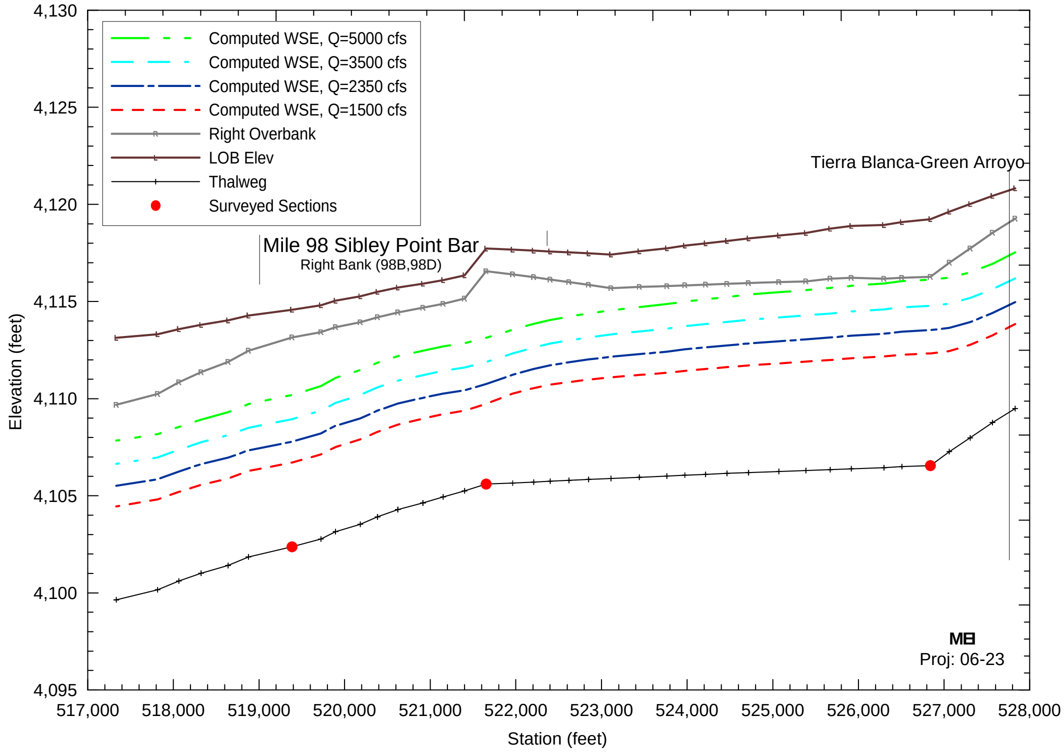


Figure 6.18. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Sibley Point Bar site.

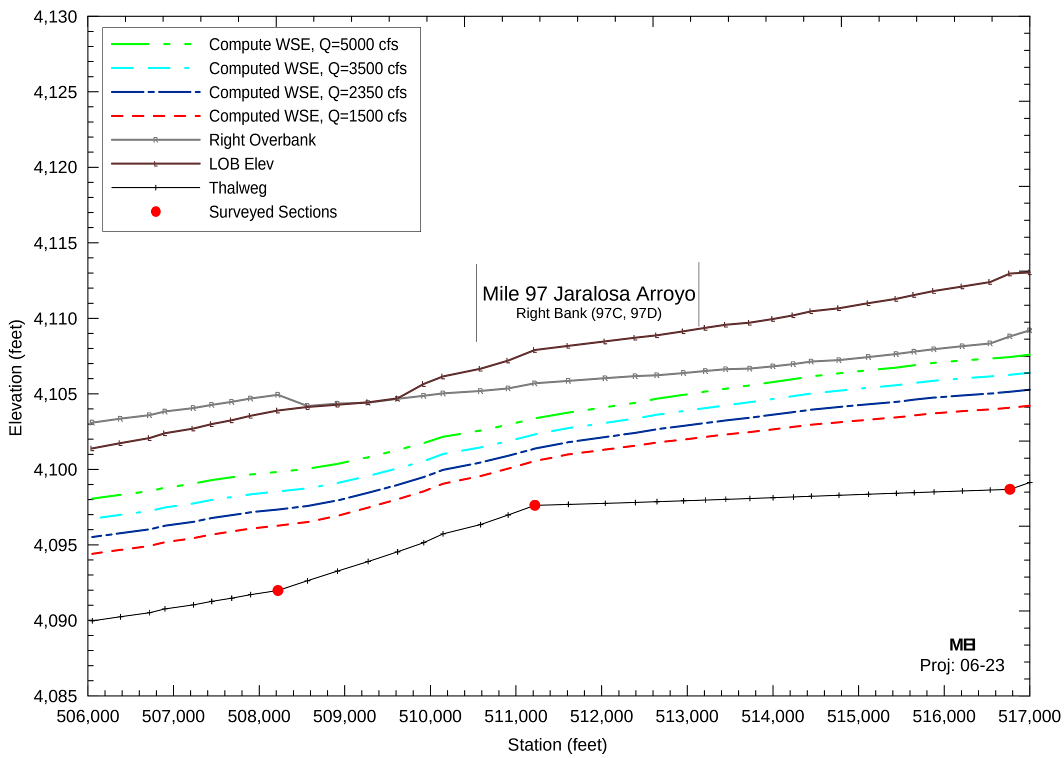


Figure 6.19. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Jaralosa Arroyo site.

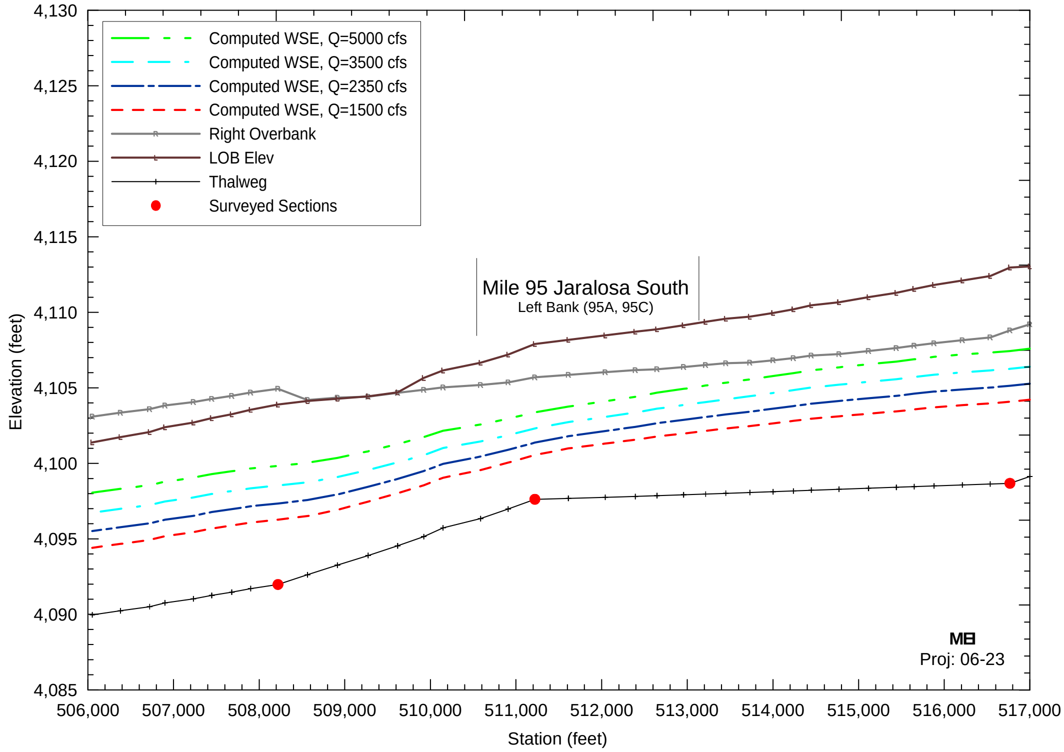


Figure 6.20. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Jaralosa South site.

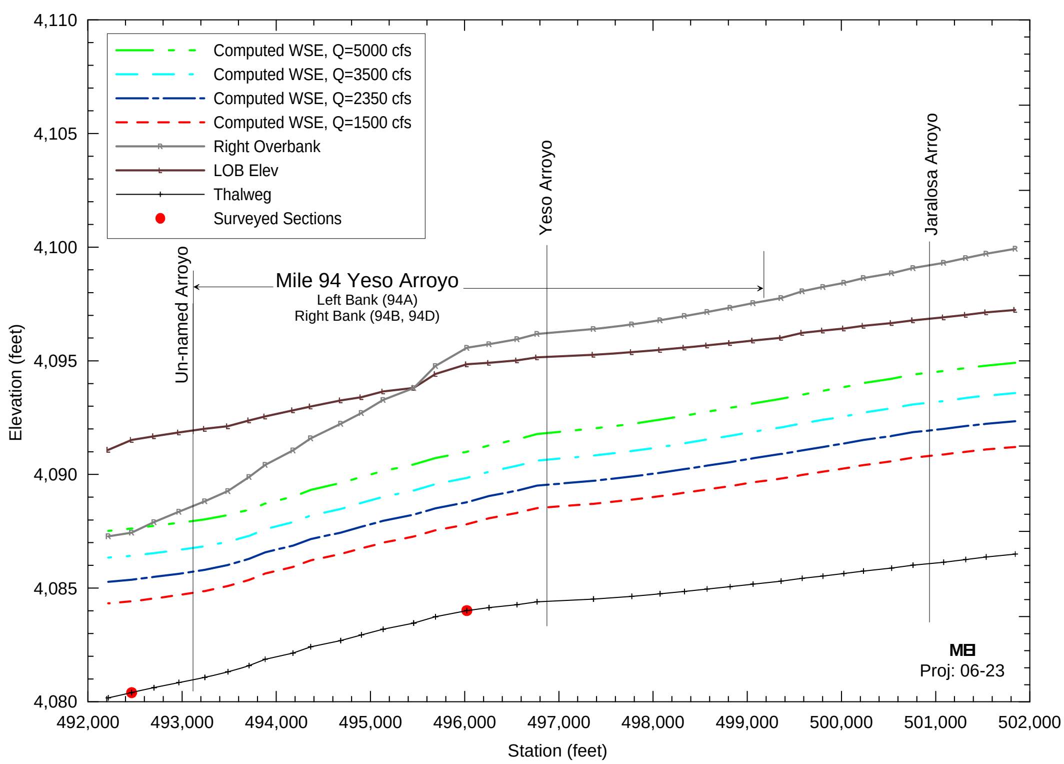


Figure 6.21. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Yeso Arroyo site.

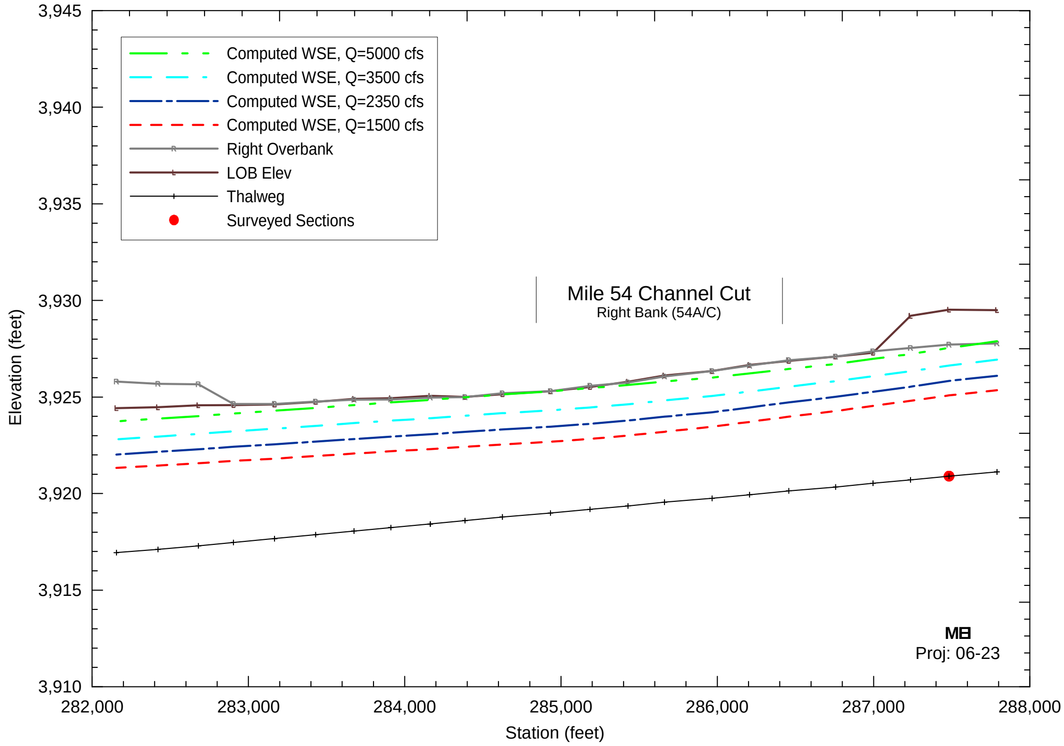


Figure 6.22. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Mile 54 Channel Cut site.

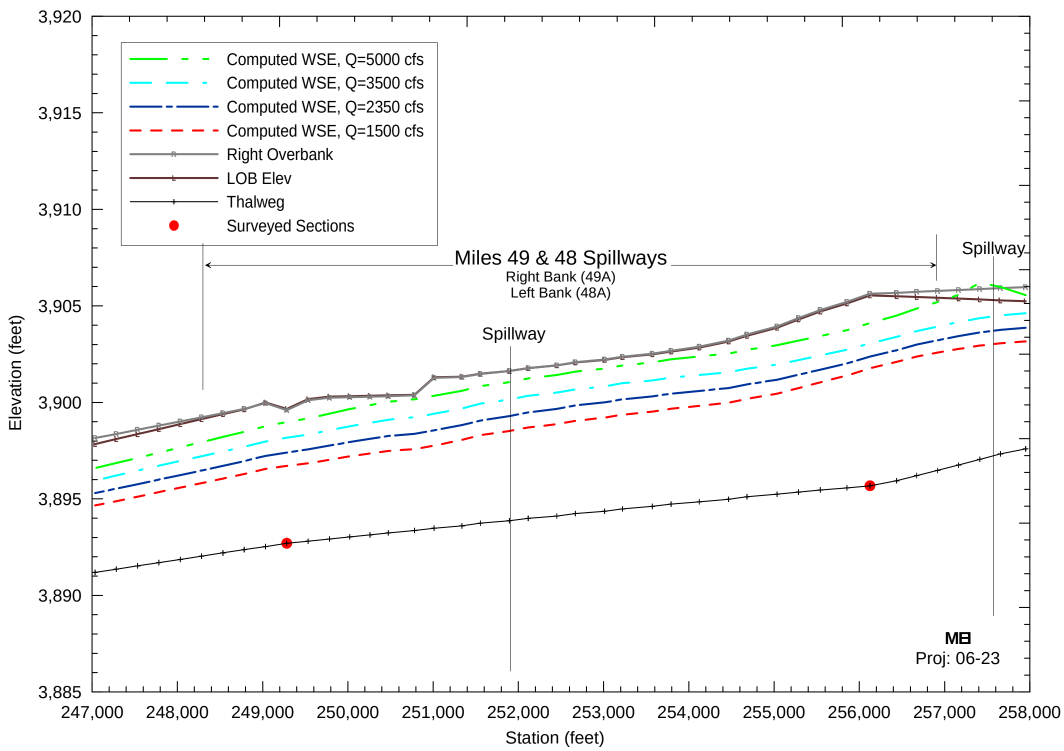


Figure 6.23. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Mile 49 and 48 Spillways site.

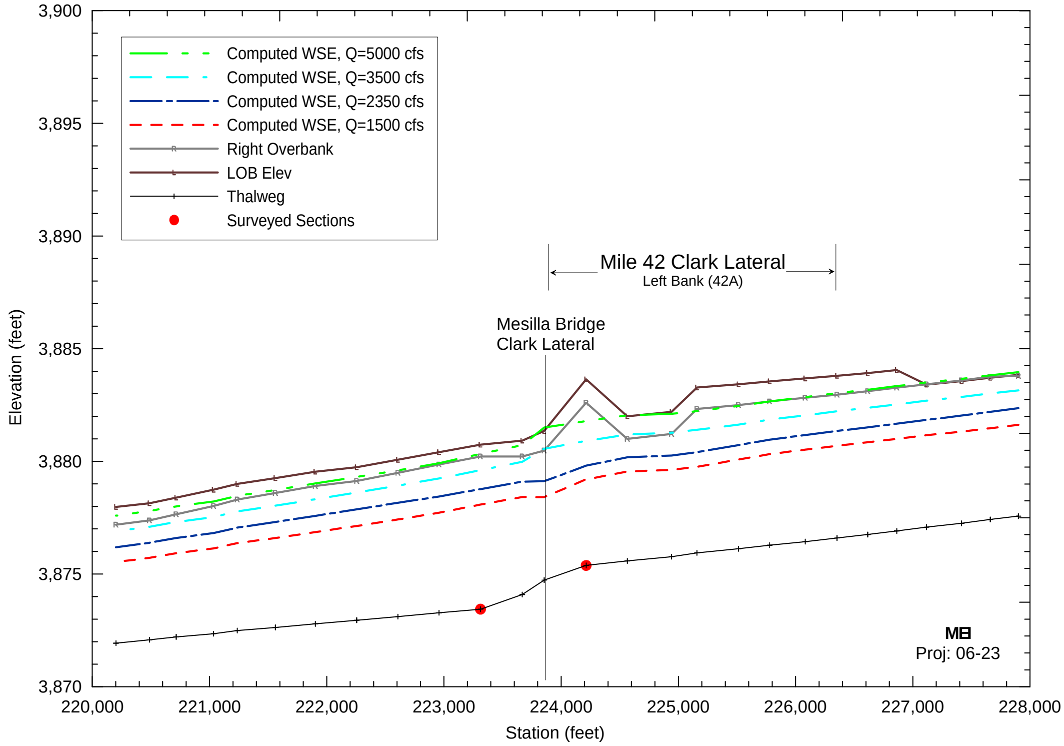


Figure 6.24. Thalweg, bank and water-surface profiles for flows of 1,500, 2,350, 3,500 and 5,000 cfs at the Clark Lateral site.

7. SUMMARY AND CONCLUSIONS

The Albuquerque District of the U.S. Army Corps of Engineers (Corps) is conducting this baseline investigation for the USIBWC to support an evaluation of long-term river management alternatives for the Rio Grande Canalization Project (RGCP) under Authority of the Economy in Government Act (31 USC 1535). USIBWC will use the information to support the management evaluation for the RGCP. The primary goal of this baseline conditions investigation was to modify an existing FLO-2D hydraulic model (Tetra Tech, 2004) to assess overbank flow potential, sediment transport and geomorphologic processes within the RGCP reach to provide information to the stakeholders that can be used to identify potential restoration sites and strategies.

Specific objectives for the RGCP reach of the Rio Grande include:

1. investigation of river channel/overbank connectivity
2. production of enhanced cover and aquatic diversity
3. restoration of healthy riparian function to enhance natural riverine processes and improved terrestrial wildlife habitat, and
4. protection of existing structural features including pipelines, bridges and levees with a preference to using biostabilization techniques when the structures are found to be at risk from natural geomorphologic processes.

7.1. Summary

This investigation of the RGCP reach of the Rio Grande included analysis of the geologic and geomorphic setting (Chapter 2), mean daily and peak flow hydrology (Chapter 3), hydraulic conditions along the reach (Chapter 4), sediment transport and channel stability (Chapter 5), and implications for restoration potential (Chapter 6). The RGCP was subdivided into three primary subreaches for purposes of assessing overall restoration potential. Because of the effects of geomorphic and anthropogenic controls, the reach was further subdivided into seven geomorphic subreaches that correspond closely to the USIBWC River Management Units (RMU) (Table 2.1). For the purposes of the sediment-transport analysis, Subreach 1 and Subreach 7 were further subdivided to account for the effects of existing hydraulic controls (Figure 3.1).

7.1.1. Geomorphology

The geologic and geomorphic investigation indicated that the quantity and caliber of the sediments delivered to the RGCP by arroyos downstream of Caballo Dam (that has a very high sediment trap efficiency) is closely related to the local geologic setting. In general, the west-side tributaries deliver coarser sediments to the river than the east-side tributaries because they drain areas that produce much coarser sediments (Figure 2.2 a, b). The coarse-grained fans that form at the tributary confluences cause channel constrictions, upstream backwater, overbank flows and sediment deposition in the mainstem. Additionally, deposition of sediment on the coarse tributary fans can cause damage to existing bank protection on the opposing banks, or lateral migration of the channel towards the project levees or other infrastructure.

Comparison of the pre-canalization thalweg profile with the 1943 as-built profile showed that the canalization project significantly increased the depth of the Rio Grande channel through most of the RGCP (Figure 2.3). Comparison of the 1943 and 2004 profiles indicates that the channel has generally degraded since 1943, except in Subreaches 7.1 and 7.2 (El Paso) where there has been up to 2 feet of aggradation. Between Percha Dam and the Hatch Siphon in Subreaches 1.2 and 1.3, there has been up to about 6 feet of degradation. Immediately downstream of the Hatch Siphon at the head of Subreach 2.1 and downstream of the Rincon Siphon there has been between 9 and 10 feet of degradation. Less than 2 feet of degradation has occurred in the Salem Bridge-Hatch portion of Subreach 2 where vegetated mid-channel bars are present in the channel. In the lower portion of Subreach 2.2, there has been up to 2 feet of aggradation, primarily in the reach upstream of Bignell Arroyo. No historical data were available for the Selden Canyon reach (Subreach 3), but field observations suggest that the canyon may in fact be somewhat aggradational. Downstream from Leasburg Diversion Dam there has been between 2 and 4 feet of degradation in Subreach 4. The Las Cruces reach (Subreach 5) has experienced about 2 feet of degradation. Downstream of the Mesilla Diversion Dam in Subreaches 6.1 and 6.2, degradation ranges from about 6 feet near the dam to negligible at the Vinton Bridge.

Several samples of the bed material from the mainstem and the mouths of tributaries along the RGCP have been collected over the past 10 to 15 years. Prior to this investigation, bed material samples were collected by Resource Technology Inc. (RTI) in 1996 (three samples) and by Tetra Tech in June 2004 (six samples). In February 2007, MEI collected 14 bulk samples of sediment from the bed of the Rio Grande and at the mouths of tributary arroyos, and conducted pebble counts (Wolman, 1954) of the coarse surface bed material at two locations in the Rio Grande and one location at the mouth of Tierra Blanca Arroyo. The longitudinal distribution of the D_{50} and D_{84} values from the RTI, Tetra Tech and MEI samples are shown on Figure 2.7. As expected, the bed material is coarsest in the reaches upstream from the Hatch Siphon, where the most degradation and bed armoring has occurred, and where there are a large number of tributaries that deliver sediment from the west side of the valley that drain through the Lower Santa Fe Group and Tertiary volcaniclastic sedimentary units. In the remainder of the RGCP reach, the bed material is primarily sand, with little variation in the bed-material gradations.

7.1.2. Hydrology

To provide a basis for assessing the hydrologic characteristics of the study reach, the available streamflow records were used to quantify the flow for the post-Caballo Dam period (WY1938-WY2006) at several mainstem gages and the significant diversions and return flows along the project reach. The resulting flow-duration curves (Figure 3.9) that were developed for the 25-year period between 1975 and 2006 were used in the sediment-transport analyses. These curves demonstrate that the flows for a given exceedence value typically decrease in the downstream direction as water is diverted from the river. For example, the 50-percent flow exceedence decreases from 800 cfs below Caballo Dam to 425 cfs at El Paso, and the 1-percent flow exceedence decreases from 3,360 cfs below Caballo Dam to 2,510 cfs at El Paso.

A flood-frequency analysis was conducted at the El Paso (Courchesne) gage based on historic flow records (Figure 3.12). No peak flow data are available for the Rio Grande below Leasburg or the Rio Grande below Caballo gages. Based on the rainfall-based flood-frequency analysis, the 2, 5-, 10-, 20-, 50- and 100- year peak flow event discharges are approximately 4,040, 6,000, 7,270, 8,470, 9,980, and 11,100 cfs, respectively. Due to the absence of peak flow data at the Leasburg and Caballo gages, a comparison of the annual peak mean daily flow values for the Leasburg, Caballo, and El Paso gages was conducted using the Weibull Plotting Position (Figure 3.12). At discharges greater than the 5-year return interval, the peak mean daily flow values at all three gages are very similar. This is probably a result of the limited storage capacity of the diversion pools, and the relatively small effect of the flow diversions at higher discharges.

7.1.3. Hydraulics

An updated FLO-2D model of the RGCP reach from Caballo Dam to American Dam (105 miles) was used to estimate hydraulic conditions in the project reach and to aid in evaluating the restoration opportunities. The model results indicate that, under the no-diversion scenario, there is essentially a linear increase in the area of inundation with discharge for the range of modeled steady-state releases from Caballo Dam from 2,350 to 4,500 cfs, and a higher rate of increase between the 4,500 and 5,000 cfs releases. With the diversions operating at their typical levels, the amount of overbank flooding is negligible for Caballo Dam releases up to about 3,000 cfs, increasing linearly to about 1,200 ac at 5,000 cfs. Downstream from Mesilla Dam, the channel capacity is about 1,500 cfs; thus, most of the overbank flooding at the range of modeled flows occurs in this portion of the reach. (It should be noted that the accuracy of the FLO-2D model to predict very shallow and limited overbank flooding is dependent on the bank and floodplain grid element elevations, and therefore, the results are less accurate for shallow overbank flows.) The FLO-2D results for the lower range of discharges from 2,350 to 3,000 cfs showed minimal flooding just north of El Paso (Subreach 7.1). There was very little flooding in Subreaches 4 and 5 (Mesilla to Leasburg) and no flooding north of Leasburg. For the mid-range of steady flows from 3,250 to 3,750 cfs, increased flooding occurs in the El Paso reach (Subreaches 7.1 and 7.2), while limited overbank flow occurs in the upstream portions of the RGCP reach. For discharges greater than 4,000 cfs, flooding is predicted at locations throughout the entire RGCP reach, with the reach from Las Cruces to El Paso experiencing the most flooding, the reach from Leasburg to Las Cruces having moderate flooding and the reach from Percha Dam to Leasburg showing minimal flooding. This pattern is consistent for all of the higher flows. Flooding is most significant at 5,000 cfs for both the diversion and no-diversion simulations, with little difference between the diversion and no-diversion flooding simulations at 4,500 and 5,000 cfs.

To evaluate the channel hydraulic characteristics over a broad range of flows and to provide input to the sediment-transport calculations, a stepped hydrograph was modeled using the FLO-2D model for a range of steady-state releases from Caballo Dam from 10 to 6,000 cfs, with the discharge increasing in 250-cfs increments up to 3,000- and 500-cfs increments between 3,000 and 6,000 cfs. Each increment of flow was modeled for a period of 120 hours to allow the model to reach steady-state conditions during each discharge period. This range of discharges encompasses the range of flows observed in the available flow records.

The one-dimensional hydraulic results for the main channel (e.g., flow velocity, depth, topwidth, and energy slope) were taken from the model output for the stepped hydrograph and were used to develop reach-averaged hydraulic conditions for each subreach (Table 4.1). The subreach-averaged hydraulics were subsequently used in the sediment-transport analysis.

7.1.4. Sediment-continuity Analysis

A baseline sediment-continuity analysis was performed to evaluate the potential for aggradation or degradation with the present channel configuration and reservoir operations. In general, the analysis was conducted by estimating the annual bed-material transport capacity of each consecutive subreach, and comparing the resulting transport capacity with the supply from the upstream river and tributaries within the reach. The transport capacity was estimated by developing bed-material transport capacity rating curves for each subreach using Yang's (Sand) sediment-transport equation (Yang, 1973) and integrating the rating curves over the applicable mean daily flow-duration curves to obtain a transported volume.

Tributary sediment loadings used in the sediment continuity analysis were estimated based on results from Tetra Tech (2004) with an assumption, based on experience with other tributaries to the Rio Grande, that the bed material load represents 35 percent of the total supply (Table 5.1). The long-term aggradation/degradation tendencies along the study reach were evaluated by comparing the average annual bed material load in each subreach with the upstream and tributary supply (Figure 5.6).

An incipient motion analysis was conducted for Geomorphic Subreach 1 using the subreach-averaged hydraulics for the range of flows from 10 to 6,000 cfs, and the representative bed material gradation that had a median grain size of 51.7 mm (Figure 5.1). The analysis indicates that the bed is effectively armored over the range of flows that could reasonably occur in this portion of the reach (Figure 5.2). The bed-material load in Subreaches 1.2 and 1.3 were, therefore, assumed to be negligible and the sand-sized sediment delivered from the tributaries is assumed to be transported as a veneer over the existing bed material, without significant accumulation.

The sediment continuity analysis indicated that Subreach 2.1 is net degradational (about -0.03 feet per year) due to the high sediment-transport capacity compared to the upstream sediment supply (34 ac-ft/yr of supply and 50 ac-ft/yr of transport capacity) (Figure 5.7). This subreach is located below the Hatch Siphon, where approximately 10 feet of degradation has occurred since completion of the Canalization Project in the early-1940s (Figure 2.3). The degradation rate indicated by the continuity analysis is less than the historical rate, which is reasonable since the channel has undergone substantial adjustment during the period and is likely approaching equilibrium with the existing upstream sediment supply. Subreach 2.2 is slightly aggradational (0.04 feet per year), with the sediment-transport capacity and sediment supply approximately in balance (65 ac-ft/yr of supply and 44 ac-ft/yr of transport capacity). The aggradational trend of Subreach 2.2 is consistent with aggradation observed within the subreach. Subreach 2.3 is net degradational (-0.13 ft/yr) due to the high sediment-transport capacity (103 ac-ft/yr) and little or no tributary supply to the reach. This subreach is located within the steeper and confined section between Bignell Arroyo and Selden Canyon. Compared to the degradation rates in the other subreaches (e.g. 2.1), the estimated rate in Subreach 2.3 may be unreasonably high. It is possible that the bed material in this relatively inaccessible reach is coarser than the gradation that was used in the analysis, but sufficient data are not available to confirm this. The analysis indicates that the transport capacity is approximately in balance with the upstream sediment supply from Subreach 3 through the downstream end of the study reach, with a small aggradational trend in Subreaches 5 and 6.1 (0.03 and 0.04 ft/yr, respectively) due to the lower transport capacities. This result is also consistent with observed trends. As discussed in Section 2.6, USIBWC has excavated and removed sediment from this portion of the reach on numerous occasions since construction of the Canalization Project.

7.1.5. Implications for Restoration Potential

Measures to meet some of the habitat improvement objectives were previously identified at 20 locations within the RGCP (Table 2-9, USIBWC, 2004). These measures included native vegetation plantings, bank shave-downs for riparian vegetation, opening up of former meanders and modifications of dredging practices at the mouths of the tributary arroyos (USIBWC, 2004). Other potential restoration sites will be identified in the next phase of this study.

To provide a preliminary basis for assessing restoration potential along the RGCP, the FLO-2D model was used to evaluate the potential for overbank flows. In general, the greatest potential for overbank flows with the existing topography occurs downstream from Messila Dam. Based on the model results, the 20 previously identified sites for potential restoration were subdivided into those at which some overbank flooding would occur at flows between 3,500 and 5,000 cfs (Table 6.1), and those at which no flooding would occur at these flows (Table 6.2). At each of the sites where flooding would not occur with the existing topography, an estimate was made of the amount of bank lowering that would be required to attain a reasonable frequency of overbank flooding (Table 6.2). Additionally, a review of available groundwater information was conducted to determine whether the water table is sufficiently shallow to support riparian vegetation. Shallow groundwater elevations within the Mesilla Valley portion of the RGCP are generally controlled by the drain elevations, and the water table is typically between 8 and 10 feet below the existing ground surface in most locations (SSPA, 1987).

Comparison of the 1943 design thalweg profile of the RGCP with the thalweg profile developed from the 2004 Tetra Tech survey (Figure 2.3) suggests that, since 1943, the channel has degraded at most locations downstream of Percha Dam. The exceptions occur upstream from Bignell Arroyo in the lower part of Subreach 2.2 and in Subreaches 7.1 and 7.2 where up to 2 feet of aggradation has occurred since 1943. Localized aggradation is also occurring upstream of the Rincon Siphon. The results of the sediment continuity analysis (Figure 5.7) suggest that most of the subreaches are either armored (Subreaches 1.2 and 1.3), nearly in balance or locally degradational (Subreach 2.1), or slightly aggradational (Subreaches 3 through 7.2). In combination, the profile and sediment continuity data suggest that there may be more hydraulic capacity in the RGCP than was initially designed, and that extensive removal of sediment from the river may not be necessary to maintain conveyance capacity. Review of the USIBWC O&M records (Table 2.5), indicates that most of the in-channel sediment removal since 1994 has occurred upstream from the American and Mesilla Diversion Dams. Construction of the NRCS sediment and flood detention structures in tributaries upstream from Selden Canyon has significantly reduced the sediment supply and need to remove sediment from the river (USIBWC, 2004)

Tributary sediment delivery events, such as those that occurred during the 2006 monsoon season, have significant local impacts on the mainstem Rio Grande, primarily in the portions of the RGCP upstream from Selden Canyon. Channel blockage by coarse-grained tributary fans causes upstream backwater and can cause overbank flows that result in flow conveyance losses. Where the river banks opposite the fans are already armored, there is a potential for damage to the bank protection, and depending on the proximity to the levees, potential for threats to the integrity of the levee system or other channel margin infrastructure such as bridges and siphons. Where the opposing banks are not currently armored, deposition of coarse grained tributary fans leads to lateral migration, which can also threaten local infrastructure. While this condition creates O&M challenges, it may also provide some unique restoration opportunities by providing vertical control that could increase upstream overbank inundation and/or allowing lateral adjustment in the river that can rejuvenate in-channel and overbank habitat. These opportunities should be explored further in the next phase of this study to determine whether reasonable gains in habitat quality can be achieved while protecting local infrastructure.

7.2. Conclusions

The following conclusions can be drawn from the information developed for this baseline investigation of the RGCP:

1. The Rio Grande in Subreach 1 (Upper Rincon) has degraded by between 4 to 6 feet since 1943, and the bed is currently armored. Consequently, it is unlikely that there will be future changes in the stage-discharge relationship within the subreach that would adversely affect any constructed restoration projects.
2. In Subreach 2 (Lower Rincon), there has been significant degradation (8 to 10 feet) since 1943 downstream of the Hatch and Rincon Siphons. However, the amount of degradation diminishes in the downstream direction of both siphons, and there is evidence of some aggradation upstream of Bignell Arroyo that could increase the frequency of overbank flows.
3. In Subreaches 4 (Upper Mesilla) and 6 (Lower Mesilla), there has been up to 6 feet of degradation since 1943 below the Leasburg and Mesilla Diversion Dams. The amount of degradation diminishes in the downstream direction from both dams. Stage-discharge rating curves are unlikely to change significantly in Subreach 4, but aggradation in Subreach 6 could increase the frequency of overbank flows.
4. Subreach 5 (Las Cruces) has experienced about 2 feet of degradation since 1943. The existing mild aggradational trend in the subreach could increase the frequency of overbank flows.
5. Since 1943 Subreach 7 (El Paso) has experienced about 2 feet of aggradation, and continuing aggradation is likely to increase the frequency of over bank flows.
6. With the exception of Subreach 7 (El Paso), the hydraulic capacity in the RGCP appears to be higher than the design capacity because of channel degradation that has occurred since its construction; thus, dredging and sediment removal over extended reaches is probably unnecessary to maintain flood conveyance capacity.
7. Because of the potential for local sediment accumulation, arroyo tributary confluences should be monitored to insure that flood protection is not compromised and existing infrastructure is protected in these areas. This may require some method of adaptive management if river restoration is pursued at these locations to take advantage of the opportunities for increased overbank inundation and lateral channel migration that can rejuvenate in-channel habitat.
8. Under existing topographic conditions, the greatest potential for overbank flooding that could be used to enhance riparian vegetation occurs in the portion of the reach downstream from Mesilla Dam. Future changes in overbank roughness associated with any restoration projects that are developed in this area could, however, impact in-levee capacity during extreme floods, a factor that must be carefully considered in planning such projects.
9. At a number of the previously identified Point Project Measures restoration sites (USIBWC, 2004), overbank flows currently occur at steady-state Caballo releases between 3,500 and 5,000 cfs (Table 6.1). Significant lowering of the banks would, however, be required to create suitable conditions for riparian restoration at several of these sites (Table 6.2).

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APPENDIX A

Photographs of Canalization Reach of the Rio Grande Between Percha Dam (RM 105) and American Dam (RM 0)

Figure A.1. View east of the tributary mouth fan formed at the confluence of Holguin Arroyo and the Rio Grande.

Figure A.2. View downstream of cobbles and boulders that constrict the channel of the Rio Grande at the Angostura Arroyo fan.

Figure A.3. View upstream of a coarse-grained riffle formed at the confluence of Montoyas Arroyo and the Rio Grande.

Figure A.4. View upstream of sediment deposition in the backwater area caused by the Reed Arroyo constriction in Subreach 2.

Figure A.5. View upstream of destroyed bank protection on the left bank of the Rio Grande at the confluence with Montoyas Arroyo.

Figure A.6. View east across the Rio Grande at the confluence with Bignell Arroyo showing lateral erosion of the left bank and the RGCP levee in the background.

Figure A.7. View downstream of aggradation of the Rio Grande downstream of the Tierra Blanca Arroyo confluence.

Figure A.8. View east of USIBWC crews removing sediment that accumulated in 2006 at the mouth of Thurman I Arroyo in Subreach 2 about 0.8 miles downstream from the Hatch (Hwy) Bridge.

Figure A.9. View downstream of an excavated reach of the Rio Grande, and reconstruction and armoring of the west bank opposite Thurman I Arroyo in Subreach 2.

Figure A.10. View downstream of low relief gravel bar located downstream of Arrey Bridge where bed material samples WC 1 and SS-1 were collected.

Figure A.11. Close up view of bar surface sediments at WC 1, where the D_{50} is 45 mm.

Figure A.12. Close up view of bar surface and subsurface sediments where WC 1 and SS-1 (D_{50} – 15.6 mm) were collected.

Figure A.13. View upstream of reconstructed section of the RGCP at the mouth of Tipton Arroyo.

Figure A.14. View of reworked Tipton Arroyo sediments (S-1) that were sampled by MEI (D_{50} – 3.5 mm).

Figure A.15. View upstream of the fan formed at the mouth of Tierra Blanca Arroyo.

Figure A.16. Close up view of the reworked arroyo sediments at the upstream margin of the Tierra Blanca fan. The surface sediments were sampled with WC-2 (D_{50} – 45 mm).

Figure A.17. Close up view of un-reworked sediments on the Tierra Blanca fan that had a D_{50} of 16 mm (S-2).

Figure A.18. View upstream of a locally aggraded reach of the Rio Grande about 0.4 miles downstream of the confluence with Tierra Blanca Arroyo. Sample S-3 was collected from the bar in the middle of the picture.

Figure A.19. Close up view of the bar materials at sample S-3. The D_{50} of the bar materials is 4 mm (S-3).

Figure A.20. View downstream of the low relief alternate bar that was sampled (S-4) at the Sibley Point Bar site.

Figure A.21. Close up view of bar surface covered with freshwater mussel shells at the Sibley Point Bar site where sample S-4 was collected (D_{50} – 0.14 mm).

Figure A.22. View downstream of the low relief gravel bar that was sampled (WC-3 and S-4#2) downstream of Yeso Arroyo.

Figure A.23. Close up view of the gravel bar surface sediments downstream of Yeso Arroyo that were sampled with a pebble count (WC-3). The D_{50} of the surface materials is 47 mm (S-3).

Figure A.24. Close up view of the subsurface sediments at the gravel bar downstream of Yeso Arroyo. The D_{50} of the subsurface materials is 21 mm (SS-2).

Figure A.25. Close up view of the subaqueous sample that was collected upstream of the Hatch Siphon (S-4#2). The D_{50} of the bed materials is 2.2 mm.

Figure A.26. View upstream of the split flow reach of the Rio Grande downstream of the Salem Bridge. Sample S-5 was collected on the low relief gravel bar in the center-right of the picture.

Figure A.27. Close up view of the surface sediments on the gravel bar downstream of Salem Bridge. The D_{50} of the bar materials is 0.34 mm (S-5).

Figure A.28. View downstream of the aggraded reach of the Rio Grande located upstream of the BNSF Railroad Bridge, Highway 140 Bridge and the Rincon Siphon. Sample S-6 was collected from the bed of the river in the foreground of the picture.

Figure A.29. View upstream of the bed of the Rio Grande at Mile 54 Cut where sample S-9 was collected. The D_{50} of the bar materials is 0.4 mm.

Figure A.30. View upstream of alternate sand bars in the Rio Grande upstream of the Mesilla Bridge. Sample S-10 was collected from the upstream bar.

Figure A.31. View upstream of the sampling site on the alternate bar at S-10. The D_{50} of the bar materials is 0.33 mm.

Figure A.32. View of a west-side tributary arroyo fan that is delivering sediment to the Rio Grande about 2.1 miles downstream of the Mesilla Bridge.

Figure A.33. Close up view of sample S-11 on the surface of an alternate bar located 2.1 miles downstream of the Mesilla Bridge. The D_{50} of the bar materials is 0.29 mm.

Figure A.34. View upstream of Percha Dam at the head of Subreach 1 (Upper Rincon).

Figure A.35. View upstream of rock riprap protection at the Hatch Siphon at the downstream end of Subreach 1.

Figure A.36. View downstream of the Rio Grande immediately downstream of Percha Dam showing the coarse bed material.

Figure A.37. View downstream of the Rio Grande from the Arrey Bridge showing the channel depth that has resulted from 4 to 6 feet of degradation.

Figure A.38. View downstream of the reconstructed channel of the RGCP at the mouth of Trujillo Arroyo.

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APPENDIX B.1

Riada Engineering, Inc. Report

FLO-2D Modeling, Rio Grande - Caballo Dam to American Dam: Baseline Report on Existing Conditions, FLO-2D Model Development

FLO-2D Modeling
Rio Grande - Caballo Dam to American Dam

Baseline Report on Existing Conditions
FLO-2D Model Development

Submitted to:

Mussetter Engineering, Inc.

for
U.S. Army Corps of Engineers
Albuquerque District

Delivery Order 012
Contract No.   DACW47-03-D-0005

Prepared by:

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September 4, 2007

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Report Content: The FLO-2D model development, study and report “FLO-2D Model Development Below Caballo Dam,” were prepared by Jimmy S. O’Brien Ph.D., P.E. for the U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, New Mexico while an employee of Tetra Tech, Inc., Albuquerque, New Mexico in 2004. This report is also prepared by Dr. O’Brien and some text, tables and figures in the original report are reproduced herein with the permission of Tetra Tech, Inc. for background information and consistency and clarity in presenting the information.

FLO-2D Model Rio Grande - Caballo Dam to American Dam
Rio Grande Canalization Project - Restoration

Introduction

This report describes the application of the FLO-2D model to the Rio Grande Canalization Project (RGCP) reach from Caballo Dam to American Dam (105 river miles) for the purposes of developing restoration alternatives. FLO-2D is a two-dimensional flood routing model that predicts floodwave attenuation, floodplain inundation and spatially variable water surface elevations. This project builds on the FLO-2D model originally used to support the Upper Rio Grande Water Operations Model (URGWOM) for this reach. Both the original FLO-2D model development and this restoration project are collaborative projects between the U.S. Army Corps of Engineers (Corps) and the International Boundary and Water Commission (IBWC).

The original FLO-2D RGCP model was developed in 2004 by Tetra Tech, Inc. for the Corps of Engineers to predict the potential flood inundation associated with the 100-yr design flood event. The Corps'1996 report, 'Rio Grande Canalization Improvement Project, Hydrologic and Hydraulic Analyses' for the IBWC provided the background information to assess the return period and project design flooding. In this study, only discharges less that 5,000 cfs (approximately the 2-year flood) are simulated with the FLO-2D model for the purpose of investigating riparian restoration opportunities. This report describes the FLO-2D model development and results for riparian restoration baseline conditions.

FLO-2D Model Development

This section briefly describes initial FLO-2D model development and the subsequent model revisions for this project.

Restoration Hydrology

The flows that will be analyzed in this study are prescribed restoration flows that are within the range of operational releases from the Caballo Dam outlet works. Caballo Dam is typically operated in the spring and summer months at flows less than bankfull discharge. Average monthly flows range from 2,350 cfs in the upper Leasburg reach to 1,600 cfs in the lower Las Cruces reach. The RGCP channel has a conveyance capacity that ranges from 2,500 cfs to 3,000 cfs in the Upper Rincon Valley to less than 2,000 cfs in the Lower Mesilla and El Paso Valleys. Based on discussions between IBWC and the Corps of Engineers in 2004, it was decided that the project design flood event would consist of the tributary design storm flood inflows to the Rio Grande with a constant release of 2,350 cfs from Caballo Dam. The maximum outlet works discharge is 5,000 cfs.

The incremental restoration flows tested for this project were:

2,350 cfs	3,000 cfs	4,000 cfs
2,500 cfs	3,250 cfs	4,500 cfs
2,750 cfs	3,500 cfs	5,000 cfs

These discharges cover the entire possible range of release that would result in some overbank flooding from the average irrigation diversion to the maximum outlet release from Caballo Dam. Each incremental discharge represents 0.5 ft or less increase in stage. A brief note about Caballo Dam releases follows:

What is the potential for a Caballo Dam 5,000 cfs release? Appendix F of the IBWC Draft EIS (Parsons, 2003), states that a controlled release of 5,000 cfs from Caballo Dam can only occur "…when the reservoir reaches maximum water surface elevation (p. F-1, DEIS). The maximum water surface elevation is 4,182, approximately 10 ft above the top of the active conservation pool elevation and is "…above typical reservoir operation conditions (p. F-1, DEIS). The Caballo Reservoir water surface elevation has reached 4,182 only once (1942) since dam construction in 1938. The reservoir has been operated under Court Order No. CIV-90-95 HB/WWD since 1997 and the reservoir level during the summer irrigation has been controlled at about elevation 4,145 (plus or minus about 3 ft). When the flood pool reaches an elevation of 4,182, the outlet works can discharge 5,000 cfs. The DEIS (Parsons DEIS, p. 19, Appendix G, 2003) indicates that "…at present the feasibility of any release is questionable as…Caballo Dam operation regime…would not support peak discharges near the 5,000 cfs theoretical maximum value."

Future opportunities for a 5,000 cfs release appear to be limited. The DEIS (p. F-1, Appendix F) states, "...(w)hile the potential extent of overbank flows was analyzed based on a maximum theoretical value - 5,000 cfs discharge - it is important to emphasize that full discharge conditions would be reached only after several years of planning, gradual implementations and regular monitoring." This statement is echoed on page 4-6 of the DEIS where it is suggested that "…the maximum Caballo Dam discharge value would be reached at the end of a 20-year implementation period by gradually increasing releases of small magnitude."

The fact that 5,000 cfs dam release or higher has been achieved so infrequently (four times in the past 65 years: 1942, 1987, 1992, 1995 at the USGS gage below Caballo Dam), underscores that it is highly unlikely that 5,000 cfs would be released without some change in the outlet design. Discharges over 3,000 cfs have occurred about 11% of the time in post-Caballo gage record. Without an increase in water supply, a change in water operations or replacement of the Caballo Dam outlet facilities, it is unlikely that a 5,000 cfs would be released frequently enough to be effective in riparian restoration project opportunities (Tetra Tech, 2005)

How does the Project Design Storm Relate to Restoration Flows? To put the restoration flows in perspective, the discharges ranging from 2,350 cfs to 5,000 cfs, can be compared with the project design flood event. Noting the flood control afforded by Caballo Dam, all of the infrequent large flooding occurs from tributary arroyo inflow downstream. In the initial study for the Corps and IBWC, it was confirmed that the 24-hr general storm over the entire basin will produce the highest peak discharge and largest storm volume. Some adjustments to the Corps 1996 runoff parameters were made to the HEC-1 model that was utilized in the 2004 study. The HEC-1 flooding routing results for the Rio Grande channel are reproduced in Table 1. The first two columns represent the HEC-1 routing results and the last column is the FLO-2D flood routing.

Table 1. 100-year 24-hr Peak Discharge Caballo Dam to American Dam			
	HEC-1 Results		FLO-2D Results
Location	1996 Corps Original Q_p (cfs)	2004 Q_p (cfs) 5,000 cfs release + orig. hydrology	2004 Q_p (cfs) 2,350 cfs release + revised hydrology
Caballo Dam release	5,000	5,000	2,350
Trujillo Canyon	9,100	12,700	4,880
Montoya Arroyo	11,300	15,900	8,470
Green Canyon	11,700	15,800	11,600
Tierra Blanca Arroyo	15,600	23,200	10,430
Sibley Arroyo	17,600	24,300	12,970
Berrenda Arroyo	18,700	25,200	14,900
Arroyo Cuervo	18,900	24,300	15,150
Placitas Arroyo	19,100	21,300	14,690
Angostura Arroyo	17,800	19,500	14,300
Rincon Arroyo	22,400	24,100	14,070
Reed Arroyo	22,500	24,300	14,110
Broad Canyon	22,400	20,800	11,690
Faulkner Canyon	22,200	19,300	10,990
Leasburg Diversion Dam	22,200	19,200	12,060
Shalem Bridge	20,900	18,100	13,120
Dona Ana Dam	21,000	18,200	12,580
Picacho Dam	21,300	18,400	12,700
Mesilla Diversion Dam	20,000	17,400	12,870
Vinton, Texas	16,500	14,600	12,110
Nuway, Texas	16,300	14,500	13,130
Canutillo, Texas	15,900	14,200	13,090
Borderland, Texas	15,000	13,400	11,170
Courchesne Bridge	14,400	12,800	9,790
American Diversion Dam	14,000	12,500	10,990

Table 1 indicates that the Tetra Tech HEC-1 modifications resulted in a 100-year 24 hour storm peak discharge that occurs further upstream in response to the runoff from the larger watersheds in the upper third of the drainage with a slightly higher peak discharge. Floodwave attenuation was more significant in the downstream reaches.

Diversions and Return Flows

To replicate historic flow events and calibrate the RGCP FLO-2D model in the 2004 study, it was necessary to compile diversion flows and return flows for selected periods of record. River flow is diverted from the river at the four diversion dams and the associated irrigation return flows were analyzed. Only a few selected wasteways for the return flow from the diversion dams are monitored by EBID and some of these had discharges of less than 10 cfs. Those returns that were less than 10 cfs for the calibration period were excluded from the model. For this study, Mussetter Engineering, Inc. provided mean annual diversion flows during the irrigation. These were input as steady diversions into the FLO-2D model as follows: Percha Dam (combined Percha Canal and Arrey Canals) = 244 cfs; Leasburg Dam = 395 cfs; Mesilla Dam (combined Eastside Canal and Del Rio Lateral) = 203 cfs. While some return flows were simulated in the flood model, no return flows were modeled in the restoration analysis. This will provide a more conservative estimate of flood inundation.

Topographic Data, River Cross Sections and Model Details

A brief discussion is presented to highlight the topographic and cross section data base with which the FLO-2D model was developed. This topographic, orthographic and cross section data base for this reach of river is considered to be excellent. In early 2005 a comprehensive digital mapping project was completed for a significant portion of Dona Ana County, New Mexico including the Rio Grande corridor which was fully mapped with color digital orthophotos, LIDAR digital terrain data and contour graphics files. The project was administered by the Dona Ana County Flood Commission (DACFC). Over 1,200 square miles were topographically mapped by the project. The mapping products were parsed into files that correspond with the Public Land Survey System (PLSS). A digital ortho file, a terrain data file, and a contour file were prepared for each section of land that was mapped. The New Mexico State Plane Coordinate Grid System NAD 83 Central zone was utilized for map geo-reference control. Coordinate files were written in U.S. survey feet and elevation data was referenced to the North American Vertical Datum 1988 (NAVD 88) and digital orthophotos were generated from the 1:12000 scale aerial photography. The photography was scanned and rectified at a resolution which produced 1 foot pixels in the final digital image files. These high resolution images were delivered in 120 mega-byte files and show substantial detail of the floodplain features.

The mass point LIDAR data was edited and filtered to eliminate points that did not reflect "bare earth" ground points. The DTM points were imported to the FLO-2D Grid Developer System (GDS) along with the images in 12 groups and the data base was edited to represent the Rio Grande potential floodplain. This reduced the overall number of points that had to be interpolated for grid element elevation assignment. Each of the 12 groups of DTM points were filtered for both high and low DTM elevations and grid element elevations were then interpolated and assigned. The 12 groups of grid elements were then combined into one grid system consisting of 43,937 grid elements that were 250 ft square.

The surveyed channel cross sections were separated into three groups. The "Below Caballo" (BC) lines begin below the dam and extend to the Leasburg Diversion Dam. The "Leasburg Dam" (LD) lines begin at Leasburg Dam and extend to the Mesilla Diversion Dam. The "Mesilla Dam" (MD) lines begin at Mesilla Dam and extend to the American Diversion Dam in El Paso. There were a total of 145 cross sections that were delineated as sixty-six (66) BC lines, twenty-five (25) LD lines, and fifty-four (54) MD surveyed cross sections. A cross section was located about one every half mile with more cross sections surveyed in the vicinity of hydraulic structures. These cross sections were distributed and interpolated to 2,046 channel elements.

To complete the FLO-2D model, various floodplain details were added to the model including levees, hydraulic structures, infiltration and evaporation. The levees on both sides of the river constitute an important control for limiting overland flooding through most of the RGCP project reach. There are approximately 65 miles on the east side and 56 miles on the west side of the river. Generally the levees are set back from the active river channel less than seven hundred feet. Levees block grid element flow directions and are represented by a crest elevation. Flooding can overtop and fail the levee, but levee failure was not simulated in the FLO-2D model for this project. Levee discontinuities created by wasteways, tributary arroyos and roadway/railroad embankments were coded in the model.

A total of 27 bridges, 2 siphons and 4 diversion dams were added to the model as hydraulic structures with stage-discharge rating tables. Of the four diversion dams, only the Mesilla Diversion Dam was included in the original 1996 HEC-2 model because the model was divided into reaches around the other diversion dams. To create a rating table for the FLO-2D model, the HEC-2 data was upgraded to a HEC-RAS model and a series of discharges ranging from 100 cfs to 30,000 cfs were run to compile a table of discharge as function of flow depth. A rating table was also used to represent the flow past the four diversion dams (Percha Dam, Leasburg Dam, Mesilla Dam and American Dam) in the FLO-2D model. To construct the rating table, the HEC-RAS model was applied with critical flow for the range of discharges up to the diversion canal capacity. A broad crested weir equation with a coefficient of 2.85 was applied to compute the discharges over the diversion dam.

The FLO-2D model computes water losses due to infiltration and evaporation. Channel and overland flow infiltration is calculated using the Green-Ampt infiltration model. In the absence of spatially variable soil data, uniform infiltration parameters were assigned for the floodplain and channel. An open water surface evaporation routine in the FLO-2D model accounts for evaporation losses associated with long duration flood flows. Evaporation is computed based on a mean monthly total evaporation distributed daily on the basis an assumed diurnal hourly variation. The evaporation loss does not include evapotranspiration from vegetation.

FLO-2D Model Calibration

Model calibration encompassed three flood routing characteristics: hydrograph shape (volume), hydrograph timing and water surface elevation. The flood hydrograph shape is primarily defined by inflow discharge, irrigation diversions, and system losses (infiltration and evaporation). Peak discharge or discharge spike timing (arrival) at various locations in the system is primarily a function of volume, but is also dependent on resistance to flow. To calibrate the FLO-2D model, historical hydrographs were replicated and the water surface elevation surveys were matched.

The first calibration effort was focused on the water surface elevations surveyed during the channel cross section data collection in June and July 2004. The calibration procedure involved reach n-value adjustment so that the difference between the surveyed and predicted water surface elevation was less than 0.5 ft. The final calibration had differences in predicted and surveyed water surfaces that ranged from -0.45 ft to 0.49 ft with an average of 0.034 ft difference per cross section.

Recorded gage discharge hydrographs were compared with the FLO-2D predicted hydrographs for the period of June-July 2004. The differences between the measured and predicted hydrographs are attributed to gage calibration errors and return irrigation drain flow that is not considered in the model. The return irrigation drainage increases in the downstream direction resulting in more discrepancy between the measured data and predicted results. There were no overbank flows for the 2004 simulation. The comparison of predicted flow hydrographs with four gaging station hydrographs are shown in Figures 1-4. A storm inflow spike occurs in the reach from Leasburg to Mesilla Dam as shown in Figures 2 thru 4.

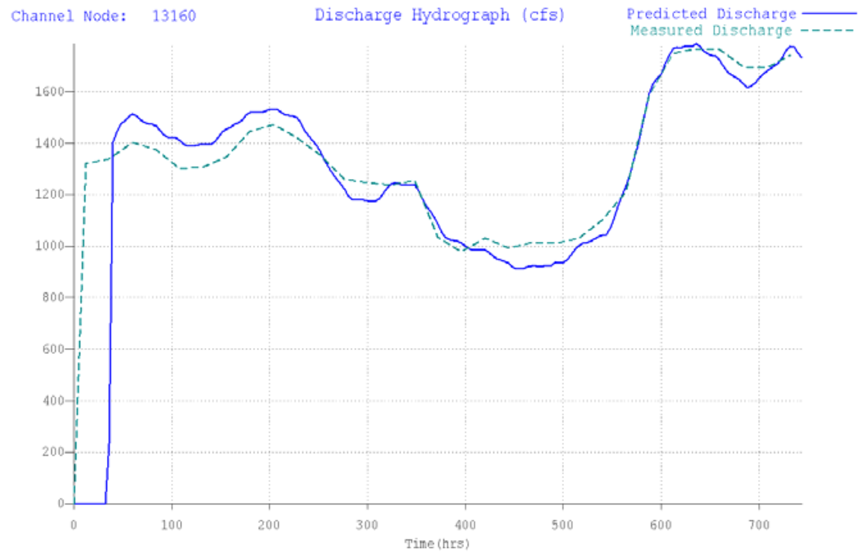

Figure 1. 2004 Haydon Gage Data vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

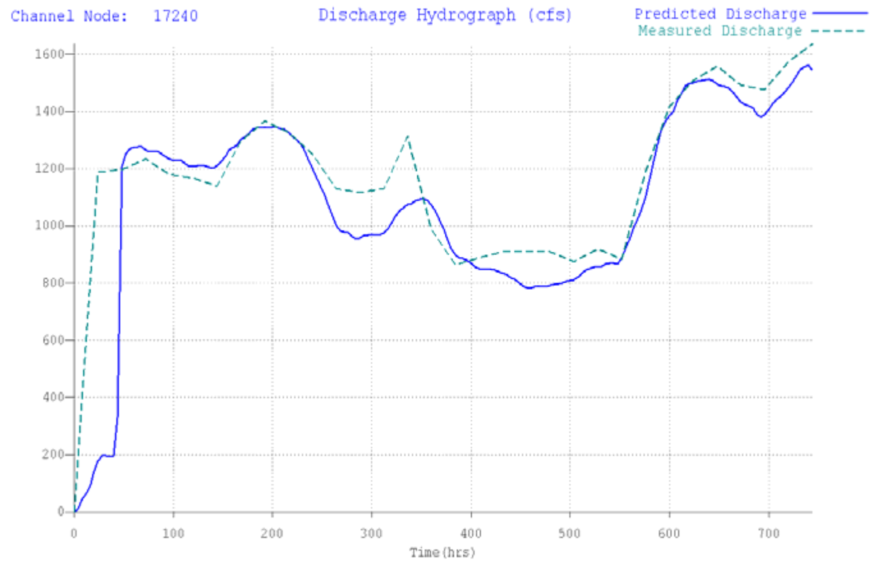

Figure 2. 2004 Leasburg Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

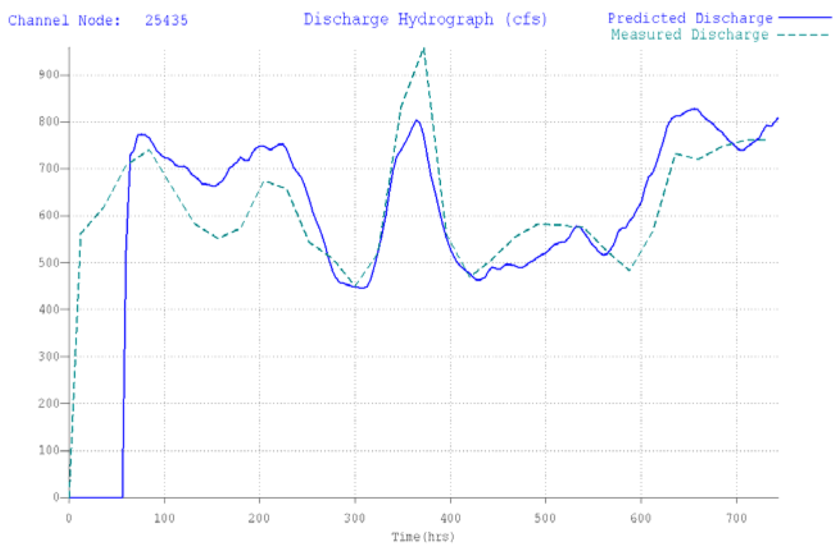

Figure 3. 2004 Mesilla Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

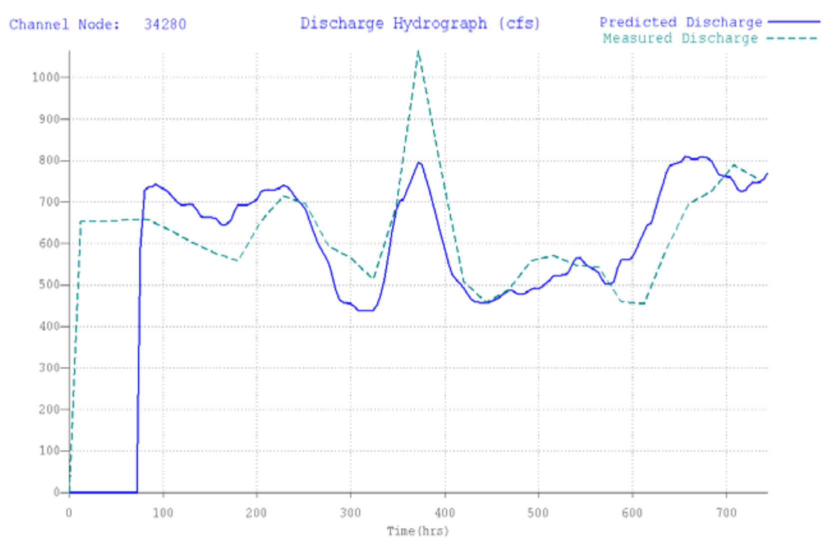

Figure 4. 2004 Anthony Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

The second calibration effort focused on the shape of the hydrograph for higher flows. Flows during July 1995 were used when the Caballo Dam release ranged from 3,600 to 4,540 cfs. This 31 day period had a relatively complete record of irrigation diversions and return flows throughout river system that was made available by EBID. Since the n-values were calibrated for the 2004 surfaced water surface elevations, only minor n-value adjustments were made to the 1995 data set to account for potential variation in roughness with flow depth. To provide a better match of the hydrographs at the various river gage locations, the channel hydraulic conductivity was adjusted by reach. Again, it should be noted that the gaging data may be inaccurate and there are irrigation return flows that are either ungaged or not included in the data base. The cumulative return flow that is not accounted for is less than 200 to 300 cfs.

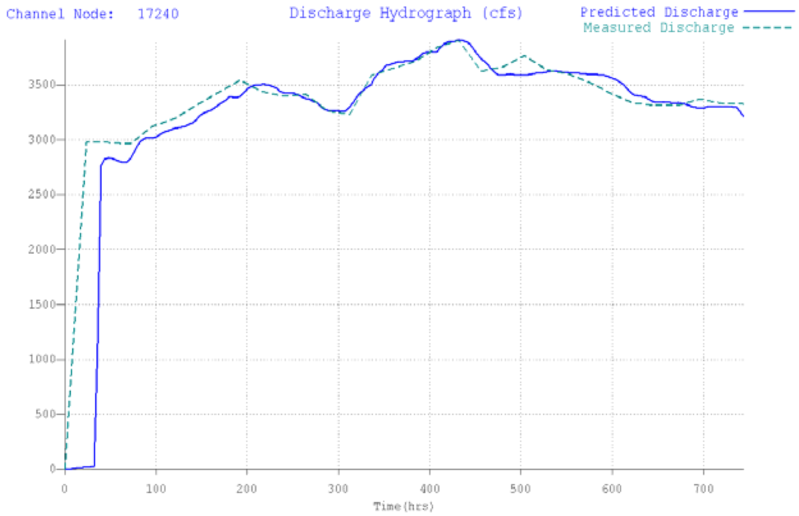

Figure 5. 1995 Leasburg Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

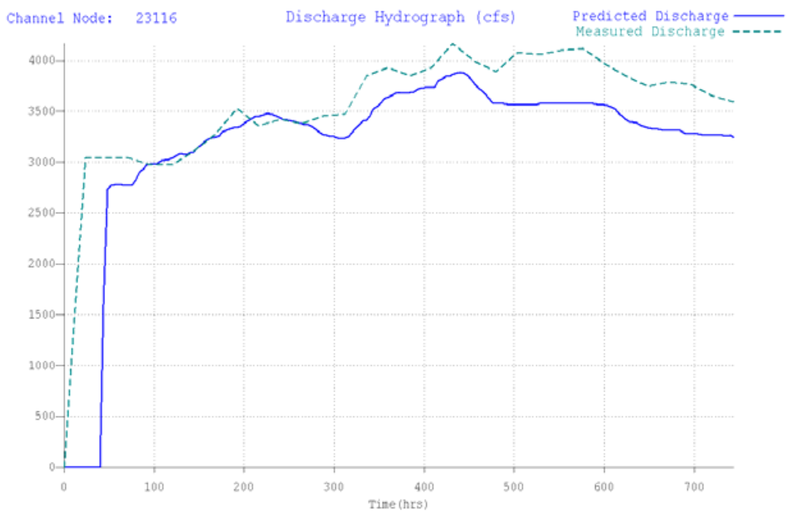

Figure 6. 1995 Picacho Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

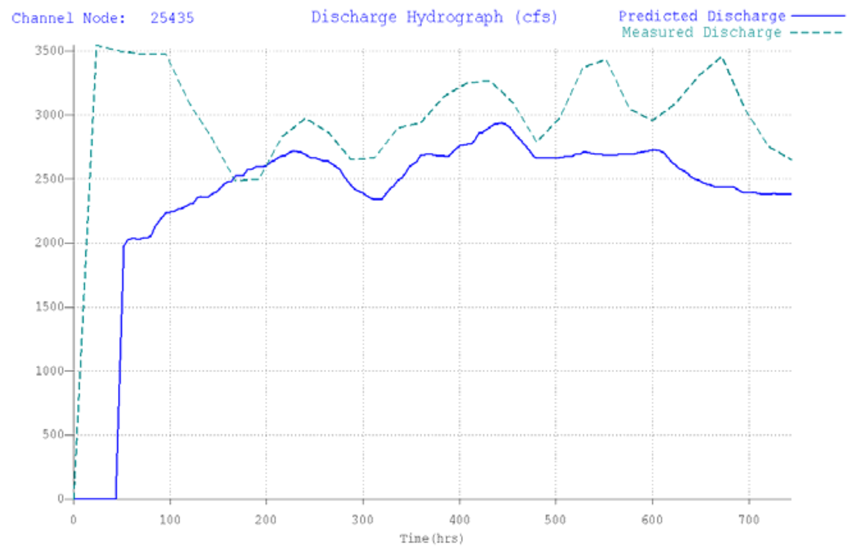

Figure 7. 1995 Mesilla Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

A final calibration run was undertaken for July 1998 where the discharge was entirely contained with the channel. This calibration effort was used to verify the previously calibrated channel *n*-values and geometry. The average *n*-value in the RGCP reach was 0.029. The results indicate a similar pattern as the previous calibration runs where the difference between measured and predicted discharge increased in the downstream direction. Both the Picacho and Mesilla gages show increased divergence between measured and predicted flows revealing the increased return flows with time. These calibration results confirmed that the model replicated both water surface elevation and hydrographs shape and timing as noted by correlation of the spikes and troughs in the discharge hydrographs (Tetra Tech, Inc., 2004).

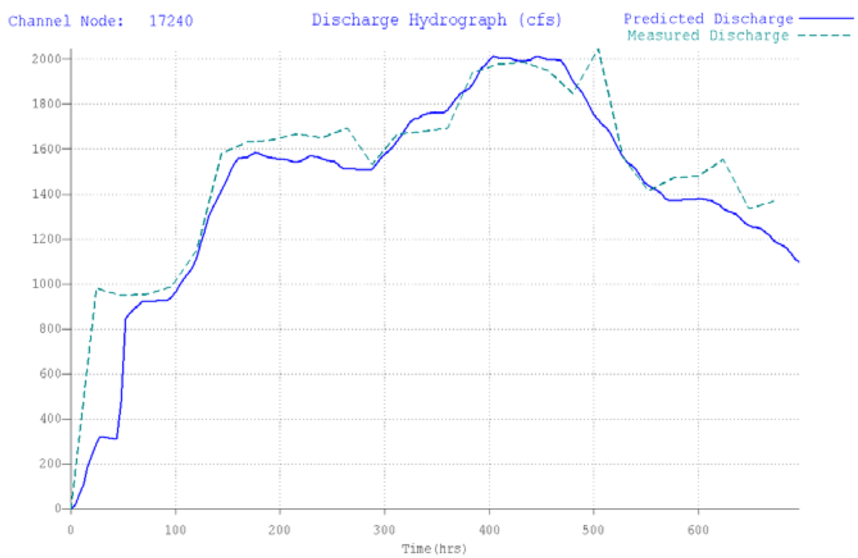

Figure 8. 1998 Leasburg Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

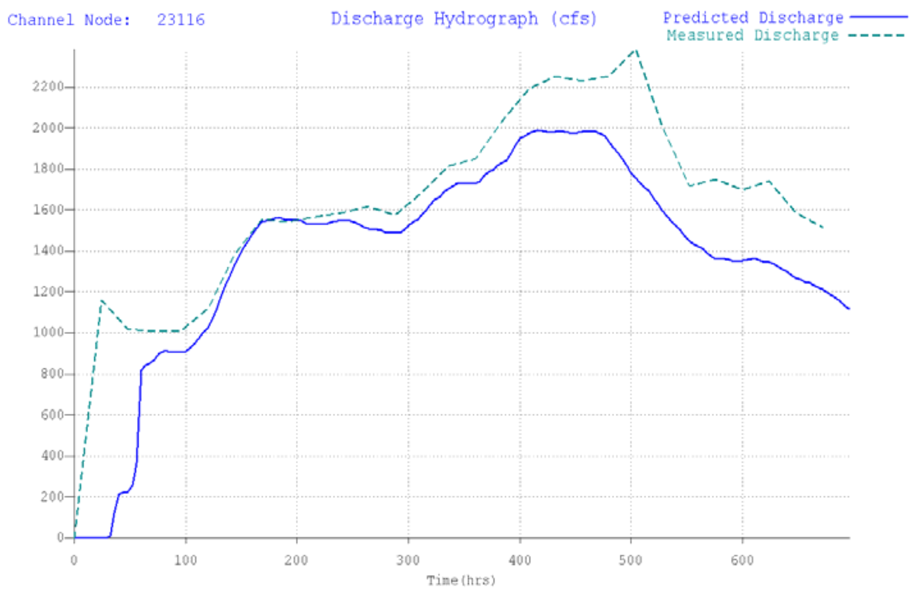

Figure 9. 1998 Picacho Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

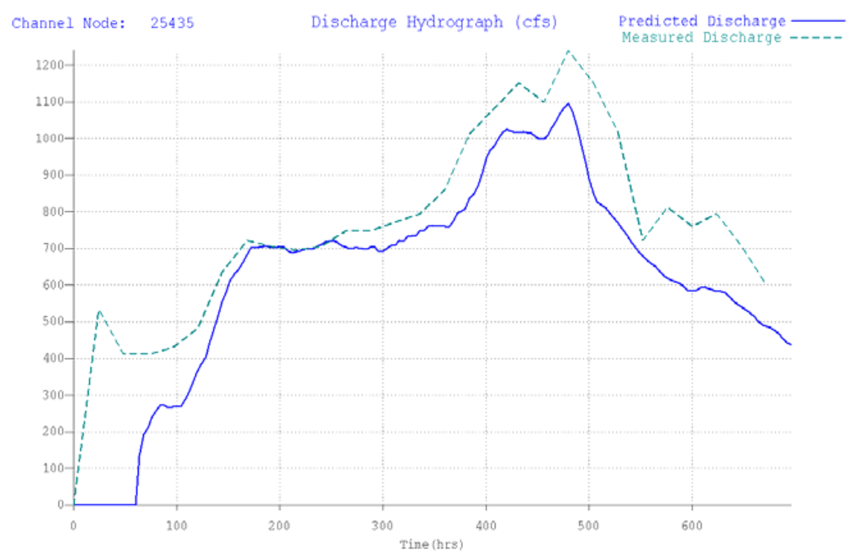

Figure 10. 1998 Mesilla Gage vs. FLO-2D Predicted Hydrograph
(after Tetra Tech, Inc., 2004)

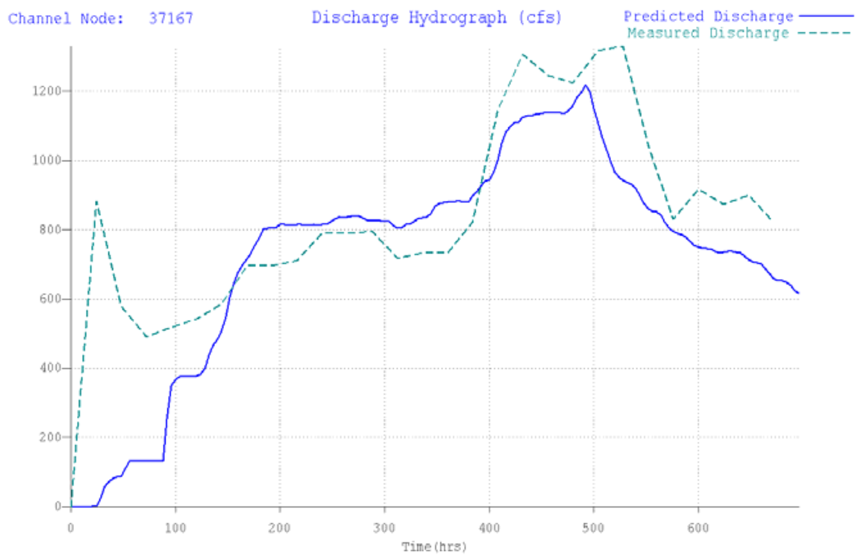

Figure 11. 1998 Canutillo Gage vs. FLO-2D Predicted Hydrograph (after Tetra Tech, Inc., 2004)

FLO-2D Results

2004 Flood Hazard Simulation Results

A brief summary of the initial Tetra Tech (2004) flood hazard delineation results for the six return period floods is presented followed by a discussion of the results for the restoration project existing condition runs. In the flood hazard delineation project, the flood flows varied through the RGCP reach in both time and space based on the timing of rainfall runoff that was contributed from the tributary arroyos. Each tributary inflow flood hydrograph was routed accounting for channel-floodplain interaction, floodplain storage, infiltration, evaporation and irrigation diversion and return flows. The six return period peak discharge results are presented in Table 2.

Table 2. Predicted Rio Grande Peak Discharge (cfs)

Return Period	Peak Discharge (cfs)*
2-yr	7,560
5-yr	8,400
10-yr	10,450
25-yr	14,800
50-yr	18,630
100-yr	21,760

*A maximum peak discharge in RGCP for each return period; generally occurs in the vicinity of Rincon Arroyo. Specific location varies with return period.

These results reflect a 2,350 cfs constant irrigation release from Caballo Dam. The peak discharge results from the revised hydrology and 2,350 cfs release are shown in Figure 12 as function of river mile (red line). These results are plotted against the Corps 1996 results (dark blue line) that were computed using the HEC-1 model and Muskingum-Cunge routing. The

FLO-2D results for the constant 5,000 cfs Caballo Dam release and the original flood hydrology are also displayed (light blue line). The revised hydrology and smaller irrigation release combined with overbank storage floodwave attenuation results in a significantly smaller peak discharge throughout the entire river reach. The HEC-2 peak discharge ranges from 5,000 cfs at Caballo Dam to 22,500 cfs at river mile 27.4 and to 14,300 cfs at American Dam. The FLO-2D predicted peak discharge reaches 17,700 cfs at river 28.8 and is only 10,800 cfs at American Dam indicating that floodwave attenuation is more significant than that computed in the Corps 1996 HEC-2 analysis.

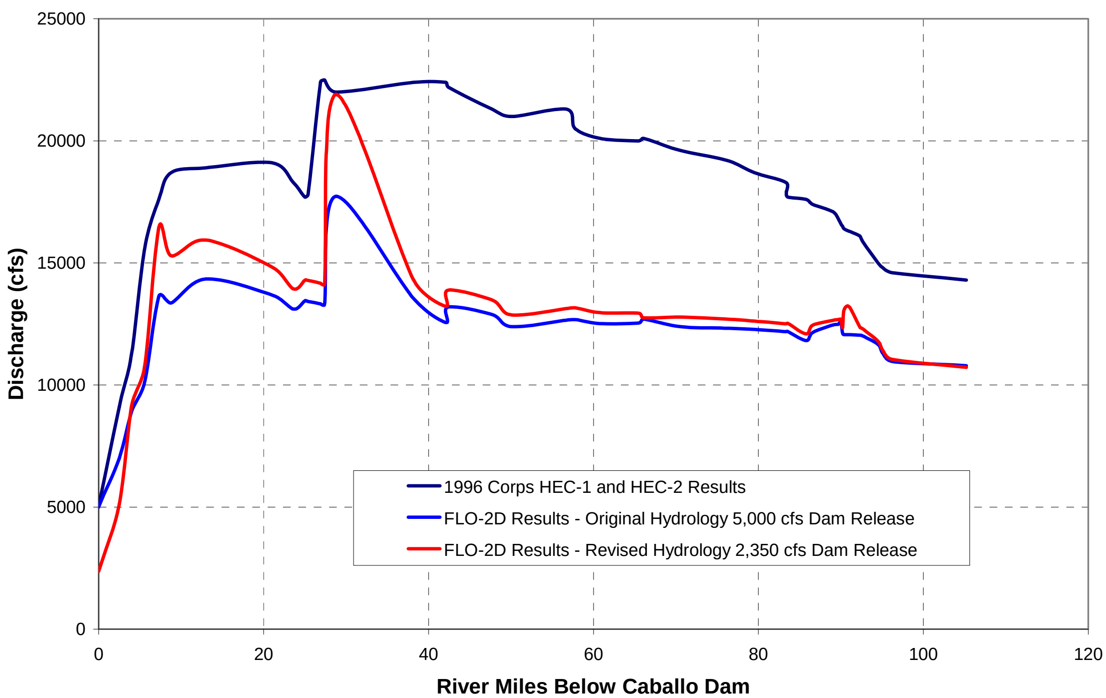

Figure 12. Project Design Flood 100-year, 24-hr storm Peak Discharge as a function of River Mile (after Tetra Tech, Inc., 2004)

Table 3 lists the FLO-2D predicted area of inundation for 2,350 cfs constant release from Caballo Dam with the revised hydrology for an inflow flood volume of 100,210 af. Predicted levee overtopping was concentrated in two reaches, the Lower Rincon Valley and the El Paso area.

Table 3. Predicted Areas of Inundation (after Tetra Tech, Inc., 2004)	
2,350 cfs Release – Revised Flood Hydrology (acres)	
Maximum Wetted Floodplain	6089
Maximum Wetted Channel Surface Area	3761
Total Maximum Area	9850

The selected restoration flows cover a range of discharges from approximately bankfull flow conditions (2,350 cfs) to the maximum Caballo Dam outlet releases (5,000 cfs). The FLO-2D model runs were conducted both with and without diversions in increments of 250 cfs to 500 cfs. No irrigation return flows were simulated. The same FLO-2D data files were used for each simulation and these were essentially the same calibrated data files used in the 2004 flood hazard delineation study. The data files were converted to FLO-2D Version 2007 which included elimination of a few parameters and simplification of several data files. In addition, Version 2007 also has improved numerical stability and is more computationally efficient. In conducting the FLO-2D simulations of the baseline conditions, the following difficulty with the hydraulic structure data base was noted.

The original 1995 Corps HEC-2 model was converted to a HEC-RAS model to generate the original rating tables for the bridges, siphons and diversion dams and two issues arose:

1. The channel (0.02) and floodplain (0.032) n-values were underestimated.
2. The original model cross sections were extracted from DTM data based on aerial photogrammetry that was flown when there was water in the channel. The cross sections are missing the lower portion of the channel cross section (see Figure 13).

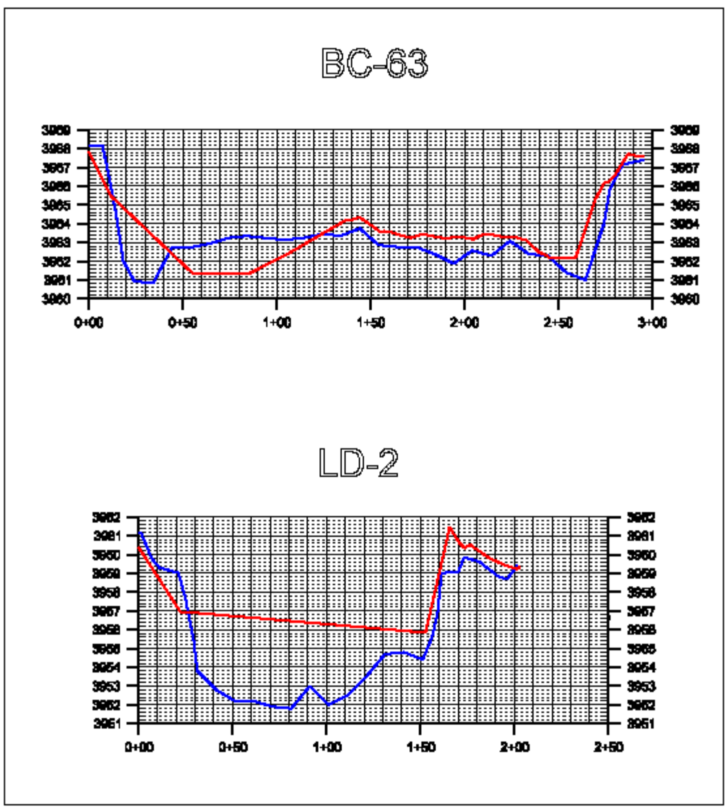

Figure 13. HEC-2D (red) Cross Section vs. 2004 Surveyed Cross Sections (blue) (after Tetra Tech, 2004)

In Figure 13, if there was low flow in the channel at the time the aerial photography was flown, there were relatively minor differences between the two cross section data bases (BC-63). At locations were there was backwater or pools as in the case of bridges or diversion dams, the discrepancy between the cross section was much greater (LD-2). This missing portion of the cross section distorted the rating tables generated by the HEC-RAS model and created surging in the FLO-2D (numerical instability) around the hydraulic structures. At the outset of the restoration project it was not anticipated that the rating tables would be an issue because 100-year flood model did not display numerical stability problems. Most of the observed surging was limited to only a grid element or two around the hydraulic structures but included most of the bridges. The range of restoration flows (2,350 cfs to 5,000 cfs) was significantly lower than the 100-year peak flow that exceeded 12,000 cfs. The effect on the FLO-2D model results of the distorted rating curve was more pronounced on the lower flows than the bankfull flows. The hydraulic structure rating tables for the preliminary FLO-2D runs were adjusted by increasing the flow depth for a given discharge and all of the numerical surging was eliminated. The hydraulic structure rating tables, however, are essentially fabricated.

It is unlikely that any selected restoration projects will be located near hydraulic structures. If a specific restoration project site is impacted by bridge backwater effects, it would be possible to create a new rating table for the specific structure. The HEC-RAS model will be updated in the future with the surveyed cross sections and the DTM floodplain data base. This will create a complete HEC-RAS model that would be available to both the Corps and IBWC for future projects in addition to providing more accurate rating tables for the FLO-2D model.

The FLO-2D area of inundation as function of discharge for of the incremental restoration steady flows is presented in Figure 14. For the no diversion scenario, there is essentially a linear increase of the area of inundation with discharge for the range of restoration flows from 2,350 cfs to 5,000 cfs and an increase in the area of flooding for the 4,500 cfs and 5,000 cfs flows. For the 2,350 cfs restoration flows with diversions, there is only about 1 acre of overbank flooding. Due to channel losses and diversions, the discharge that initiates overbank flooding below Mesilla Dam is about 1,500 cfs. It should be noted that at some discharge, the flooding would essentially cover the entire the active floodplain and then the rate of increase in the area of inundation with increasing discharge would begin to decline. Also, the accuracy of the FLO-2D model to predict will very shallow and limited overbank flooding is dependent on the bank and floodplain grid element elevations interpolated from the DTM data. The elevation accuracy is on the order of plus or minus 1 ft (about the same as the 2 ft contour intervals that are developed from LIDAR data). The FLO-2D results are less accurate for shallow overbank flows than for the large flood events.

The location of the predicted areas of overbank flooding has been prepared on ArcGIS shape files. Example of the shape files are shown on Figures 15 and 16. These shapes file were prepared by generating FLO-2D Mapper shaded contour plots that were edited in ArcGIS to display only the overbank flooding. Some editing was necessary to correctly display the flooding with respect to the levees or other floodplain features confining the flood. The flood maps show flooding at all discharge levels for both the diversion and no diversion simulations. The FLO-2d results for the lower range of discharges from 2350 cfs to 3000 cfs showed minimal flooding just north of El Paso and the railroad bridge. There was very little flooding in the middle reach (Mesilla to Leasburg) and no flooding north of Leasburg. For the mid-range of steady flows from 3250 cfs to 3750 cfs, increased flooding in the El Paso reach was evident but again limited overbank flow in the middle and northern subreaches. For discharges greater than 4000 cfs, flooding was predicted throughout the entire Caballo reach, with the Las Cruces-El Paso experiencing the most flooding, the Leasburg-Mesilla reach having moderate flooding and the Caballo-Leasburg reach showing minimal flooding. This pattern was consistent for all of the higher flows. Flooding was most significant for the 5000 cfs discharge for both diversion and no diversion. There was not much difference between the diversion and no diversion flooding for 4,500 cfs and 5,000 cfs simulations.

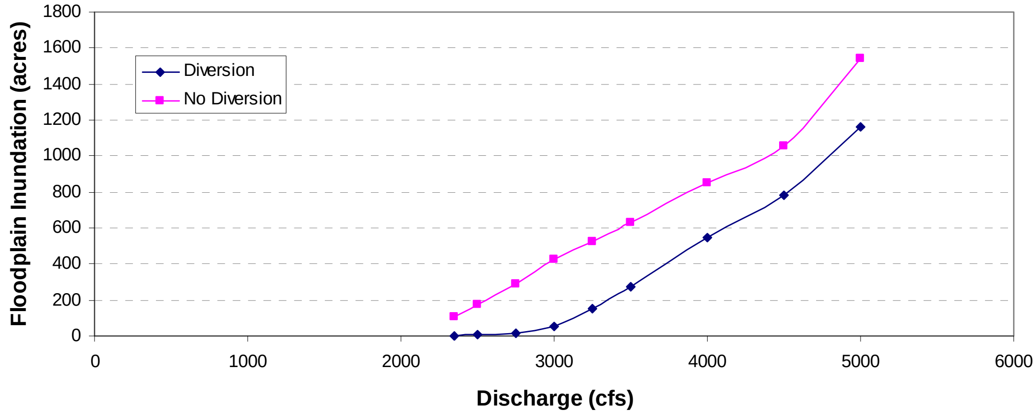

Figure 14. Predicted Area of Inundation for the Range of Potential Restoration Flows

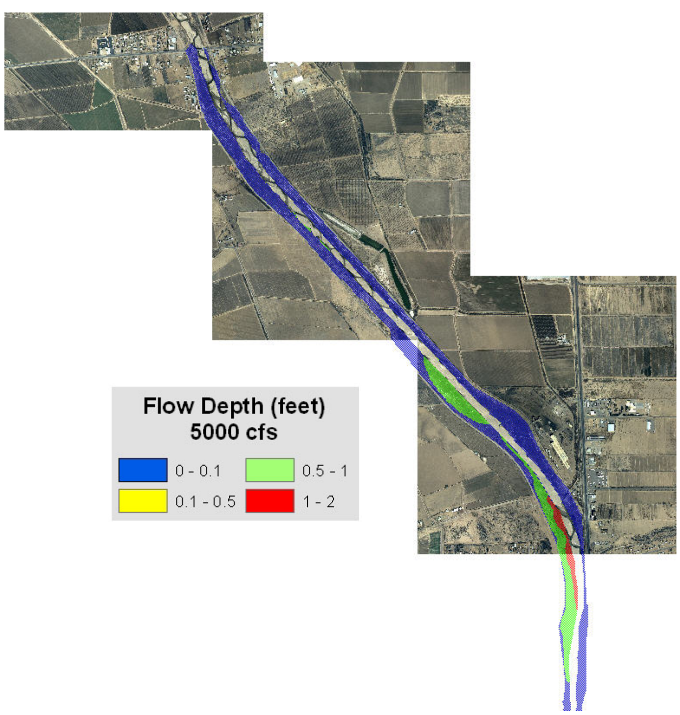

Figure 15. Example: FLO-2D Predicted Area of Inundation (5,000 cfs – No Diversion)

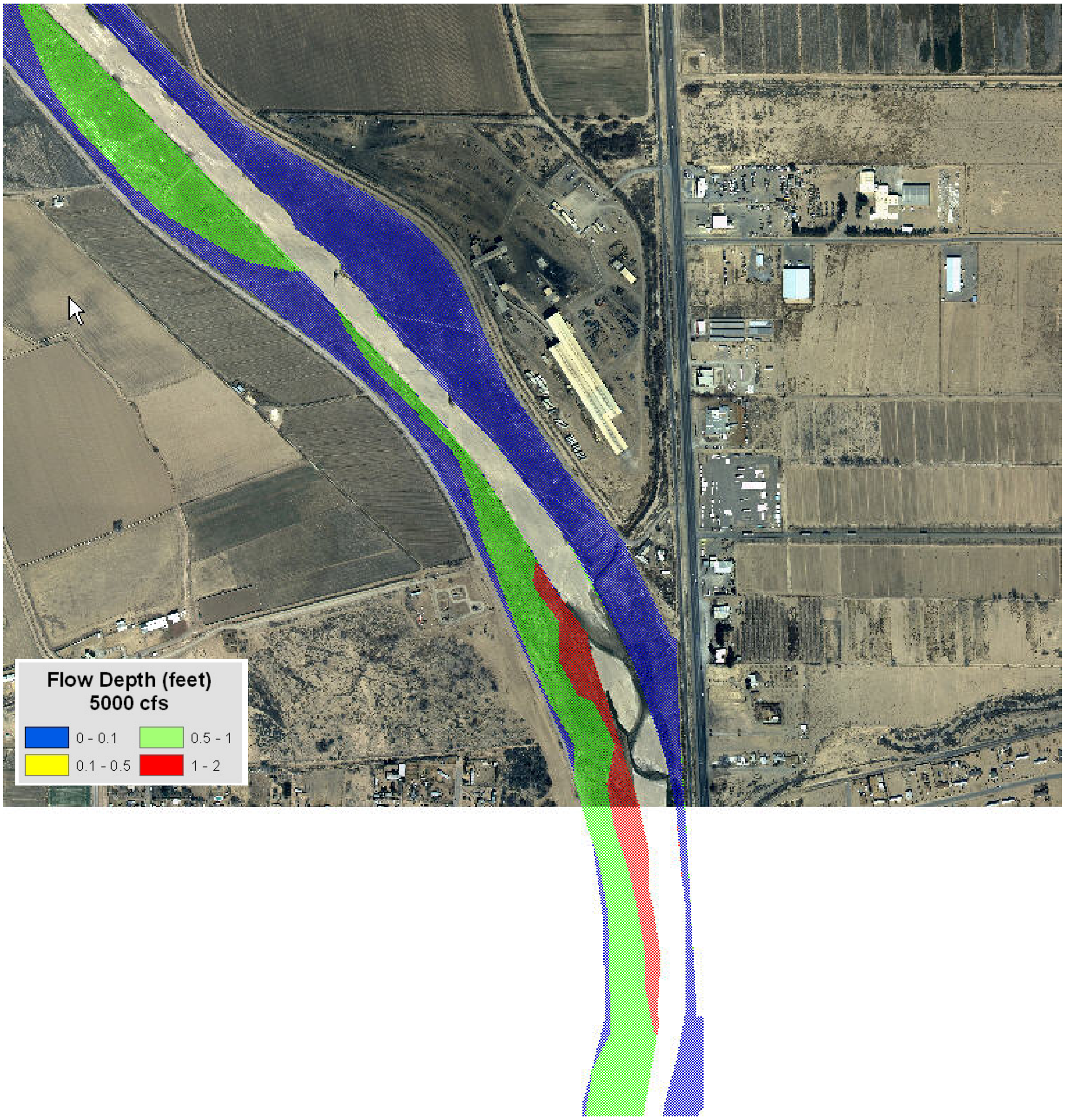

Figure 16. Close-Up Example: FLO-2D Predicted Area of Inundation
(5,000 cfs – No Diversion)

The shape file maps can be used to locate areas for potential riparian restoration opportunities that can be currently flooded or flooded in the future with minimal enhancement related to bank shaving or floodplain lowering. Increased overbank flooding could also be induced with downstream channel constrictions to raise water surface elevations associated with a specific range of discharge. Additional FLO-2D analysis will be performed on the selected project designs to enhance the aquatic and riparian environment in the Caballo reach of the Rio Grande.

Summary

This investigation used the FLO-2D RGCP model developed for flood hazard delineation in 2004 by Tetra Tech, Inc. for the Corps of Engineers and IBWC. The 2004 FLO-2D model was calibrated to three hydrographs replicating surveyed water surface elevations as well as hydrograph timing and shape. Flood hydrology, topographic/orthographic data base and cross section surveys used to build the 2004 model are discussed.

To establish baseline conditions for potential riparian restoration opportunities, the FLO-2D model was applied to the RGCP reach from Caballo Dam to America Dam for a series of incremental steady flows that ranged from approximately bankfull discharge above Mesilla Dam (2,350 cfs) to the maximum Caballo Dam outlet release (5,000 cfs). The steady flow discharge scenarios were simulated for both non-diversion conditions and irrigation diversions from Percha, Leasburg and Mesilla Diversion Dam. From the model output, the relationship between the area of inundation as function of discharge was generated. The predicted area of inundation for each flow scenario was plotted, edited and saved as shape files for importing into ArcGIS. These areas of inundation can now be reviewed in ArcGIS using background aerial images for reference to identify potential riparian restoration opportunities within the active floodplain.

Recommendations

The following details can be added to the model as information and data becomes available or as more detail is required in specific reaches or areas to support developing restoration alternatives.

Local Floodplain Details. Accurate flood hazard delineation in local reaches depends on roadway/railroad embankment, wasteways and irrigation system ditches and spoil pile embankments. These may be important details for analyzing the shallow flooding associated with specific restoration projects. Additional floodplain topographic survey may be required to justify adding more floodplain details.

Hydraulic Structure Operation During Flooding. Hydraulic structures are important to local overbank flooding associated with backwater conditions, but are not critical to the passage of the floodwave through the system. The bridges, diversion dams and siphons have negligible upstream storage and therefore accuracy of the rating tables is not critical to the design flood progression through the system. If restoration project alternatives appear to be within the influence of hydraulic structure backwater effects, then improvements to the rating tables will be considered.

Spatially Variable Infiltration. Spatially variable infiltration would improve estimates of the water depletion/salvage associated with restoration flooding. A detailed review of soil maps would be required to add this component detail. Adding spatially variable infiltration to the FLO-2D model would be appropriate for analyzing potential losses associated with proposed restoration flooding.

References

Parsons, 2003. “River Management Alternatives for the Rio Grande Canalization Project,” Draft Environment Impact Statement prepared for the United States Section International Boundary and Water Commission, El Paso, Texas.

Tetra Tech, Inc., 2004. “FLO-2D Model Development Below Caballo Dam,” Report prepared for the U.S. Army Corps of Engineers, Albuquerque District, Albuquerque, New Mexico.

U.S. Army Corps of Engineers and Resource Technology, Inc. 1993-1996. “Rio Grande Canalization Improvement Project, Percha Dam to American Diversion Dam, Texas, Study Documentation, Volume 3,” Prepared for the IBWC.

APPENDIX B.2

Rio Grande Canalization Program (RGCP) Restoration FLO-2D Results (on attached DVD)