# Evaluation of Bar Morphology, Distribution and Dynamics as Indices of Fluvial Processes in the Middle Rio Grande, New Mexico

Submitted to: **New Mexico Interstate Stream Commission and Middle Rio Grande Endangered Species Act Collaborative Program (Project 04-081 Science)**

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# EXECUTIVE SUMMARY

## ES.1. Introduction

Previous studies have demonstrated that changes in the types and numbers of bars in an alluvial river can be related to changes in fluvial processes (Brice, 1964; Maizels, 1979; Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993). This investigation of the morphology and dynamics of bars in the Middle Rio Grande was designed to evaluate these relationships within the reach of the Rio Grande between Cochiti Dam and San Marcial in central New Mexico, and to develop a bar classification system for this reach of river that could provide a first-cut understanding of the fluvial processes operating at sites within this reach proposed for habitat restoration or other modifications. The study addressed bar changes through time and space in response to man-induced and climatic changes in the watershed hydrology, sediment supply to the river, and channel morphology. This project was conducted under Fiscal Year (FY) 2003 and 2004 funding from the Middle Rio Grande Endangered Species Act Collaborative Program and the New Mexico Interstate Stream Commission (NMISC),

## ES.2. Objectives

The objectives of this study were to:

1. Develop a Bar Classification: Conduct site-specific field surveys in a set of subreaches deemed representative of the range of geomorphic conditions in the Middle Rio Grande, and based on these surveys, develop a field-based classification for the bar types identified in the river and on the channel margins.
2. Evaluate Bar Changes over Time: Perform analysis of time-sequential aerial photography for the study subreaches to evaluate and classify changes in the number and types of bars in the river over time.
3. Summarize Changes in Fluvial Processes: Summarize the morphological, hydrological and sedimentological changes that have occurred in the Middle Rio Grande in general, and the study subreaches in particular, over the last approximately 85 years.
4. Relate Fluvial Processes to Bar Types and Distributions: Determine, using hydraulic modeling, whether the collected data demonstrate a relationship between the classified bar types and flow magnitudes, frequencies, durations and shear stresses.
5. Develop Design Criteria for River Restoration: If a relationship is established between the bar classification and fluvial processes, use this relationship to develop a set of design criteria for restoration purposes.

## ES.3. Approach

Detailed site investigations were performed at ten sites that together are deemed representative of the range of geomorphologic conditions in this reach (MEI, 2002). The 10 representative sites selected for evaluation and analysis were located at:

- Pena Blanca [River Mile (RM) 227.5],
- Bernalillo (Highway 550; RM 203.6),

- Central Avenue, Albuquerque (RM 183.1),
- Belen (RM 149.6),
- Bernardo (RM 130.9),
- La Joya (RM 124.4),
- Lemitar (RM 107.5),
- Escondida (RM 104.5),
- North boundary of the Bosque del Apache National Wildlife Refuge (RM 84.1), and
- San Marcial (RM 67.9).

The locations of these sites are shown on **Figure ES-1**. Field investigations at these sites included topographic surveys (topographic mapping of bars, and cross sectional and longitudinal surveys for use in hydraulic modeling), as well as sediment sampling and lab analysis, and geomorphic mapping. Morphologic changes through time at the study sub-reaches were evaluated with time-sequential aerial photography that spanned the period from 1935 to 2002. Changes in channel width and elevation were evaluated with ground-based and photogrammetrically-based surveys primarily conducted by the U.S. Reclamation Service and the Bureau of Reclamation (BOR) between 1917/1918 and 2002.

Hydrologic changes within the Middle Rio Grande were evaluated with the annual peak flow and mean daily flow records from the six USGS gages that are located between Cochiti Dam and San Marcial. Changes in sediment gradations were determined from USGS and BOR sampling over time, and changes in sediment transport were determined from the bed-material and suspended sediment-transport measurements at the USGS gages (MEI, 2002 and 2004).

## ES.4. Bar Classification

A hierarchical bar classification was developed from field observations and measurements to characterize the individual bars within a site. The classifications were based on the following characteristics:

- location—mid-channel or bank-attached,
- subaqueous or subaerial exposure,
- relative height (within a bar category), and
- vegetative status.

The following basic descriptions of braid and mid-channel bar types and their sequential formation resulted:

- Level-1 braid bars are formed from linguoid (low-relief submerged tongue-shaped bars) bars during recessional flows**.** Braid bars are, by definition, bounded on either side by flow channels.
- Level-2 braid bars form from the vertical accretion of sand onto Level-1 braid bars. This vertical accretion is most effective if mud drapes are deposited on the Level-1 bars.
- Level-1 mid-channel bars form from further vertical accretion onto Level-2 braid bars of sand and/or gravel, generally accompanied by a number of mud drapes. The mud drapes appear to enhance the establishment of perennial vegetation on the Level-1 mid-channel bars.
- Level-2 mid-channel bars: Further deposition of sediment onto Level-1 mid-channel bars, assisted by the high hydraulic roughness created by the perennial vegetation (mainly

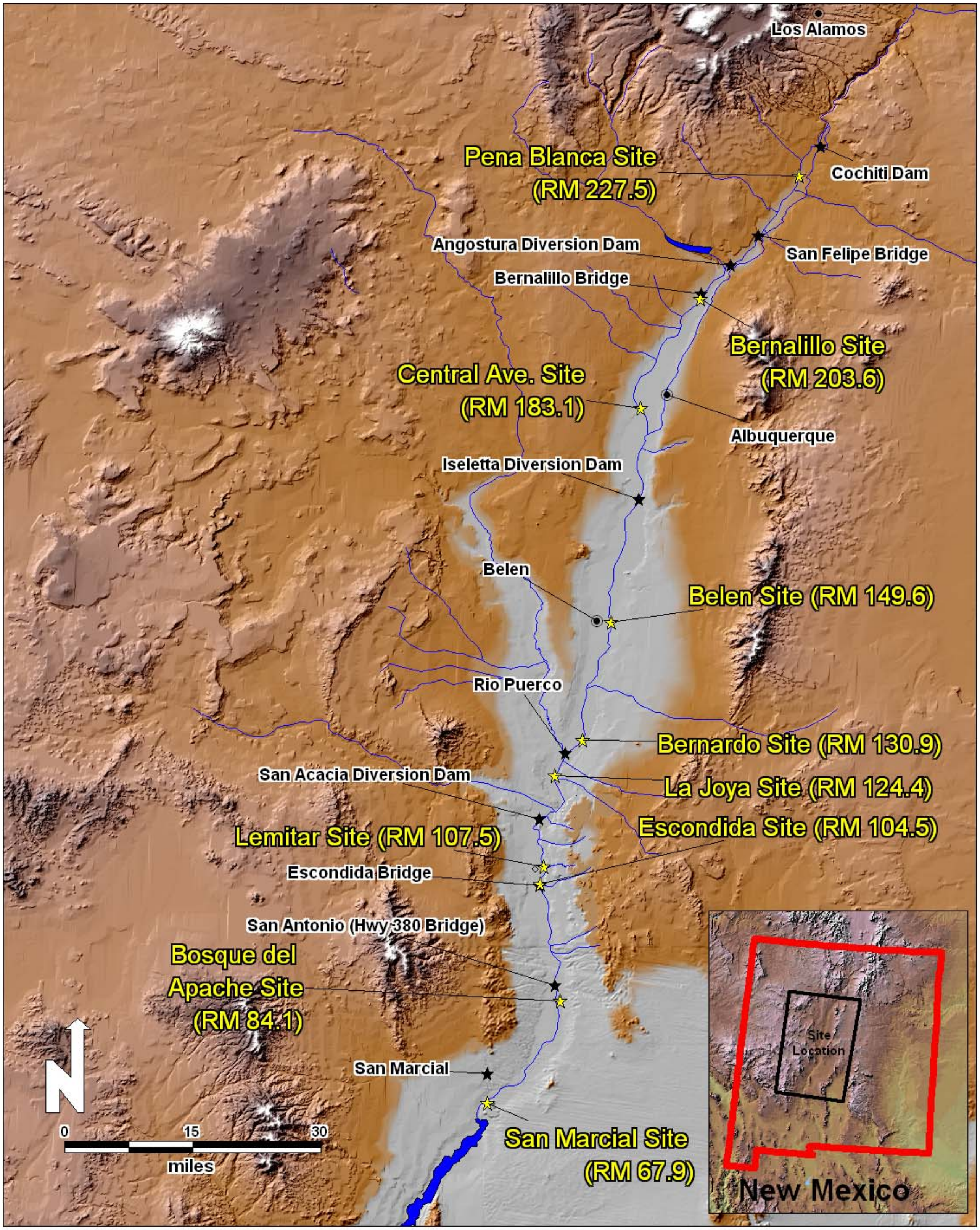


Figure ES.1. Map showing the locations of the 10 sites in the Middle Rio Grande that were investigated in this study.

sandbar/coyote willows, salt cedar, cottonwoods and Russian olives), leads to the formation of a Level-2 mid-channel bar.

A similar sequence of events characterizes the bank-attached bars:

- Low-elevation alternate bars form along the margins of the channel in response to recessional flows, and are bounded by channel flow only on one side. Alternate bars are unvegetated, mobile features.
- Level-1 bank-attached bars form from the vertical accretion of sediments over time onto the low-elevation alternate bars that become immobile and vegetated.
- Level-2 bank-attached bars form from further vertical accretion of sediments onto Level-1 bank-attached bars. Level-2 bank-attached bars have similar internal sedimentary architecture to the Level-2 mid-channel bars. Both the Level-2 mid-channel bars and the Level-2 bank-attached bars are colonized with tree-like vegetation species (e.g., willows, cottonwoods, Russian olives, salt cedar).

The ultimate height of the bars is governed by the height of the channel banks. If the channel is confined by terraces, then it is theoretically possible to have bar heights as high as the terraces, provided that flows of sufficient magnitude occur to accrete sediments onto the bars up to this height. Channel degradation is likely to cause relative bar heights to increase as a result of bed lowering, but the frequency of bar overtopping and, therefore, vertical accretion will be reduced as a consequence. On the other hand, if the channel is aggrading, the relative height of the bars and the banks will initially decrease. However, this will result in an increase in the frequency of overbank flows, and therefore will cause the vertical accretion on the bars and banks to increase. In this way, the heights of the bars are able to keep pace with the increase in elevation of the banks.

## ES.5. Bar Morphology and Indices

Once the bars at a site have been categorized, the array of bar forms and numbers at a site can be represented by an index of braiding intensity for the site, the Modified Braiding Index (MBI) (Brice, 1964; Germanoski, 1989). Higher MBI values indicate more intense braiding at a site. Morphometric changes to the channel resulting from changes in discharge, sediment supply and sediment gradation should be reflected in the MBI values as follows:

- If the bed material coarsens, provided there is still a supply of sediment, the MBI values will increase because gravel-bed channels are more intensely braided than sand-bed channels because of reduced rates of migration of linguoid bars in the gravel-bed channels,
- If aggradation has occurred, the MBI will be higher because there should be an increase in the number of braid bars, in both sand-bed and gravel-bed subreaches, and
- If degradation has occurred, the MBI will be lower because there should be a reduction in the number of braid bars, and increases in the size of the individual braid bars, especially in gravel-bed reaches.

Changes in the MBI values at the studies sites in the MRG between 1935 and 2001 (between 1972 and 2001 for the San Marcial site) were documented from time-sequential aerial photography as part of this investigation. From this analysis of bar changes through time, the following conclusions were drawn for the study site:

- Upstream sites – Pena Blanca and Bernalillo: channel degradation and bed material coarsening have resulted in a reduction in the number of braid bars, and therefore a reduction in braiding intensity.
- Central Avenue and Belen sites - the number of braid bars and the braiding intensity have decreased over time, primarily as a result of channel narrowing.
- Bernardo site – Aggradation of the sand bed at this site has resulted in an increased braiding intensity and a higher MBI value.
- La Joya site – Degradation of the sand bed at this site has reduced braiding intensity and resulted in a lowering of the MBI value.
- Lemitar site - Channel narrowing and degradation have not resulted in reduced braiding intensity, probably because of a relatively high sediment load that has maintained the braiding intensity.
- Escondida - channel narrowing and the incision have been sufficient to eliminate braid bars from this site.
- Downstream sites - North Boundary of Bosque del Apache and San Marcial - aggradation has resulted in an increase in braiding intensity.

## ES.6. Magnitude, Frequency and Duration of Bar Inundation

One-dimensional (1-D) hydraulic models (HEC-RAS) of the 10 sites were developed from the topographic surveys, and output from the models was used to identify the magnitude, duration and frequency of inundation of the different bar types at each of the sites. The magnitude of flows required to inundate the various categories of bars at each location were site specific. However, generalizations can be made from these analyses of the inundation recurrence intervals (frequency) and duration of inundation for the bar types at the sites that have not experienced excessive aggradation or degradation during the historical period studied.

Table ES-1 summarizes average inundation recurrence intervals, frequencies, and percent-of-year-inundated for bars at the Central Avenue, Belen, Bernardo, La Joya, Lemitar and Bosque del Apache sites. The three sites with the most channel degradation (Pena Blanca, Bernalillo and Escondida), and the site with the highest rate of aggradation (San Marcial) have been removed from the averaging process used to prepare Table ES-1.

At any given site, there will be a range of values for any given bar type. At the most degraded sites (Pena Blanca, Bernalillo and Escondida) most of the Level-2 bank-attached bars are probably better described as terraces, and at the San Marcial site where the aggradation rate is the highest, the high rate of aggradation tends to blur the distinction between the bar types.

## ES.7. Bed Mobilization and Vertical Stability of the Gravel- and Cobble-Bed Sites

Output from the HEC-RAS models for the gravel/cobble-bed sites, Pena Blanca and Bernalillo, was used to evaluate the potential for bed material mobilization and further channel degradation.

| Table ES-1. Summary of frequency and duration of inundation of the classified bar types at sites without excessive aggradation or degradation.* | | | |
|---|---|---|---|
| Bar Type | Inundation Recurrence Interval | Days per Year of Inundation | Percent of Year Inundated |
| Level 1 braid bars | < 1 year | 290 | 80% |
| Alternate bars | < 1 year | 290 | 80% |
| Level 2 braid bars | < 1 year | 146 | <40% |
| Level 1 mid-channel bars | 1.5 years | 90 | 25% |
| Level 1 bank-attached bars | 1.5 years | 90 | 25% |
| Level 2 mid-channel bars | 2 years | 36 | <10% |
| Level 2 bank-attached bars | 2 years | 36 | <10% |

*excluding the Pena Blanca, Bernalillo, Escondida and San Marcial sites.

At the Pena Blanca site, analysis of particle mobilization was done for the surface sediments on the Level-1 bar ($D_{50}$=30 mm) and for the riffle sediments ($D_{50}$=56 mm). Based on the reach-averaged hydraulics, incipient conditions (the point at which sediment just begins to move) for the Level-1 bar surface sediments are reached at a flow of about 5,500 cfs, but substantial sediment transport does not occur even at the 100-year flow of 12,800 cfs. If the hydraulic model is set up to employ conveyance weighting techniques to better represent the local hydraulic conditions, the output indicates that significant sediment transport occurs at about 11,000 cfs (~50-year event). Therefore, it can be concluded that mobilization of gravel supplied by the tributaries downstream of Cochiti Dam occurs infrequently. Because of the limited supply of sediment downstream of Cochiti Dam, and the infrequent mobilization of the gravels, it is unlikely that there will be a future increase in the number of bars within the Pena Blanca site. Analysis of the mobilization potential of the riffle sediments from the Pena Blanca site enabled evaluation of the likelihood of further degradation of the bed. Based on the reach-averaged hydraulics, incipient conditions on the riffle occur at a flow of about 10,000 cfs, which is approximately the 25-year event. General mobilization of the bed material and significant sediment transport does not occur at the 100-year event. Therefore, it can be concluded that it is highly unlikely that there will be further degradation of the bed at the Pena Blanca site, and that the bed is armored.

At the Bernalillo site, incipient conditions are reached in the riffles at a flow of about 9,000 cfs (10-year event) based on the reach averaged hydraulics, but significant sediment transport does not even occur at the 100-year flow event flow of 12,600 cfs. Conveyance weighting reduces the flow required to attain incipient conditions to about 7,500 cfs (about 5-year event), but significant sediment transport does not even occur at the 100-year event. Therefore, it can be concluded that further degradation is unlikely to occur at the Bernalillo site. However, if sediment supply is increased from the Rio Jemez, it is likely that more bars will form within the reach, and braiding intensity will also increase.

## ES.8. Limiting Shear Stresses

Hydraulic analysis was used to identify the range of shear stresses at sand-bed sites where bars are present. Table ES-2 presents a comparison of the maximum in-channel shear stresses determined for flows up to the bankfull capacity at the individual sites, where the recurrence intervals ranged from less than 1 year (San Marcial) to greater than 25 years (Escondida), to the presence of active bars at the analyzed sites.

Table ES-2: Comparison of maximum in-channel shear stresses to the prevalence of bars in the sand-bed sites.

| Site Names | Maximum In-Channel Shear Stresses (lb/ft$^2$) | Prevalence of Active Bars |
|---|---|---|
| Central Avenue | <0.1 | moderate to high number of active bars |
| Bosque del Apache, San Marcial | 0.1 | high number of active bars |
| Bernardo, La Joya, Lemitar | 0.12 - 0.15 | active bars are present |
| Belen | 0.2 | moderate number of active bars |
| Escondida | 0.3 | virtually no active bars |

Table ES-2 shows that, provided there is a supply of sand-sized sediment, active braid and alternate bars are present when maximum in-channel shear stresses are between about 0.1 and 0.2 lb/ft$^2$. If the maximum in-channel shear stress is higher than about 0.3 lb/ft$^2$, as it is at the Escondida site, the sediment-transport rate is too high for bar formation, even if there is a supply of sediment.

## ES.9. Bar Inundation during Seasonal High Flows

Shear stresses were also computed from the hydraulic model output to determine whether flows in the MRG were capable of removing vegetation from the vegetated bars. Review of the bioengineering literature (Schiechtl and Stern, 1994; Gray and Leiser 1989; NRCS, 1998; Allen and Fischenich, 2001; Sotir and Fischenich, 2003) suggests that newly planted vegetation, on its own (i.e. without structural support) can be used to provide erosion protection where shear stresses reach a maximum of about 1 lb/ft$^2$. Once the plants become established, they can withstand shear stresses up to about 6 lb/ft$^2$.

Mean shear stress was calculated for flows with recurrence intervals of 1.5, 2, 5 and 10 years for each of the bar types present at all of the sites to evaluate the potential for hydraulic removal of the established vegetation on the bars. The maximum shear stresses at the sites tested were all 0.3 lb/ft$^2$ or lower. Therefore, it is highly unlikely that either the more recent vegetation on the Level-1 bars or the more established vegetation on the Level-2 bars will be removed by flows alone. Vegetation removal will require some form of mechanical intervention.

## ES.10. Application of Study Results to Restoration

This study succeeded in demonstrating relationships between bar morphology and dynamics and fluvial processes. The development of a bar classification that captures these relationships provides a simple mechanism, through the mapping of in-channel and channel-margin bars, to characterize fluvial processes, including flow magnitudes, frequencies, durations and shear stresses, at any Middle Rio Grande site of interest. The bar classification also provides a tool that can be used to improve the interdisciplinary communication that is required for successful restoration of the MRG.

A number of specific recommendations for habitat restoration were developed from the results of the study. Several of these are described below:

1. Although natural variability will assure that there will be a range of values for any given bar type, at locations that are neither significantly incised nor rapidly aggrading, the frequency and duration of inundation of the various bar categories can be generally categorized as shown in Table ES-1. These relationships can be used to characterize the general frequency and duration of inundation at proposed habitat rehabilitation sites in the absence of site specific surveys or hydraulics.
2. Evaluation of bar changes over time suggests a likely decrease in the intensity of braiding and the number of braid bars in the future, in both the gravel-bed and sand-bed reaches of the MRG. In gravel-bed reaches, this would likely be due to coarsening of the bed material over time, and in sand-bed reaches, it would be due to further channel narrowing. Therefore, restoration activities should be aimed at preventing further coarsening of bed material and narrowing of the channel. Increased sand sediment supply from the Rio Jemez, as well as mechanical destabilization of heavily vegetated bank-attached bars will promote channel widening, and in so doing may prevent further reduction in both braiding intensity and the number of braid bars.
3. Based on the results of the incipient motion analyses of the bed material at the Pena Blanca and Bernalillo sites, it is unlikely that further bed degradation will occur at the coarser-bed-material locations within the MRG. Hydrologically-abandoned bar surfaces in this reach of the river can be reduced in elevation by mechanical means to meet specific targets for inundation frequency and duration, without fear of future channel degradation that would adversely affect the stage-discharge relationship.
4. In the sand-bed reaches of the MRG, active bars can be maintained at reach-averaged shear stresses at the channel-capacity discharge of up to about 0.2 $lb/ft^2$. At reach-averaged shear stresses higher than 0.3 $lb/ft^2$, bars are unlikely to be present. Therefore, any channel modifications designed to increase physical habitat should aim for reach-averaged shear stresses less than 0.2 $lb/ft^2$.
5. Physical reductions to existing bar-surface elevations to promote increased frequency and duration of inundation will have a limited life span. The lower the bar surface is cut, the more frequently it will be inundated, and the higher the rate of sediment deposition and vertical accretion will be. For example, within the Albuquerque reach, an average of 1.5 feet of sand deposited on Level-1 bar surfaces during the sustained high flows of 2005. This deposition reduced the future duration of inundation of these bars from 20 days per year to 4 days per year, and increased the flow magnitude required for inundation from 1,500 cfs to 4,000 cfs.
6. Within the MRG, shear stresses on bar surfaces rarely exceed 0.3 $lb/ft^2$. Since shear stresses in excess of about 1 $lb/ft^2$ are required to prevent colonization of bars by vegetation, it is unlikely that flows will prevent colonization of bars by both native and non-native vegetation species. Additionally, shear stresses in excess of about 6 $lb/ft^2$ are required to remove established vegetation from bars. Therefore, vegetation management within the MRG will require mechanical intervention.

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# 1. INTRODUCTION

## 1.1. Background

The success and sustainability of the numerous active and passive river habitat improvement projects that are being proposed for increasing habitat for the endangered Rio Grande silvery minnow in the Middle Rio Grande (MRG) (Tetra Tech, 2005) will depend, in large measure, on the interaction of the specific project-created in-channel and channel-margin habitats with the dynamics of the river. Therefore, a detailed understanding of the interaction of the flows in the river and the boundary sediments that form the channel is necessary for project design and performance evaluation, and for assuring that the various projects do not adversely affect one another. In the absence of a full sediment-transport study of the Middle Rio Grande, we proposed this study of the dynamics and spatial distribution of bar types that would integrate the hydrological and sediment regime of the river to provide a quantifiable basis for evaluating channel and habitat restoration projects (Germanoski, 1989). Additionally, the long history of both hydrologic and sedimentologic and morphologic modifications to the MRG should be represented by changes in the number and types of bars in the river. Therefore, an analysis of time-sequential aerial photography should provide a means of tracking the changes in channel and bar morphology, which in turn is related to the amount of habitat available to both aquatic and terrestrial species.

This bar dynamics investigation builds on a number of other studies that have been conducted within the MRG including: (1) geomorphic investigations of the MRG (Graf, 1994; Mussetter Engineering, Inc. [MEI], 2002; Massong et al., 2002; Massong et al., 2006 in press), (2) sediment-transport studies (Lagasse, 1994; MEI, 2002, 2004), (3) two-dimensional hydrodynamic and aquatic habitat studies conducted for the Upper Rio Grande Water Operations (URGWOPS) Review and EIS by Bohannan-Huston, MEI and Miller Ecological Consultants (2003), (4) tributary sediment yield investigations downstream of the Rio Puerco confluence (MEI, 2004), (5) 2005 overbank flow monitoring studies (Tetra Tech, 2005) and (6) topographic surveys of mid-channel and bank-attached bars in the Albuquerque reach (SWCA, Inc. and MEI, in prep). Additional sources of valuable information included the US Reclamation Service 1917/1918 survey of the Rio Grande, Bureau of Reclamation (BOR) photogrammetric and range line surveys (1962 to 2002) and aerial photography (1935 to 2002). Sediment data collected by the US Geological Survey (USGS) and BOR over time provided a valuable data set for investigating changes in bed material gradations through time and space. Long-term hydrologic data are available from the USGS gages throughout the MRG.

## 1.2. Man-made Changes in the Middle Rio Grande

The Middle Rio Grande has been significantly affected by human interventions since the 1800s, when abstractions for irrigation in the San Luis Basin in Colorado, reduced the natural flows in the river by 40 to 60 percent (National Resources Commission, 1938). Sediment loads to the river were elevated in the late 1800s by arroyo incision and changes in land use in the basin (Happ, 1948). Major increases in sediment load occurred downstream of the Rio Puerco confluence as a result of incision of the Rio Puerco (Rittenhouse, 1944; Happ, 1948; Elliott, 1979). By about 1880, a substantial area of land was under cultivation in the Middle Rio Grande Valley, and this led to both increased water abstraction from the river, and removal of riparian vegetation (Crawford et al., 1993). The earliest detailed information available on the planform characteristics of the river was a 1917-1918 survey (U.S. Reclamation Service, 1922), but by the time this survey was conducted, the hydrology and sediment supply to the river had changed considerably.

By 1935, the Middle Rio Grande Conservancy District (MRGCD) had constructed El Vado Dam on the Rio Chama, as well as diversion dams at Cochiti, Angostura, Isleta, and San Acacia. MRGCD also constructed more than 180 miles of riverside drains and 160 miles of interior drains that improved conditions for irrigation. As part of the drain project, linear piles of spoils were placed between the riverside drains and the river. These piles followed the existing river planform and eventually became levees that were used for flood control (Graf, 1994). The design consisted of a floodway that averaged 1,500 feet wide between 8-foot levees (Lagasse, 1980). The levees were built to withstand a design discharge of 40,000 cfs and the levees, near the City of Albuquerque, were raised to pass a design flow of 75,000 cfs (Woodson and Martin, 1963). High flows in 1941 and 1942 with discharges over 21,000 cfs caused severe damage in the valley. As much as 50,000 acres were inundated as the levees were breached in 27 different locations (Scurlock, 1998; Graf, 1994). After these devastating floods the USBR and the Army Corps of Engineers (USACE) devised the Rio Grande Comprehensive Plan (Lagasse, 1980). The Comprehensive Plan involved a system of reservoirs on the Rio Grande (Cochiti, 1973) and its tributaries (Jemez 1954; Abiquiu 1963; Galisteo 1970), as well as rehabilitation of the floodway constructed by MRGCD (Woodson and Martin, 1963).

In order to improve efficiency of water conveyance to Elephant Butte Reservoir, the Low Flow Conveyance Channel (LFCC) that extended from San Acacia to the reservoir was built with a capacity of about 2,000 cfs. From 1959 to 1985 virtually all the flows were conveyed in the LFCC, except under flood conditions. Since 1985 the flows have been returned to the river.

The present day hydrology of the Middle Rio Grande has been changed due to flow importation, wastewater discharge, abstraction for irrigation and returns from irrigation flows, and the construction of water supply and flood-control reservoirs. Importation of flows via the San Juan-Chama project has added about 97,000 ac-ft of flow to the basin annually since 1971, of which about 54,000 ac-ft is delivered to the Otowi gage (Annual Rio Grande Compact Accounting Report). The City of Albuquerque wastewater delivery to the river is on the order of 60,000 ac-ft annually. These changes have had an effect on the amount of water in the Rio Grande downstream of Albuquerque where median flows ($50^{th}$ percentile) on the mean daily flow-duration curves for the Bernardo, San Acacia and San Marcial gages have increased. The flood-control reservoirs have reduced the magnitude of flood peaks, and there have been no significant floods on the river since the 1970s. At the Cochiti gage there has been a 30 percent reduction in the magnitude of the 2-year flood, and about a 55 percent reduction in the magnitude of the 100-year flood. Similar reductions apply at the other gages downstream of Cochiti (MEI, 2002).

The flood- and sediment-control reservoirs have had a major effect on sediment transport downstream of Cochiti Dam (MEI, 2004). Suspended-sediment loads and bed-material loads are both lower than they were in the pre-Cochiti Dam period, but the effects of the dams diminish in the downstream direction because of tributary sediment delivery and in-channel sources of sediment. Average annual suspended-sediment concentrations have been reduced by about 99 percent at the Cochiti gage, but by only 70 percent at the San Marcial gage. However, other watershed factors appear to be the cause of some of the reduced sediment loads, because average annual suspended-sediment concentrations have also diminished by about 55 percent at the Otowi gage in the same time period. Watershed factors could include improved land use in the basin, as well as storage of sediment in many of the arroyos that initially incised in the 1800s and then widened sufficiently to permit sediment deposition (Schumm et al., 1994).

## 1.3. Project Objectives

The primary objectives of this project were to:

1. Summarize the morphological, hydrological and sedimentological changes that have occurred in 10 representative reaches of the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir over the last approximately 85 years (**Figure 1.1**).

2. Determine whether the effects of the morphological, hydrologic, and sedimentologic changes could be quantified and predicted through changes in the number and types of bars in the river as determined by analysis of time-sequential aerial photography and resulting morphometric bar indices, and

3. Conduct site-specific field surveys at the 10 sites to develop a field based classification for the bar types identified in the river and on the channel margins and to relate the various bar types to flow magnitudes, frequencies, durations, and shear stresses, thereby developing a set of design criteria for habitat restoration purposes.

Morphometric relationships developed from analysis of aerial photography and the field studies at the 10 locations will provide a quantitative basis for prediction of future changes in habitat availability as a result of changes in sediment supply and discharge, as these are reflected by bar types and their spatial distribution.

## 1.4. Authorizations

This study was funded by the New Mexico Interstate Stream Commission (NMISC) and the Middle Rio Grande Endangered Species Act Collaborative Program and was conducted by Mussetter Engineering, Inc. (MEI) as a subcontractor to S.S. Papadopulos and Associates, Inc. The NMISC project manager was Ms. Page Pegram, and the MEI project manager was Dr. Michael D. Harvey. Permission to conduct field surveys was provided at individual sites by the Middle Rio Grande Conservancy District, Bureau of Reclamation, City of Albuquerque Open Space, and the Bosque del Apache National Wildlife Refuge.

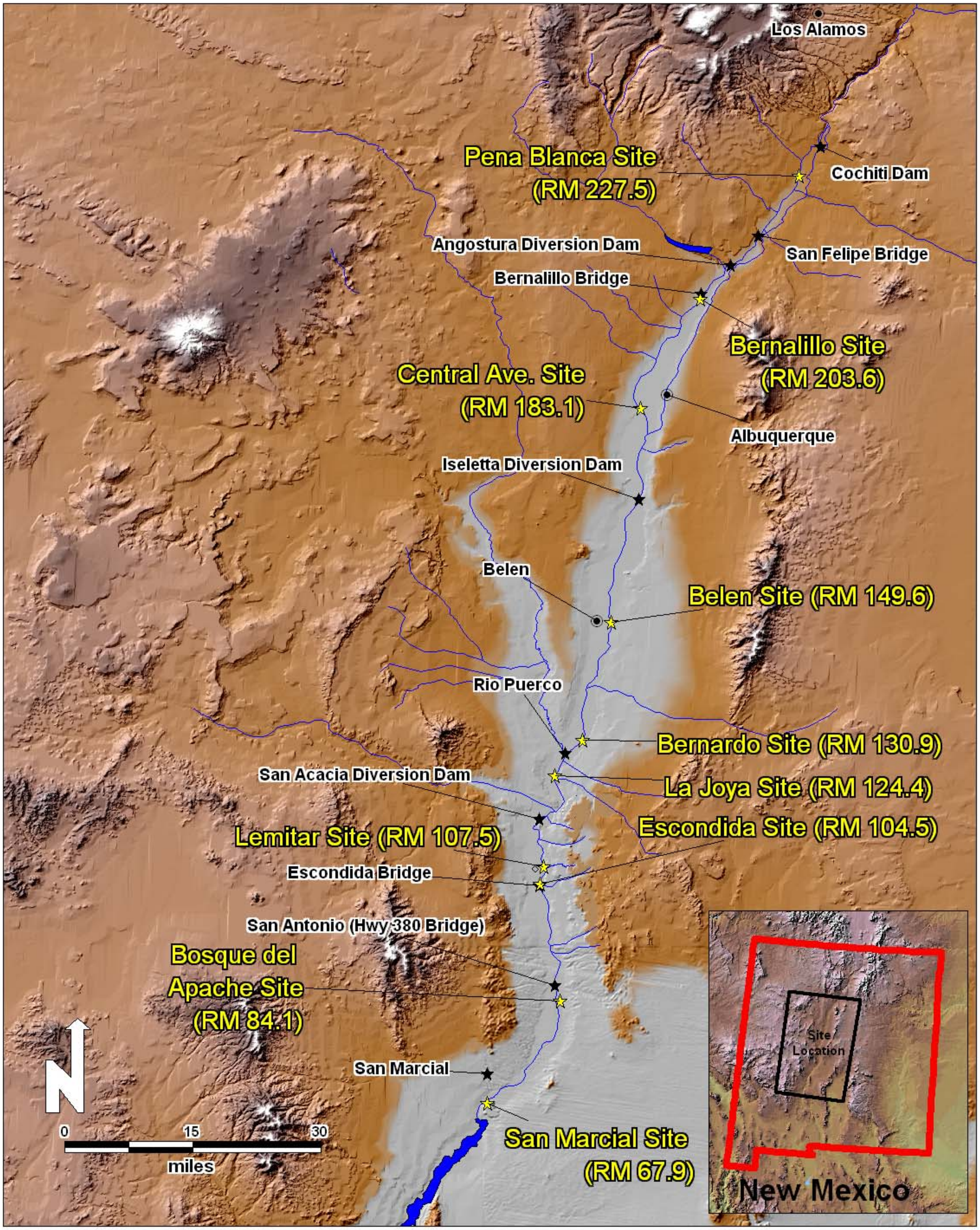


Figure 1.1. Map showing the locations of the ten sites in the Middle Rio Grande that were investigated in this study.

# 2. SITE SELECTION AND DATA COLLECTION

## 2.1. Site Selection

The Rio Grande in the Middle Valley can be subdivided into eight geomorphic subreaches (MEI, 2002, 2004) on the basis of morphologic characteristics, geomorphic and geologic processes and controls, and man-made modifications, as follows:

1. Cochiti Dam to Angostura Diversion (RM 232-210)
2. Angostura Diversion to Isleta Diversion (RM 210-169)
3. Isleta Diversion to Belen (upstream end of the influence of the Socorro Uplift (RM 169-150)
4. Belen to Canada Ancha confluence (RM 150-121)
5. Canada Ancha to San Acacia Diversion (RM 121-116)
6. San Acacia Diversion to Escondida (RM 116-105)
7. Escondida to San Antonio (RM 105-87)
8. San Antonio to San Marcial (RM 87-69)

Selection of sites for this project was based primarily on an attempt to include all the identified geomorphic subreaches, but considerations of site access, previous site surveys, availability of aerial photographic coverage, historical survey data, gauging station records and historical sediment data tempered the final site selection process. Based on the available data and information, ten sites were selected for the project (Figure 1.1), and these are considered to be reasonably representative of the geomorphic conditions within the MRG. General characteristics of the 10 sites are summarized in **Table 2.1**.

## 2.2. Data Collection

To quantify the time sequential changes in the number and types of bars present at the sites, changes in channel morphology (width, slope, mean bed elevation) and changes in bed material gradations, available information was obtained from a number of agencies and other sources that are identified in the following sections.

### 2.2.1. Aerial Photography

All available aerial photography of the identified sites was acquired to evaluate the planform characteristics of the channel and the bars. In general, aerial photographs were available in 1935, 1947, 1955, 1972, 1973, 1992, 1996, 2001 and 2002. However, due to incomplete coverage of the Rio Grande, and in some cases poor photographic quality, the range of useable photographs for specific sites was more limited. The majority of the aerial photographs were obtained from the Office of the State Engineer archives. The 1966 photographs were obtained from the USGS in digital orthophotography quarter quadrangle format. The available photography for each site is summarized in **Table 2.2.**

Table 2.2 also includes the flight date associated with the aerial photography and the mean daily discharge on the date of the flight. Photography that was used for subsequent analysis of bars was restricted to relatively low flows to permit better comparison between years, even though the analysis is not very sensitive to flow levels provided that the differences are not extreme (Germanoski and Schumm, 1993). All of the aerial photographs with the boundaries of the various bar types mapped on them for each of the sites are provided in **Appendix A**.

| Table 2.1. Summary of site characteristics. | | | |
|---|---|---|---|
| Site (RM) | Site Morphology | Bed Sediment Size Range | Bar Types |
| Pena Blanca (227.5) | Incised 3-4 feet, multiple channels, terrace bounded | Gravel and cobble | Vegetated mid-channel and bank-attached bars |
| Bernalillo (203.6) | Incised 5-8 feet, multiple channels at higher flows, bounded by terraces, jetty jacks present | Sand and gravel | Vegetated and unvegetated mid-channel and bank-attached bars |
| Central Avenue (183.2) | Incised 2-3 feet, single channel, bounded by terraces, jetty jacks present | Sand and gravel | Vegetated and unvegetated mid-channel and bank-attached bars |
| Belen (149.6) | Incised 2-3 feet, single channel, bounded by terraces, jetty jacks present | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |
| Bernardo (130.9) | Incised 3-4 feet, single channel, bounded by terraces, jetty jacks present | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |
| La Joya (124.4) | Incised 4-6 feet, single channel, bounded by terraces, jetty jacks present | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |
| Lemitar (107.5) | Incised 5-6 feet, single channel, bounded by terraces, jetty jacks present | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |
| Escondida (104.5) | Incised 8-10 feet, single channel, bounded by terraces, | Sand | Unvegetated mid-channel and bank-attached bars |
| Bosque del Apache (84.1) | Aggraded, multiple channels at higher flows, jetty jacks present | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |
| San Marcial (67.9) | Aggraded, single channel | Sand | Vegetated and unvegetated mid-channel and bank-attached bars |

Table 2.2. Summary of aerial photography and river discharges for each of the sites.

| Site | Year of Photography | Date of Photograph | Discharge (cfs) |
|---|---|---|---|
| Pena Blanca | 1935 | Unknown | Unknown |
| | 1955 | Jun 30 | 270 |
| | 1972 | Apr | 955-2820 |
| | 1992 | Feb 21-28 | 284-1120 |
| | 1996 | Oct 7 | 441 |
| | 2001 | Feb | 528-894 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 304-583 |
| Bernalillo | 1935 | Unknown | Unknown |
| | 1955 | Jun 30 | 38 |
| | 1972 | Apr | 150-913 |
| | 1992 | Feb 21-28 | 329-1120 |
| | 1996 | Oct 9 | 410 |
| | 2001 | Feb | |
| | 2002 | Jan 22-26<br>Feb , 6, 10<br>Mar 13 | 306-836 |
| Central | 1935 | Unknown | Unknown |
| | 1955 | Jun 30 | 56 |
| | 1972 | Apr | 150-913 |
| | 1973 | May 29 | 6530 |
| | 1992 | Feb 21-28 | 329-1120 |
| | 1996 | Oct 6 | 509 |
| | 1999 | Jun | 1440-3330 |
| | 2001 | Feb | 604-952 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 306-836 |
| Belen | 1935 | Unknown | Unknown |
| | 1947 | Aug 10 | 429 |
| | 1972 | Apr | 174-4360 |
| | 1973 | Nov 12 | 164 |
| | 1992 | Feb 21-28 | 549-1060 |
| | 1996 | Oct 6 | 46 |
| | 2001 | Feb | 539-875 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 372-712 |

| Table 2.2. Summary of aerial photography and river discharges for each of the sites (continued). | | | |
|---|---|---|---|
| Site | Year of Photography | Date of Photograph | Discharge (cfs) |
| Bernardo | 1935 | Unknown | Unknown |
| | 1947 | Aug 14 | 292 |
| | 1972 | Apr | 174-4360 |
| | 1992 | Feb 21-28 | 549-1060 |
| | 1996 | Oct 9 | 171 |
| | 2001 | Feb | 539-875 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 372-712 |
| La Joya | 1935 | Unknown | Unknown |
| | 1947 | Aug 11 | 292 |
| | 1955 | Jun 29 | 27 |
| | 1972 | Apr | 174-4360 |
| | 1992 | Feb 21-28 | 549-1060 |
| | 1996 | Oct 6 | 46 |
| | 2001 | Feb | 539-875 |
| | 2002 | Jan 22-26<br>Feb 1,6,10<br>Mar 13 | 372-712 |
| Lemitar | 1935 | Unknown | Unknown |
| | 1947 | Aug 14 | 292 |
| | 1972 | Apr | 2-12 |
| | 1992 | Feb 21-28 | 609-1200 |
| | 1996 | Oct 6 | 484 |
| | 2001 | Feb | 689-860 |
| | 2002 | Jan 22-26,<br>Feb 1, 6, 10<br>Mar 13 | 281-914 |
| Escondida | 1935 | Unknown | Unknown |
| | 1947 | Aug 14 | 292 |
| | 1955 | Jun 29 | 0 |
| | 1972 | Apr | 2-12 |
| | 1992 | Feb 21-28 | 609-1200 |
| | 1996 | Oct 6 | 484 |
| | 2001 | Feb | 689-860 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 281-914 |

| Table 2.2. Summary of aerial photography and river discharges for each of the sites (continued). | | | |
|---|---|---|---|
| Site | Year of Photography | Date of Photograph | Discharge (cfs) |
| Bosque del Apache | 1935 | Unknown | Unknown |
| | 1947 | Nov 26 | 2010 |
| | 1955 | Jun 29 | 0 |
| | 1972 | Apr | 0 |
| | 1992 | Feb 21-28 | 305-416 |
| | 1996 | Oct 9 | 458 |
| | 2001 | Feb | 349-469 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 412-603 |
| San Marcial | 1972 | Apr | 0 |
| | 1992 | Feb 21-28 | 305-416 |
| | 1996 | Sep 29 | 0 |
| | 2001 | Feb | 349-469 |
| | 2002 | Jan 22-26<br>Feb 1, 6, 10<br>Mar 13 | 412-603 |

### 2.2.2. Historic Sediment Data

Bed material gradation data, as well as suspended sediment and bed material sediment-transport data were acquired from a range of sources including the USGS, BOR, and from published and unpublished papers, theses and reports that had previously been synthesized by MEI (2002). With the exception of the Belen site, historical bed material gradation data were available for each of the sites. However, based on conditions at both upstream (Central Avenue) and downstream (Bernardo) sites, it is unlikely that the size of the bed material (sand) has changed at the Belen site. Bed material size trends (**Figure 2.1**) show that the median size ($D_{50}$) of the bed material at the Pena Blanca and Bernalillo sites has changed from sand to gravel in the post-Cochiti Dam period, but that the bed material at the other sites for which historic data are available has remained sand.

### 2.2.3. Historic Survey Data

Photo-interpreted (1962, 1972, 1992) and surveyed range line (1970 to 1999) data were obtained from the BOR for the purposes of determining changes in the channel morphology at each of the sites. These data were used to develop longitudinal and cross section profiles for each of the sites, as well as for determining mean bed elevations for the period of record. Channel widths were obtained from the surveys in conjunction with review of the aerial photography. The US Reclamation Service 1917/1918 survey of the MRG was used to provide a baseline bed profile for each of the sites. While it is recognized that there may be both vertical and horizontal inaccuracies in the 1971/1918 survey, the magnitude of the changes in the river likely exceed the survey inaccuracies and therefore, the survey provides a reasonable baseline with which to assess vertical changes in riverbed elevation.

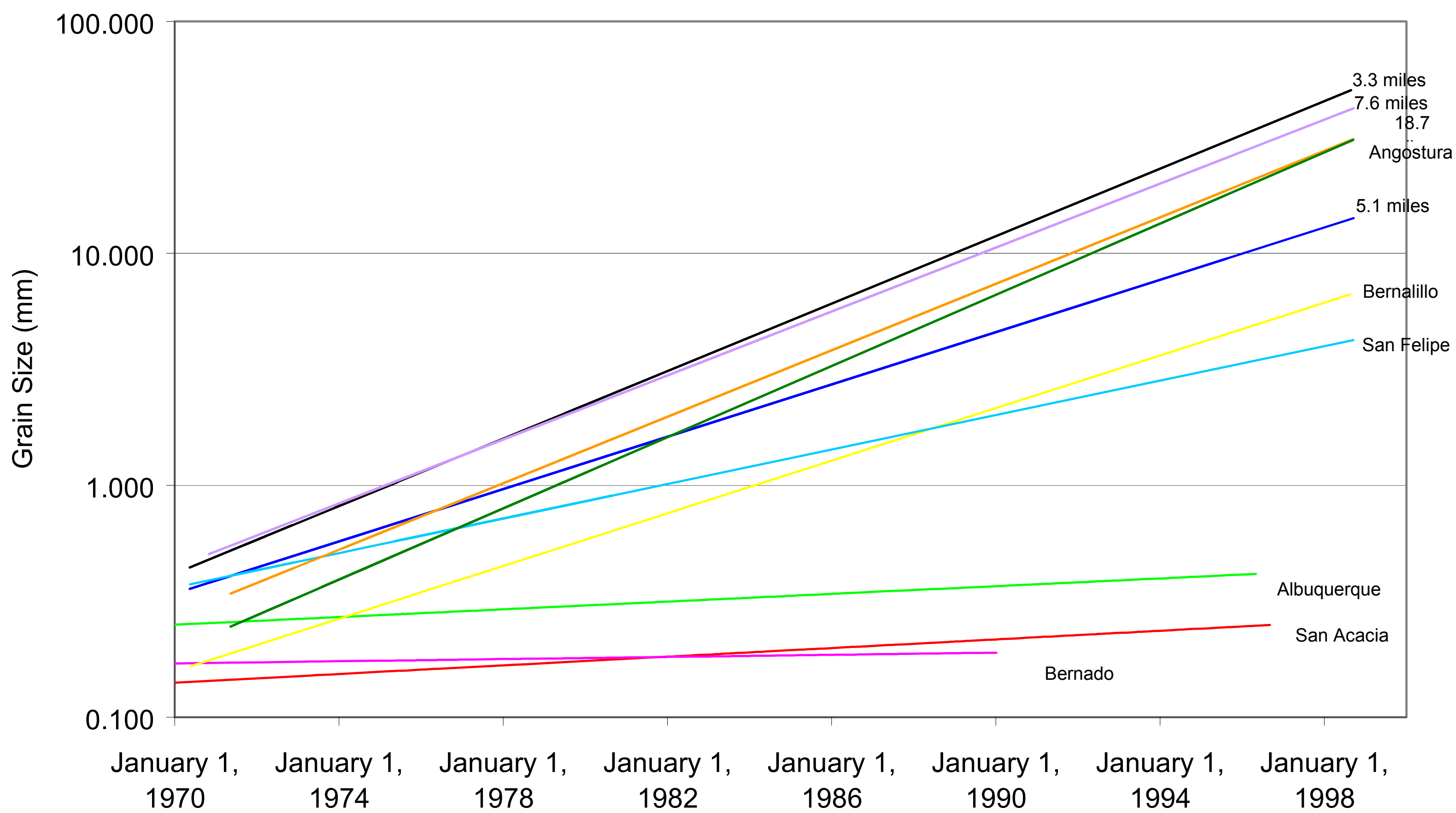


Figure 2.1. Regression lines showing the changes in the $D_{50}$ of the bed material between 1970 and 1998 at gage locations and other BOR identified range lines (MEI, 2002). Miles refer to distance below Cochiti Dam.

#### 2.2.4. Site Surveys

Topographic surveys of 6 of the sites were conducted as part of the URWOPS (Upper Rio Grande Water Operations) review process in 2003 (Bohannan Huston, MEI, MEC, 2004). The surveyed sites included Pena Blanca, Bernalillo, Central Avenue, Bernardo, Bosque del Apache and San Marcial. In general, topographic mapping of the channel and some overbank areas extended for a distance of about 2,500 feet at each site in 2004. With the exception of the Pena Blanca site which is located between the Cochiti and Santo Domingo Pueblos, the sites were extended both upstream and downstream with cross section surveys for this project. Cross section and longitudinal profile surveys for the remainder of the sites, Belen, La Joya, Lemitar and Escondida, were conducted in August and November 2004. The extent of the surveys and the survey boundaries for each of the sites is provided in **Table 2.3**.

Table 2.3. Summary of site locations and lengths.

| Site | River Mile | Upstream Limit (RM) | Downstream Limit (RM) | Reach Length (miles) | Latitude (N) | Longitude (W) |
|---|---|---|---|---|---|---|
| Pena Blanca | 227.5 | 227.9 | 227 | 0.9 | 35° 33' 58.3" | 106° 21' 29.8" |
| Bernalillo | 203.6 | 204.5 | 202.6 | 1.9 | 35° 18' 49.0" | 106° 33' 30.2" |
| Central Ave. | 183.1 | 184.1 | 182.1 | 2 | 35° 5' 8.5" | 106° 40' 37.3" |
| Belen | 149.6 | 150.4 | 148.7 | 1.7 | 34° 39' 12.0" | 106° 44' 19.5" |
| Bernardo | 130.9 | 131.9 | 129.8 | 2.1 | 34° 25' 10.9" | 106° 47' 57.1" |
| La Joya | 124.4 | 125.1 | 123.6 | 1.5 | 34° 20' 44.1" | 106° 51' 30.1" |
| Lemitar | 107.5 | 108.5 | 106.4 | 2.1 | 34° 9' 37.6" | 106° 52' 53.5" |
| Escondida | 104.5 | 105.2 | 103.8 | 1.4 | 34° 7' 15.8" | 106° 53' 13.1" |
| Bosque del Apache | 84.1 | 84.5 | 83.6 | 0.9 | 33° 52' 12.3" | 106° 50' 57.1" |
| San Marcial | 67.9 | 68.7 | 67 | 1.7 | 33° 40' 38.9" | 106° 59' 47.4" |

The site surveys were conducted to obtain the location and elevation of the various bar surfaces relative to the channel bed and bounding terraces, and to acquire cross-sectional data for use in hydraulic modeling. The majority of the sites were surveyed in August 2004 by a three-person crew using differentially corrected, real-time kinematic GPS technology (the Leica Geosystems GS50 GIS Data Collection System). BOR or New Mexico Department of Transportation monuments were used for survey control at all of the sites. A second survey effort was conducted during November 2004 by a two-person crew using conventional survey technology (Pentax PCS-1s Total Station). A summary of the date and type of survey for each site is provided in **Table 2.4**.

Each of the cross sections surveyed extended across the channel (between the left and right bank terraces). The cross-sectional surveys included points defining the main channel(s), high flow channel(s), terrace or overbank, and any type of bar located along the cross section. Designation of the bar type was based on the relative elevation of the surface with respect to the channel bed, evidence of frequency of disturbance, and the type, age, and density of vegetation on the bar. Water-surface elevations and high-water marks were also collected during the surveys to aid in calibration of the hydraulic models. In many cases, the high-water marks represented either spring peaks, summer peaks, or very recent high flows, and were noted as such in the surveys. In general, high-water marks associated with spring peaks were identified as leafy or woody debris, while high-water marks associated with summer peaks were identified by the presence of significant mud-laden debris deposited at the base of woody vegetation, and high-water marks associated with recent storms were identified as the wetted line along the active channel banks. Longitudinal profiles along the top of various bar features were collected to better define the various surfaces. Additionally, shots defining bridge structures (bridge abutments, piers, top and bottom of bridge deck) or other hydraulic controls were also collected for use in the hydraulic models. The number of cross sections surveyed at each site is included in Table 2.4. To aid in bar definition and development of the hydraulic models, a series of photographs, notes and a sketch of the cross section accompanied the cross-sectional surveys. The photographs, notes and sketches included the location of the various bar features, the type, age and density of vegetation on the bar surfaces, and the change in hydraulic roughness and the size of sediment along the cross section.

Table 2.4. Summary of survey information for each of the sites.

| Site | Date of Surveys | Type of Survey | Number of Cross Sections |
|---|---|---|---|
| Pena Blanca | 2/1-2/02 and 8/10/04 | GPS | 11 |
| Bernalillo | 8/11-12/04 | GPS | 13 |
| Central Ave. | 8/13/2004 | GPS | 15 |
| Belen | 8/14-15/04 | GPS | 17 |
| Bernardo | 8/15-16/04 | GPS | 14 |
| La Joya | 11/11-12/04 | Conventional | 7 |
| Lemitar | 8/17,20/04 | GPS | 9 |
| Escondida | 8/19/2004 | GPS | 9 |
| Bosque del Apache | 8/18-19/04 | GPS | 19 |
| San Marcial | 1/01,11/02 and 8/20/04 | GPS | 8 |

Aerial photographs showing the locations of the surveyed cross sections, locations where bed material samples were collected and stratigraphic sections were measured in pits dug in various types of bars are shown on **Figures 2.2 through 2.11**.

### 2.2.5. Sediment Sampling

At each of the sites sediment samples were collected to provide current information on the sizes of the sediment in transport and involved in construction of the bars. At the sites with the coarsest sediments, Pena Blanca and Bernalillo, pebble counts (Wolman, 1954) were used to determine the gradations of the surface sediments, and bulk samples of the subsurface sediments were obtained for laboratory sieve analysis. At the remainder of the sites where the sediments were primarily composed of sands, the bed and bar materials were sampled and sieved to determine their gradations. Finer-grained (silts and clays) sediments that represent lateral accretion and vertical accretion (mud drapes) deposits were sampled at some of the sites and were subjected to both sieve and hydrometer analysis. The locations of the samples are shown on Figures 2.2 through 2.11. Gradations for all of the samples are provided in **Appendix B**.

Pits were dug at all of the sites to enable the subsurface characteristics and sedimentary architecture of the bars to be identified and described. Stratigraphic sections developed from the pits for each of the sites are provided in **Appendix C**, and the locations of the pits are shown on Figures 2.2 through 2.11.

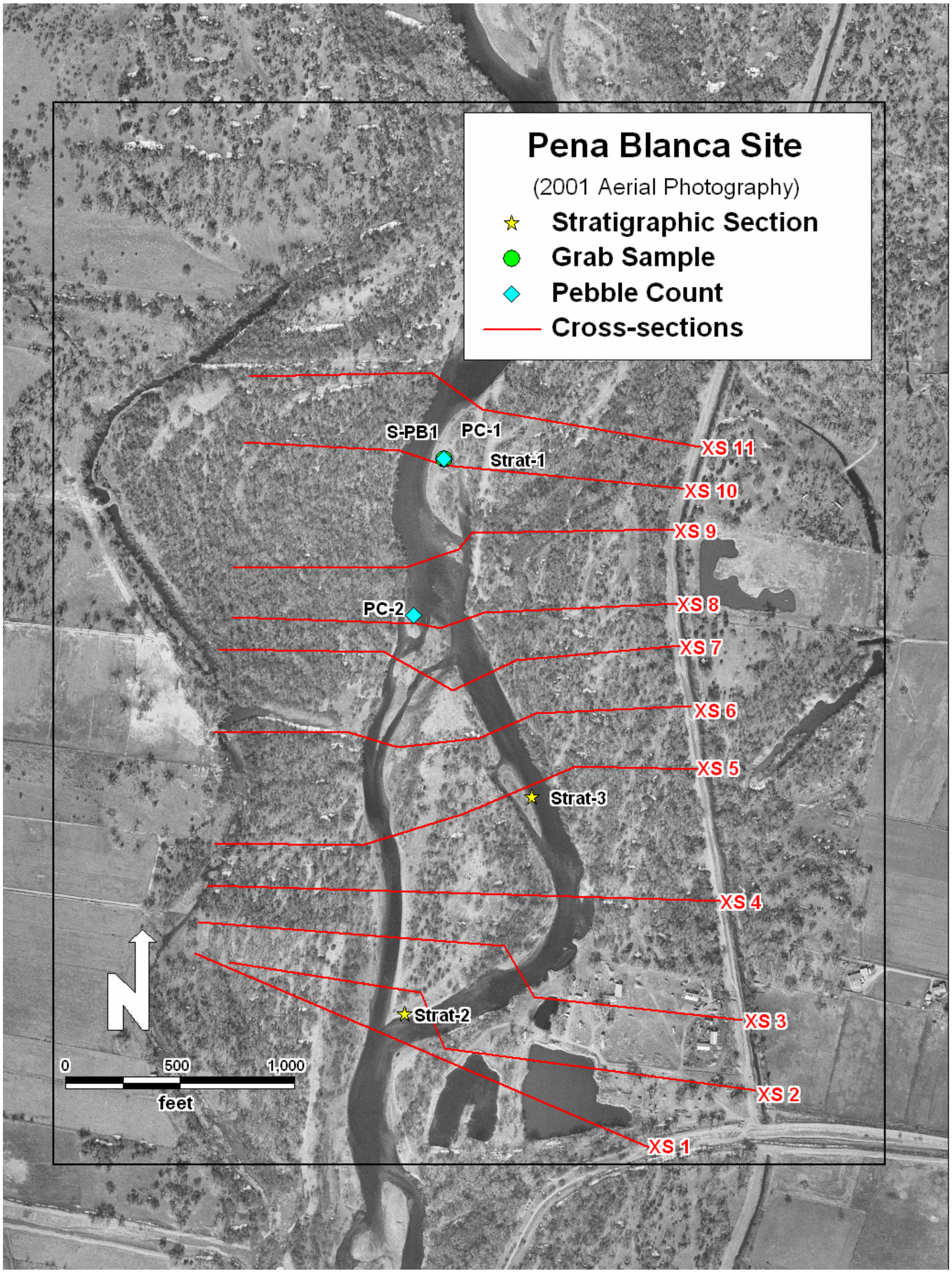


Figure 2.2. Aerial photograph of the Pena Blanca site showing the locations of the cross sections, sediment samples and stratigraphic sections.

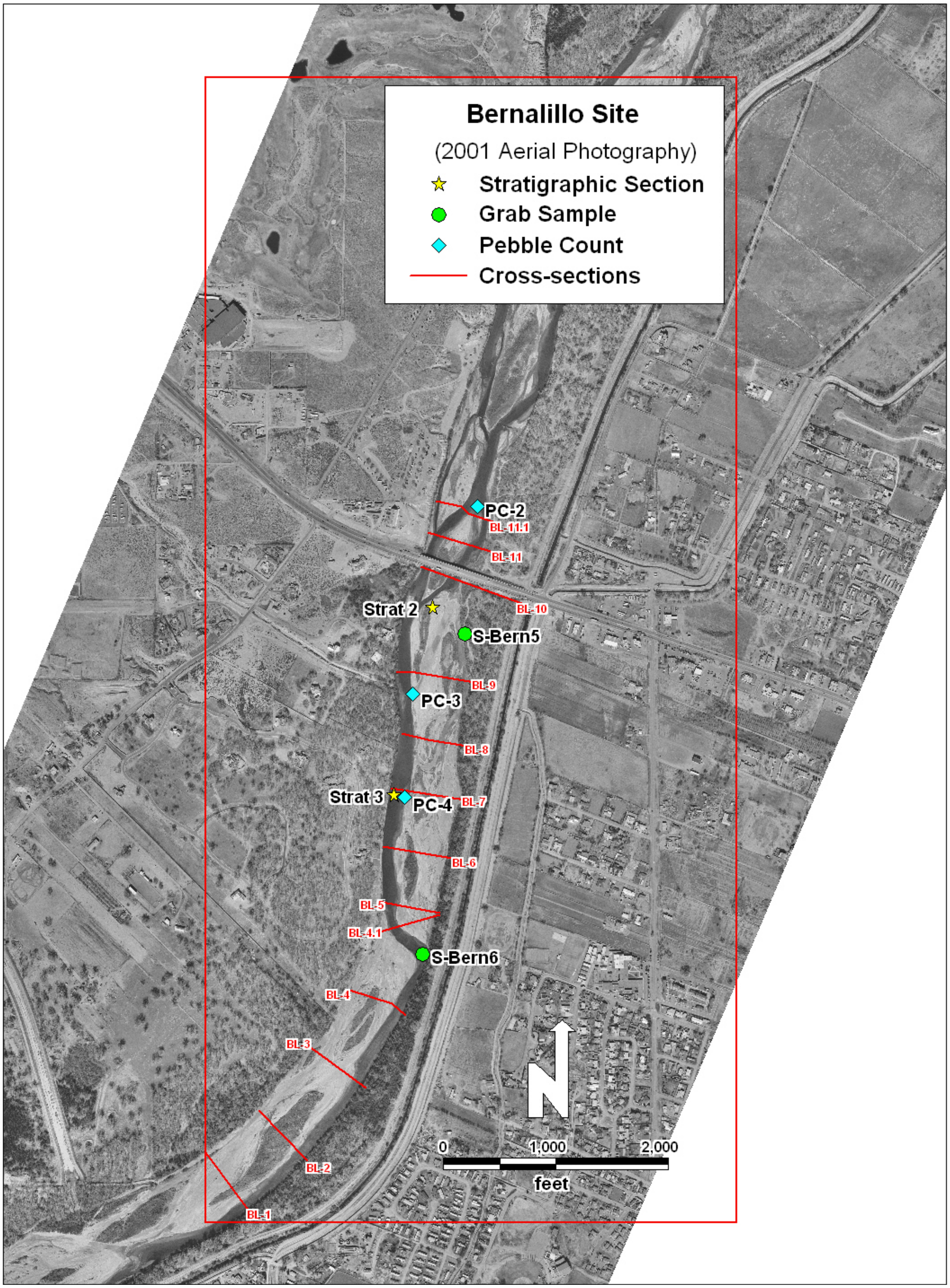


Figure 2.3. Aerial photograph of the Bernalillo site showing the locations of the cross sections, sediment samples and stratigraphic sections.

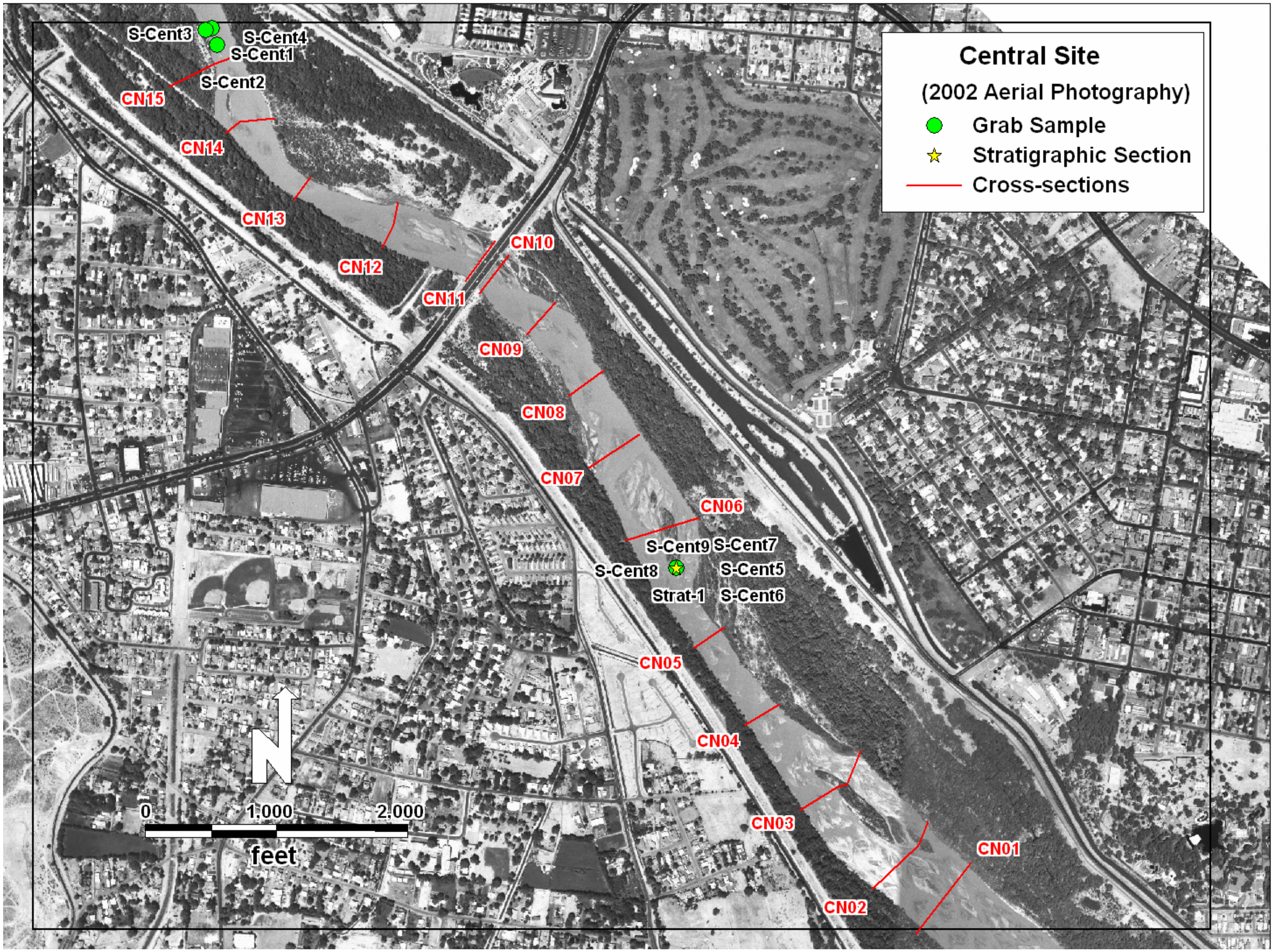


Figure 2.4. Aerial photograph of the Central Avenue site showing the locations of the cross sections, sediment samples and stratigraphic sections.

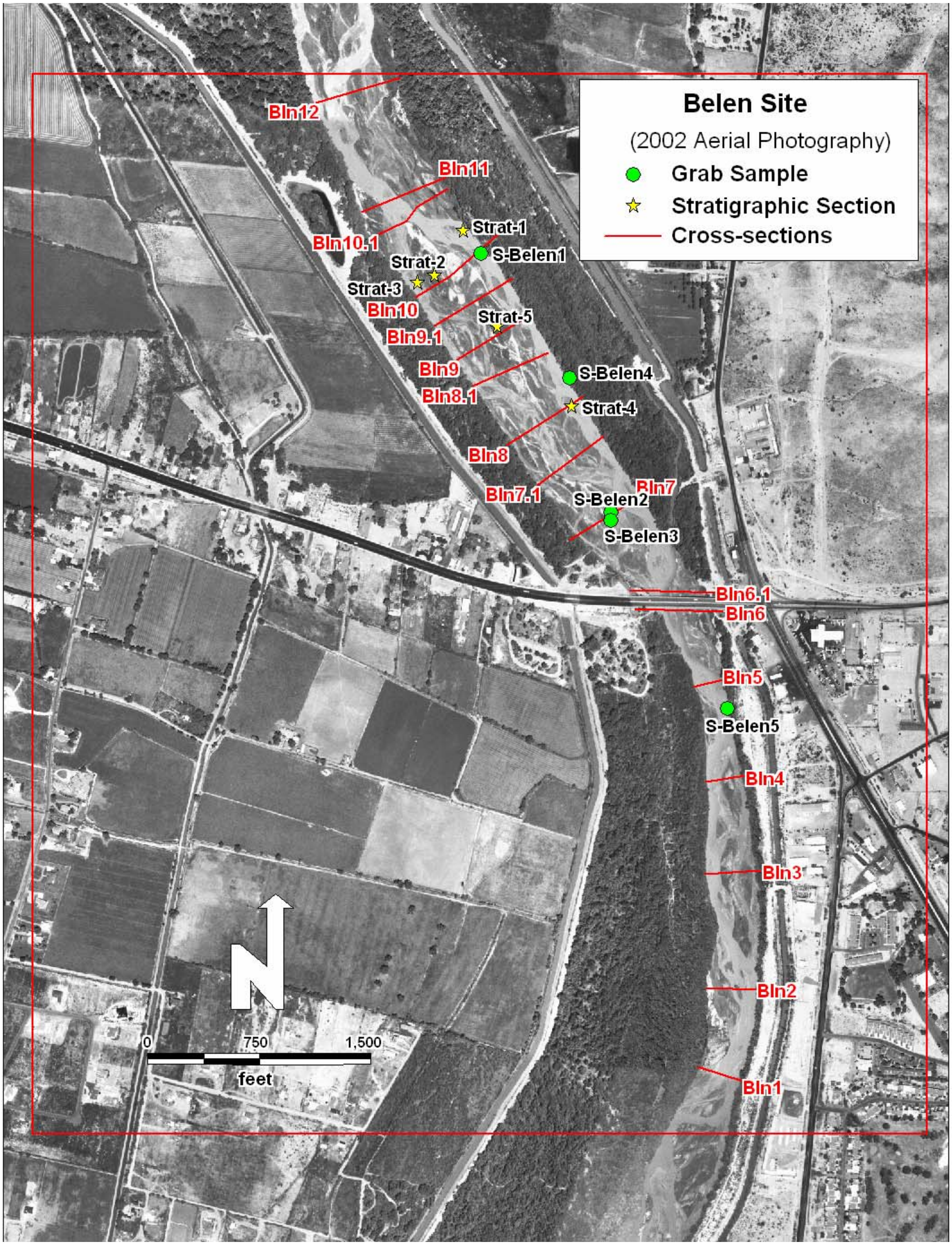


Figure 2.5. Aerial photograph of the Belen site showing the locations of the cross sections, sediment samples and stratigraphic sections.

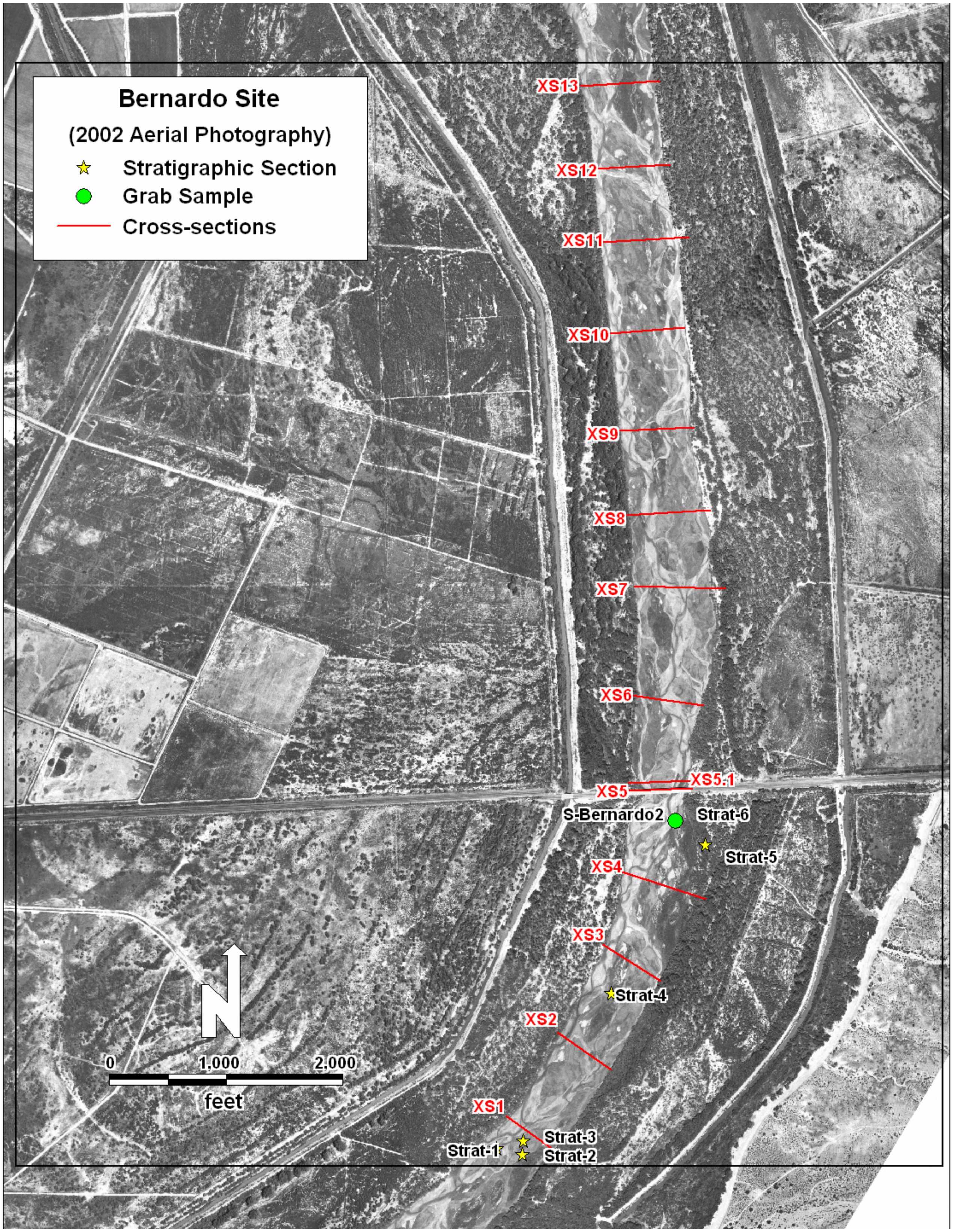


Figure 2.6. Aerial photograph of the Bernardo site showing the locations of the cross sections, sediment samples and stratigraphic sections.

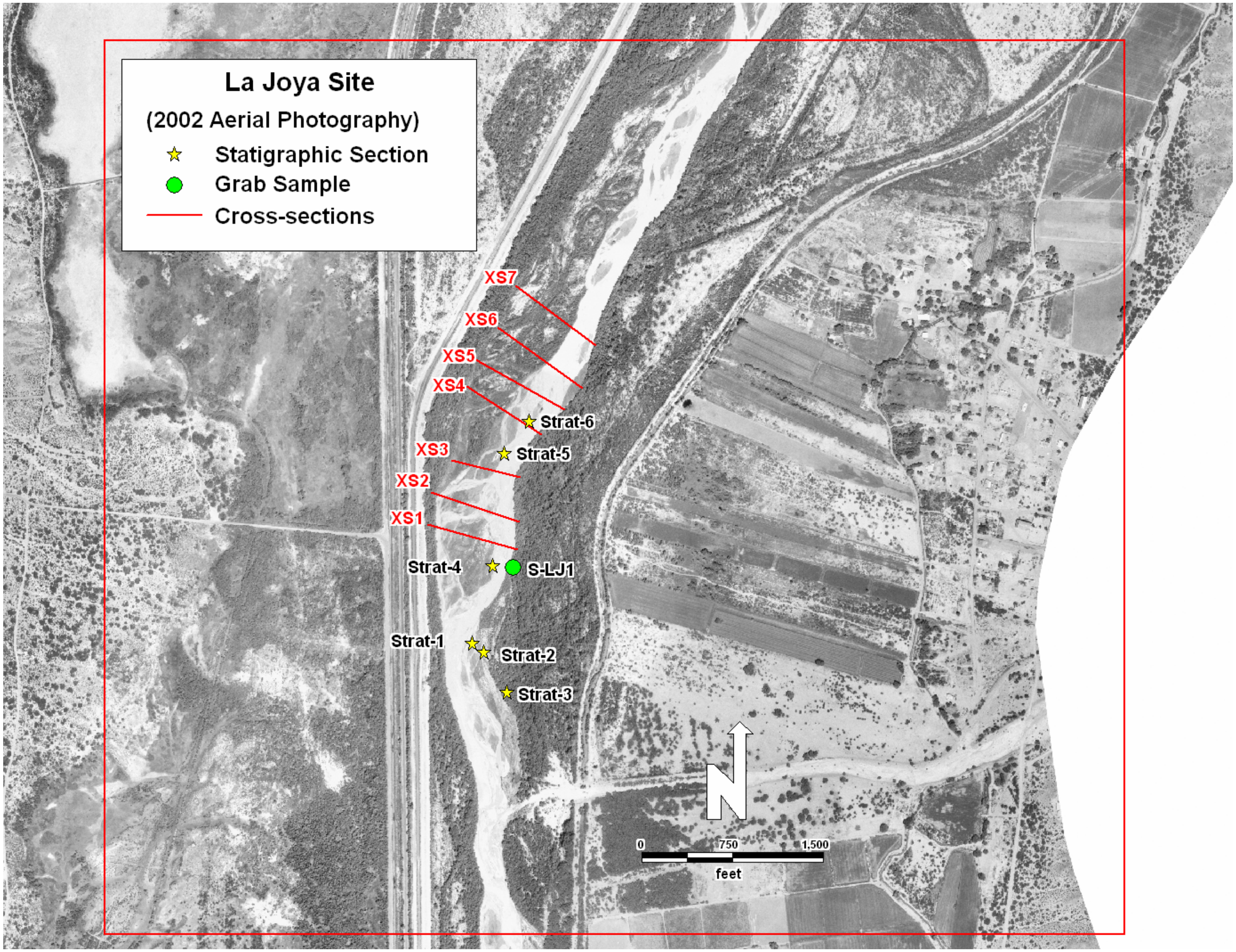


Figure 2.7. Aerial photograph of the La Joya site showing the locations of the cross sections, sediment samples and stratigraphic sections.

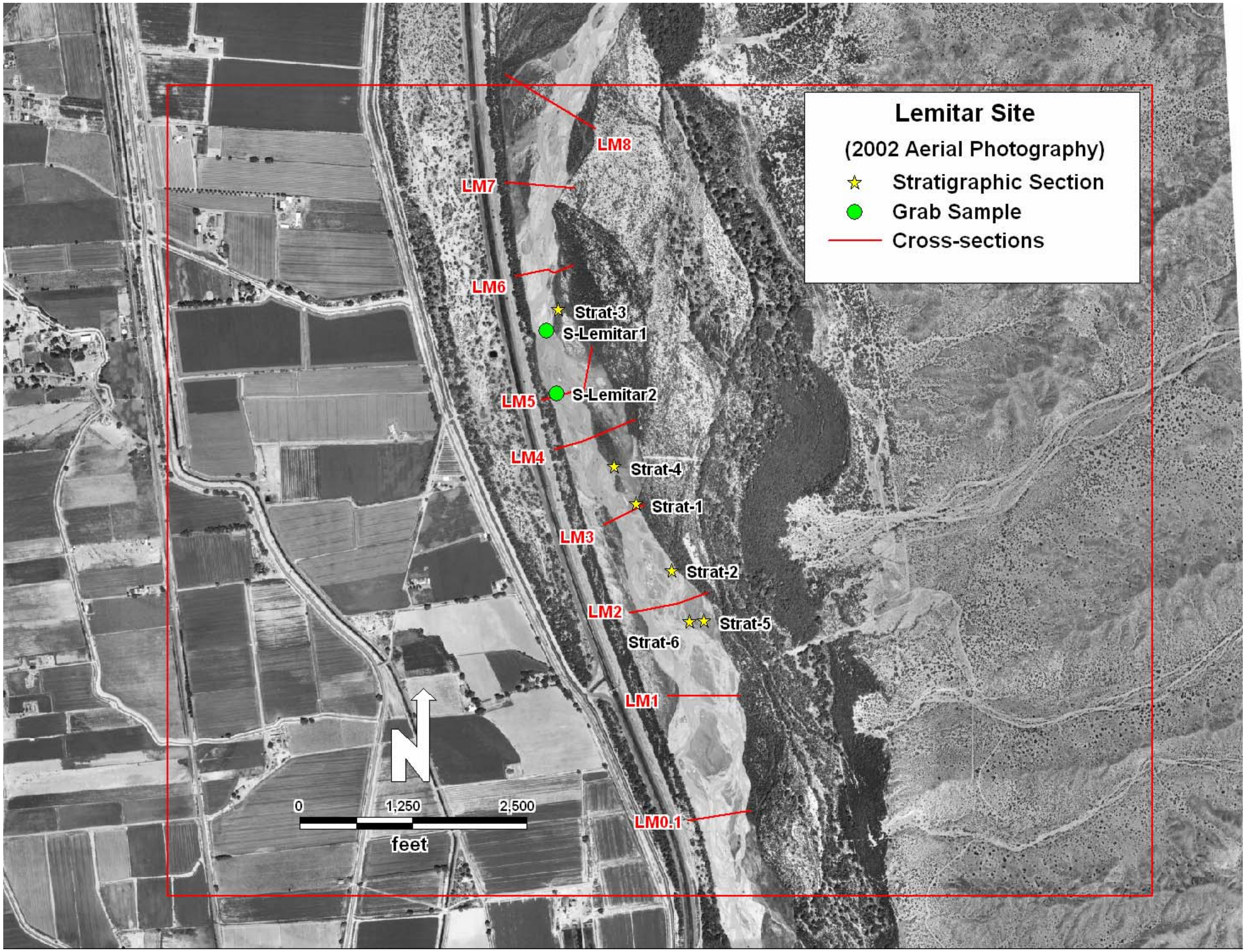


Figure 2.8. Aerial photograph of the Lemitar site showing the locations of the cross sections, sediment samples and stratigraphic sections.


Figure 2.9. Aerial photograph of the Escondida site showing the locations of the cross sections, sediment samples and stratigraphic sections.

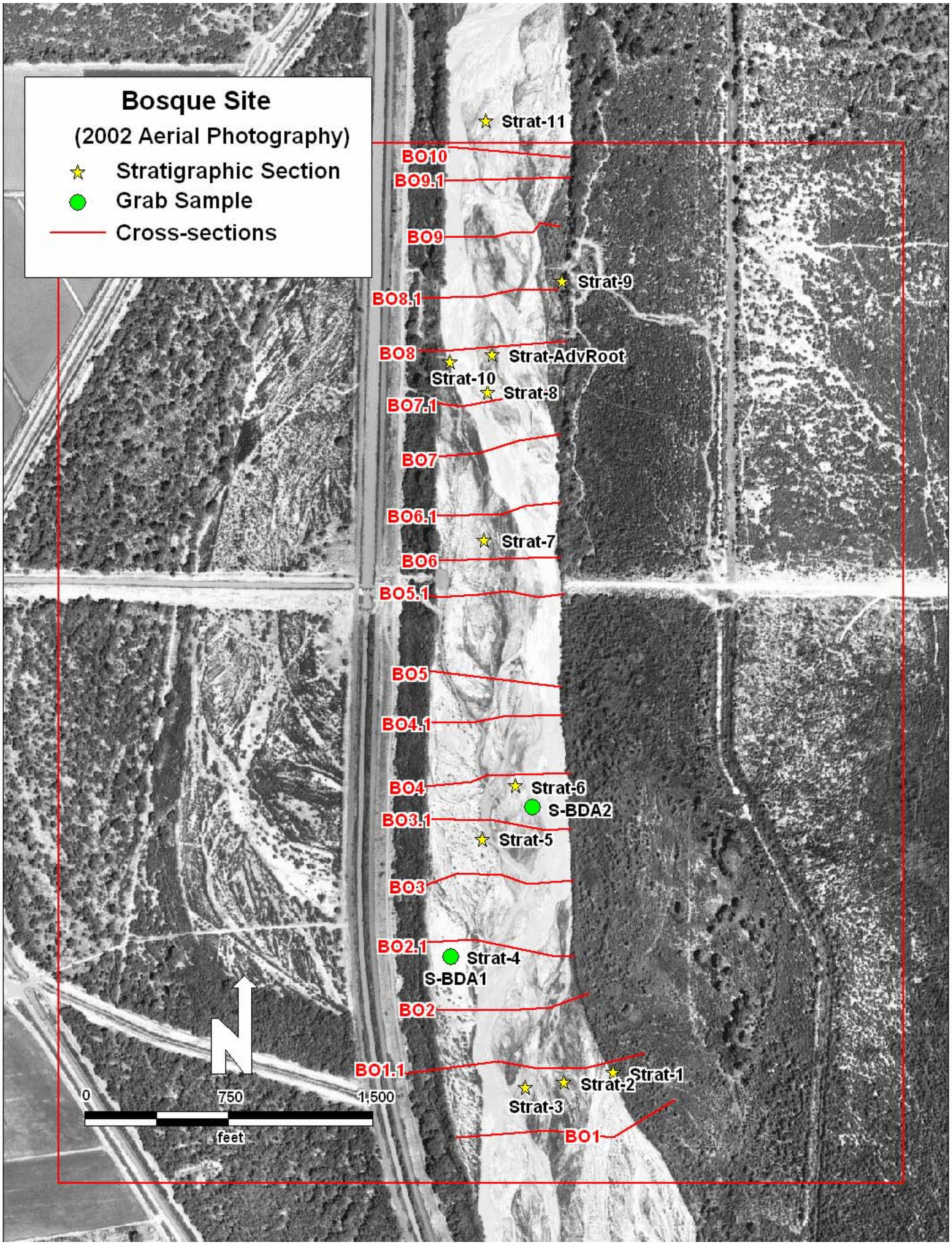


Figure 2.10. Aerial photograph of the Bosque del Apache site showing the locations of the cross sections, sediment samples and stratigraphic sections.

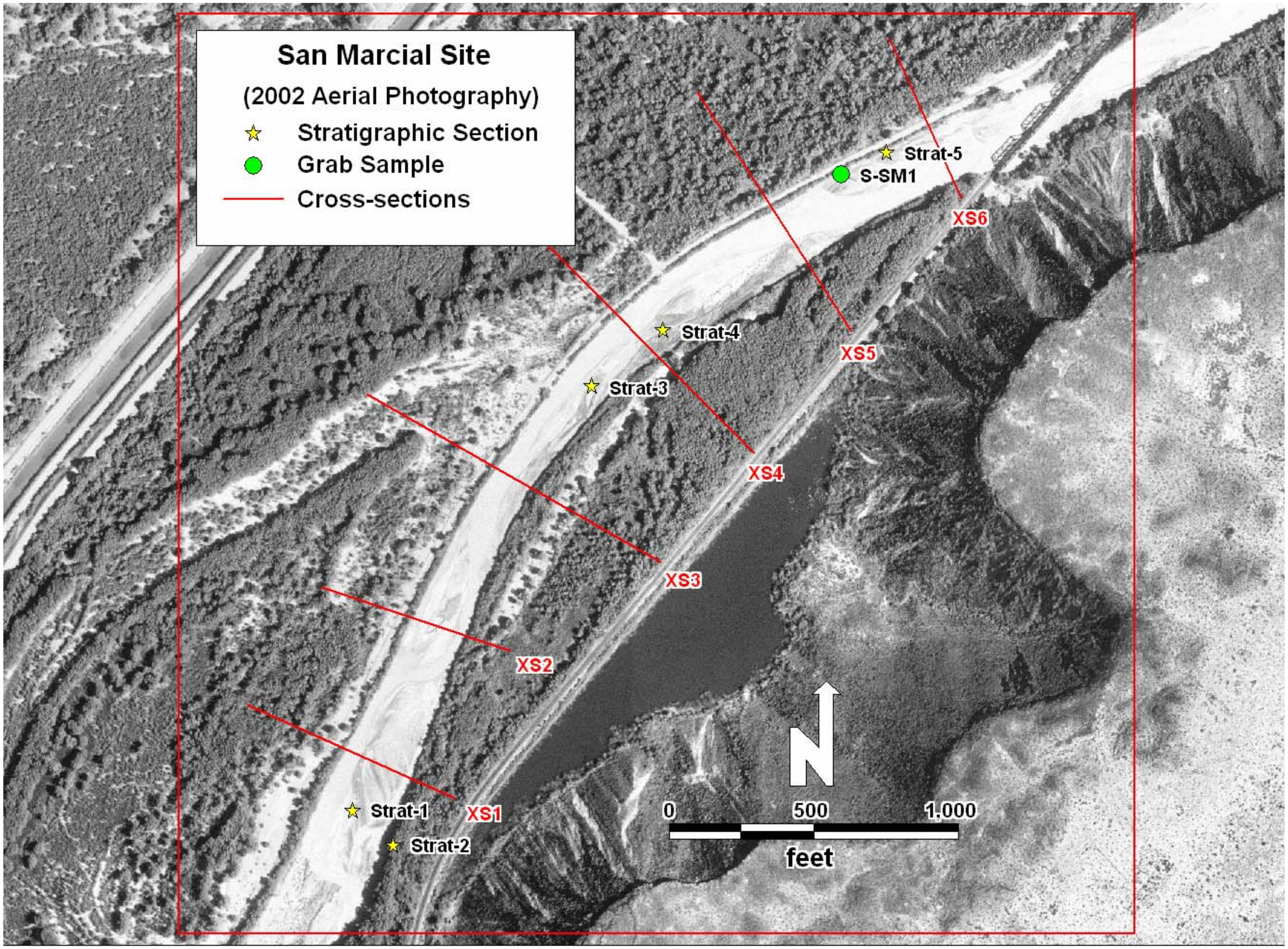


Figure 2.11. Aerial photograph of the San Marcial site showing the locations of the cross sections, sediment samples and stratigraphic sections.

Working-level geomorphic maps were made at each of the sites using the latest available aerial photography as a base map. The mapping included defining the boundaries of the bar types present, the locations and extent of geomorphic features at the sites, including terraces and man-made features, and the types of vegetation present at the sites. The field-based bar classification used in this (as discussed in Chapter 3) report was developed from the field observations, and was modified as necessary to encompass the range of conditions encountered at all of the sites.

### 2.2.6. Morphologic, Hydrologic, and Sedimentologic Changes in the Middle Rio Grande

As discussed in Chapter 1, there have been significant man-made and natural (climatic) changes that have affected the morphology and dynamics of the MRG. The details of these changes are provided in Appendix B. **Table 2.5** provides a summary of the magnitude of the morphologic, hydrologic, and sedimentologic changes for each of the 10 sites.

Table 2.5. Summary of morphologic, hydrologic, and sedimentologic changes affecting bar dynamics in the Middle Rio Grande.

| Site | Channel Morphology | | | | | Hydrology | | Sediment Size | Sediment Load | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Change in Width (ft) | Period of Change in Width | Change in Mean Bed Elevation (ft) | Rangeline Used for Change in MBE | Period of Change in MBE | Change in 2-year Peak Q (cfs)[1] | Change in Median Mean Daily Q (cfs)[2] | Change in Mean Bed Material Size (mm)[3] | Change in Bed Material Load (Mtons/yr)[4] | Change in Suspended Sediment Load (Mtons/yr)[5] |
| Pena Blanca | -1,180 | 1935-2001 | -2.6 | CO-5 | 1970-1995 | -1,920 | 924 | 42.6 | -3.94 | -3.11 |
| Bernalillo | -330 | 1935-2001 | -3.2 | CO-29 | 1971-1998 | -1,680 | 882 | 33.3 | -6.00 | -2.72 |
| Central Ave. | -830 | 1935-2002 | -2.5 | CO-36 | 1970-1998 | -1,680 | 882 | 0.20 | -5.97 | -3.16 |
| Belen | -270 | 1935-2002 | -3.3 | CO-858.1 | 1962-1998 | -780 | 870 | 0.25 | -1.09 | -0.75 |
| Bernardo | -790 | 1935-2002 | -1.9 | CO-1044 | 1962-1998 | -220 | 860 | 0.11 | -1.09 | -0.81 |
| La Joya | -1,630 | 1935-2002 | -6.6 | CO-1104 | 1962-1998 | -2,090 | 920 | 0.13 | 0.04 | -0.44 |
| Lemitar | -2,120 | 1935-2002 | -4.9 | CO-1292 | 1962-1999 | -4,030 | 920 | 0.23 | -0.01 | -0.44 |
| Escondida | -710 | 1947-2002 | -5 | CO-1320 | 1962-1991 | -3,850 | 920 | 0.22 | -0.01 | -0.44 |
| Bosque del Apache | -1,210 | 1935-2001 | 0.7 | CO-1508 | 1962-1996 | -2,430 | 660 | 0.15 | -0.41 | -1.18 |
| San Marcial | 90 | 1972-2001 | 12.1 | Photo-Int[6] | 1962-2002 | -1,240 | 660 | 0.10 | -0.42 | -1.18 |

[1]From flood-frequency curves for pre- and post-Cochiti periods of record.
[2]From flow-duration curves for pre-Heron and post-Cochiti periods of record.
[3]Using earliest available sample in vicinity of site and bed material samples collected at site for this study.
[4]Using pre-Cochiti bed material rating curves (MEI, 2002; with pre-Heron flow-duration curves) and existing bed material volumes from MEI, 2004.
[5]Using pre- and post-Cochiti suspended rating curves (MEI, 2002) with pre-Heron and existing conditions flow-duration curves.
[6]Used USBR photo-interpreted Profiles to compute change in mean-bed elevation.

# 3. BAR CLASSIFICATION, DYNAMICS AND TREND

## 3.1. Bar Dynamics Literature Review

Experimental flume studies (Germanoski, 1989; Ashmore, 1991; Hoey and Sutherland, 1991) and field-based studies (Maizels, 1979; Harvey et al., 1987; Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993) of braided rivers have shown that the morphologic characteristics of the channel and islands/bars can be related to the sediment load, sediment size, and aggradational or degradational status of the river. Bars have been classified in many ways, but in general most bars can be categorized according to the following characteristics (Ashley, 1990; Germanoski, 1989):

1. mid-channel or bank-attached,
2. vegetated or unvegetated,
3. subaerial or sub-aqueous,
4. stationary or mobile,
5. fine-grained (sand and finer) or coarse-grained (gravel and coarser).

The principle morphologic components of braided rivers include multiple braid channels, stationary subaerially-exposed braid bars that separate flows into multiple channels and submerged, migrating linguoid (tongue-shaped) bars within the braid channels (Germanoski and Schumm, 1993). Braid bars form by dissection and further accretion of stalled linguoid bars (Germanoski, 1989), which are then sculpted by fluid shear to form characteristic streamlined shapes (Komar, 1983). The types, numbers, dimensions, and elevations of bars can be used to develop quantifiable indices (Brice, 1964; Williams, 1978; Smith, 1970) of fluvial system response to changes in hydrology (Mosley, 1982), sediment supply and sediment caliber (Maizels, 1979; Harvey et al., 1987; Germanoski, 1989;Germanoski and Schumm, 1993; Germanoski and Harvey, 1993). Changes, which can be expected to occur as a result of watershed land use changes or installation of dams (Koch et al., 1977; Williams and Wolman, 1984; Lagasse, 1980; Collier, et al., 1996), can be monitored and tracked using the indices. Stabilization and preservation of bars composed of non-cohesive sands and gravels have been shown to be affected by riparian vegetation (Koch et al., 1977; Nadler and Schumm, 1981; Smith, 1976; Gray, 1974; Hupp and Osterkamp, 1985) as well as cohesive mud drapes (Schumm et al., 1984; Harvey and Watson, 1986).

The findings of Maizels (1979), Germanoski (1989), Germanoski and Schumm (1993), Germanoski and Harvey (1993) regarding bar morphology and dynamics can be summarized as follows:

1. The kinematics and processes of linguoid bar migration and braid bar formation are similar regardless of sediment size and sediment load,

2. Gravel-bed channels are more intensely braided than sand-bed channels because of reduced rates of migration of linguoid bars in the gravel-bed channels,

3. Aggradation causes an increase in the number of braid bars, and causes an increase in braiding intensity in both sand-bed and gravel-bed channels

4. The number of linguoid bars in sand-bed channels is sediment-supply limited, but in gravel-bed channels it is transport limited,

5. Degradation results in a reduction in braiding intensity and the number of braid bars, and increases the size of the individual braid bars, especially in gravel-bed channels.

6. Although braiding intensity varies with discharge, pattern changes associated with aggradation or degradation are maintained, which permits aerial photographic comparison of different time periods even if the discharges are different,

7. Downstream-progressing degradation increases the sediment supply to downstream reaches, thereby maintaining the braided characteristics of the channel in the downstream reaches until the upstream sediment supply is exhausted and the point of inflection between degradation and aggradation moves downstream.

Bar forms have been related to fluvial process through the development of quantifiable morphometric indices. The planview morphology of the braided channels can be characterized by a Modified Braiding Index (MBI) (Brice, 1964; Germanoski, 1989), which is a measure of braiding intensity, as follows:

MBI = [2(Sum length of bars)/length of channel reach] + [total number of bars/length of reach]

MBI values can be determined from measurements of aerial photographs. Although braiding intensity varies with discharge, pattern changes associated with aggradation or degradation are maintained, which permits aerial photographic comparison of different time periods even if the discharges are different (Germanoski and Schumm, 1993).

Morphometric changes to the channel resulting from changes in discharge, sediment supply and sediment gradation should be reflected in the MBI values as follows:

1. If the bed material coarsens, the MBI values will increase because gravel-bed channels are more intensely braided than sand-bed channels because of reduced rates of migration of linguoid bars in the gravel-bed channels,

2. If aggradation has occurred, the MBI will be higher because there should be an increase in the number of braid bars, in both sand-bed and gravel-bed subreaches, and

3. If degradation has occurred, the MBI will be lower because there should be a reduction in the number of braid bars, and increases in the size of the individual braid bars, especially in gravel-bed reaches.

## 3.2. Bar Classification for the MRG

Based on a review of the time-sequential aerial photography and field observations and measurements at the 10 sites in the MRG, a hierarchical bar classification was developed for the MRG that was based on the location, height, subaqueous or subaerial exposure, and vegetative status of the bars (**Table 3.1**). The classification encompasses a genetic association between the various levels in the bar hierarchy. In both the mid-channel and bank-attached locations, vertical accretion of the lower order bars (bed, Level-1) results in re-classification to a Level-2 order. Increased height of a bar results in a reduced frequency and depth of inundation and, therefore, a reduced rate of vertical accretion through time (Wolman and Leopold, 1957).

| Table 3.1. Hierarchical bar classification for the MRG. | | | | |
|---|---|---|---|---|
| Bar Type | Location | Elevation | Subaqueous or Subaerial | Perennial Vegetation |
| Linguoid | Mid-channel | Bed | Subaqueous | No |
| Braid | Mid-channel | Level-1,2 | Subaerial | No |
| Alternate | Bank-attached | Level-1 | Subaerial | No |
| Mid-channel | Mid-channel | Level-1,2 | Subaerial | Yes |
| Bank-attached | Bank-attached | Level-1,2 | Subaerial | Yes |

Level-1 braid bars are formed by both accretion and erosion of linguoid bars (**Figure 3.1**) during recessional flows (**Figure 3.2**). They are, in turn, vertically accreted by additional sand deposition to form higher elevation Level-2 braid bars (**Figure 3.3**), especially if mud drapes are deposited on the Level-1 bars (**Figures 3.4 and 3.5**). Further vertical accretion of both sand and/or gravel, generally accompanied by a number of mud drapes that appear to enhance the establishment of perennial vegetation, leads to the development of a Level-1 mid-channel bar (**Figure 3.6**). Further deposition of sediment, assisted by the high hydraulic roughness created by the perennial vegetation (mainly sandbar/coyote willows, salt cedar, cottonwoods and Russian olives), leads to the formation of a Level-2 mid-channel bar (**Figures 3.7 and 3.8**). As the elevation of the bar increases over time, the frequency of inundation of the bar is reduced, and the size of the sediment deposited on the bar is also reduced since the finer sediment fractions are transported in the upper part of the flow, thereby producing the classical fining-upwards sequence that is typical of fluvial bar forms (Reineck and Singh, 1975: Miall, 1978). A similar sequence of events characterizes the bank-attached bars. Low elevation alternate bars form along the margins of the channel (**Figure 3.9**), and with time they are accreted vertically to form vegetated Level-1 bank-attached bars (**Figure 3.10**). Further vertical accretion leads to the development of the Level-2 bank-attached bar (**Figure 3.11**) that has very similar internal sedimentary architecture to the Level-2 mid-channel bars. Both the Level-2 mid-channel bars and the bank-attached bars are colonized with tree-like vegetation species (e.g., tree willows, cottonwoods, Russian olives, salt cedar). The ultimate height of the bars is governed by the height of the channel banks. If the channel is confined by terraces, then it is theoretically possible to have bar heights as high as the terraces, provided that flows of sufficient magnitude occur. Channel degradation is likely to cause bar heights to increase as a result of bed lowering, but the frequency of bar overtopping and, therefore, vertical accretion will be reduced as well (**Figure 3.12**). On the other hand, if the channel is aggrading the height of the bars will keep pace with the increase in elevation of the banks resulting from the increased frequency of overbank flows.

Because of the resolution and quality of some of the aerial photography, as well as the inability to accurately resolve elevations on the photographs, the bar classification was simplified for the historical morphometric analysis. The following bar types were used in the analysis: Braid bars, Alternate bars, Mid-channel bars and Bank-attached bars. To perform the bar morphometry analysis, it was necessary to measure the planform attributes of the bars at each of the sites. After geo-rectifying the aerial photographs from the selected years at all sites, the various bar types were delineated using standard geographic information systems (GIS) techniques. The geo-rectified photographs with the delineated bar types for all of the sites are provided in Appendix A.

Aerial photography for the Pena Blanca site in 1935, 1955, 1972, 1992, 1996 and 2001 provides an example of the site morphological and bar type changes over time. In 1935, the active channel width was about 1,450 feet (Figure B.1), and there were a large number of braid bars

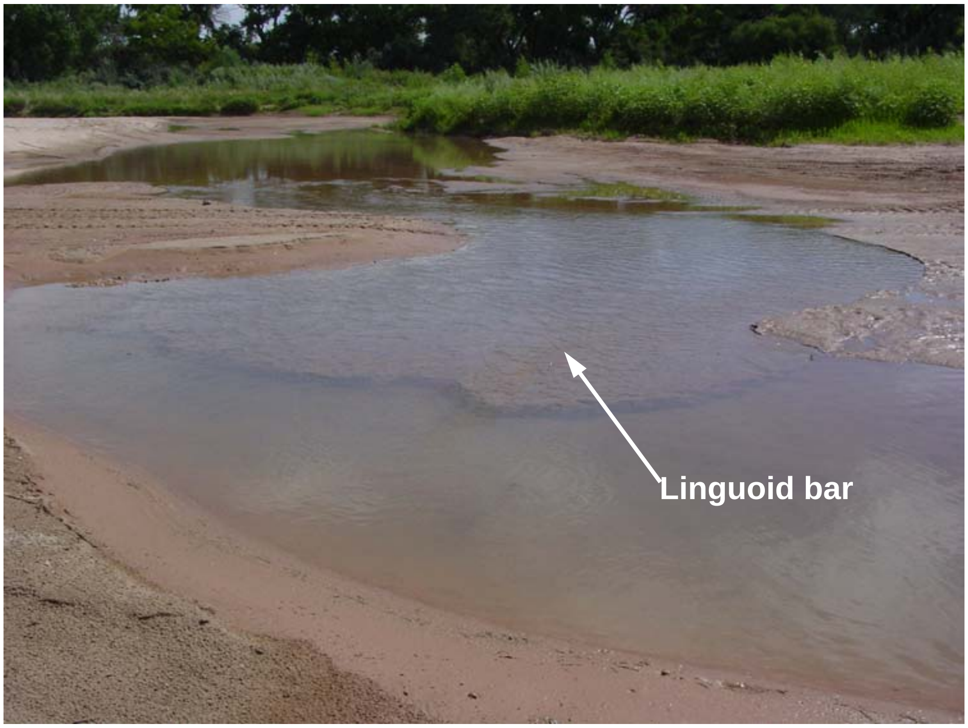


Figure 3.1. View of a subaqueous linguoid bar at the Belen site.


Figure 3.2. View of recently emergent Level-1 braid bars at the Bosque del Apache site.

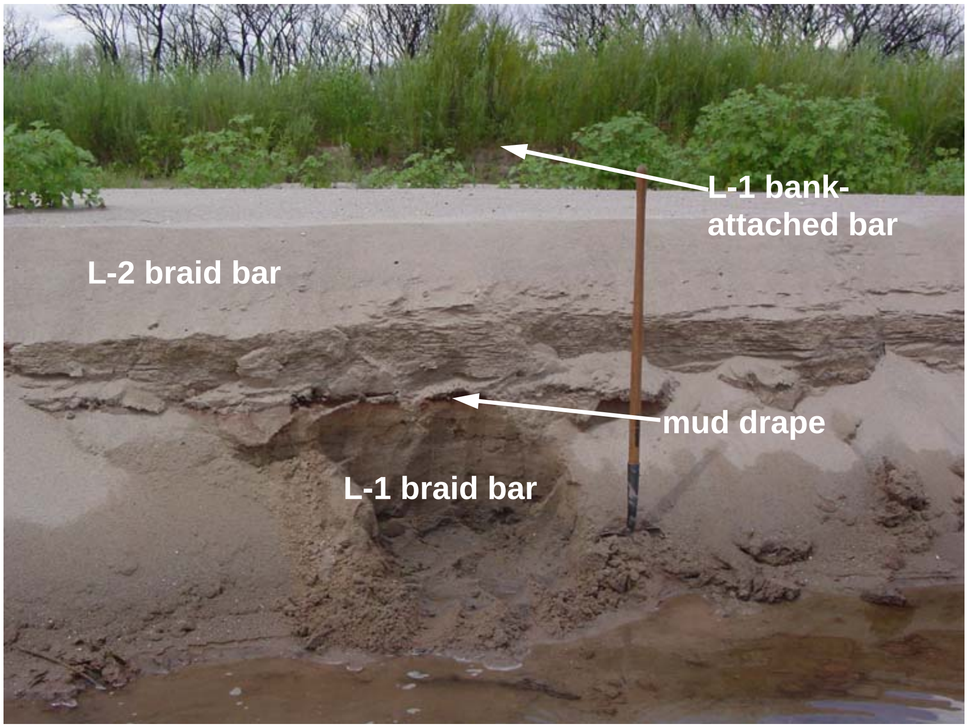


Figure 3.3. View of vertically accreted Level-2 braid bar with Level-1 bank-attached bar in background at the Bernardo site. Note the mud drape on the top of the Level-1 braid bar surface.

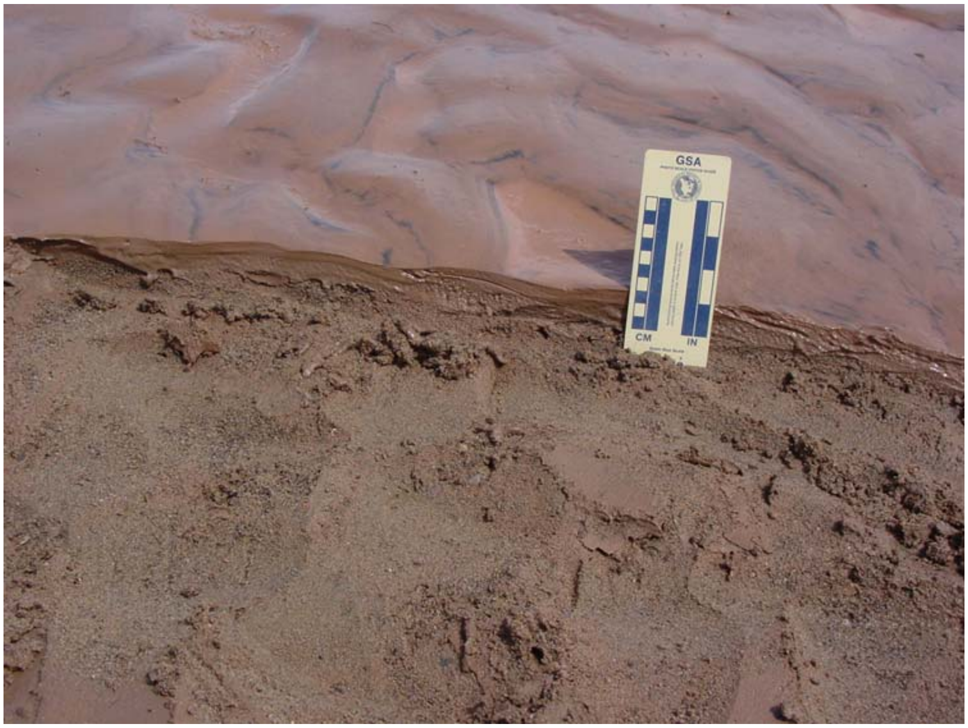


Figure 3.4. View of mud drape on the top of a Level-1 braid bar at the Lemitar site.

Figure 3.5. View of recently deposited mud drapes on Level-1 braid bars at the Escondida site.

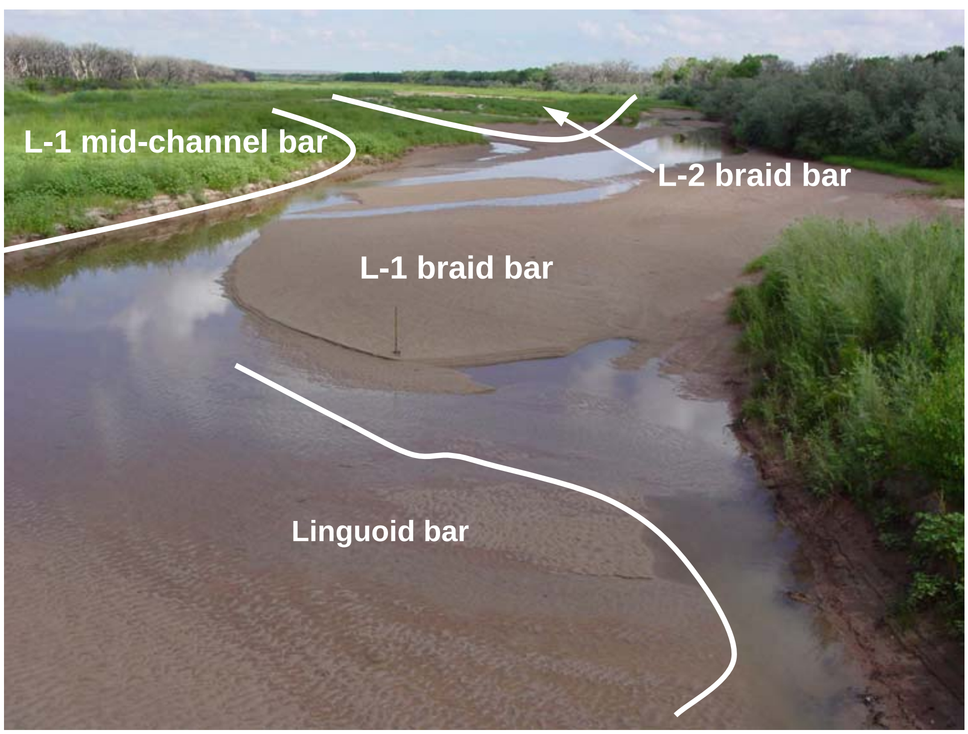


Figure 3.6. View of the relationships between the Level-1 braid bars, Level-2 braid bars and a Level-1 mid-channel bar at the Bernardo site. Annual weeds are growing on the Level-2 braid bar, whereas perennial willows are growing on the Level-1 mid-channel bar.


Figure 3.7. View of a Level-2 mid-channel bar at the Central Avenue site.

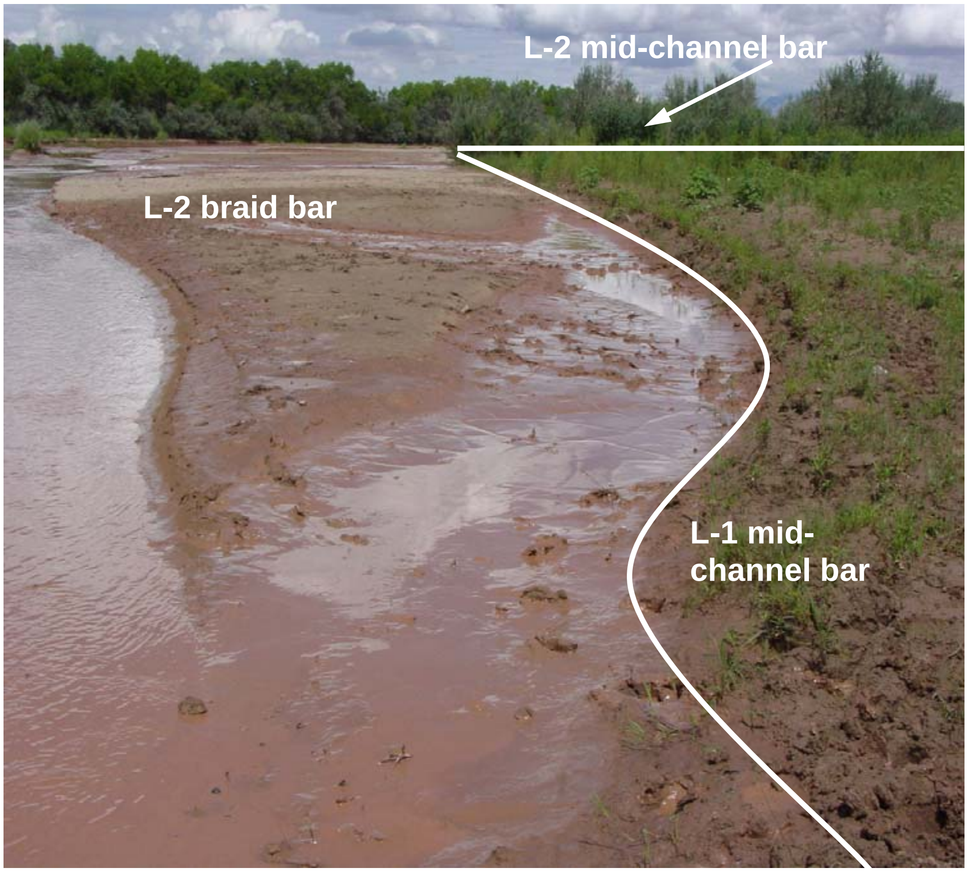


Figure 3.8. View of relationships between Level-2 braid bars, Level-1 mid-channel bars and Level-2 mid-channel bars at the Lemitar site.

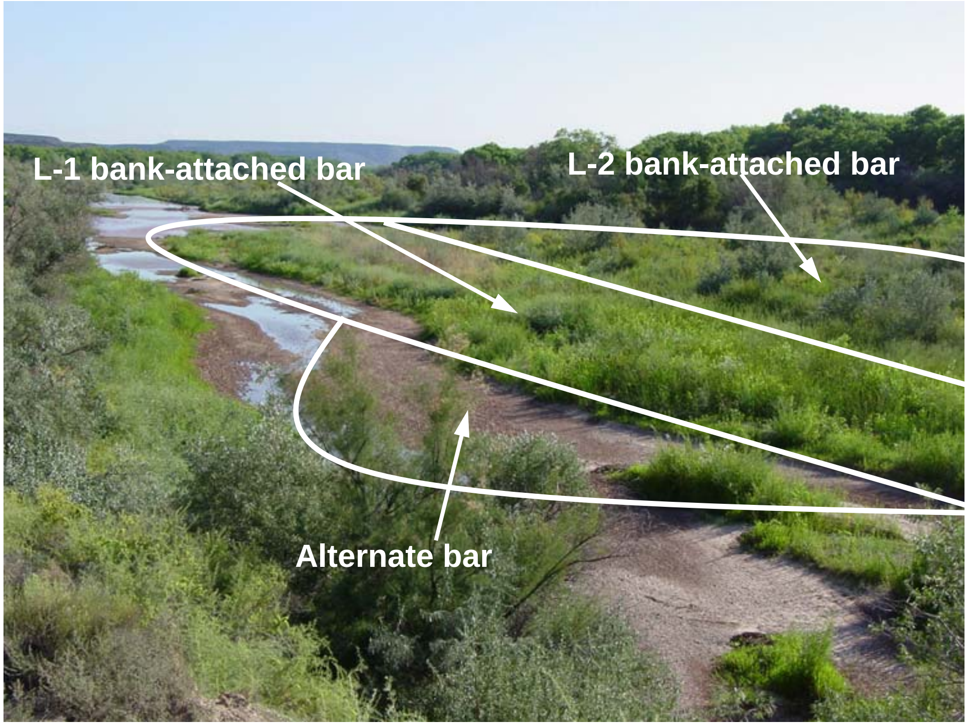


Figure 3.9. Relationships between Alternate bars, Level-1 bank attached bars and Level-2 bank-attached at the Bernalillo site.

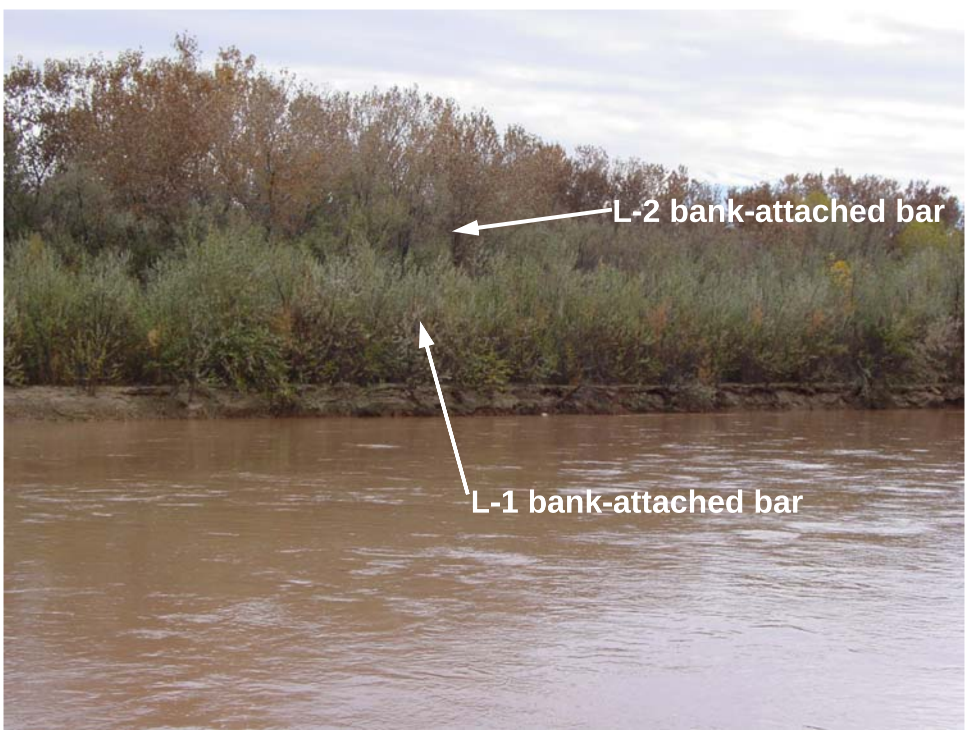


Figure 3.10. View of a Level-1 bank-attached bar in the foreground with a Level-2 bank-attached bar in the background at the La Joya site.


Figure 3.11. View of a Level-2 bank-attached bar at the Central Avenue site.

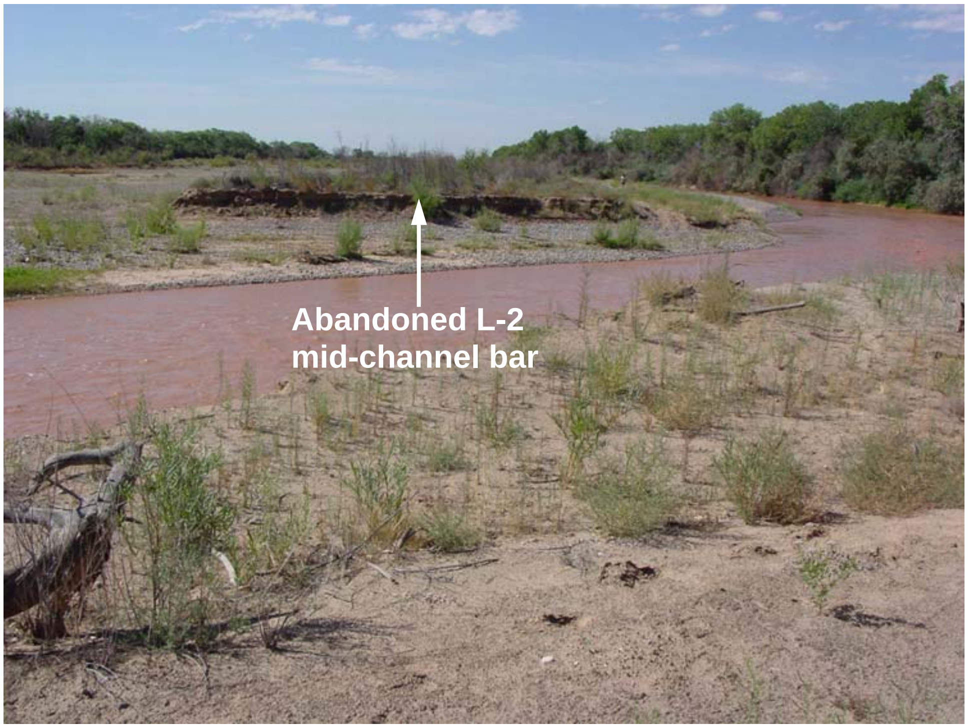


Figure 3.12. View of an abandoned Level-2 mid-channel bar at the Bernalillo site. Cactus and cryptogrammic soils are present on the bar surface.

as well as alternate bars, mid-channel bars and bank-attached bars (**Figure 3.13**). In 1955, following the large floods of the 1940s, the number of braid bars increased and the previously mapped mid-channel bars were dissected (**Figure 3.14**). By 1972, the active channel width had reduced to about 500 feet, and a large portion of the site was composed of vegetated bank-attached bars and mid-channel bars, with few unvegetated braid bars evident (**Figure 3.15**). By 1992, the active channel width had reduced to about 400 feet, and the areas of mid-channel and bank-attached bars had increased further (**Figure 3.16**). On the 1996 photography most of the remaining braid and alternate bars on the 1992 photograph had been colonized by vegetation and converted to either bank-attached or mid-channel bars (**Figure 3.17**). By 2001, the non-vegetated area at the site had been further reduced, and most of the bars are classified as bank-attached or mid-channel, with very few braid bars present (**Figure 3.18**).

## 3.3. Bar Indices

Bar forms were quantified with two morphometric indices. The Modified Braiding Index (MBI), (Germanoski, 1989) was used to quantify the braiding intensity and an Alternate Bars Index (ABI), developed for this project, was used to quantify the presence of bank-attached bars. The photographic record for each of the 10 sites was used to develop the two indices.

The MBI was computed as follows:

$$MBI = \frac{2(\sum L_{BraidBar})}{L_{Channel}} + \frac{n_{bars}}{L_{Channel}} \qquad (3.1)$$

where $MBI$ = Modified Braiding Index
$L_{BraidBar}$ = Length of each braid bar in channel reach
$L_{Channel}$ = Length of channel reach
$n_{bars}$ = Total number of bars in channel reach

The MBI was developed to account for the effective additional bank-length that results from channel braiding (the first term in Equation 3.1), and also includes the number of bars to account for the effects of multiple channels. Although braiding intensity varies with discharge, pattern changes associated with aggradation or degradation are maintained, which permits aerial photographic comparison of different time periods even if the discharges are somewhat different (Germanoski and Schumm, 1993). At discharges in the lower end of this range, the narrow flow path has a low depth of flow that exposes the lowest elevation braid bars. At a somewhat higher discharge, the depth of flow submerges the braid bars exposed at the lower discharge, but the flow path widens and splits around higher-elevation features, which are, by definition, braid bars at this discharge. The sequence of braid bar submergence and flow splitting around higher-elevation braid bars continues with increasing discharge until the upper threshold of the range of discharges is reached, which corresponds to a point when any further increase in discharge only causes further submergence of the highest features that could be considered braid bars.

The alternate bar index (ABI) was computed in a similar manner to the MBI, using the length of the alternate bars as the primary variable:

$$ABI = \frac{\sum L_{AltBar}}{L_{Channel}} + \frac{n_{AltBars}}{L_{Channel}} \qquad (3.2)$$

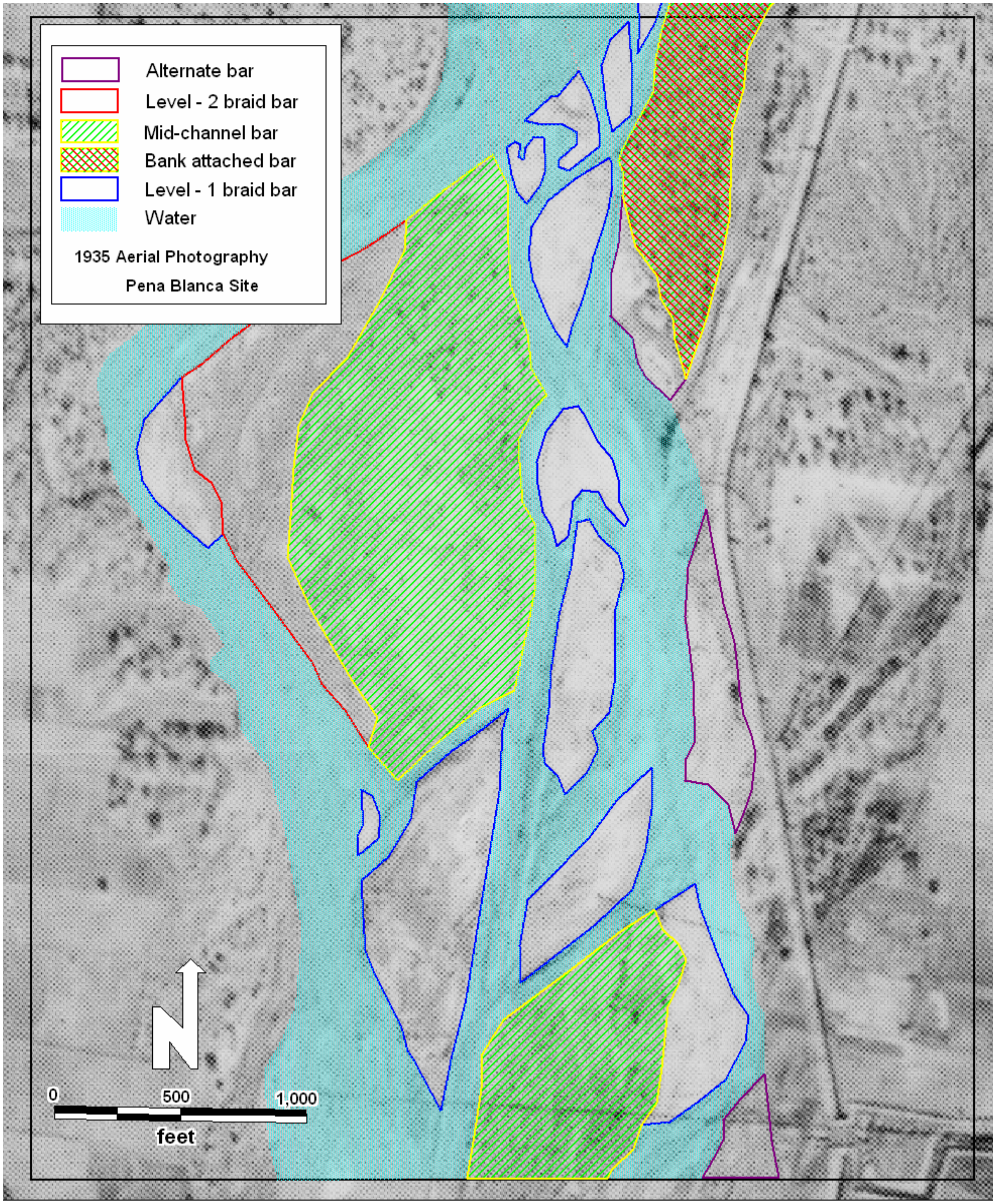


Figure 3.13. 1935 geo-rectified aerial photograph of the Pena Blanca site.

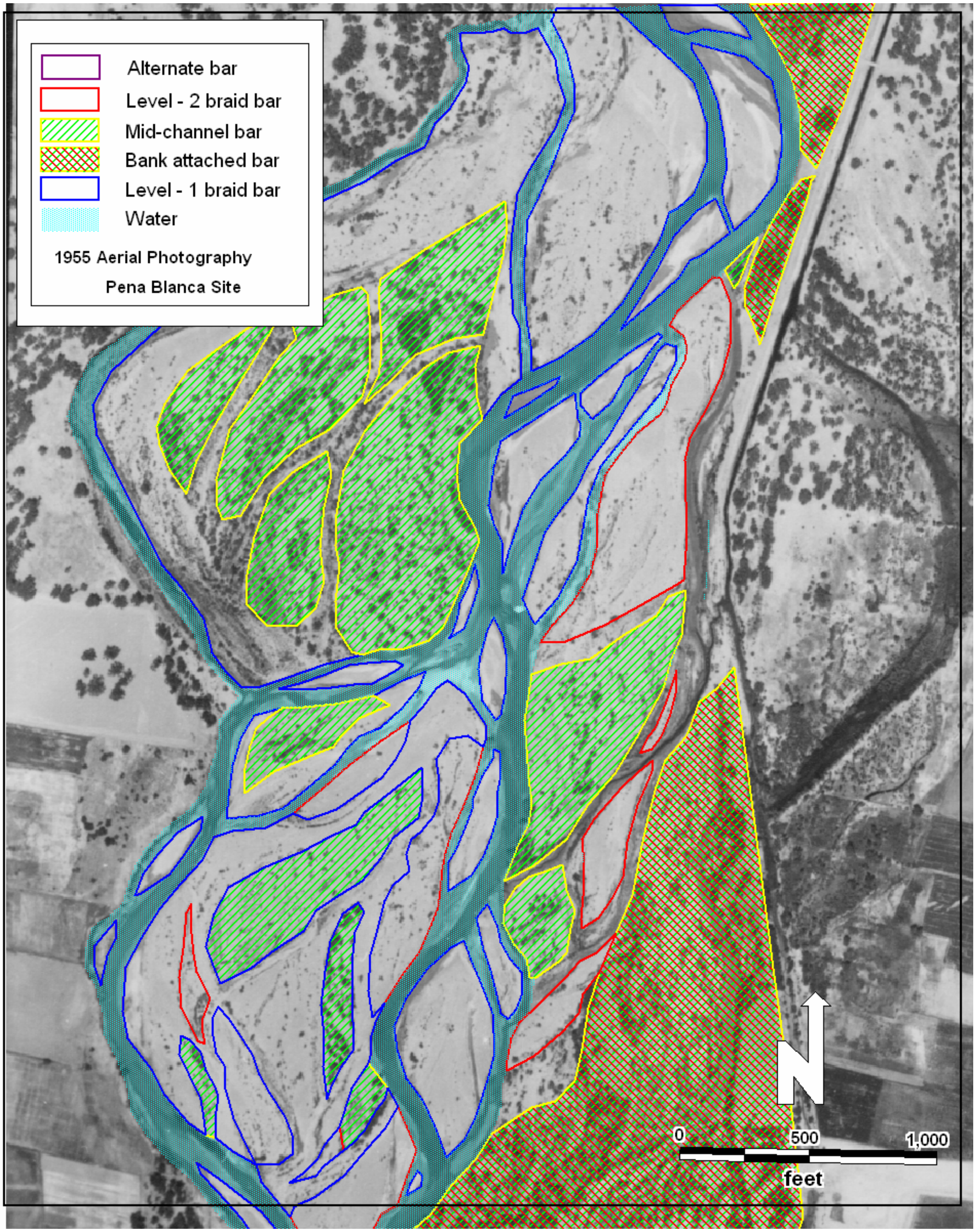


Figure 3.14. 1955 geo-rectified aerial photograph of the Pena Blanca site.

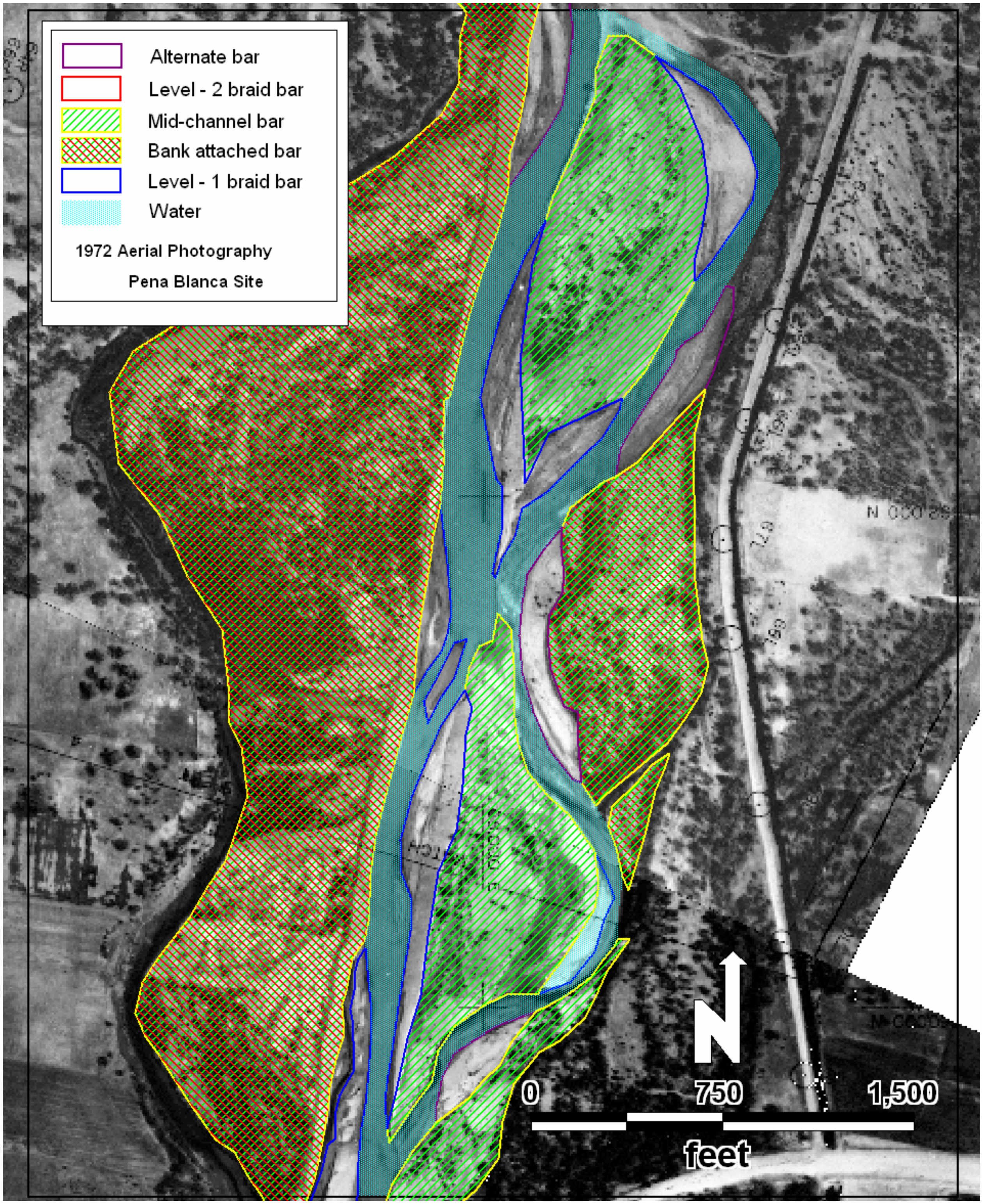


Figure 3.15. 1972 geo-rectified aerial photograph of the Pena Blanca site.

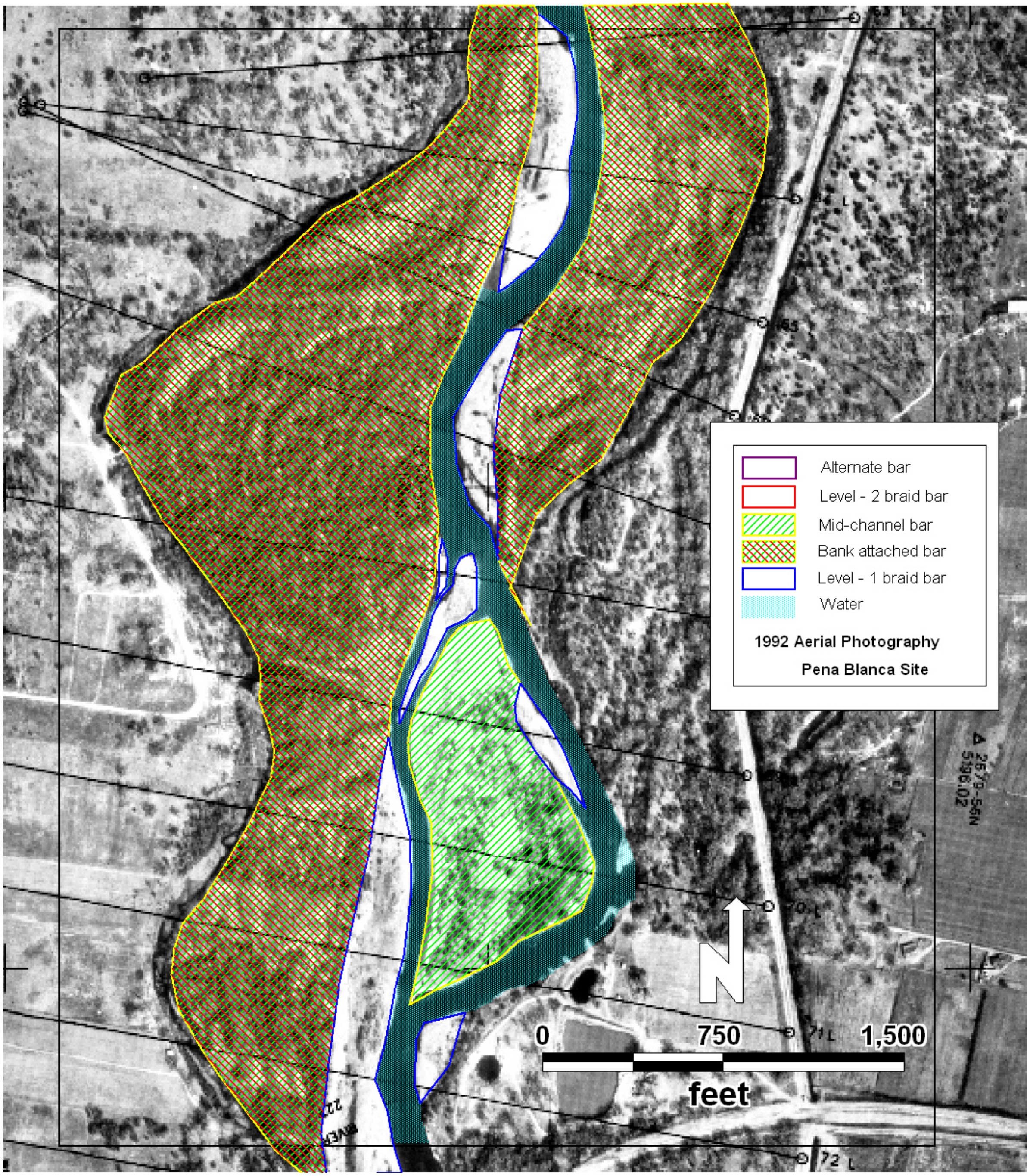


Figure 3.16. 1992 geo-rectified aerial photograph of the Pena Blanca site.

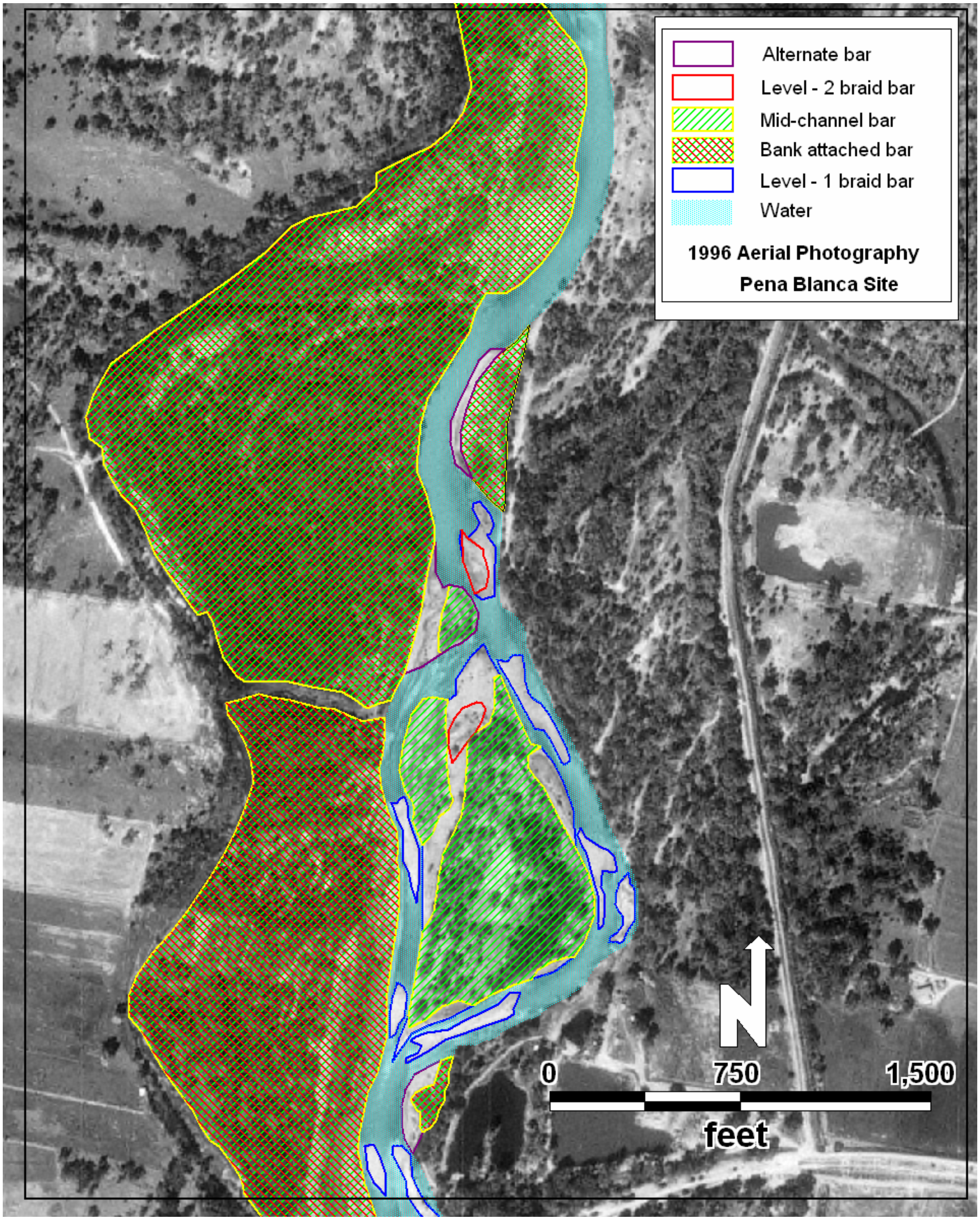


Figure 3.17. 1996 geo-rectified aerial photograph of the Pena Blanca site.

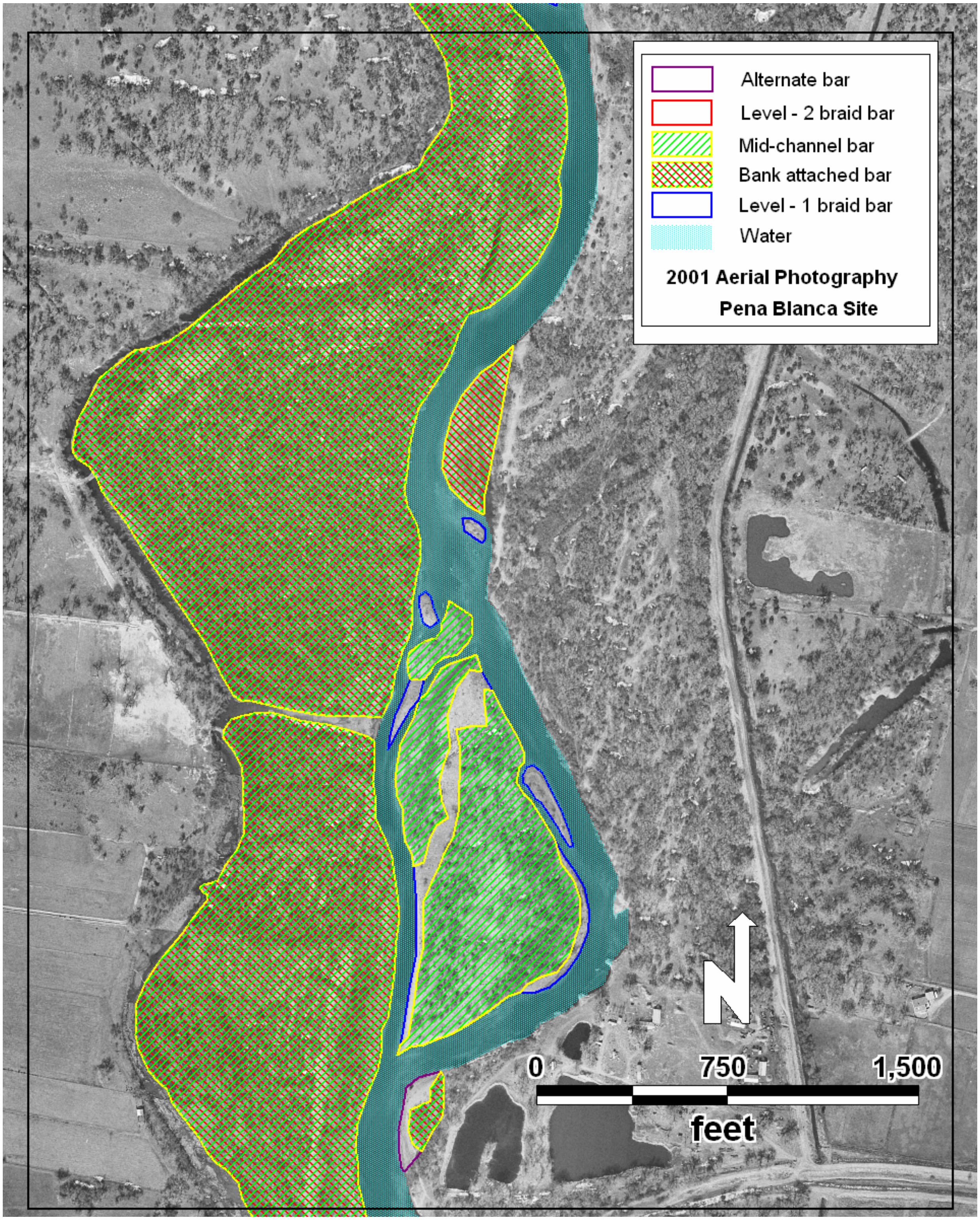


Figure 3.18. 2001 geo-rectified aerial photograph of the Pena Blanca site.

where $ABI$ = Alternate Bar Index
$L_{AltBar}$ = Length of each alternate bar in channel reach
$L_{Channel}$ = Length of channel reach
$n_{AltBars}$ = Total number of alternate bars in channel reach

Unlike the MBI, the first term in the ABI does not represent an increase in effective bankline, but instead represents the portion of the site affected by alternate bars. Alternate bars, like braid bars, create constrictions of the low-flow channel that result in localized channel bed scour. Upstream of alternate bars, where backwater conditions occur, a wider and shallower low-flow channel exists with relatively low velocity with an increased number of bars. Braid bar formation is in many cases interconnected with the presence of alternate bars.

Table 2.5 provides a summary of the magnitudes of the changes in channel morphology (width and mean bed elevation), hydrology (2-year peak flow and median discharge), bed-material size and bed-material and suspended-sediment load, all factors which should affect the number of bars at each of the 10 sites.

### 3.3.1. Pena Blanca

**Figure 3.19** shows the changes in the active channel width and MBI and ABI values between 1935 and 2001 for the Pena Blanca site. Prior to channelization, the increase in MBI value between 1935 and 1955 reflected the floods of the 1940s which increased the number of braid bars. As expected in a highly braided channel, the ABI values were lowest when the MBI was highest. Following channelization, the channel width decreased sharply and the MBI value also decreased sharply as more of the site became stabilized. ABI values increased as the MBI values decreased indicating that more of the sediment was being deposited in alternate bars.

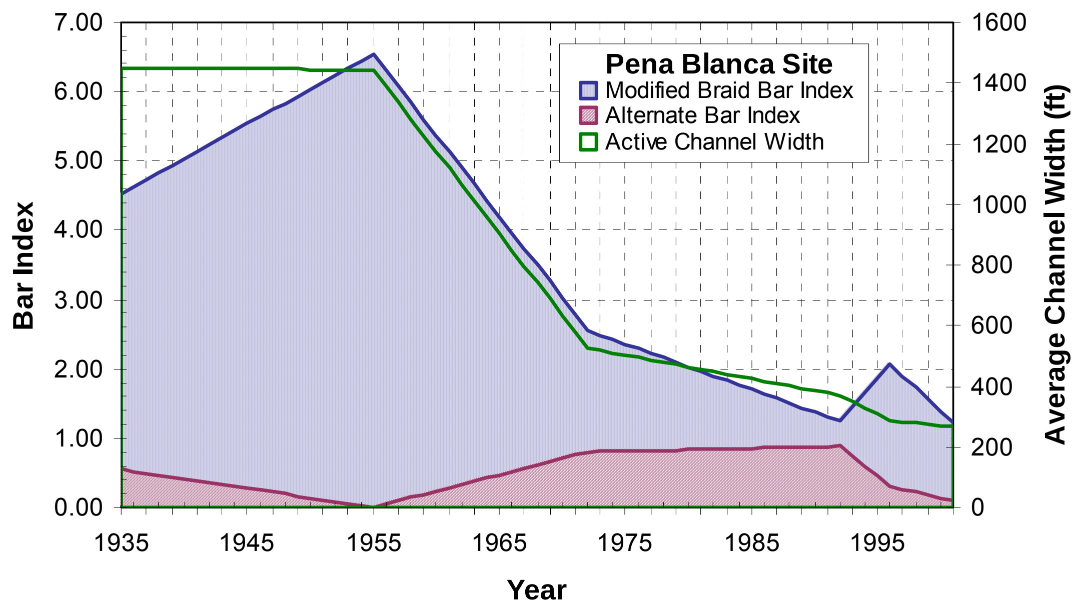


Figure 3.19. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Pena Blanca site.

Following closure of Cochiti Dam in 1974 and the consequent reduction in flood flows and sediment supply to the site, as well as channel incision and coarsening of the bed material (Table 2.5), the MBI values continued to decrease and the ABI values continued to increase. MBI values increased briefly following the high flows in 1995, but then decreased. The ABI values also decreased after 1992 as a result of colonization by vegetation of the alternate bars. Reduction in both the MBI and ABI values indicates that there is very little sediment being supplied to the site under current conditions. In summary, at the Pena Blanca site, the reduction in the sediment supply, channel narrowing and incision and bed material coarsening caused the expected reduction in MBI values (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

### 3.3.2. Bernalillo

At the Bernalillo site, both the MBI and ABI values increased between 1935 and 1992 even though the channel width was reduced significantly in the same time period (**Figure 3.20**). The cause of the increased index values was most likely on-going aggradation of the channel between 1935 and 1972 (Figure B.3). After 1992, the MBI values dropped significantly most likely as a result of the cumulative effects of channel incision, reduced sediment supply and bed material coarsening (Table 2.5). ABI values remained relatively constant and indicate that most of the sediment being deposited within the incised channel is in alternate bars. In summary, at the Bernalillo site, the cumulative effects of reduced sediment supply, channel narrowing and incision and bed material coarsening caused a sharp reduction in the MBI values after they had increased in response to an increase in sediment supply and channel aggradation (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

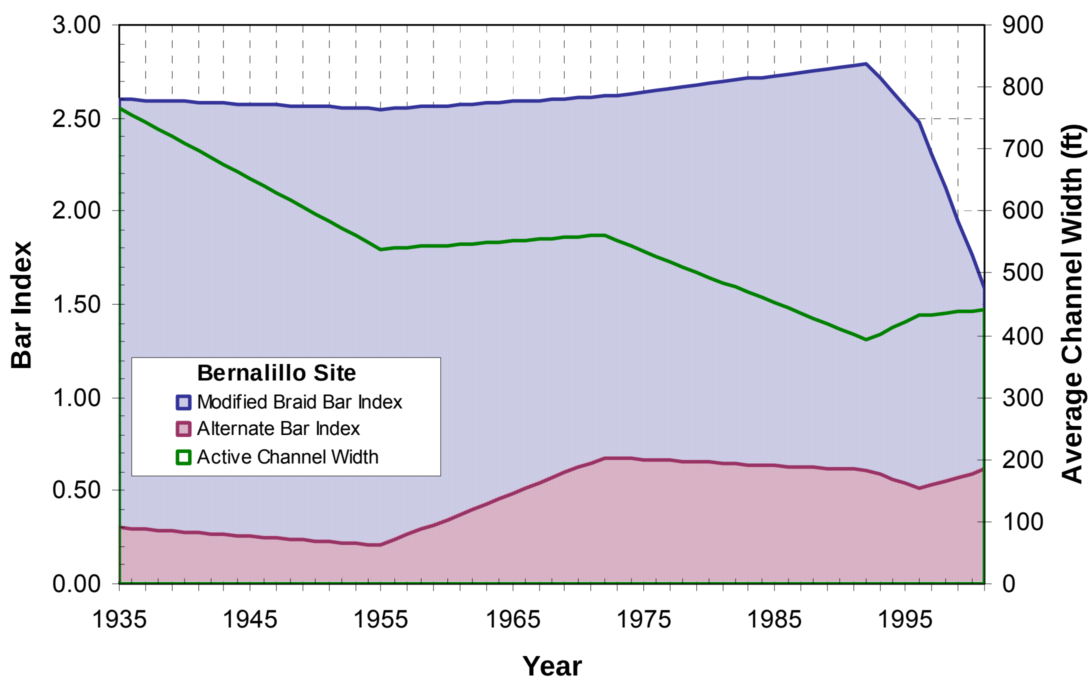


Figure 3.20. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Bernalillo site.

### 3.3.3. Central Avenue

**Figure 3.21** shows the changes in the active channel width and MBI and ABI values between 1935 and 2001 for the Central Avenue site. The increase in MBI value and reduction in the ABI values between 1935 and 1955 probably reflects the large floods of the 1940s that resulted in significant aggradation in this reach of the river (Lagasse, 1980). Channelization of the river caused channel narrowing and a reduction in both the MBI and ABI values between 1955 and 1972 even though the channel was still aggrading in this period (Figure B.4). Between 1972 and 1992, the MBI values continued to reduce, but there was a sharp increase in the ABI values while the channel was continuing to narrow suggesting that more sediment was being stored in alternate bars. After 1992, the MBI values increased while the ABI values decreased suggesting that the alternate bars were being stabilized by vegetation which was reflected in the reduced channel width, and that the available sediment was being stored in braid bars. In summary, at the Central Avenue site it appears that the major factors affecting the MBI are reductions in the channel width, sediment supply and flood magnitude since there has been minor degradation of the channel and very little bed material coarsening, and this is consistent with predicted responses to these changes (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

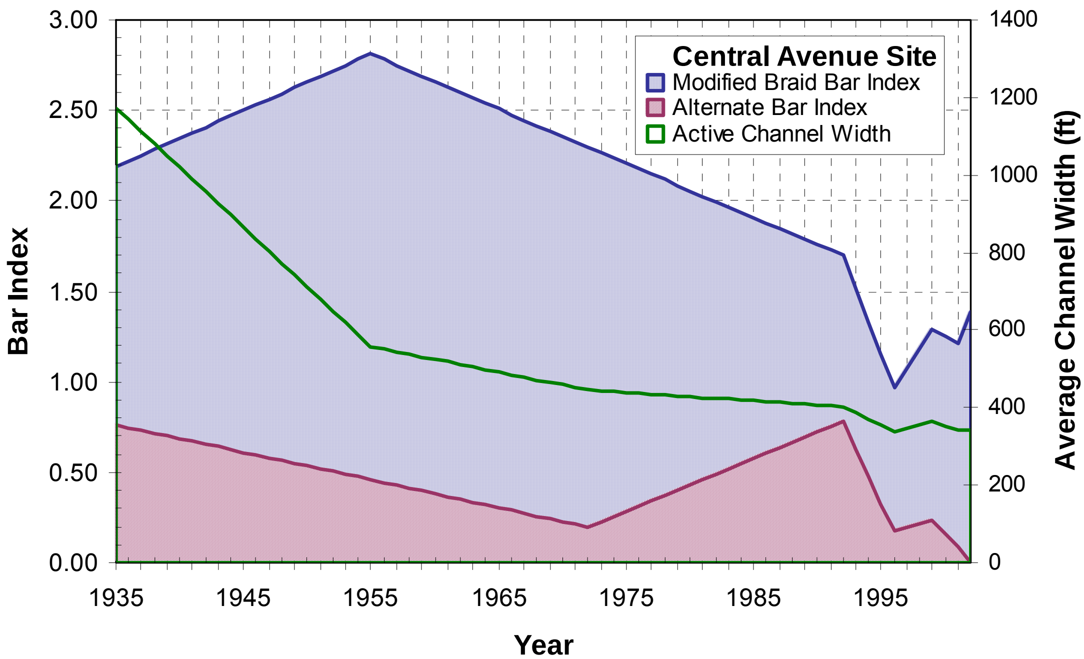


Figure 3.21. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Central Avenue site.

### 3.3.4. Belen

At the Belen site, the MBI increased between 1935 and 1947 as a result of the floods in the 1940's and the ABI decreased (**Figure 3.22**). Channelization between 1947 and 1972 caused channel narrowing, but the thalweg data (Figure B.5) indicated that the channel was aggrading in this period, and this may explain why the MBI values show a small decline and the ABI values show a similar pattern. Between 1972 and 1996, the MBI values decreased more steeply and were mirrored by the increasing ABI values, possibly as a result of some degradation of the bed. After 1996, the MBI values have increased and the ABI values have decreased suggesting that the alternate bars have been stabilized by vegetation and most of the available sediment is being stored in braid bars. In summary, at the Belen site it appears that the major factors affecting the MBI are reductions in the channel width, sediment supply and flood magnitude since there has been minor degradation of the channel and very little bed material coarsening, and this is consistent with predicted responses to these changes (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

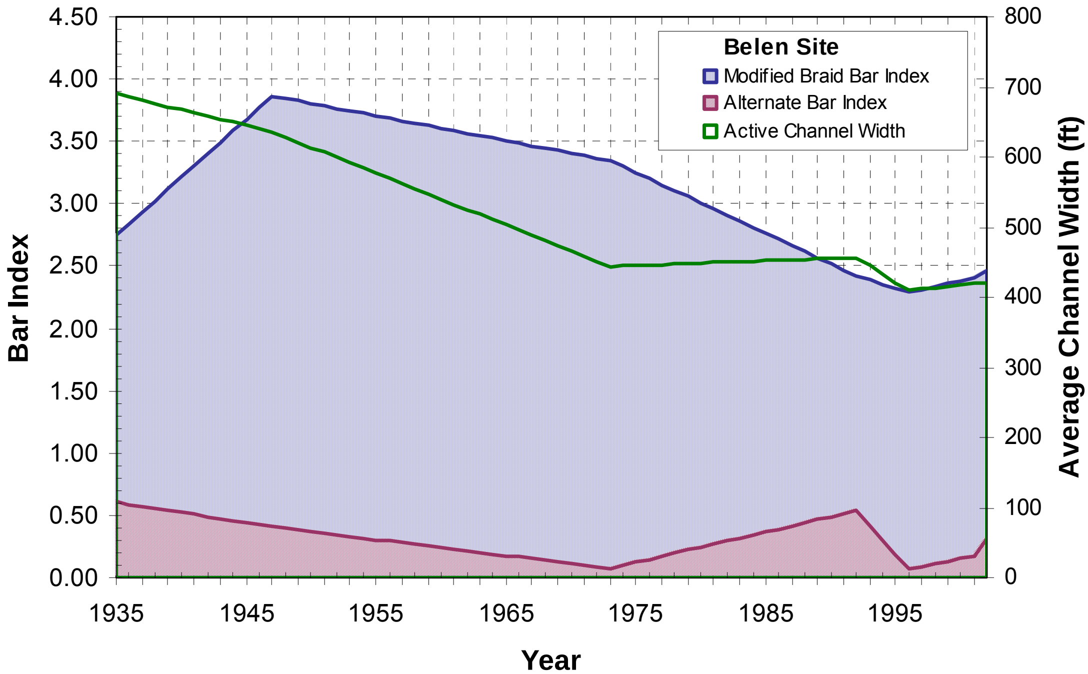


Figure 3.22. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Belen site.

### 3.3.5. Bernardo

At the Bernardo site the MBI values have progressively increased between 1935 and 2001 even though the active channel width has declined in the same period (**Figure 3.23**). The increase in MBI values and the decrease in the ABI values between 1935 and 1947 are probably related to the large floods in the 1940s, as well as channel aggradation (Happ, 1948), even though there was a marked reduction in channel width. Between 1962 and 1972 the channel aggraded (Figure B.6) and the MBI values increased, as did the ABI values. Between 1972 and 1992 the channel degraded slightly, but the MBI values increased and the ABI values decreased. Aggradation between 1992 and 2002 resulted in increases in MBI values and in ABI values. In summary, at the Bernardo site it appears that the major factor affecting the MBI is aggradation of the channel, and this is consistent with predicted response to this change (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

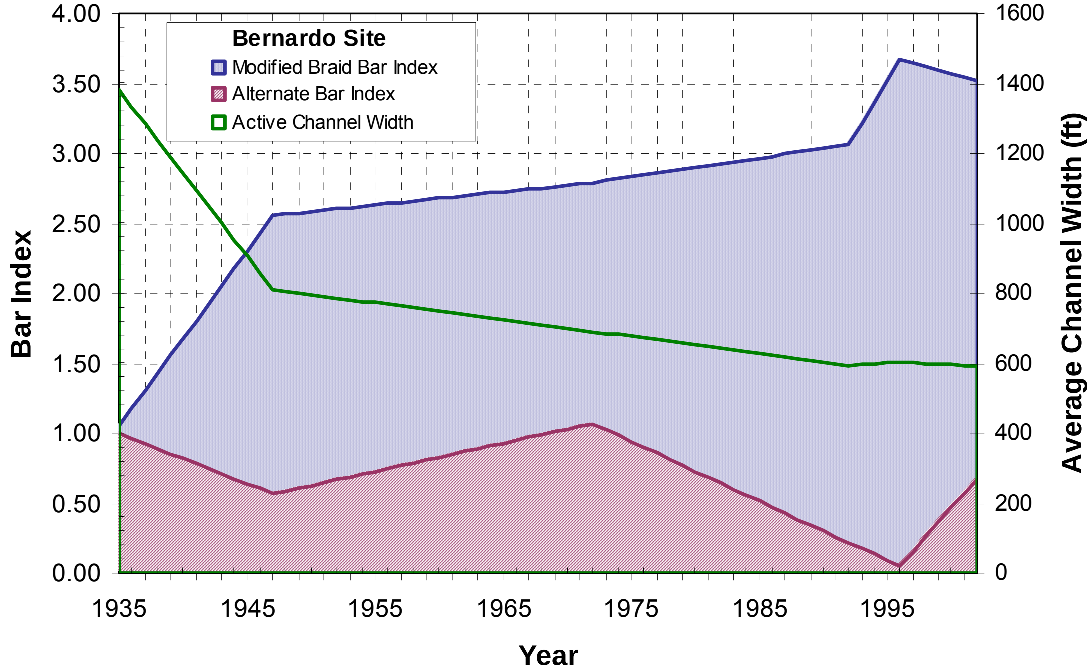


Figure 3.23. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Bernardo site.

### 3.3.6. La Joya

At the La Joya site, the MBI values declined sharply between 1935 and 1947 even though the channel width increased in the same time period (**Figure 3.24**). MBI values increased and ABI values decreased between 1947 and 1972 in response to channel aggradation (Figure B.7), even though channel width decreased sharply in this time period. Degradation between 1972 and 1992 caused a reduction in MBI value. This was followed by an increase in MBI values between 1992 and 1996 and a decrease between 1996 and 2002, even though the channel aggraded in this period. ABI values decreased over time, probably as a result of stabilization of the alternate bars by vegetation. In summary, at the La Joya site it appears that the MBI values are most closely related to phases of aggradation and degradation of the channel as would be expected (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993), but other undefined factors also affect the bar indices at this site.

### 3.3.7. Lemitar

At the Lemitar site, MBI values and the channel width declined between 1935 and 1972 as the channel degraded (**Figure 3.25**). ABI values in the same time period increased. With the exception of 1996, the MBI values remained reasonably constant between 1972 and 2002 even though the channel continued to narrow and degrade in this period (Figure B.8). ABI values increased slightly during the period. In summary, at the Lemitar site it appears that regardless of the channel narrowing and degradation there is a sufficient supply of sand-sized sediment to maintain the braided channel pattern, and this is consistent with the expected response (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

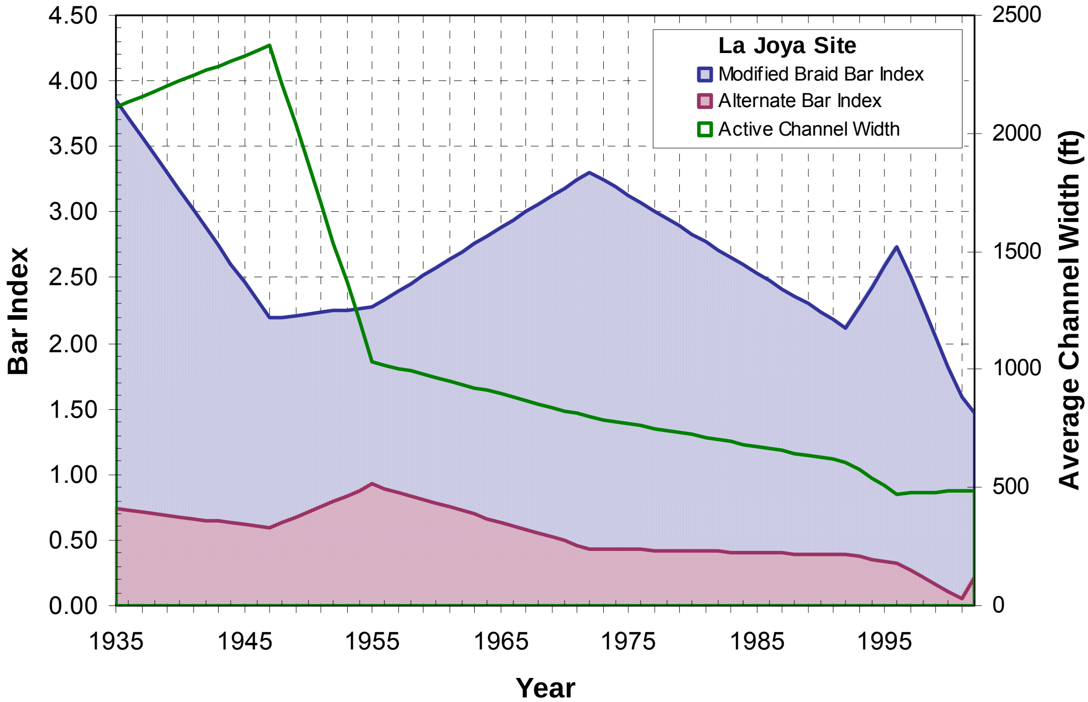


Figure 3.24. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the La Joya site.

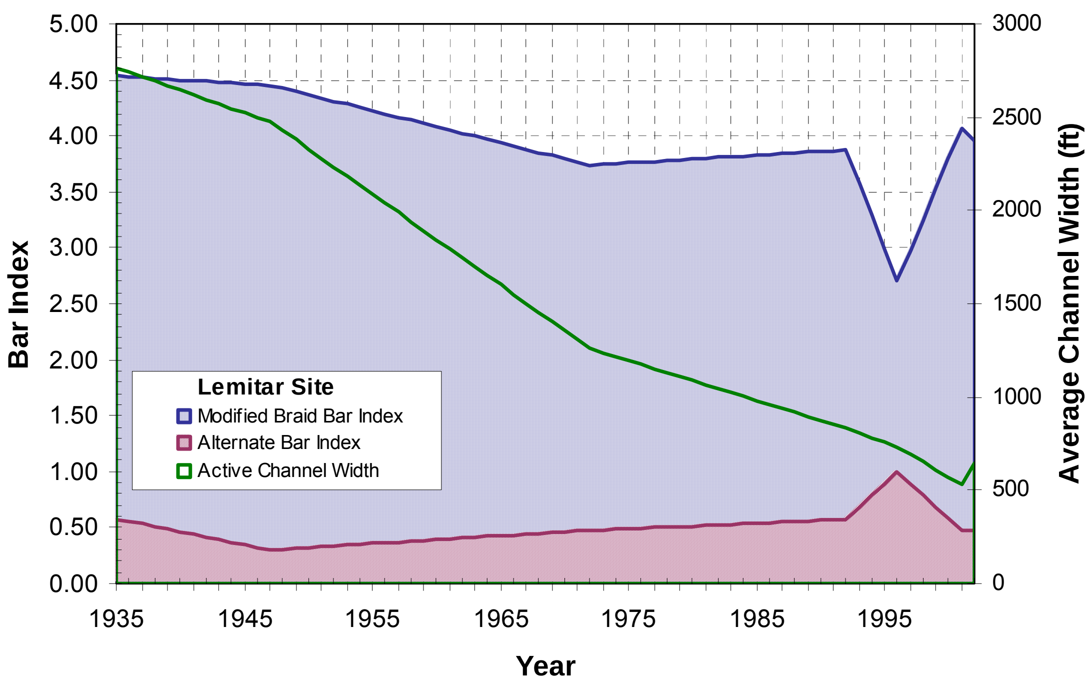


Figure 3.25. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Lemitar site.

### 3.3.8. Escondida

At the Escondida site, significant channel narrowing and incision between 1935 and 1972 led to the elimination of all of the braid bars and the MBI value went to zero (**Figure 3.26**). The combined effects of the channel narrowing and incision (Figure B.9) increased the sediment-transport capacity to the point where there is now very little potential for sediment storage of the sand-sized bed material within the site. As the channel incised and narrowed ABI values increased, but even these declined over time as the sediment-transport capacity increased. In summary, at the Escondida site the absence of braid bars is due primarily to channel degradation and narrowing which is consistent with the expected response (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

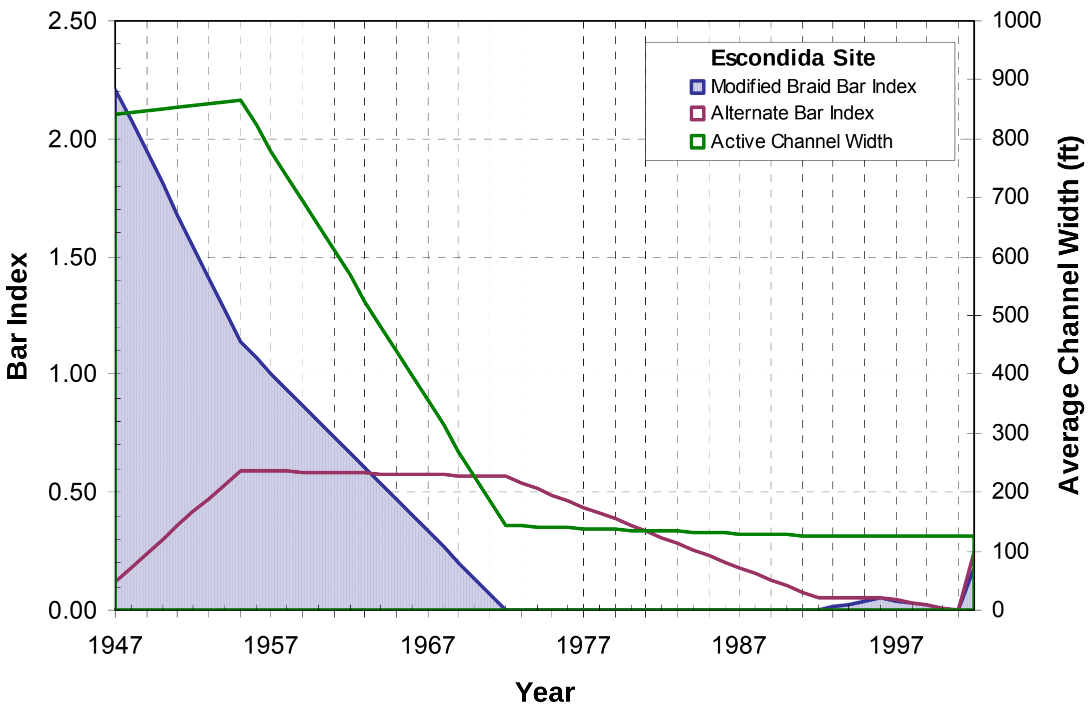


Figure 3.26. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Escondida site.

### 3.3.9. Bosque del Apache

At the Bosque del Apache site, there was a major reduction in the channel width and the MBI values between 1935 and 1972 (**Figure 3.27**). ABI values remained relatively constant during this time period. The reduced channel width and MBI values are most probably the result of widespread encroachment of non-native plant species during this period following the large floods of the 1940s (Crawford et al., 1993). Between 1972 and 1992 there was some aggradation of the channel (Figure B.10) and the MBI values increased marginally. However, following the cessation of flow diversion to the LFCC in 1985, MBI values increased in response to the aggradation. ABI values have remained relatively constant through time. In summary, during the early period of record at the Bosque del Apache site, the primary control on the MBI values appears to have been the significant increase in vegetation associated with the reduction in flows. Once flows were restored to the sand bed reach, the MBI values increased in response to the aggradation, which is the expected response ((Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

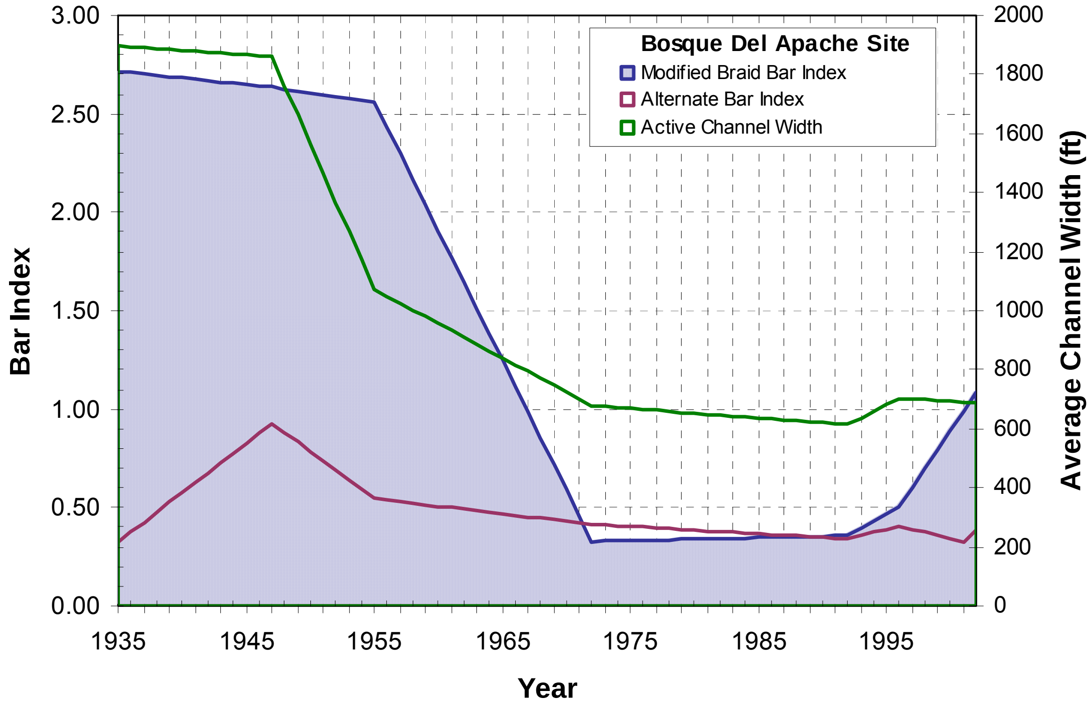


Figure 3.27. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the Bosque del Apache site.

### 3.3.10. San Marcial

Since 1972, the width of the man-made channel at the San Marcial site has increased as the channel has aggraded (Figure B.11), and as a result the MBI values have also increased (**Figure 3.28**). Except for 1996, the ABI values have declined as the MBI values increased. In summary, at the sand bed San Marcial site the primary control on the MBI values has been channel aggradation, and this is the expected response (Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993).

### 3.3.11. Summary

**Figure 3.29** provides a summary through time and space of the changes in the MBI values in the MRG between 1935 and 2001, with the exception of the San Marcial site where the period of record is from 1972 to 2001. From this analysis of bar changes through time, it is apparent that channel degradation and bed material coarsening in the more upstream sites (Pena Blanca and Bernalillo) have resulted in a reduction in the number of braid bars and reduced braiding intensity at those sites. At the Central Avenue and Belen sites, the number of braid bars and the braiding intensity have decreased over time, primarily as a result of channel narrowing. Aggradation at the Bernardo site and degradation at the La Joya site have resulted in increased braiding intensity and higher MBI values, and reduced braiding intensity and lower MBI values, respectively at these sand-bed sites. Channel narrowing and channel degradation with a relatively high sediment load has maintained the braiding intensity at the Lemitar site, but because of the magnitude of both the channel narrowing and the incision at the Escondida site, braid bars have been eliminated. Aggradation at the Bosque del Apache and San Marcial sites has resulted in an increase in braiding intensity.

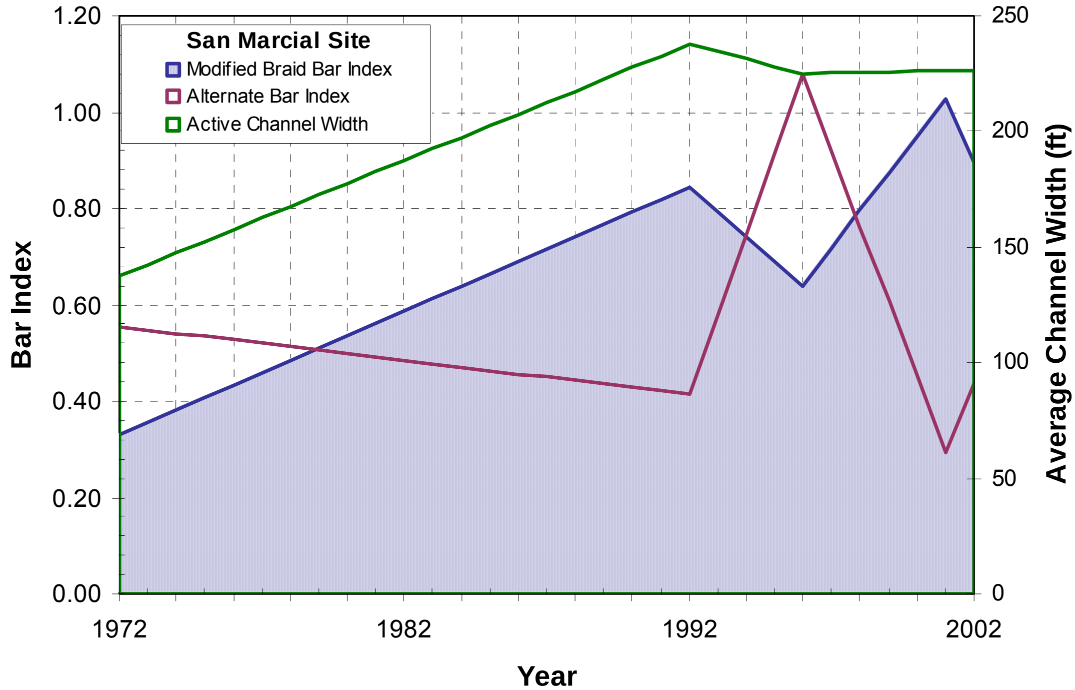


Figure 3.28. Modified Braid Index values, Alternate Bar Index values and active channel widths between 1935 and 2001 at the San Marcial site.

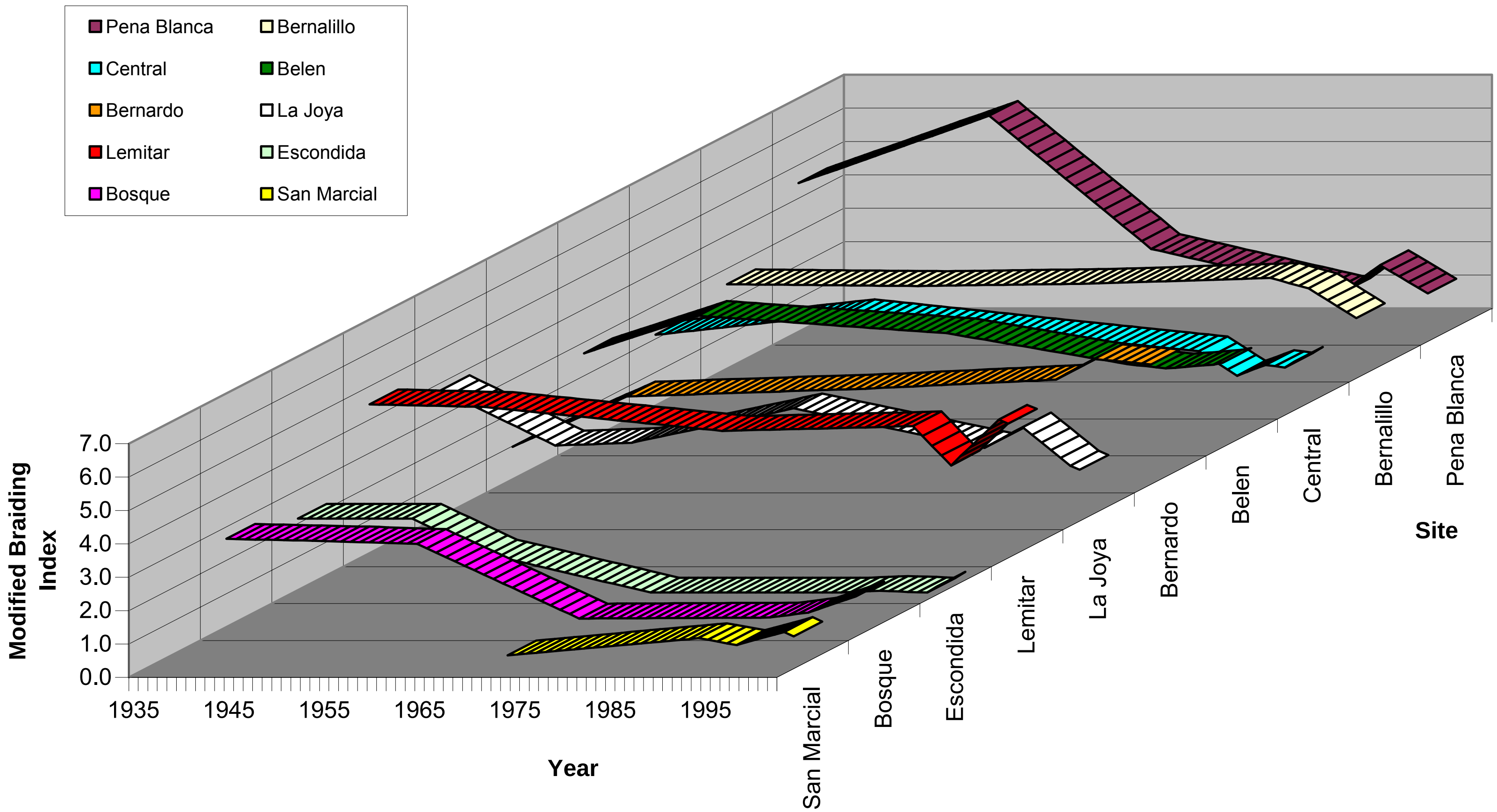


Figure 3.29. Ribbon plot of the Modified Braid Index values at each of the sites between 1935 and 2001.

# 4. BAR HYDRAULICS AND DYNAMICS

One-dimensional (1-D) hydraulic analyses were conducted at each of the sites to determine the magnitude, frequency and duration of flows required to inundate the various bar types. Additionally, output from the hydraulic models (HEC-RAS) was used to compute shear stresses at each of the sites to investigate bed material mobilization and the potential for removal of vegetation by flows.

## 4.1. Hydrology

The flow-duration and flood-frequency data presented in Appendix B were used to evaluate the flow magnitudes, frequencies and durations at each of the sites. For the mean daily flows, the entire post-Cochiti Dam period of record was used at the below Cochiti and Albuquerque gages, but for the Bernardo, San Acacia, and San Marcial gages, only that portion after the cessation of diversions to the LFCC was considered for development of the existing conditions mean daily flow-duration curves. For the peak flow-frequency analysis, the entire post-Cochiti Dam period of record was used at each of the gages. A summary of the period of record at gages used to analyze the recent hydrology is summarized in **Table 4.1**. (Note that no recorded peaks are available in the post-Cochiti Dam period at the Bernardo and San Acacia gages.)

Table 4.1. Summary of gage periods of record used for the existing conditions hydrologic analysis.

| Gage Name | Gage Number | Existing Conditions Period of Record | |
|---|---|---|---|
| | | Mean Daily Flow | Peak Flow |
| Rio Grande below Cochiti Dam, NM | 8317400 | WY1975-WY2001 | WY1974-WY1999 |
| Rio Grande at Albuquerque, NM | 8330000 | WY1975-WY2001 | WY1974-WY1999 |
| Rio Grande Floodway near Bernardo, NM | 8332010 | WY1986-WY2002 | N/A |
| Rio Grande Floodway at San Acacia, NM | 8354900 | WY1986-WY2002 | N/A |
| Rio Grande Floodway at San Marcial, NM | 8358400 | WY1986-WY2002 | WY1974-WY1990 |

For the Central Avenue, Bernardo, and San Marcial sites, the flow-duration and flood-frequency curves developed at the gages located within the study reach (Albuquerque, Bernardo, and San Marcial gages) were used to evaluate the site hydrology. The flow-duration and flood-frequency curves developed for the below Cochiti gage were adopted at the Pena Blanca site since no diversions exist along the approximately 4-mile reach between the gage and the site to significantly affect the flow-duration curve, and minimal flood attenuation will occur over the relatively short distance. The Bernalillo site (RM 203.6) lies approximately midway between the San Felipe (RM 216.6) and Albuquerque (RM 183.5) gages. Because a significant volume of flow is diverted upstream of the Bernalillo site, and relatively minor inflows and outflows exist between the site and the Albuquerque gage, the flow-duration and flood-frequency curves developed at the Albuquerque gage were adopted for the site. Since no gage is located near the Belen site (RM 149.6), flow-duration values were distance-interpolated using the curves for the Albuquerque (RM 183.5) and Bernardo (RM 130.6) gages. The flow-duration curve for the San Acacia gage (RM 116.3) was applied to the La Joya (RM 124.4), Lemitar (RM 107.5) and Escondida (RM 104.5) sites because the tributary contribution from the Rio Salado, the flows lost to seepage, and the inflows from the 9-mile outfall are not quantified. Although recent pumping operations by the BOR deliver flow to the river between the Bosque del Apache site (RM 84) and the San Marcial gage (RM 68.5), the San Marcial gage flow-duration curve was adopted at the Bosque del Apache site because the inflow is somewhat, if not entirely, offset by seepage losses between the two sites.

Because no recorded peak values are available between the Albuquerque and San Marcial gages, flood-frequency curves at the Belen, Bernardo, La Joya, Lemitar, Escondida, and Bosque del Apache sites were interpolated based on the relative distance between the two gages. This approximation is adequate for the purposes of this study, given that the flood-frequency curves at the two gages are nearly parallel and the recorded peak values are usually snowmelt related and therefore do not include the sometimes significant tributary flow volumes delivered to the river during the summer monsoon season. The computed discharges for the 90-, 50-, and 10-percent exceedence values on the mean daily flow-duration curves and the 2-, 5-, and 10-year recurrence intervals on the peak flow-frequency curves at each of the 10 sites are summarized in **Table 4.2**.

Table 4.2. Summary of flow-duration and flood-frequency statistics for the study sites.

| Study Site | Discharge (cfs) | | | | | |
|---|---|---|---|---|---|---|
| | Mean Daily Flow Exceedence | | | Peak Flow Recurrence Interval | | |
| | 90% | 50% | 10% | 2-yr | 5-yr | 10-yr |
| Pena Blanca | 400 | 920 | 3,670 | 4,480 | 6,830 | 8,350 |
| Bernalillo | 330 | 880 | 3,490 | 5,410 | 7,600 | 8,940 |
| Central Avenue | 330 | 880 | 3,490 | 5,410 | 7,600 | 8,940 |
| Belen | 190 | 870 | 3,160 | 5,120 | 7,150 | 8,410 |
| Bernardo | 120 | 860 | 3,040 | 4,960 | 6,900 | 8,110 |
| La Joya | 150 | 920 | 3,120 | 4,910 | 6,820 | 8,020 |
| Lemitar | 150 | 920 | 3,120 | 4,770 | 6,600 | 7,750 |
| Escondida | 150 | 920 | 3,120 | 4,750 | 6,560 | 7,710 |
| Bosque del Apache | 10 | 660 | 2,600 | 4,570 | 6,290 | 7,390 |
| San Marcial | 10 | 660 | 2,600 | 4,440 | 6,080 | 7,140 |

## 4.2. Hydraulic Modeling

A hydraulic analysis was performed for each of the study sites. The analyses were carried out using the U.S. Army Corps of Engineers HEC-RAS, Version 3.1.2 (USACE, 2004) software package. HEC-RAS uses the 1-D, step-backwater method to predict water-surface elevations and the associated hydraulic conditions based on the cross-sectional geometry of the channel and channel roughness. The models were developed from the cross sections shown on the site maps in Figures 2.2 through 2.11 (**Appendix D**).

The cross-sectional spacing varied from site-to-site depending on the width and conveyance of the low-flow channel, the width of the active channel, and the distribution, density, and longitudinal variation of bars, and ranged from 282 feet at the Bosque del Apache site to about 920 feet at the Lemitar site. Hydraulic roughness, a measure of flow resistance, an important input parameter for hydraulic modeling is quantified with the Manning's equation:

$$n = \frac{A}{Q} R^{2/3} S^{1/2} \quad (4.1)$$

where $n$ = Manning's $n$-value
$A$ = Flow area (ft$^2$)
$Q$ = Flow rate (ft$^3$/s)
$R$ = Hydraulic radius (ft)
$S$ = Energy slope (ft/ft)

The resistance to flow is affected by bed-material size, bedforms, vegetation, and irregularities in the bed and banks. The field-identified low-flow channel Manning's *n*-values ranged from 0.020 at the San Marcial site to 0.040 at the Pena Blanca site, while the *n*-values outside of the low-flow channel ranged from 0.025 to 0.12, depending on the density and stability of vegetation. **Table 4.3** summarizes the length of the modeled reach, the average cross-sectional spacing, and the range of Manning's *n*-values used in each of the site models.

Table 4.3. Summary of average cross section spacing and roughness values used in the hydraulic modeling.

| Site | Length of Model (ft) | Number of Cross Sections | Average Cross-Section Spacing (ft) | Low-Flow Manning's *n*-value | Overbank Manning's *n*-value (range) |
|---|---|---|---|---|---|
| Pena Blanca | 3,450 | 12 | 288 | 0.04 | 0.08-0.12 |
| Bernalillo | 7,040 | 13 | 542 | 0.025-0.035 | 0.025-0.12 |
| Central Avenue | 8,740 | 15 | 583 | 0.025 | 0.04-0.12 |
| Belen | 7,510 | 17 | 442 | 0.025 | 0.025-0.12 |
| Bernardo | 9,390 | 14 | 671 | 0.025 | 0.025-0.12 |
| La Joya | 1,930 | 7 | 276 | 0.02-0.03 | 0.025-0.12 |
| Lemitar | 8,260 | 9 | 918 | 0.023 | 0.04-0.12 |
| Escondida | 3,470 | 9 | 386 | 0.02 | 0.10-0.12 |
| Bosque del Apache | 5,350 | 19 | 282 | 0.018 | 0.04-0.12 |
| San Marcial | 3,170 | 8 | 396 | 0.02 | 0.1-0.12 |

The models were calibrated, to the extent possible, using surveyed water-surface elevations and surveyed high-water marks associated with either spring (2004) peak flows, summer (2004) peak flows, or very recent, monsoon-related events. The models were calibrated by adjusting the Manning's *n*-value of the low-flow channel or channel-margins. Calibration profiles showing the measured water-surface elevations and, where available, the surveyed high-water marks and the computed water-surface elevations at the corresponding discharges are shown in **Figures 4.1 through 4.8**.

## 4.3. Bar Inundation Analysis

The results from the hydraulic models were used to evaluate the duration and frequency of flows required to inundate the various bar surfaces at each of the survey sites. The inundation analysis was performed by computing the longitudinal station of each of the bar surface survey points. Since each of the cross-sections typically included several bar features, and numerous

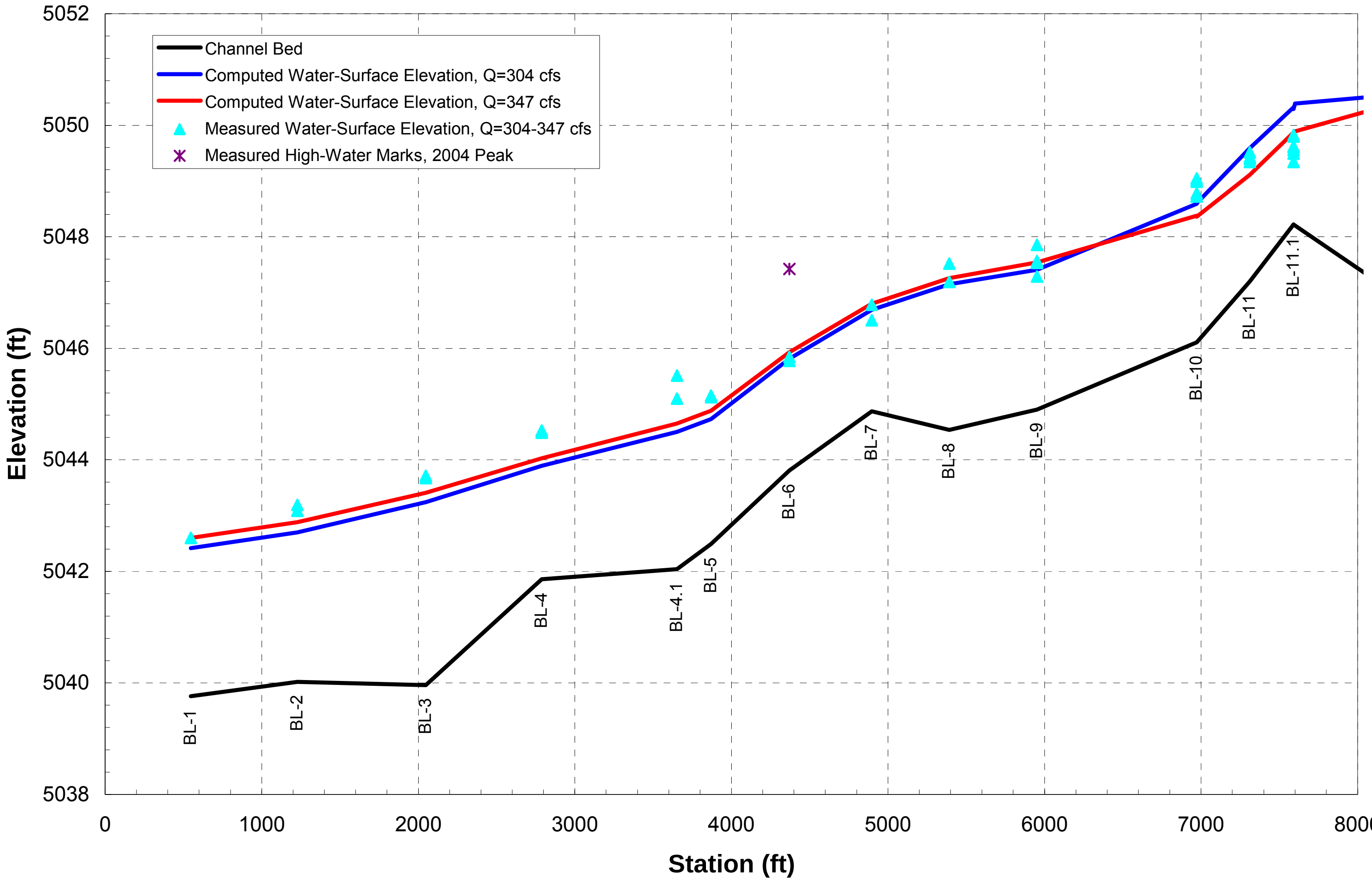


Figure 4.1. Thalweg and computed water-surface profiles and measured water-surface elevations used for model calibration at the Bernalillo site.

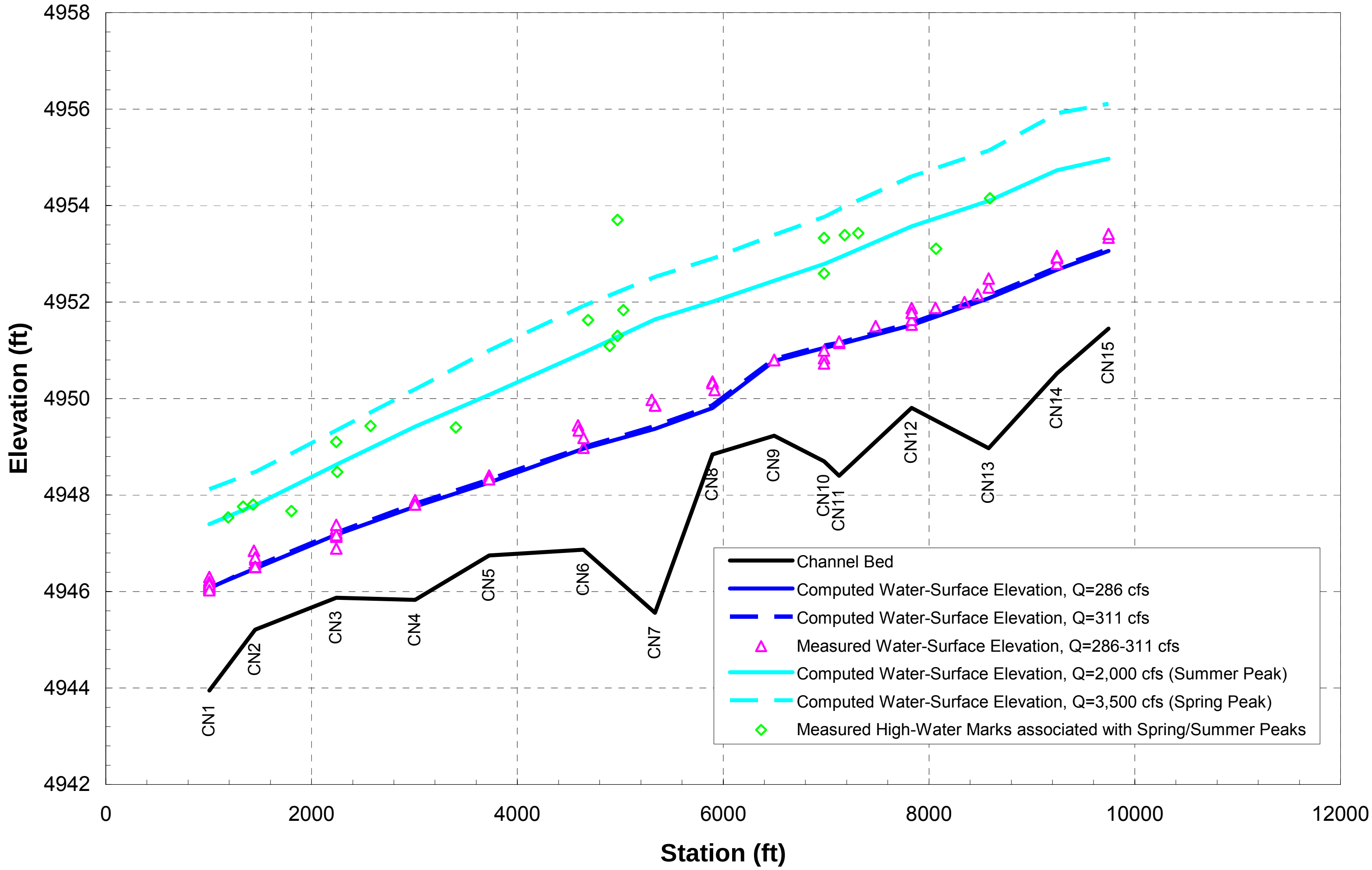


Figure 4.2. Thalweg and computed water-surface profiles and measured water-surface elevations used for model calibration at the Central Avenue site.

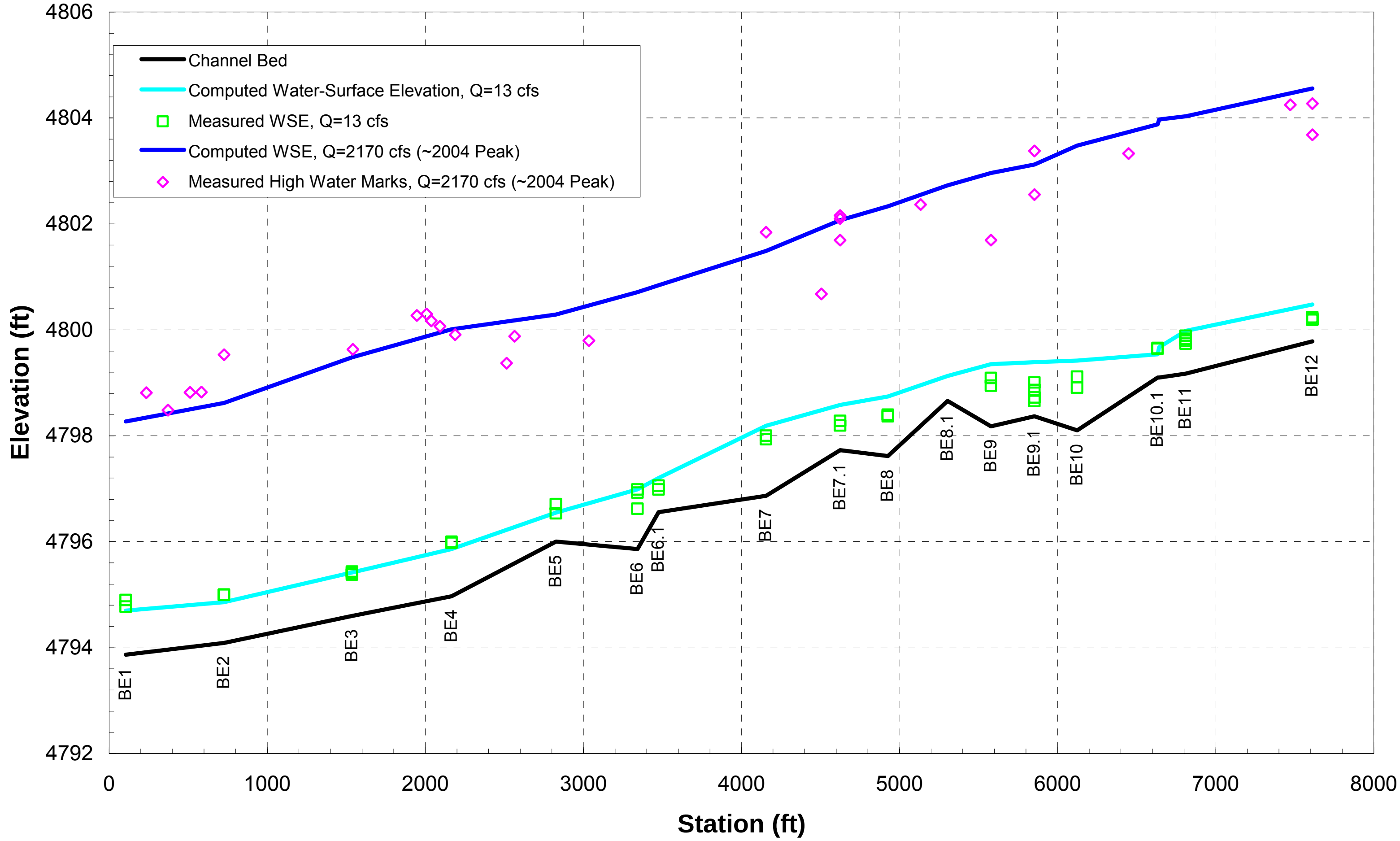


Figure 4.3. Thalweg and computed water-surface profiles and measured water-surface elevations used for model calibration at the Belen site.

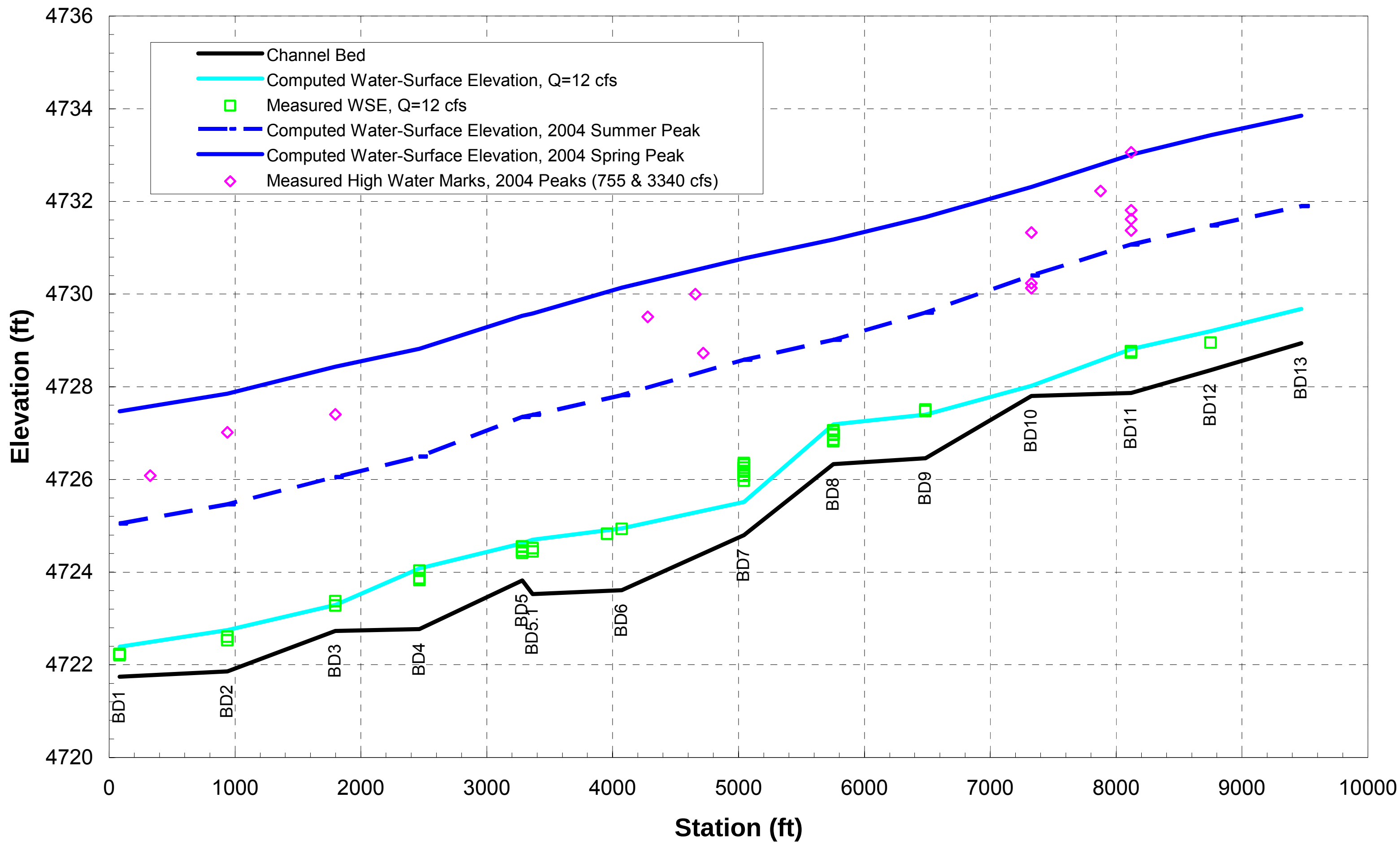


Figure 4.4. Thalweg and computed water-surface profiles and measured water-surface elevations used for model calibration at the Bernardo site.

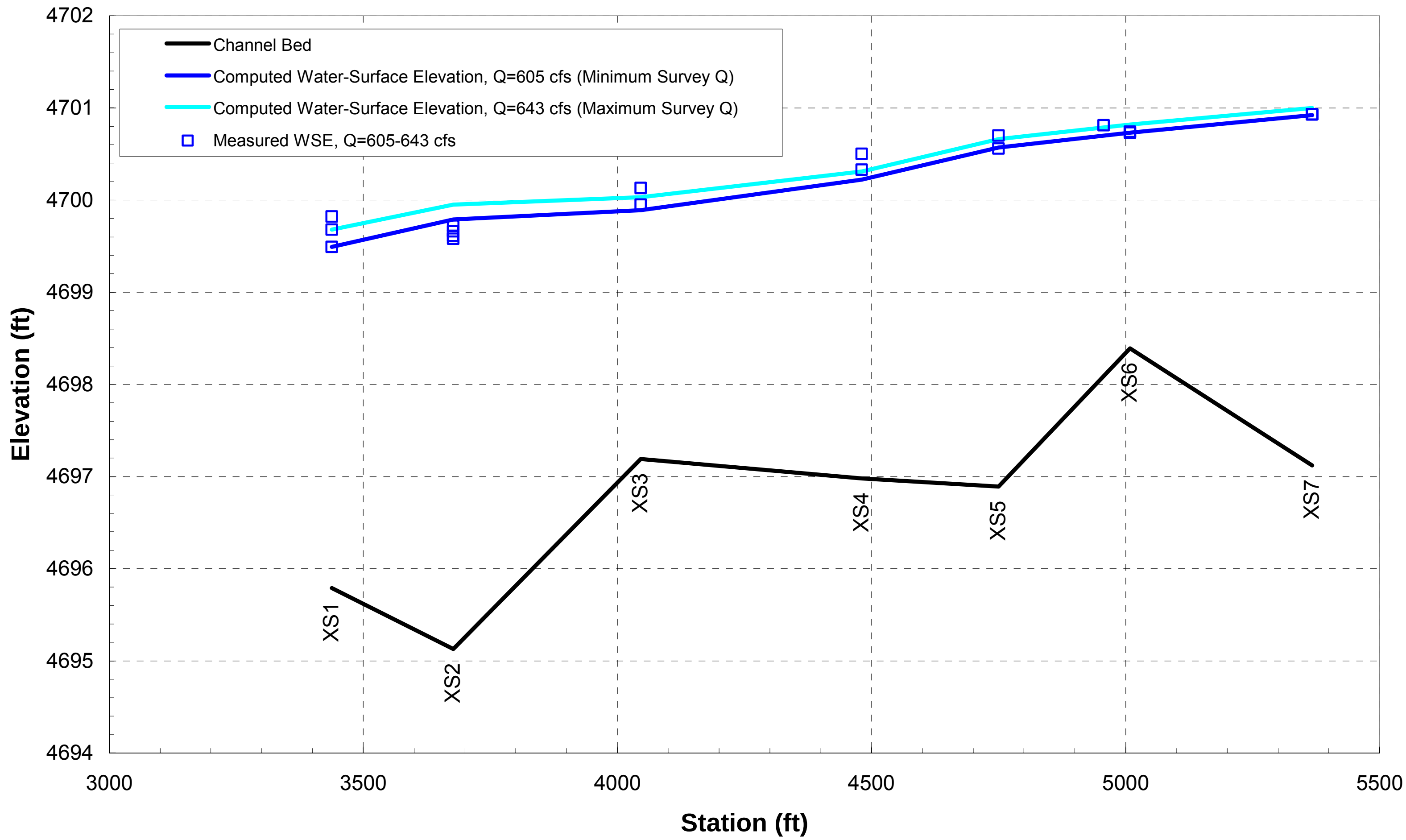


Figure 4.5. Thalweg, computed water-surface profiles and measured water-surface elevations used for model calibration at the La Joya site.

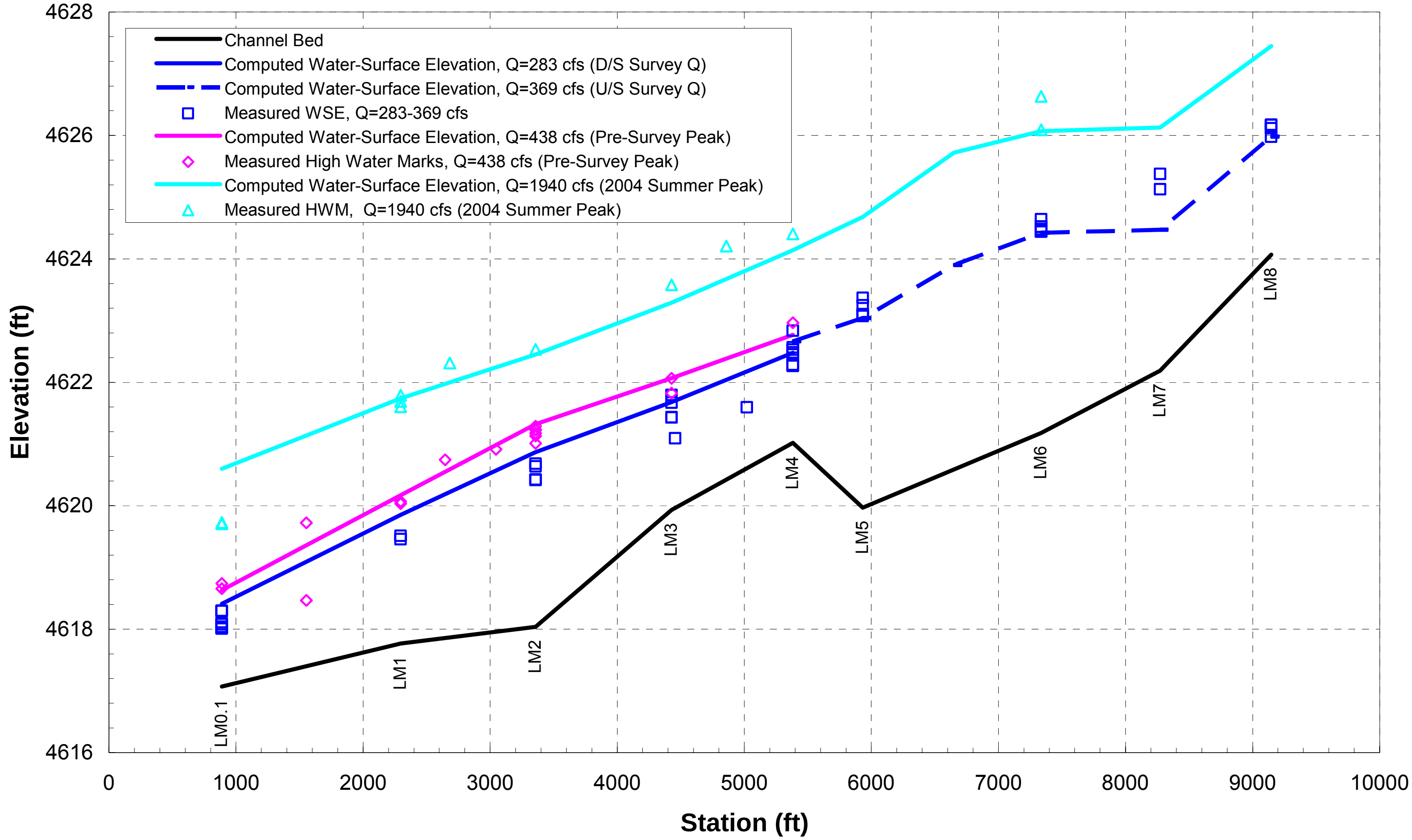


Figure 4.6. Thalweg, computed water-surface profiles and measured water-surface elevations used for model calibration at the Lemitar site.

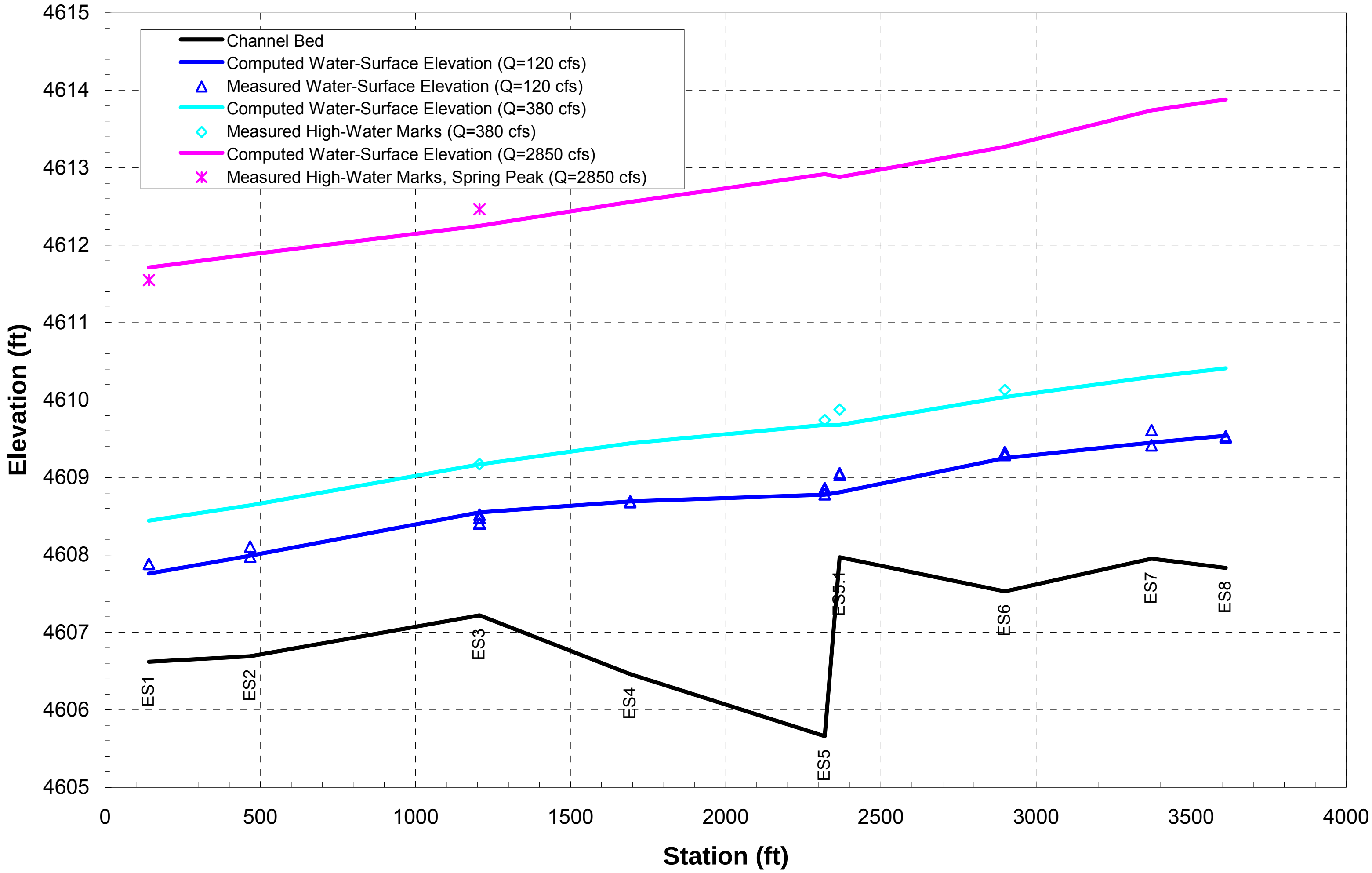


Figure 4.7. Thalweg, computed water-surface profiles and measured water-surface elevations used for model calibration at the Escondida site.

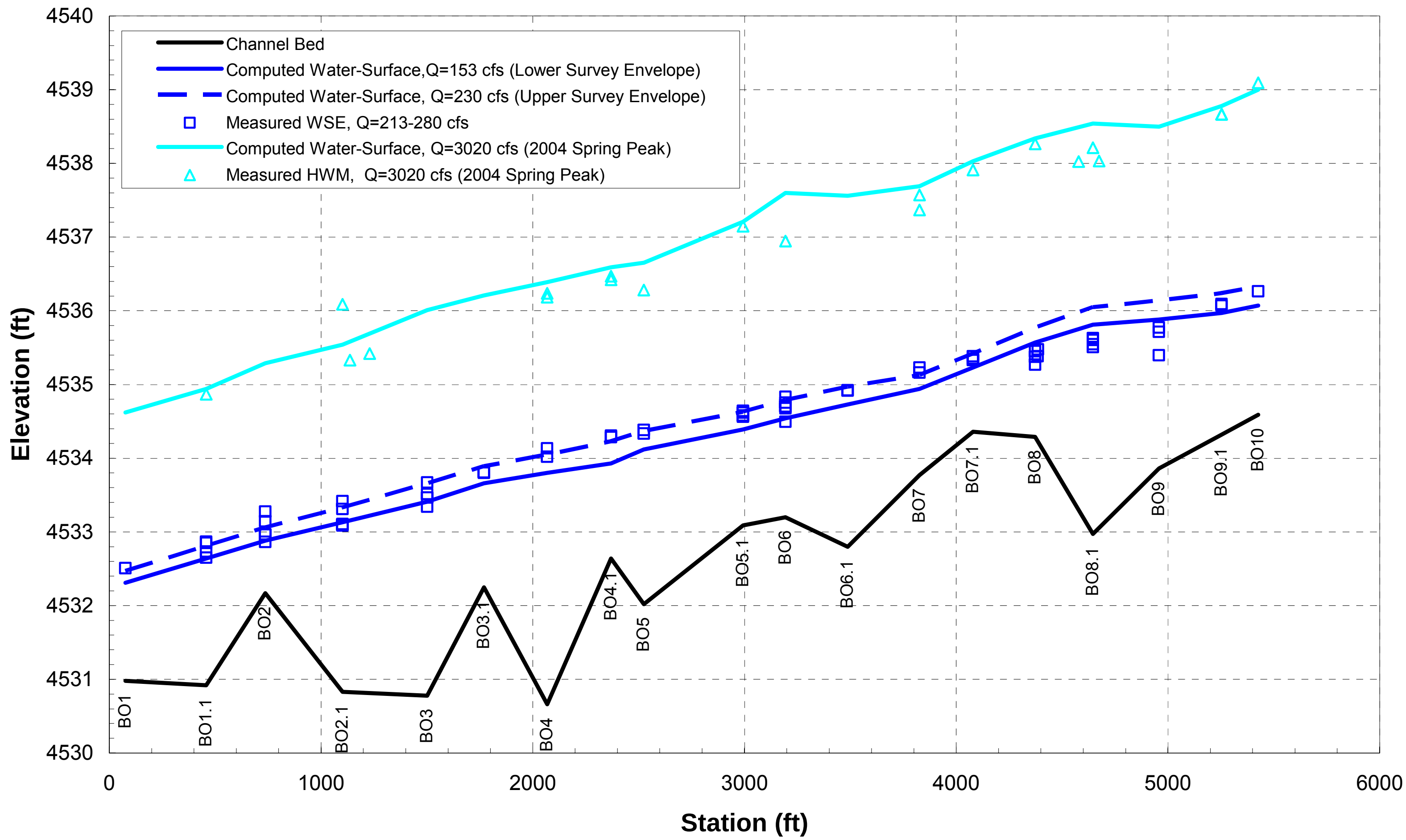


Figure 4.8. Thalweg, computed water-surface profiles and measured water-surface elevations used for model calibration at the Bosque del Apache site.

survey points were collected across each of these features, the maximum elevation of each bar type at a given station was filtered from the overall data set. After running the hydraulic models for a range of flows up to and exceeding the active channel capacity, longitudinal water-surface profiles were extracted from the hydraulic model and compared to the maximum elevations of the individual bar types at each site. The profiles for each of the sites are presented in **Figures 4.9 through 4.18**.

While there is significant scatter among the points representing each type of bar in Figures 4.9 through 4.18, general trends relating the different bar type elevations to discharge are evident. To evaluate these trends, it was necessary to determine the discharge associated with the elevation of each bar type by interpolating between the discharges associated with the bounding water-surface elevations. The minimum, mean, and maximum discharges for the different bar types at each site were computed. A logarithmic-probabilistic interpolation routine was then used to determine the mean daily flow exceedence percentage and flood-frequency recurrence interval for the minimum, mean, and maximum inundation discharges for each bar type.

### 4.3.1. Pena Blanca

At the Pena Blanca site, the Level-1 braid bars are inundated on average about 66 percent of the time and by flows with less than a 1-year recurrence interval (**Figure 4.19**). Alternate bars, Level-2 braid bars and Level-1 mid-channel bars are inundated on average about 30 percent of the time by flows with about a 1-year recurrence interval. Level-1 and Level-2 bank-attached bars are inundated on average about 8 and 3 percent of the time, respectively by flows with recurrence intervals of about 2 and 4 years, respectively. On average, the Level-2 mid-channel bar is not inundated based on the post-dam period of record, and is overtopped by flows with a recurrence interval of about 9 years. Given the wide range of recurrence intervals of flows required to overtop the Level-2 mid-channel bars, it is highly likely that the bars are unrelated to the present hydrologic regime of the river, but are remnants from the pre-dam era. Post-dam channel degradation has increased the heights of the Level-2 bars, thereby reducing the frequency of inundation. The presence of cactus, chamissa and sage brush on the tops of the bars further suggests that the bar tops are dissociated from the present hydrologic regime of the river.

### 4.3.2. Bernalillo

At the Bernalillo site, the Level-1 braid bars and the alternate bars are inundated on average about 30 percent of the time and by flows with about a 1-year recurrence interval (**Figure 4.20**). Level-2 braid bars are inundated on average about 6 percent of the time by flows with recurrence intervals of about 1.6 years. Based on the mean daily flow record, Level-1 and Level-2 mid-channel bars are not inundated on average in the post-dam period, and require flows with recurrence intervals of 3.6 and 4.2 years to overtop them, respectively. Level-2 bank-attached bars are also not inundated on average, and require flows with recurrence intervals of between 1.8 and 100 years to overtop them. The wide range of flow magnitudes required to overtop this bar type is clear evidence of degradation at the site, which is further reinforced by the presence of cactus, sage brush, chamissa and dead salt cedar on the bar surfaces.

### 4.3.3. Central Avenue

At the Central Avenue site, the Level-1 braid bars and the alternate bars are inundated on average between 50 and 30 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.21**). Level-2 braid bars are inundated on average about 12

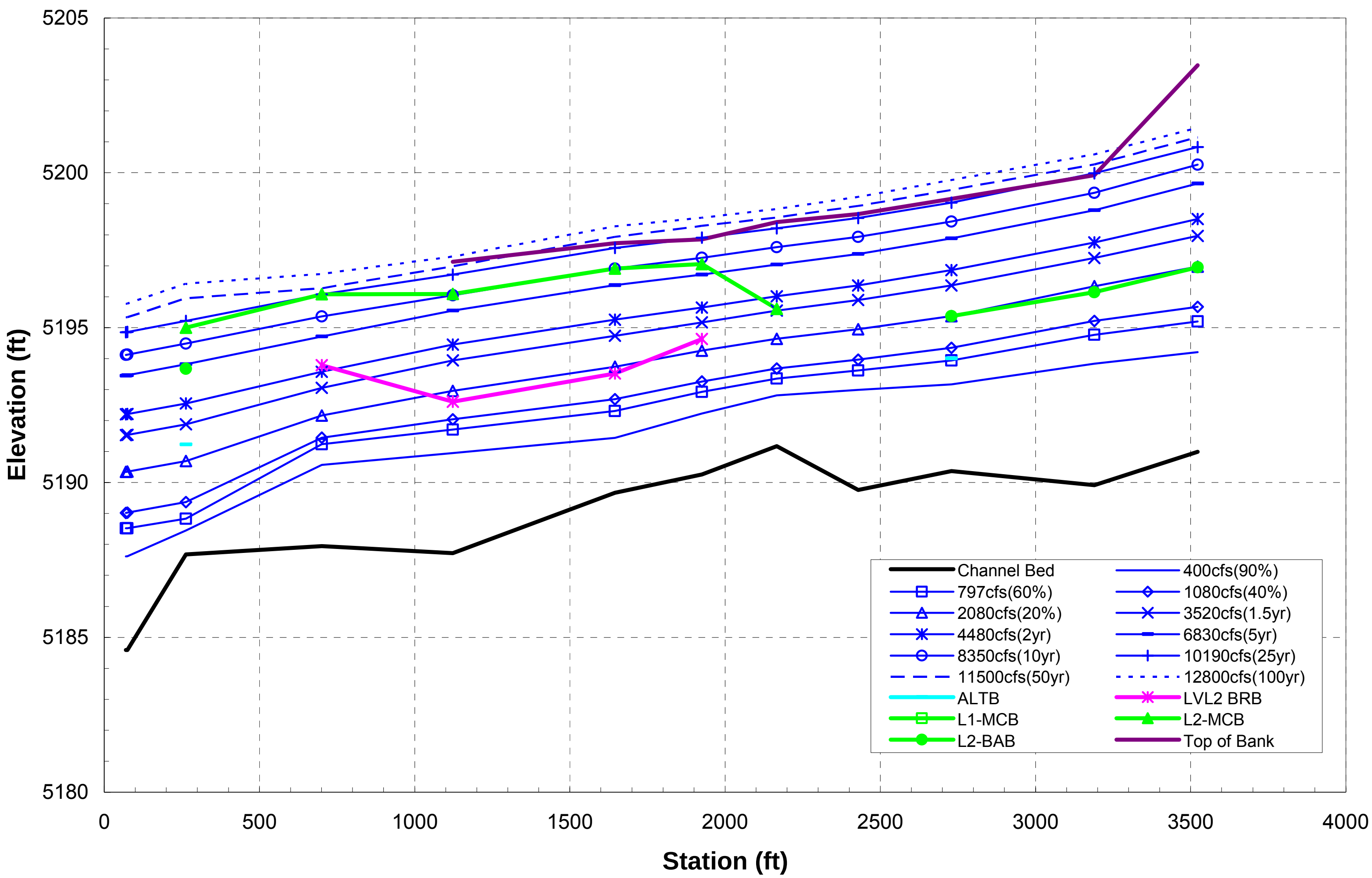


Figure 4.9. Relationships between the water-surface profiles for a range of flows between 400 and 12,800 cfs and the elevations of the various bar types on the cross sections at the Pena Blanca site.

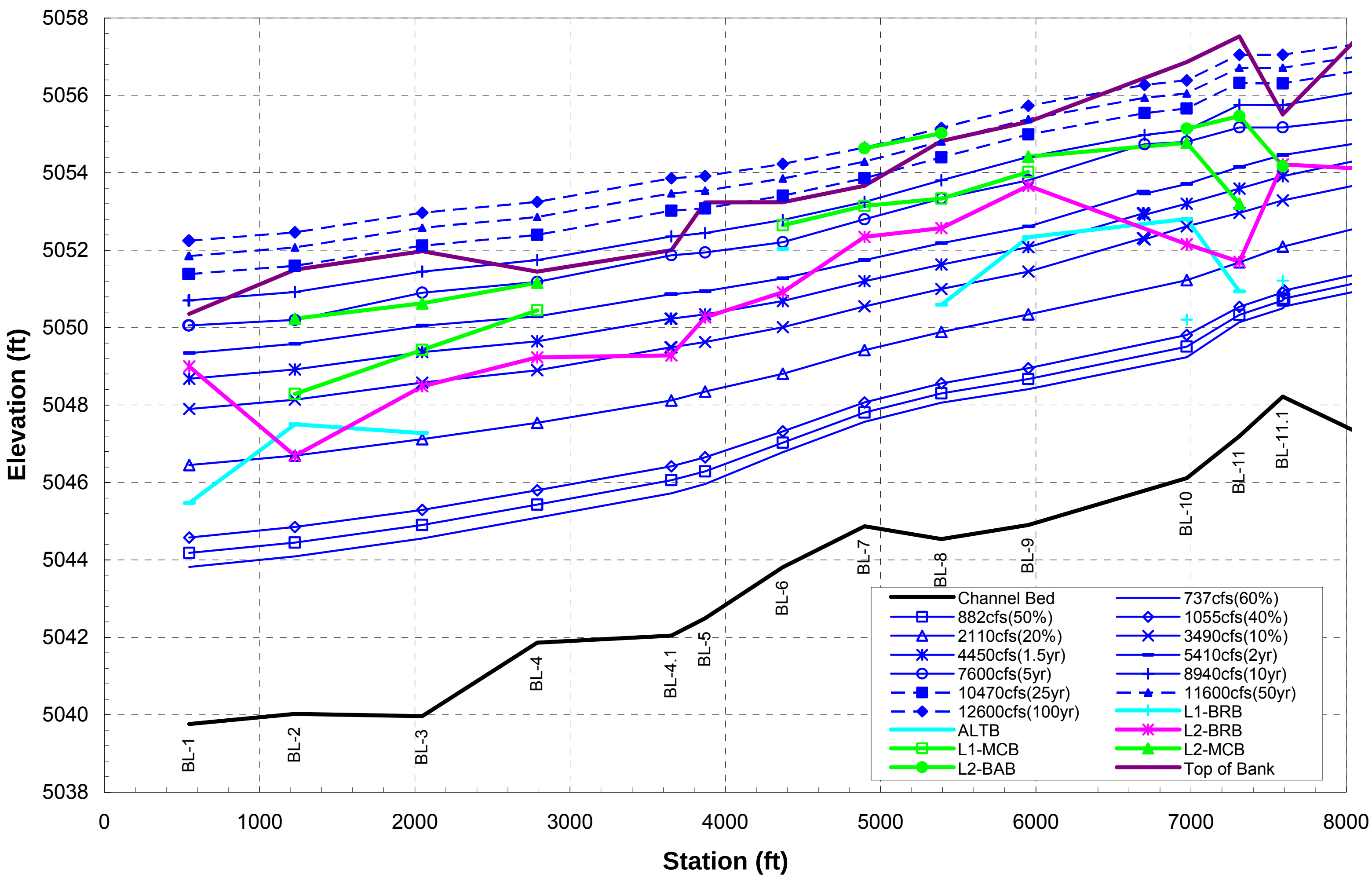


Figure 4.10. Relationships between the water-surface profiles for a range of flows between 737 and 12,600 cfs and the elevations of the various bar types on the cross sections at the Bernalillo site.

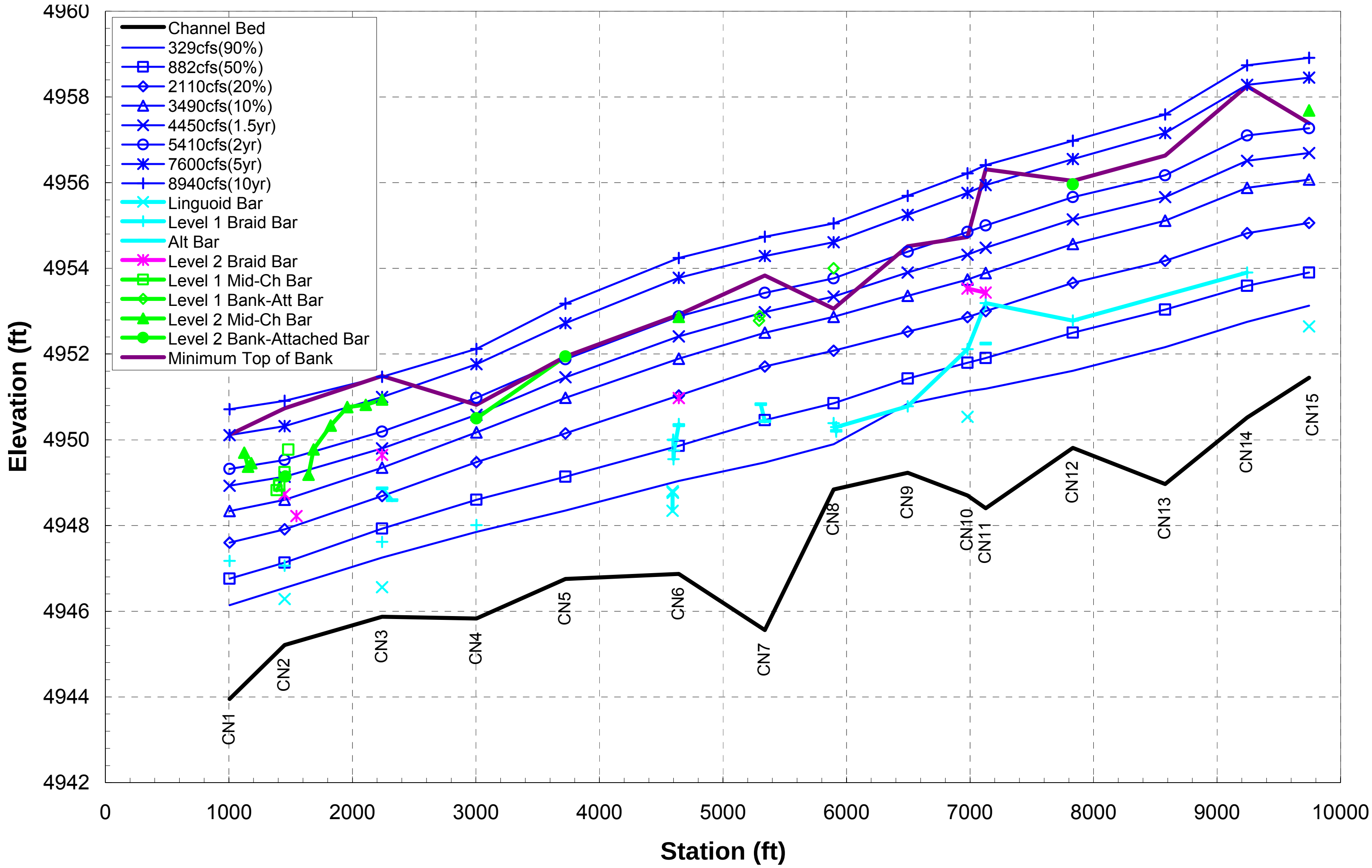


Figure 4.11. Relationships between the water-surface profiles for a range of flows between 329 and 8,940 cfs and the elevations of the various bar types on the cross sections at the Central Avenue site.

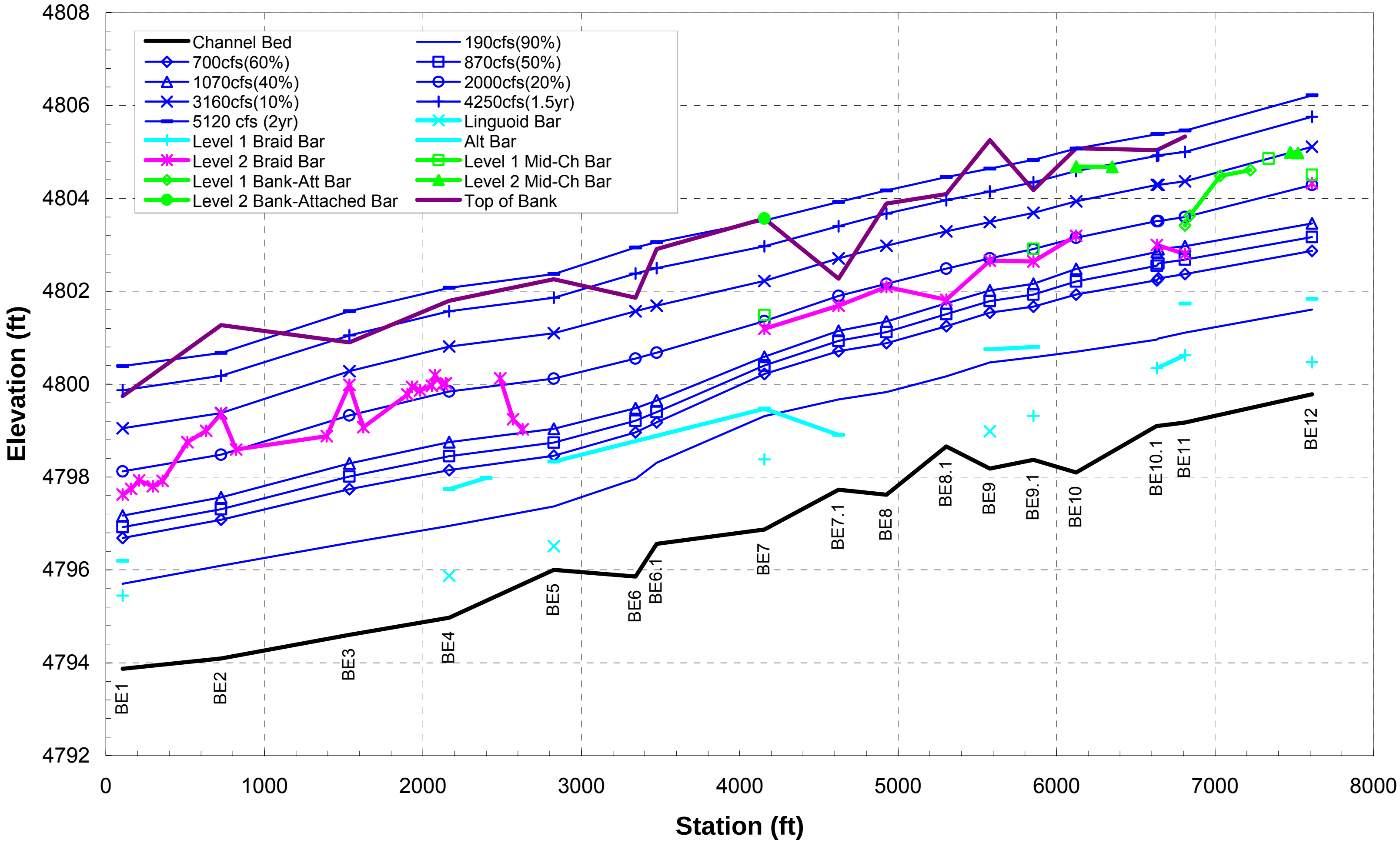


Figure 4.12. Relationships between the water-surface profiles for a range of flows between 190 and 5,120 cfs and the elevations of the various bar types on the cross sections at the Belen site.

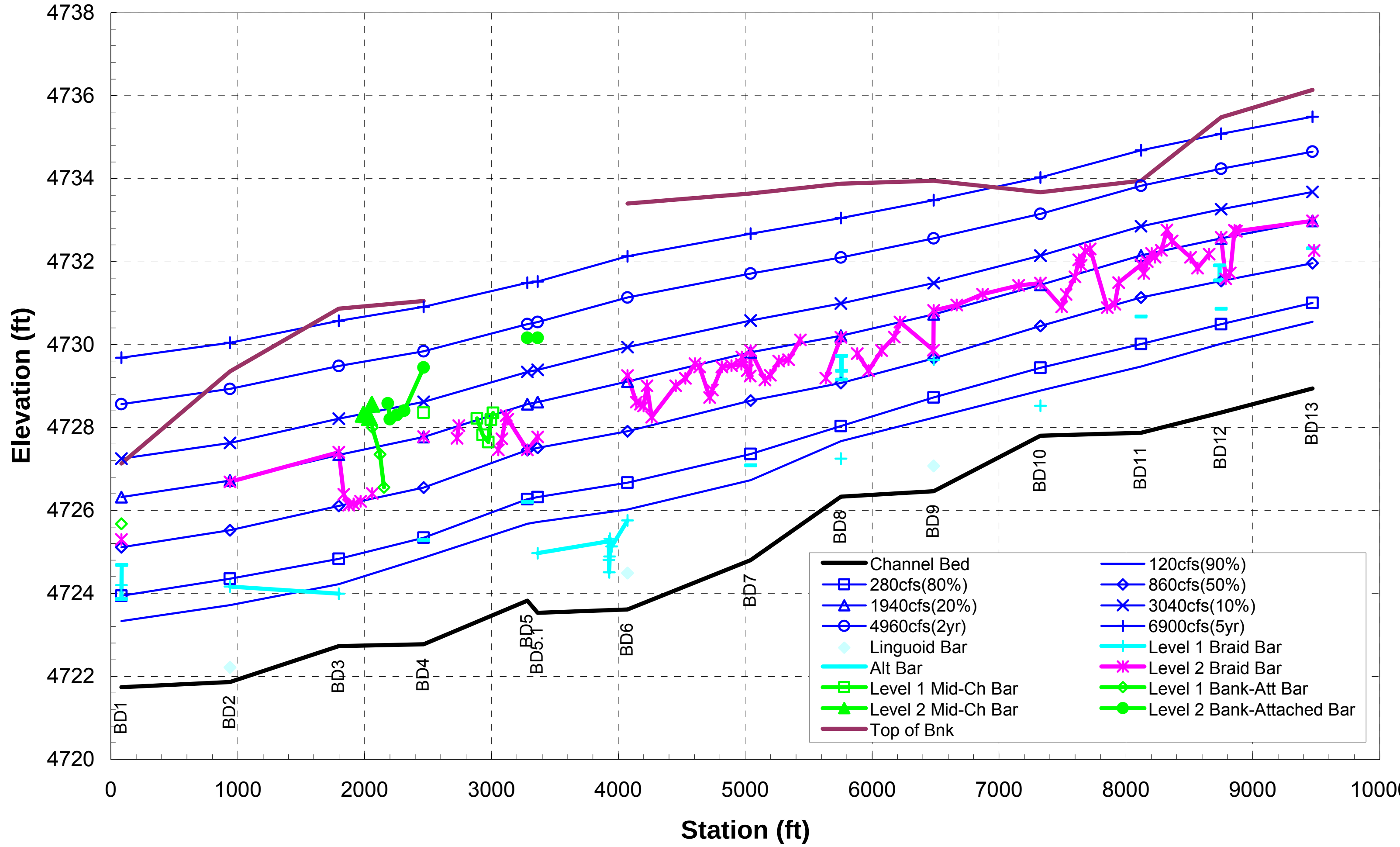


Figure 4.13. Relationships between the water-surface profiles for a range of flows between 120 and 6,900 cfs and the elevations of the various bar types on the cross sections at the Bernardo site.

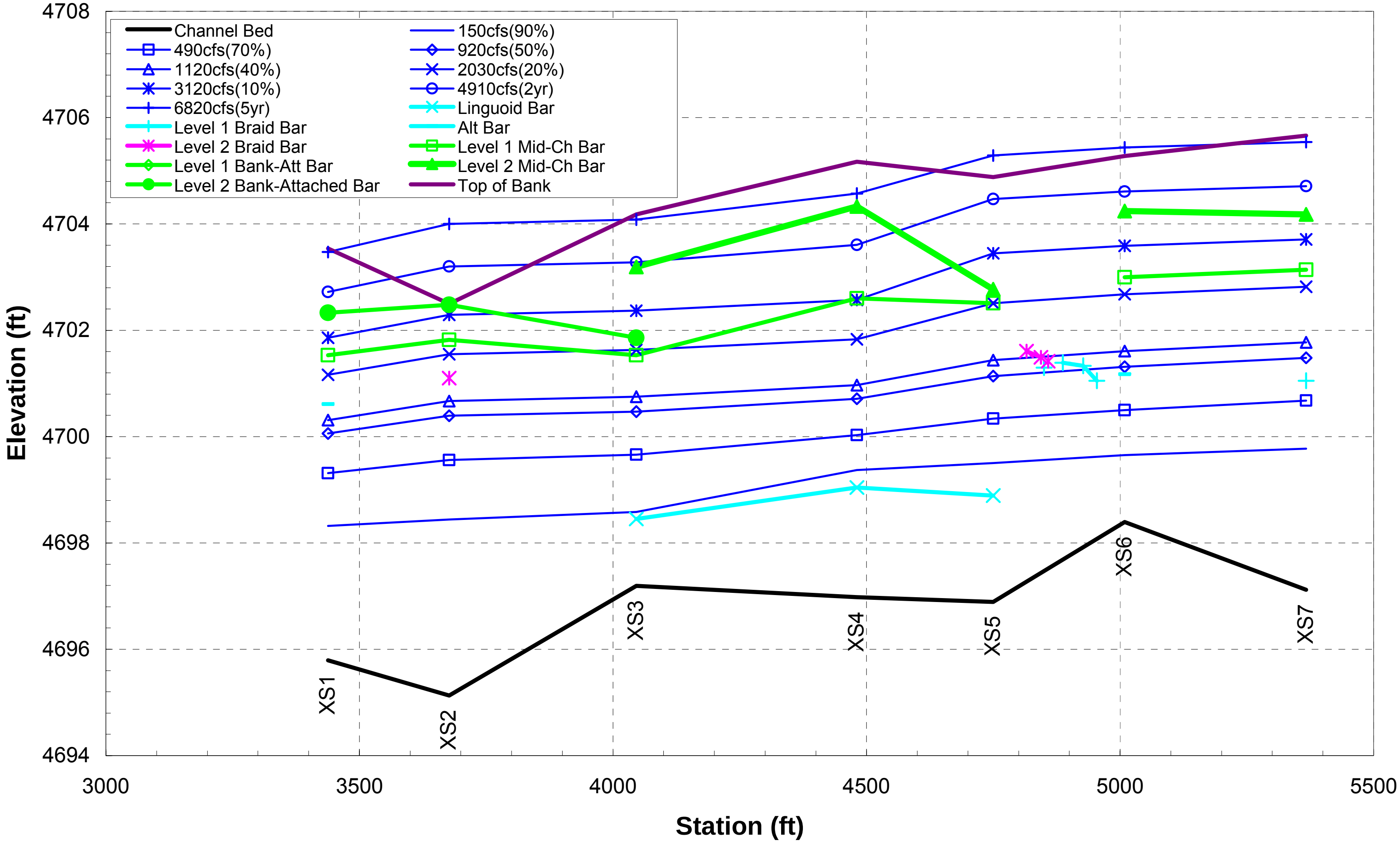


Figure 4.14. Relationships between the water-surface profiles for a range of flows between 150 and 6,820 cfs and the elevations of the various bar types on the cross sections at the La Joya site.

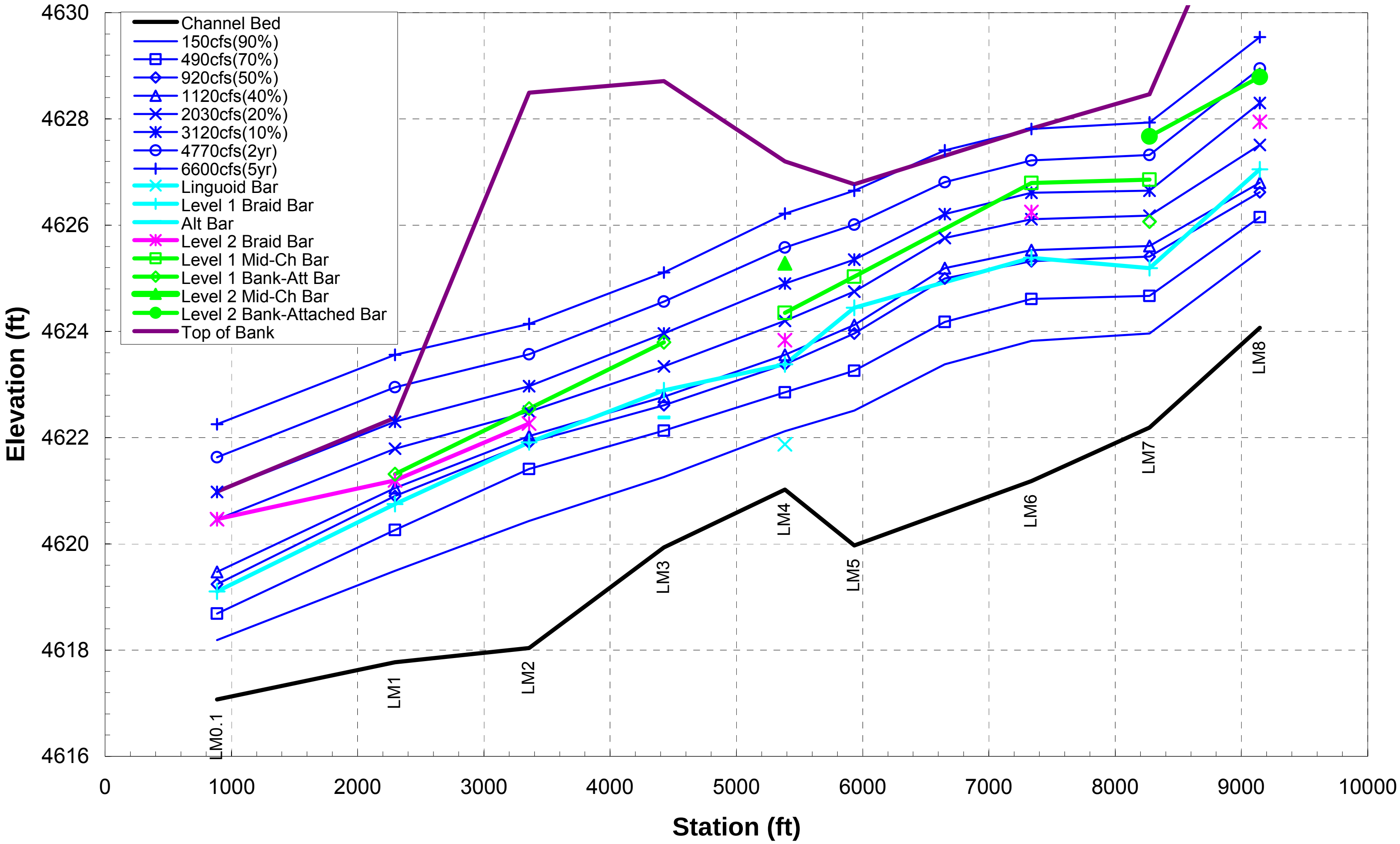


Figure 4.15. Relationships between the water-surface profiles for a range of flows between 150 and 6,600 cfs and the elevations of the various bar types on the cross sections at the Lemitar site.

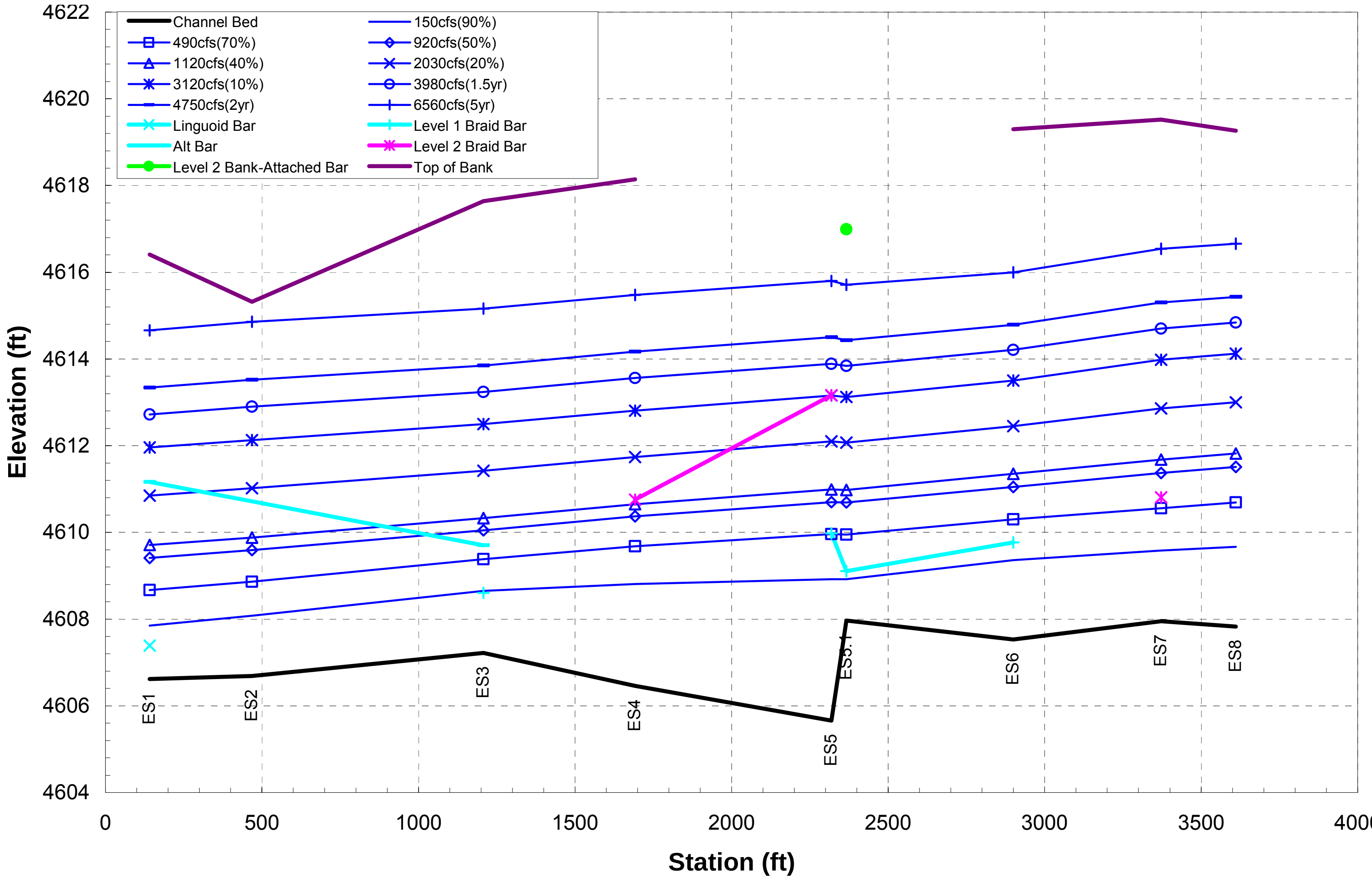


Figure 4.16. Relationships between the water-surface profiles for a range of flows between 150 and 6,560 cfs and the elevations of the various bar types on the cross sections at the Escondida site.

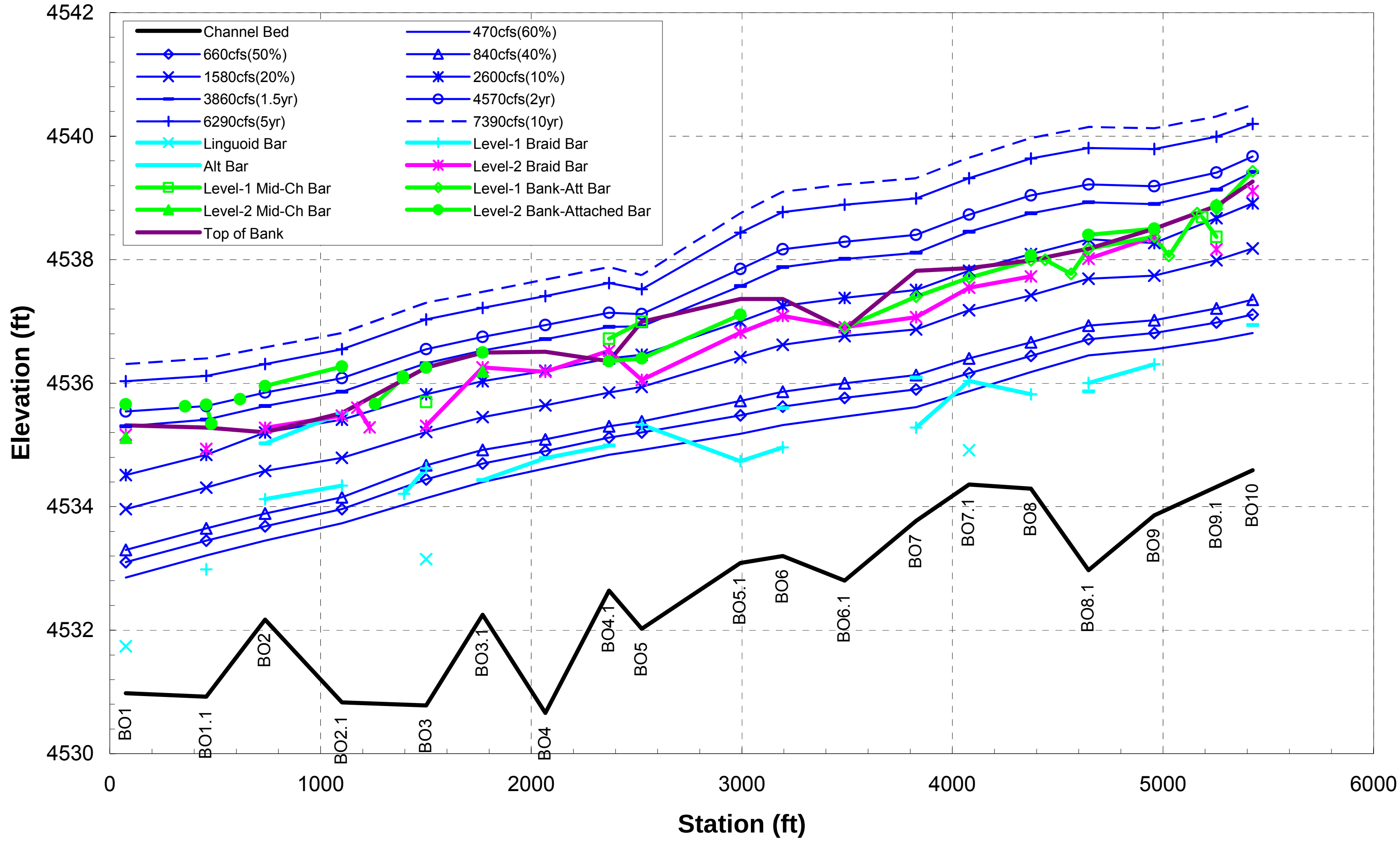


Figure 4.17. Relationships between the water-surface profiles for a range of flows between 470 and 7,390 cfs and the elevations of the various bar types on the cross sections at the Bosque del Apache site.

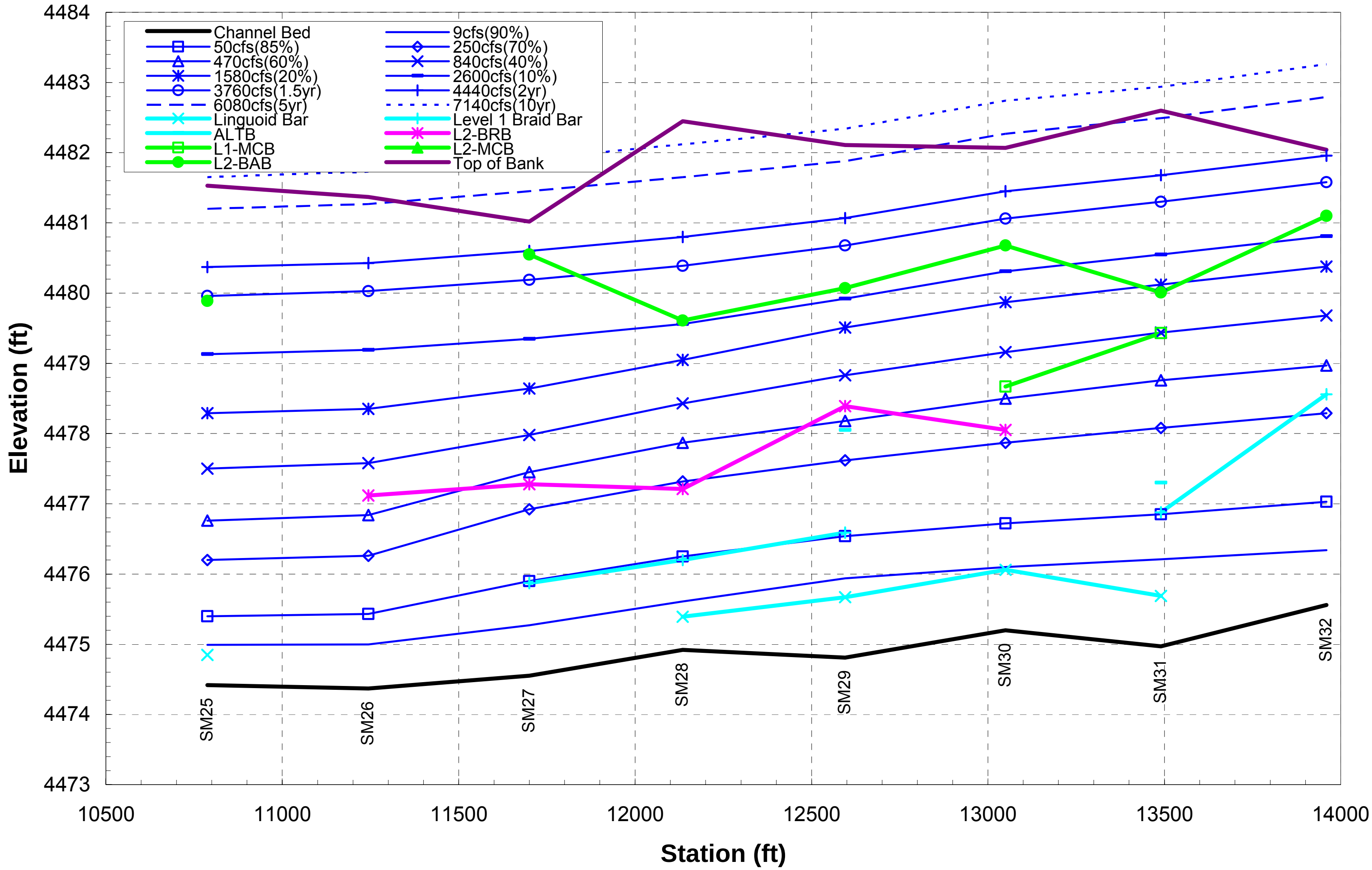


Figure 4.18. Relationships between the water-surface profiles for a range of flows between 9 and 7,140 cfs and the elevations of the various bar types on the cross sections at the San Marcial site.

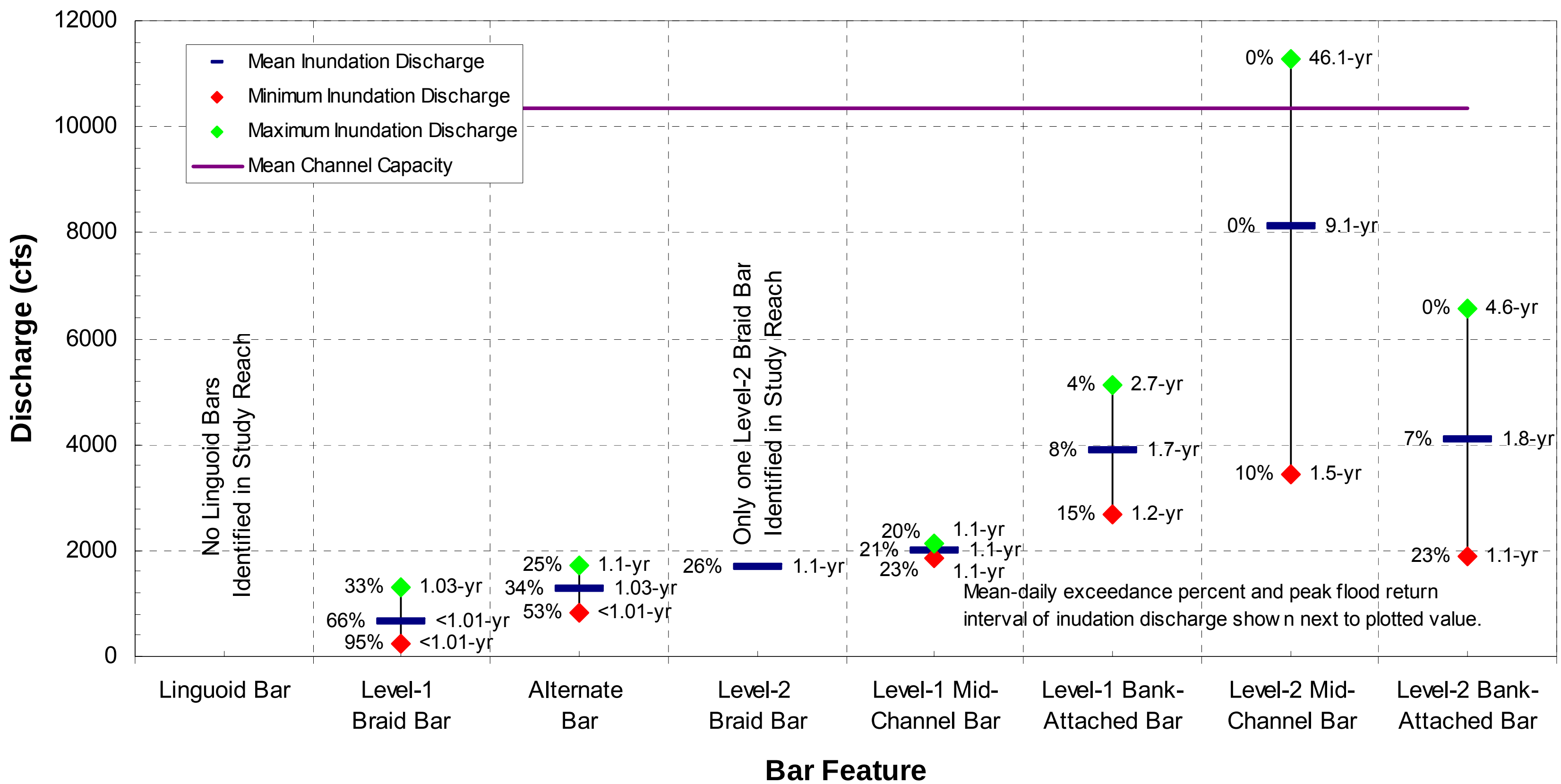


Figure 4.19. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Pena Blanca site.

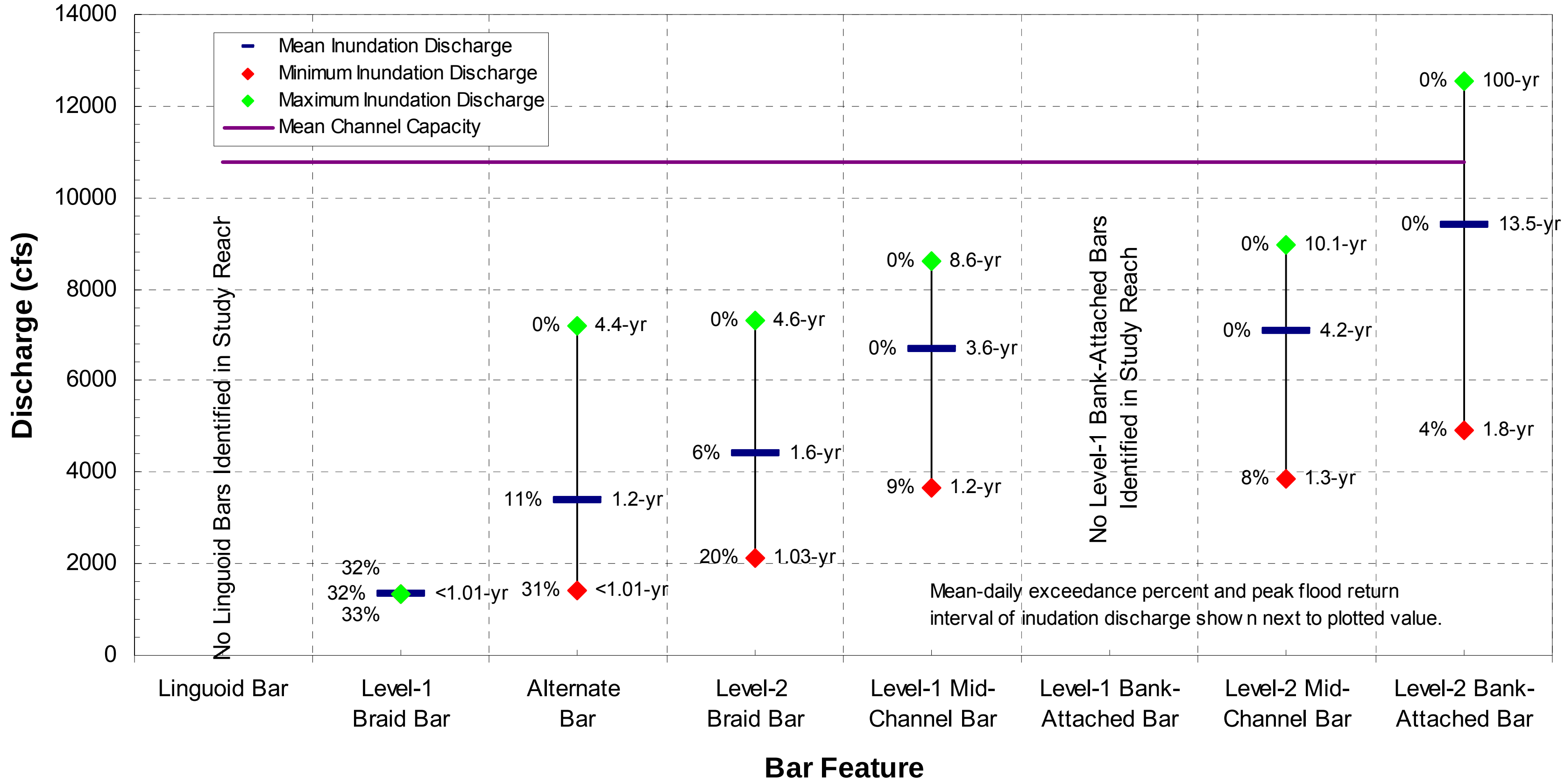


Figure 4.20. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Bernalillo site.

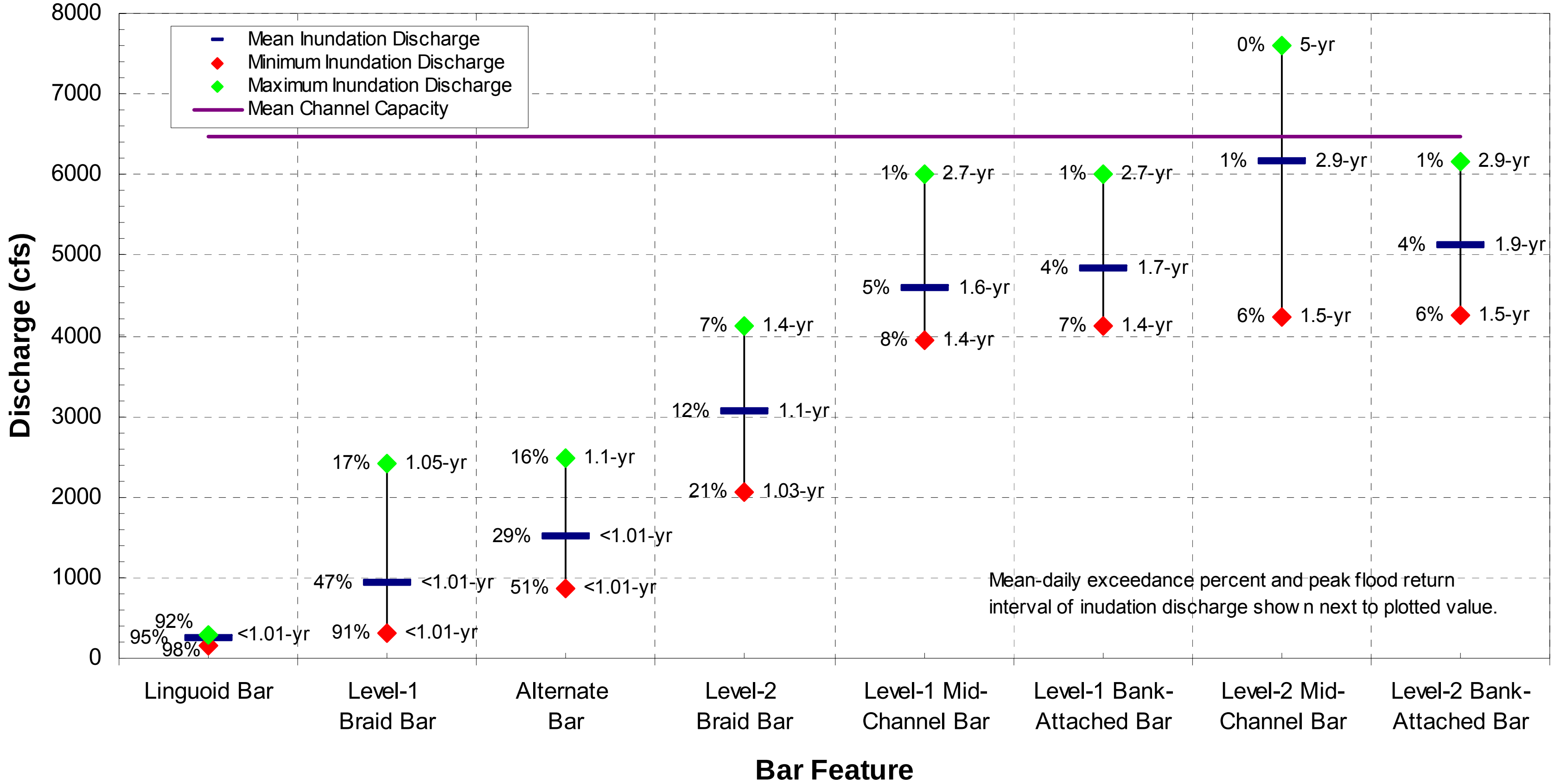


Figure 4.21. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Central Avenue site.

percent of the time by flows with recurrence intervals of about 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average about 5 percent of the time, by flows with a recurrence interval of about 1.6 years. Level-2 bank-attached bars are inundated on average 4 percent of the time by flows with a recurrence interval of about 2 years. On average, the Level-2 mid-channel bars are inundated for about 1 percent of the time by flows with a recurrence interval of about 3 years. However, the range of recurrence intervals that overtop these bars is wide and varies from 1.5 to 5 years, which indicates that some of the bars are relics of the pre-dam flow regime, and that the bar heights have been increased by channel degradation.

#### 4.3.4. Belen

At the Belen site, the Level-1 braid bars and the alternate bars are inundated on average between 95 and 76 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.22**). Level-2 braid bars are inundated on average about 21 percent of the time by flows with recurrence intervals of about 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average about 15 percent of the time, by flows with a recurrence interval of about 1.1 years. Level-2 mid-channel bars and Level-2 bank-attached bars are inundated on average between 7 and 2 percent of the time by flows with recurrence intervals of 1.3 and 2.1 years, respectively.

#### 4.3.5. Bernardo

At the Bernardo site, the Level-1 braid bars and the alternate bars are inundated on average between 87 and 57 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.23**). Level-2 braid bars are inundated on average about 26 percent of the time by flows with recurrence intervals of less than 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average about 23 percent of the time, by flows with a recurrence interval of about 1 year. Level-2 mid-channel bars and Level-2 bank-attached bars are inundated on average between 10 and 7 percent of the time by flows with recurrence intervals of 1.5 years.

#### 4.3.6. La Joya

At the La Joya site, the Level-1 braid bars and the alternate bars are inundated on average between 51 and 39 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.24**). Level-2 braid bars are inundated on average about 36 percent of the time by flows with recurrence intervals of less than 1 year. Level-1 mid-channel bars are inundated on average about 15 percent of the time, by flows with a recurrence interval of about 1 year. Level-2 mid-channel bars and Level-2 bank-attached bars are inundated on average between 3 and 8 percent of the time by flows with recurrence intervals of 1.7 and 1.2 years, respectively. The relatively wide range of recurrence intervals for overtopping the Level-2 mid-channel bars probably reflects recent channel degradation.

#### 4.3.7. Lemitar

At the Lemitar site, the Level-1 braid bars and the alternate bars are inundated on average between 43 and 59 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.25**). Level-2 braid bars are inundated on average about 22 percent of the time by flows with recurrence intervals of about 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average about 11 and 19 percent of the time, respectively by flows with a recurrence interval of about 1 year. Level-2 mid-channel bars and

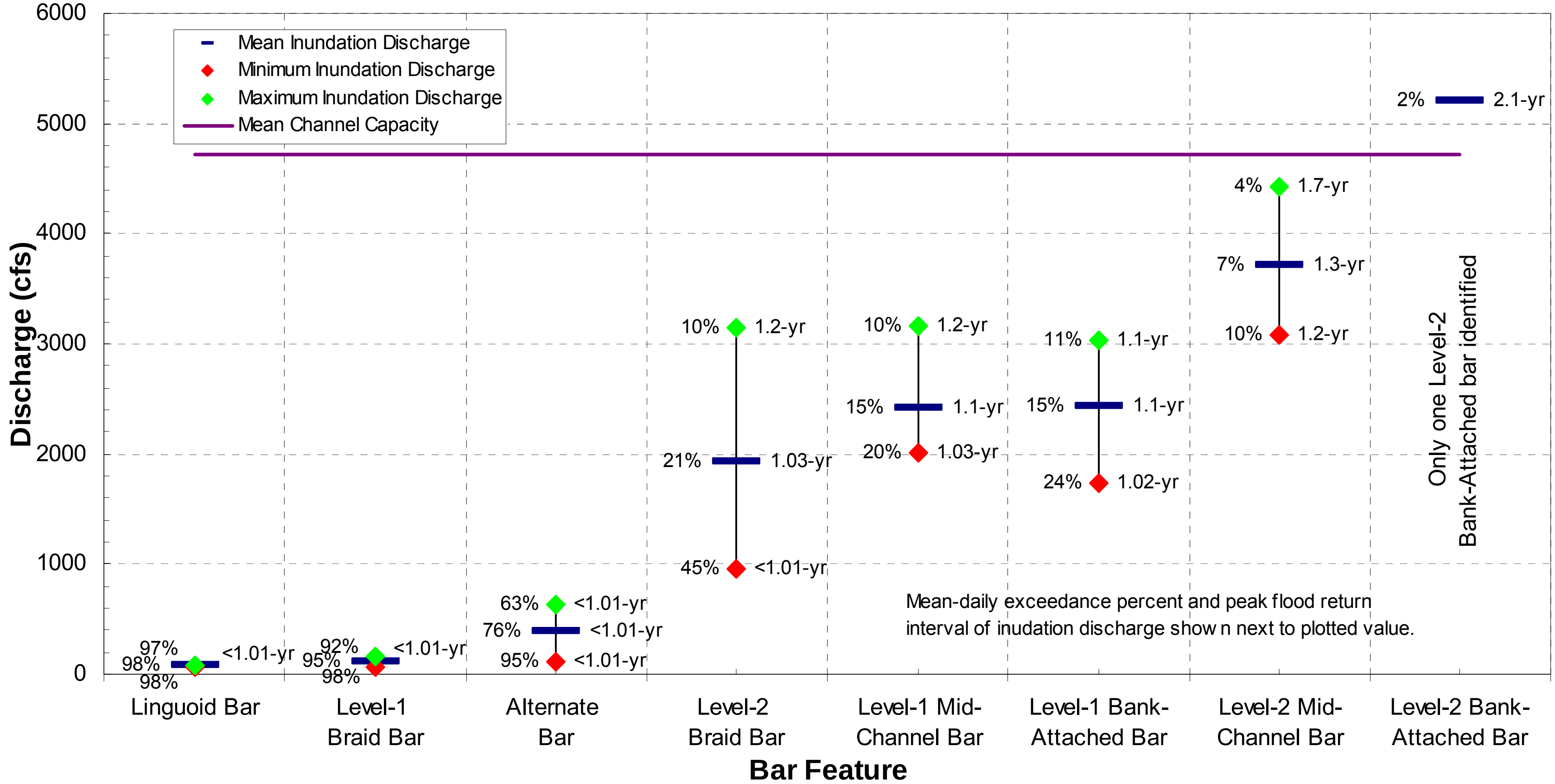


Figure 4.22. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Belen site.

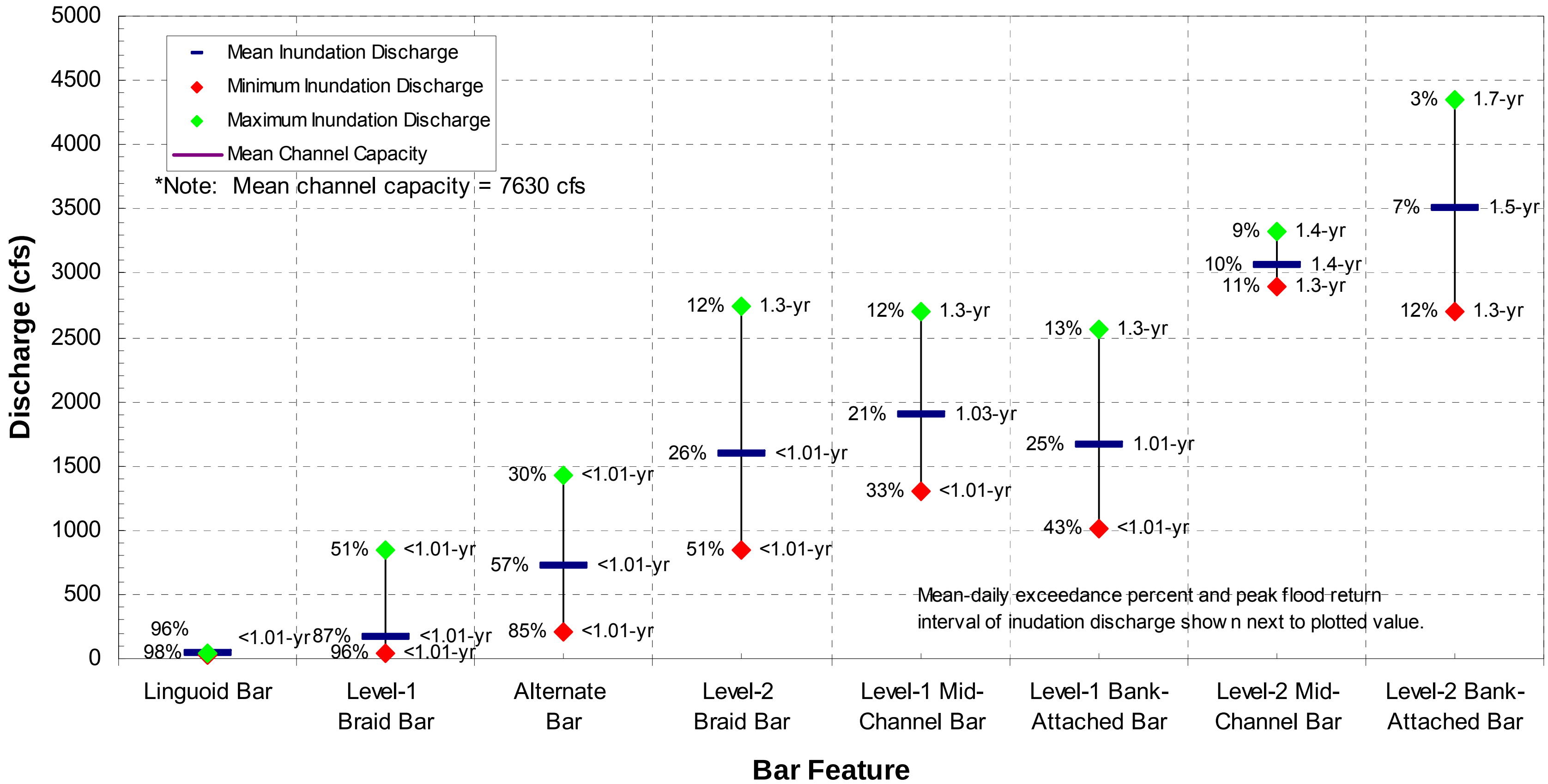


Figure 4.23. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Bernardo site.

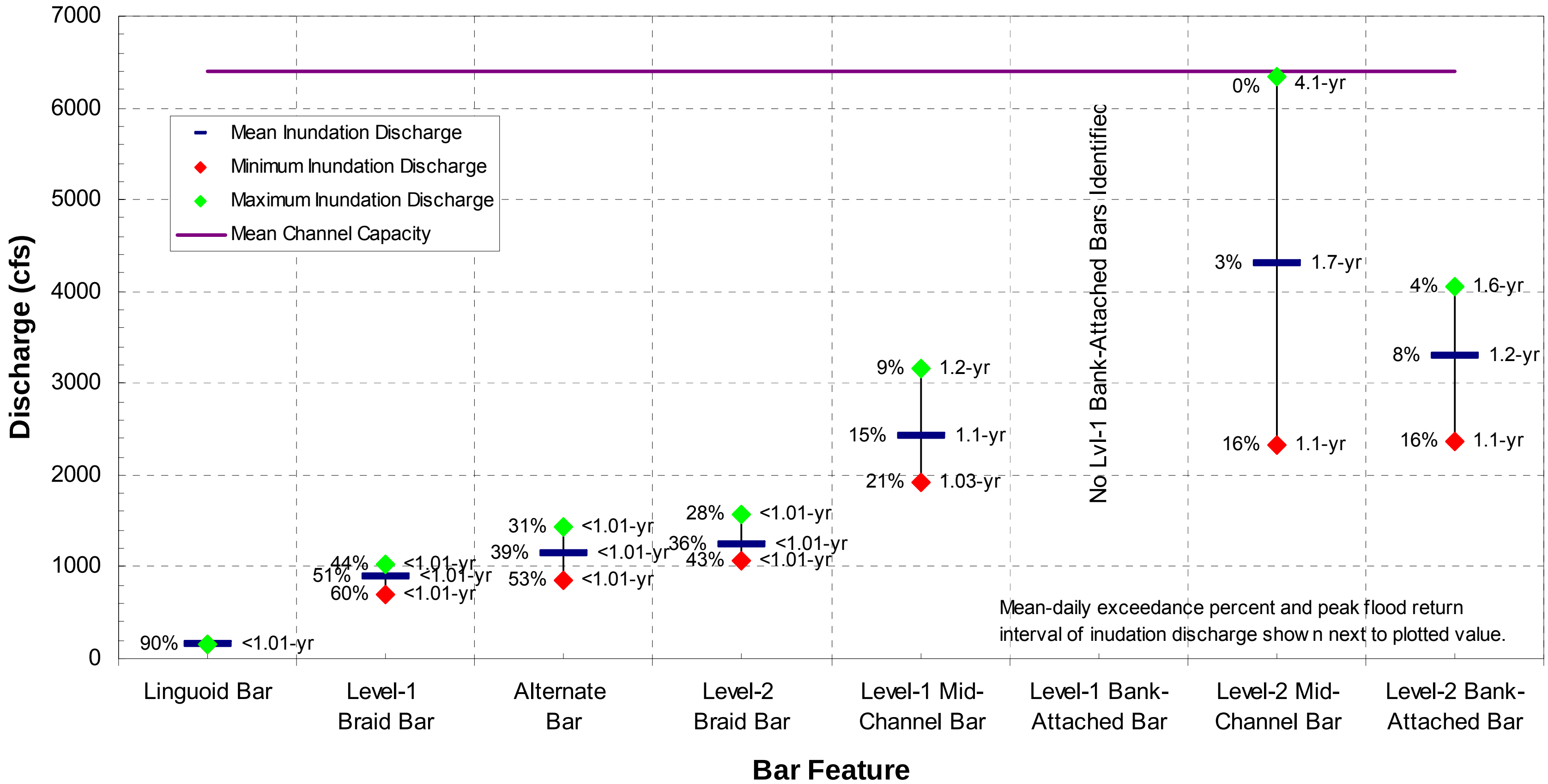


Figure 4.24. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the La Joya site.

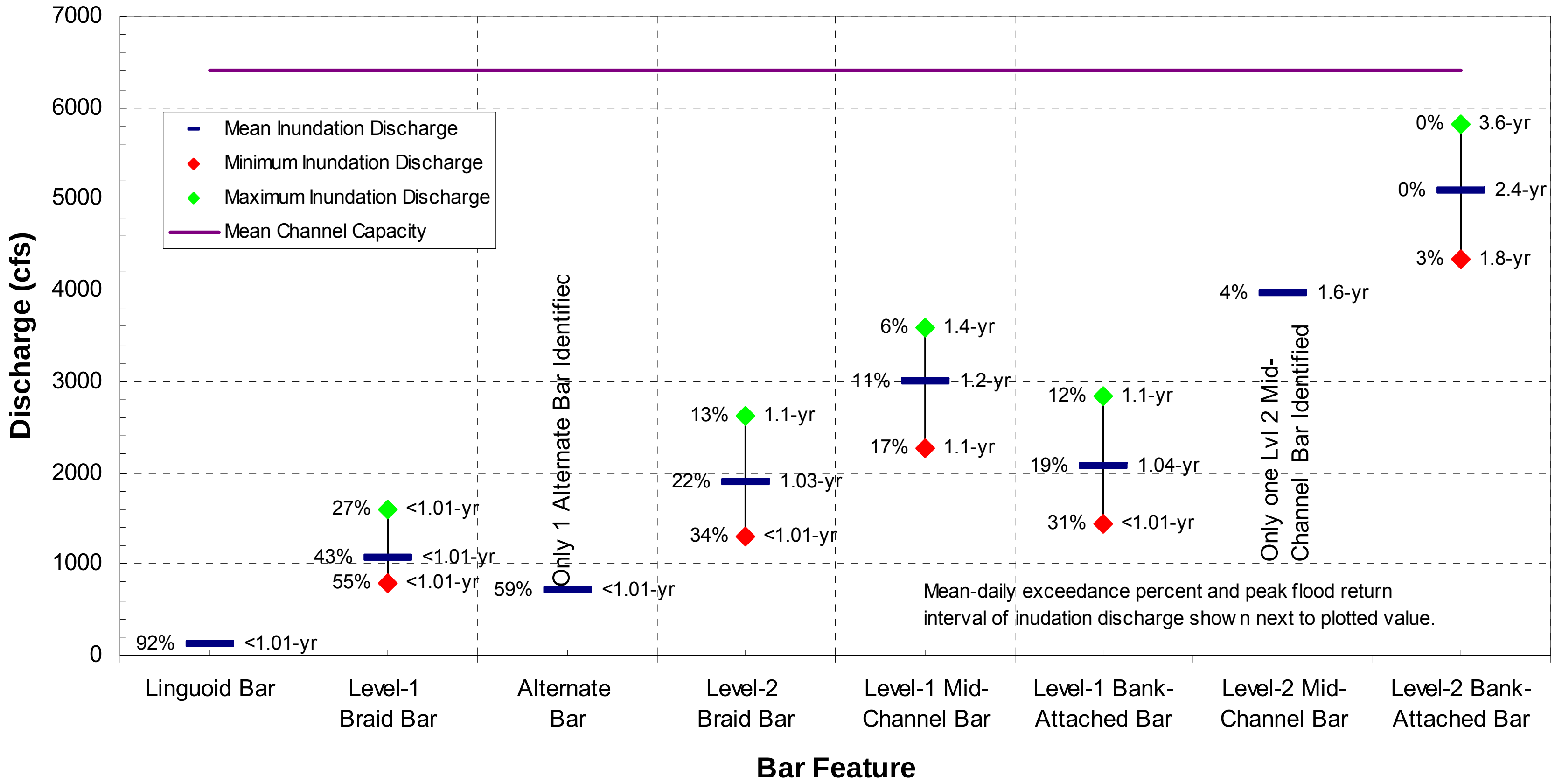


Figure 4.25. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Lemitar site.

Level-2 bank-attached bars are inundated on average between 4 and 0 percent of the time by flows with recurrence intervals of 1.6 and 2.4 years, respectively.

### 4.3.8. Escondida

At the Escondida site, the Level-1 braid bars and the alternate bars are inundated on average between 80 and 47 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.26**). Level-2 braid bars are inundated on average about 26 percent of the time by flows with recurrence intervals of about 1 year. Because of the narrow and deep channel at this site, there are no Level-1 mid-channel, Level-1 bank-attached or Level-2 mid-channel bars. One Level-2 bank-attached bars is present at the site, and it is inundated by a flow with an 18-year recurrence interval which indicates that it is a pre-incision remnant feature.

### 4.3.9. Bosque del Apache

At the Bosque del Apache site, the Level-1 braid bars and the alternate bars are inundated on average between 53 and 33 percent of the time, respectively and by flows with less than a 1-year recurrence interval (**Figure 4.27**). Level-2 braid bars are inundated on average about 11 percent of the time by flows with recurrence intervals of about 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average about 10 percent of the time, by flows with a recurrence interval of about 1 year. Level-2 mid-channel bars and Level-2 bank-attached bars are inundated on average between 5 and 3 percent of the time by flows with recurrence intervals of 1.3 and 1.5 years, respectively.

### 4.3.10. San Marcial

At the San Marcial site, the Level-1 braid bars, the alternate bars, Level-2 braid bars and the Level-1 mid-channel bars are inundated on average for 78, 70, 62 and 48 percent of the time, respectively by flows with less than a 1-year recurrence interval (**Figure 4.28**). Level-1 and Level-2 bank-attached bars are inundated on average 22 and 8 percent of the time, respectively by flows with recurrence intervals of 1 and 1.2 years, respectively.

### 4.3.11. Summary

If the three sites with the most channel degradation, Pena Blanca, Bernalillo and Escondida, and San Marcial with a high rate of aggradation are removed from the averaging process, Level-1 braid bars, alternate bars and Level-2 braid bars are inundated on average by flows with recurrence intervals of less than 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average by flows with recurrence intervals of about 1.5 years. Level-2 mid-channel and Level-2 bank-attached bars are inundated on average by flows with a recurrence interval of about 2 years. At any given site, there will be a range of values for any given bar type. At the most degraded sites most of the Level-2 bank-attached bars are probably better described as terraces, and at the San Marcial site where the aggradation rate is the highest, the high rate of aggradation tends to blur the distinction between the bar types. Excluding the Pena Blanca, Bernalillo, Escondida and San Marcial sites, Level-2 mid-channel and Level-2 bank-attached bars are inundated on average for less than 10 percent of the time (36 days/year). Level-1 mid-channel and Level-1 bank-attached bars are inundated on average for less than 25 percent of the time (90 days/year). Level-2 braid bars are inundated on average for less than 40 percent of the time (146 days/year). Alternate bars and Level-1 braid bars are inundated on average for about 80 percent of the time (290 days/year).

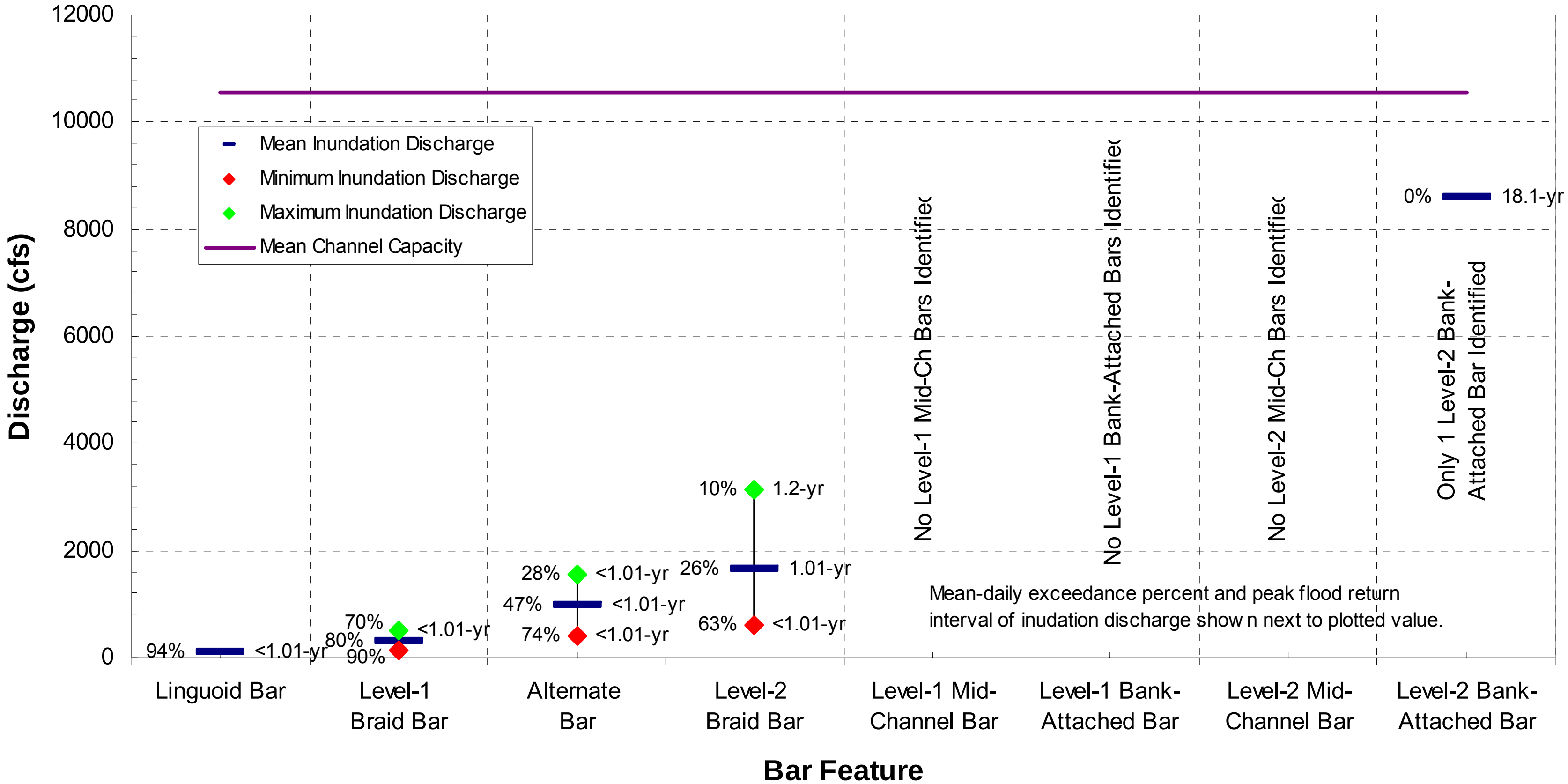


Figure 4.26. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Escondida site.

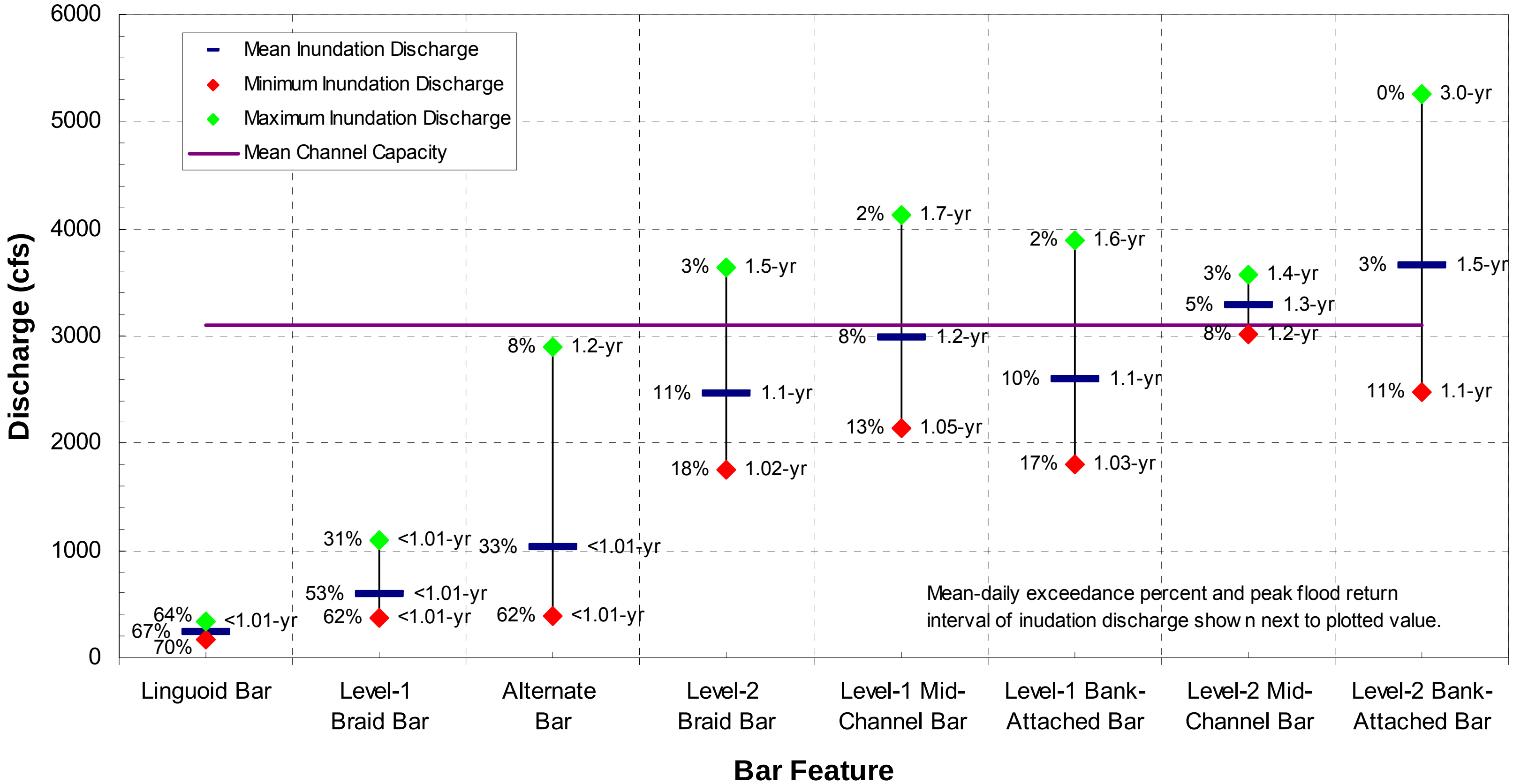


Figure 4.27. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the Bosque del Apache site.

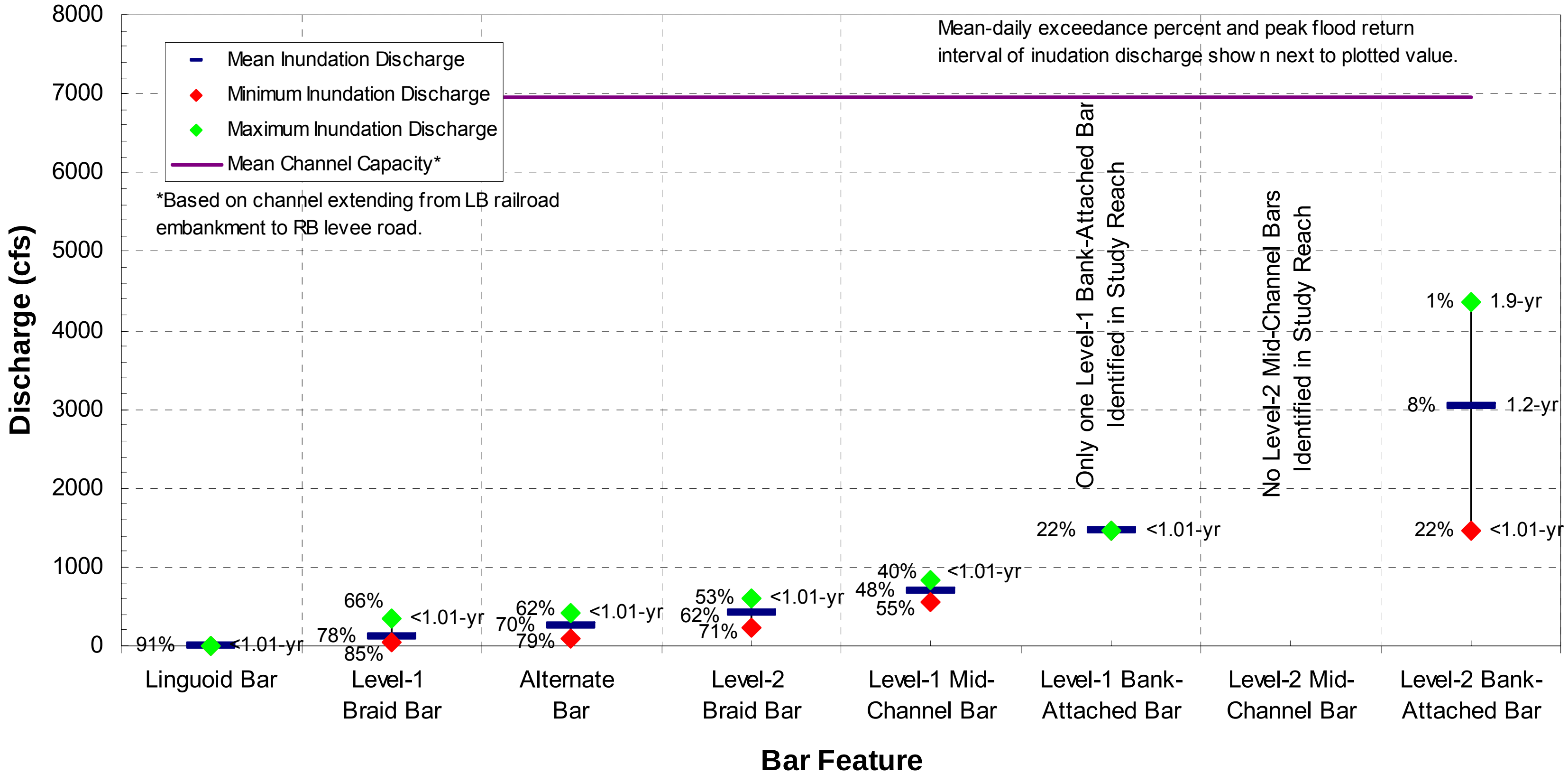


Figure 4.28. Relationships between flow magnitude, frequency and duration for inundating the different types of bars at the San Marcial site.

## 4.4. Shear Stress Analysis

In addition to evaluating the flow magnitudes, frequencies and durations required to inundate the different bar types, the HEC-RAS hydraulic model output for each site was also used to determine shear stresses for the range of modeled flows. Shear stress was used to evaluate the flows required to mobilize the coarse bed material at the Pena Blanca and Bernalillo sites, as well as to evaluate whether flows would be capable of removing vegetation that has become established on many of the Level-1 and Level-2 mid-channel and bank-attached bars.

### 4.4.1. Incipient Motion

An incipient-motion analysis (evaluation of flows required to move the bed material) was performed by evaluating the effective shear stress on the channel bed in relation to the amount of shear stress that is required to move the surface particles at the Pena Blanca and Bernalillo sites. The shear stress required for bed mobilization was estimated using the Shields (1936) relation, given by:

$$\tau_C = \tau_{*C}(\gamma_S - \gamma)D_{50} \qquad (4.2)$$

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

In gravel- and cobble-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 ($\tau'$) 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:

$$\tau' = \gamma Y'S \qquad (4.3)$$

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 semilogarithmic velocity profile equation:

$$\frac{V}{V'_*} = 5.75 + 6.25 \log\left(\frac{Y'}{K_S}\right) \qquad (4.4)$$

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:

$$V_*' = \sqrt{gY'S} \tag{4.5}$$

The characteristic roughness height of the bed ($K_s$) was assumed to be 3.5 $D_{84}$ (Hey, 1979). Normalized grain shear stress ($\phi'$) is the ratio of the grain sheer stress ($\tau'$) to the critical shear stress for particle mobilization ($\tau_c$ ). When $\phi'$ 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).

#### 4.4.1.1. Pena Blanca

At the Pena Blanca site, analysis of particle mobilization was done for the surface sediments on the Level-1 bar (PC 1: $D_{50}$=30 mm) and for the riffle sediments (PC 2: $D_{50}$=56 mm) (**Figure 4.29**). Based on the reach-averaged hydraulics, incipient conditions ($\phi'$=1) for the Level-1 bar surface sediments are reached at a flow of about 5,500 cfs (approximately 4-year recurrence interval), but substantial sediment transport ($\phi'$>1.5) does not occur even at the 100-year flow (12,800 cfs). Using conveyance weighting techniques to better represent the local hydraulic conditions, significant sediment transport occurs at about 11,000 cfs (~50-year event). Therefore, it can be concluded that mobilization of gravel supplied by the tributaries downstream of Cochiti Dam occurs infrequently. Because of the limited supply of sediment from the tributaries downstream of Cochiti Dam, and the infrequent mobilization of the gravels, it is unlikely that there will be an increase in the number of bars within the Pena Blanca site in the future.

Analysis of the mobilization potential of the riffle sediments (PC2) enables the likelihood of further degradation of the bed to be evaluated. Based on the reach-averaged hydraulics, incipient conditions occur at a flow of about 10,000 cfs, which is approximately the 25-year event. General mobilization of the bed material and significant sediment transport does not occur at the 100-year event. Therefore, it can be concluded that it is highly unlikely that there will be further degradation of the bed at the Pena Blanca site, and that the bed is armored.

#### 4.4.1.2. Bernalillo

At the Bernalillo site, incipient conditions ($\phi'$=1) are reached at a flow of about 9,000 cfs (10-year event) based on the reach-averaged hydraulics and a riffle $D_{50}$ of 37 mm, but significant sediment transport does not even occur at the 100-year flow event (**Figure 4.30**). Conveyance weighting reduces the flow required to attain incipient conditions to about 7,500 cfs (about 5-year event), but significant sediment transport does not even occur at the 100-year event. Therefore, it can be concluded that further degradation is unlikely to occur at the Bernalillo site. However, if sediment supply is increased from the Rio Jemez, it is likely that more bars will form within the reach, and braiding intensity will increase.

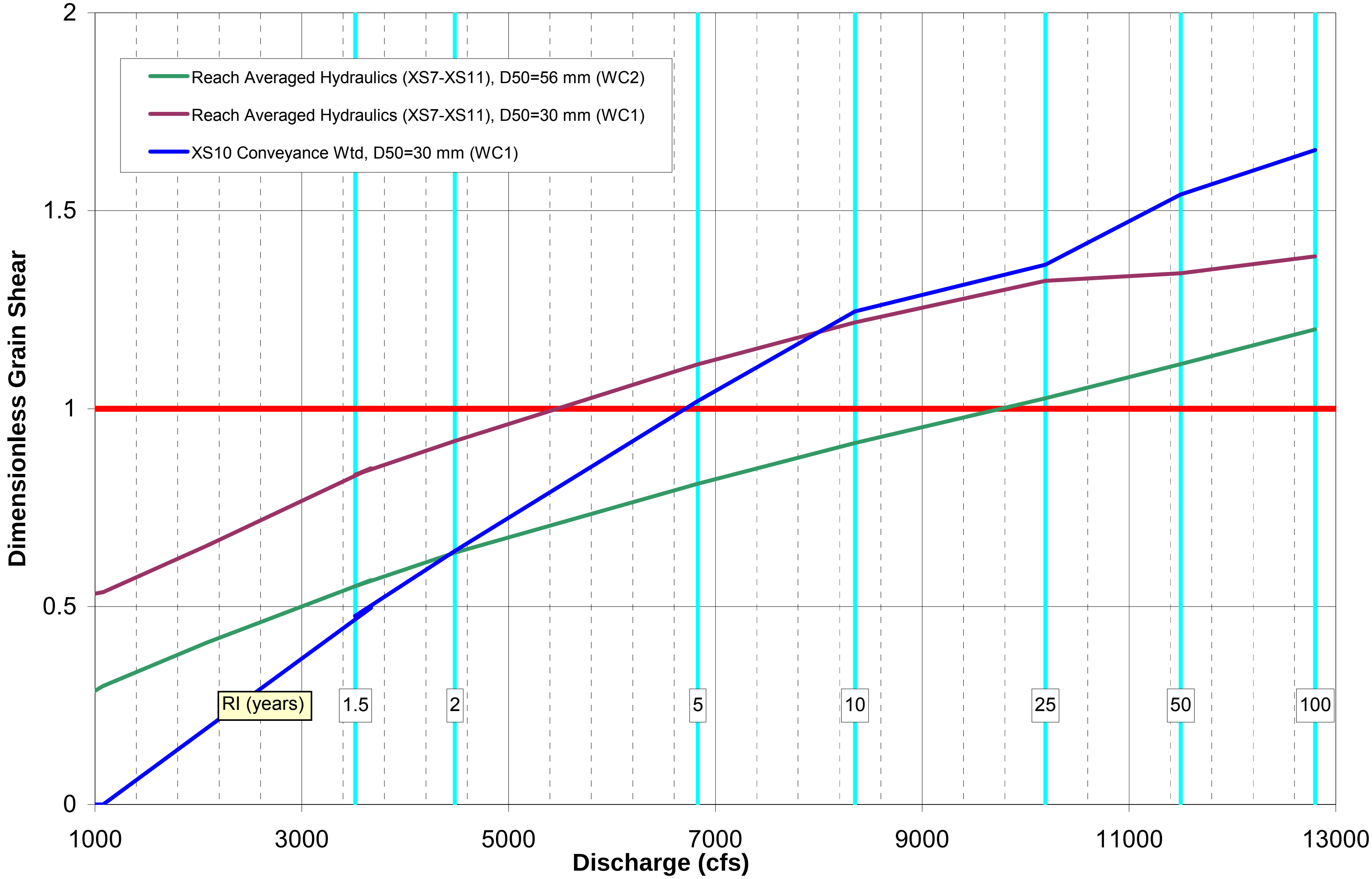


Figure 4.29. Dimensionless grain shear plots for Level-1 bar surface sediments and riffle sediments at the Pena Blanca site.

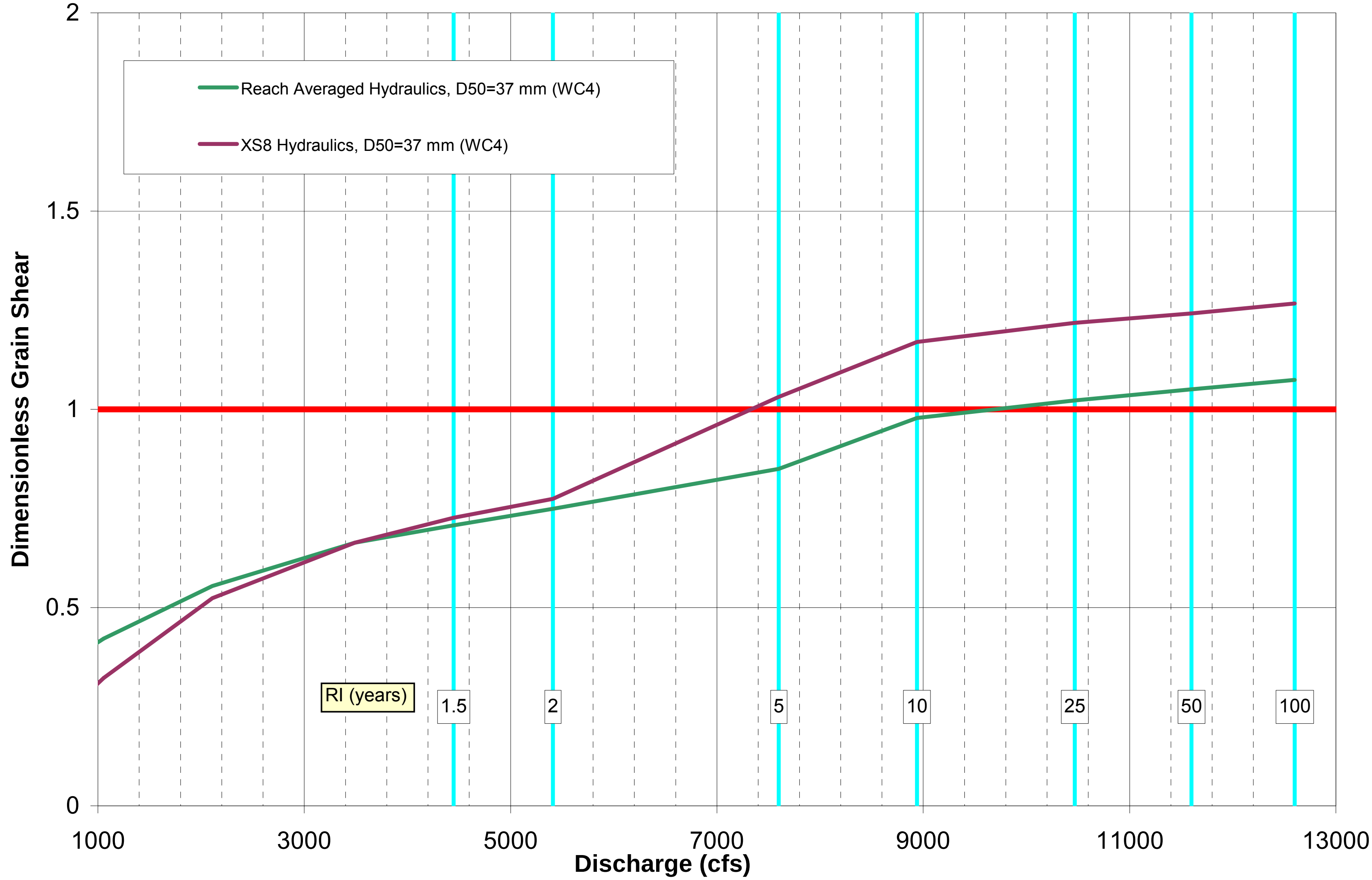


Figure 4.30. Dimensionless grain shear plots for Level-1 bar surface sediments and riffle sediments at the Bernalillo site.

### 4.4.2. Shear Stress

At the remainder of the sites where the bed material is composed of sand, incipient conditions do not pertain, since sand is mobilized at shear stresses far less than 0.1 lb/ft$^2$. However, sediment transport and deposition are the critical factors involved in bar formation. The shear stress distribution for a typical cross section at each of the sites was plotted to evaluate the relationship between shear stress and the presence of active bars. At the Central Avenue site, maximum in-channel bed shear stresses barely exceed 0.1 lb/ft$^2$ even at the 10-year recurrence interval flow (**Figure 4.31**), and numerous active bars are present throughout the site. At the Belen site, the maximum in-channel shear stress is nearly 0.2 lb/ft$^2$ (**Figure 4.32**) and there are a number of active bars at the site. At the Bernardo (**Figure 4.33**), La Joya (**Figure 4.34**) and Lemitar (**Figure 4.35**) sites the maximum in-channel shear stresses are between 0.12 and 0.15 lb/ft$^2$ and active bars are present at these sites. In contrast, at the Escondida site, maximum in-channel shear stresses are about 0.3 lb/ft$^2$ and there are virtually no bars present at the site (**Figure 4.36**). At the Bosque del Apache (**Figure 4.37**) and San Marcial (**Figure 4.38**) sites, maximum in-channel shear stresses are about 0.1 lb/ft$^2$ and at these are the sites with the largest number of active bars. Therefore, provided that there is a supply of sand-sized sediment, active braid and alternate bars are present when maximum in-channel shear stresses are between about 0.1 and 0.2 lb/ft$^2$. If the maximum in-channel shear stress is higher than about 0.2 lb/ft$^2$ the sediment-transport rate is too high for bar formation, even if there is a supply of sediment.

### 4.4.3. High-flow Deposition and Erosion, Albuquerque Reach

As part of the NMISC's bar restoration project within the Albuquerque reach of the MRG, detailed (0.5-foot contour interval) topographic surveys of 6 mid-channel bars were conducted by MEI before and after the 2005 runoff (**Figure 4.39**). Repeat surveys of the bars provided an opportunity to evaluate the effects of a relatively high and long duration flows on both deposition and erosion of the various types of bars. Three of the bars were located in the South Diversion Channel (SDC) reach downstream of the Rio Bravo Bridge, and the other three were located in the North Diversion Channel (NDC) reach upstream of the Alameda Avenue Bridge. The initial survey of the bars was completed in March 2005 before the onset of the 2005 runoff period. The repeat survey of the bars was conducted in September 2005 after the runoff period in which the peak flow in the reach was 6,300 cfs, and flow levels exceeded 5,000 cfs for over a month between May 12 and June 15, 2005.

The control bar for the SDC reach is a thickly vegetated Level-2 mid-channel bar (**Figure 4.40**), and SDC bars 2 (**Figure 4.41**) and 3 (**Figure 4.42**) are composed of higher-elevation Level-2 mid-channel bar cores with lower elevation laterally attached Level-1 mid-channel bars. The original survey 0.5-foot contour interval mapping for these three bars is provided on **Figures 4.43 and 4.44**. The control bar for the NDC reach is a thickly vegetated Level-2 mid-channel bar (**Figure 4.45**) with a relatively narrow laterally attached Level-1 mid-channel bar on the west side. NDC bar 2 (**Figure 4.46**) has a small Level-2 mid-channel bar core with an extensive laterally attached Level-1 bank-attached bar. NDC bar 3 (**Figure 4.47**) is composed entirely of a Level-1 mid-channel bar. The original survey 0.5-foot contour interval mapping for these three bars is provided on **Figures 4.48 and 4.49**.

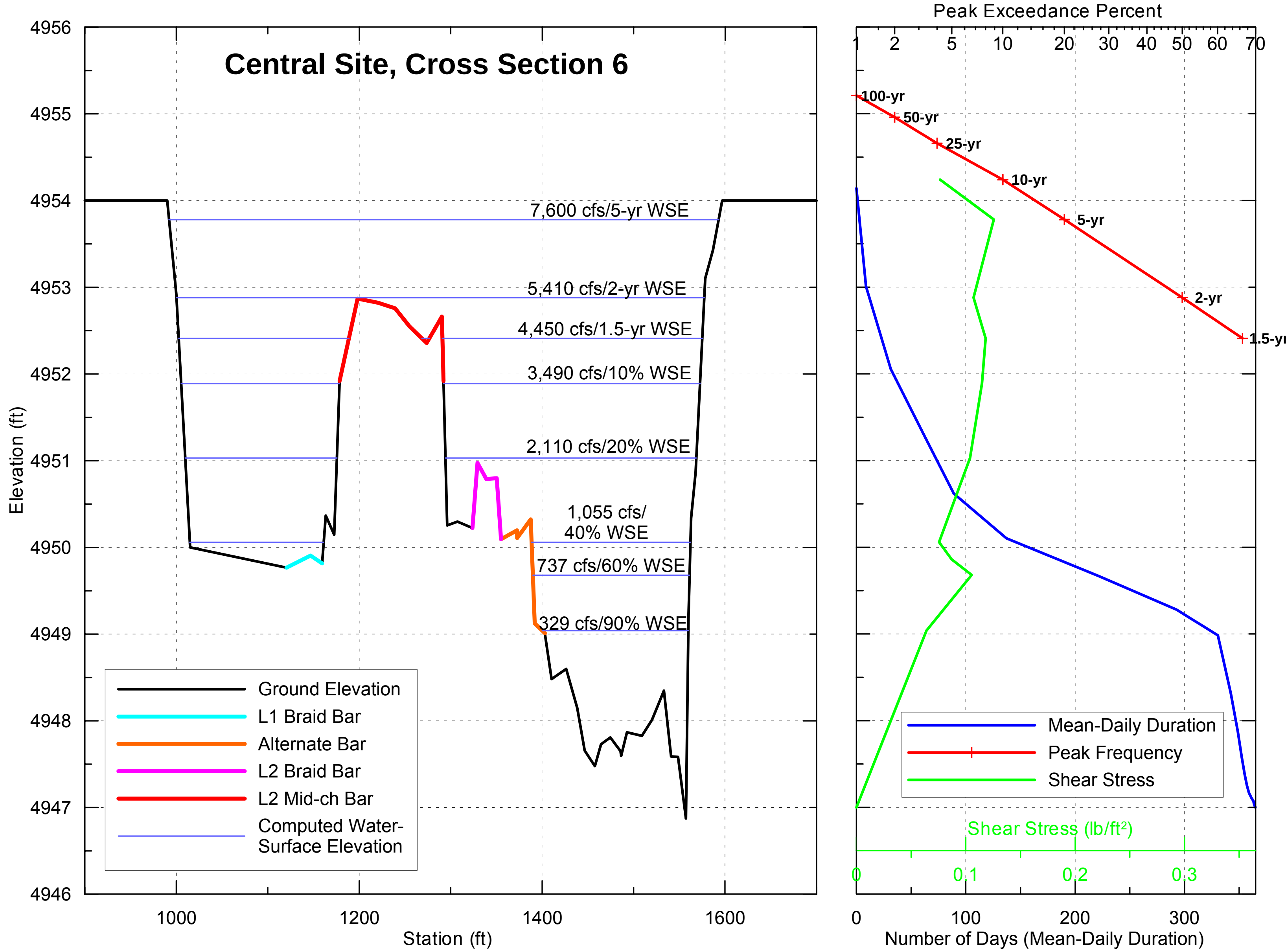


Figure 4.31. Typical cross section at the Central Avenue site showing water-surface elevations for a range of flows between 329 and 7,600 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

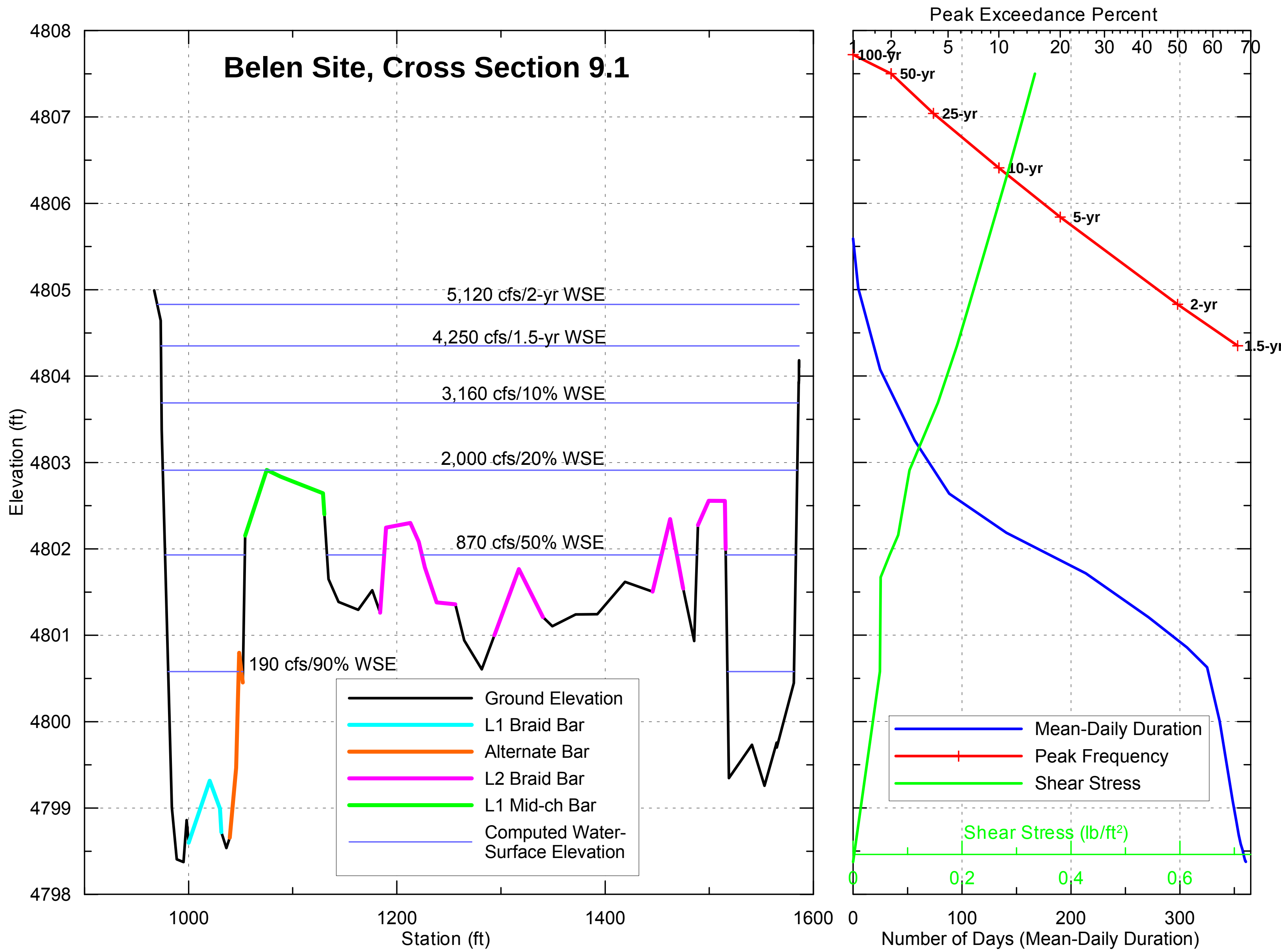


Figure 4.32. Typical cross section at the Belen site showing water-surface elevations for a range of flows between 190 and 5,120 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

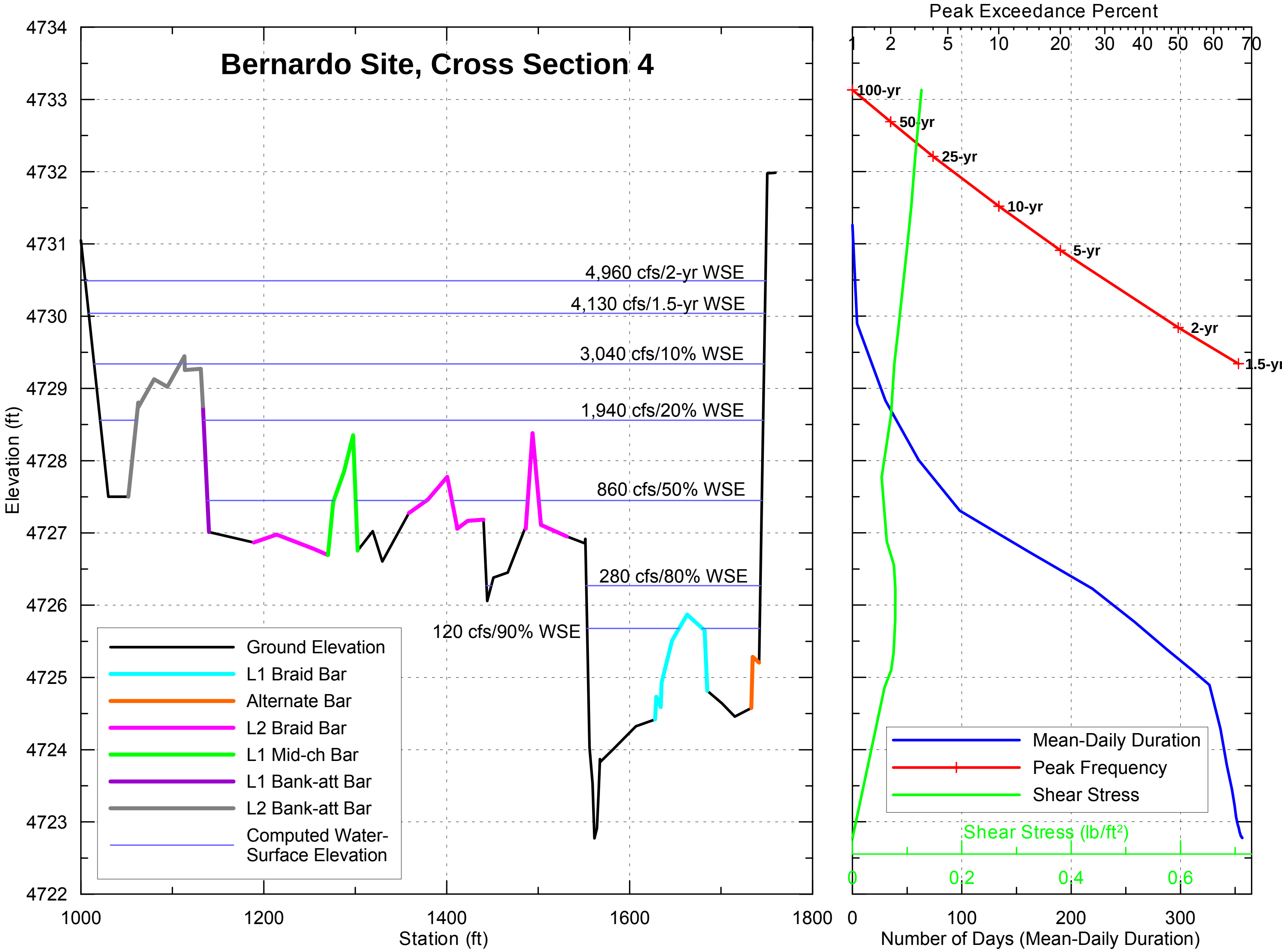


Figure 4.33. Typical cross section at the Bernardo site showing water-surface elevations for a range of flows between 120 and 4,960 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

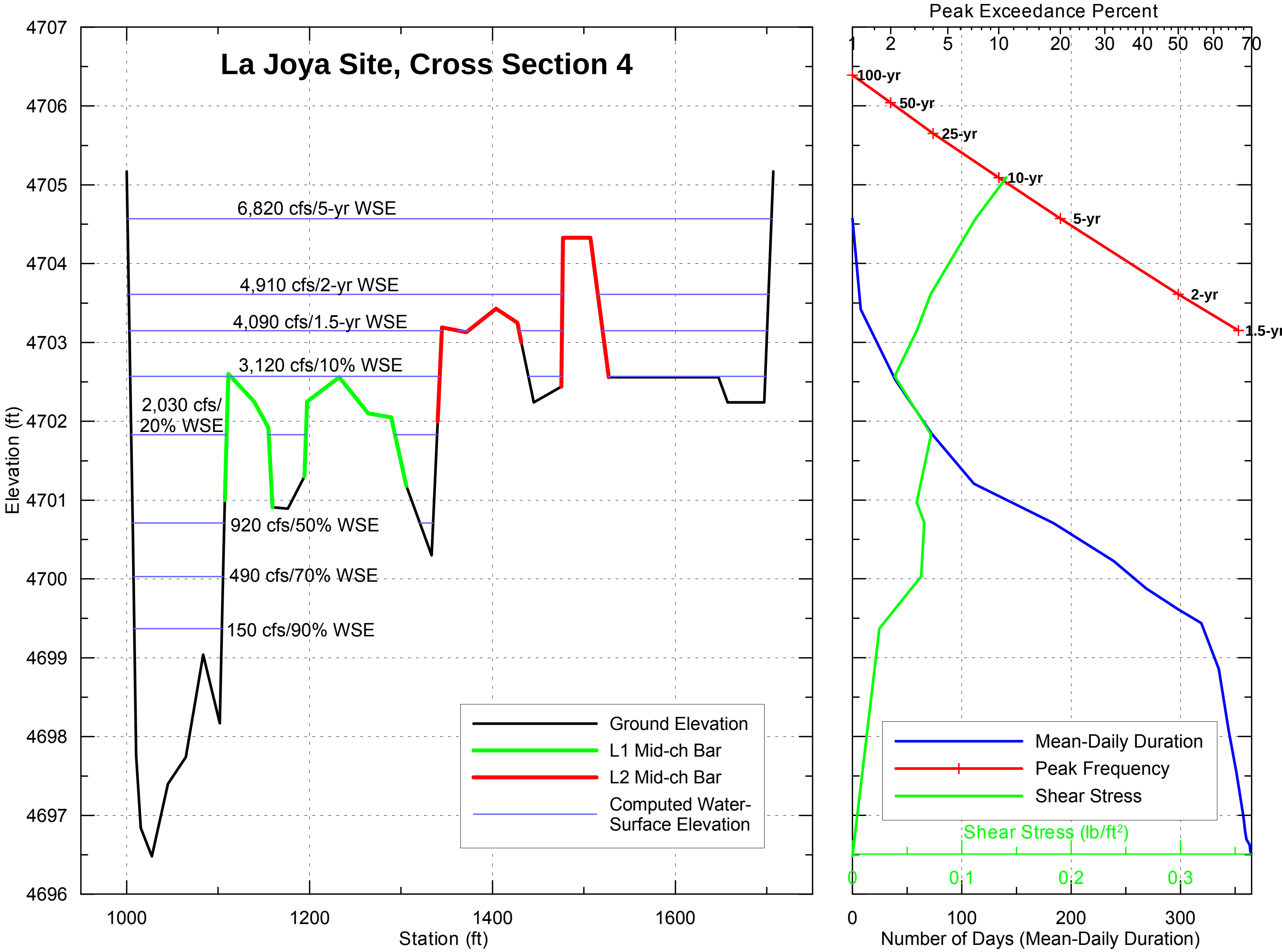


Figure 4.34. Typical cross section at the La Joya site showing water-surface elevations for a range of flows between 150 and 6,820 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

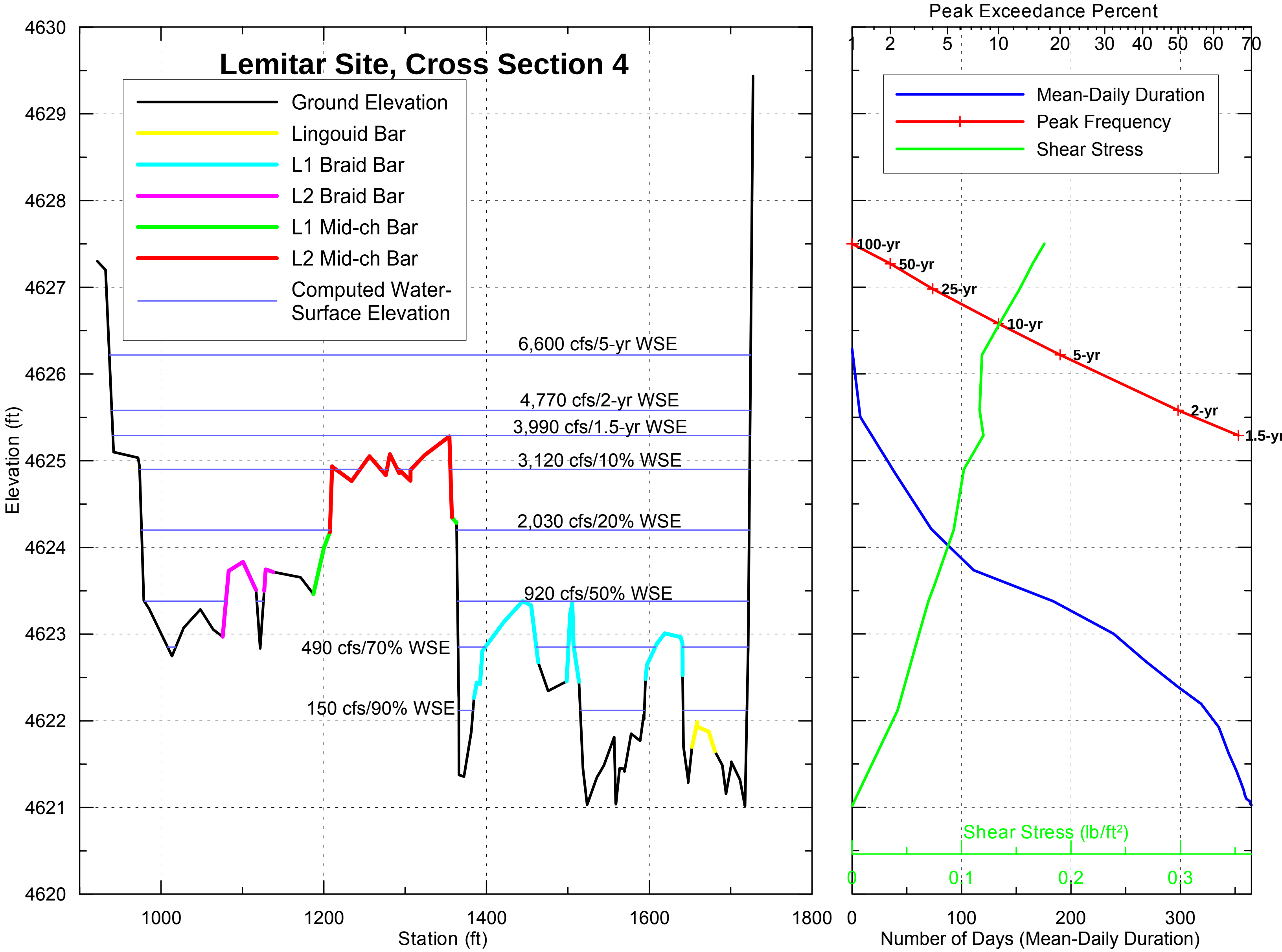


Figure 4.35. Typical cross section at the Lemitar site showing water-surface elevations for a range of flows between 150 and 6,600 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

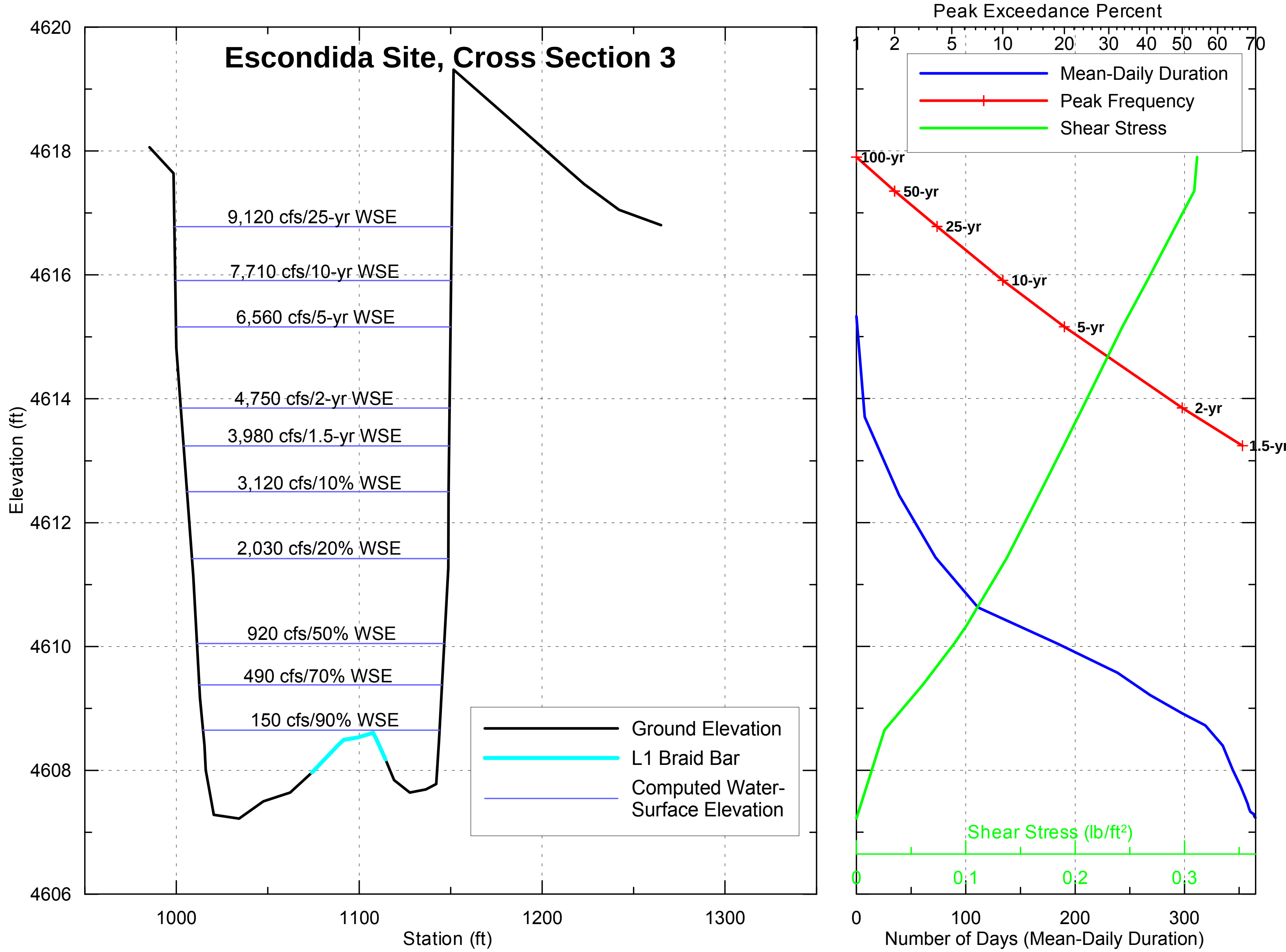


Figure 4.36. Typical cross section at the Escondida site showing water-surface elevations for a range of flows between 150 and 9,120 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

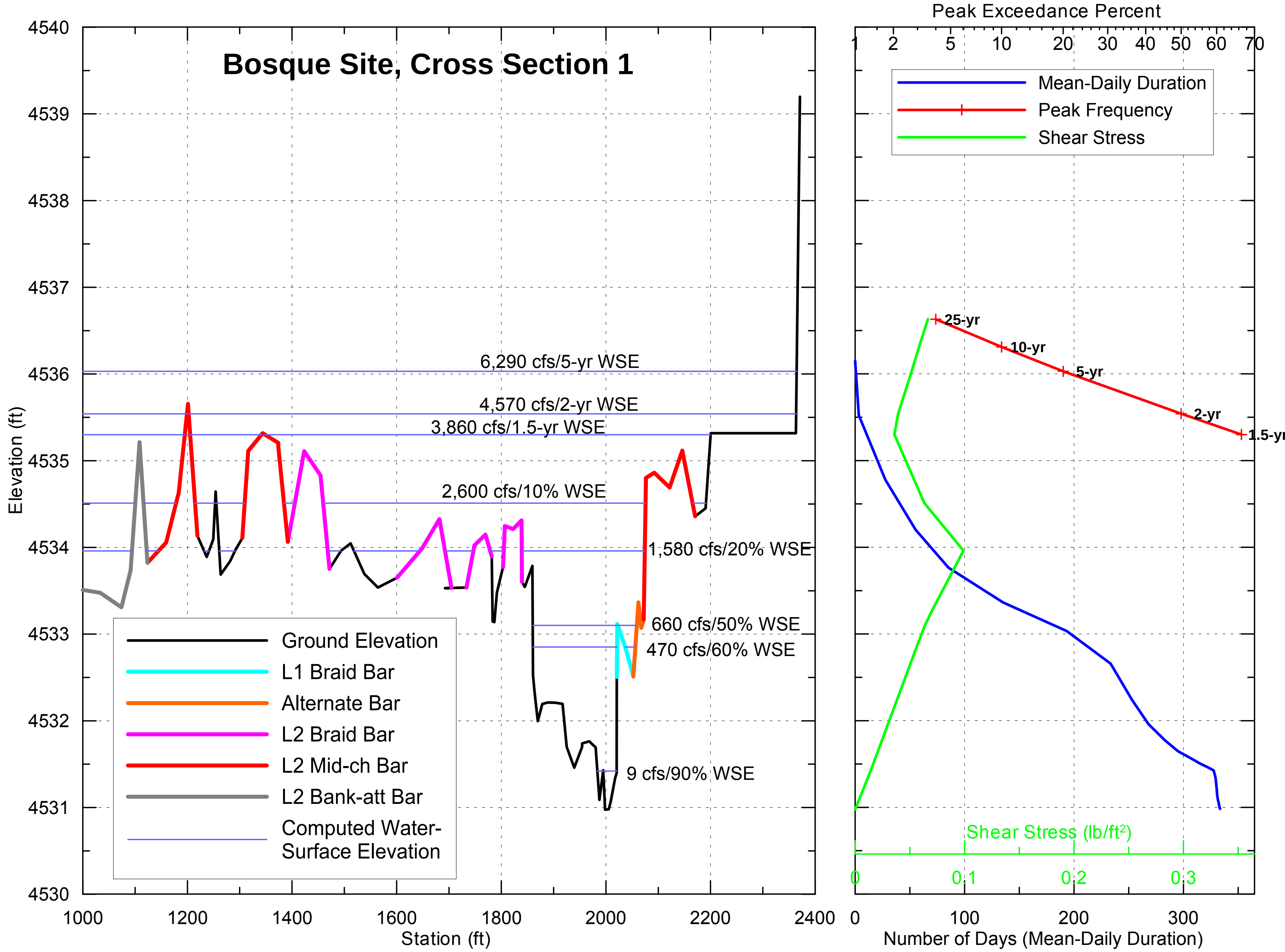


Figure 4.37. Typical cross section at the Bosque del Apache site showing water-surface elevations for a range of flows between 9 and 6,290 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

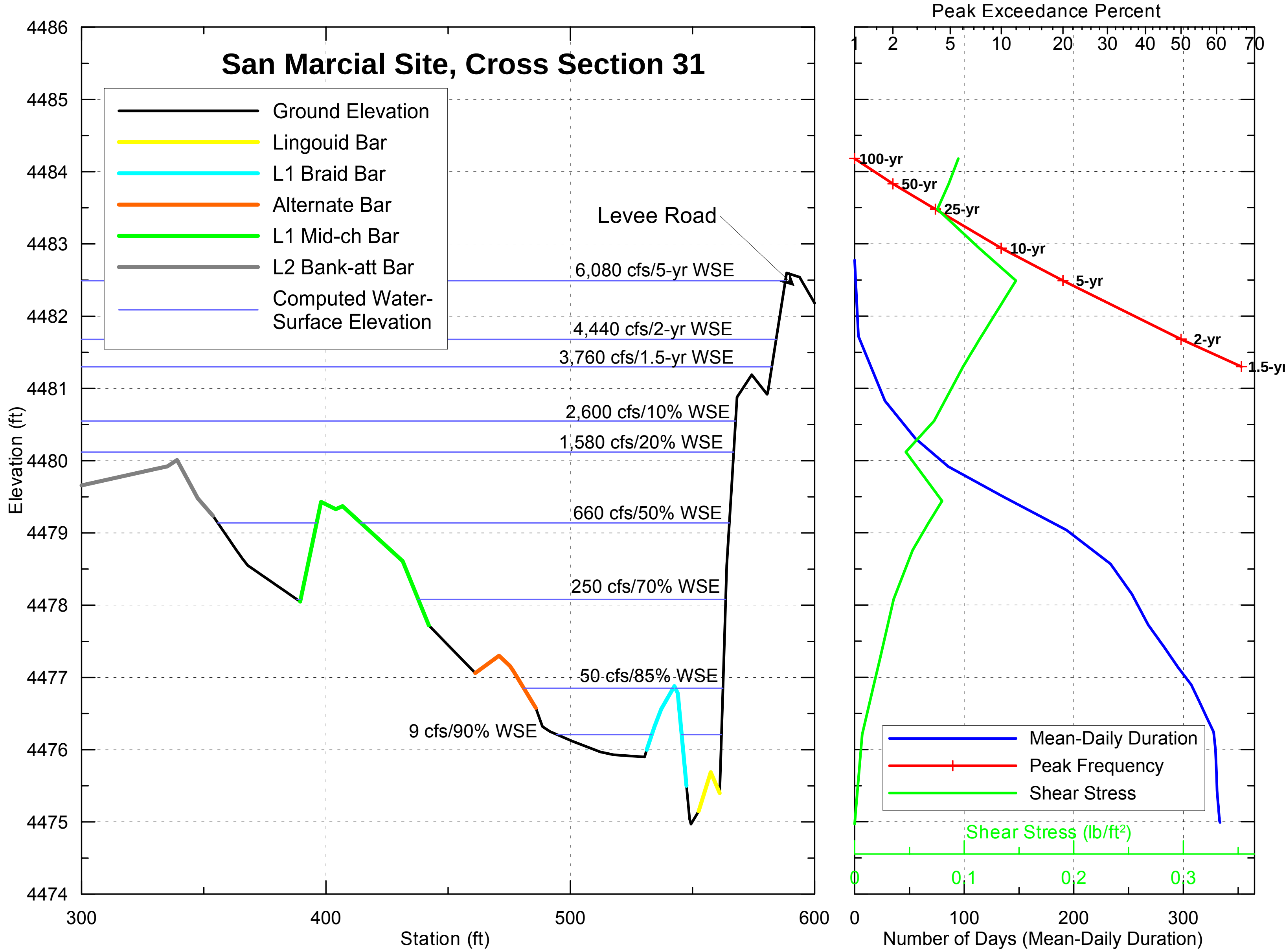


Figure 4.38. Typical cross section at the San Marcial site showing water-surface elevations for a range of flows between 9 and 6,080 cfs, as well as flood frequency, flow duration and shear stress profiles at the cross section.

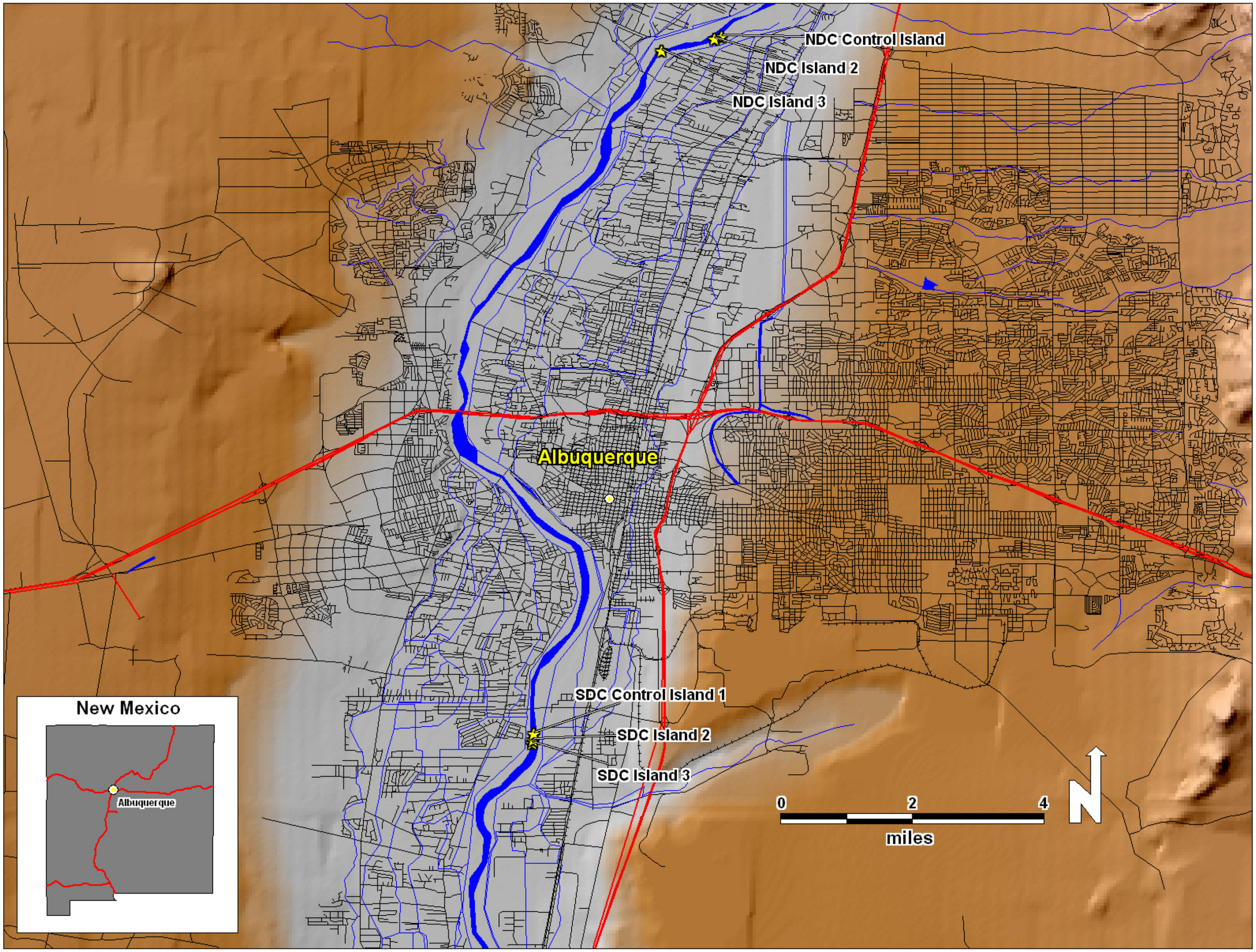


Figure 4.39. Map showing the locations of the Level-1 and Level-2 mid-channel bars surveyed in the Albuquerque reach of the MRG in March and September 2005 (SWCA and MEI, in prep.).


Figure 4.40. View downstream of the Level-2 SDC control mid-channel bar.


Figure 4.41. View upstream of the SDC 2 Level-2 with attached Level-1 mid-channel bar.

Figure 4.42. View downstream of the SDC 3 Level-2 with attached Level-1 mid-channel bar.

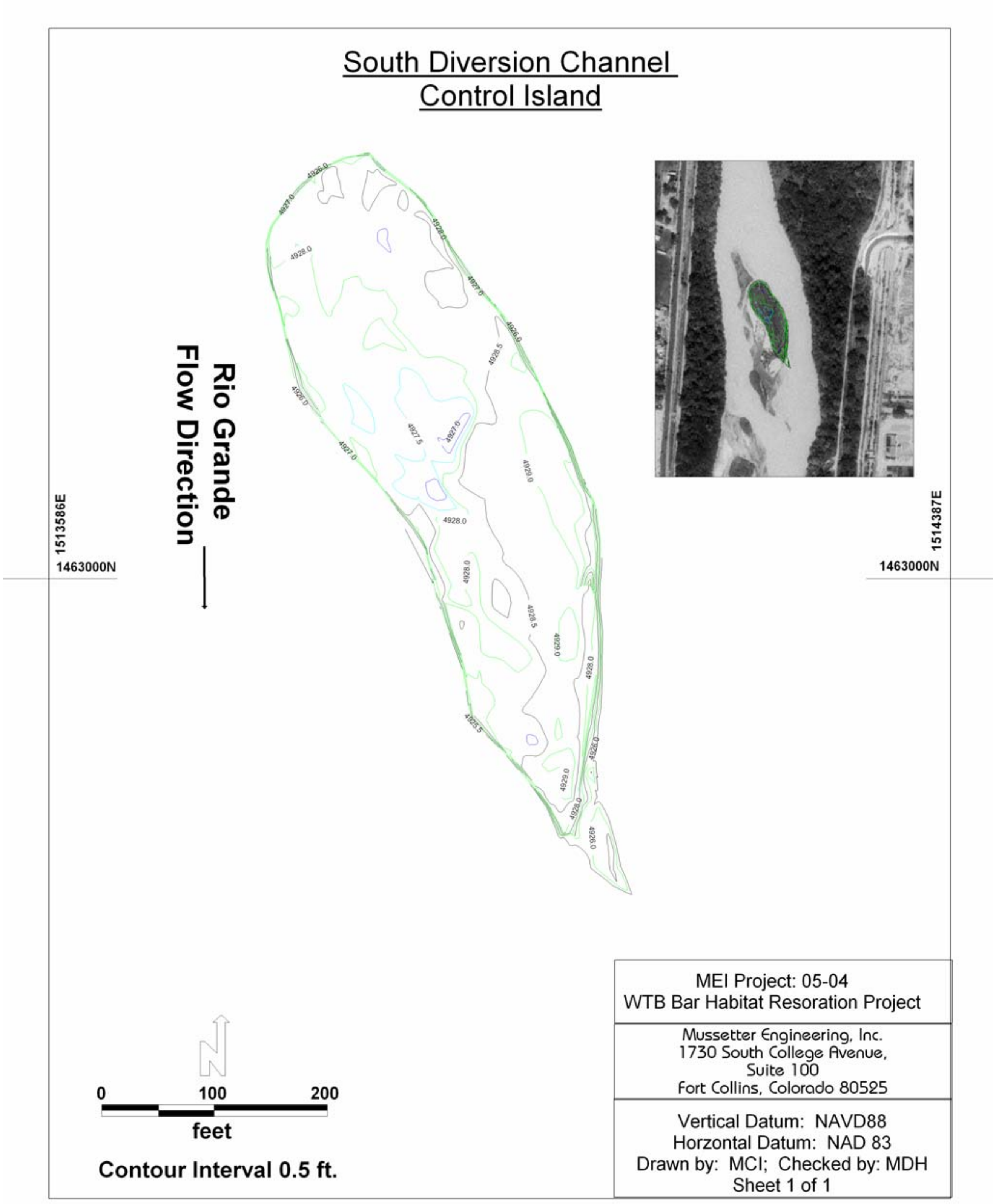


Figure 4.43. March 2005 topographic map with 0.5-foot contour interval of SDC control mid-channel bar.

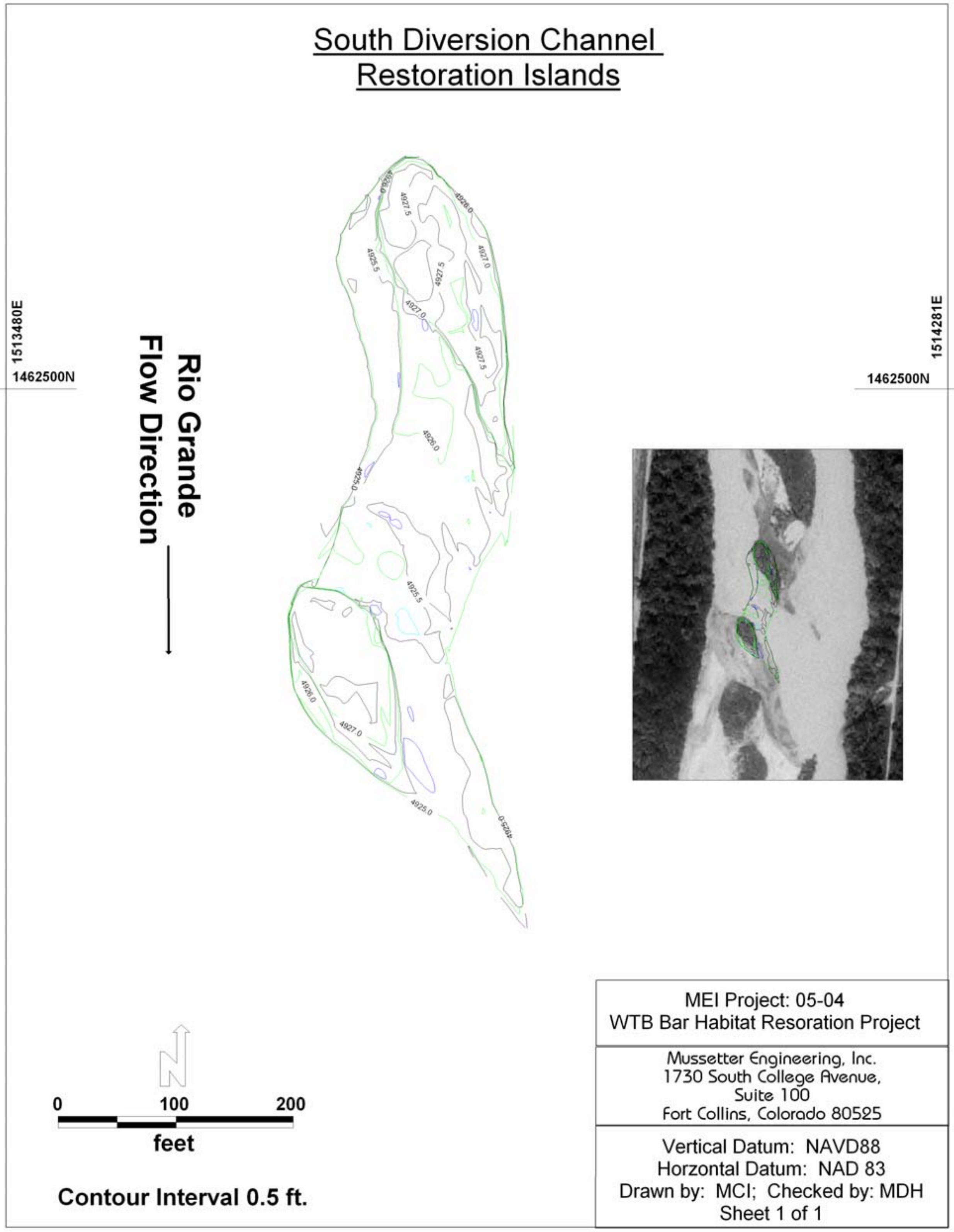


Figure 4.44. March 2005 topographic map with 0.5-foot contour interval of SDC 2 and 3 mid-channel bars.


Figure 4.45. View upstream of the Level-2 NDC control mid-channel bar.


Figure 4.46. View downstream of the NDC 2 Level-2 with attached Level-1 mid-channel bar.


Figure 4.47. View upstream of NDC 3 Level-1 mid-channel bar.

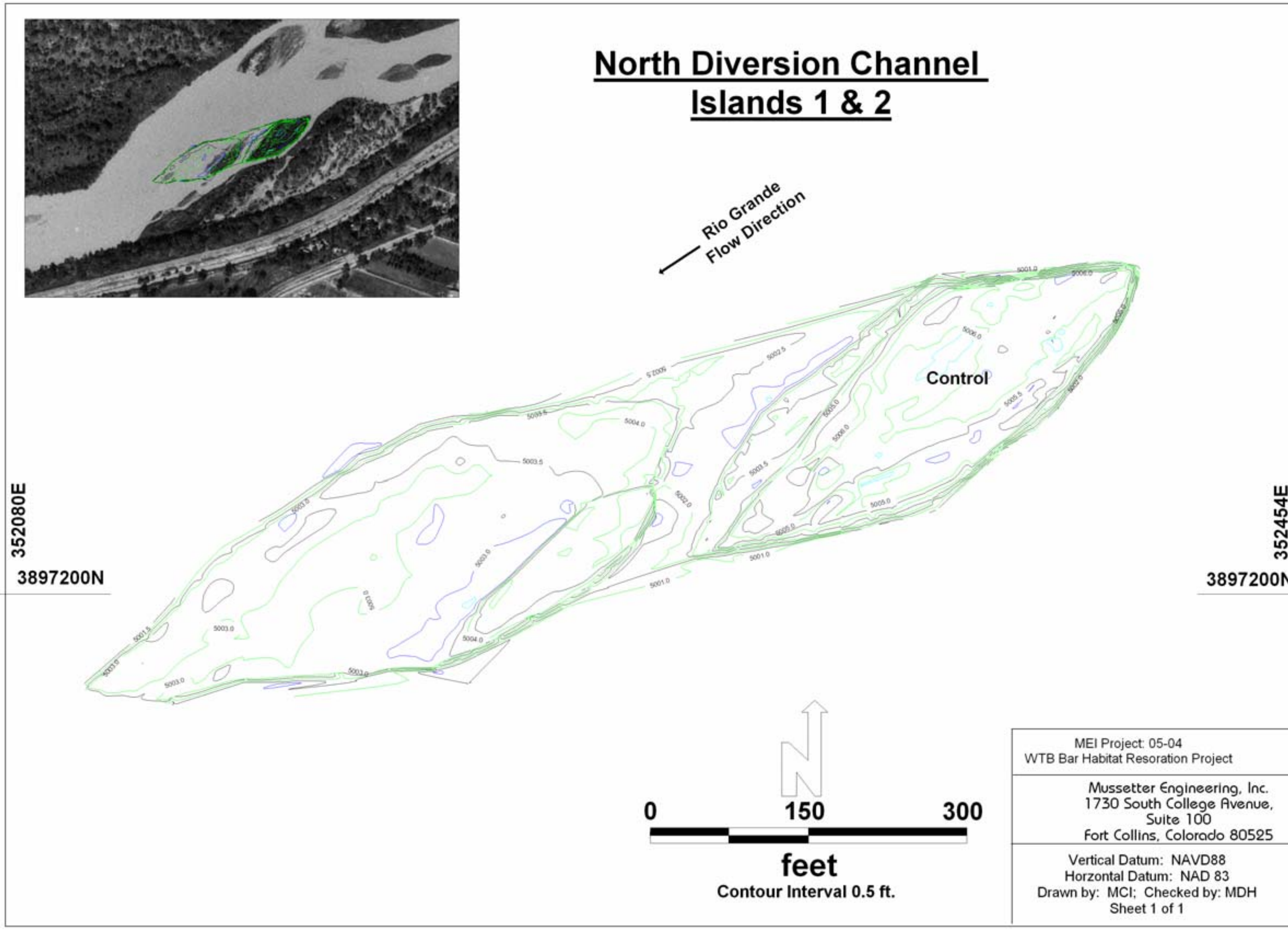


Figure 4.48. March 2005 topographic map with 0.5-foot contour interval of NDC control mid-channel bar and NDC 2 Level-2 with attached Level-1 mid-channel bar.

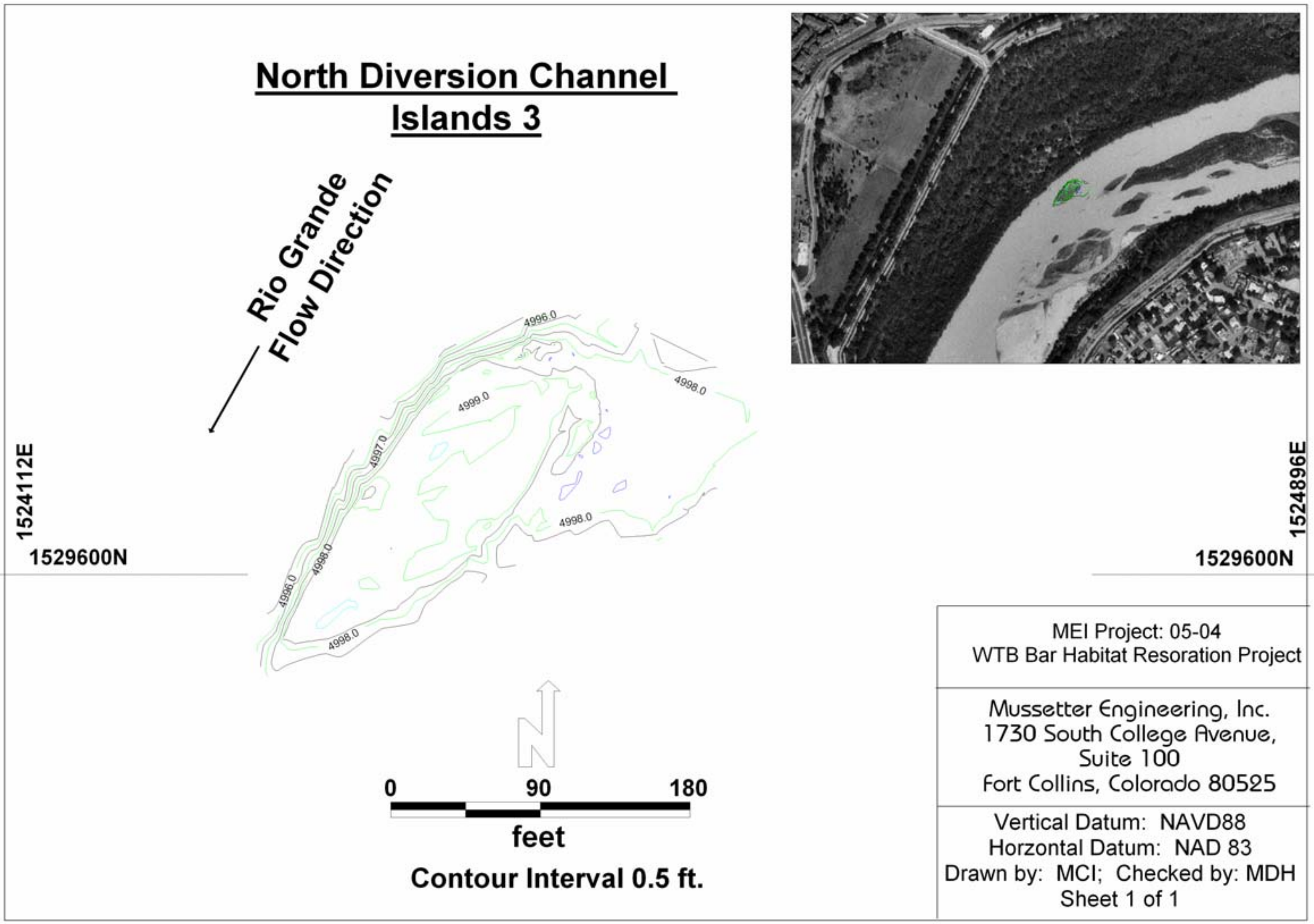


Figure 4.49. March 2005 topographic map with 0.5-foot contour interval of NDC 3 Level-1 mid-channel bar.

Color-gradient maps of the changes in elevation between the two surveys were prepared to identify areas of vertical accretion or lateral erosion of the bars. Because only a small portion of the Level-2 SDC control mid-channel bar was inundated, there was little change to the bar. Four to six feet of bed scour at the head of the bar indicates how erosion resistant the root-reinforced materials are (**Figure 4.50**). At the SDC 2 bar, little change occurred on the Level-2 portion of the bar, but up to 1.5 feet of vertical accretion occurred on the vegetated Level-1 bar surface (**Figure 4.51**). Up to 2 feet of vertical accretion occurred on the Level-1 vegetated bar surface at SDC 3 mid-channel bar (**Figure 4.52**). Similar patterns of deposition were observed at the NDC bars. On the NDC control bar, there was little or no vertical accretion on the Level-2 surface, but up to 1.5 feet of vertical accretion on the Level-1 attached surface (**Figure 4.53**). Up to 2 feet of vertical accretion occurred on the Level-1 surface at NDC bar 2 (Figure 4.53). Almost the entire surface of the Level-1 NDC bar 3 experienced vertical accretion, with up to 3 feet occurring on the west side of the bar (**Figure 4.54**). The 2 to 4 feet of scour along the east side of the bar was due to channel avulsion during the flow event. **Figure 4.55** shows typical sand deposition on the Level-1 mid-channel bar on the west side of the NDC control bar.

Based on the results of the comparative surveys it appears that on average the vegetated Level-1 mid-channel bars in the Albuquerque reach experienced about 1.5 feet of vertical accretion during the 2005 runoff event. The degree of vertical accretion has significant implications with respect to the magnitude and frequency of future inundation. On average, an increase in elevation of 1.5 feet on a Level-1 mid-channel bar surface will increase the magnitude of the flow required to inundate the bar from about 1,500 to 4,000 cfs and would reduce the average annual duration of inundation from about 20 to 4 days.

The deposition that occurred during the 2005 runoff period is very consistent with the evidence of vertical accretion seen in the bar stratigraphy at all of the sites (Appendix C). As indicated in Section 3.1, there is a vertical accretion sequence that links the bar types identified in the bar classification (Table 3.1). **Figure 4.56**, which was developed from bar stratigraphic sections at the San Marcial and Bosque del Apache sites, shows the vertical accretion sequences that occur as bars develop from the Level-1 braid bars or Alternate bars to the Level-2 mid-channel or bank-attached bars. Level-1 braid or alternate bars are composed primarily of sands that are transported and deposited in linguoid bars, and that are subaerially exposed and sculpted during recessional flows (Komar, 1983; Germanoski, 1989). Stabilization of the sand bar surface by mud drapes deposited during summer thunderstorm-generated, high suspended sediment concentration, tributary events (MEI, 2004) and overlying sand deposition leads to the development of a Level-2 braid bar. Further deposition of both mud drapes and sand leads to the formation of a Level-1 mid-channel or bank-attached bar. Field observations suggest that the presence of the mud drapes is important to establishment of the perennial vegetation since the drapes tend to provide perched water tables in the bars that permit the plants to establish their roots and tap the summer low flows without being desiccated. Once perennial vegetation becomes established the hydraulic roughness on the bar surface is increased and this induces further sand deposition, as was observed following the 2005 runoff event. Eventually, the vertical accretion produces a Level-2 bar, that is inundated less frequently, and the rate of vertical accretion slows, unless the channel as a whole is experiencing net aggradation (Wolman and Leopold, 1957).

#### 4.4.4. Vegetation Effects on Bar Stability

Shear stresses were also computed to determine whether flows were capable of removing vegetation from the vegetated bar types. Review of the bioengineering literature (Schiechtl and Stern, 1994; Gray and Leiser 1989; NRCS, 1998; Allen and Fischenich, 2001; Sotir and Fischenich, 2003) suggests that plant materials on their own (i.e. without structural support) can

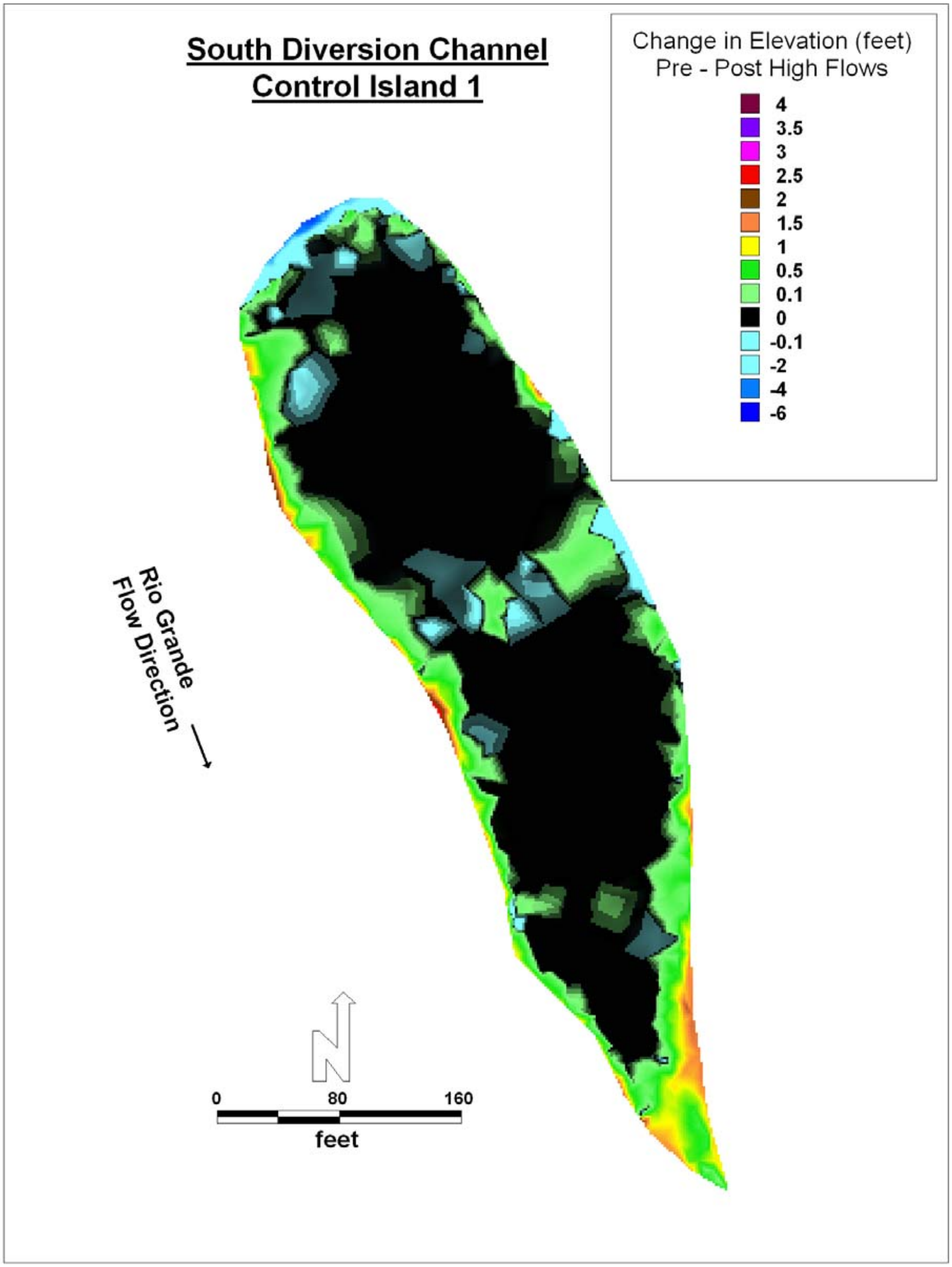


Figure 4.50. Color gradient map of elevation changes between March and September 2005 surveys at SDC control mid-channel bar.

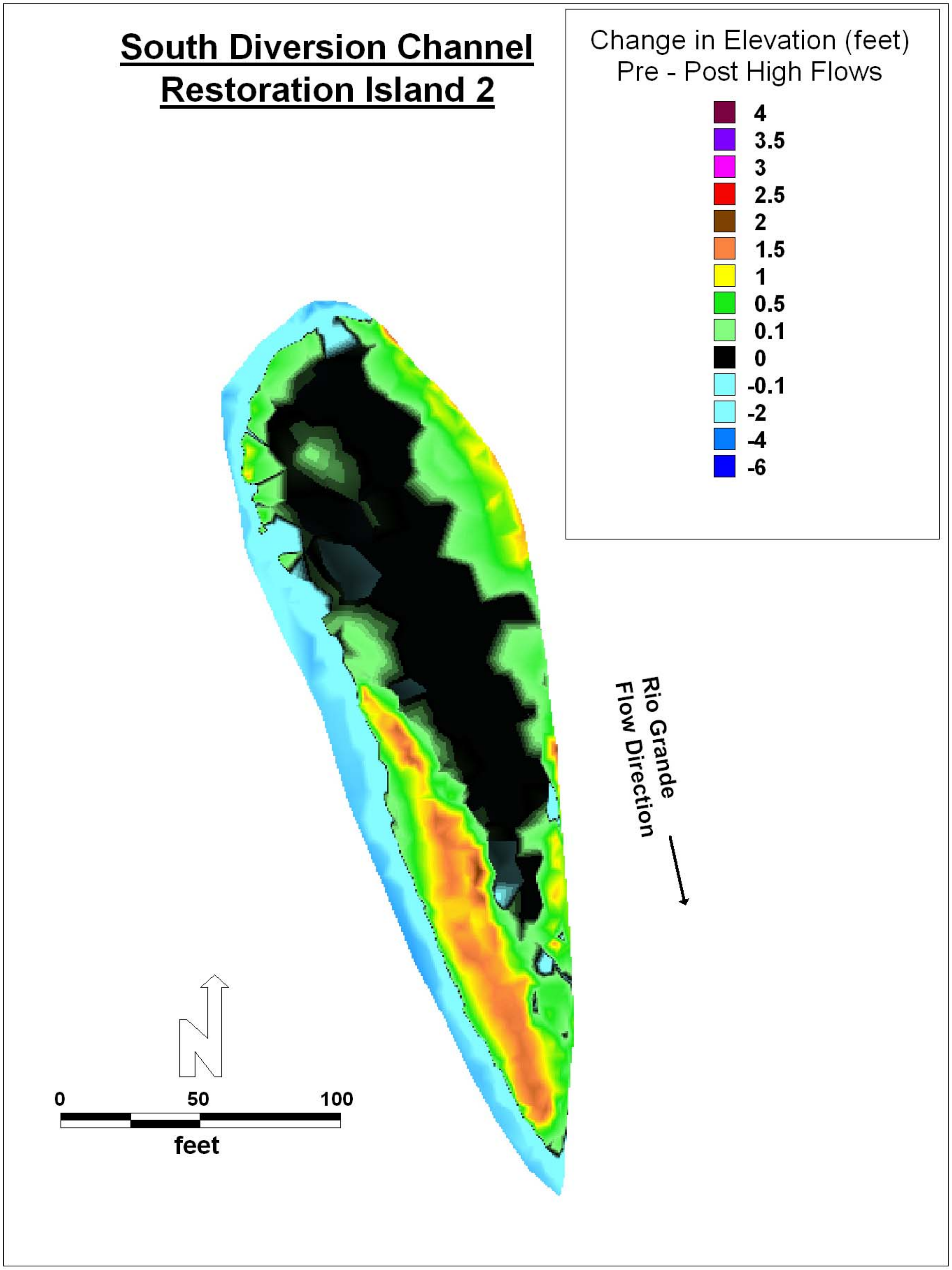


Figure 4.51. Color gradient map of elevation changes between March and September 2005 surveys at SDC 2 mid-channel bar.

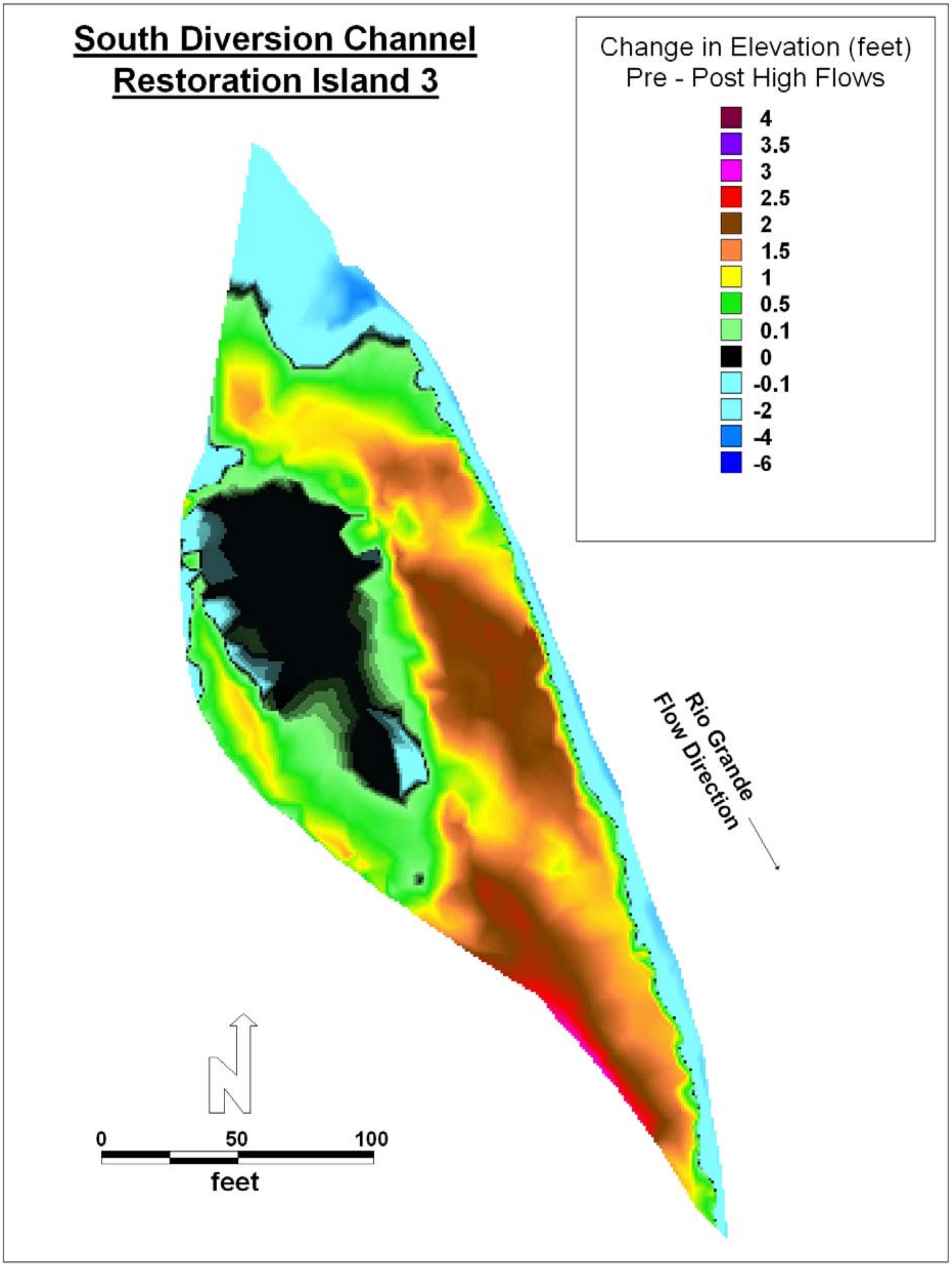


Figure 4.52. Color gradient map of elevation changes between March and September 2005 surveys at SDC 3 mid-channel bar.

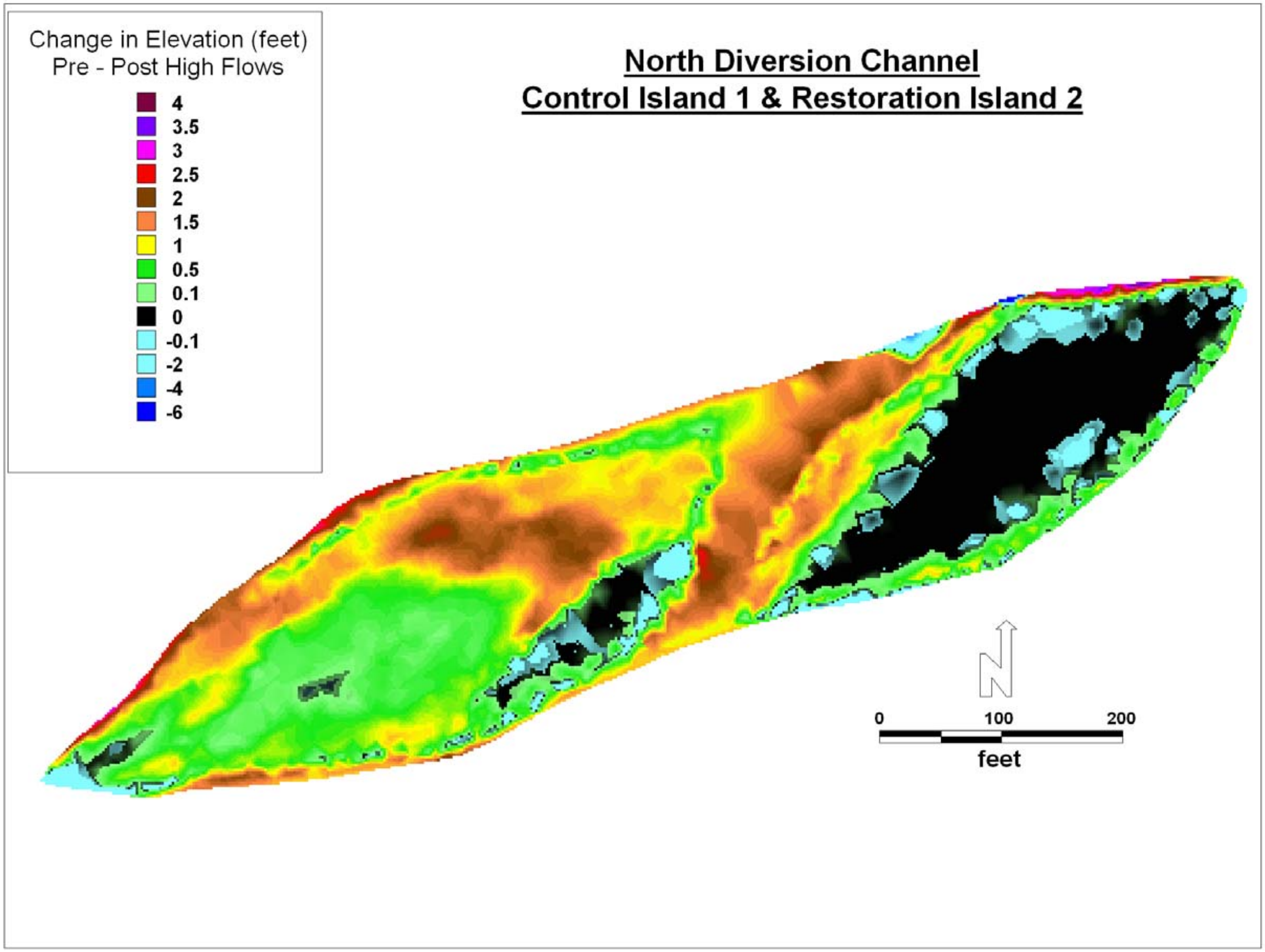


Figure 4.53. Color gradient map of elevation changes between March and September 2005 surveys at NDC control and NDC 2 mid-channel bars.

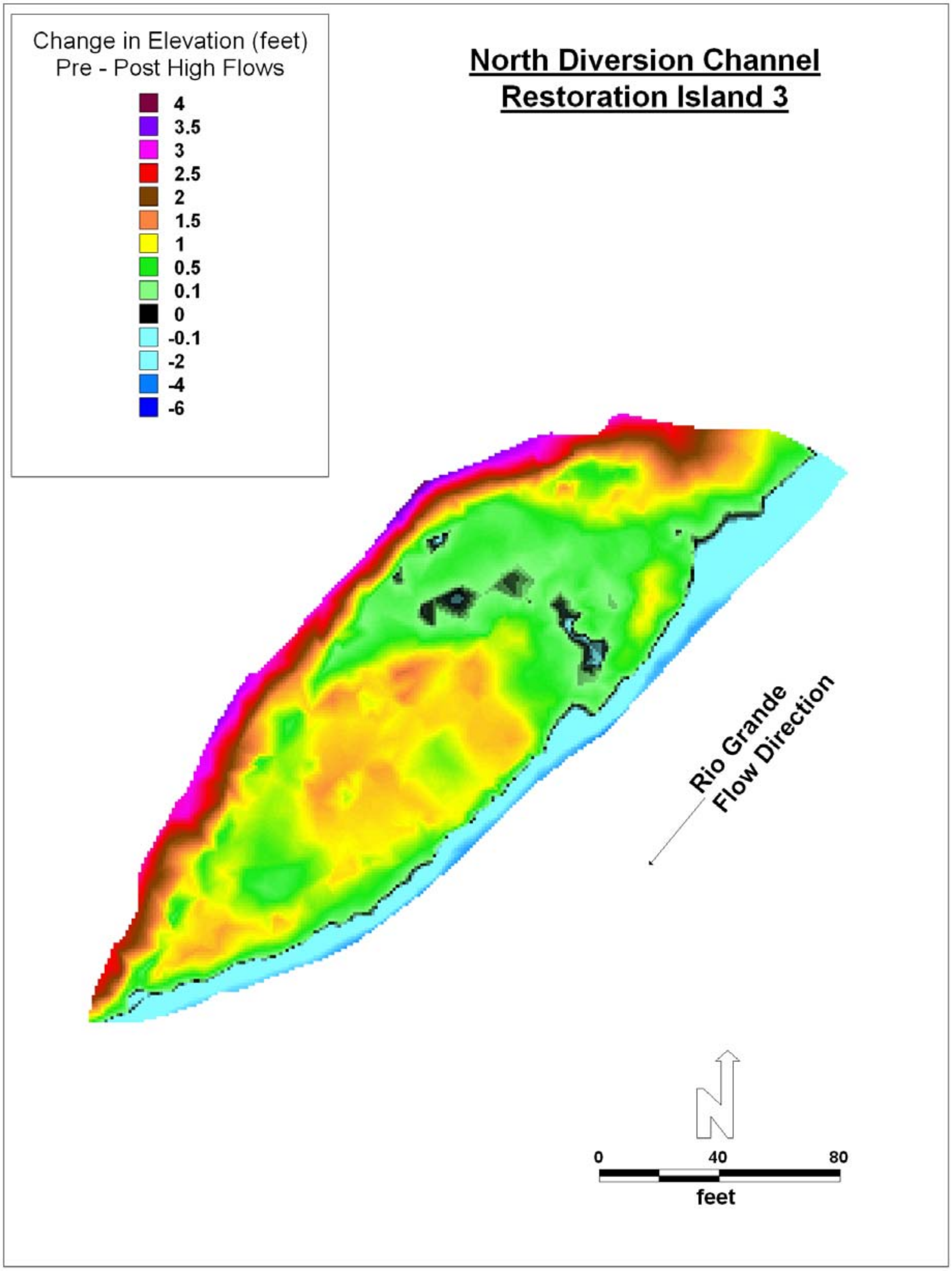


Figure 4.54. Color gradient map of elevation changes between March and September 2005 surveys at NDC 3 mid-channel bar.


Figure 4.55. View upstream of typical sand deposition on Level-1 mid-channel bar resulting from the 2005 runoff.

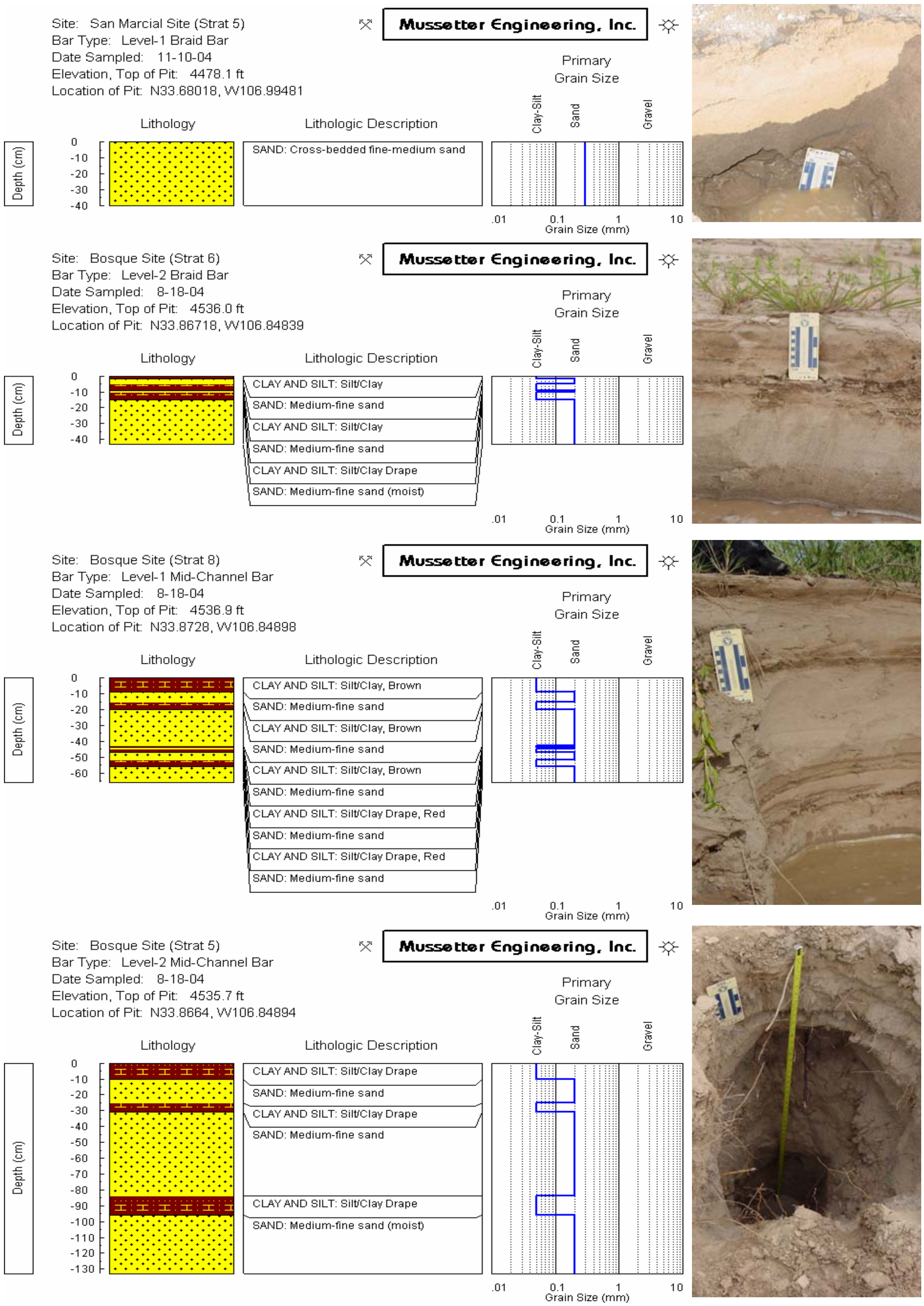


Figure 4.56. Arranged stratigraphic sections that show the evolution of a braid bar to a Level-2 bar.

be used to provide erosion protection initially where sheer stresses reach a maximum of about 1 $lb/ft^2$. Once the plants become established they can withstand shear stresses up to about 6 $lb/ft^2$. Smith (1976) demonstrated that up to about 16 percent of roots by volume increased the erosion resistance of alluvial sediments by a factor of about 600. Gray (1974) showed that root presence increases the effective cohesion of essentially cohesionless alluvial sediments by a factor of 2 to 3, and MEI (1996), on the basis of field shear box measurements, showed that up to 1 percent roots by volume increased the shear strength of alluvial soils by factors of between 30 and 300 percent depending on the depths of the roots.

Mean shear stress was calculated for flows with recurrence intervals of 1.5, 2, 5 and 10 years for each of the bar types present at all of the sites to evaluate the potential for hydraulic removal of the established vegetation on the bars. At the Pena Blanca site (**Figure 4.57**), the highest shear stress on the Level-1 mid-channel bar occurs at the 10-year event, but is only about 0.3 $lb/ft^2$, which is significantly less than 1 $lb/ft^2$ threshold value for newly planted vegetation identified from the bioengineering literature. On the Level-2 bar surfaces, shear stress values are less than 0.2 $lb/ft^2$ which is also significantly less than the 6 $lb/ft^2$ threshold value identified for mature vegetation in the bioengineering literature. Therefore, it is highly unlikely that flows up to the 10-year peak will be capable of removing the vegetation on either the Level-1 or Level-2 bars. At the Bernalillo (**Figure 4.58**), Central Avenue (**Figure 4.59**), Lemitar (**Figure 4.60**), and Bosque del Apache (**Figure 4.61**) sites, the maximum shear stresses on the Level-1 and Level-2 bars are less than 0.1 $lb/ft^2$. At the Belen (**Figure 4.62**), Bernardo (**Figure 4.63**), La Joya (**Figure 4.64**) and San Marcial (**Figure 4.65**) sites, the maximum shear stresses on the Level-1 and Level-2 bars are less than 0.2 $lb/ft^2$. Therefore, it is highly unlikely that either the more recent vegetation on the Level-1 bars, or the more established vegetation on the Level-2 bars will be removed by flows alone, and that vegetation removal will require some form of mechanical intervention.

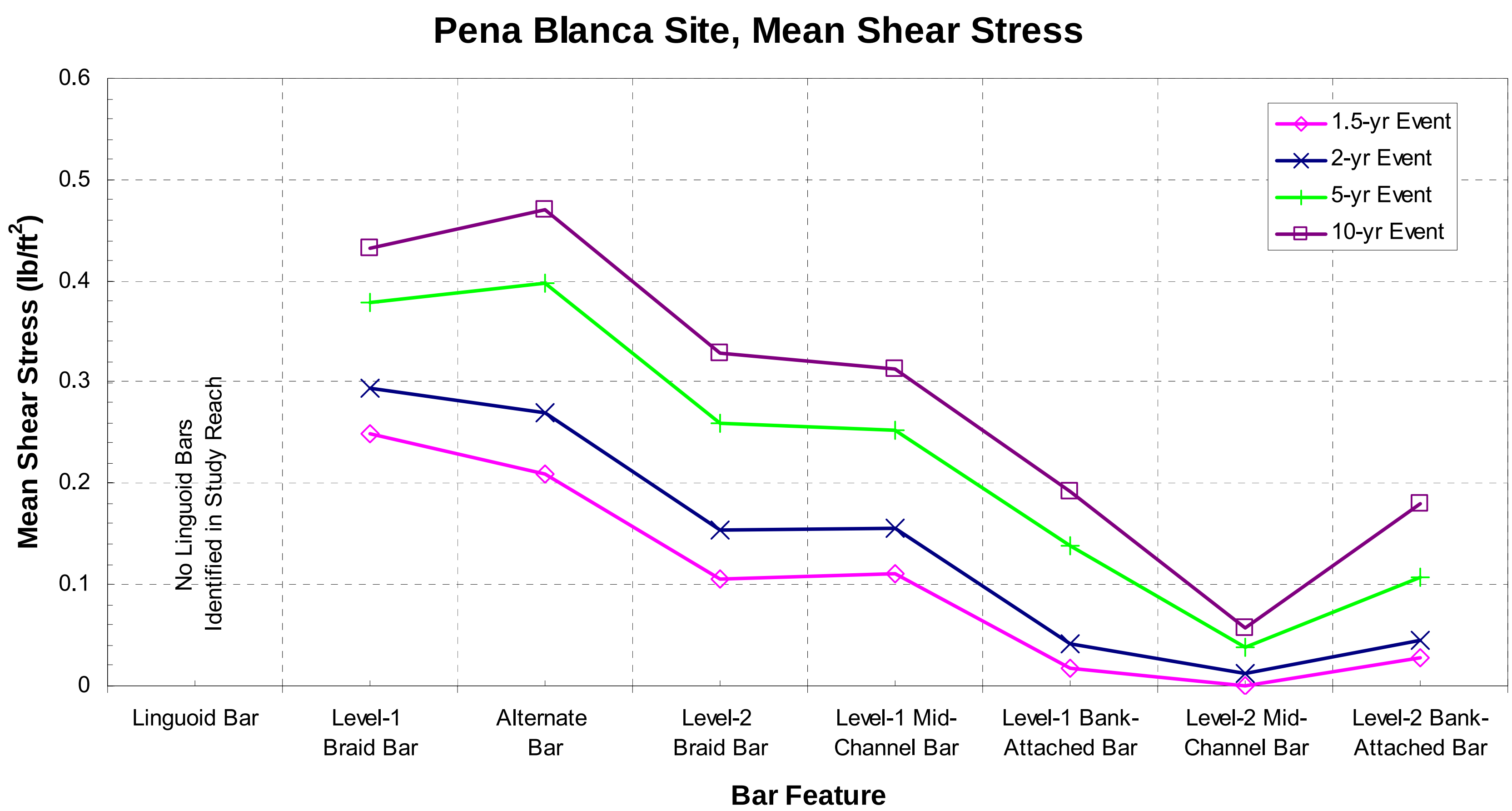


Figure 4.57. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Pena Blanca site.

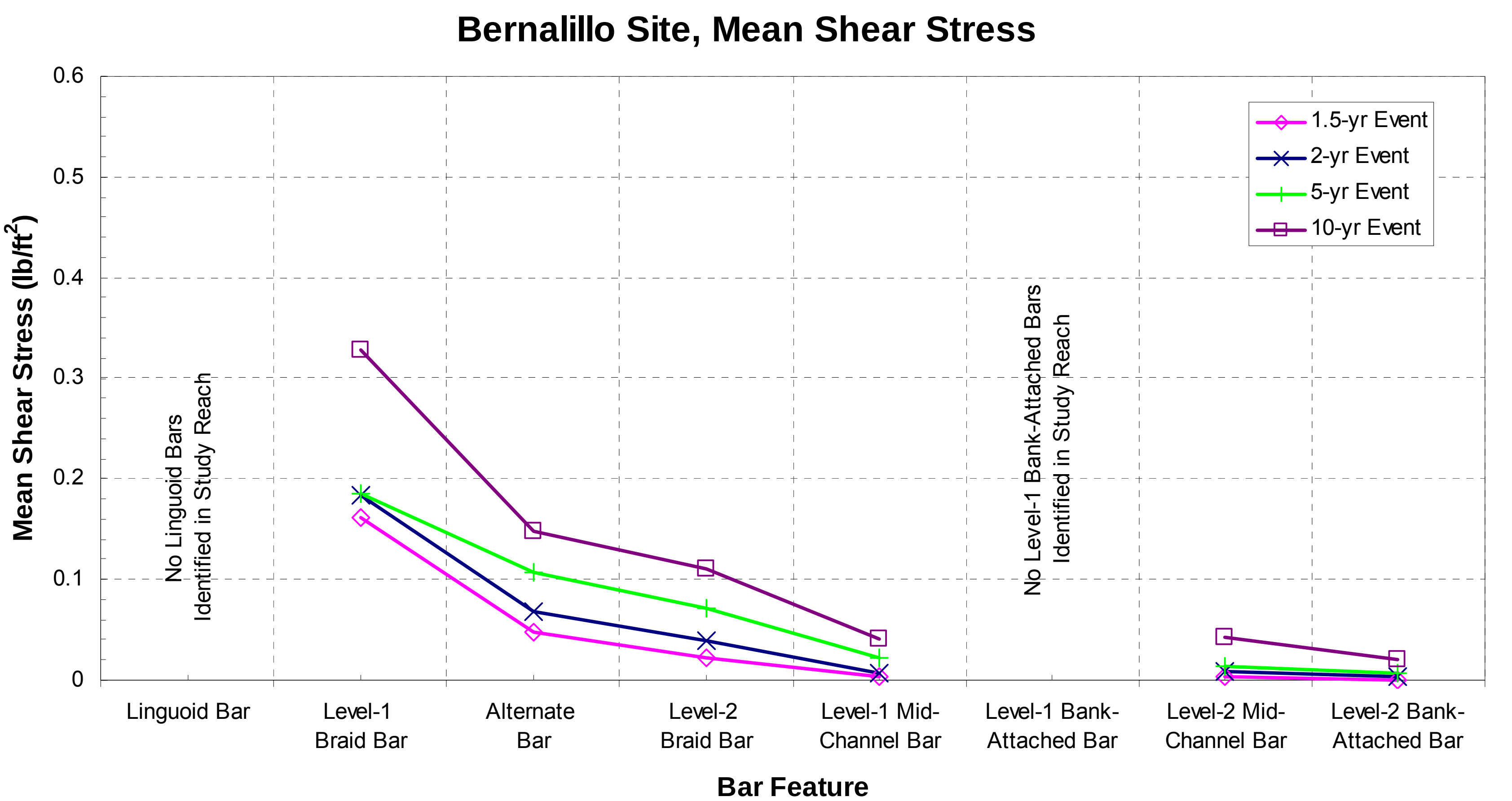


Figure 4.58. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Bernalillo site.

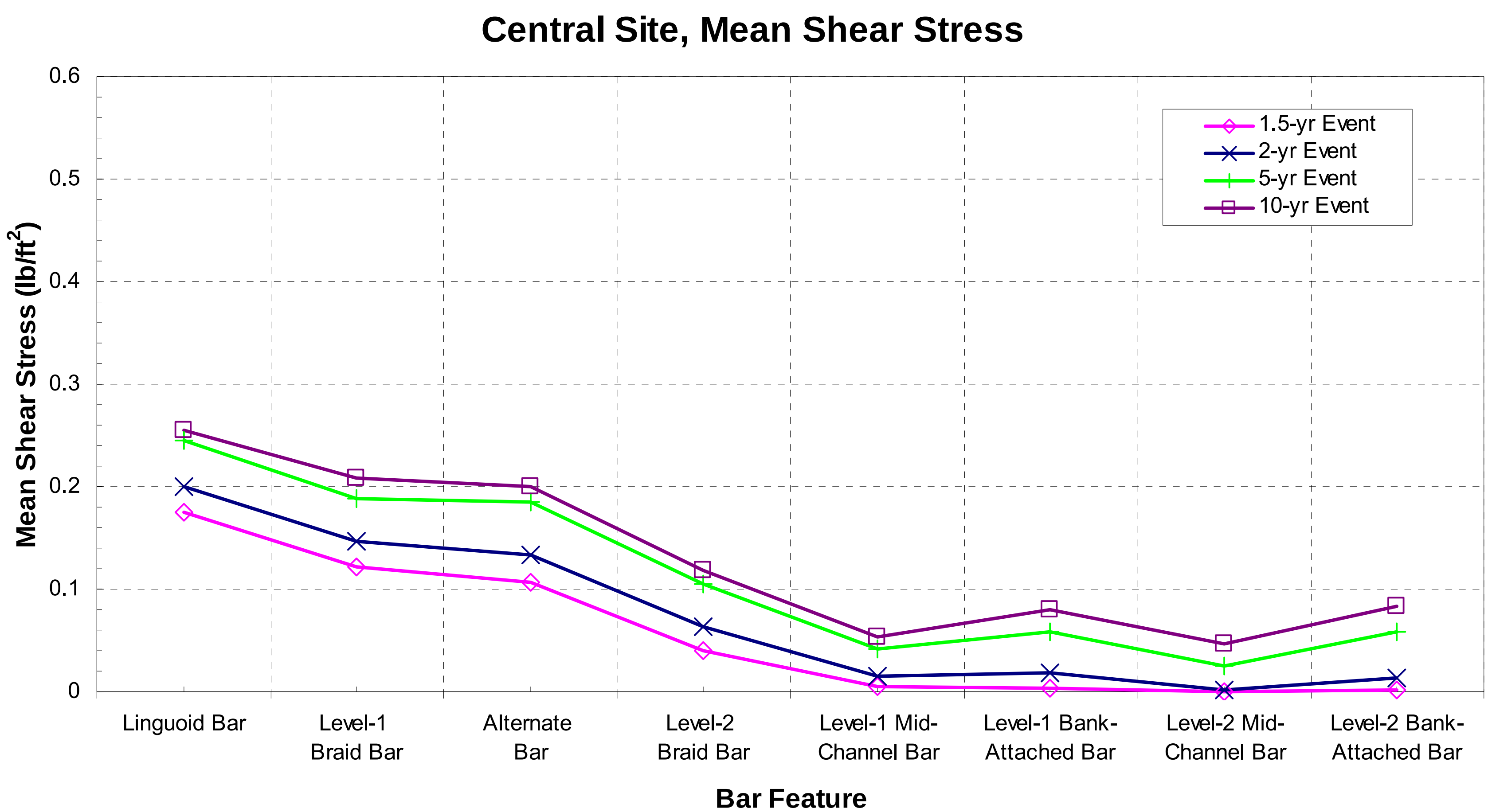


Figure 4.59. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Central Avenue site.

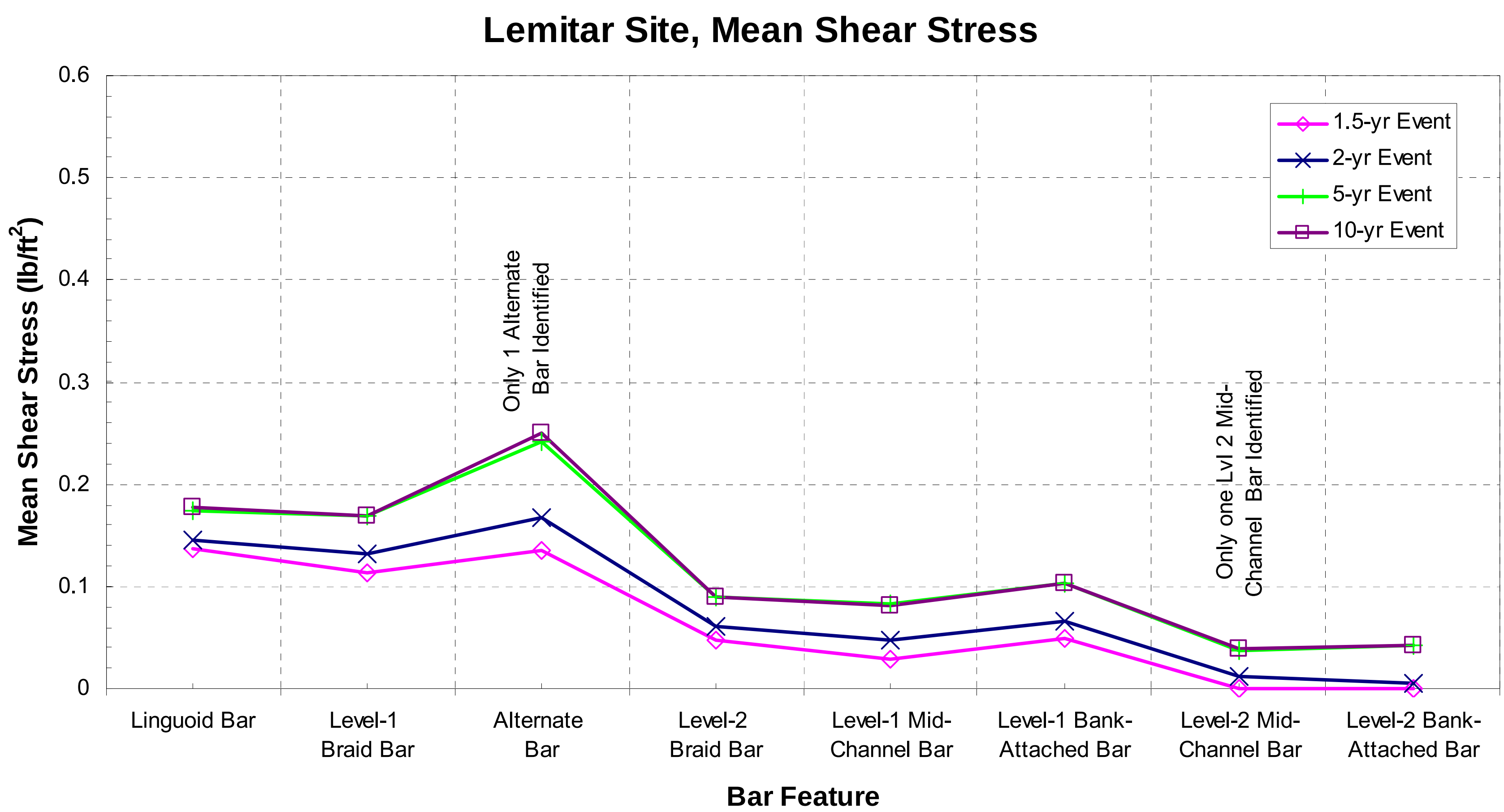


Figure 4.60. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Lemitar site.

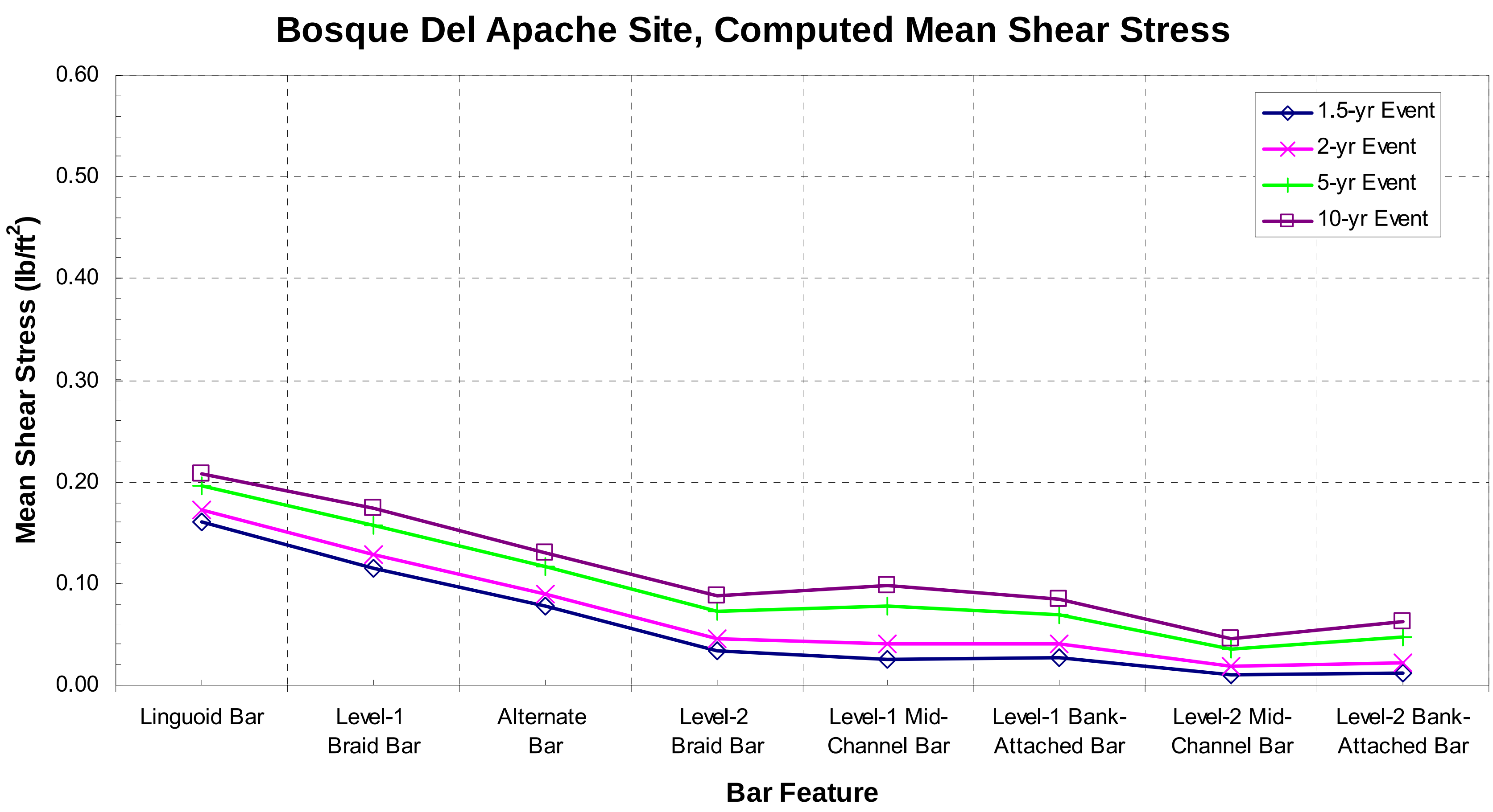


Figure 4.61. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Bosque del Apache site.

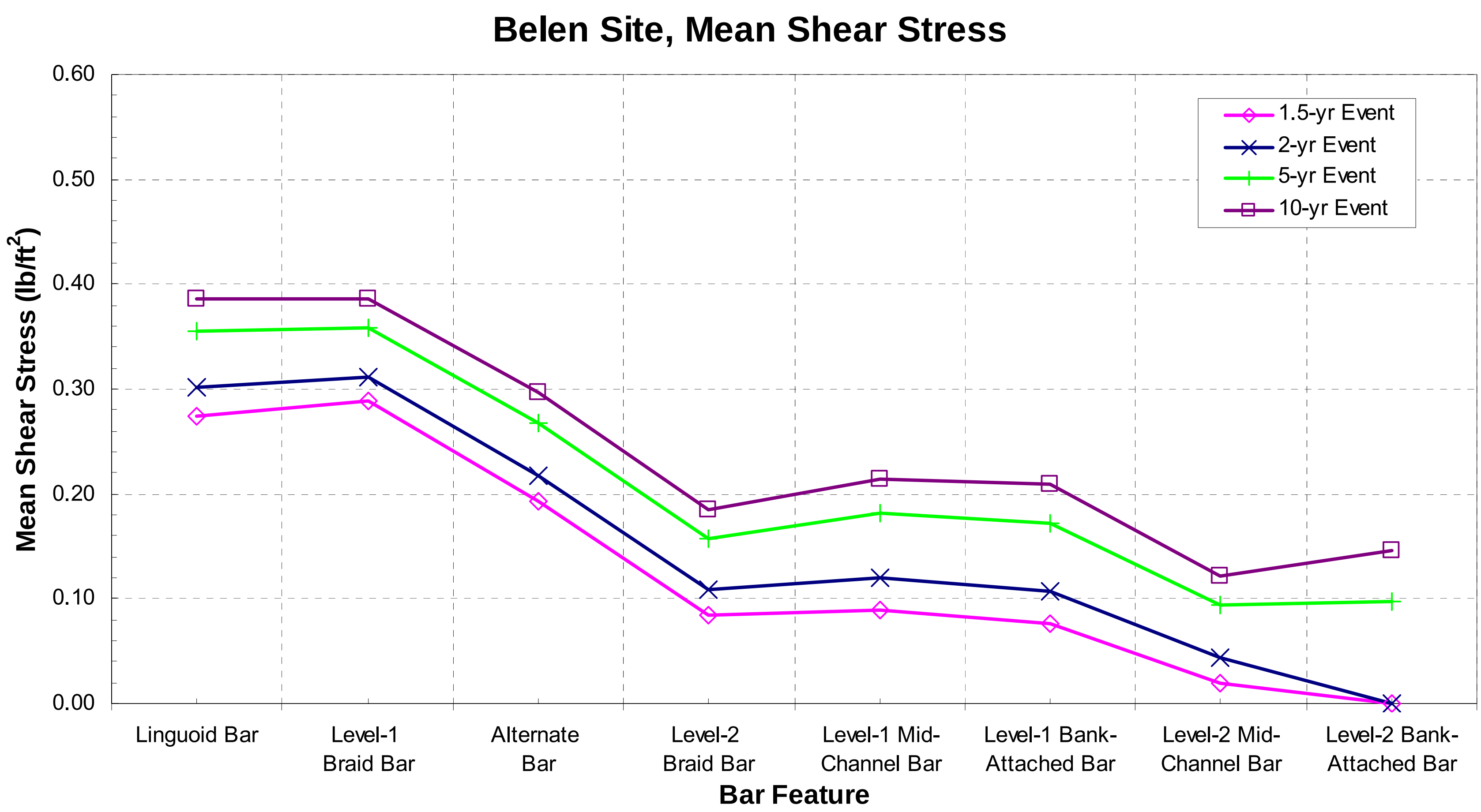


Figure 4.62. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Belen site.

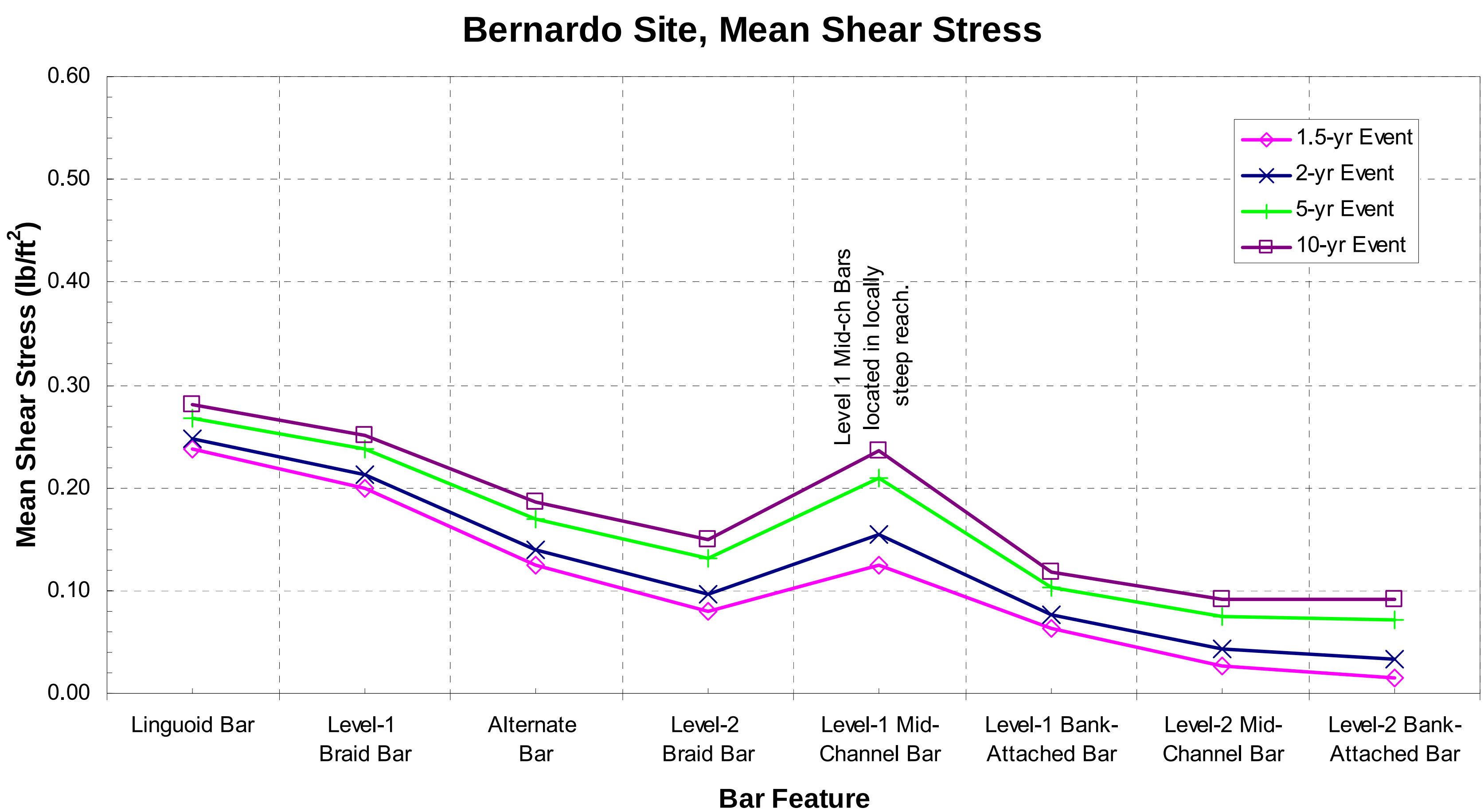


Figure 4.63. Shear stress values for the indicated recurrence interval flows for the various types of bars at the Bernardo site.

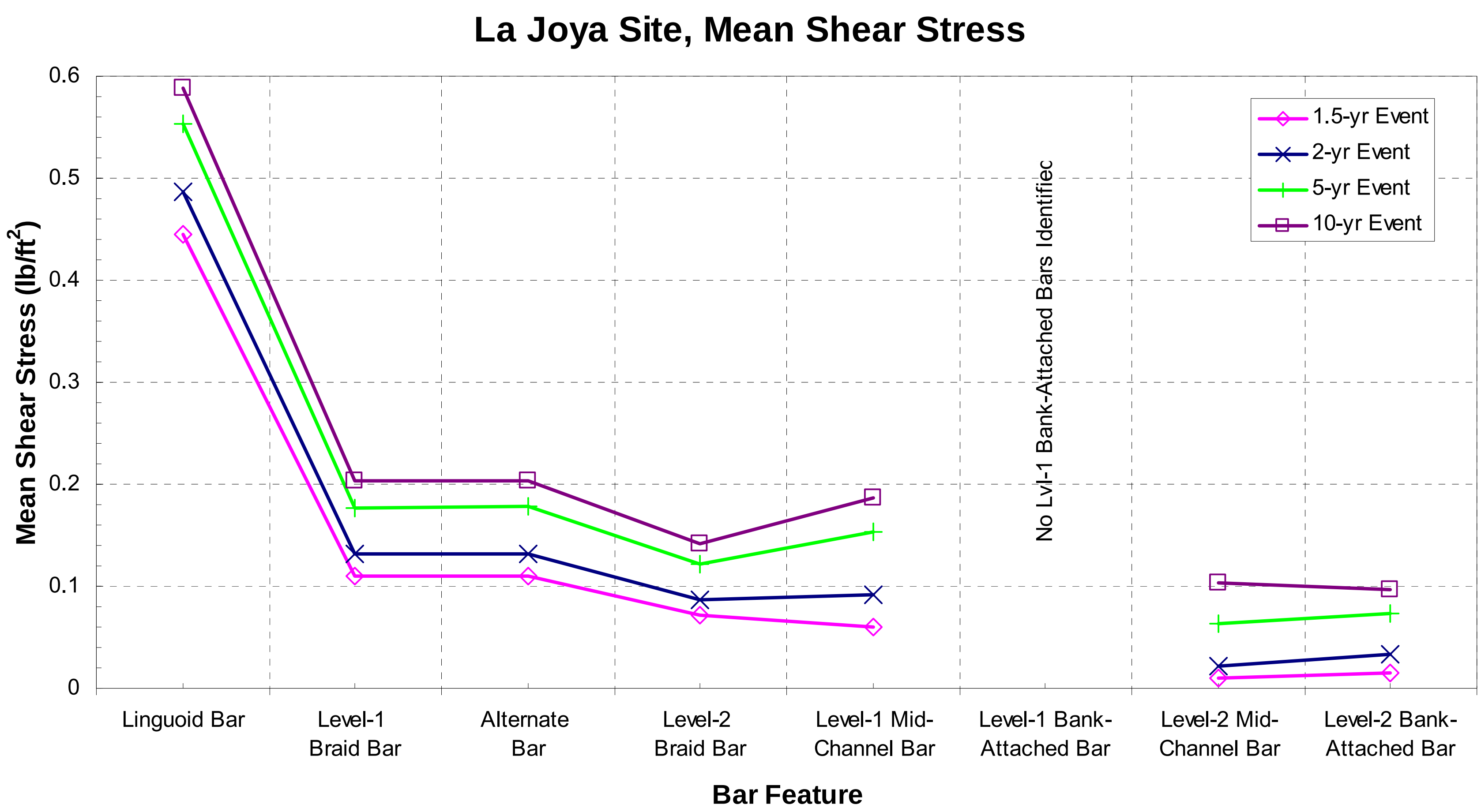


Figure 4.64. Shear stress values for the indicated recurrence interval flows for the various types of bars at the La Joya site.

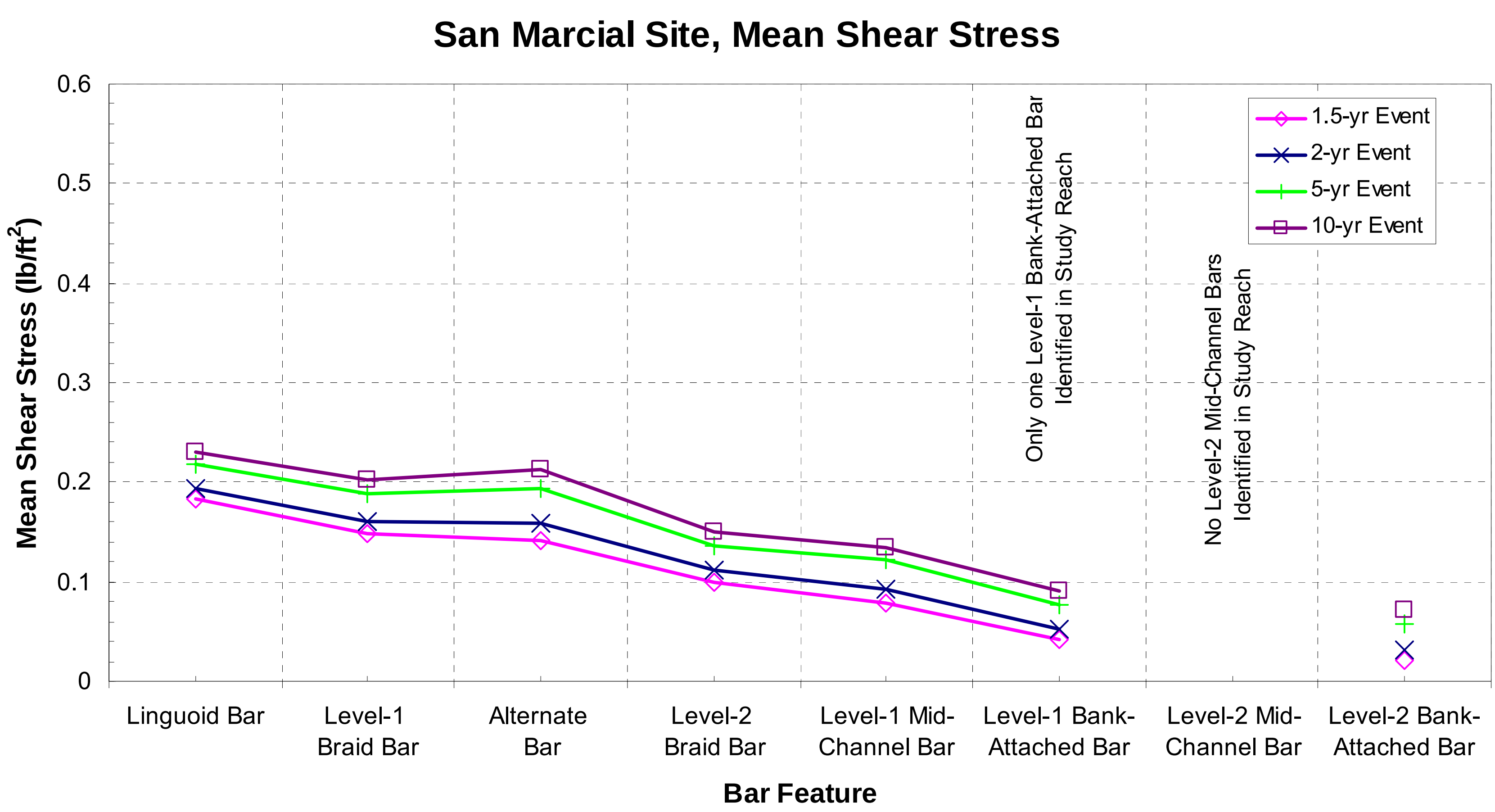


Figure 4.65. Shear stress values for the indicated recurrence interval flows for the various types of bars at the San Marcial site.

# 5. SUMMARY, CONCLUSIONS, AND APPLICATIONS

## 5.1. Summary

This investigation of the morphology and dynamics of bars at 10 locations that are representative of geomorphologic conditions in the Middle Rio Grande between Cochiti Dam and San Marcial (MEI, 2002) is predicated on the fact that changes in bar forms and numbers can be related to changes in fluvial processes in an alluvial river (Brice, 1964; Maizels, 1979; Germanoski, 1989; Germanoski and Schumm, 1993; Germanoski and Harvey, 1993). Bar form and numbers can be represented by an index of braiding intensity (MBI)(Brice, 1964; Germanoski, 1989). Morphometric changes to the channel resulting from changes in discharge, sediment supply and sediment gradation should be reflected in the MBI values as follows:

1. If the bed material coarsens, provided there is still a supply of sediment, the MBI values will increase because gravel-bed channels are more intensely braided than sand-bed channels because of reduced rates of migration of linguoid bars in the gravel-bed channels,

2. If aggradation has occurred, the MBI will be higher because there should be an increase in the number of braid bars, in both sand-bed and gravel-bed subreaches, and

3. If degradation has occurred, the MBI will be lower because there should be a reduction in the number of braid bars, and increases in the size of the individual braid bars, especially in gravel-bed reaches.

The investigation addressed bar changes through time and space in response to man-induced and climatic changes in the watershed hydrology, sediment supply to the river and channel morphology. Morphologic changes through time were evaluated with time-sequential aerial photography that spanned the period from 1935 to 2002. Changes in channel width and elevation were evaluated with ground-based and photogrammetrically-based surveys primarily conducted by the BOR between 1917/18 and 2002. Hydrologic changes were evaluated with the annual peak flow and mean daily flow records from the USGS gages that are located between Cochiti Dam and San Marcial. Changes in sediment gradations were determined from USGS and BOR sampling over time, and changes in sediment transport were determined from the bed-material and suspended sediment-transport measurements at the USGS gages. The morphological, hydrologic, and sedimentologic changes at each of the 10 sites are summarized in Table 2.5.

The 10 representative sites selected for evaluation and analysis are located at: Pena Blanca (RM 227.5), Bernalillo (RM 203.6), Central Avenue (RM 183.1), Belen (RM 149.6), Bernardo (RM 130.9), La Joya (RM 124.4), Lemitar (RM 107.5), Escondida (RM 104.5), Bosque del Apache (RM 84.1) and San Marcial (RM 67.9) (Figure 1.1). The general characteristics of the sites are summarized in Table 2.1.

The objectives of the study were to:

1. Summarize the morphological, hydrological and sedimentological changes that have occurred in the 10 representative reaches of the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir over the last approximately 85 years,

2. Determine whether the effects of the morphologic, hydrologic, and sedimentologic changes could be quantified and predicted through changes in the number and types of bars in the river as determined by analysis of time-sequential aerial photography and resulting morphometric bar indices, and

3. Conduct site-specific field surveys at the 10 sites to develop a field-based classification for the bar types identified in the river and on the channel margins and to relate the various bar types to the flow magnitudes, frequencies, durations and shear stresses, thereby developing a set of design criteria for habitat restoration purposes.

A hierarchical bar classification was developed from field observations and measurements that was based on the location (mid-channel or bank-attached), height (Levels-1, -2), subaqueous or subaerial exposure, and vegetative status of the bars (Table 3.1). In general, Level-1 braid bars are formed from linguoid bars (Figure 3.1) during recessional flows (Figure 3.2). They are vertically accreted by additional sand deposition to form higher elevation Level-2 braid bars (Figure 3.3), especially if mud drapes are deposited on the Level-1 bars (Figures 3.4 and 3.5). Further vertical accretion of both sand and/or gravel, generally accompanied by a number of mud drapes that appear to enhance the establishment of perennial vegetation, leads to the development of a Level-1 mid-channel bar (Figure 3.6). Further deposition of sediment, assisted by the high hydraulic roughness created by the perennial vegetation (mainly sandbar/coyote willows, salt cedar, cottonwoods and Russian olives), leads to the formation of a Level-2 mid-channel bar (Figures 3.7 and 3.8). A similar sequence of events characterizes the bank-attached bars. Low elevation alternate bars form along the margins of the channel (Figure 3.9), and with time they are accreted vertically to form vegetated Level-1 bank-attached bars (Figure 3.10). Further vertical accretion leads to the development of the Level-2 bank-attached bar (Figure 3.11) that has very similar internal sedimentary architecture to the Level-2 mid-channel bars. Both the Level-2 mid-channel bars and the bank-attached bars are colonized with tree-like vegetation species (e.g., willows, cottonwoods, Russian olives, salt cedar). The ultimate height of the bars is governed by the height of the channel banks. If the channel is confined by terraces, then it is theoretically possible to have bar heights as high as the terraces, provided that flows of sufficient magnitude occur. Channel degradation is likely to cause bar heights to increase as a result of bed lowering, but the frequency of bar overtopping and, therefore, vertical accretion will be reduced as well (Figure 3.12). On the other hand, if the channel is aggrading the height of the bars will keep pace with the increase in elevation of the banks resulting from the increased frequency of overbank flows.

## 5.2. Conclusions

Based on the results of the analyses presented in Chapters 3 and 4, the following can be concluded from this investigation:

1. Channel narrowing and degradation as well as coarsening of the bed material have resulted in a reduction in the braiding intensity and number of bars in the Pena Blanca and Bernalillo reaches.

2. With the exception of the San Marcial site that has a long history of aggradation, within the sand-bed reaches, channel narrowing as a result of construction of the floodway and establishment of primarily non-native vegetation species has also resulted in a reduction in the braiding intensity and number of bars over time, but there is currently sufficient sediment being transported in the river to maintain a low-water braided planform at all of the sites except Escondida where the channel is too confined and the shear stresses are too high to permit sediment deposition and bar formation.

3. Where there has been a history of aggradation of the channel at the Bernardo, Bosque del Apache and San Marcial sites, braiding intensity and the number of bars have increased over time.

4. With the exclusion of the Pena Blanca and Bernalillo sites that have significantly degraded and coarsened and the San Marcial site that has significantly aggraded, the magnitudes, frequencies and durations of flows that inundate the various bar types are similar among the sites. However, because of site specific conditions, values can vary quite significantly at any given location.

5. Level-1 braid bars, Alternate bars and Level-2 braid bars are inundated on average by flows with recurrence intervals of less than 1 year, and are inundated on average for between 146 and 290 days/year.

6. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average by flows with a recurrence interval of about 1.5 years, and are inundated on average for about 90 days/year

7. Level-2 mid-channel and Level-2 bank-attached bars are inundated on average by flows with recurrence intervals of about 2 years, and are inundated on average for about 36 days/year.

8. Incipient motion analyses indicate that the bed sediments at the Pena Blanca and Bernalillo sites are armored, and it is unlikely that further bed degradation will occur in the future.

9. Increased sediment supply from the Rio Jemez to the Bernalillo site is likely to result in an increase in the number of bars and braiding intensity since the shear stresses at this site have been reduced by degradation.

10. In the sand- bed reaches, active/mobile bar numbers are highest when the maximum bed shear stress at the channel capacity discharge is about 0.1 $lb/ft^2$. Active bars are still present at maximum shear stresses up to about 0.2 $lb/ft^2$, but at maximum shear stresses in excess of 0.3 $lb/ft^2$ the sediment-transport capacity is too high for sediment deposition and bar formation.

11. Relatively high magnitude and long duration runoff flows between May and June, 2005, caused significant vertical accretion of vegetated Level-1 bars in the sand-bed portion of the MRG. In the Albuquerque reach, an average 1.5 feet of sand was deposited on the Level-1 bars, and this has effectively increased the magnitude of the flows required to inundate the Level-1 bars in the future (4,000 vs 1,500 cfs) and reduced the future duration of inundation from about 20 to 4 days/year.

12. Threshold shear stress values for removal of recently established (1 $lb/ft^2$) and mature (>6 $lb/ft^2$) vegetation from Level-1 and Level-2 bars, respectively, are not developed or exceeded at any of the sites by the maximum in-channel capacity flows, and therefore, it is highly unlikely that flows alone will ever be able to remove, or significantly modify, vegetated bars. Therefore, mechanical intervention is likely to be required in any habitat restoration projects.

## 5.3. Application to Restoration of Physical Habitat in the MRG

The findings of this study of 10 sites, that encompass the range of geomorphic variability in the MRG between Cochiti Dam and San Marcial, provide information that can be of value to future physical habitat restoration projects in the MRG, as follows:

1. The bar classification developed from field observations and measurements at the 10 sites provides a common tool for classifying both in-channel and channel-margin bars within the MRG, thereby improving communication among the range of disciplines involved in the restoration process.

2. In the absence of site-specific surveys or hydraulic modeling, the bar classification provides a first-cut determination of the magnitude and frequency of flows that will inundate the various bar types, thereby identifying the level of physical modification that would be required to meet restoration targets for both the frequency and duration of inundation.

3. At locations that are neither significantly incised nor rapidly aggrading, Level-1 braid bars, alternate bars and Level-2 braid bars are inundated on average by flows with recurrence intervals of less than 1 year. Level-1 mid-channel and Level-1 bank-attached bars are inundated on average by flows with recurrence intervals of about 1.5 years. Level-2 mid-channel and Level-2 bank-attached bars are inundated on average by flows with a recurrence interval of about 2 years. Level-2 mid-channel and Level-2 bank-attached bars are inundated on average for less than 10 percent of the time (36 days/year). Level-1 mid-channel and Level-1 bank-attached bars are inundated on average for less than 25 percent of the time (90 days/year). Level-2 braid bars are inundated on average for less than 40 percent of the time (146 days/year). Alternate bars and Level-1 braid bars are inundated on average for about 80 percent of the time (290 days/year). At any given site, there will be a range of values for any given bar type.

4. Based on the results of the MBI analyses, significant coarsening of the bed material in the gravel-bed reaches of the MRG in the future will result in a reduction of both the braiding intensity and the number of braid bars. Within the sand-bed reaches, further channel narrowing will also result in a reduction in the braiding intensity and the number of braid bars. Therefore, restoration activities should be aimed at preventing further coarsening of bed material and narrowing of the channel. Increased sand sediment supply from the Rio Jemez, as well as mechanical destabilization of heavily vegetated bank-attached bars that will promote channel widening, will increase both braiding intensity and the number of braid bars.

5. Based on the results of the incipient motion analyses of the bed material at the Pena Blanca and Bernalillo sites, it is unlikely that further bed degradation will occur at the coarser bed-material locations within the MRG. Hydrologically abandoned bar surfaces in this reach of the river can be reduced in elevation to meet specific inundation frequency and duration targets without fear of future channel degradation that would adversely affect the stage-discharge relationship.

6. In the sand-bed reaches of the MRG, active bars can be maintained at reach-averaged shear stresses at the channel capacity discharge of up to about 0.2 $lb/ft^2$. At reach-averaged shear stresses higher than 0.3 $lb/ft^2$, bars are unlikely to be present. Therefore, any channel modifications for increasing physical habitat should aim for reach-averaged shear stresses less than 0.2 $lb/ft^2$.

7. It should be recognized that any physical reductions to existing bar surfaces elevations to promote increased frequency and duration of inundation will have a limited life span. The lower the bar surface is cut, the more frequently it will be inundated and the higher will be the rate of sediment deposition and vertical accretion. For example, within the Albuquerque reach, an average of 1.5 feet of sand deposition on Level-1 bar surfaces

during the sustained high flows of 2005 reduced the future duration of inundation from 20 to 4 days per year, and will require an increase in flow magnitude from 1,500 to 4,000 cfs to achieve inundation.

8. Within the MRG shear stresses on bar surfaces rarely exceed 0.3 $lb/ft^2$. Since it requires shear stresses in excess of about 1$lb/ft^2$ to prevent colonization of bars by vegetation it is unlikely that flows will prevent colonization of bars by both native and non-native vegetation species. Additionally, once established shear stresses in excess of about 6 $lb/ft^2$ are required to remove vegetation from bars. Therefore, vegetation management within the MRG will require mechanical intervention.

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