5.0 IMPACTS OF *ARUNDO*: Hydrology, Geomorphology and Flooding

5.1 Hydraulics, Sediment Transport, Geomorphology

5.1.1. Introduction

Arundo is a highly aggressive, non-native plant species that has invaded riparian areas and floodplains, displacing native plants, degrading habitats, and altering channel characteristics. The biology and ecology of *Arundo* have been fairly well studied and reported, but comparatively few studies have examined the effects of *Arundo* on river form and process. The changes in river geomorphology, flood risk, and sediment erosion, storage, and delivery that follow *Arundo* invasion are not well understood.

The overall goal of this study is to describe the potential effects of *Arundo* invasion on river processes in selected of Southern California watersheds. The specific objectives are to:

- Develop an understanding of the typical response of river forms and processes to invasion by *Arundo*, or other non-native plants (tamarisk), from review of published literature and reports
- Summarize the geomorphic environments and extent of *Arundo* infestation for three of the Southern California study streams – the Santa Margarita, San Luis Rey, and Santa Ana Rivers – from GIS
- Prepare a case study of the effects of the *Arundo* invasion on the hydraulic characteristics, geomorphology, sediment budgets and sediment transport capacity of the Santa Margarita River
- Based on the GIS analyses and the case study results, develop a simplified scoring system to evaluate the potential response of the San Luis Rey and Santa Ana Rivers to their *Arundo* infestations.

This section relies on existing information from previous reports and studies, as well as information collected for this study. This information included review of the existing literature on the effects of *Arundo* on geomorphology. Data generated for this study included: GIS databases and maps of river environments and *Arundo* distributions (mapped for this project: Section 3), a HEC-RAS model of the Santa Margarita River initially developed by NHC (1997a), and other reports on the Santa Margarita River. The documents reviewed for this study are listed in the References Section.

Work completed specifically for this project included: additional HEC-RAS runs for different vegetation scenarios and analysis of RAS model output to assess hydraulic and sediment transport capacity characteristics. The Santa Margarita River was inspected on October 1st, 2010. Study methods and their limitations are described further in the text.

To the extent practical, the analyses and results for this study were prepared in a GIS environment. We relied on GIS support from other team members for the analysis and mapping of *Arundo* and fluvial landforms on the three Southern California Rivers included in this study. Further details on their methods and procedures are described in Sections 3 and 5.2.

Section 5.1.2 summarizes the effects of *Arundo* infestation on river form and process from a review of published and unpublished literature and develops a general understanding of riverine response to infestation. Section 5.1.3 summarizes the riverine and riparian or floodplain vegetation characteristics of three of the Southern California study streams. Section 5.1.4 provides a case study of the Santa Margarita River, briefly describing its watershed and historical geomorphology before analyzing the potential effects of *Arundo* infestation on hydraulic conditions, sediment transport capacity and long-term sediment budgets. The relationship between changes in hydraulics and sediment transport and river form and process are summarized at the end of this chapter.

Section 5.1.5 then combines the geomorphic analyses of the three rivers studied herein with the trends and observations on hydraulics and sediment transport along the Santa Margarita River to predict likely impacts of *Arundo* on the San Luis Rey and Santa Ana Rivers. Section 5.1.6 provides conclusions and recommendations.

Elevations are reported in feet and refer to the North American Vertical Datum of 1988 (NAVD 88). Elevations originally reported in the National Geodetic Vertical Datum of 1929 (NGVD 29) were approximately converted to NAVD 88 by adding 2.74 feet, a value obtained for the Santa Margarita study area using the datum and coordinate system conversion software program Corpscon (USACE 2004). All GIS data for this project are in the UTM Zone 11N NAD 83 (m) coordinate system.

The Marine Corps Base, Camp Pendleton and U.S. Naval Facilities Engineering Command are gratefully acknowledged for their support of this study which included the use of hydraulic and sediment transport models previously developed by NHC. In addition, Base Command and the Navy granted access to Camp Pendleton and permitted discussions with base personnel involved with *Arundo* control and management on the Santa Margarita River.

5.1.2 Arundo and River Morphology

This chapter briefly summarizes the establishment, spread, and distribution of *Arundo* in the river environment and the observed effects of the spread of *Arundo* on the morphology and characteristics of rivers and streams from existing literature. The riverine response to *Arundo* infestation focuses on large, low-gradient, braided rivers in the American Southwest that are similar to selected coastal rivers being studied in Southern California.

The general purpose of this chapter is to develop a qualitative understanding of river morphology evolution under *Arundo* infestation and identify gaps in our understanding. This conceptual model will be used to help extend and interpret specific hydraulic and sediment studies on the Santa Margarita River, which are discussed in Section 5.1.4.

5.1.2.1 *Arundo* in the River Environment

General Characteristics

Arundo donax (Giant Reed) is a member of the grass family (Poaceae) and is native to tropical and subtropical areas of Asia and Europe. *Arundo* was introduced to America in the 1800s for use as construction material and for erosion control along streams and ditches. Tamarisk (*Tamarix* spp.), or salt cedar, is another invasive, non-native species with a similar distribution to *Arundo*. The two species are often found together and studies of *Arundo* in the river environment often also include this species. Tamarisk includes several shrub and tree species native to drier areas of Eurasia and Africa that were introduced to North America in the 1800s as an ornamental shrub, windbreak, and for shade.

Arundo tends to be found on bare, moist substrate where water is plentiful, including the bed, banks, unvegetated bars and islands, and the floodplain of rivers (Else 1996; Stillwater Sciences 2007). *Arundo* requires significantly more water than native plants to support its very fast growth rate (Iverson 1994, Watts 2009, Abichandani 2007). Once established, *Arundo* plants grow very quickly, as much as 10 cm per day in its early growth stages (Quinn and Holt 2004), and mature stands reach heights of 6 m to 10 m (Rieger and Kreager 1998, Lawson et al. 2005, this study-Chapter 2). *Arundo* stands spread laterally via rhizomes (Rieger and Kreager 1998), often resulting in extremely dense, monotypic stands. Growth rates are so high that it often out-competes other species, particularly when colonizing sites that have been disturbed by erosion or wildfire.

Tamarisk grows in similar environments to *Arundo* and appears as shrubby trees growing as high as 35 ft tall along rivers in the American Southwest (Graf 1978). Tamarisk spreads by both adventitious roots and by seeds that are dispersed by wind or flowing water. Tamarisk is salt tolerant and survives in dry conditions by growing roots that extend up to 100 feet deep, as they follow a slowly receding ground water table (Graf 1982).

Dispersal & Establishment

Arundo relies on downstream dispersal of stem or rhizome fragments for vegetative propagation, which primarily occurs during seasonal floods. *Arundo* seeds are thought to be infertile (Khudamrongsawat and Holt 2004, Bhanwra et al. 1982). Thus, new *Arundo* stands are limited to the lateral extent of river flows and floodplain inundation. *Arundo* can be widely dispersed into disturbed soils when large floods occur, such as those in Southern California in 1969 (Ambrose and Rundel 2007).

The dynamics of *Arundo* establishment in the river environment have been examined on the Santa Margarita and Santa Clara Rivers in Southern California. Else (1996) examined *Arundo* establishment after a large flood on the Santa Margarita River. She found the density of establishment was greatest on depositional bars, followed by channel banks, and floodplain areas nearest to the river. Establishment was least common on the channel bed. *Arundo* dispersal was directly correlated with flood magnitude and it was most widely distributed in broad, unconfined reaches of the Santa Margarita River with low stream gradients. Steeper confined reaches showed less *Arundo* establishment, presumably as a result of greater flow velocities that provided fewer areas for *Arundo* propagules to deposit and grow.

Rates of Spread

Over a period of decades, *Arundo* stands can laterally propagate throughout the floodplain from points where it was deposited during flood events. Large floods can cause much more extensive lateral spreading of *Arundo* in a single season but these events are infrequent. Based on mapping of *Arundo* extents on the Santa Margarita, Santa Ana, and San Luis Rey Rivers by Cal-IPC (2010b), the maximum coverage of the floodplain by mature *Arundo* along a river reach may be from 40% to 55% of the total area occupied by the floodplain and active channel.

Erosion of *Arundo* Stands by Floods

During floods, large rafts of *Arundo* are observed to float downriver and deposit on the inundated floodplain. It is also common for tidal currents and wave action to cover beaches with *Arundo* that was transported downstream during a large flood (Else 1996; Cal-IPC 2010a). While *Arundo* stands are eroded during large, infrequent floods, it is not known what velocities or shear stresses can be resisted by the *Arundo* stands. It appears floods remove the plants and roots, and in some situations only the above-ground vegetation is mobilized.

5.1.2.2 Observed Effects on Rivers

Introduction and Context

Arundo (and to some extent, Tamarisk) is typically found in rivers and streams in Southern California to elevations of 1,000 feet. This elevation range, and geographic area, includes a broad range of river types and environments. However, the focus of this study is on large, low-gradient coastal rivers where *Arundo* was found to be most abundant (Chapter 3). As described in the next section, the riparian systems of the Southern California coastal study streams are dominated by *Arundo*, which often occupies most of the surrounding low floodplain (Jackson et al 1994). Effects may be very different in other river types and environments where the dispersal and establishment of *Arundo* is limited by channel or flood characteristics.

Most of our understanding of the effects of *Arundo* on river morphology is based on historical case studies, generally from analysis of maps or air photographs. These studies have two weaknesses. One is that the study period is relatively short, generally less than 70 years, so the role of large floods in eroding existing stands or distributing propagules is not well understood.

The second complicating factor is that the study period also includes human impacts on watersheds and flows that may reinforce the observed riverine response to *Arundo*. The effect of *Arundo* on river morphology in these human-modified streams would be correctly interpreted as the difference between the channel evolution that would have occurred without *Arundo* and that which occurred with *Arundo* present. We found no studies that had adequate control or had completed sufficient analyses to resolve this issue.

Long-term Historical Studies

The effects of *Arundo* and Tamarisk infestation on long-term geomorphic change have been studied on several large rivers in the American southwest, including the Rio Grande in Texas (Dean and Schmidt 2010), the Green River in Utah (Graf 1978; Allred and Schmidt 1999; Birken and Cooper 2006) and the Rio Puerco in Arizona (Friedman et al. 2005). These studies relied on interpretation of historical aerial and ground photographs to assess and measure changes in the river planform. Information on channel profiles, invert elevations and cross-section areas was often not available.

General Observations

Historically, rivers in the arid southwest were often dry during the summer and fall and they typically exhibited a wide, shallow, laterally unstable channel, with multiple flow paths around large, unvegetated sand and gravel bars. Studies on these rivers reported similar trends following *Arundo* and Tamarisk infestation, with the planform showing long-term channel narrowing coupled with a simplified channel form and increased lateral channel stability.

The braided channels transformed into a narrower, more laterally stable single thread channel with root-stabilized, steep banks supporting both native and non-native vegetation. Few unvegetated bars remained and secondary channels were eventually filled in with sediment, covered by vegetation, and attached to the adjacent floodplain. In some cases, bed scour and channel deepening occurred due to confinement of flows.

Channel narrowing primarily occurred through the development of floodplains from vertical accretion of bar surfaces along the river bank. Plant colonization, by *Arundo* and Tamarisk, stabilized the bar surface and increased floodplain and bar roughness and sediment trapping efficiency, creating a mechanism for further sediment capture, deposition and vertical accretion.

Trends in Width and Planform

Allred and Schmidt (1999) noted a long-term trend to narrowing and bed aggradation on the Green River, based on comparing re-surveys of cross-sections. Similarly, Friedman et al (2005) found long-term channel narrowing and bed aggradation along the Rio Puerco, which led to a 27% decline in cross-section area at their study site. In contrast, Pollen-Bankhead et al. (2009) reported channel narrowing and incision following non-native plant infestation in Canyon de Chelly, Arizona. At this site, channel incision may have resulted from flow confinement and erosion-resistant banks, the latter resulting from root reinforcement and vertical accretion of fine-grained, cohesive bank sediments.

The relationship of the channel width and area following *Arundo* infestation has not been related to the local flood regime and to typical dominant discharges and it is not clearly understood how the rivers have adjusted to narrowing, increased bank strength, and dense vegetation on the floodplain. It has been noted on the Green River, Rio Grande and Rio Puerco, that channel narrowing and floodplain accretion after infestation have resulted in a more frequent overbank flooding than occurred historically, suggesting that channel dimensions have not adjusted to the local flood regime. Further adjustments, likely to channel depth, might be expected.

On the Rio Grande, Dean and Schmidt (2010) reported that large floods acted as a negative feedback mechanism or ‘reset’ event, restoring the channel condition to a previous wider and more laterally unstable state but that channel narrowing resumed immediately thereafter. Since the last large flood in 1991, they found as much as 90% of unvegetated sand and gravel bars in the active channel bed had become part of the vegetated floodplain (which is dominated by *Arundo*). No such effect was observed following large floods in Tamarisk infested sections of the Green River (Birken and Cooper 2006). Whether this is a result of the differing resistance to erosion of the two species or to the differing hydraulic forces exerted on the floodplain vegetation is not known. It is also not known if floodplain and bed elevations are “re-set” by these large floods.

The above indicates that large floods do not always ‘reset’ channel and floodplain characteristics in river reaches altered by non-native plant infestation. Little is known of the hydraulic forces that can be resisted by these invasive plants so it is not possible to predict a particular flood frequency or magnitude that will lead to their erosion and partial removal. However, the Dean and Schmidt (2010) study suggests that the time to return to the channel form observed under *Arundo* infestation is much less than the typical period between large floods that disturb the channel and floodplain.

Vertical Adjustments of the Bed and Floodplain

Dean and Schmidt (2010) measured sediment accretion on the floodplain of the Rio Grande that occurred during a rapid invasion of *Arundo* and Tamarisk. Average rates of vertical floodplain accretion of 0.6 ft/yr to 0.77 ft/yr were estimated using anatomical changes to tree rings caused by burial. The accretion occurred over a 15 year period following a large flood ‘reset’ event. Friedman et al. (2005) measured rates of channel filling in response to hydrologic changes and Tamarisk infestation on the Rio Puerco, New Mexico. Channel filling occurred in two phases, a period of channel narrowing with little change in thalweg elevation followed by vertical accretion of the floodplain and channel bed at an average rate of 0.26 ft/yr from 1962 to 2000.

Lateral Migration and Bank Erosion

Gran and Paola (2001) conducted flume experiments that documented how vegetation affects channel form and process in braided stream environments. In general, they observed channel responses that were similar to those following *Arundo* and Tamarisk infestations discussed above. They found that vegetation reduced the number of channel braids because smaller channels were choked with sediment and could not reestablish themselves. Gran and Paola (2001) noted a direct relationship between channel stability and the density and extent of vegetation. Vegetation also created less variability in flow velocity through the channel cross-section and resulted in increased bank strength (associated with dense root mats that are characteristic of these species) and decreased bank shear stress due to added roughness effects. Consequently, lateral migration rates declined. Increased bank strength also increased channel relief through the formation of higher and steeper banks and promoted channel scour, increasing maximum channel depths.

Additional studies examining the effects of invasive plant colonization on bank stability were conducted by Pollen-Bankhead et al (2009) and Brinke (2010). Pollen-Bankhead et al (2009) documented the effects of invasive plants on bank stability and bank retreat rates in Canyon de Chelly National Monument, Arizona. They found that tamarisk and Russian Olive, another invasive plant species, significantly increased bank stability through root reinforcement of the sand banks in the study area. Bank retreat rates doubled from an approximate rate of 2.5 ft/yr to 5 ft/yr following vegetation removal.

Brinke (2010) measured the root density and tensile strength of *Arundo* on stream banks of the Santa Clara River, California. When compared with Red Willow, a common native species, *Arundo* had a denser root mass and provided 40% greater tensile strength in the upper 10 cm of the bank. The converse was true below 10 cm depth, where Red Willow showed higher root density and greater tensile strength. Brinke (2010) concluded that *Arundo* contributed to less bank cohesion on stream banks exceeding one vertical foot and speculated that undercutting and cantilever failure were a primary bank erosion mechanism for *Arundo*-topped stream banks.

5.1.2.3 Observed Effects on Hydraulics and Sediment Transport

We found very few studies that compared hydraulic and sediment transport characteristics of large, low-gradient rivers; either prior to or following *Arundo* infestation. NHC (1997a,b; 2001) did complete geomorphic, hydraulic, and sediment transport studies of the lower Santa Margarita River in support of bridge and levee improvement projects at the Marine Corps Base Camp Pendleton (MCBCP). Section 5.1.4 discusses these studies in detail.

Although they do not specifically address the effects of *Arundo* on hydraulic capacity, numerous HEC-RAS models that include estimates for the hydraulic roughness effects of non-native vegetation have been used to support flood control and river management applications (USACE 2009). Few studies have reliable flow and water level data available to accurately calibrate hydraulic models for the effects of *Arundo*. However, where adequate calibration data are available, analysis of the specific effects of *Arundo* infestation scenarios may be possible with these existing HEC-RAS models.

Spencer (2010) investigated the hydraulic effects of *Arundo* on Manning's *n*, flow velocity and flow direction at study sites on Cache Creek and Stony Creek, California. Flow velocity measurements were collected around five *Arundo* plants growing in Cache Creek and a set of artificial *Arundo* stalks placed in the river bed on Stony Creek. Measured Manning's *n* roughness coefficients were found to vary between 0.019 and 0.121 with an average roughness of 0.066. Channel roughness was higher when *Arundo* was present, resulting in higher water surface elevations for the 2-year and 100-year flood events when modeled using HEC-RAS, a software program that simulates one-dimensional, open channel flow (USACE 2010).

Response to *Arundo* Removal or Eradication

Despite a number of programs to eradicate *Arundo* on rivers throughout California, we did not find any reports in the literature that documented the geomorphic, hydraulic or sediment transport effects of widespread *Arundo* removal. In particular, the period between *Arundo* eradication and re-establishment of native vegetation presents significant opportunity for local and downstream channel adjustment and changes in sediment transport processes, particularly if large floods occur during this period.

5.1.2.4 Summary of Understanding

Since its introduction in the late 1800s, *Arundo* (and to some extent, Tamarisk) has flourished on rivers and streams in Southern California to elevations of about 1,000 feet. This elevation range, and geographic area, includes a broad range of river types; however, our focus has been on large, low-gradient, braided rivers similar to the Southern California study rivers. It is in this river type that *Arundo* is likely to best disperse and establish most rapidly.

These river types have also been altered by humans. For instance, water development projects that divert flows, reduce flood flows or capture coarse sediment from the upper watershed are expected to narrow channels and convert braided rivers to simpler forms, among other effects, even in the absence of *Arundo*. Channel confinement through levees and construction of bank protection or river training structures may also have similar effects on river morphology. Other factors, such as altered seasonal flow patterns, changes to groundwater elevations, or more frequent and greater low flows, may also affect riparian vegetation, *Arundo* establishment, and channel form. The effects of some these changes may be confounded with those that directly result from *Arundo* establishment and growth.

Based on the existing literature, the response of this river type to *Arundo* infestation consists of a simplification of channel form, increased lateral stability, floodplain accretion, and long-term channel narrowing. Bed aggradation and shallower channels have been observed in some studies; channel incision or deepening in others. The long-term expectation would be for a deeper channel following narrowing and confinement of flows. However, this may be obscured by changes in watershed hydrology, the time required to erode sufficient sediment to deepen the main channel, or by rapid floodplain accretion.

Historically, braided and laterally unstable channels prior to infestation transform to narrower, more laterally stable single thread channels with root-stabilized, steep banks following infestation. Plant colonization stabilizes bar and floodplain surfaces, increasing channel roughness and sediment trapping efficiency, thereby creating a mechanism for further sediment capture, deposition and vertical accretion. Observed long-term rates of vertical accretion vary widely in the reported literature and are as high as 0.8 ft/yr. Long term average annual accretion rates likely vary with the magnitude and frequency of flooding, volume of sediment in transport, as well as the specific river conditions.

The local depths of deposits following large floods can be much greater, NHC (1998, 2001) observed several feet of sediment deposition in many locations on the floodplain adjacent to the Santa Margarita River following the 1993 flood that flooded the Marine Corps Air Station (MCAS).

There may be an upper limit on vertical accretion, which would about correspond to the elevations of typical floods. This may be reached fairly soon if the channel bed incises or does not accrete as rapidly as the floodplain. If the channel bed fills as the floodplain accretes, this limit may not be reached for a long time.

Most research on the effects of *Arundo* and Tamarisk on river systems is limited by the duration of study (about the last 70 years) and the simultaneous occurrence of human-caused changes affecting basin hydrology and sediment load. These changes often produce river responses that are similar to those from *Arundo* infestation and may obscure identification of geomorphic change specifically due to *Arundo*.

5.1.3 Southern California Study Streams

5.1.3.1 Introduction

This chapter summarizes geomorphic and vegetation characteristics of the three Southern California study streams: the Santa Margarita, Santa Ana and San Luis Rey Rivers. These study streams were selected because they contain some of the greatest observed concentrations of *Arundo* found in Southern California coastal rivers (Chapter 4, Cal-IPC 2010b). The geomorphic and vegetation characteristics presented in this chapter form the basis for comparing results from the Santa Margarita River case study (Chapter 4) to other study streams (Section 5.1.5).

5.1.3.2 Study Streams

The Santa Margarita, Santa Ana and San Luis Rey are large, sand bed, Southern California Rivers that cross coastal lowlands before discharging into the Pacific Ocean. Cal-IPC has identified specific sections of the lowland portions of these rivers as areas of interest (AOI). These management sections ranged from 17 to 37 miles in length and either ended at the Pacific Ocean or, in the case of the Santa Ana River, at a reservoir.

The AOIs were divided into broad reaches based on changes in channel planform, the degree of confinement by hillslopes or levees, and the extent of *Arundo* infestation. Geomorphic and riparian vegetation characteristics from the GIS analysis are summarized by reach in Tables 5-1.1, 5-1.2 and 5-1.3. The management sections and stream reaches are shown in Figures 5-1.1, 5-1.2 and 5-1.3; yellow areas in each figure represent the extent of the floodplain mapped in the GIS for each reach.

5.1.3.3 CAL-IPC GIS Analysis

Cal-IPC (2010b) mapped geomorphic and vegetation characteristics of the study streams in a GIS (see Methods in Section 5.2). They divided channel and floodplain into the categories described below from 2009 aerial photos and digital elevation models (DEM) from the U.S. Geological Survey (USGS 2010). No field verification was completed.

Fluvial Landforms

- *Low Flow Channel* – The part of the main channel where water was flowing at the time of the aerial photos.
- *Bar / Channel / Floodplain - unvegetated* – Main channel or floodplain areas with less than 50% vegetation cover, usually consisting of bar surfaces, dry channel beds or recent flood deposits or erosion
- *Floodplain - vegetated* – Areas on the river floodplain with more than 50% vegetation cover.

- *Floodplain / Low Terrace – vegetated* – Areas on either the river floodplain or an adjacent low terrace with more than 50% vegetation cover.
- *Upper Terrace - vegetated* – Areas on higher ground adjacent to the low terraces with more than 50% vegetation cover.

The above mapped landforms were used to calculate river characteristics by reach. Channel width was defined as the area of the low flow channel divided by the reach length. This width may not be representative of the active or main channel width commonly adopted for river studies. This is discussed further throughout the text.

Floodplain area was defined as the sum of the "low water channel", "bar/channel/ floodplain unvegetated", "floodplain – vegetated" and "Floodplain/ low terrace" areas. The average floodplain width was defined as the above area divided by the reach length. A width ratio (expressed as a percentage) was then constructed for each reach by dividing the average channel width by the average floodplain width.

Anthropogenic Features

- *Line Features* – Levee crests, bridge berms, in-stream grade control weirs, and dams
- *Point Features* – bridge crossings, water infiltration ponds, stormwater and treatment pond inflow points

Longitudinal Profile – Longitudinal stream profiles of each study reach were generated from USGS 10 m grid DEM data (USGS 2010).

Arundo Coverage – The spatial extent of *Arundo*, as mapped by Cal-IPC (2010b) from 1996 to 2009. The quoted coverage in Tables 5-1.1 to 5-1.3 represents the maximum observed extent of *Arundo* infestation. *Arundo* coverage has changed on the study streams in recent years because of eradication programs.

5.1.3.4 Study Stream Characteristics

General Morphology

In the late 1990s, the study streams had single thread channels at low flows that were bordered by well-vegetated floodplains; only a few reaches had less than 50% vegetation cover. Except where the rivers were confined by natural topography or levees, the low flow channel width (See definition above) was generally less than 10% of the floodplain width (see Width Ratio; Tables 5-1.1 to 5-1.3); alternatively, the floodplain was at least 10 times as wide as the low flow channel.

The San Luis Rey and Santa Ana Rivers study streams are about twice as steep as the Santa Margarita River, on average. However, the three study streams have a common pattern of steeper slopes in their upstream reaches and shallower slopes near the mouth. Along the study stream, slopes near the mouth are about one-fourth to one-eighth of those in the most upstream reaches.

Floodplain widths averaged 1,100 feet in the Santa Margarita River, 800 feet in the San Luis Rey River and 1,300 feet in the Santa Ana River (removing the very wide Reach 1) and they varied considerably from one study reach to another, as a result of both human and topographic confinement. Width ratios and the portion of the floodplain that was not vegetated were greatest in the Santa Ana study reaches; the portion of the floodplain that was vegetated was greatest in the San Luis Rey study reaches, where less than 15% of the floodplain and channel area has less than 50% vegetation coverage.

Arundo Characteristics

Arundo coverage varied from 15 to 23% of the total floodplain and channel area in the three management sections. The percentage *Arundo* cover was not a consistent portion of the total vegetation cover and it covered from less than 1% to more than 50% of the total floodplain area when averaged over the study stream reaches. *Arundo* was uncommon within the low flow channel width (Section 5.2).

All three study streams show a marked decline in *Arundo* coverage in the upstream study reaches compared to the downstream ones. Such an observation may result from slow upstream propagation, flood history, or the role of steeper stream slopes in limiting the establishment and development of *Arundo*. The relative importance of these two factors cannot be resolved with the existing information, but Tables 5-1.1 to 5-1.3 suggest that *Arundo* is an insignificant portion (in terms of geomorphic processes) of total cover in those study reaches where slopes exceed 0.004, including those steep reaches on the San Luis Rey River that have much of their floodplain covered with other vegetation.

There also appears to be a pattern along the study streams, and particularly on the Santa Margarita River, where the reaches with the highest *Arundo* concentrations occur where slope declines or the floodplain widens considerably when compared to the reach upstream. The best example is on Reach 7 of the Santa Margarita River which has the highest percent *Arundo* coverage of the study reaches (Table 5-1.1). The slope in Reach 7 is about half of that in Reach 6 and the floodplain is about twice as wide. This pattern is thought to occur because the less steep, wider reach has much lower average velocities which promote deposition of *Arundo* propagules and increase the likelihood of *Arundo* establishment and propagation. Section5.1.5 discusses this observation in more detail.

Table 5-1.1. Santa Margarita River summary of GIS analysis.

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Ave Low Flow Channel Width (ft)	Width Ratio (%)[1]	Vegetated Area (%)[2]	*Arundo* Area (%)[3]
1	1.52	0.0008	1270	163	12.8%	59.7%	1.5%
2	1.47	0.0017	773	66	8.5%	91.0%	14.7%
3	1.70	0.0015	1444	58	4.0%	87.4%	21.5%
4	0.42	0.0015	2493	52	2.1%	91.5%	18.9%
5	0.90	0.0014	1929	72	3.8%	87.5%	44.3%
6	1.30	0.0024	2505	61	2.4%	92.2%	28.2%
7	0.42	0.0015	2213	87	3.9%	93.1%	54.8%
8	1.60	0.0023	1045	73	7.0%	71.7%	44.6%
9	0.77	0.0024	630	52	8.2%	66.9%	18.2%
10	1.21	0.0031	823	58	7.0%	73.9%	10.2%
11	1.89	0.0026	664	105	15.7%	68.7%	24.9%
12	4.11	0.0033	424	48	11.3%	69.7%	21.0%
Weighted Ave		**0.0023**	**1,078**	**73**	**8.7%**	**76.3%**	**23.1%**
Total	**17.32**						

[1] – Width Ratio = Average Floodplain Width / Average Low Flow Channel Width
[2] – Vegetated Area = Percent area of the floodplain and channel surface with more than 50% vegetation cover
[3] – *Arundo* Area = Percent area of the floodplain and channel surface occupied by *Arundo* (Cal-IPC 2010b)

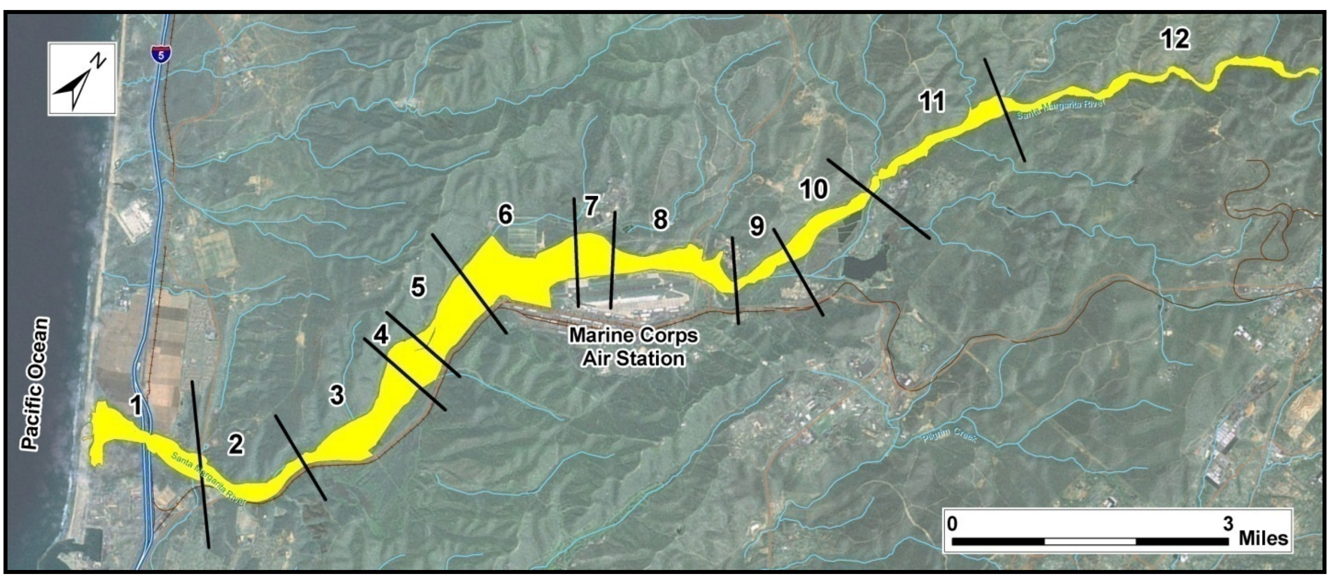


Figure 5-1.1. Santa Margarita River study reaches, with yellow denoting extent of mapped floodplain.

Table 5-1.2 Santa Ana River summary of GIS analysis.

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Ave Low Flow Channel Width (ft)	Width Ratio (%)[1]	Vegetated Area (%)[2]	*Arundo* Area (%)[3]
1	3.16	0.0012	9146	90	1.0%	98%	12.5%
2	12.17	0.0025	1758	136	7.7%	82%	41.2%
3	2.08	0.0030	733	207	28.3%	56%	10.5%
4	2.35	0.0047	2312	219	9.5%	76%	19.4%
5	9.67	0.0038	749	197	26.3%	30%	0.2%
6	3.98	0.0058	529	151	28.5%	36%	0.4%
7	3.44	0.0097	1441	133	9.3%	49%	0.0%
Weighted Average		**0.0039**	**1942**	**159**	**15.7%**	**59.8%**	**16.6%**
Total	**36.86**						

[1] – Width Ratio = Average Floodplain Width / Average Low Flow Channel Width
[2] – Vegetated Area = Percent area of the floodplain and channel surface with more than 50% vegetation cover
[3] – *Arundo* Area = Percent area of the floodplain and channel surface occupied by *Arundo* (Cal-IPC 2010b)

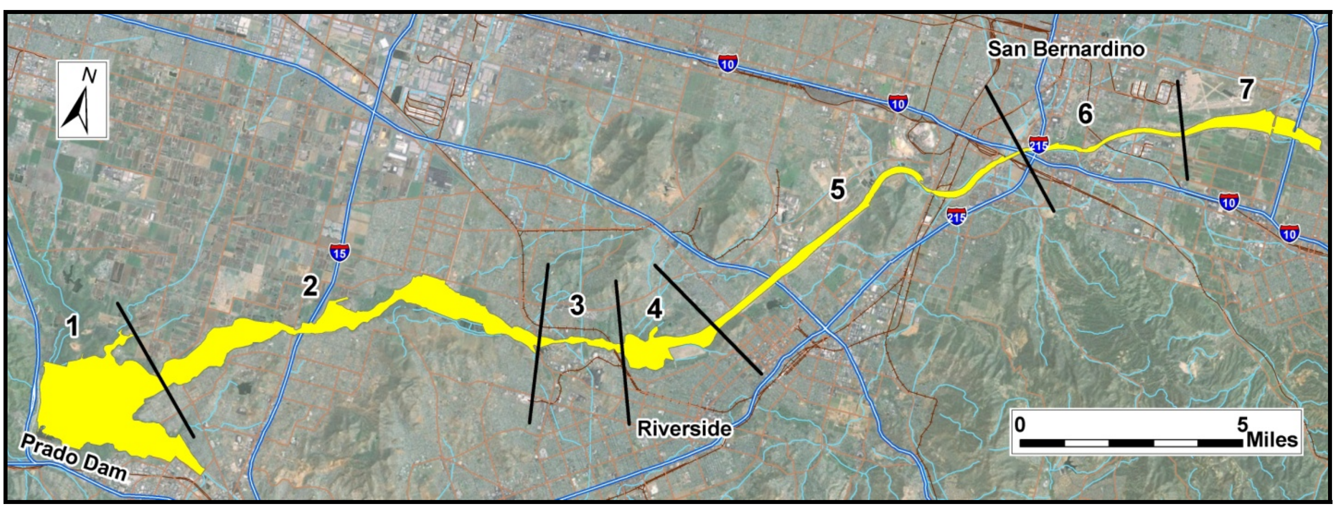


Figure 5-1.2. Santa Ana River study reaches with extent of mapped floodplain denoted in yellow.

Table 5-1.3 San Luis Rey River summary of GIS analysis.

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Ave Low Flow Channel Width (ft)	Width Ratio (%)[1]	Vegetated Area (%)[2]	*Arundo* Area (%)[3]
1	0.86	0.0007	506	178	35.2%	52.9%	11.4%
2	1.66	0.0015	582	52	9.0%	80.4%	47.1%
3	5.79	0.0023	509	44	8.7%	91.4%	20.4%
4	5.53	0.0021	834	48	5.7%	85.5%	29.9%
5	0.62	0.0030	544	38	7.0%	94.7%	22.3%
6	5.07	0.0029	1232	60	4.8%	92.4%	12.8%
7	3.73	0.0037	443	37	8.4%	89.6%	7.7%
8	3.73	0.0050	1186	29	2.4%	83.7%	0.1%
9	2.03	0.0110	797	24	3.0%	86.0%	0.2%
10	2.01	0.0148	424	31	7.3%	74.4%	0.3%
11	1.16	0.0048	1157	33	2.8%	68.1%	0.0%
Weighted Average		**0.0042**	**790**	**46**	**6.8%**	**85.7%**	**14.9%**
Total	**32.19**						

1 – Width Ratio = Average Floodplain Width / Average Low Flow Channel Width
2 – Vegetated Area = Percent area of the floodplain and channel surface with more than 50% vegetation cover
3 – *Arundo* Area = Percent area of the floodplain and channel surface occupied by *Arundo* (Cal-IPC 2010b)

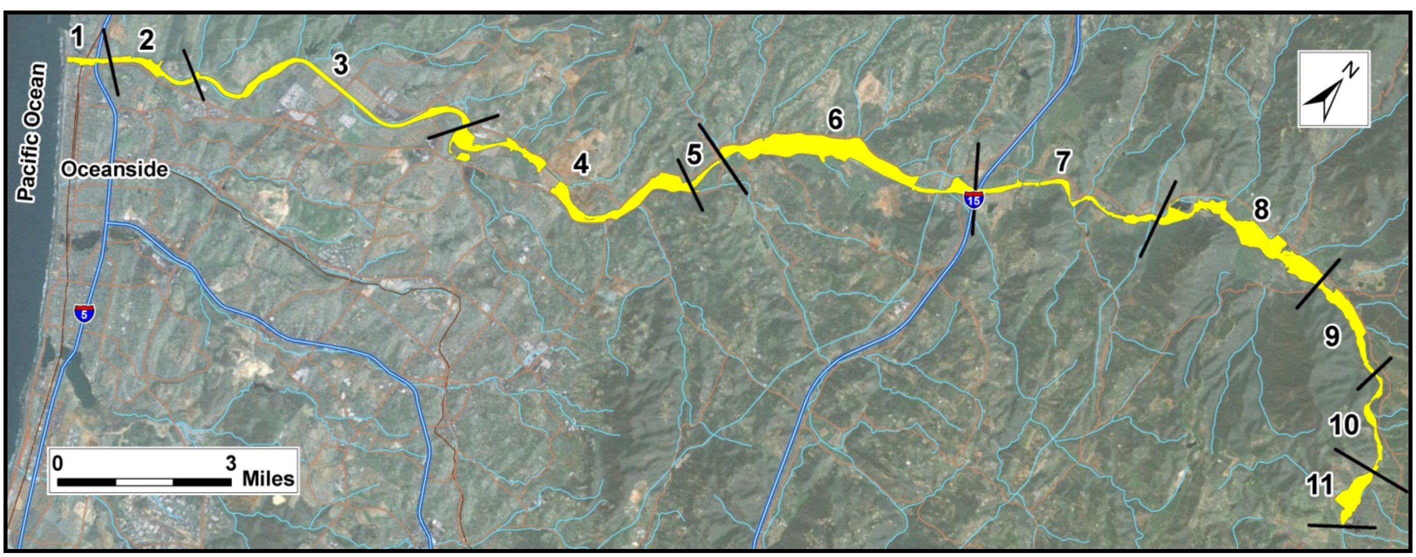


Figure 5-1.3 San Luis Rey River study reaches with extent of mapped floodplain denoted in yellow.

5.1.4. Santa Margarita River Case Study

5.1.4.1 Introduction

This chapter briefly describes the Santa Margarita River watershed, its climate and hydrology, and the morphology and historical behavior of the lower Santa Margarita River, before describing the effects of *Arundo* infestation on hydraulics, sedimentation and geomorphology. The effects of *Arundo* on these characteristics were determined from surveys, field observations, other consultant reports, and rerunning of hydraulic models developed in NHC (1997b) and NHC (2001). The NHC studies were completed during the period of maximum *Arundo* infestation, prior to the eradication programs that began in the late 1990s.

5.1.4.2 Santa Margarita Watershed

The Santa Margarita River watershed has an area of 740 square miles and drains into the Gulf of Santa Catalina (Pacific Ocean) near the city of Oceanside. Maximum elevations are about 6,825 ft at Thomas Mountain near the eastern end of the watershed. The upper watershed of the Santa Margarita River is mostly underlain by granitic rocks of pre-Cenozoic age; the central watershed, near Temecula and Murrieta, is mantled by Holocene and Pleistocene alluvial deposits (Jennings 1977). Occasional outcrops of Eocene and Jurassic marine rocks and metasedimentary and metavolcanic rocks are found in the central and lower watershed.

Three reservoirs regulate flows from the watershed. Vail Dam was completed in 1949 and regulates inflows from about 320 mi^2 of the upper Temecula watershed. Vail Lake storage capacity is about 40,000 acre-ft and it captures nearly all the winter runoff from its watershed, having overtopped only twice since the late 1940s (CDM 2003). Skinner Reservoir on Tucalota Creek, constructed in 1974 by the Metropolitan Water District (MWD), regulates a 51 mi^2 watershed and primarily stores imported water, releasing local inflows. Diamond Valley Lake Reservoir stores 800,000 acre-ft of imported water for the MWD; it reached full capacity in 2002. Skinner and Diamond Valley Lake Reservoirs have little effect on winter floods.

Lake O'Neill, operated by Camp Pendleton, provides off-stream storage for up to 1,200 acre-ft, which is diverted from the Santa Margarita River in spring and used for groundwater recharge in late fall. Releases for recharge are between 8 and 10 cfs (CDM 2003).

5.1.4.3 Climate and Hydrology

The Santa Margarita watershed has a Mediterranean climate, characterized by warm summers and cool, wet winters. Summers are dry and there are often several months without rain. About 90% of the annual precipitation falls as rain during large frontal storms that occur from November through April. Average annual precipitation is about 11 to 13 inches near the coast and over 25 inches at the highest watershed elevations, where it may include some snowfall.

The USGS has operated the Santa Margarita River at Ysidora (11046000) gage, near the mouth of the river, since 1923. Suspended sediment records were collected in the 1968-71, 1972-74 and 1977 water years. Inspection of the gage records shows an annual hydrograph where runoff primarily occurs during winter months, and is event-driven with most of the water discharge (and also most of the sediment discharge) occurring during a few, intense storms (Warrick and Rubin 2007). Annual maxima vary dramatically from year to year; annual instantaneous peaks at the Ysidora gage have ranged from zero to 44,000 cfs (Figure 5-1.4).

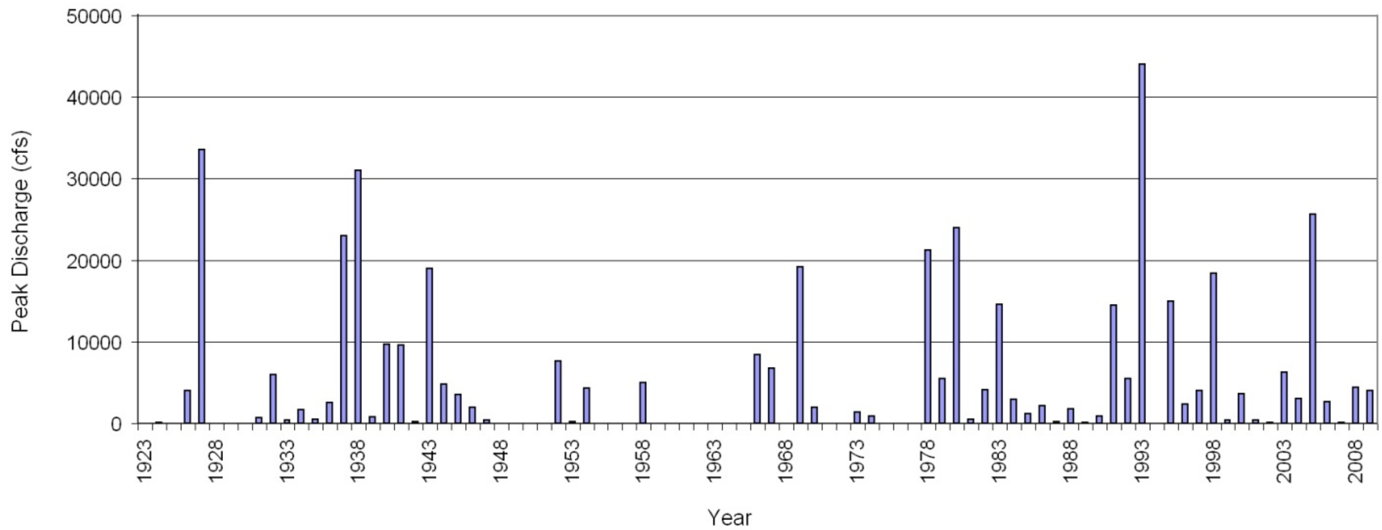


Figure 5-1.4. Annual peak discharges recorded at USGS stream gage 11046000 on Santa Margarita River near Ysidora.
Years with zero values or no data are shown as blank.

Large floods, those with return periods of more than 10 years and flows greater than 15 to 20,000 cfs, have been recorded at the gage in 1927, 1937, 1938, 1943, 1969, 1978, 1980, 1993, 1998, and 2005. Figure 5-1.4 shows a twenty-five year gap starting in the 1940s and lasting until 1969 that had no large floods. The 1993 flood was by far the largest on record; its peak discharge of 44,000 cfs is now about equivalent to the 50-year flood (USACE 1994a; Table 4.2=5-1.4). Before installation of the gage, large floods occurred in 1916 and 1884 (McGlashan and Ebert 1918). Stetson (2001) provides accounts of historical flooding and flood damages.

Most years include a long period of very low (<5 cfs) flows at the gage in the summer and fall, often extending for three or four months. Examination of decadal flow duration curves at the Ysidora gage shows a trend toward an increased duration of flows exceeding 10 cfs since the 1970s (Figure 5-1.5). This shift to a sustained, year-round, base flow is thought to be due to urbanization, water regulation since the construction of Vail Reservoir and groundwater recharge releases.

5.1.4.4 Lower Santa Margarita River

The Santa Margarita River begins at the confluence of Murrieta River and Temecula Creek near the City of Temecula. It is about 30 miles long; about 19 miles flow through Camp Pendleton near the mouth of the watershed. The lower Santa Margarita River begins at the mouth of DeLuz Canyon. Downstream, it flows through a 500 to 5,000 ft wide valley bordered by hilly terrain underlain by marine sedimentary rocks. The greatest widths are adjacent to the Marine Corps Air Station (MCAS) and at Ysidora Flats. The MCAS occupies a large part of the floodplain and is protected by a levee; otherwise the lower river valley is not developed, except for five bridges crossings and a few connecting roads.

The focus for this chapter is a 5.5 mile long project reach of the lower Santa Margarita River, which is adjacent to the MCAS and extends from De Luz Canyon to Ysidora Flats (Figure 5-1.6).

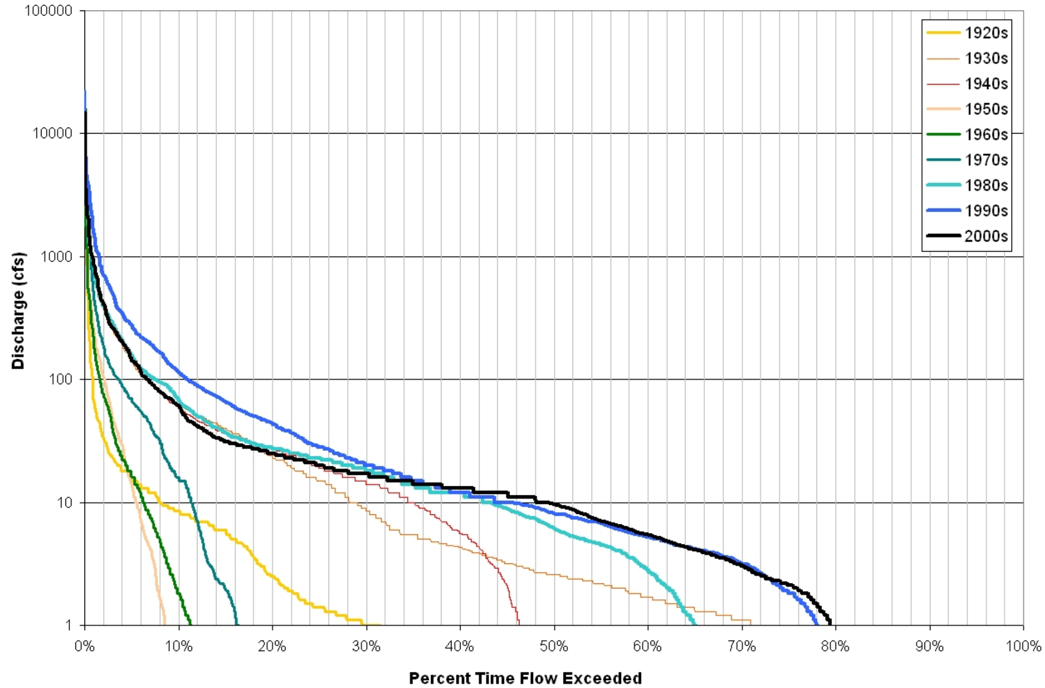


Figure 5-1.5. Flow duration curves plotted by decade at the Ysidora gage (11046000).

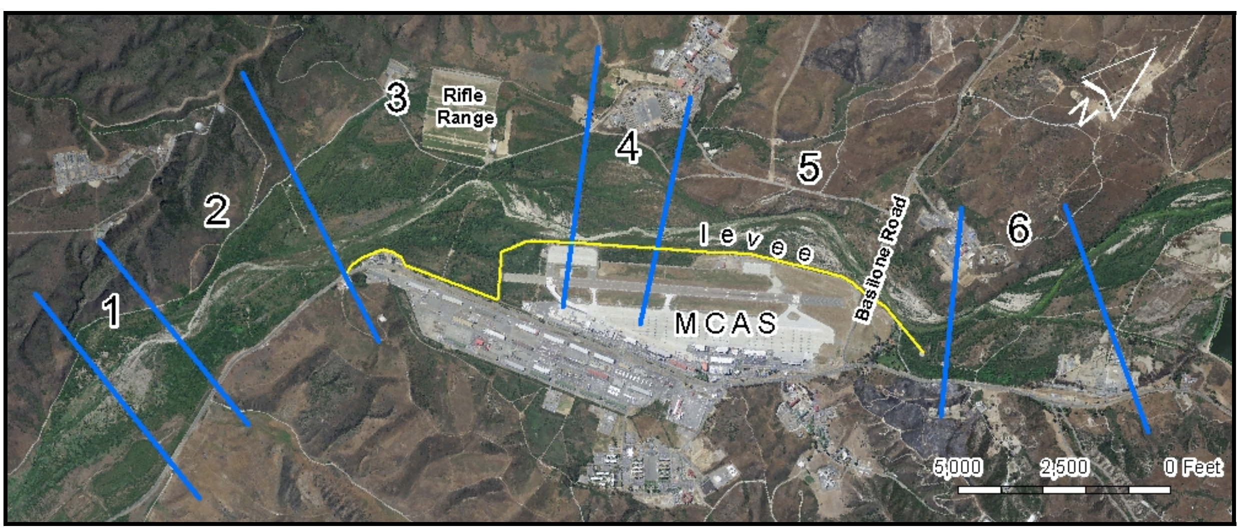


Figure 5-1.6. Sub-reaches (numbers 1 through 6) in the lower Santa Margarita River project reach.

This project reach is where NHC examined hydraulics and sediment transport capacity with mature stands of *Arundo* on the river bank and floodplain (NHC 1997a; 1997b; 2001) and covers about the same river mileage as Reaches 4 through 9 in Table 5-1.1 and Figure 5-1.1. The river floodplain is confined to varying degrees throughout the project reach, particularly upstream of the O'Neill Lake diversion and in the vicinity of Basilone Road Bridge (Table 5-1.4; Figure 5-1.6).

The sub-reach breaks on Figure 5-1.6 were set based on the degree of confinement, channel dimensions and longitudinal slope, using historical air photos, ground inspections and surveyed channel cross-sections. Channel confinement resulted from geologic and anthropogenic features, including high bluffs, bridges, in-channel road or pipeline crossings, and levees along the MCAS. The sub-reaches are described on Table 5-1.4.

In the late 1990s, the main channel, as defined by channel banks, was typically 200 ft to 400 ft wide and bordered by moderate to abundant vegetation where the floodplain had not been developed. The main channel was generally four to eight times wider than the low flow channel defined in Table 5-1.1. The floodplain surface was generally 4 to 6 feet higher than the low flow channel invert, as indicated by field inspection and channel surveys. Small, concentrated flow paths (distributary or chute channels) were common on the floodplain and on vegetated bar surfaces throughout the project reach (Figure 5-1.7).

River banks generally consisted of loose or partially consolidated sand and were between four and six feet high. Stream bed materials consisted of coarse and medium sands with some fine gravel. Sands and silts were the common deposits observed on overbank floodplain areas.

Figure 5-1.7. View of the Santa Margarita River in Sub-Reaches 2 & 3 (view is upstream) taken on May 16, 1995.

Table 5-1.4. Description of the lower Santa Margarita project sub-reaches.

Sub-Reach	Reach Length (ft)	Slope (ft/ft)	Average Floodplain Width (ft)	Ave Channel Width (ft)	General Observations
Sub-Reach 1 (sta. 0 to sta. 18+61) *Downstream sub-reach*	1,900 ft	0.0011	3,200 ft	205 ft	Narrow active channel bed flowing in an undeveloped and well vegetated floodplain.
Sub-Reach 2 (sta. 18+61 to sta. 71+07)	5,250 ft	0.0023	1,900 ft	350 ft	Valley narrows due to adjacent hillslopes through this undeveloped sub-reach located just downstream of the MCAS airfield.
Sub-Reach 3 (sta. 71+07 to sta. 143+98)	7,300 ft	0.0023	3,500 ft	405 ft	Wide valley section with broad floodplain partly confined by MCAS levee and the Rifle Range and Rifle Range Road crossing.
Sub-Reach 4 (sta. 143+98 to sta. 162+66)	1,900 ft	0.0025	2,300 ft	310 ft	Short reach of intermediate width connecting the very wide sub-reach 3 with narrow sub-reach 5
Sub-Reach 5 (sta. 162+66 to sta. 241+58)	7,900 ft	0.0022	1,100 ft	325 ft	Narrow floodplain sub-reach due to the Basilone Road crossing and MCAS levee along the right bank.
Sub-Reach 6 (sta. 241+58 to sta. 274+55) *Upstream sub-reach*	3,300 ft	0.0030	1,500 ft	345 ft	Narrow floodplain sub-reach due to flow confinement and infrastructure on the south side of the valley.

5.1.4.5 Historical Changes in the Project Reach

Planform

NHC (1997a) examined the position of the lower Santa Margarita River on historical air photos and maps and found that it maintained the same overall course since 1938. Its course had been more or less straight, except where it followed the natural curvature of valley walls or was guided by levees along the MCAS. The channel mostly lay on the northwestern portion of the valley bottom, due to encroachment by the MCAS facilities.

Within this general alignment, the main or active channel has shifted several hundred feet at some locations and exhibited a general decrease in width since 1938, interrupted by dramatic increases in channel width following large floods, such as in 1969 (NHC 1997a; see also Figure 5-1.8). Large floods also restored multiple flow channels and braid bars in the project reach. Vegetation encroached on recently deposited bar and overbank sediments and a single channel re-established over time.

Figure 5-1.8. Comparison of 1970 (left) and 2008 (right) air photos of Sub-reach 3.

Bed Profiles

NHC (1997b) compared channel invert (thalweg) profiles from 1946 to 1994 and found no consistent trend in elevations. Rather, the sub-reaches showed bed elevations that varied around a mean value over time, suggesting a relatively stable profile that responded to large floods, bar development, scour and sediment deposition. No channel invert elevation surveys have been completed since 1994, and a profile that shows the potential effects of recent *Arundo* eradication on channel elevations has not been surveyed.

NHC (1997a) concluded that there was no clear evidence of recent aggradation or incision along the lower Santa Margarita River. However, numerical modeling of long-term sediment transport suggested aggradation rates of 1.5 ft per 100 years, as a result of the lower bed slopes in the downstream end of the project reach (Table 5-1.4).

Floodplain Vegetation

Figure 5-1.8 compares air photos of Sub-reach 3 from 1970 and 2008. The non-vegetated active channel bed is several times wider in 1970 than 2008, despite the recent *Arundo* eradication. Channel and floodplain conditions in the 1970 air photo resulted from the 1969 flood, which followed a twenty-five period with no significant floods. Stetson Engineers (2001) reported that large floods in 1927 and 1993 also scoured much of the valley bottom and dramatically enlarged the active channel in Deluz Canyon just upstream of the project reach.

Interestingly, the 2008 air photos were taken not long after the 2005 flood, whose peak was slightly greater than that in 1969. Despite this, the 2008 channel shows no evidence that it had recently enlarged to the width observed after the 1969 flood. This different behavior is assumed to result from changes in the riparian vegetation in the channel and on the floodplain, or changes in channel and floodplain geometry, that resulted in greater bank and floodplain resistance to erosion.

While intriguing, such behavior is not well documented or understood. However, it suggests that the large floods that once greatly altered the channel and floodplain vegetation on the lower Santa Margarita River conditions may not be as effective under current conditions.

Arundo Eradication Programs

Efforts to control *Arundo* in the Santa Margarita River watershed began in 1997 (Lawson et al. 2005), and eradication has proceeded upstream to downstream, beginning at Interstate 15 in the middle watershed. *Arundo* removal continued for over a decade until 2009 when the river mouth was reached. The distribution of *Arundo* along the lower Santa Margarita River and the years when stands were removed are documented in a GIS database prepared by the California Invasive Plant Council (Cal-IPC 2010b).

The total area of *Arundo* stands in the project reach near Camp Pendleton was estimated to be about 400 acres in 1997 (Cal-IPC 2010b). Cal-IPC (J. Giessow, pers. comm.) provided a comparison of the 1997 and 2010 geomorphology in the project reach (See section 5.2.4), noting that the area of low flow channel and unvegetated bar or floodplain had increased from 120 acres in 1997 to 360 acres in 2010. Bed level changes or adjustments associated with the increased width for the main channel have not been documented.

<u>5.1.4.6 Project Reach Hydraulics</u>

HEC-RAS Model

In the late 1990s, NHC developed a calibrated, steady, one-dimensional HEC-RAS model (USACE 2010) of the Santa Margarita River project reach, as part of studies for a new levee (NHC 2001). The model was based on 62 cross-sections in the project reach, an average of one every 470 ft, developed either from July 1998 LiDAR, September 1996 air photos or June and July 1998 cross section surveys (Figure 5-1.9).

Figure 5-1.9. Location of HEC-RAS model cross-sections (in yellow) (NHC 2001).

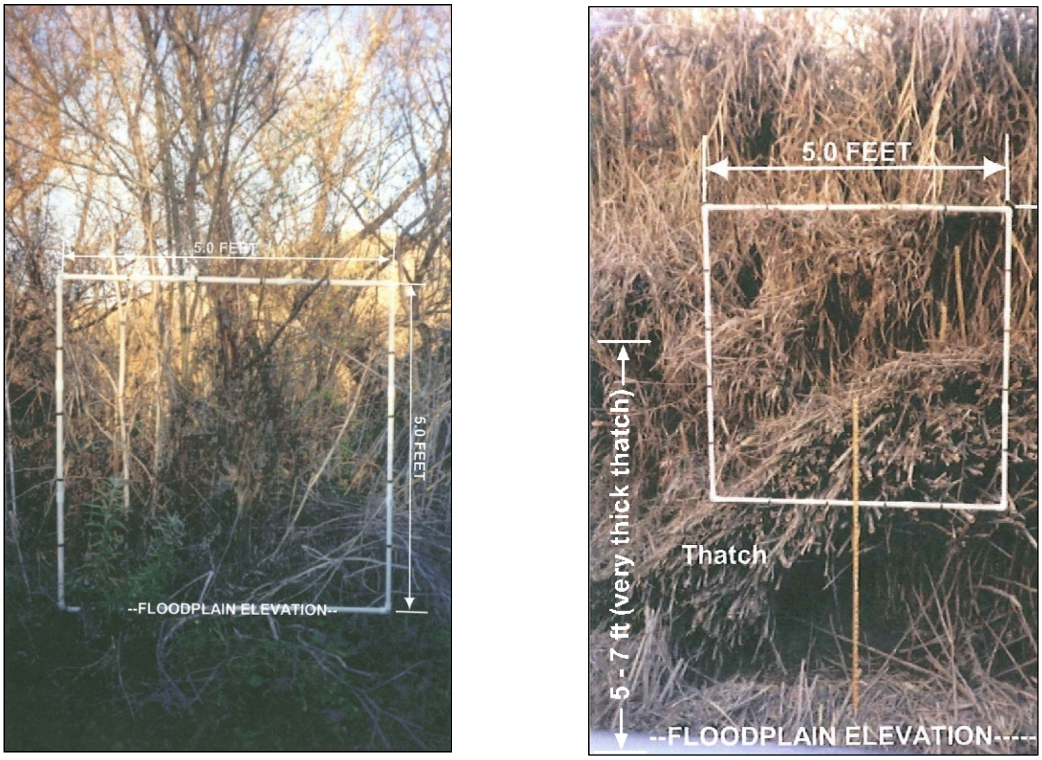
Model Calibration

The HEC-RAS model was calibrated to high water marks surveyed after the 1993 (44,000 cfs) and 1998 (18,400 cfs) floods. Calibration consisted of adjusting Manning's roughness and floodplain characteristics until calculated water surface profiles matched those observed during the floods. The initial calibration in *Arundo* infested areas resulted in Manning's n value on the floodplain that seemed unreasonably high, as much as 0.35 to 0.40, and were considerably higher than typical published values for roughness on vegetated floodplains.

Field observations of mature *Arundo* stands showed an extremely dense thatch of interlocking plant stems that extended 5 to 7 feet above the ground surface that effectively blocked conveyance on the floodplain (Figure 5-1.10). Above that elevation, the *Arundo* stems were not as interlocked or densely spaced and appeared to be able to bend in the flow, similar to native plant species such as willow. However, the *Arundo* exhibited a much higher density of stalks or stems than native willow species (Figure 5-1.10).

These observations led to a modified approach to hydraulic modeling in thick *Arundo* stands on the overbank or floodplain. The calibrated model eliminated flow conveyance in the first 5 feet in mature *Arundo* stands and used an average Manning's n value of 0.15 for water levels over 5 ft from the ground (NHC 2001). This range of roughness was in general agreement with the results of flume measurements of Manning's n for woody vegetation that included tamarisk (Freeman et al. 2000).

Additionally, a Manning's n of 0.10 was adopted for native vegetation on the floodplain and one of 0.05 for bare (un-vegetated) floodplain. A Manning's n of 0.04 to 0.06 was adopted for the low flow or main channel.



(a) Native Riparian Vegetation (b) Mature Stand of *Arundo*

Figure 5-1.10. Photographs of floodplain vegetation on the Santa Margarita River (1/4/1999).

Model Scenarios

The floodplain roughness in the calibrated HEC-RAS model described above was then adjusted to predict hydraulic characteristics over a range of flows for four different floodplain vegetation scenarios. These were:

- *Scenario 1 – Total Mature Arundo Infestation:* This scenario represents the ultimate extent of *Arundo* infestation, where the entire floodplain surface is covered by mature, monotypic stands.
- *Scenario 2 – Native Vegetation*: This scenario assumes that native vegetation covers the entire floodplain surface and that no *Arundo* is present.
- *Scenario 3 – Bare Floodplain:* This scenario assumes a floodplain surface where floodplain sediments are exposed as a result of fire, *Arundo* eradication, or a large flood event.
- *Scenario 4 – 1997 Floodplain:* This scenario represents the mix of *Arundo*, native vegetation, and bare surface on the floodplain observed in 1997, as interpreted from aerial photos onto the cross sections. Manning's n values vary across the floodplain in each cross section, based on the appropriate values adopted for the different vegetation types observed in the 1997 air photos.

In those scenarios where *Arundo* was present, floodplain elevations were raised 5 ft to simulate zero conveyance in mature *Arundo* stands (Scenarios 1 and 4). Otherwise, the low flow or main channel geometry and floodplain geometry were not altered and remain as described for the NHC (2001) model.

Peak Flows

Table 5-1.5 summarizes the peak flows adopted for the steady state HEC-RAS model runs that were performed as part this study.

Table 5-1.5. Peak flows adopted for the project reach (USACE 1994).

Return Period (years)	*Peak Discharge (cfs)*
2	3,000
5	9,400
10	17,000
25	31,500
50	46,000
100	64,000

Hydraulic Model Results for the 4 Scenarios

Table 5-1.6 provides a general summary of the variation in reach-averaged hydraulic variables for the various scenarios, compared to the native vegetation scenario (Scenario 2).

Table 5-1.6. Differences in hydraulic characteristics between scenarios.

Scenario	**Wetted Width[1]**	**Average Depth**	**Average Flow Velocity**	
			Channel	**Overbank**
1 – *Arundo* Infestation	Wider	Deeper	Faster	Slower
2 – Native Vegetation	*(baseline)*	*(baseline)*	*(baseline)*	*(baseline)*
3 – Bare Floodplain	Narrower	Shallower	Slower	Faster
4 – 1997 Floodplain	Variable	Variable	Variable	Variable

[1] Wetted Width – width of the wetted channel cross-section for a given flow discharge

The ratios of values for Scenarios 1 and 3 compared to Scenario 2 are generally consistent throughout the range of peak flows in Table 5-1.5. The ratios comparing Scenario 4 (1997 vegetation) to Scenario 2 vary. This occurs because the floodplain roughness varies from one cross section to another largely because the extent of the total floodplain area occupied by *Arundo* varies from one sub-reach to another (Table 5-1.7).

Table 5-1.7. Extent of *Arundo* by sub-reach as of 1997.

Sub-Reach [1]	*Floodplain Area (ac)*	*Arundo (ac)*	*Percentage*
1	128	24	19
2	210	93	44
3	396	112	28
4	113	62	55
5	203	90	45
6	59	11	18

[1] See Figure 5-1.6 for location of sub-reaches.

Design Water Surface Profiles

Figure 5-1.11 shows the project reach water surface profiles for the 100-year flood for each of the four scenarios. For the 1997 floodplain vegetation scenario (Scenario 4), 100-year water levels are typically close to that for native vegetation, but rise two to three feet in sub-reaches 4 and 5 where the infestation is dense (Table 5-1.7). Complete coverage by *Arundo* (Scenario 1) raises flood levels by 4 to 5 feet above those for native vegetation throughout the project reach; bare soil or no floodplain vegetation (Scenario 3) lowers them 2 to 3 feet throughout the project reach.

Water surface profiles for the 5-year flood show a similar pattern to that for the 100-year flood, but have smaller differences in stage. The full *Arundo* coverage scenario (Scenario 1) raises water levels up to 3 ft above those for native vegetation, whereas bare soil or no floodplain vegetation (Scenario 3) lowers them about 1 ft. The 5-year water levels for the 1997 vegetation scenario (Scenario 4) are close to those for complete native vegetation coverage, but rise one to two feet in sub-reaches where the infestation is particularly concentrated.

Comparison of results from Scenarios 1 and 4 to those from Scenario 2 suggests that there is a threshold for floodplain coverage by mature *Arundo*, below which impacts on average depths and water surface profiles are relatively insignificant. A rough idea of the threshold can be obtained by comparing *Arundo* densities in Sub-reaches 4 and 5 to those further downstream (Table 5-1.7). On this basis, percent *Arundo* coverage somewhere over 30% generally results in significant adjustments to the water surface profile.

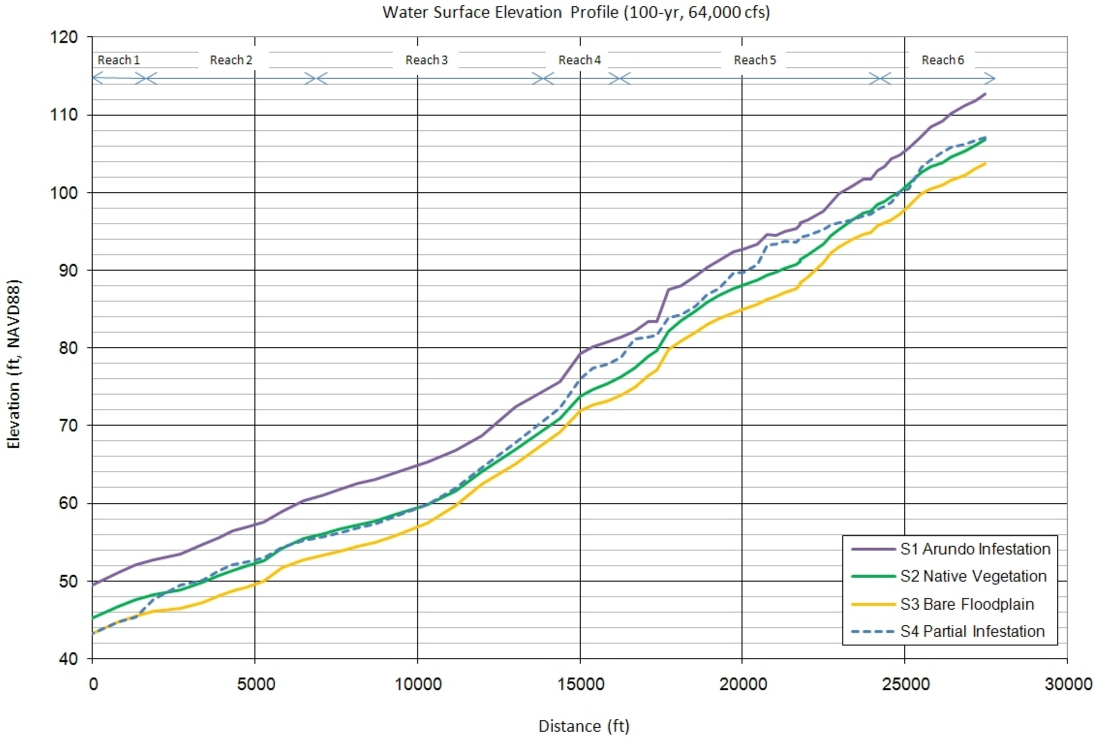


Figure 5-1.11. Project reach water surface profiles for scenarios 1 to 4: 100-year peak flow.

Channel and Floodplain Velocities

Table 5-1.6 indicated that complete coverage by *Arundo* results in the deepest flows and greatest velocities in the main channel and the slowest velocities on the floodplain. This illustrates a key characteristic of dense vegetation, such as *Arundo,* in the hydraulic model: flows are concentrated in the main channel by dense stands along the stream banks, resulting in deeper and faster flow through the main channel for a given discharge.

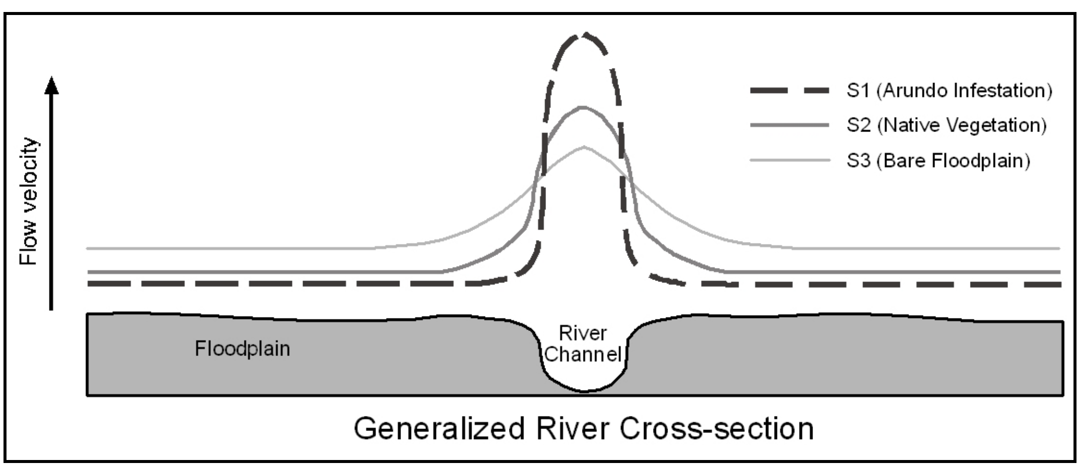


Figure 5-1.12. Generalized illustration of the effects of floodplain roughness (dense vegetation) on velocity across the section for Scenarios 1, 2, and 3.

In contrast, removal of floodplain vegetation results in the lowest average velocities in the main channel. Main channel velocities with floodplain vegetation removed would be lower still if channel widening due to the lower bank strength was incorporated in the RAS model. These observations are summarized in Figure 5-1.12.

Results by Sub-Reach

Table 5-1.8 compares hydraulic characteristics for the four scenarios for Sub-reaches 3 and 5. Sub-reach 5 has a 100-year floodplain width of about 1,100 feet; Sub-reach 3 is less confined and its floodplain width averages 3,500 feet (Table 5-1.4). As expected, the narrower Sub-reach 5 has greater average depths and velocities in the channel and on the floodplain than the wider Sub-reach 3 at the 100-year peak for all the scenarios. However, the percentage increases in average depths and velocities in Sub-reach 5, when comparing Scenario 1 to Scenario 2, are smaller than in Sub-reach 3. This is thought to occur because the main channel, whose roughness is not affected by differing vegetation types, occupies a larger portion of the total floodplain width and conveys a greater portion of the total flow. When Scenario 4 is compared to Scenario 2, the results are complicated by the different *Arundo* coverage percentages, but velocities increase in Sub-reach 3 and decrease in Sub-reach 5. In sub-reach 5, the increased floodplain roughness seems to be accommodated more by increased depths than velocities in the main channel, potentially as a result of backwater from Sub-reach 4.

Table 5-1.8. Depths and Velocities in Sub-reach 3 (wide floodplain) and Sub-reach 5 (narrow floodplain) for the 100-year peak flow.

Scenario	Sub-Reach 3 (wide floodplain)					Sub-Reach 5 (narrow floodplain)				
	Wetted Width (ft)[1]	Average Flow Depth (ft)		Average Flow Velocity (ft/s)		Wetted Width (ft)[1]	Average Flow Depth (ft)		Average Flow Velocity (ft/s)	
		CH	OB	CH	OB		CH	OB	CH	OB
1 – *Arundo* Infestation	3,530	17.5	7.5[2]	10.3	1.5	1,150	20.2	10.5[2]	13.4	2.3
2 – Native Vegetation	3,480	12.3	7.2	8.0	2.2	1,140	15.7	10.4	11.8	3.6
3 – Bare Floodplain	3,400	9.9	4.9	7.2	3.6	1,120	12.9	7.8	10.4	6.0
4 – 1997 Floodplain	3,280	12.2	6.6	8.4	2.5	1,140	17.5	10.0	10.9	3.7

[1] Wetted Width – width of the wetted channel cross-section for a given flow discharge
[2] Represents depth of active flow conveyance area only, and does not include 5 ft thickness of ineffective flow in *Arundo* areas.
Note: CH = Channel; OB = Overbank or floodplain

As noted earlier, the above results assume the same geometry for the main channel and floodplain for each scenario; only roughness changes from one scenario to another.

5.1.4.7 Project Reach Sediment Budget

Introduction and Context

Sediment transport in rivers is complex and this chapter considers only two of its components. This section discusses reach-based sediment budgets and addresses the question of whether *Arundo* infestation might reduce sediment delivery to downstream reaches and, ultimately, to the Pacific Ocean. This section also discusses the potential changes in sediment transport capacity that might result from the altered hydraulics discussed in the previous section and considers the likely channel response. The analyses are speculative for both of these components.

Sediment Budget Considerations

The sediment budget for a particular reach – such as the project reach on the Santa Margarita River – can be expressed as follows:

$$\text{Sediment}_{\text{Out}} = \text{Sediment}_{\text{In}} \pm \Delta\text{Storage} \qquad (1)$$

In (1), the change in sediment storage in the reach over time (ΔStorage) can be either negative (erosion from the reach) or positive (deposition in the reach), with erosion increasing the sediment output; deposition reducing it.

The budget can be constructed for various time periods or grain size classes. The analysis for the project reach focuses on long-term averages and the transport of sand. In the Santa Margarita River, sand makes up much of the bed material. It is transported both in suspension and as bed load (Slagel and Griggs 2006).

If we can assume that the sediment delivered to the project reach is reasonably constant over the long-term then the sediment that leaves the reach will differ from that arriving as a result of changes in sediment storage within the reach, including those that result from *Arundo* establishment. Changes in storage within the reach are best measured by comparing repeated surveys of channel and floodplain cross sections to define volumes and by sediment sampling to define the size distribution of the materials that have been eroded or deposited. Such information is not available on the Santa Margarita River and is seldom available for large rivers in Southern California. Instead, we rely on observations in other reports to roughly define the changes in sediment storage expected with *Arundo* infestation and sediment delivery studies to define the long-term sediment input to the stream reach.

Santa Margarita River Sediment Loads

Previous studies (Slagel and Griggs 2006, Inman and Jenkins 1999) have estimated annual sediment transport in the Santa Margarita River from sediment gaging at the Ysidora gage, which is downstream of the project reach. Average annual transport was between 50 and 70 acre-feet (65,000 and 80,000 m^3) in the two studies. Slagel and Griggs (2006) also concluded that average annual sand transport was about 20 acre-feet (25,000 m^3), or about 30 to 40% of the total transport.

Sediment Capture by *Arundo*

Previous studies (see Section 5.1.2) indicate that deposition occurs on the floodplain as *Arundo* stands establish and mature. Rates have not been measured on the Santa Margarita River but the average annual accretion rates discussed in Chapter 2 ranged from about 0.3 to 0.7 feet per year. Given these rates, the average annual storage in the *Arundo* stands on the floodplain might then be from 120 to 280 acre-feet over the 400 acres of *Arundo* growth that was present in 1997. Roughly one-third of the total is sand (see

Slagel and Griggs 2006), or about 40 to 90 acre-feet. This represents the average annual loss of sand in transport to storage in *Arundo* stands. Sediment deposition is also likely to occur on the remainder of the floodplain but this has been ignored in the simple budget constructed to evaluate *Arundo* impacts.

It is not known how long the above average rates of accretion or deposition might continue. Rates may be curtailed as the floodplain and braid channels fill with sediment, particularly because the channel thalweg does not seem to be aggrading on the Santa Margarita River.

Adding the above annual estimate of sand trapped on the floodplain to the transport observed at the Ysidora gage (the sediment leaving the reach) indicates that the annual sand inflow to the project reach might have been 60 to 110 acre-feet during the period of *Arundo* establishment and growth. On this basis, the sediment output from the reach was reduced to one-third or less of the sediment input by storage in the *Arundo* stands. This suggests that *Arundo* establishment and growth on the floodplain of the project reach has the potential to capture a substantial portion of the sediment delivery from the upper watershed. As discussed in the next section, losses to deposition on the floodplain may be partly compensated for by erosion from the channel bed.

Erosion in the Main Channel from *Arundo* Growth

Based on the literature review, at the same time as the *Arundo* stands on the floodplain are trapping sediment in transport, the main channel can be expected to narrow. We have no good measurements of the change in width that occurred as *Arundo* stands established and dominated the riparian and floodplain vegetation on the Santa Margarita River. However, measurements by Cal-IPC (Section 4.5) show that the main channel width about tripled in width following *Arundo* eradication. Assuming that the same results would occur in reverse during *Arundo* establishment and growth, the main channel with *Arundo* infestation might be about one-third to one-half as wide as it was prior to *Arundo* establishment.

As the channel narrows it would be expected to deepen to pass typical floods, as is commonly observed in regime studies. Such a response was not observed often in the literature review but that may be because the channel bed or thalweg rose as the floodplain filled but to a lesser extent, creating a deeper flow channel. It is not known how channel depths have changed on the Santa Margarita River following *Arundo* infestation.

A rough estimate of the increased depth required to pass typical floods as the channel narrows can be obtained by applying Blench's (1969) regime equation. It suggests that the increase in channel depth for the above reductions in width might be about 50 to 100%. The typical channel depth before *Arundo* establishment is not known, but the observed channel bank height in the project reach as of 1997 or so, with *Arundo* in place, was about 4 to 6 feet, consistent with calculated average depths at the 2-year flood. Based on the ratio above, it appears that the channel may now be 2 to 3 feet deeper than it was prior to *Arundo* establishment. The greater channel depth might result from bed erosion, increased floodplain height adjacent to the channel, or a combination of the two processes.

The area of the main channel in 1997 was 118 acres and the bed material was sand. Assuming that 2 to 3 feet of erosion occurred over twenty years, the average annual net loss of bed material from the reach could be as much as 12 to 18 acre-feet over the project reach. As noted above, the net erosion might be zero if the channel deepens by filling on the floodplain rather than by eroding its bed.

Project Reach Sediment Budget Summary

The above suggests that annual trapping of sand on the floodplain during *Arundo* establishment and growth in the project reach was about 40 to 90 acre-feet; the erosion from the channel bed as it adjusted to narrower widths is expected to be less than 20 acre-feet. The above estimates are based on accretion and erosion rates from the literature rather than from measurements on the Santa Margarita River. However, they suggest that *Arundo* establishment and growth is likely to reduce the volume of sand transported through the project reach to the coast. As noted above, two-thirds of the sand transported from the upper Santa Margarita River watershed might be trapped in *Arundo* stands in the project reach during their establishment and growth.

After *Arundo* has established and reached its maximum coverage, we anticipate that accretion of sediment on the floodplain will slow, unless the channel fills rapidly so that flood waters continue to spill onto the higher floodplain. As the accretion on the floodplain slows or stops, the adjustment of channel depth to the narrower channel width will also slow or stop. At this point, sand transport out of the reach will be in equilibrium with sediment supply.

The observed difference between losses to sediment storage and gains from bed erosion in the Santa Margarita River may not be the same in other Southern California Rivers with different overall geomorphology. Where the floodplain is narrower than in the Santa Margarita River, bed erosion may be a large portion of storage and the reduction in sand transport towards the coast with *Arundo* establishment may be smaller. Where the floodplain is much wider, the opposite result may occur.

5.1.4.8 Project Reach Sediment Transport Capacity

Introduction and Context

Suspended sediment transport has been measured at the Ysidora gage on the Santa Margarita River; however, there are no measurements of bed load transport. Bed load and bed material load transport have been modeled by NHC (1997b) and West Consultants (2000) but only for the *Arundo* coverage that existed in the late 1990s. Consequently, an evaluation of the potential effects of varying *Arundo* coverage or *Arundo* eradication on sediment transport capacity must be calculated from the hydraulic output from the HEC-RAS model runs.

The RAS model runs have some limitations for calculating sediment transport capacity for different conditions. The actual channel and floodplain geometries under different vegetation scenarios are not known; nor do we know if the size of material on the channel bed differs for these scenarios. Instead, as described earlier, the RAS model adopted the channel and floodplain geometry from 1997 for all the scenarios, altering the floodplain roughness and conveyance to simulate different vegetation scenarios, and assumed the same bed material distribution.

Approach to Transport Capacity

We have adopted stream power as the best proxy for sediment transport capacity differences among the four floodplain vegetation scenarios (Bagnold 1966; Vanoni 1975). Stream power per unit length of channel, which is essentially a measure of the energy available to transport sediment once a critical threshold for mobility is passed, is defined as:

$$\Omega = \rho g Q S \qquad (2)$$

where Ω is stream power, ρ is the density of water, g is the acceleration due to gravity, Q is a discharge and S is energy slope, roughly parallel to the bed slope. For calculations from the model output, $Q = wdv$, where w is channel width, d is average channel depth and v is average sectional velocity, was substituted into Equation (2) and terms regrouped as:

$$\Omega = \tau v w \qquad (3)$$

In Equation (3), τ is the average bed shear stress. Stream power was calculated separately for the channel and floodplain for each of the four scenarios, for the 5-year through 100-year peak flows (see Table 4.2). Average annual stream powers were then calculated based on an expression reported in USACE (1995) that incorporates the stream power exerted by floods up to the 100-year return period and approximates the area under the annual probability-event yield curve.

Stream Power for Different Scenarios

Table 5-1.9 summarizes the stream power calculated for Scenarios 1, 3, and 4 as a ratio to that calculated for Scenario 2 (Native Vegetation), the adopted baseline or index condition. Numbers >1 indicate more power and greater sediment transport, and numbers <1 indicate less power and sediment transport. This table shows that the ratios of the stream power to that for Scenario 2 are not particularly sensitive to the magnitude of the flood, under the model assumption of fixed channel and floodplain geometry. In the Santa Margarita River we expect that the channel will respond rapidly to increased stream power, altering its depth, width (where geometry permits) or bed material size until thresholds for transport are increased or bed stresses are reduced. Thus, the observed differences may not persist for the frequent floods, but are likely to persist for the largest ones.

Table 5-1.9 is helpful when considering potential channel and floodplain responses to changes in floodplain vegetation. For example, it suggests that as vegetation changes from native to a mixture of *Arundo*, native vegetation and bare soil (Scenario 4) the stream power exerted in the main channel will increase and, hence, it will begin to deepen. Stream power exerted on the floodplain will decrease and filling of secondary channels and deposition on the floodplain might be anticipated. When floodplain changes from a vegetated state to bare soil (Scenario 3), as it would under the *Arundo* eradication program, the stream power exerted in the main channel reduces and deposition or channel filling might occur. On the floodplain, stream power is greatly increased and rapid development of channel braids would be expected, returning the channel form to a braided appearance, such as has been observed in the Santa Margarita River. This assumes that the *Arundo* root mass has been removed or that it does not affect stability of the sediments. Areas with rhizome mats still in place would be expected to be more erosion resistant than bare soil, and might reduce or prevent geomorphic change.

Table 5-1.9. Summary of relative differences in stream power by scenario for entire study area, (S2: native is baseline).
>1 = more power and sediment transport, <1 = less power and sediment transport

	Channel				**Floodplain**			
Flow Event	**S1 *Arundo***	**S2 Native**	**S3 Bare**	**S4 Mix-1997**	**S1 *Arundo***	**S2 Native**	**S3 Bare**	**S4 Mix-1997**
5-year	**1.41**	1.00	0.88	**1.02**	**0.23**	1.00	1.33	**0.95**
10-year	**1.59**	1.00	0.86	**1.06**	**0.38**	1.00	1.22	**0.92**
25-year	**1.51**	1.00	0.80	**1.10**	**0.50**	1.00	1.17	**0.89**
50-year	**1.50**	1.00	0.77	**1.13**	**0.59**	1.00	1.16	**0.92**
100-year	**1.50**	1.00	0.74	**1.14**	**0.66**	1.00	1.15	**0.95**
Average Annual	**1.50**	**1.00**	**0.83**	**1.07**	**0.49**	**1.00**	**1.20**	**0.93**

S1=all *Arundo*, S2=all native, S3=all bare, S4=1997 site conditions (mix of *Arundo*, native, bare).

Stream Power by Sub-Reach

In a similar fashion to the hydraulic characteristics, the relative changes in stream power also vary from sub-reach to sub-reach, depending on floodplain width. A narrow sub-reach (5) and a wider sub-reach (3) are presented in Table 5-1.10 to illustrate this.

Where the floodplain is wide relative to the channel there are potentially greater changes in stream power in the main channel with complete *Arundo* coverage (Scenario 1). Thus, a greater channel response (power and sediment transport) would be expected in wider floodplain reaches with complete *Arundo* coverage than in narrower ones, which is confirmed in Table 5-1.10. The lower power/sediment trapping effect on floodplains is more pronounced in narrower sub-reaches (S1 and S4 are lower). This may be off-set by the spatial extent of floodplains, however, as there is more invaded floodplain in sub-reach 3 to catch sediment, wider floodplain seems to balance in terms of sediment transport, narrower reaches may trap more.

Table 5-1.10. Differences in relative stream power for sub-reaches 3 and 5.

Sub-reach 3 (wider floodplain)

	Channel				Floodplain (overbank)				Total			
Flow Event	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97
10-year	**1.75**	1.00	0.82	**1.09**	**0.42**	1.00	1.18	**1.02**	**0.99**	1.00	1.02	**1.05**
10o-year	**1.78**	1.00	0.82	**1.20**	**0.72**	1.00	1.18	**1.09**	**0.99**	1.00	1.09	**1.12**

Sub-reach 5 (narrower floodplain)

	Channel				Floodplain (overbank)				Total			
Flow Event	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97	**S1** *Arundo*	**S2** Native	**S3** Bare	**S4** Mix'97
10-year	**1.30**	1.00	0.86	**0.89**	0.28	1.00	1.28	**0.68**	**0.90**	1.00	1.02	**0.81**
10o-year	**1.33**	1.00	0.73	**0.83**	0.57	1.00	1.22	**0.69**	**0.91**	1.00	1.00	**0.76**

S1=all *Arundo*, S2=all native, S3=all bare, S4=1997 site conditions (mix of *Arundo*, native, bare).

5.1.4.9 Case Study Summary

This section summarizes our understanding of the effects of *Arundo* establishment on hydraulics, sediment transport and geomorphology, based on the case study in the lower Santa Margarita River project reach.

Similar to other rivers in Southern California and throughout the American Southwest, the establishment and spread of *Arundo* on the lower Santa Margarita River has narrowed the active river channel and simplified its river cross-section. This has resulted in a shift from a wide, braided river planform to a single channel with defined banks and few bare active geomorphic surfaces. The narrowing trend has been interrupted by occasional large floods which remove floodplain vegetation and widen the channel, such as occurred in 1969 and 1993. It is not understood or known what the minimum channel width might be in the absence of large floods.

Inspection of historical air photos suggest that there has been much less channel widening from recent large floods than occurred in 1969, presumably because of different erosion resistance of the floodplain since the *Arundo* stands have been established. Little is known of the hydraulic forces that can be withstood by the *Arundo* stands in various types of floodplain deposits (soils) so there is no good understanding of how large a flood would be required to remove stems, erode the root mass, and reset the floodplain vegetation. In any event, it appears that *Arundo* will out-compete native vegetation on the disturbed floodplains and re-establish mature stands on much of the floodplain in the time interval between very large floods.

The mature *Arundo* stands essentially eliminated flow conveyance during low and moderate floods on the portions of the floodplain that they occupy, increasing the portion of the flow passing through the low flow or active channel. During large peak flows, when water levels are more than 5 feet or so over the floodplain surface, flow is conveyed over the mature *Arundo* stands but considerable roughness is created by the stems and leaves. During very great flows, the *Arundo* stems may be broken off and carried downstream, substantially altering local resistance to flow.

Hydraulic modeling of four different floodplain vegetation scenarios (all *Arundo*, all native, all bare, 1997 field conditions) suggested that the conversion from native vegetation to complete coverage by mature *Arundo* stands would have three important implications. First, 100-year water levels are raised by 3 or 4 feet from the increased roughness. Second, the portion of the total discharge carried in the main channel increases and, thus, depths and velocities also increase for a particular return period flood. Third, the (modeled) conveyance on the floodplain is much less with *Arundo* infestation.

There are some interesting and significant subtleties suggested by the hydraulic modeling. First, there appears to be a threshold for *Arundo* coverage before there are significant effects on hydraulics. The exact portion of the floodplain that must be occupied for a significant effect is not fully understood. Second, the magnitude of the effect on hydraulics of *Arundo* infestation and the threshold for observing significant effects depends on the overall floodplain and channel width. Narrow total widths show less effect for a particular flood than wide ones, likely because there is less conveyance on the narrow floodplains for the native vegetation scenario, so there is a smaller increase in flows in the main channel when *Arundo* coverage is complete. Note that velocities are higher in the narrower reaches; the above differences refer only to the observed percentage increases with the *Arundo* scenario in the hydraulic model.

The results of the hydraulic model studies are limited because they do not account for channel adjustments that are expected to occur rapidly in response to the altered hydraulics on the floodplain and in the main channel. Stream power calculations, which were adopted as a proxy for sediment transport, show greatly increased stream power in the main channel and greatly reduced stream power exerted on the floodplain under complete *Arundo* coverage, when compared to native vegetation, and a smaller increase and smaller decrease for partial coverage (Scenario 4). The consequences of the changes in stream power (or any measure of forces exerted on the bed) when banks are less erodible because of *Arundo* establishment are expected to be increased depths of the main channel and sediment trapping and accretion on the floodplain and in overbank areas. Regime considerations suggest that average depths might increase by about 50% to 100% for frequent floods to compensate for the narrowed channel. However, this is only a rough estimate and has not been confirmed with field surveys or measurements.

Both of the channel responses described above change the sediment storage in the project reach on the Santa Margarita River and potentially affect the delivery of sediment from the upper watershed to downstream reaches and the Pacific Ocean. Considering only the sediment balance for sand, and relying on accretion rates observed in the literature, it appears that the annual loss of sand to trapping on the floodplain during *Arundo* establishment is much larger than the compensating erosion from the adjustments of the channel. In the Santa Margarita River project reach, the net deposition on the floodplain is a very large portion of the sand carried down from the upper watershed. As discussed, different conclusions might be drawn for rivers with much wider or much narrower floodplains.

Once *Arundo* reaches its maximum coverage, floodplain trapping and channel adjustments will eventually cease, and delivery from the upper watershed to the reach will equal that which passes through to downstream reaches and the Pacific Ocean.

5.1.5. Study Stream Arundo Responses

5.1.5.1 Introduction

This section applies the results of the literature review (section 5.1.3) and the case study analysis (section 5.1.4) to develop a method to qualitatively assess the potential impacts of *Arundo* infestation on river hydraulics, sediment transport capacity and geomorphology. Once developed, the method is applied to the Santa Margarita, Santa Ana and San Luis Rey Rivers, utilizing the river and riparian vegetation characteristics provided in Chapter 5.1.3. Stream responses to *Arundo* discussed in this chapter are based on the maximum extent of *Arundo* mapped in these study reaches by Cal-IPC, as presented in Chapter 5.1.3.

5.1.5.2 *Arundo* Impact Scoring System

The potential impacts of *Arundo* infestation on river characteristics and, to some extent, the potential impacts of reach characteristics on the maximum extent of *Arundo* coverage, were qualitatively assessed by totaling scores that were developed from the key findings and observations from the literature review, Santa Margarita River case study and GIS mapping effort (Chapter 5.1.3).

The Width Ratio and *Arundo* Coverage scores express the potential for modification of the river as a result of *Arundo* Infestation. The Changes in Floodplain Width and Bed Slope, and Other Features scores express the potential for *Arundo* to dominate the riparian vegetation on the floodplain in the reach. We have defined the *Arundo* Impact Score to be the sum of the individual scores, as defined below. As scores increase, significant changes in river characteristics become more likely and differences between the *Arundo* and native vegetation river characteristics become greater. The specific impacts of *Arundo* on river characteristics are likely to be different in each stream reach and river system; however, the general effects will be similar to those described in Sections 5.1.2.4 and 5.1.4.9.

Width Ratio Score

The Santa Margarita River case study demonstrated that wider floodplain reaches may have a greater hydraulic response to *Arundo* infestation than narrower ones. A score was developed based on this observation using the Width Ratio (see Chapter 5.1.3), which is the ratio of the low flow channel width to the floodplain width (Table 5-1.11).

Table 5-1.11. Width ratio score.

Width Ratio	Width Ratio Factor	Comment
Below 4%	2	Wide floodplain reach
4% - 8%	0	Average width floodplain reach
Above 8%	-1	Narrow floodplain reach, typically confined by either topography or levees

Width ratios of 4% and 8% were selected as the cut-offs between wide, average, and narrow floodplain categories, based on the differences observed between Sub-reach 3 (wide floodplain) and Sub-reach 5 (narrow floodplain) in the Santa Margarita case study. Note that Sub-reach 3 is Reach 6 (width ratio =

3.8%) and Sub-reach 5 is Reach 8 (width ratio = 7.0%) in Table 5-1.1. The scores assigned to the different width ratios is shown in Table 5-1.11.

Arundo Coverage Score

The Santa Margarita case study suggested that a threshold of floodplain coverage by mature *Arundo* exists, below which impacts on average depths and water surface profiles are relatively insignificant. This percent coverage seemed to be between 28% and 45% *Arundo* coverage for the case study river (see Section 5.1.4.6). Table 5-1.12 shows the scoring that was developed based on the percent *Arundo* Coverage mapped for each reach in section 5.1.3. Cut-off points of 25% and 40% were selected for scoring the impact of percent *Arundo* cover on river characteristics.

Table 5-1.12. *Arundo* coverage score.

% *Arundo* Coverage	*Arundo* Coverage Factor	Comment
Below 25%	0	The effects of *Arundo* on hydraulics may not be significant in this reach
25% - 40%	1	This range of *Arundo* coverage represents a transition zone within which significant impacts to the water surface profile and consequently river hydraulics and sediment transport and geomorphology may occur
Above 40%	3	High percent *Arundo* coverage suggests this reach provides optimal conditions for *Arundo* establishment and changes in hydraulic, sediment transport and geomorphic effects are likely to be significant

Changes in Floodplain Width and Bed Slope Scores

The GIS analysis in Section 5.1.3 showed a relationship between the maximum percent *Arundo* coverage observed in a reach by Cal-IPC and changes in floodplain width and bed slope relative to the reach upstream. As previously discussed, large increases in floodplain width and declines in bed slope contribute to decreased flow velocities and sediment transport capacity. This promotes deposition and increases the likelihood of *Arundo* dispersal in that reach. Conversely, abrupt declines in floodplain width or increases in bed slope may promote the opposite effect and limit *Arundo* propagules from depositing.

Chapter 5.1.3 also noted there may be an upper slope limit for significant *Arundo* coverage in the floodplain vegetation that may be a proxy for a number of other factors. Also, the above discussion does not apply to river estuary reaches where salt water intrusion restricts *Arundo* growth and coverage. This is a narrow range, however, as *Arundo* tolerates up to 90% salt water.

Large increases (>100%) in floodplain width relative to the reach upstream are observed in Reach 7 of the Santa Margarita River, Reach 6 of the San Luis Rey, and Reaches 2 and 4 of the Santa Ana River. Each reach exhibits either a large (>50%) increase in *Arundo* cover from the reach upstream and more than 40% total *Arundo* cover. Conversely, Reach 3 of the Santa Ana River exhibits a 100% decline in floodplain width and nearly 50% decline in percent *Arundo* cover relative to the reach upstream. The scores associated with changes in floodplain width are summarized in Table 5-1.13.

Large decreases (>33%) in bed slope relative to the reach upstream are observed in Reach 7 of the Santa Margarita River, Reaches 2, 4 and 8 of the San Luis Rey, and Reach 3 of the Santa Ana River. Reach 7 exhibits greater than 45% *Arundo* cover and Reaches 2 and 4 exhibit large (>33%) increases in percent *Arundo* cover relative to the reach upstream. Reach 3 shows a decline in percent *Arundo* cover, possibly because of a large decline in floodplain width, and Reach 8 has negligible *Arundo* cover as does the reach upstream. The effect of changes in channel bed slope on the *Arundo* impact score are summarized in Table 5-1.14.

Table 5-1.13. Floodplain width score.

% Change in Floodplain Width	Floodplain Width Factor	Comment
>100% Decrease	-1	Flow confinement promotes higher average flow velocity, limiting the potential for deposition of *Arundo* propagules in this reach
Less than 100% Change	0	Changes in floodplain width may be significant in affecting the deposition of *Arundo* propagules but do not show a clear impact.
>100% Increase	1	Floodplain widening promotes a decline in average flow velocity and promotes deposition of *Arundo* propagules in this reach.

Table 5-1.14. Bed slope score.

% Change in Bed Slope	Bed Slope Factor	Comment
>33% Decrease	1	Decreases in bed slope promote lower average flow velocity which favors the deposition of *Arundo* propagules in this reach.
Less than 33% Change	0	Changes in bed slope may be significant in affecting the deposition of *Arundo* propagules but do not show a clear impact.
>33% Increase	-1	Increases in bed slope promote higher average flow velocity, limiting the potential for deposition of *Arundo* propagules in this reach

Other Features

Other features not already incorporated into the *Arundo* impact score are also indentified and, if present, provide an additional factor of '1' or '-1' depending on the feature observed. These include salt water intrusion that limits *Arundo* growth at the river mouth, and anthropogenic features that could potentially influence *Arundo* impacts on a river reach. Features specific to each stream are discussed in the next section.

5.1.5.3 Santa Margarita River

Table 5.5 shows the *Arundo* impact scores for the Santa Margarita River study reaches (Figure 5-1.1 shows reaches). Note that the case study Sub-reaches 1 through 6 conform to Reaches 4 through 9 in the GIS mapping in Chapter 5.1.3.

Table 5-1.15. Santa Margarita River *Arundo* impact scores.

Reach	Reach length (mi)	Case Study Sub-Reach	*Total Score*	*Arundo* Impact Scores				
				Width Ratio	*Arundo* Coverage	Floodplain Width	Bed Slope	Other Features
1	1.52		***-1***	-1	0	0	1	-1
2	1.47		***-1***	-1	0	0	0	0
3	1.70		***0***	0	0	0	0	0
4	0.42	1	***2***	2	0	0	0	0
5	0.90	2	***6***	2	3	0	1	0
6	1.30	3	***2***	2	1	0	-1	0
7	0.42	4	***7***	2	3	1	1	0
8	1.60	5	***4***	0	3	0	0	1
9	0.77	6	***0***	-1	0	0	0	1
10	1.21		***0***	-1	0	0	0	1
11	1.89		***-1***	-1	0	0	0	0
12	4.11		***-1***	-1	0	n/a	n/a	0

Table 5-1.15 shows that Reaches 4 through 8 (Sub-reaches 1 through 5) are the most susceptible to changes in river form and process from *Arundo* infestation. For the most part, these reaches have low slopes, wide floodplains with abundant opportunity for *Arundo* establishment and propagation, and historically large areas of *Arundo* stands. Other features that affect *Arundo* distribution and potential impacts on river characteristics includes salt water that limits *Arundo* growth in Reach 1 and groundwater recharge from Lake O'Neill and infiltration ponds in Reaches 8, 9 and 10 that provides additional water.

Table 5-1.15 identifies sub-reaches 2 and 4 as those where *Arundo* is likely to exert the greatest impact on river characteristics. Such a result is reasonably consistent with the case study observations in section 5.1.4. Sub-reach 4 does show a rise in the water surface profile compared to the base case (Figure 5-1.11) and other modifications to the reach hydraulics occur. Sub-reach 2 shows no rise in the water surface profile (Figure 5-1.11); instead, the increased flow through the main channel is accommodated by increases in velocities. The highest scoring contiguous river sections (Reaches 4 to 8) is about 8 miles long. This is a significant portion of the river.

5.1.5.4 San Luis Rey River

Table 5-1.16 shows the *Arundo* impact scores for the San Luis Rey study reaches. Based on this table, the greatest modification to river characteristics from *Arundo* impacts are expected to be in Reaches 2 and 4. *Arundo* has also historically been well established in Reaches 3 and 5 but they do not score very high due to floodplain confinement by urban levees. Further upstream, in Reaches 8 through 11, a score of -3 was assigned in Other Features to reflect that these steeper reaches have little or no *Arundo* in their floodplain vegetations, suggesting that *Arundo* has not successfully colonized this area. This may be a result of steep bed slopes in these upper reaches that reduce opportunities for *Arundo* establishment, or lack of source propagules or plants.

The overall scores for the San Luis Rey River reaches are considerable less than for the Santa Margarita River reaches suggesting that *Arundo* impacts on river forms and processes may be less significant. However, Reaches 2, 4 and 6 constitute most of the functional lower river (9 mi), and these areas are impacted. Reaches 3 and 5 only function to convey water, and they have limited geomorphic or biologic function.

Table 5-1.16. San Luis Rey *Arundo* impact scores.

Reach	Reach length (mi)	*Total Score*	*Arundo* Impact Scores				
			Width Ratio	*Arundo* Coverage	Floodplain Width	Bed Slope	Other Features
1	0.86	***-1***	-1	0	0	1	-1
2	1.66	***3***	-1	3	0	1	0
3	5.79	***-1***	-1	0	0	0	0
4	5.53	***2***	0	1	0	1	0
5	0.62	***-1***	0	0	-1	0	0
6	5.07	***1***	0	0	1	0	0
7	3.73	***-2***	-1	0	-1	0	0
8	3.73	***0***	2	0	0	1	-3
9	2.03	***-1***	2	0	0	0	-3
10	2.01	***-5***	0	0	-1	-1	-3
11	1.16	***-1***	2	0	n/a	n/a	-3

5.1.5.5 Santa Ana River

Table 5-1.17 summarizes the *Arundo* Impact scores for the Santa Ana River reaches (Figure 3-2 shows reaches). Based on these scores, the greatest modification to river processes and form are expected to occur in Reaches 1 and 2. Note that Reach 1 is in the Prado Flood Control Basin and *Arundo* establishment and spread will be different than in other reaches because of basin filling during large runoff events and long-term sediment deposition.

Reach 2 has a meandering channel that flows through a shallow valley. The wide floodplain provides substantial opportunity for *Arundo* establishment and the gradual reduction in slope down the reach and its location downstream of a steeper, more confined Reach 3 also contribute to the high score. Impacts of *Arundo* on river form and process are expected to similar to those observed in the Santa Margarita River here. It should be noted that Reach 2 is very long (8 mi), equaling the length of 3-5 reaches on the San Luis Rey or Santa Margarita. Impacts to reaches 1 and 2 total 10 miles, and this is most of the broad floodplain on the river.

Table 5-1.17. Santa Ana River *Arundo* impact scores.

Reach	Reach length (mi)	*Total Score*	*Arundo* Impact Scores				
			Width Ratio	*Arundo* Coverage	Floodplain Width	Bed Slope	Other Features
1	3.16	***5***	2	0	1	1	1
2	12.17	***4***	0	3	1	0	0
3	2.08	***-1***	-1	0	-1	1	0
4	2.35	***0***	-1	0	1	0	0
5	9.67	***0***	-1	0	0	1	0
6	3.98	***-2***	-1	0	-1	0	0
7	3.44	***-1***	-1	0	n/a	n/a	0

5.1.5.6 Application of Scoring System

The scoring system proposed above is preliminary and might be modified based on experience and further analyses of river response to *Arundo* infestation by adjusting scoring or weighting of the different scores. At this time, the scoring system can be used to identify and rank those river reaches where *Arundo* establishment is likely to have significant effects on river hydraulics, sediment transport and morphology. This could be used to prioritize areas for additional monitoring to look at: flood risk damage (bridges and overbank), sediment retention and loss, as well as setting control priorities and/or temporary reduction of vegetation to maintain flows.

5.1.6. Conclusions and Recommendations

The overall goal of this study was to describe the potential effects of *Arundo* establishment and growth on the hydraulics, sediment transport characteristics and morphology in Southern California Rivers. The study results are based on literature review, GIS analysis of river and floodplain vegetation characteristics, and hydraulic modeling of four floodplain vegetation scenarios on the Santa Margarita River.

Arundo is a highly aggressive, non-native plant species that has invaded riparian areas and floodplains of the sandy, braided Southern California Rivers, displacing native plants and degrading habitats. These historically braided and laterally unstable channels are transformed by *Arundo* into narrower, more laterally stable single thread channels with root-stabilized, steep banks. Inspection of historical air photos suggest that there has been much less channel widening from recent large floods than occurred earlier, presumably because of the replacement of native floodplain vegetation with much denser *Arundo* stands. In any event, it appears that if sufficient soil moisture is available *Arundo* will out-compete native vegetation on the disturbed floodplains and re-establish mature stands on much of the floodplain in the time interval between very large floods.

Plant colonization stabilizes bar and floodplain surfaces, increasing channel roughness and sediment trapping efficiency, thereby creating a mechanism for further sediment capture, deposition and vertical accretion. Long-term observed rates of vertical accretion on the floodplain vary widely in the reported literature but are as high as 0.8 ft/yr. Several feet may accumulate locally during a large flood.

Accretion rates likely vary with the volume of sediment in transport as well as the specific river conditions. There may be an upper limit on vertical accretion, which would about correspond to the elevations of typical floods. This may be reached fairly soon if the channel bed incises or does not accrete as rapidly as the floodplain. If the channel bed fills as the floodplain accretes, this limit may not be reached for a long time. Human modification to upstream and downstream reaches (such as levees or bridges) and to flood flows and sediment supply (such as by reservoir construction or groundwater recharge) may alter river and *Arundo* establishment processes and affect the above observations on river response to *Arundo* establishment and growth.

Hydraulic modeling and field inspection suggests that the mature *Arundo* stands essentially eliminate flow conveyance during low and moderate floods on the portions of the floodplain that they occupy, increasing the portion of the flow passing through the low flow or active channel. During large peak flows, when water levels are about 5 feet higher than the floodplain surface, flow that is conveyed over the mature *Arundo* stands also slows as considerable roughness is created by the stems and leaves. During very large flow events, the *Arundo* rhizomes and stems may be carried downstream, substantially altering local resistance to flow. Modeling of different floodplain vegetation scenarios suggested that the conversion from native vegetation to complete coverage by mature *Arundo* stands has three important implications. First, 100-year water levels are raised by the increased roughness. Second, the portion of the total discharge carried in the main channel increases and, thus, depths and velocities for a particular return period flood. Third the conveyance on the floodplain is much less. The hydraulic model does not include morphologic change that results from the altered depths and velocities and these may eventually mute the increases in water levels during floods.

There are some interesting subtleties suggested by the hydraulic modeling. First, there appears to be a threshold for *Arundo* coverage before there are significant effects on hydraulics. The exact portion of the floodplain that must be occupied for a significant effect is not fully understood. Second, the threshold for observing significant effects and the percentage increase in velocities and sediment transport capacity in the main channel seems to depend on the ratio of the main channel width and floodplain width. Where the channel is wide relative to the floodplain, there is less effect on velocities and sediment transport capacity for a particular flood than where the channel is narrow compared to the floodplain. This is thought to occur because there is less conveyance on the narrower floodplains compared to the main channel, so there is a smaller increase in flows in the main channel when *Arundo* coverage is complete and conveyance on the floodplain is reduced.

The results of the hydraulic model studies are limited because they do not account for the channel adjustments that are likely to occur rapidly in response to the altered hydraulics on the floodplain and in the main channel. Stream power calculations, which were adopted as a proxy for sediment transport, show greatly increased stream power in the main channel and greatly reduced stream power exerted on the floodplain under complete *Arundo* coverage, when compared to native vegetation, and a smaller increase and smaller decrease for partial coverage (Scenario 4). The consequences of the changes in stream power when banks are less erodible because of *Arundo* establishment are expected to be increased depths in the main channel and sediment trapping and accretion on the floodplain and in overbank areas. Regime considerations suggest that channel depths should increase to accommodate frequent floods, as compensation for the narrowed channel. Part of this increase may result from higher floodplain elevations rather than from channel incision or bed lowering.

Both channel responses described above change the sediment storage in the project reach on the Santa Margarita River and potentially affect the delivery of sediment from the upper watershed to downstream reaches and the Pacific Ocean. Considering the sediment balance for sand, and basing accretion rates on those observed in the literature, it appears that the trapping of sand on the floodplain in *Arundo* stands is large compared to the inflow from the upper watershed. The trapping on the floodplain may be partly compensated by erosion of the stream bed to accommodate flood flows with the narrower channel but this gain to downstream reaches appears to be considerably smaller than the trapping on the floodplain. These conclusions are also appropriate for the Santa Ana and San Luis Rey Rivers but different ones might be drawn for rivers with much wider or much narrower floodplains, or those where channel filling or other conditions allows extensive floodplain accretion. In the long-term, as accretion on the floodplain slows, the sand transported out of the study reaches will return to being about equal to the supply from the upper watershed.

Based on the above results, the study developed a qualitative scoring system that can be applied to measured river and floodplain vegetation characteristics to identify those reaches where significant impacts on river processes may occur. Total scores that reflect potential *Arundo* impacts were developed by summing scores for the ratio of low flow channel width to floodplain width, the percentage of *Arundo* on the floodplain and the changes in floodplain width and channel slope from one reach to the next downstream one. The scoring system was reasonably consistent with the modeled hydraulic impacts on the Santa Margarita River and thus was thought to be appropriate for the Santa Ana and San Luis Rey Rivers.

Application of the scoring systems suggests that impacts on river form and process are less significant in the Santa Ana and San Luis Rey Rivers than in the Santa Margarita River project reaches, with the possible exception of Reach 2 of the Santa Ana River.

While the scoring system is preliminary it provides a simple procedure to identify those reaches where the riverine response to *Arundo* infestation may be most severe and also provides a useful tool to identify those reaches where monitoring may be concentrated.

5.2 Geomorphology and Hydrology: Spatial Analysis

5.2.1 Arundo's Distribution Within Geomorphic Forms

5.2.1.1 Methods

Geomorphology Attributes and Methods

Methods used to delineate floodplain geomorphic forms involved visual interpretation of imagery and topological data within a GIS. Due to time constraints and budget, groundtruthing and follow-up field *surveys were not possible at this time. Guidelines for defining geomorphic forms were based on the Riparian Ecosystem Restoration Plan for the Otay River Watershed (Army Corps of Engineers 2006) and consultations from staff at NHC.* Issues involving criteria for delineating terraces within the floodplain and the subjectivity of this classification was thoroughly discussed. Considering the subjectivity, several rounds of sample data and images were reviewed to determine the efficacy in characterizing geomorphic forms for each analysis. The most recently available imagery was used for each watershed.

San Luis Rey was used as a test case to work through the methodology. Other watersheds were completed after an approach was established. Using base imagery from ESRI, Google Earth, and Bing 3D pictometry (where available), areas of interest were reviewed to develop visual recognition of the potential terrace structures. Additionally, several sample locations and field photos taken by the analyst previously from the *Arundo* field mapping exercise were used to further visually train the analyst in the separation of terrace forms. A significant number of images were gathered including several panoramas of the river valley that illustrate elevation changes.

The mapping delineation always started within the low flow channel and built out from this classification using the *Auto-Complete Polygon* tool in ArcGIS. The digitization was completed at a scale of 1:5,000. The following classifications (as described in Section 5.1.3.3) were selected:

- *Low Flow Channel* – The part of the main channel where water was flowing at the time of the aerial photos. In those cases where the riverbed is dry, the area appearing to have the most recent flows were delineated as low flow.
- *Bar / Channel / Floodplain - unvegetated* – Main channel or floodplain areas with less than 50% vegetation cover, usually consisting of bar surfaces, dry channel beds, or recent deposition or scour.
- *Floodplain - vegetated* – Areas on the river floodplain with more than 50% vegetation cover.
- *Floodplain / Low Terrace – vegetated* – Areas on either the river floodplain or an adjacent low terrace with more than 50% vegetation cover.
- *Upper Terrace - vegetated* – Areas on higher ground adjacent to the low terraces with more than 50% vegetation cover. This classification was rarely used in part because nearly all of the upper terrace areas on most rivers had been leveed or developed. The mapping did not go beyond levees or roads in most cases. In some specific areas where there were *Arundo* records, the levee sides were marked using this category. Hillslopes were typically not tagged unless they were surrounded by an apparent floodplain or if *Arundo* was present.

Terraces edges were extremely subjective because the field verification was not feasible and high-resolution elevation data was not available for all areas. One of several visual cues used to help delineate between terraces was based on the type and amount of vegetation present (USACE ref.).

There were instances where the imagery used to map geomorphology (usually 2006) did not match the same time period in which *Arundo* was mapped. These temporal mismatches caused alignment problems when *Arundo* stand mapping was compared to geomorphology mapping. Initial mapping/analysis placed large historical stands of *Arundo* in what are now the main low flow channel or sand bars. But in the time period when the *Arundo* stands were present, these areas were floodplain. The two rivers with the largest number of mismatched data were the San Luis Rey and Santa Margarita, which have had significant *Arundo* control. Both rivers had mapping data from the late 1990's and early 2000's reflecting areas that were controlled. Therefore, select geomorphic records were altered to match their historical form based on imagery that matched the mapping date of the *Arundo*. *Arundo* removal on the Santa Margarita has influenced the river channel geomorphology to change course and in many cases it allowed the river to revert back to having more open bars and seasonal channels.

5.2.1.2 Results

The area of interest (AOI) covers the six most *Arundo* invaded watersheds within the study area. This represents 77% of the gross *Arundo* acreage calculated for the entire study area (Figures 5-2.1 & 5-2.2). Since these are the most invaded areas, it is important to examine the distribution of *Arundo* within geomorphic forms found in the riparian zone.

The overall level of *Arundo* invasion for the AOI was 13% cover of the riparian zone (all geomorphic forms) (Figure 5-2.3, Table 5-2.1). Invasion levels of *Arundo* ranged from 8% to 16% cover for the AOI on the watersheds examined. There seem to be two levels of invasion on these large, broad watersheds: a higher level of 12-18%, and a lower level of 8-9%. Individual reaches within a riparian system can have much higher *Arundo* cover. Highly invaded reaches on Santa Ana and Santa Margarita had invasion levels >40%. Establishing a 'peak level' of invasion over large areas is difficult to assess, but an upper range of 40-45% seems plausible (as the Santa Margarita River illustrates – Section 5.1).

An examination of *Arundo*'s distribution across geomorphic forms reveals that *Arundo* is relatively absent from the low flow channel (Figures 5-2.4 & 5-2.5, Tables 5-2.2 & 5-2.3). If *Arundo* was evenly distributed across geomorphic forms in proportion to a geomorphic class's acreage, it would have a distribution shown in Figures 5-2.6 to 5-2.11. There is less *Arundo* on all watersheds in the channel areas than would be predicted. This represents the high energy and dynamic riparian zone that has flows every year. Establishment and persistence of *Arundo* is difficult and little *Arundo* acreage (52 acres or 1.5%) of this form is invaded. Each watershed's geomorphic structure is shown in Figure 5-2.4 and Table 5-2.2 to allow examination of which forms dominate each system.

The bar/channel zone also has low cover of *Arundo* (102 acres of 6,575 acres, or 1.5 %). Much lower cover is present on each watershed than would be predicted if an even distribution of *Arundo* occurred (Figures 5-2.5 to 5-2.10). This is an active portion of the riparian floodplain with little vegetation, so it would be expected to have low cover of *Arundo*.

Most *Arundo* acreage is found in the floodplain and low terrace geomorphic forms (Figure 5-2.3, Tables 5-2.2 & 5-2.3). Floodplains have consistently high levels of invasion with an average of 19.7. As presented by watershed, *Arundo* cover exceeds predicted levels of distribution on all six watersheds (Figures 5-2.5 to 5-2.10). This is an important observation, as high *Arundo* cover in this geomorphic form tends to lock the low flow channel in a set location (Section 5.1).

Low terraces were also found to have high *Arundo* cover, averaging 15.4% (Table 5-2.3). Observed acreage was equivalent to, or higher than what would be predicted if an even distribution of *Arundo* occurred on most, but not all systems (Figures 5-2.5 to 5-2.10). Lower terraces, as a geomorphic form, vary significantly in acreage between watersheds (Figure 5-2.4, Table 5-2.2). Salinas and Santa Margarita have a significant proportion of this form, while Santa Ana has little. This is reflected in the *Arundo* acreages found on low terraces within these systems. Santa Clara is distinctly different due to a very low proportion of floodplain and terrace acreage. However, the floodplain and terrace acreage that does occur within a system is highly invaded with *Arundo*. Floodplain and low terrace geomorphic forms are a subjective distinction. These are essentially the more stable portions of the floodplain. They could be combined, but separating them helps characterize different watersheds.

Upper terraces comprise a small proportion of overall geomorphic composition for most watersheds (Figure 5-2.4, Table 5-2.3). Many of these areas have been developed or modified and are no longer part of the riparian system (examined in section 5.2.2). Where upper terraces do exist, they have a lower proportion of *Arundo* acreage than would be predicted if *Arundo* were evenly distributed. This is likely a result of the high elevation, which makes establishment and persistence of *Arundo* less common than the more hydrologically favorable floodplains and lower terraces

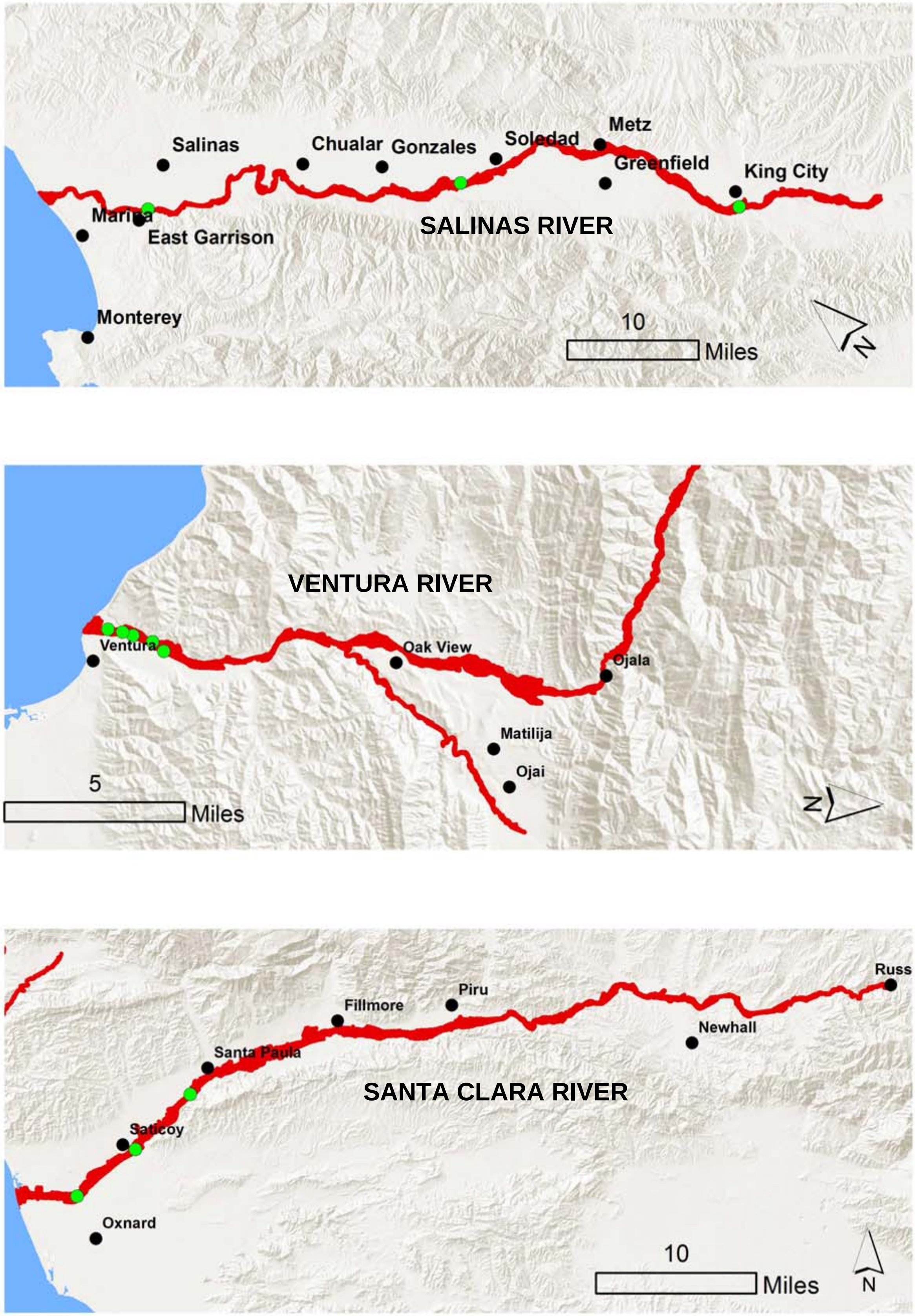


Figure 5-2.1. Location of the Area of Interest and cross-sections (northern watersheds).

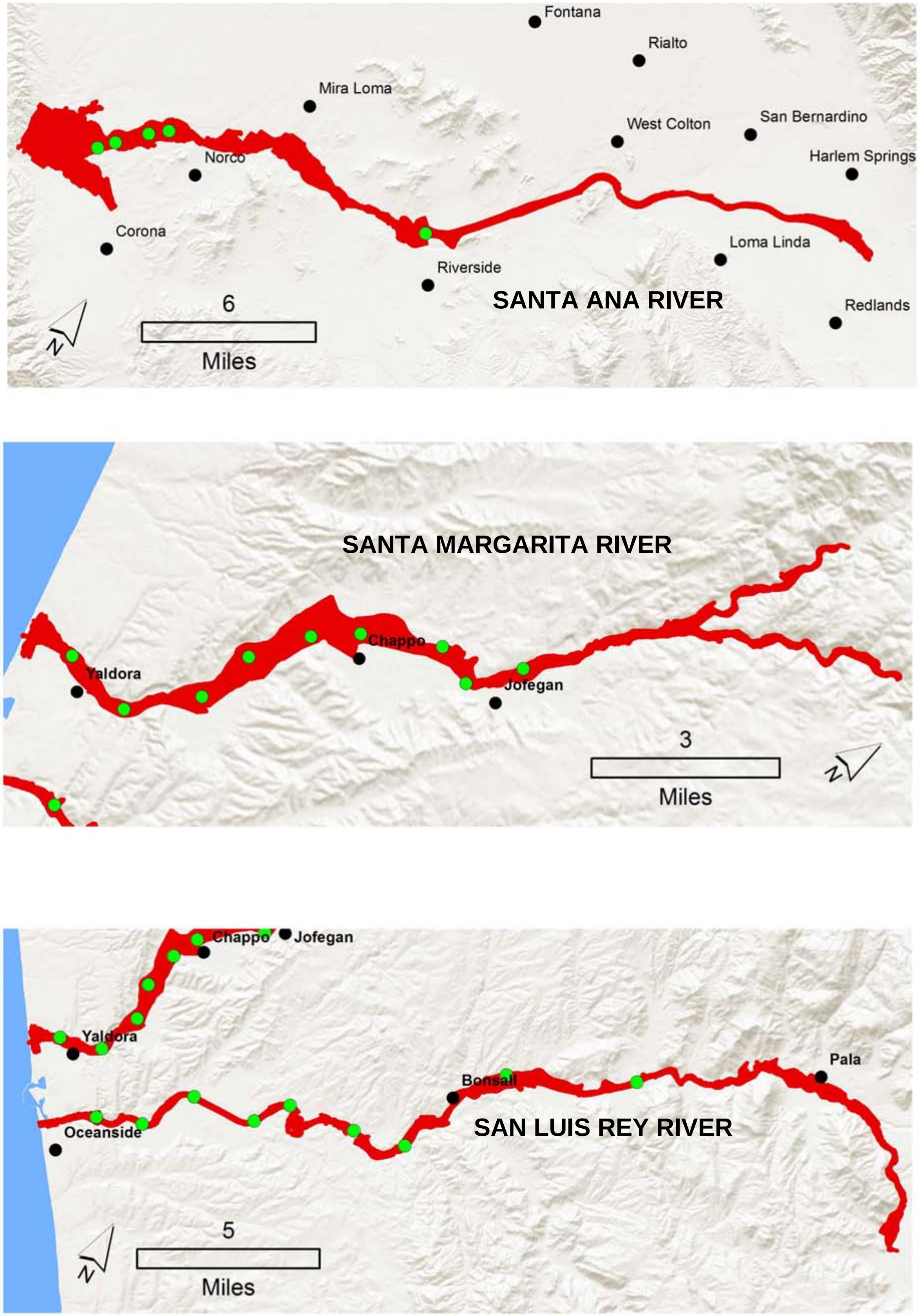


Figure 5-2.2. Location of the Area of Interest and cross-sections (southern watersheds).

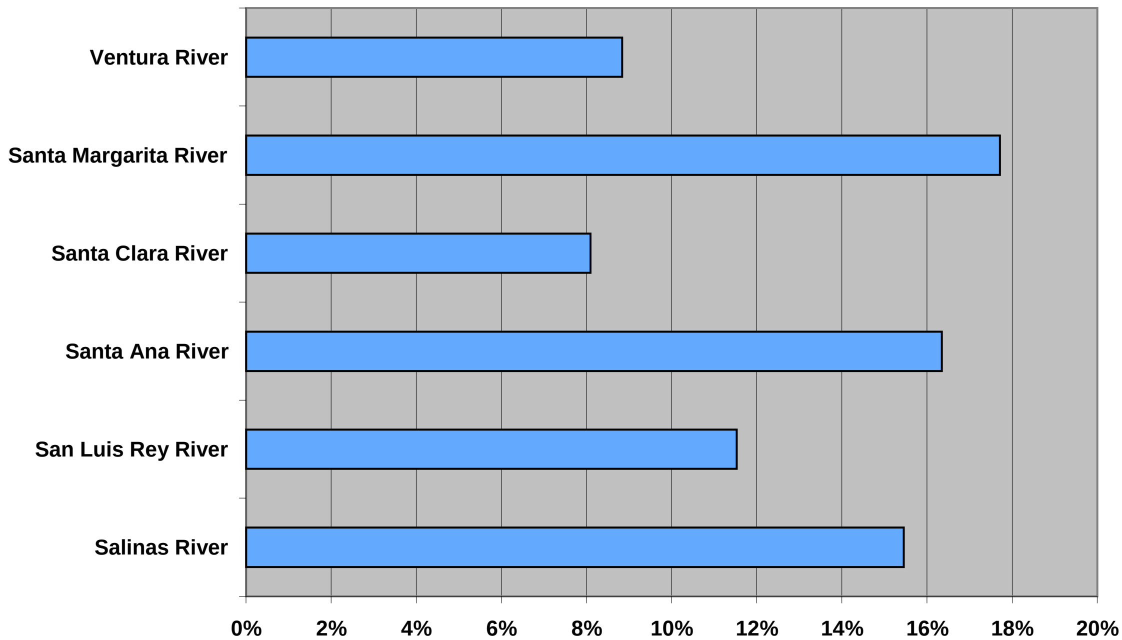


Figure 5-2.3. *Arundo* acreage as a percent of system acreage within the Area of Interest (AOI).

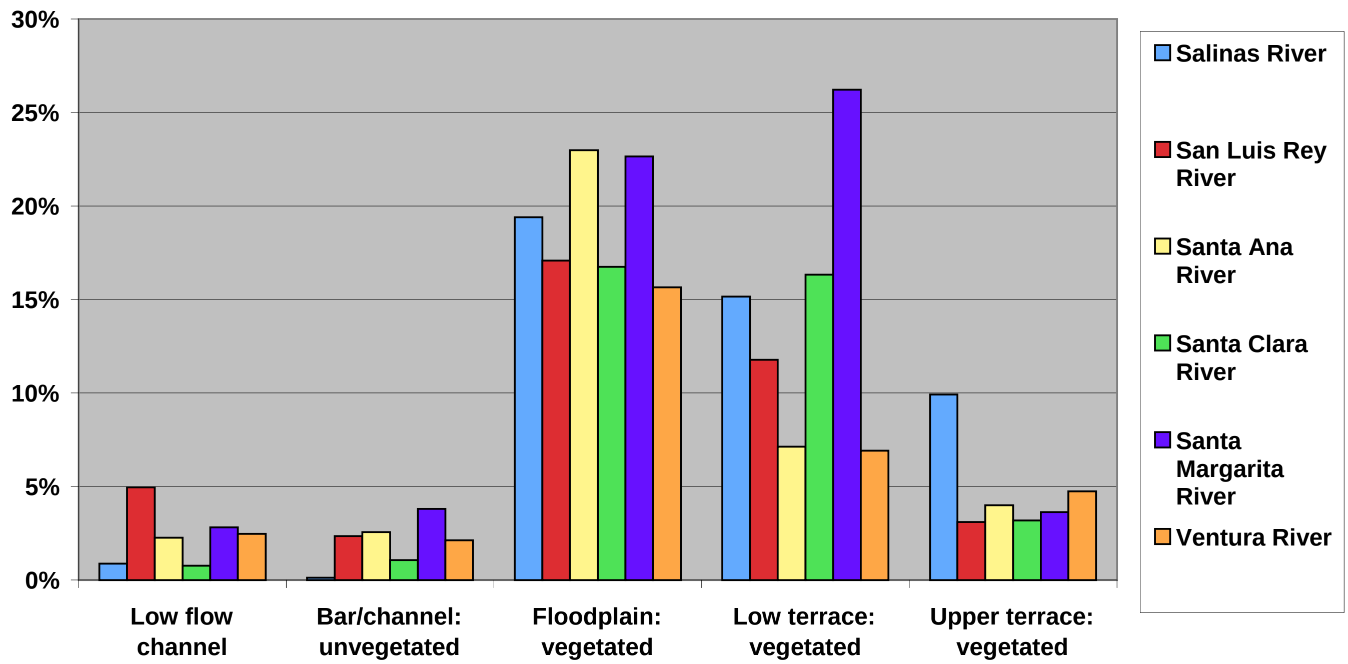


Figure 5-2.4. Percent of geomorphic form invaded by *Arundo* for the Area of Interest (AOI). This shows that the highest levels of invasion are in the floodplain and low-terrace geomorphic forms, regardless of the acreage of the geomorphic form itself.

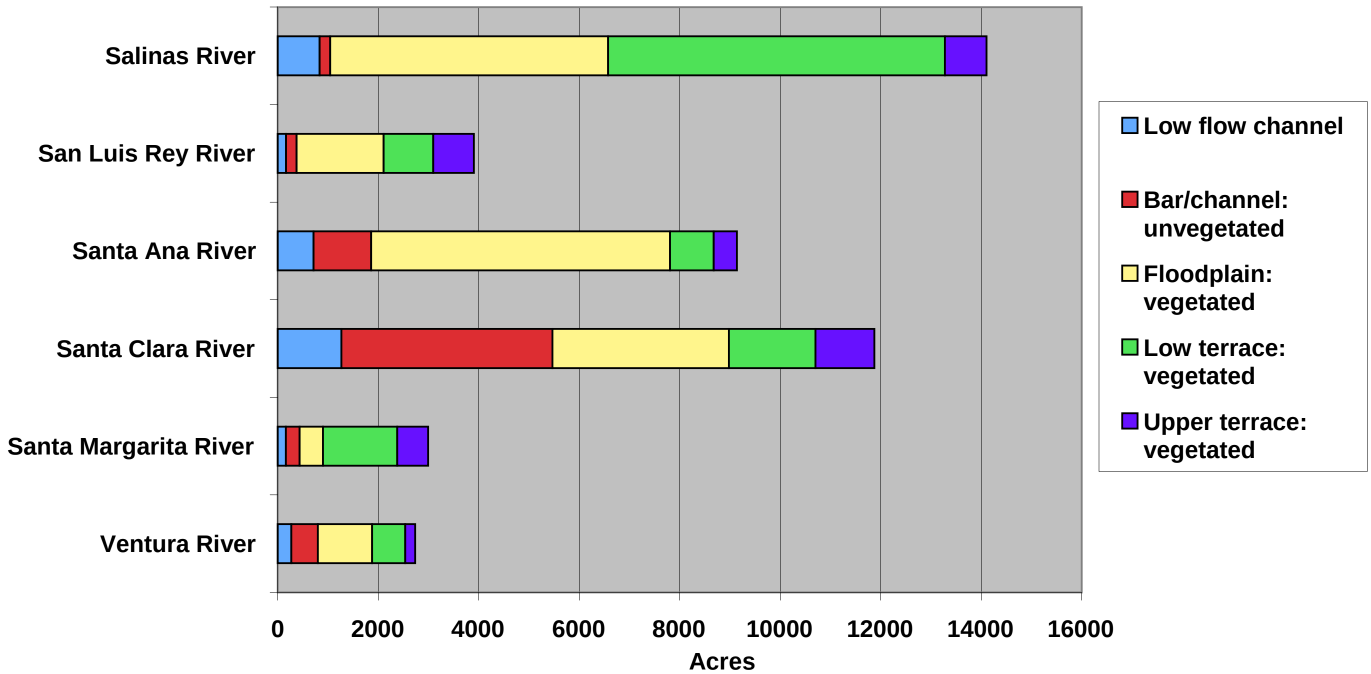


Figure 5-2.5. Acreage of geomorphic forms mapped within the Area of Interest (AOI). This shows that the floodplain and terrace forms dominate most systems (within the AOI).

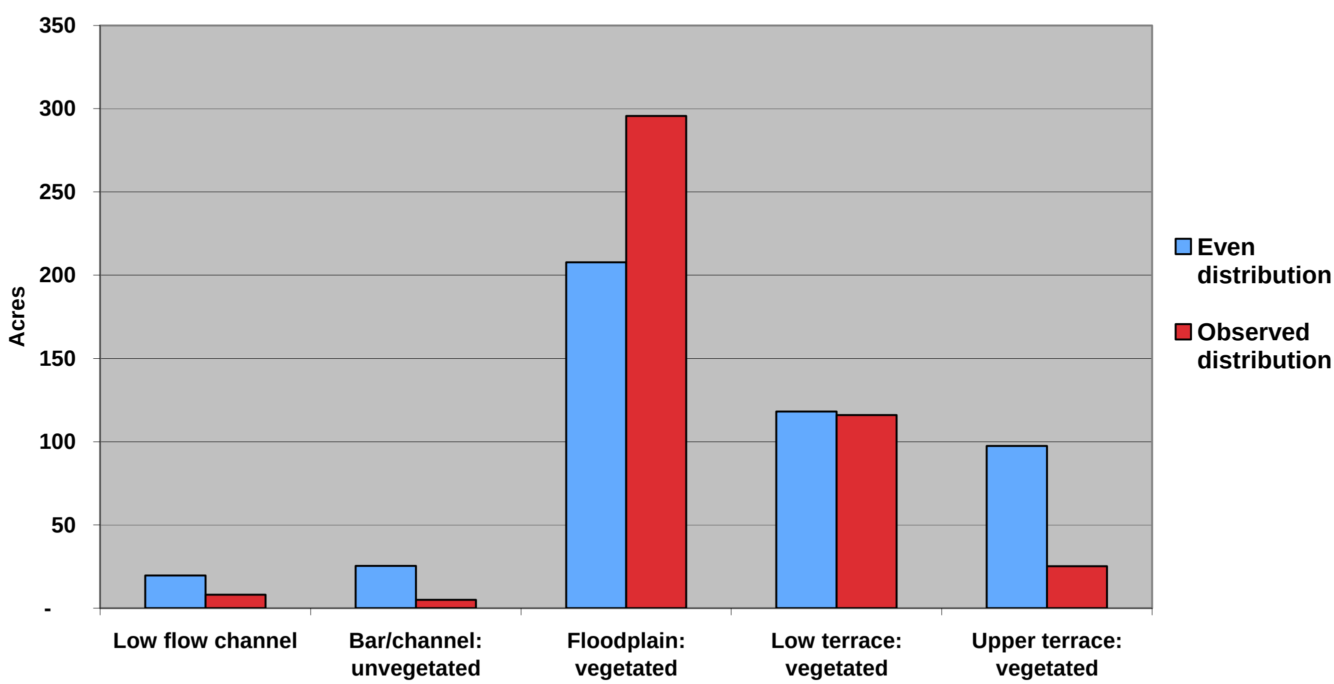


Figure 5-2.6. Observed and expected even distribution of *Arundo* acreage on the San Luis Rey watershed by geomorphic class.

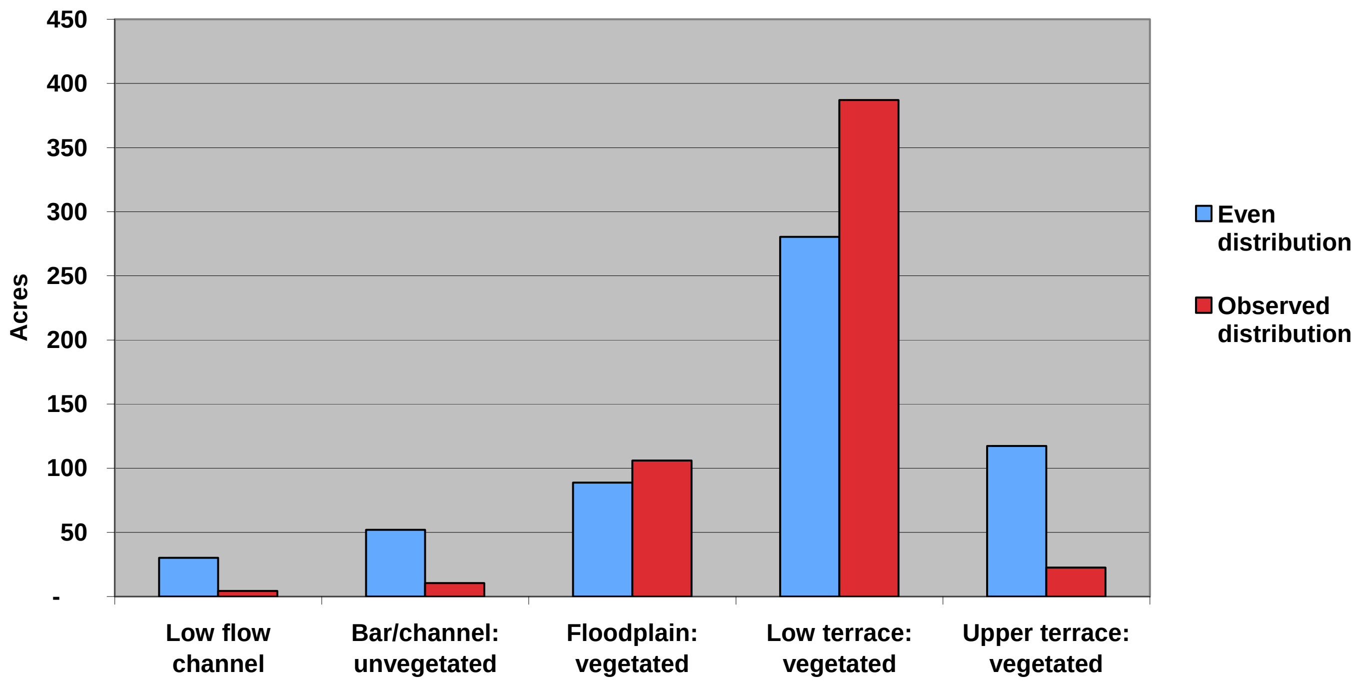


Figure 5-2.7. Observed and expected even distribution of *Arundo* acreage on the Santa Margarita watershed by geomorphic class.

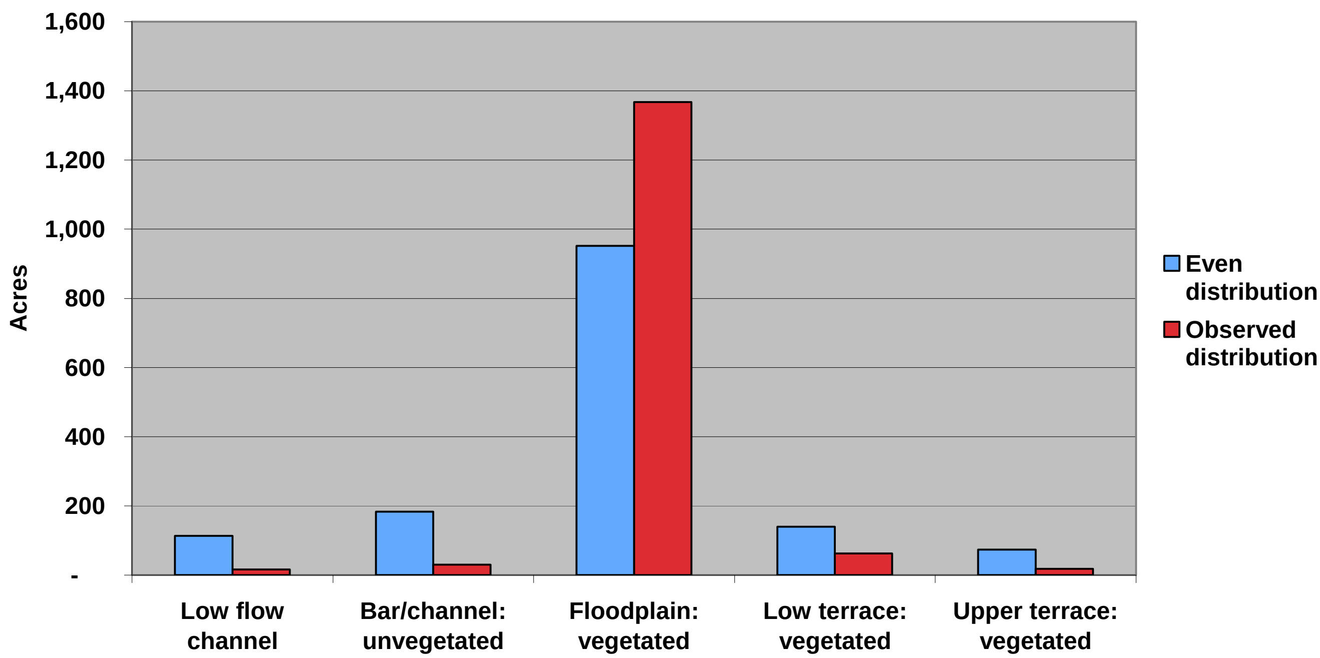


Figure 5-2.8. Observed and expected even distribution of *Arundo* acreage on the Santa Ana watershed by geomorphic class.

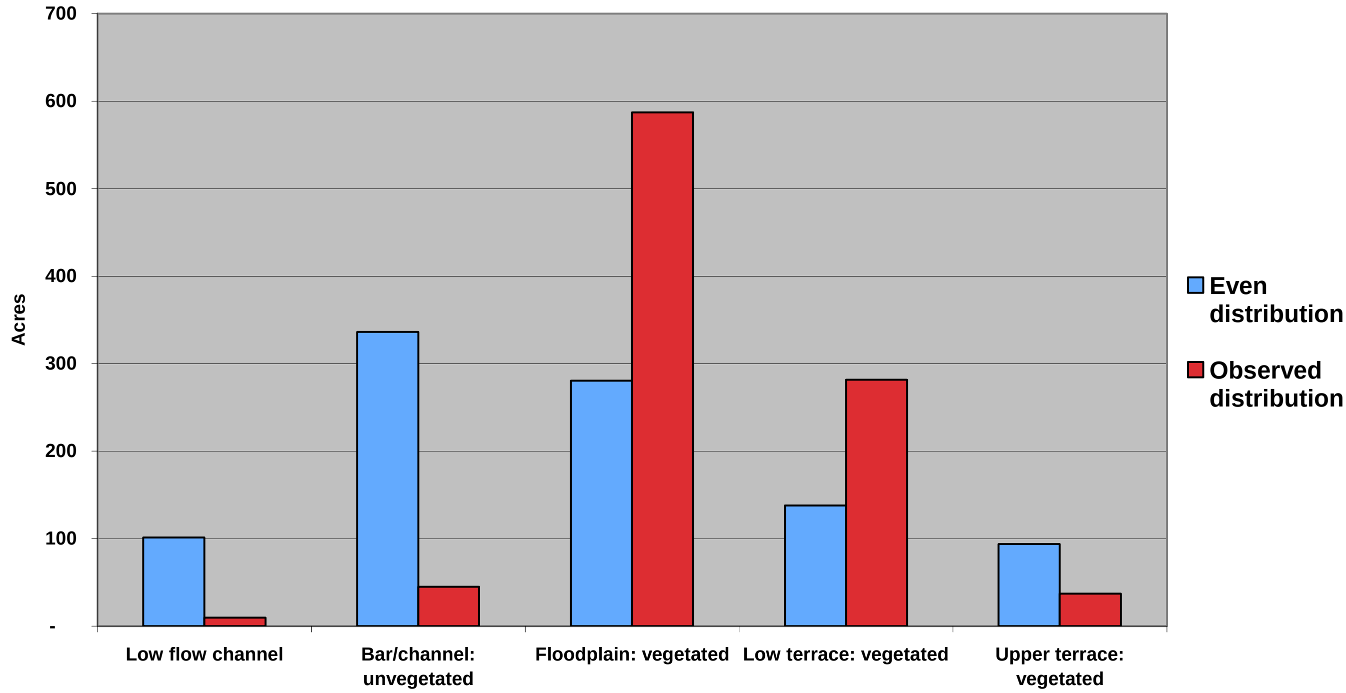


Figure 5-2.9. Observed and expected even distribution of *Arundo* acreage on the Santa Clara watershed by geomorphic class.
Santa Clara has much more low flow channel and bar/channel than the other systems.

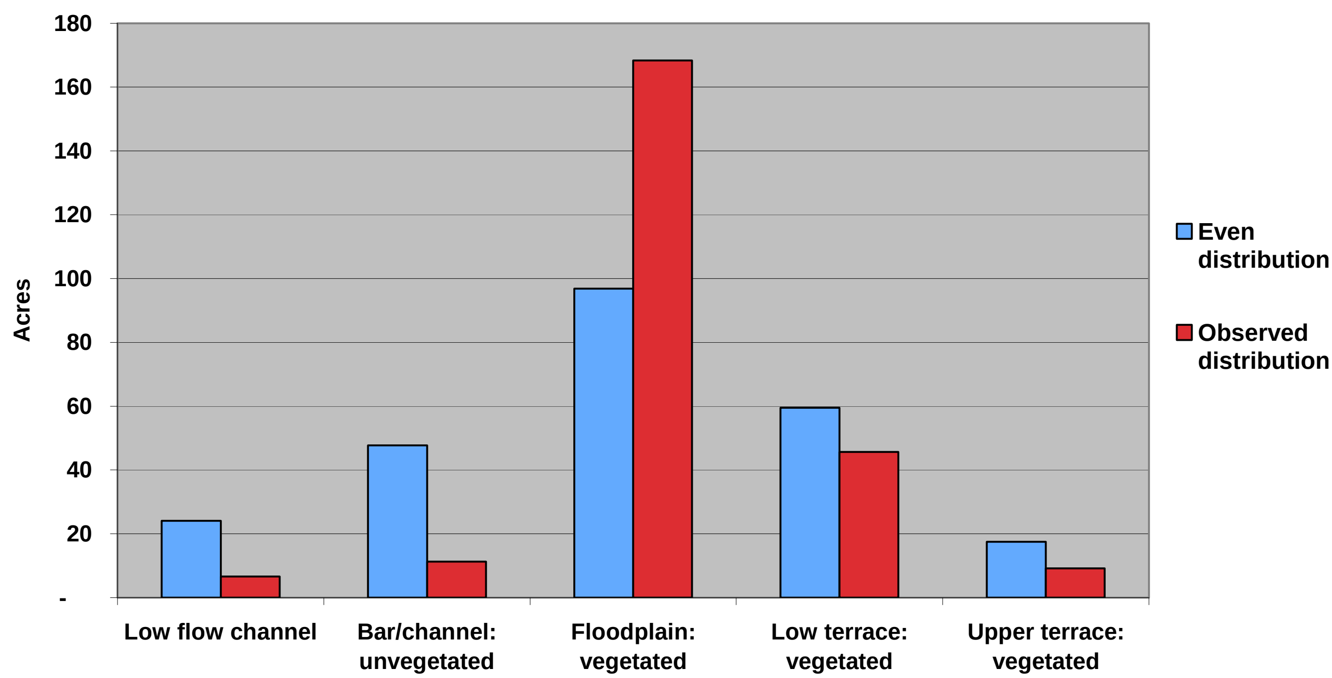


Figure 5-2.10. Observed and expected even distribution of *Arundo* acreage on the Ventura watershed by geomorphic class.

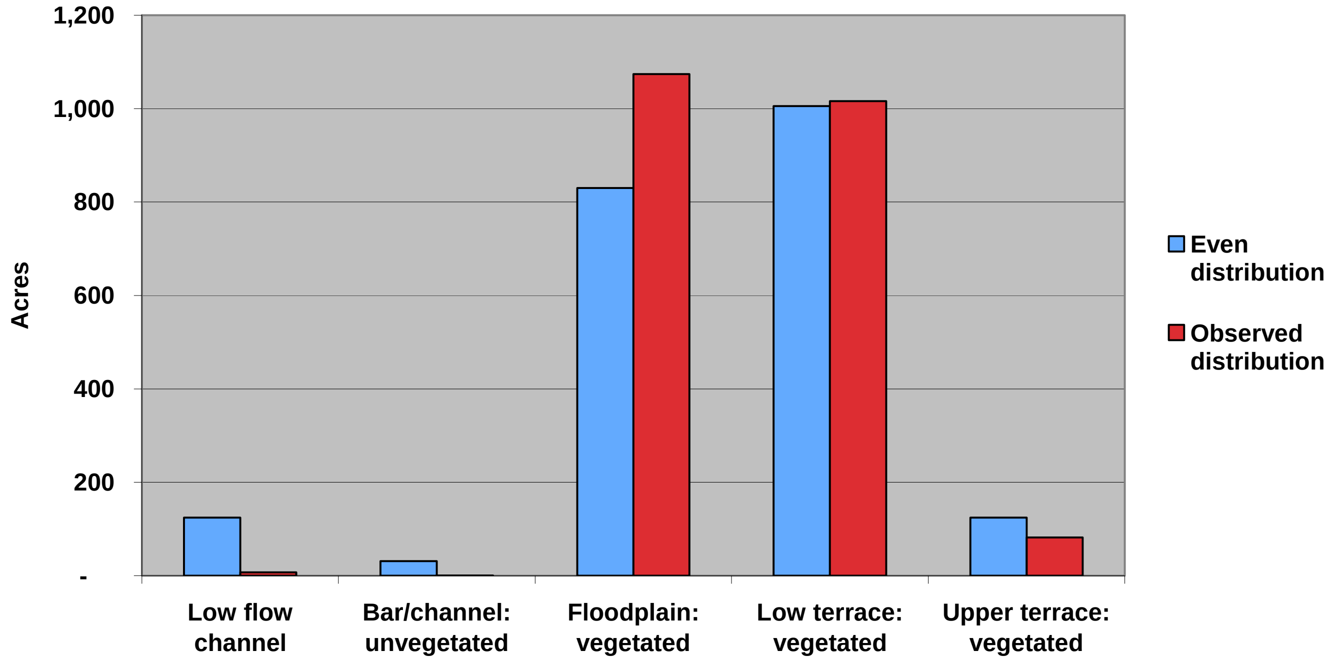


Figure 5-2.11. Observed and expected even distribution of *Arundo* acreage on the Salinas watershed by geomorphic class.

Table 5-2.1. *Arundo* and geomorphic acreage within the Area of Interest (AOI) for six selected watersheds.

Watershed (AOI area only)	*Arundo* Gross Acres	*Arundo* Net Acres	Geomorph Acres[1]	*Arundo* ac % system (net)
Salinas River	2,845	2,180	14,105	15%
San Luis Rey River	450	450	3,903	12%
Santa Ana River	1,674	1,493	9,136	16%
Santa Clara River	1,011	961	11,874	8%
Santa Margarita River	530	530	2,994	18%
Ventura River	321	241	2,730	9%
Total:	**6,831**	**5,855**	**44,741**	**13%**

[1]Geomorph areas: the acreage where geomorphic form was mapped within the AOI.

Table 5-2.2. *Arundo* and geomorphic class acreage within the AOI of six selected watersheds.

Watershed (AOI only)	Geomorphology Class	*Arundo* Gross Acres	*Arundo* Net Acres	Geomorph Gross Acres	% of geo class w/ *Arundo*
Salinas River	Low flow channel	8	7	829	1%
Salinas River	Bar/channel	0.4	0.3	209	0%
Salinas River	Floodplain	1,476	1,074	5,535	19%
Salinas River	Low terrace	1,269	1,016	6,704	15%
Salinas River	Upper terrace	92	82	828	10%
San Luis Rey River	Low flow channel	8	8	164	5%
San Luis Rey River	Bar/channel	5	5	211	2%
San Luis Rey River	Floodplain	296	296	1,731	17%
San Luis Rey River	Low terrace	116	116	984	12%
San Luis Rey River	Upper terrace	25	25	812	3%
Santa Ana River	Low flow channel	20	16	709	2%
Santa Ana River	Bar/channel	76	30	1,146	3%
Santa Ana River	Floodplain	1,492	1,367	5,948	23%
Santa Ana River	Low terrace	67	62	873	7%
Santa Ana River	Upper terrace	20	18	459	4%
Santa Clara River	Low flow channel	13	10	1,266	1%
Santa Clara River	Bar/channel	52	45	4,204	1%
Santa Clara River	Floodplain	624	587	3,506	17%
Santa Clara River	Low terrace	286	282	1,726	16%
Santa Clara River	Upper terrace	37	37	1,173	3%
S. Margarita River	Low flow channel	4	4	158	3%
S. Margarita River	Bar/channel	10	10	274	4%
S. Margarita River	Floodplain	106	106	468	23%
S. Margarita River	Low terrace	387	387	1476	26%
S. Margarita River	Upper terrace	22	22	618	4%
Ventura River	Low flow channel	10	7	267	2%
Ventura River	Bar/channel	21	11	530	2%
Ventura River	Floodplain	228	168	1,076	16%
Ventura River	Low terrace	52	46	661	7%
Ventura River	Upper terrace	9	9	194	5%
	Total:	**6,831**	**5,855**	**44,741**	**13%**

Table 5-2.3. *Arundo* and geomorphic class acreage for the entire AOI (all seven watersheds).

Geomorphologic Class	*Arundo* Present: Gross Acres	*Arundo* Present: Net Acres	Geomorphology Mapped (Current Day): Gross Acres	% *Arundo* (Net)
Low flow channel	63	52	3,393	1.5%
Bar/channel	165	102	6,575	1.5%
Floodplain	4,221	3,598	18,263	19.7%
Low terrace	2,176	1,909	12,424	15.4%
Upper terrace	206	195	4,085	4.8%
Total:	**6,831**	**5,855**	**44,741**	**13.1%**

<u>5.2.1.3 Discussion</u>

The most important observation is that *Arundo* has high cover in the floodplain and low terrace geomorphic forms, and low cover in the low flow and bar/channel forms, within each of the six systems examined. Given that *Arundo* has a similar distribution across geomorphic forms on all systems, it is likely that similar mechanisms are at play in the systems. It is also likely that *Arundo* is having the same impacts associated with its presence in floodplains. This is important in that it makes observations from the specific case study of the Santa Margarita River (section 5.1) applicable to other systems in the study area.

Arundo's ability to form dense monotypic stands on floodplains in all of the major systems within the study area is likely having significant impacts to channel form, channel depth, flow conveyance, and sediment transport, as well as putting infrastructure at risk. *Arundo*'s impacts on these abiotic processes has biotic impacts as well by affecting habitat for flora and fauna. The documented abundance of *Arundo* within systems, and its higher growth within specific geomorphic forms, helps to demonstrate that impacts to organisms are also transferable from system to system.

Reproductive strategies used by *Arundo* are strongly reflected in distribution data by geomorphic form. Channel and bar areas are too dynamic to sustain plant survival, growth and establishment. Floodplain and low terrace are optimal, with favorable hydrology and less frequent flow events that would remove newly established plants. Upper terraces only periodically receive reproductive material (rhizome fragments), and hydrology is not optimal for their establishment and survival.

Understanding geomorphic composition and *Arundo* distribution would be aided by a historical evaluation of geomorphic forms over time, as well as an examination of vegetation cover. It would be useful to know if current geomorphic form and vegetation condition are comparable to past conditions.

5.2.2 Geomorphology Historic Analysis

In the previous section, the distribution of *Arundo* within geomorphic forms was examined using recent or current conditions within the AOI. The current acreage of geomorphic forms within each river system was also given. But acreage and proportion of geomorphic forms is not set as they respond to flood events and human activities. This chapter section will examine how each watershed's geomorphology has changed over time, using historic air photos and cross-section based-data. In addition to change in geomorphic class, we will also examine the abundance of woody vegetation (open versus dense) within the floodplain and lower terrace areas. This will help characterize the hydrology of the system over time.

5.2.2.1 Methods

To quantify the changes in the river systems over time, a historical cross-section analysis was undertaken. Historic photography was aggregated from the UCSB Library, HistoricAerials.com, Google Earth, CaSIL (California Spatial Information Library) and the USGS. For each river system, the availability of imagery was evaluated on the range of years and reaches of the river where imagery timeframes overlapped. The number of photos was narrowed down to have optimal time differences of 10-15 years between samples, and equal distribution across as much of the river's extent as possible (where *Arundo* occurred). The San Luis Rey River had the widest array of images available by both area and year. Image availability dictated the extent of areas available for analysis on each river. Cross-section locations were at times determined by limited imagery coverage overlap on rivers, other than the San Luis Rey and Santa Margarita. Within each area of imagery coverage, a cross-section was digitized into the GIS (Figures 5-2.1&2). These areas were selected based on: a) the earliest available imagery showing a floodplain that was not naturally constrained by a narrows or other impediment, and b) when possible, level distribution across the full extent of the available imagery time sequence. Each cross-section was drawn perpendicular to the current channel. The length of each cross section was determined by where the upper terrace of the floodplain ended on both the oldest and most recent imagery (Figures 5-2.12&13). This takes into account flood events that eroded bluffs or hillslope in the intervening years. Cross-sections were opportunistically placed at locations along the river where: a) *Arundo* was abundantly present, b) the area was representational of changes over time, and c) cross-sections being perpendicular to the current channel line would not create a diagonal in the historic floodplains, as this would amplify any constriction or expansion of the river. Random or equidistant placement may have put cross-sections in areas that had little change due to geomorphic landform constraints like a narrows.

With the cross-section lines in place, the historical imagery was then georeferenced. Spatial inaccuracies may occur where ground control was not easily identifiable. It should also be noted that imagery varied in scale, which may affect the spatial and attribute accuracy of the interpretation. Each digitized cross-section was duplicated for each year of imagery. Using a scale of 1:3,000, the length of the line was split into pieces as it crossed each geomorphic form in the photo. Because linear cross-sections were used in place of generalized polygons[2], a higher level of detail was captured in the fluvial landforms. For instance, the polygon interpretation methodology (used to delineate current-day geomorphology) may broadly group a mixture of bare sand and scrub as one class *(Bar/Channel:Unvegetated),* while the cross-section method broke those same strips of bare sand and scrub into separate classes (*Bar/Channel:Unvegetated* and *Floodplain:Vegetated*). This level of detail was captured in an attempt to keep the mapping consistent over time and limit the amount of subjectivity in the interpretation across the variety of historical imagery.

Additional classes were added to this analysis so that cross-sections were the same length for each time period and all situations of floodplain changes could be described. These added classes include:

- Floodplain Modified: sand mining, grading /channelizing of the floodplain, and agriculture fields in the floodplain that are not protected by levees.

[2] Polygon interpretation was not feasible with the time constraints and budget available for the historical analysis.

- Levee Protected Agriculture[3]: levees may be dirt or armored with rock.
- Levee Protected Developed[3]: usually a rock-armored levee with housing, industry or airport development. On two occasions, this class includes water treatment or storage ponds.

[3] The "Levee protected" classes do not appear in the charts because they, like the hillslope, are no longer part of the floodplain.

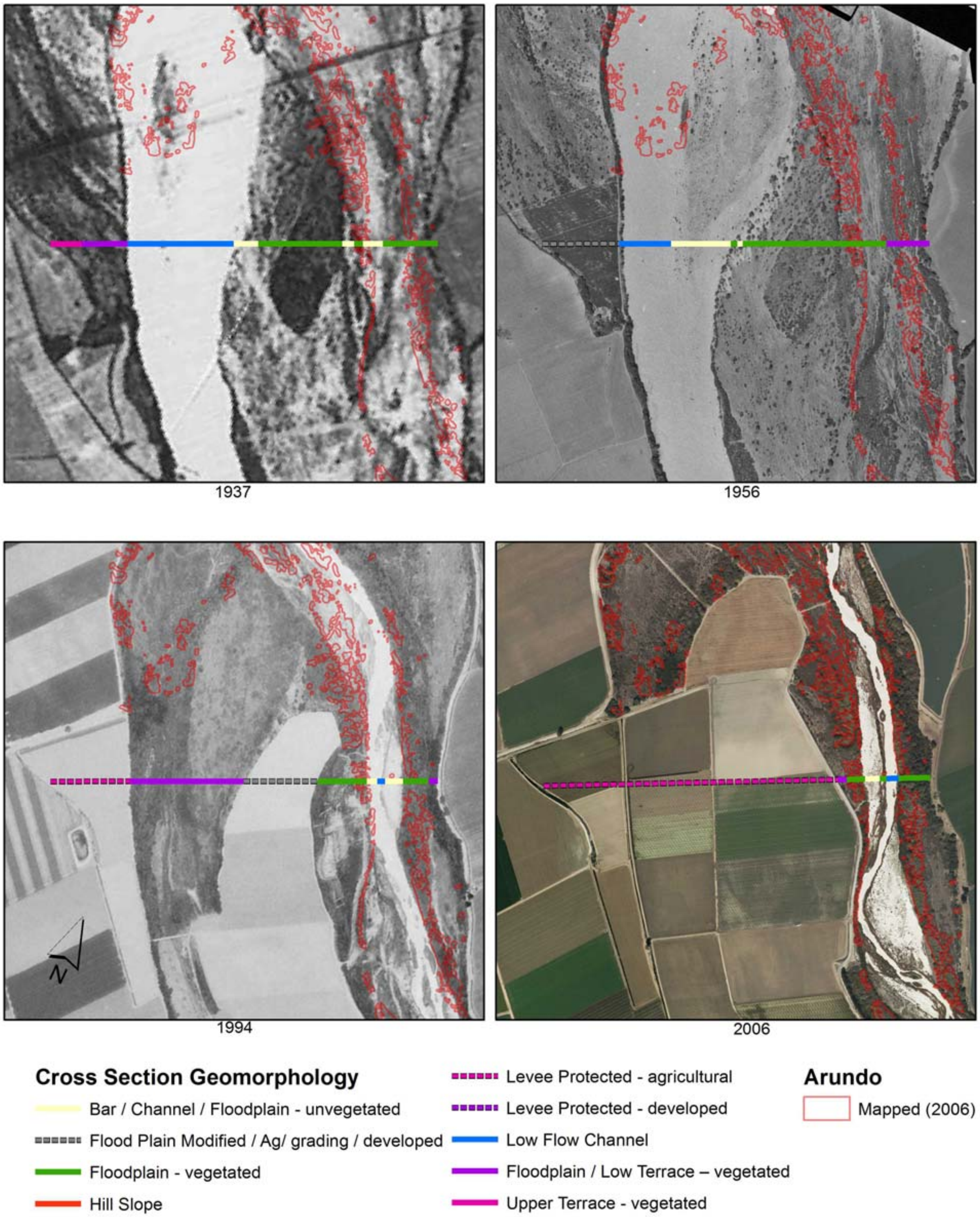


Figure 5-2.12. Cross-section geomorphology using historic aerial imagery on the Salinas watershed from 1937 to 2006.

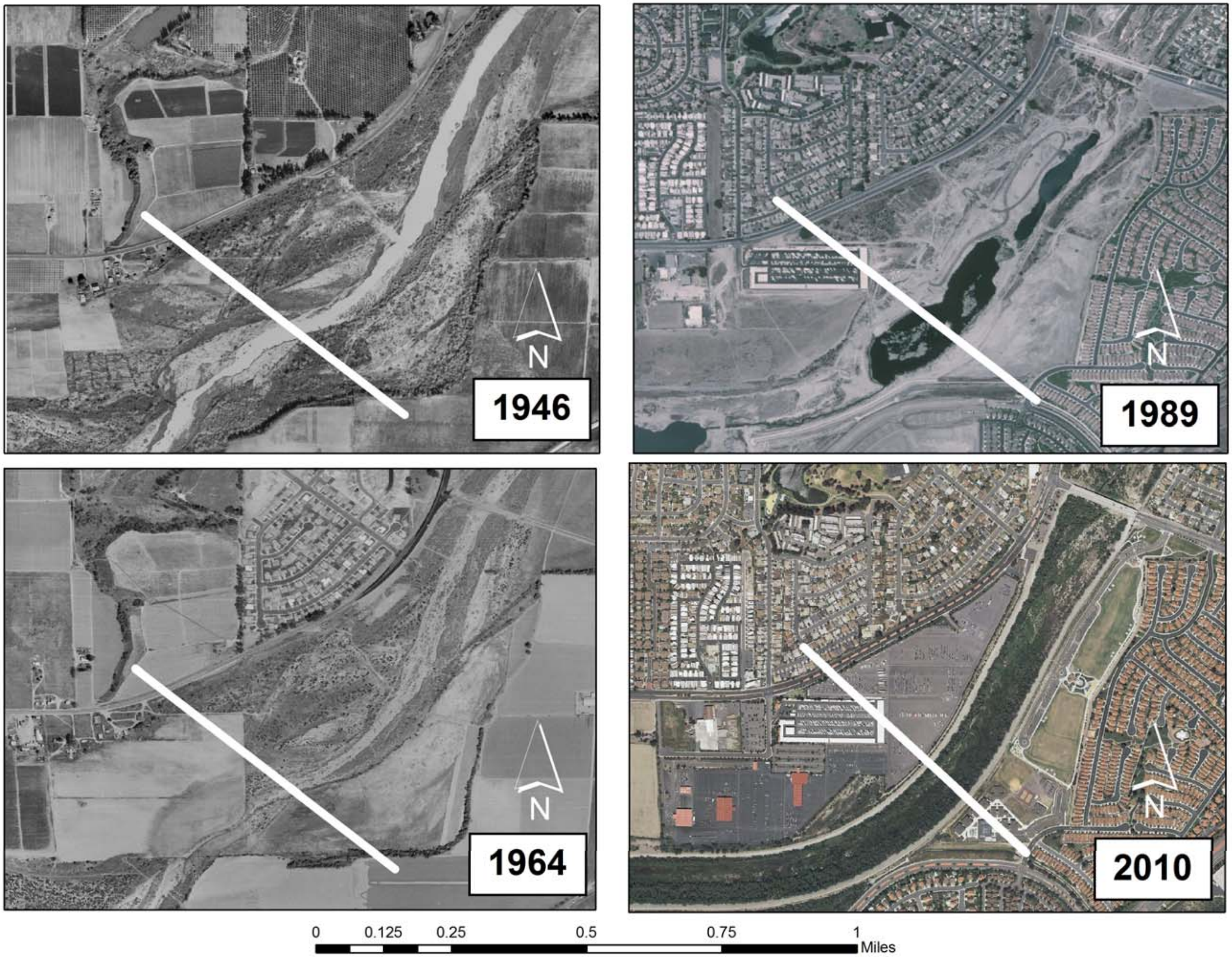


Figure 5-2.13. Historic photo analysis of geomorphic and hydrologic cross-sections on the San Luis Rey River from 1946 to 2010.

5.2.2.2 Results

There have been many changes to river systems over the past 100 years. These changes will be aggregated into two basic categories: 1) drastic increases of water in the system (from urbanization and agriculture) and 2) removal/modification of riverine areas (from development, agriculture, levees, water/flood management). High levels of water importation have transformed ephemeral riverine systems into perennial systems in southern California. This transformation occurred over time, but for the study area, this study suggests the 1960s-70s as a tipping point for most watersheds. At the same time that more water was imported and released into coastal watersheds, the functional riparian zone was reduced and modified. Use of floodplains for farming and sand mining has occurred for over 100 years. Historically these uses were not physically protected from river flows by levees and berms, so the area of activity was still functionally connected to the river. When floods occurred, these areas were inundated. However, in the 1950s and 60s permanent levees and berms were constructed in many systems. This resulted in the removal of geomorphic structure and habitat, as well as a significantly narrowing of the floodplain/riparian zone. Increased importation of water and development of riverine areas (urban or agriculture) are correlated, with both forms of development tied to increased water use.

San Luis Rey: Nine cross-sections were used. The San Luis Rey Watershed exhibited significant loss of over two-thirds of its riverine habitat from 1938 to 2010 (Figure 5-2.14). Lower and upper terraces are now nearly absent. Historic use and modification of floodplains occurred throughout the early portion of the time frame, but much of the use (agriculture and sand mining) has stopped or been permanently removed from the system. Urbanization is a significant pressure. Specifically note that open bar/channel area has drastically reduced over time (2,161m in 1938 to 175m in 2010, a 92.5% reduction; Figure 5-2.14), while floodplains are of equal, or greater, extent.

Santa Margarita: Nine cross-sections were used. The Santa Margarita Watershed has had very little riparian habitat development or permanent habitat removal. The Department of Defense manages all of the area examined in this review. This makes the Santa Margarita interesting in that is separates the two factors: loss of habitat and increased water input. As seen on the San Luis Rey, channel and bar was a large proportion of the system in 1938 (50%, 3,500m; Figure 5-2.15). A steady decline has occurred over time, and by 1997 channel/bar was 8% (of 700m) of the system. Removal of many *Arundo* stands from 1998 to 2006 may have resulted in the modest increase of channel/bar in 2010. Floodplain and terrace areas expanded from 1938 to 2010.

Santa Ana: Five cross-sections were used. The Santa Ana Watershed also had low levels of permanent development and land use change within the riverine areas of the AOI between 1938 and 2010. This is in part due to high bluffs that separate the river from upland areas. Upland areas have become highly developed, but the river bottom has not. The cessation of agriculture and sand mining activities, which was significant from the 1940's to the 1960's, has allowed most of the river to function as natural riverine areas. Trends are less clear on Santa Ana (Figure 5-2.16). Low flow channel and channel/bar areas were greatest in 1938. Ten years later they were significantly less, in part due to modification. Current and recent low flow channel and channel/bar areas are still a low proportion of the total riverine area, but it is not low as was observed on the San Luis Rey and Santa Margarita Rivers. The proportion of floodplain and terrace has been consistently high since 1980.

Ventura: Five cross-sections used. The Ventura River shows a similar pattern of permanent conversion of habitat to development and agricultural use (separated by levee) as seen on the San Luis Rey, with a 50% loss of riverine areas. Unlike San Luis Rey and Santa Margarita, Ventura has retained a large proportion of channel and bar areas (Figure 5-2.17). However, terrace areas as a class was effectively removed from the system through development and agriculture.

Santa Clara: Three cross-sections were used. The Santa Clara River has had significant development protected behind levees. The permanent land use change started as agriculture, but since 1970, it has become increasingly urbanized. Santa Clara appears to be a higher energy system than the other watersheds. A larger proportion of the system is maintained as low flow channel and bar/channel in all years (Figure 5-2.18). A slight decrease in this class has occurred, but it has been stable over the last 30 years and it is still well represented. Floodplain and terrace forms appear to be less abundant. The river has maintained open channel/bar areas, but lost floodplain and terraces, especially in comparison to 1927 and 1938.

Salinas: Three cross-sections were used. Aerial photography was difficult to obtain for the system. 1971 data is presented even though the data set was incomplete (2 of 3 cross-sections). Land use change has significantly reduced the riverine portion of the system. Protection of agriculture with levees started prior to 1971 and accelerated between 1994 and 2006. Low flow channel and channel/bar areas have decreased substantially, and the decline is linear (Figure 5-2.19). Dams have significantly reduced the riverine portion of the system. Floodplain areas are less abundant, while terrace areas have remained relatively constant.

5.2.2.3 Conclusions

Overall patterns of historical change in geomorphic forms on the six watersheds (Table 5-2.4) indicate the following:

- Significant reduction of riverine habitat (levee-protected permanent land use change) - systems are smaller (4 of 6 systems).
- A large decline of low flow channel and channel/bar (active low elevation areas) was seen on three systems.
- The retention/expansion of floodplains as a proportion of the system was observed on four of the six systems.

The long-term geomorphic changes observed on other larger river systems in the Southwest are evident on southern California coastal watersheds.

Table 5-2.4. Summary of geomorphic changes by watersheds.

Trend	San Luis Rey	Santa Margarita	Santa Ana	Santa Clara	Ventura	Salinas
Reduction in functional riverine areas	Yes >50%	No <10%	No <5%	Yes >50%	Yes >50%	Yes >50%
Reduction of low flow channel and channel/bar (in length & proportion)	Yes >70%	Yes >60%	No	Minor	No	Yes >60%
Proportion of riverine habitat that is floodplain & low terrace is stable or larger	Yes	Yes	Yes	No	No	Yes

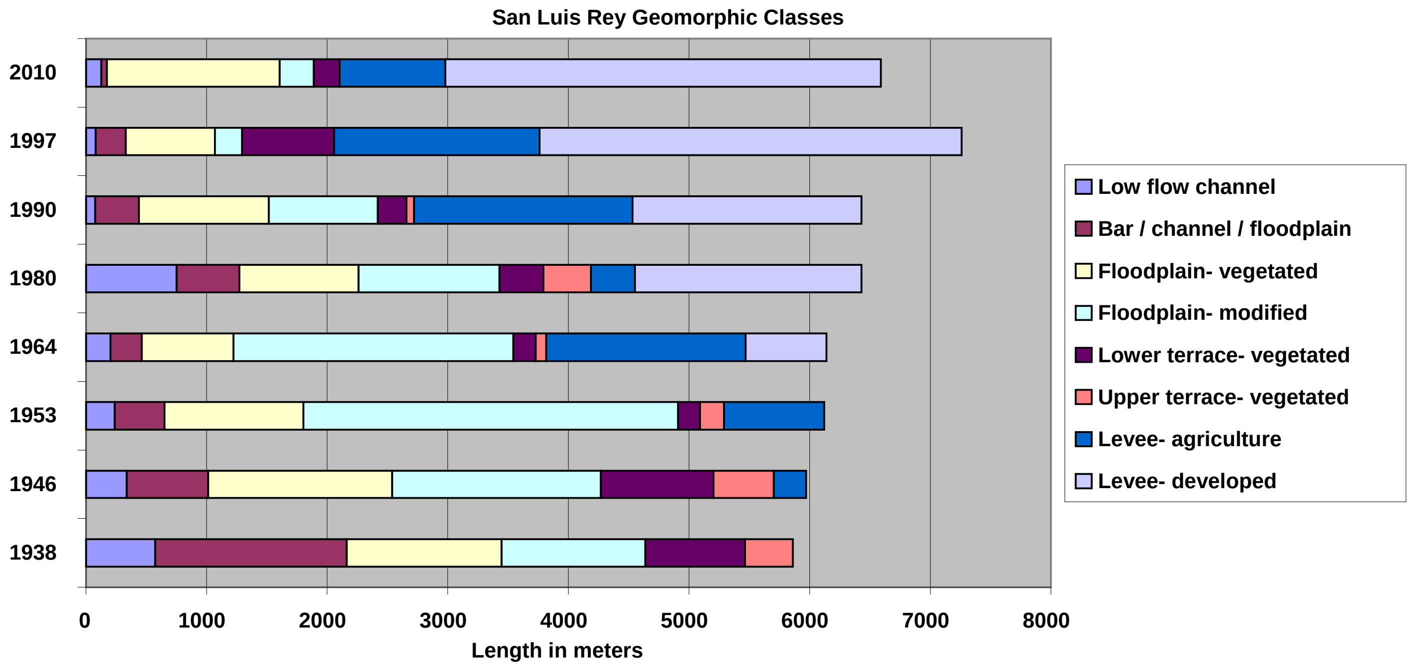


Figure 5-2.14. San Luis Rey geomorphic forms from 1938 to 2010.

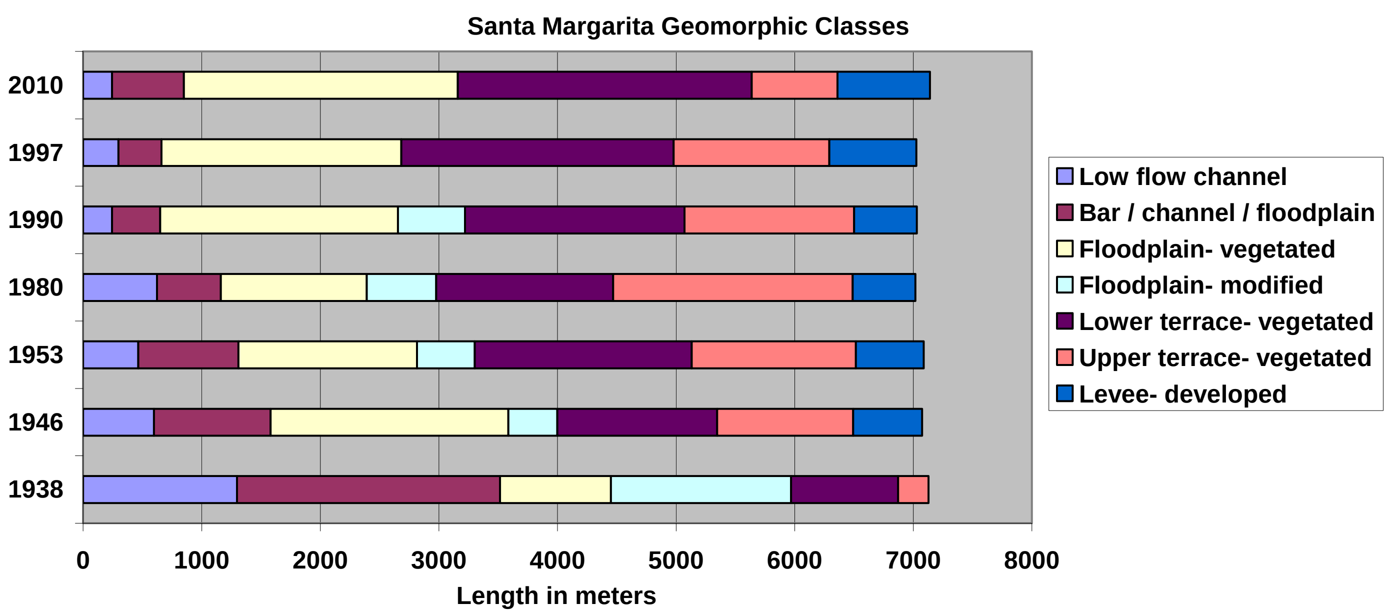


Figure 5-2.15. Santa Margarita geomorphic forms from 1938 to 2010.

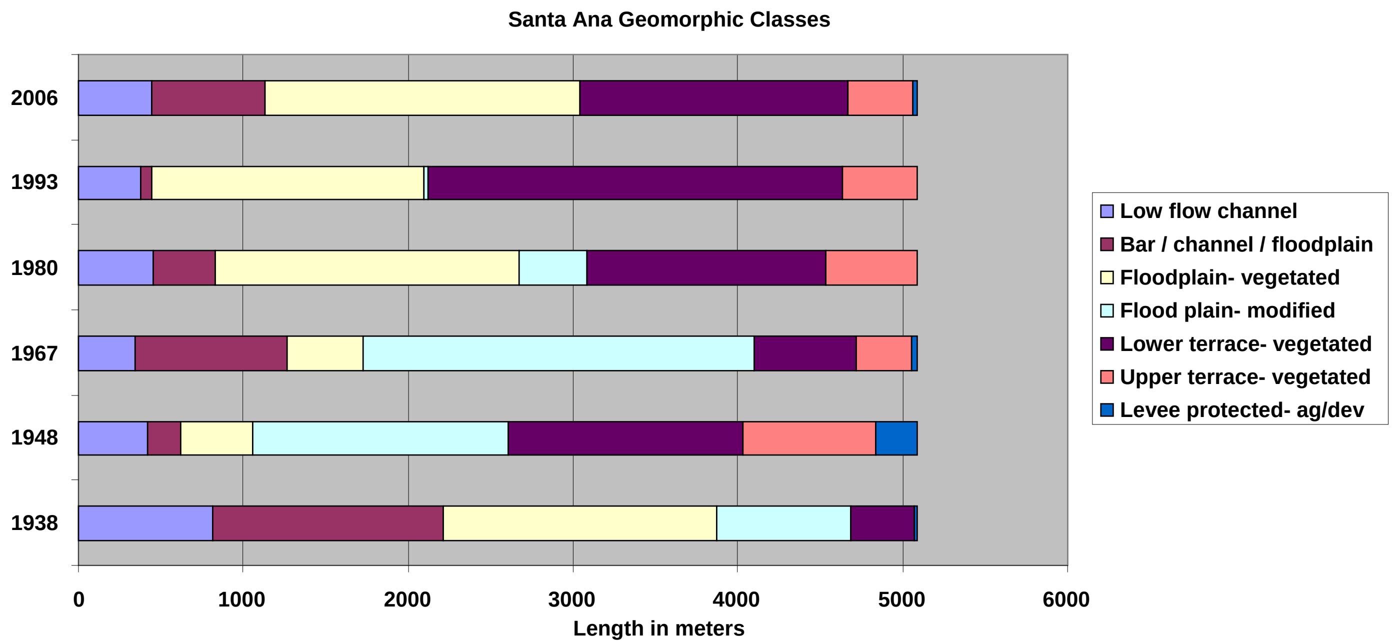


Figure 5-2.16. Santa Ana geomorphic forms from 1938 to 2006.

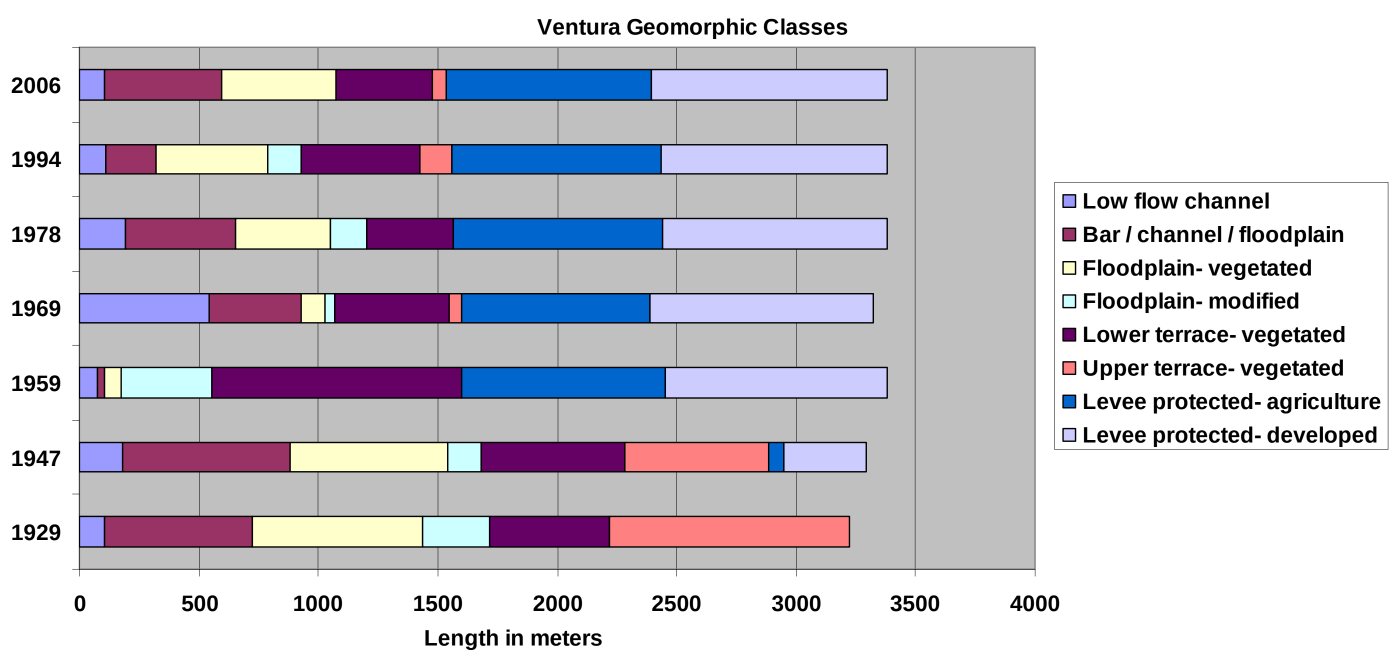


Figure 5-2.17. Ventura geomorphic forms from 1929 to 2006.

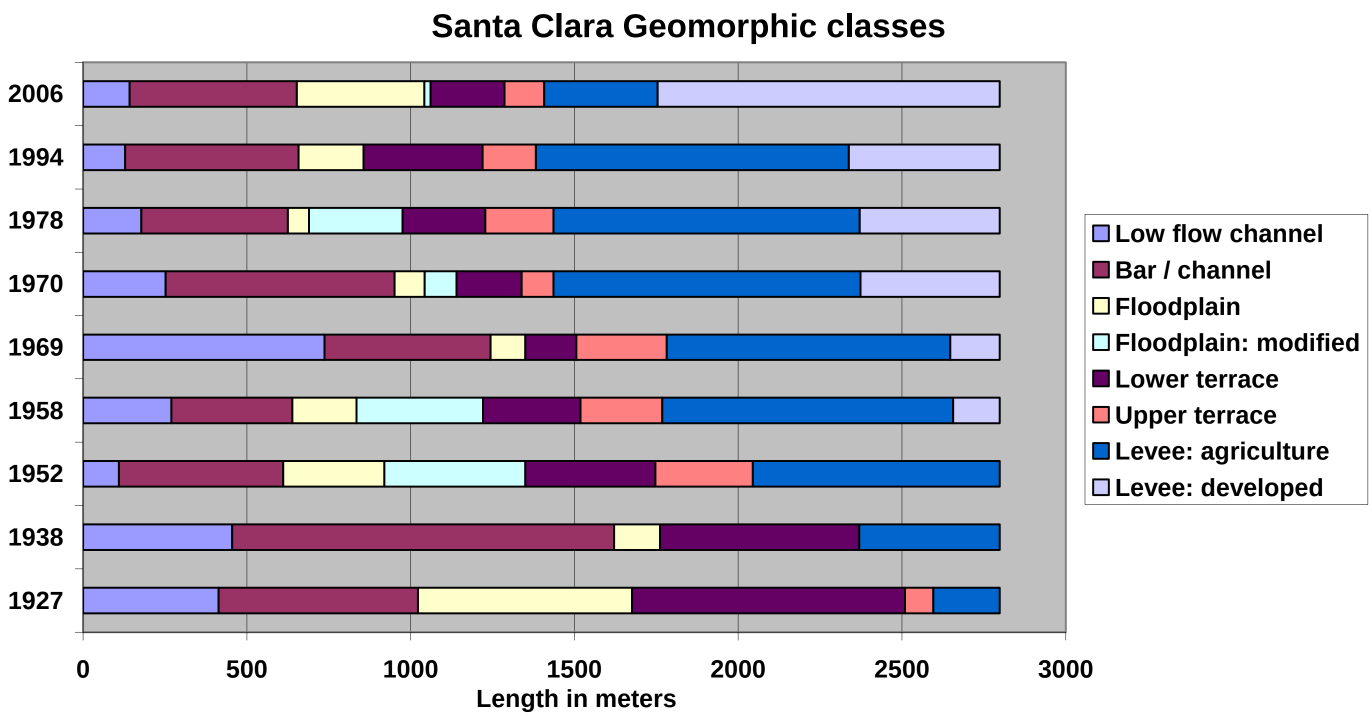


Figure 5-2.18. Santa Clara geomorphic forms from 1927 to 2006.

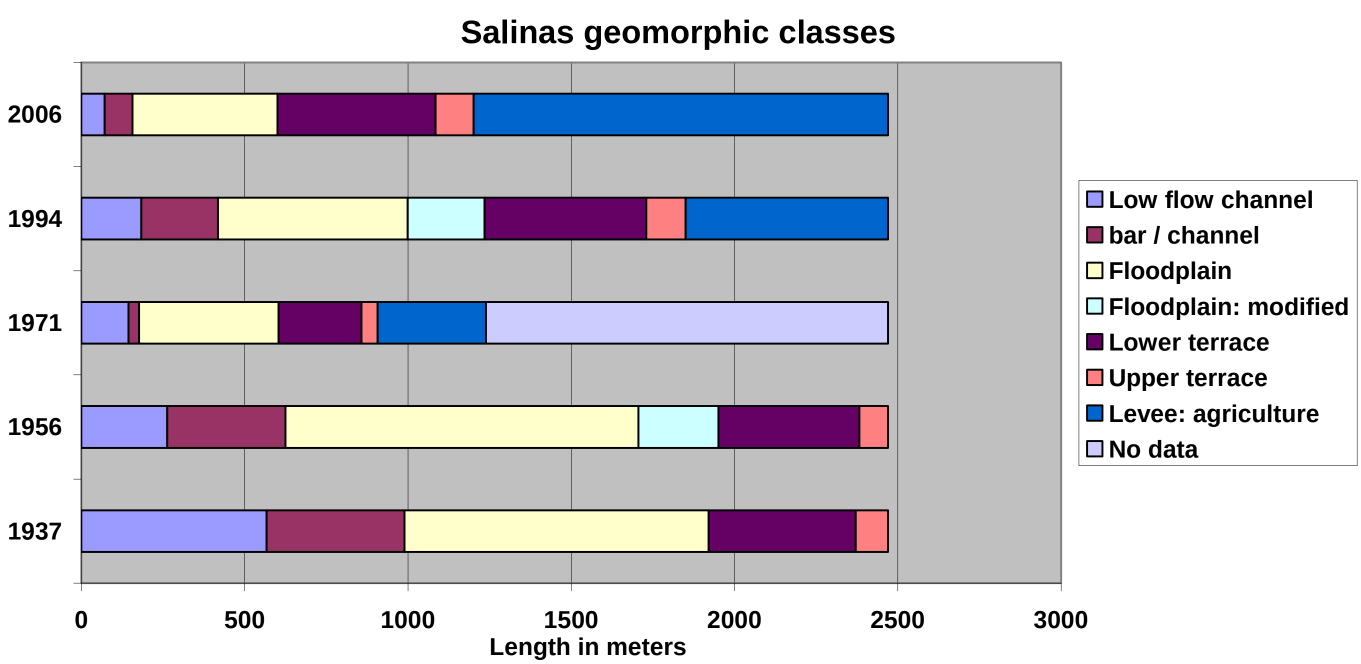


Figure 5-2.19. Salinas geomorphic forms from 1937 to 2006.

5.2.3 Vegetation Cover Historic Analysis

5.2.3.1 Methods

Preparing historic imagery for analysis reinforced a theory that many of the river systems have converted to a more heavily vegetated state over time. Supporting data was captured during the historical cross-section analysis. An attribute was added to the *Floodplain-Vegetated* and *Floodplain/ Low Terrace–Vegetated* geomorphic forms. The attribute values "dense" and "open" were used to describe the conditions and types of vegetation within these forms (see definitions below). Based on observations from the *Arundo* field mapping, the "dense" classification is the most likely place for *Arundo* to thrive, and thus, it was classified as such. An example of aerial imagery showing floodplain and terrace areas with dense and open vegetation classes marked is shown in Figure 5-2.20.

Definitions:

Dense – High woody/*Arundo* vegetation cover (>50%, typically >80%) of large, well-developed vegetation including plants like cottonwoods, sycamores, willows, mulefat and *Arundo*.

Open – Low woody/*Arundo* vegetation cover. Typically these are bare open areas, or areas with annual herbaceous cover. Areas with scattered woody vegetation and clumps of *Arundo* are also included in this category.

5.2.3.2 Results

The characterization of vegetation on the floodplains reveals a strong pattern of increasing cover of dense *Arundo* and woody vegetation. Dense woody/*Arundo* vegetation is taken to be an indicator of high water availability that allows dense vegetation to develop. Individual watersheds are illustrated over 80-90 year periods (Figures 5-2.21 to 5-2.26, Table 5-2.5). Most systems initially show low cover of dense vegetation on floodplains and terraces, except for Santa Margarita and Salinas. Over time dense vegetation cover increases, particularly on the San Luis Rey, Santa Ana, Ventura and Santa Clara from 1980 forward. The increase in proportion (percentage) of "dense" vegetation to "open" is shown in Figures 5-2.27 and 5-2.28 for all watersheds studied. A clear shift in vegetation cover is occurring. Dense cover was typically 10-30% in the 1920s and 1930s, but by the 1990s/2010 most systems were >75%. High R^2 and steep trendlines are apparent for most systems. All data aggregated show a clear upward trend, but systems apparently have different equilibrium points.

5.2.3.3 Conclusions

The strong historic trend toward greater vegetation cover on floodplain and terrace portions of river systems indicates that a major hydrologic shift has occurred within the study area. *Arundo* comprises a significant proportion of this dense vegetation. This overly vegetated condition, compared to 1928-50, seems to be moving these systems toward a more fixed geomorphic and vegetative state, with both fewer smaller size fluvial re-setting events and a faster return to a heavily vegetated state after major events. The dense growth of *Arundo* is likely compounding this effect by holding the low flow channel in a set position which converts systems from a braided unstable form to a narrow single thread that is laterally stable. The availability of water all year within riverine systems has allowed *Arundo* to drastically expand in cover. Although difficult to detect in pre-1990 aerial imagery, *Arundo* is clearly not a dominant vegetation form on systems prior to 1980. By 2000 *Arundo* has become abundant with over 40% cover on reaches of selected systems (section 5.1) and an average cover of 13% on the lower gradient floodplain areas as a whole (Table 5-2.1).

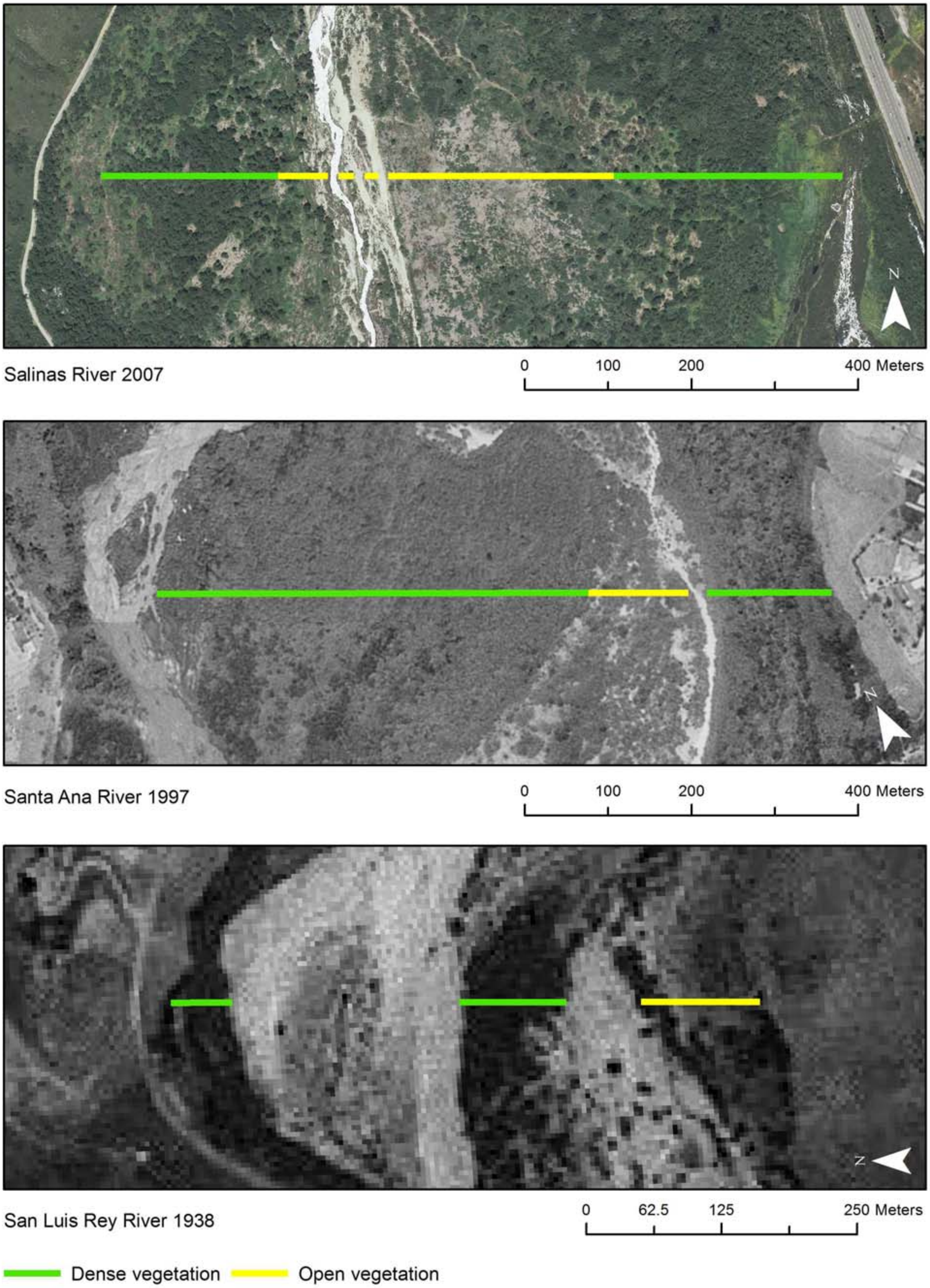


Figure 5-2.20. Aerial imagery showing floodplain and terrace areas with dense and open vegetation classes marked.

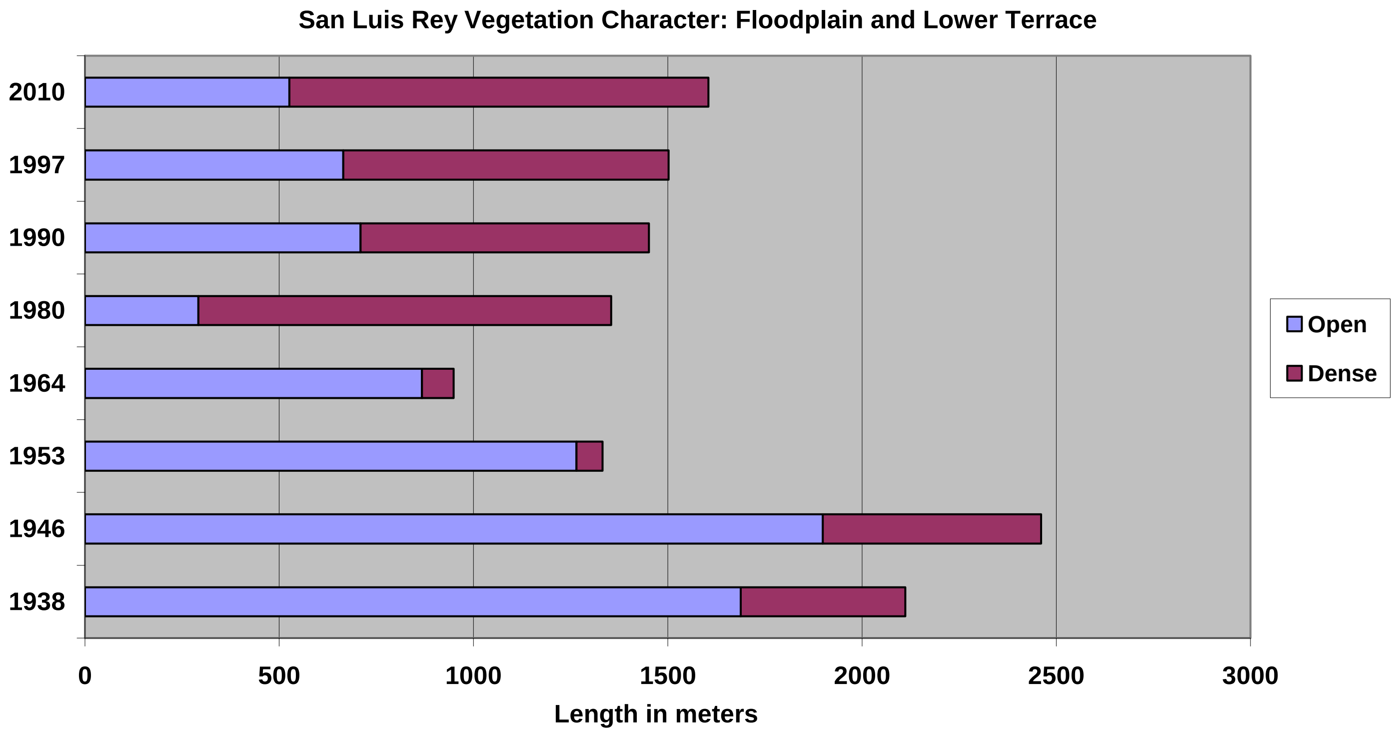


Figure 5-2.21. San Luis Rey open and dense vegetation classification on floodplain and lower terrace areas from 1938 to 2010.

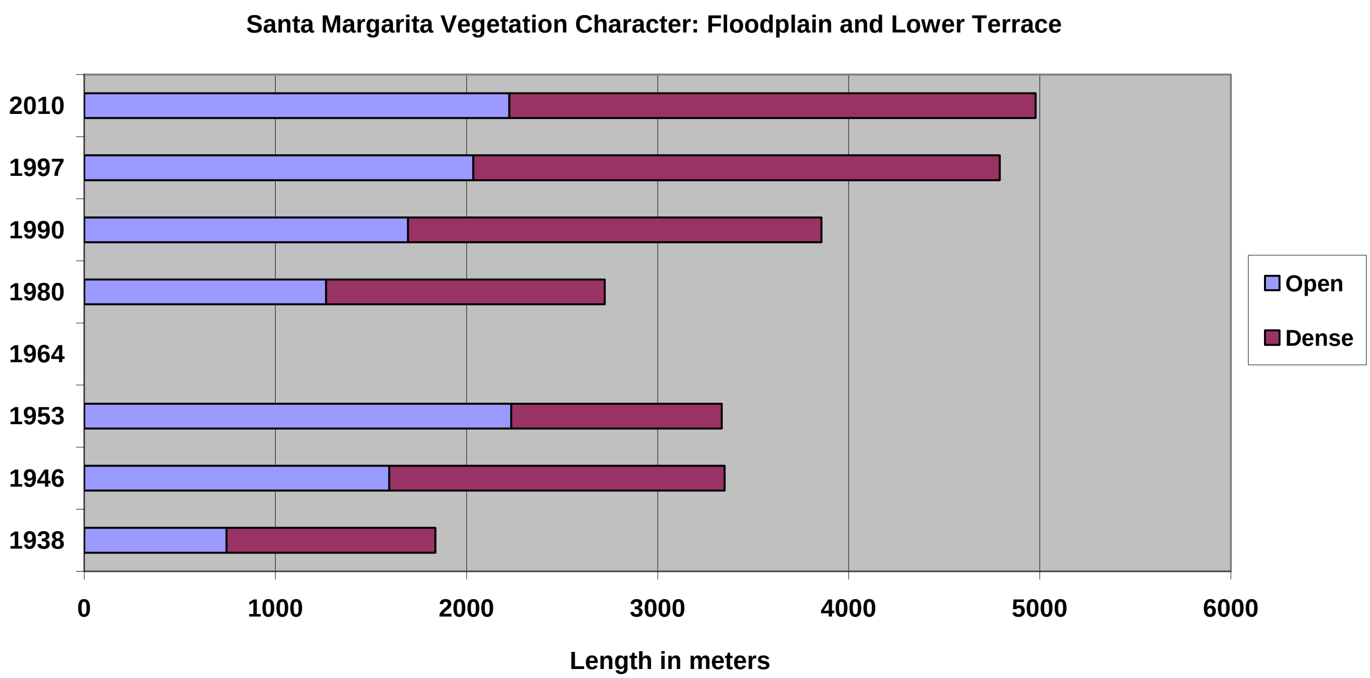


Figure 5-2.22. Santa Margarita open and dense vegetation classification on floodplain and lower terrace areas from 1938 to 2010.

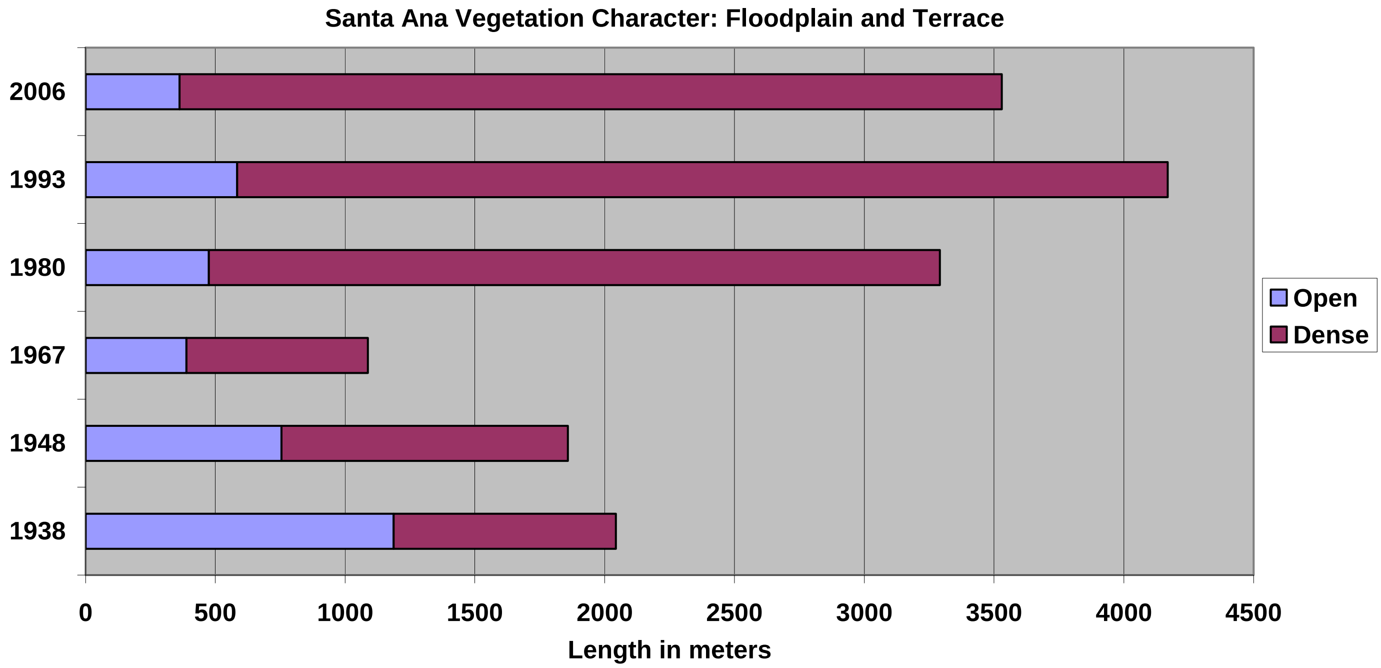


Figure 5-2.23. Santa Ana open and dense vegetation classification on floodplain and lower terrace areas from 1938 to 2006.

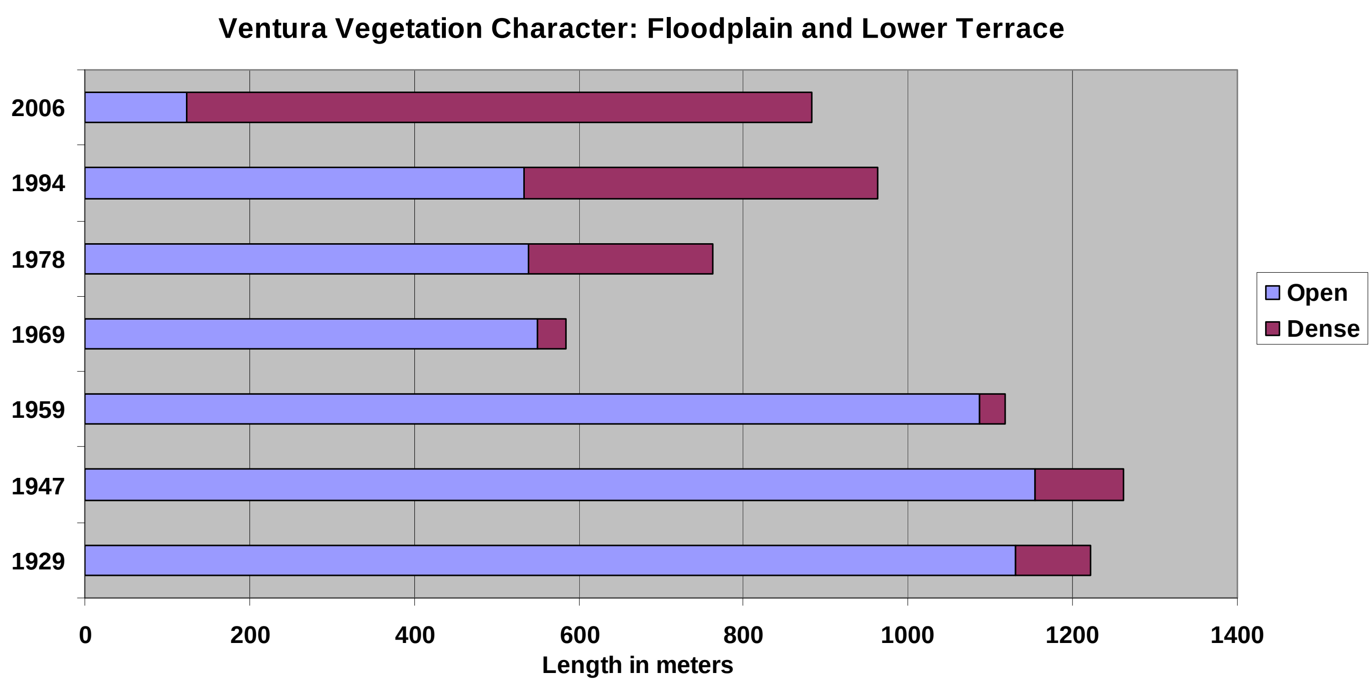


Figure 5-2.24. Ventura open and dense vegetation classification on floodplain and lower terrace areas from 1929 to 2006.

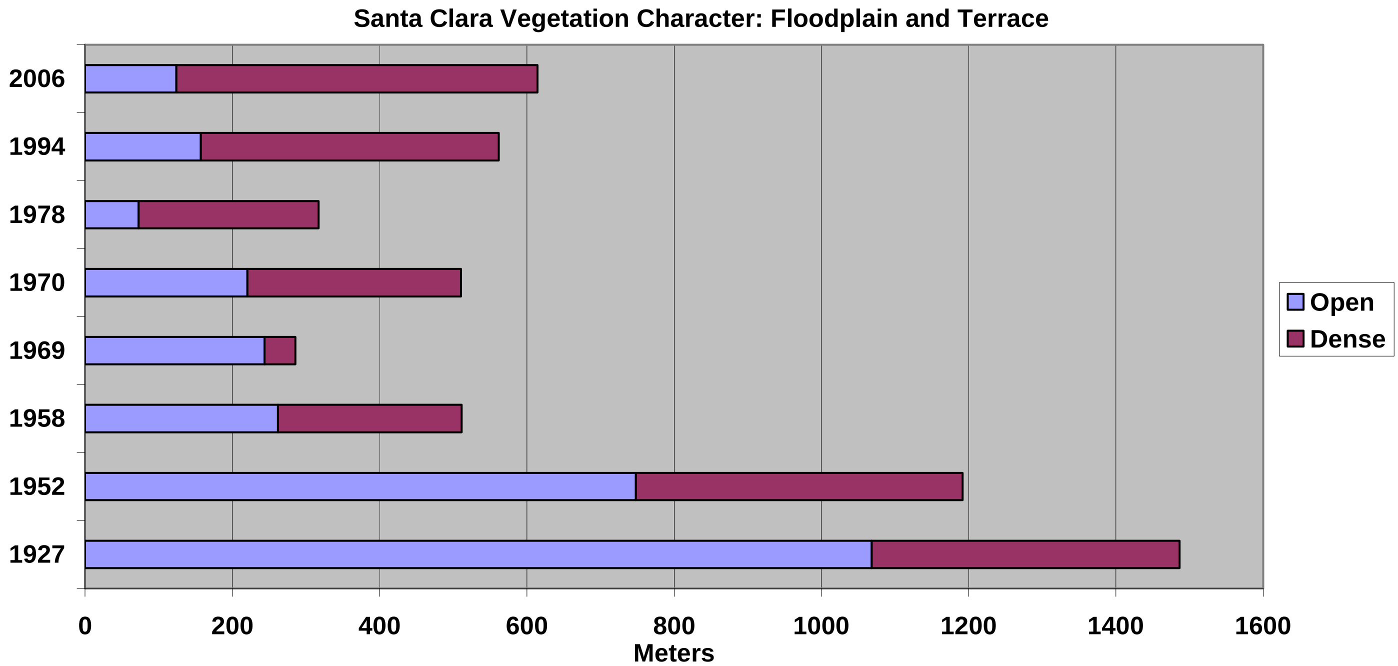


Figure 5-2.25. Santa Clara open and dense vegetation classification on floodplain and lower terrace areas from 1927 to 2006.

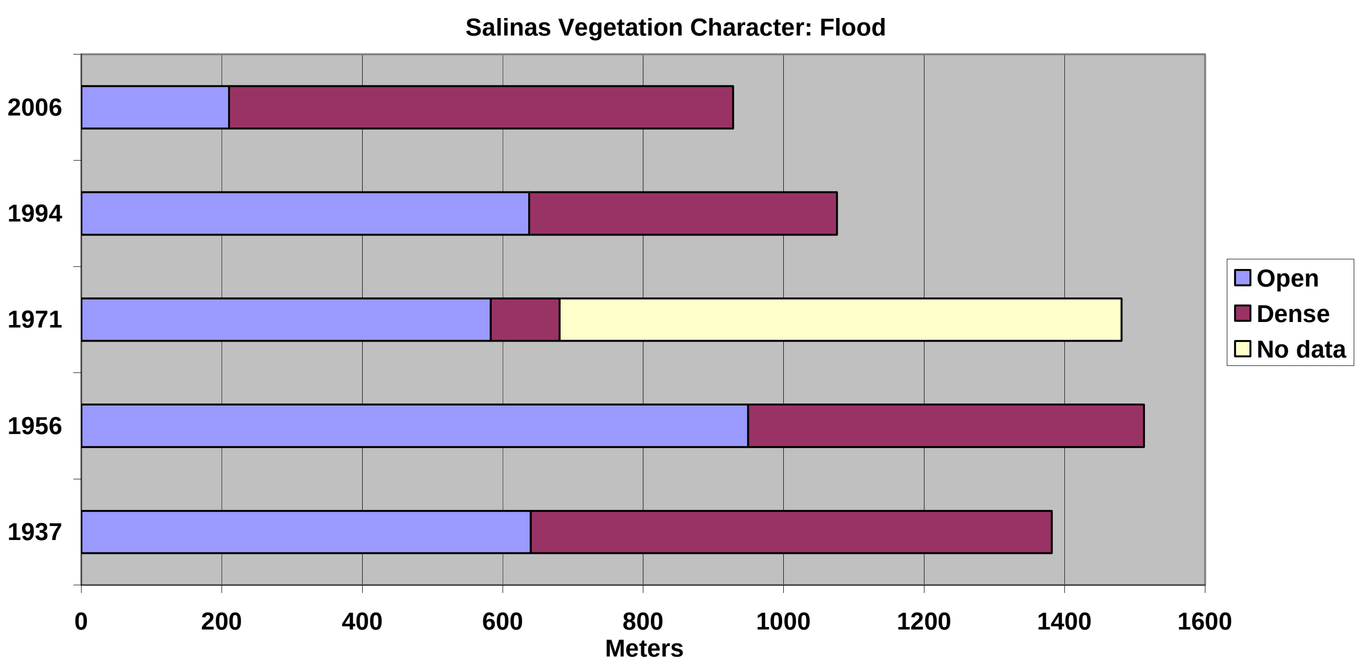


Figure 5-2.26. Salinas open and dense vegetation classification on floodplain and lower terrace areas from 1937 to 2006.

Table 5-2.5. Open and dense vegetation by year for four watersheds.

Watershed	Year	Total length (m)	Open length (m)	Dense Length (m)	% Open	% Dense
San Luis Rey	1938	2112	1688	424	80%	20%
San Luis Rey	1946	2461	1899	561	77%	23%
San Luis Rey	1953	1332	1265	67	95%	5%
San Luis Rey	1964	949	867	81	91%	9%
San Luis Rey	1980	1354	292	1062	22%	78%
San Luis Rey	1990	1451	709	742	49%	51%
San Luis Rey	1997	1502	665	837	44%	56%
San Luis Rey	2010	1605	526	1079	33%	67%
Santa Margarita	1938	1838	745	1093	41%	59%
Santa Margarita	1946	3351	1597	1754	48%	52%
Santa Margarita	1953	3336	2235	1101	67%	33%
Santa Margarita	1980	2724	1266	1458	46%	54%
Santa Margarita	1990	3857	1694	2163	44%	56%
Santa Margarita	1997	4790	2036	2753	43%	57%
Santa Margarita	2010	4978	2225	2753	45%	55%
Santa Ana	1938	2043	1187	856	58%	42%
Santa Ana	1948	1858	755	1103	41%	59%
Santa Ana	1967	1088	389	699	36%	64%
Santa Ana	1980	3292	475	2817	14%	86%
Santa Ana	1993	4169	584	3585	14%	86%
Santa Ana	2006	3530	362	3168	10%	90%
Ventura	1929	1222	1131	91	93%	7%
Ventura	1947	1262	1153	108	91%	9%
Ventura	1959	1117	1087	30	97%	3%
Ventura	1969	584	550	34	94%	6%
Ventura	1978	762	538	224	71%	29%
Ventura	1994	963	534	429	55%	45%
Ventura	2006	883	125	758	14%	86%

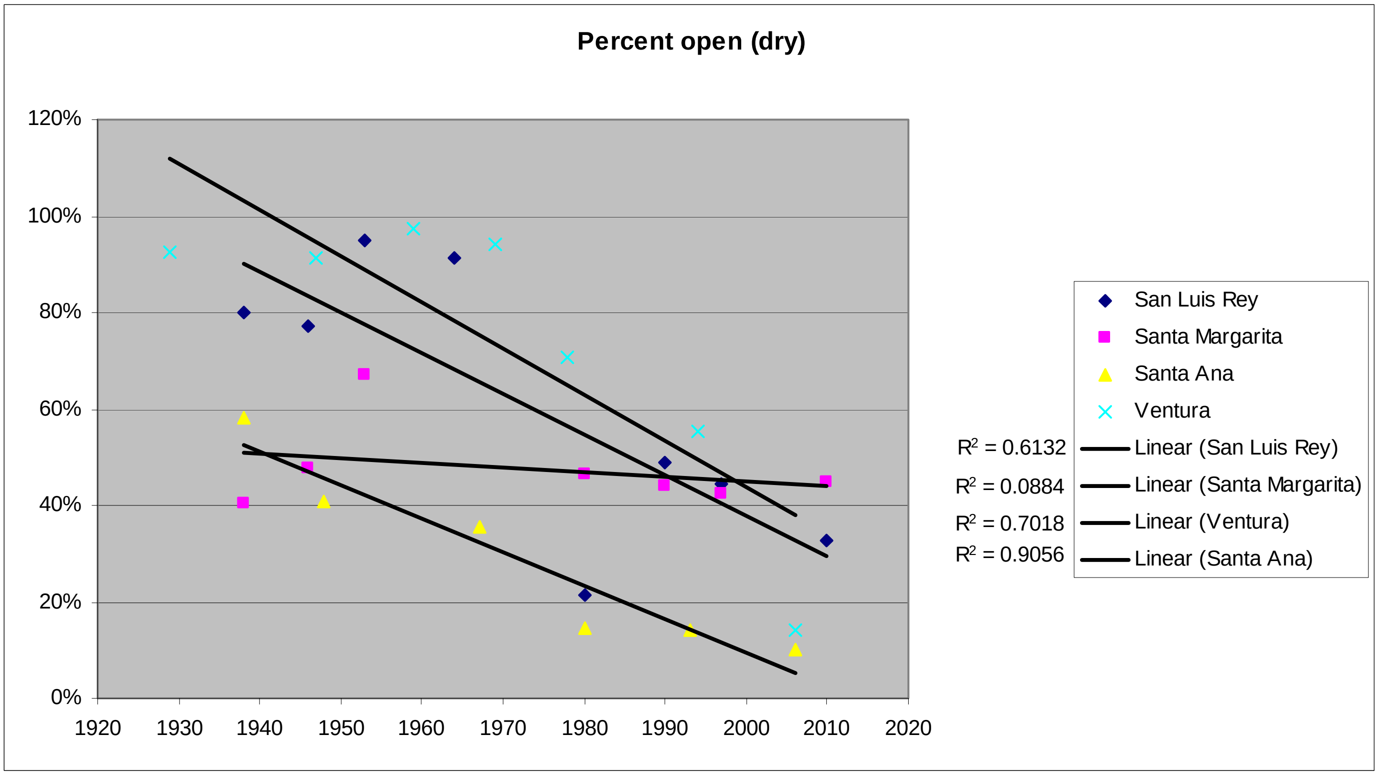


Figure 5-2.27. Trend graph of percent of the open vegetation category from 1927 to 2010 for four watersheds with the AOI.

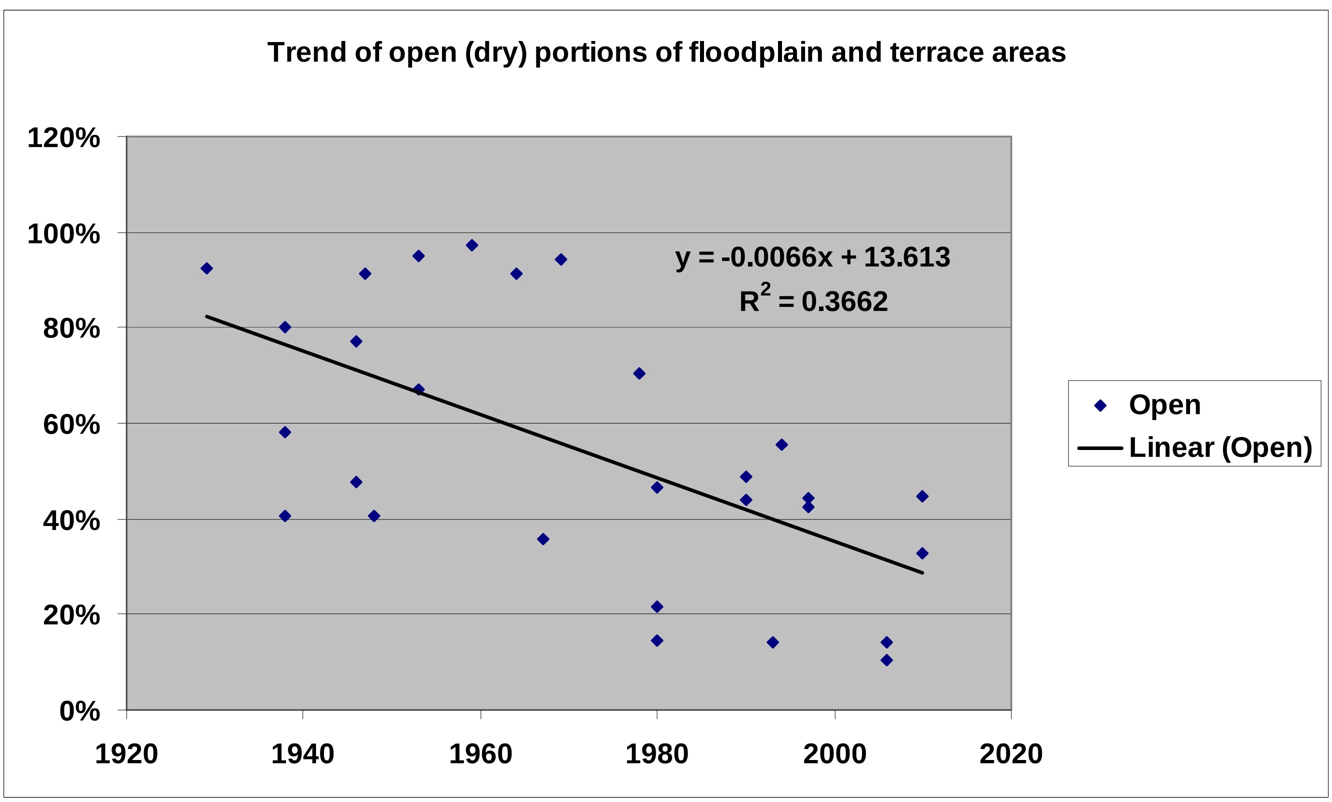


Figure 5-2.28. Trend graph of percent of the open vegetation category from 1927 to 2010 for all watersheds with the AOI.

5.2.4 *Geomorphology and Hydrologic Modification by Arundo*

What role does *Arundo* play in modifying geomorphic processes? This topic was examined in Sections 5.1 and 5.2 in the context of mapping geomorphic forms and investigating how *Arundo* interacts with river flows and sediment movement. What happens when *Arundo* is removed from a river system? *Arundo* was controlled over a large portion of the Santa Margarita watershed by 2000, so this provides an opportunity to look at one system after *Arundo* has been effectively removed. Large flood events have occurred in the ten years since then, so has the acreage of geomorphic forms changed? Mapping of geomorphic forms at peak *Arundo* cover (1997) and 10-year post *Arundo* removal (2010) show some interesting changes (Figure 5-2.15, Table 5-2.6). Low flow channel area decreased, but bar/channel area increased. Combined together they increased 38% from 118 acres to 163 acres. This is a sizeable change, especially given the linear decline of that class that had been occurring (Figure 5-2.15). A major shift in classification from floodplain to low terrace also occurred. These two classes are close in elevation, and the shift shows a movement to more stable native vegetation on terraces and more active zone area (but vegetated) on floodplains. The floodplain is no longer a dense wall of vegetation (*Arundo* with natives) that restricts flows, rather water now passes through the area. This change in functional flow area has broadened the active flow zone to 362 acres in 2010, a 307% increase over the highly invaded *Arundo* state in 1997 (118 acres). This is a major functional change with implications for groundwater recharge, flood risk, sediment transport and habitat function.

The lower elevation areas in the 2010 classification will likely be more 'dynamic' over time as the vegetation is not able to hold the low flow channel in place. Movement of the low flow channel, braiding, and changing bar/channel structure in the 362.5-acre zone is a significant re-establishment of fluvial forms that was in decline within the study area.

Table 5-2.6. Acreage of geomorphic forms within a portion of the Santa Margarita River in 1997 and 2010.

Geomorphic form	**1997 Acreage:** *Arundo* present	**Flows in a 15 Year event?**	**2010 Acreage:** *Arundo* removed	**Flows in a 15 Year event?**	**Percent change**
Low flow channel	74	Yes	49	Yes	-34%
Bar/channel	44	Yes	114	Yes	159%
Floodplain	536	No	199	Yes	-63%
Floodplain/low terrace	557	No	900	No	62%
Upper terrace	297	No	253	No	-15%

5.2.5 Infrastructure Impacts: Roads, Bridges, Levees, Sewer/Water Transfer, Beaches

5.2.5.1 Bridges & Levees

Reduced flow capacity (elevation of 5'), outlined in Section 5.1, is of great consequence for both bridges and levees. Bridges, particularly older structures, may not have been designed to account for this altered flow capacity during large flow events. The loss of 5 feet of profile over the width of a structure is a significant flow conveyance loss. Many older bridges have multiple, tightly spaced buttresses that tend to collect biomass during flows. *Arundo* mixed with large-sized tree trunks is a particularly problematic combination as it forms a block that catches what might otherwise have flowed through the structure. *Arundo* lodged against a Santa Ana River bridge that failed in 2004 (Figure 5-2.29). A bridge on the Santa Margarita River on Stuart Mesa Road was nearly lost in 1998, but crews pulled *Arundo* off pylons during the flow event, likely saving the structure. In 1993 the Basilone Bridge on the same river was lost and a levee protecting the Air Station was breached with severe flooding of the Air Station occurring. Although these losses cannot be fully ascribed to *Arundo* stands that were dense in the area, it was clearly a factor in these structural failures due to flow conveyance loss. An additional levee failure in the same area in 1998, resulting in damage to Air Station fuel pad, led to the baseline work of documenting *Arundo* impacts on flows (see Section 5.1). It was this study that demonstrated the 5' flow conveyance loss over *Arundo* stands. These higher flows overtopped the levee in 1998, an event size that should not have achieved this outcome. *Arundo* was specifically pinpointed as the reason why flows were higher than expected. Given *Arundo*'s demonstrated effect in 1998, it is certain that levee breaches and flooding in 1992 was of greater magnitude due to the presence of extensive *Arundo* stands. This realization was one of the impetuses for *Arundo* eradication on the Santa Margarita River.

A similar series of events has occurred on the San Luis Rey River. Two bridges were lost following 1992 flooding events at College Avenue and at Camino del Ray Ave. The College Bridge was located below large *Arundo* stands, but the Camino del Ray Bridge was not. An extensive levee system was constructed in the early 1990s on the lower San Luis Rey River. By 2005 significant flow capacity had been lost due to vegetation growth (*Arundo* and natives combined). This led to vegetation reduction and *Arundo* control activities initiated in 2008.

These events on three heavily invaded *Arundo* invaded river systems suggest there will likely be future impacts from *Arundo* on other watersheds in the study area. Impacts and cost valuation for bridge damage or loss is included in the Cost Benefit study in Chapter 8.

Figure 5-2.29. Floods stacked *Arundo* biomass against the River Road Bridge on the Santa Ana River, resulting in the bridge being pushed off its foundation in 2004.
Photo by Richard Zembal.

5.2.5.2 Biomass on Beaches

Arundo biomass on beaches following flow events is a recurring impact (Figure 5-2.30 & 5-2.31). In many areas, particularly from Santa Monica to San Diego, biomass is cleared by Municipal, County and State workers using tractors, loaders and sweepers. Estimating the magnitude and cost of these efforts is complicated due to their periodic nature, in addition to a large range in the amount of material. *Arundo* biomass is not the only material discharged by river flow events. There are also other non-native plants, native plants and refuse. It is not unusual for more than 80% of the material to be *Arundo* biomass near heavily invaded watersheds (San Luis Rey, Santa Margarita, Santa Clara, Ventura). Two of these systems will have lower *Arundo* biomass yields in the future as most *Arundo* has been removed (San Luis Rey, Santa Margarita). Santa Ana has lower *Arundo* discharge than other systems because most *Arundo* is present above the Prado Dam. Small and mid-sized watersheds may discharge large amounts of *Arundo* material, particularly watersheds in the Los Angeles basin (Douce 1993).

Figure 5-2.30. In Santa Barbara County, *Arundo* washes down the Santa Clara River and accumulates on Rincon Beach, blocking access for beachgoers and increasing the cost of beach maintenance. Photo by David Chang.

Figure 5-2.31. *Arundo* and other biomass washed onto the beach in Long Beach after a large flow event on the Los Angeles/San Gabriel River. Photo by Drew Ready.

Many beach areas are not maintained for public use. Some of these areas are of significant value to wildlife, particularly areas near estuaries and river mouths. These are also where *Arundo* biomass load is highest. Impact to fauna and threatened and endangered species are outlined in Chapter 7.

Approximately 21 miles of beach are likely to have routine removal of *Arundo* biomass. These areas are north San Diego, Los Angeles/Long Beach, and Ventura/Ojai. Estimates for *Arundo* biomass are based on data from Long Beach following large flood events in 2004/05 (Lopez, pers. comm. 2009, Douce 1993). The city estimates *Arundo* at 40% of total biomass/debris on their beaches. Note that the Los Angeles and San Gabriel Rivers (source of *Arundo* for Long Beach) have significantly less *Arundo* acreage compared to many other systems. Tons of *Arundo* cleared and the cost of collection are presented in Table 5-2.7. Additional flood event sizes are added to reflect a ten-year period. This data is then extrapolated to the two other regions that have higher levels of *Arundo* biomass on their beaches. Discharge of *Arundo* biomass for a single region is estimated at 875 tons/year or 8,750 tons over ten years. For the region, it would be 2,625 tons of *Arundo* biomass annually or 26,250 tons over ten years (Table 5-2.8).

5.2.5.3 Conclusions: Impacts to Infrastructure

Arundo appears to be having significant impacts to structures that cross rivers as well as structures that contain flows (levees). *Arundo* biomass combined with the loss of flow capacity are the two primary factors contributing to these impacts.

- Loss of flow capacity and presence of *Arundo* biomass is likely contributing to overbank flows and bridge loss and damage. (Section 5.2.5.1)
- Flow events mobilize large amounts of *Arundo* biomass. Part of this biomass load ends up on coastal beaches where it is frequently removed by public agencies that required an estimated annual cost of $197,000. This does not include impacts on habitat quality. (Section 5.2.5.2)

Table 5-2.7. Amount of *Arundo* biomass on beaches of Long Beach and clean-up costs for a ten-year period.

Flood Events in 10 Year Period for Long Beach (LA & San Gabriel Rivers)	Percent cost	Tons *Arundo* biomass	Cost of disposal	Cost of collection	Total cost
Large event (1 in 10)	100	5,000	$175,000	$200,000	$375,000
Medium event (2 in 10)	50	2,500	$87,500	$100,000	$187,500
Small events (2 in 10)	25	1,250	$43,750	$50,000	$93,750
No event (5 in 10)	0	0	0	0	-
10 year Total:		**8,750**	**$306,250**	**$350,000**	**$656,250**

Table 5-2.8. Estimate of the amount of *Arundo* biomass on beaches in North San Diego County, Long Beach and Ventura, and the clean-up costs for a ten-year period.

Major regions	10 yr cost	*Arundo* 10 yr biomass (tons)
Long Beach: L.A. and San Gabriel Rivers	$656,250	8,750
North San Diego: San Luis Rey, Santa Margarita	$656,250	8,750
Ventura: Ventura and Santa Clara	$656,250	8,750
10 years:	**$1,968,750**	**26,250**
Annual cost:	**$196,875**	**2,625**