

EFFECTS OF ARUNDO DONAX ON SOUTHERN CALIFORNIA RIVER PROCESSES

PRELIMINARY ANALYSIS OF RIVER HYDRAULICS, SEDIMENT TRANSPORT, AND GEOMORPHOLOGY

FINAL DRAFT

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1. INTRODUCTION

1.1 Background and Objectives

Northwest Hydraulic Consultants, Inc (NHC) is assisting Dendra, Inc and the California Invasive Plant Council (Cal-IPC) with ongoing study and reporting on the effects of *Arundo donax* (Arundo) on Southern California coastal rivers. 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 widely studied and reported, but comparatively few studies have examined the effects of Arundo on river form and process. Essentially, the changes in river geomorphology, flood risk, and sediment erosion, storage, and delivery that follow infestation are not well understood.

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

- Develop an understanding of the typical response of river forms and processes to infestation by Arundo, or other non-native plants, 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 analyses provided by Dendra, Inc
- Prepare a case study of the effects of the Arundo infestation 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.

1.2 Approach

This study relies primarily on existing information. This information included review of the existing literature on the effects of Arundo on geomorphology, GIS databases and maps of river environments and Arundo distributions developed by Dendra Inc, 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 Dendra, Inc for the analysis and mapping of fluvial

landforms on the three Southern California Rivers included in this study. Further details on their methods and procedures are described in Chapter 3 and in their separate report.

1.3 Report Organization

Chapter 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. Chapter 3 summarizes the riverine and riparian or floodplain vegetation characteristics of three of the Southern California study streams. Chapter 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.

Chapter 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. Chapter 6 provides conclusions and recommendations; Chapter 7 a list of references.

1.4 Project Datum and Coordinate Systems

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.

1.5 Acknowledgments

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.

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 Chapter 4.

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; Bell 1997). 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 can reach heights of 6 m to 10 m (Rieger and Kreager 1998; Lawson et al. 2005). *Arundo* stands spread laterally via rhizomes (Rieger and Kreager 1998) and adventitious sprouting of stem tips in contact with the ground (Boland 2006), 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 and 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 (Oakins 2001; Boland 2006). Thus, new Arundo stands are limited to the lateral extent of river flows and floodplain inundation. Arundo can be widely dispersed into disturbed soils during large floods, 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 due to competition from Tamarisk seedlings, although Arundo was denser than Tamarisk on the other landforms. 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 of Arundo

Over a period of decades, Arundo stands can laterally propagate throughout the floodplain, often extending far from the river channel. Boland (2006) measured average annual lateral spreading rates of from 0.95 ft/yr to 7.05 ft/yr in Arundo stands in the Tijuana River Valley, California. 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 and whether the floods remove the plants and roots or only the above-ground vegetation.

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, braided coastal rivers where Arundo is likely to best disperse and establish most rapidly. As described in the next chapter, the riparian systems of the Southern California coastal study

streams are dominated by *Arundo*, which often occupies part of the channel and 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 weakness 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 man-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 subtle difference.

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. 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.

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). Chapter 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.

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 these braided rivers 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.

3. SOUTHERN CALIFORNIA STUDY STREAMS

3.1 Introduction

This chapter summarizes geomorphic and vegetation characteristics of three Southern California study streams: the Santa Margarita, Santa Ana and San Luis Rey Rivers. These streams were selected because they contained some of the greatest observed concentrations of *Arundo* found in Southern California coastal rivers (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 (Chapter 5).

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 for management of *Arundo*. These management sections range from 17 to 37 miles in length and either end at the Pacific Ocean or, in the case of the Santa Ana River, at a reservoir.

The management sections 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 for these reaches in Tables 3.1, 3.2 and 3.3 (following the text). The management sections and stream reaches are shown in Figures 3.1, 3.2 and 3.3; yellow areas in each figure represent the extent of the floodplain mapped in the GIS for each reach.

3.3 CAL-IPC GIS Analysis

Cal-IPC (2010b) mapped geomorphic and vegetation characteristics of the study streams in a GIS. They divided the 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 bed, 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 3.1 to 3.3 represents the maximum observed extent of Arundo infestation for the particular reach. Arundo coverage has changed on the study streams in recent years because of eradication programs.

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 3.1-3.3); 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.

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 3.1 to 3.3 suggest that Arundo is an insignificant portion 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 3.1). 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. Chapter 5 discusses this observation in more detail.

Table 3.1: Santa Margarita River - Summary of GIS Analysis

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Average 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 Average		0.0023	1078	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 total floodplain with more than 50% vegetation cover

3 – Arundo Area = Maximum percentage area of the floodplain and channel surface occupied by Arundo (Cal-IPC 2010b)

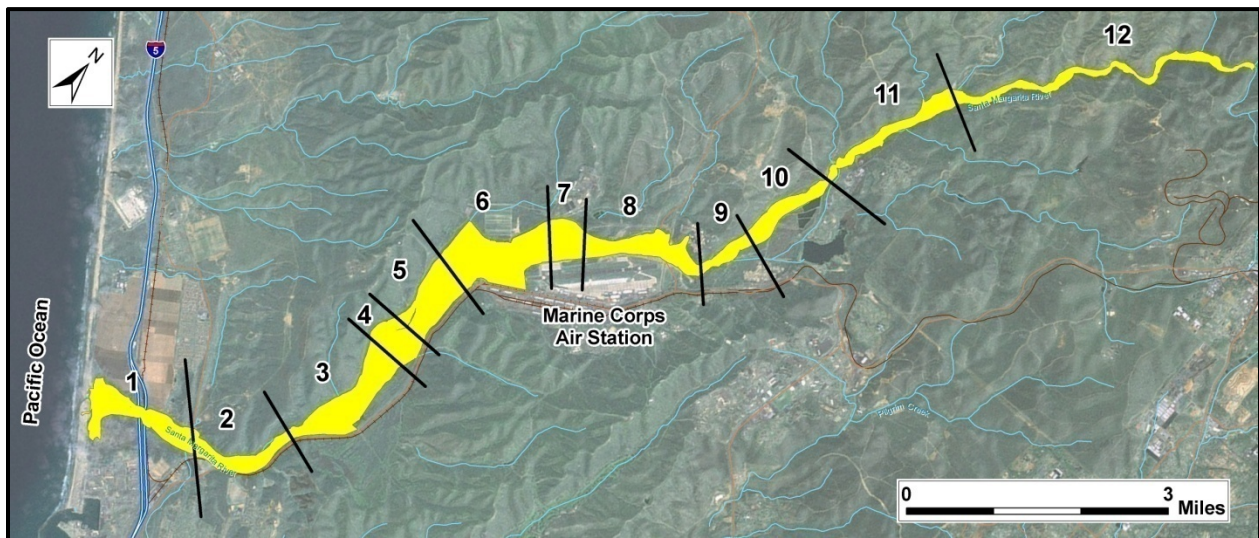


Figure 3.1: Santa Margarita River Study Reaches (yellow denotes extent of mapped floodplain).

Table 3.2: Santa Ana River - Summary of GIS Analysis

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Average 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 total floodplain with more than 50% vegetation cover

3 – Arundo Area = Maximum percentage area of the floodplain and channel surface occupied by Arundo (Cal-IPC 2010b)

1 – Width Ratio = Average Floodplain Width / Average 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)

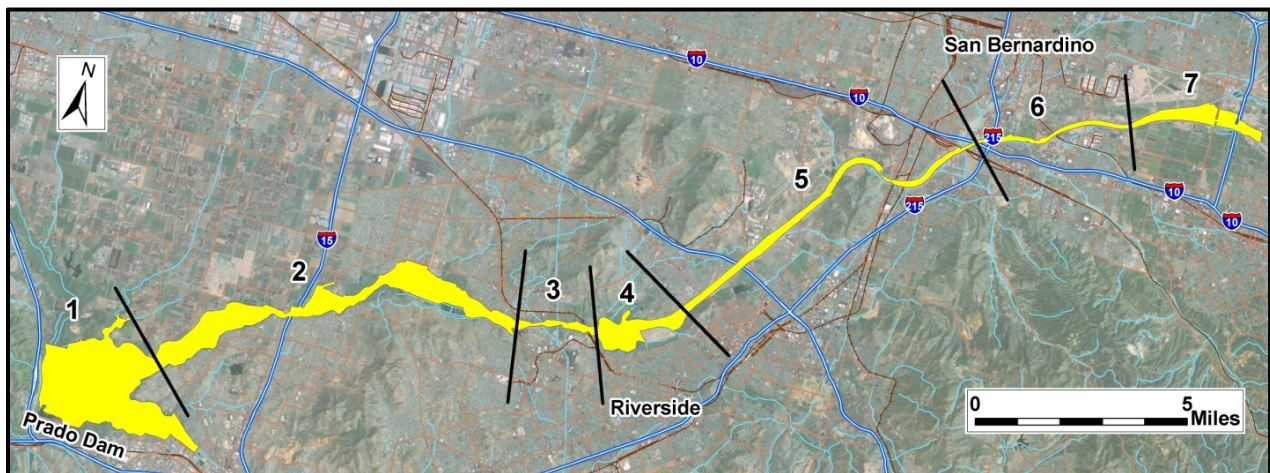


Figure 3.2: Santa Ana River Study Reaches (yellow denotes extent of mapped floodplain).

Table 3.3: San Luis Rey River - Summary of GIS Analysis

Reach No.	Reach Length (mi)	Average Slope	Average Floodplain Width (ft)	Average 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 total floodplain with more than 50% vegetation cover

3 – Arundo Area = Maximum percentage area of the floodplain and channel surface occupied by Arundo (Cal-IPC 2010b)

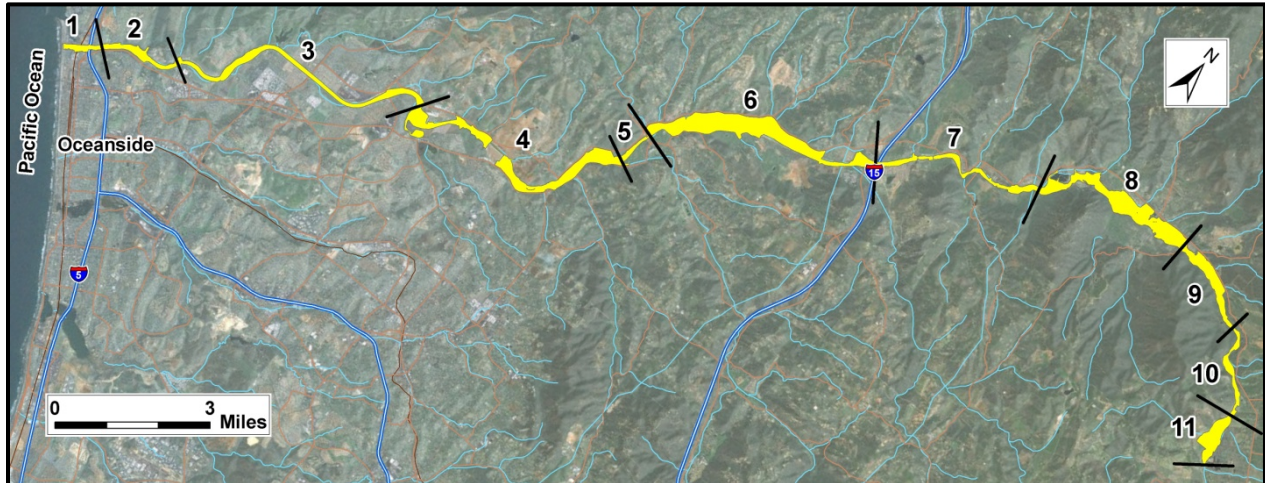


Figure 3.3: San Luis Rey River Study Reaches (yellow denotes extent of mapped floodplain).

4. SANTA MARGARITA RIVER CASE STUDY

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.

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 mi² 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 Tocalota Creek, constructed in 1974 by the Metropolitan Water District (MWD), regulates a 51 mi² 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).

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 4.1).

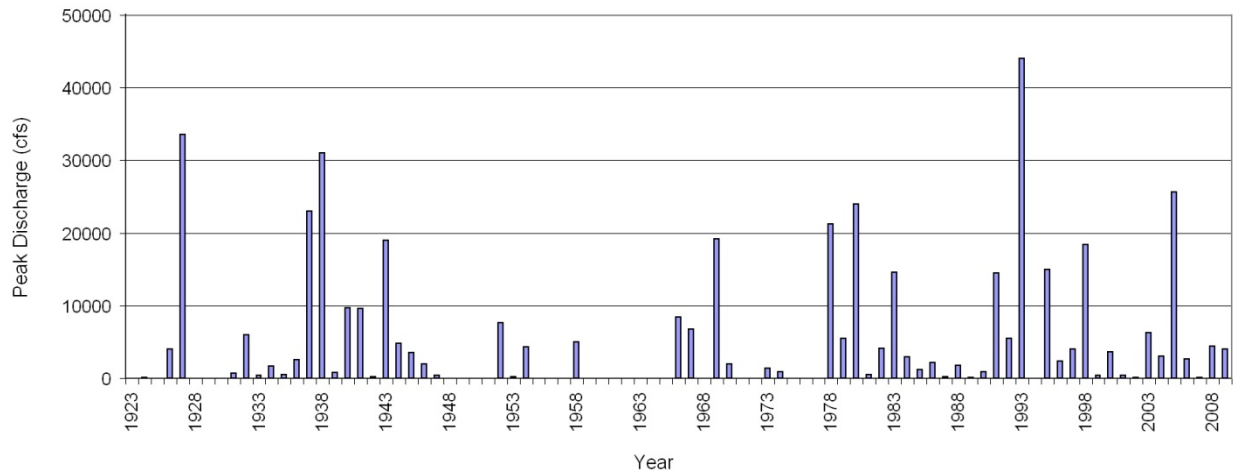


Figure 4.1: Annual peak discharges recorded at USGS stream gage 11046000 on Santa Margarita River near Ysidora. Years with zero values or no data are shown as blank.

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 4.1 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). 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 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 low flows since the 1970s (Figure 4.2; following page). 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.

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.

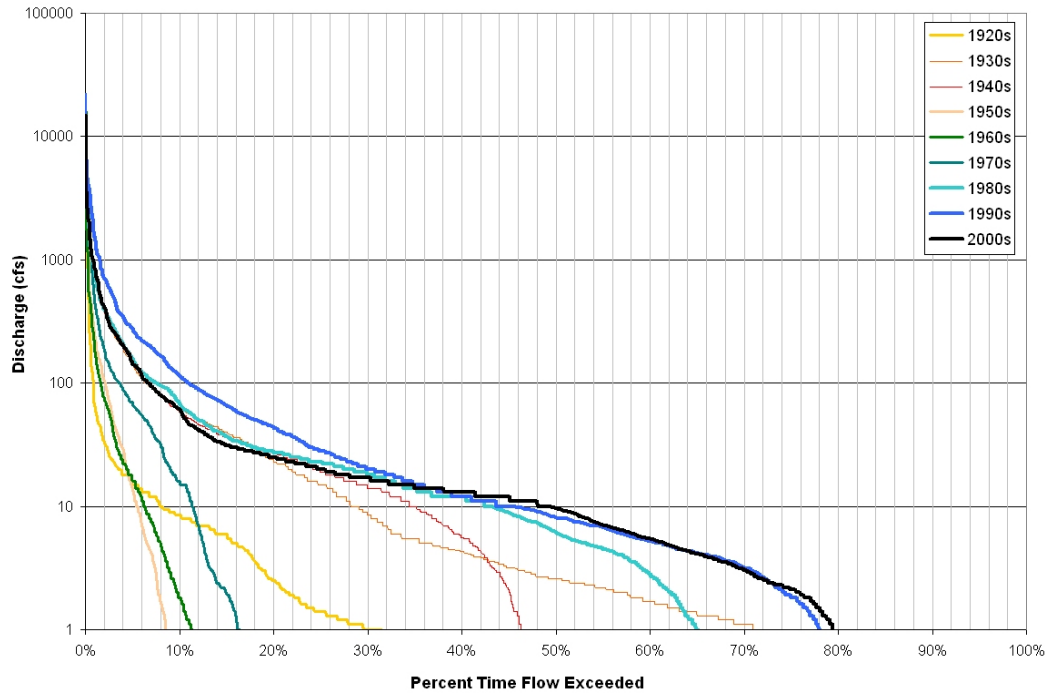


Figure 4.2: Flow duration curves plotted by decade at the Ysidora gage (11046000).



Figure 4.3: Sub-reaches (numbers 1 through 6) in the lower Santa Margarita River project reach.

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 4.3).

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 3.1 and Figure 3.1. 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 4.1; Figure 4.3).

The sub-reach breaks on Figure 4.3 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 4.1 (following page).

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 about four to eight times wider than the low flow channel defined in Table 3.1. 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 4.4).

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

Table 4.1: Description of the Lower Santa Margarita Project Sub-Reaches

Sub-Reach	Reach Length (ft)	Slope (ft/ft)	Average Floodplain Width (ft)	Average Channel Width (ft)	General Observations
Sub-Reach 1 (sta. 0 to sta. 18+61) <i>Downstream sub-reach</i>	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) <i>Upstream sub-reach</i>	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.

4.5 Historical Changes in the Project Reach

Planform

NHC (1997a) examined the lower Santa Margarita River on historical air photos and maps and found that it had maintained about 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 4.5). 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.

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 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 4.1).

Floodplain Vegetation

Figure 4.5 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, and floodplain vegetation also appears to be less dense 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 year 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.

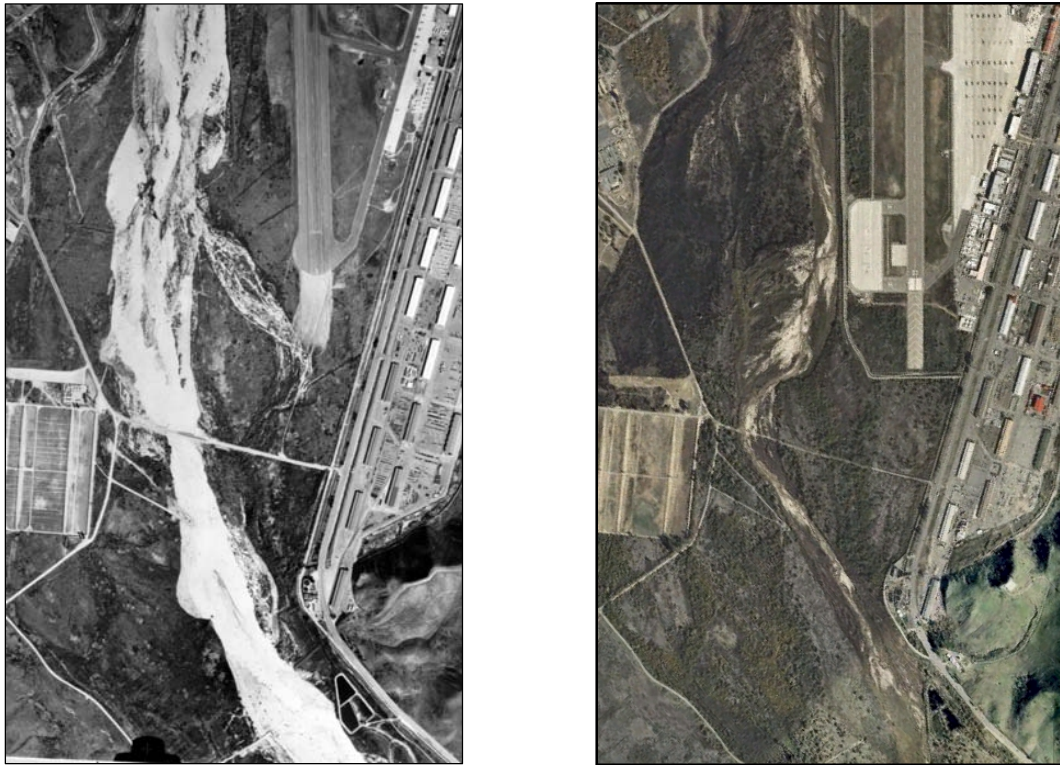


Figure 4.5: Comparison of 1970 (left) and 2008 (right) air photos of Sub-reach 3.

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 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, noting that the area of low flow channel and unvegetated bar or floodplain (main channel area) 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.

4.6 Project Reach Hydraulics

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 4.6).



Figure 4.6: Location of HEC-RAS model cross-sections (in yellow) (NHC 2001).

Model Calibration

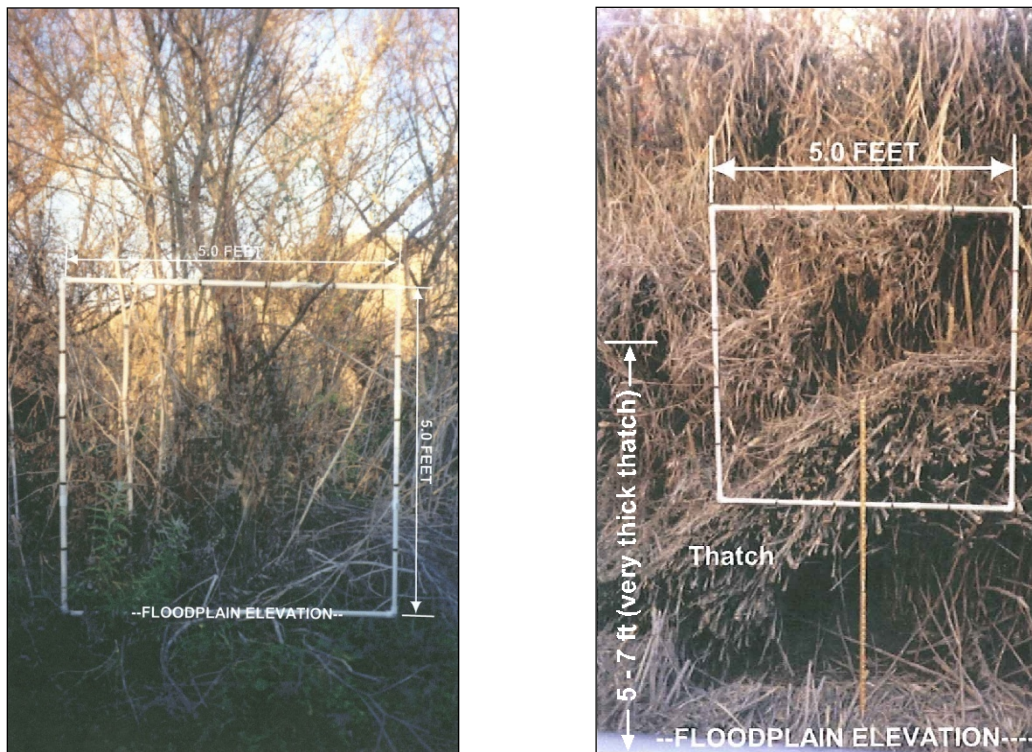
The HEC-RAS model was calibrated to high water marks surveyed after the 1993 (44,000 cfs) and 1998 (18,400 cfs) floods. Calibration consisted of adjusting Manning's roughness and floodplain characteristics until calculated water surface profiles matched those observed during the floods. The initial calibration 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 4.7). 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 4.7).

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 4.7: 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. This scenario may not represent historical conditions; floodplain vegetation may have been much less dense then.
- *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 by Dendra, Inc. 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 4.2 summarizes the peak flows adopted for the steady state HEC-RAS model runs that were performed as part this study.

Table 4.2: Peak Flows Adopted for the Project Reach (USACE 1994)

<i>Return Period (years)</i>	<i>Peak Discharge (cfs)</i>
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 4.3 provides a general summary of the variation in reach-averaged hydraulic variables for the various scenarios, compared to complete native vegetation coverage (Scenario 2).

Table 4.3: 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	<i>(baseline)</i>	<i>(baseline)</i>	<i>(baseline)</i>	<i>(baseline)</i>
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 4.2. 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 4.4).

Table 4.4: Extent of Arundo by Sub-Reach as of 1997

<i>Sub-Reach</i> ¹	<i>Floodplain Area (ac)</i>	<i>Arundo (ac)</i>	<i>Percentage</i>
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 4.3 for location of sub-reaches.

Water Surface Profiles

Figure 4.8 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 4.4). Complete coverage by Arundo (Scenario 1) raises flood levels by 4 to 5 feet above those for native vegetation coverage 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 4.4). On this basis, percent Arundo coverage somewhere over 30% generally results in significant adjustments to the water surface profile.

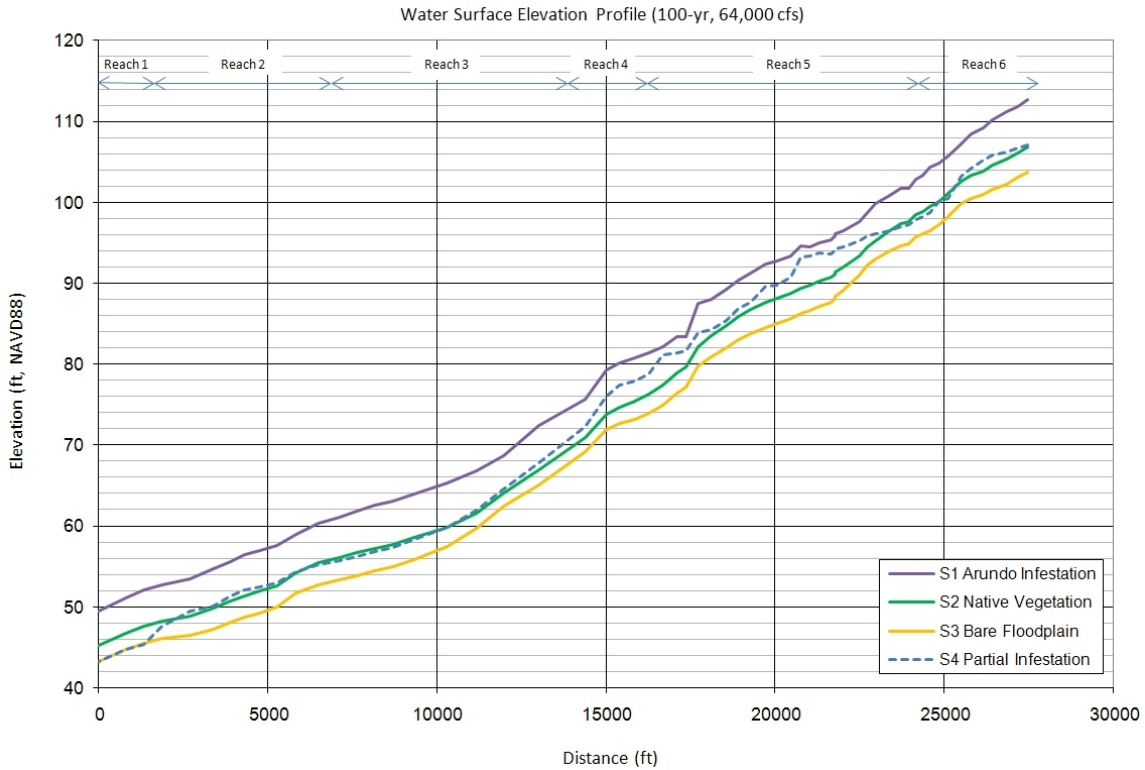


Figure 4.8: Project Reach Water surface profiles for Scenarios 1 to 4: 100-year peak flow.

Channel and Floodplain Velocities

Table 4.3 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.

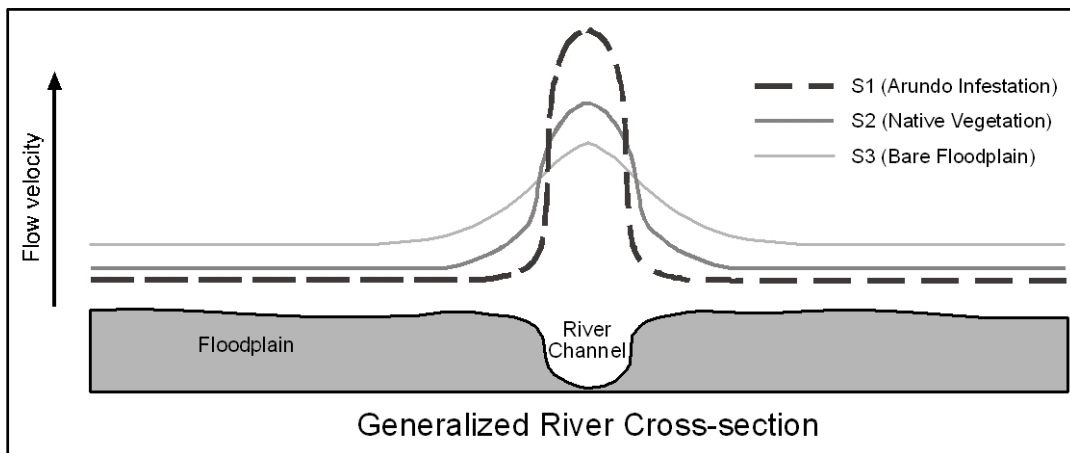


Figure 4.9: Generalized illustration of the effects of floodplain roughness (dense vegetation) on velocity across the section for Scenarios 1, 2, and 3.

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 4.9.

Results by Sub-Reach

Table 4.5 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 4.1). 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 4.5: 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 – <i>Arundo</i> 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.

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:

$$\text{Sediment}_{\text{Out}} = \text{Sediment}_{\text{In}} - \Delta\text{Storage} \quad (1)$$

In (1), the change in sediment storage in the reach over time ($\Delta\text{Storage}$) 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 on 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; also 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 m³) in the two studies. Slagel and Griggs (2006) also concluded that average annual sand transport was about 20 acre-feet (25,000 m³), or about 30 to 40% of the total transport.

Sediment Capture by Arundo

Previous studies (see Chapter 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 return to 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.

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:

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

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:

$$\Omega = \tau vw \quad (3)$$

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 4.6 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. 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 4.6 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 vegetation changes from *Arundo* to bare soil (Scenario 3), as it would under the 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 does not affect stability of the sediments.

Table 4.6: Summary of Relative Differences in Stream Power by Scenario

Flow Event	Channel				Floodplain (Overbank)				Total			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
5-year	1.41	1.00	0.88	1.02	0.23	1.00	1.33	0.95	1.00	1.00	1.04	0.99
10-year	1.59	1.00	0.86	1.06	0.38	1.00	1.22	0.92	1.04	1.00	1.02	1.00
25-year	1.51	1.00	0.80	1.10	0.50	1.00	1.17	0.89	0.95	1.00	1.01	0.99
50-year	1.50	1.00	0.77	1.13	0.59	1.00	1.16	0.92	0.95	1.00	1.01	1.00
100-year	1.50	1.00	0.74	1.14	0.66	1.00	1.15	0.95	0.96	1.00	1.00	1.02
Average Annual	1.50	1.00	0.83	1.07	0.49	1.00	1.20	0.93	0.99	1.00	1.02	1.00

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. Table 4.7 repeats Table 4.5 for relative stream power in the narrow Sub-reach 5 and the wider Sub-reach 3.

Table 4.7: Differences in Relative Stream Power for Sub-reaches 3 and 5

Sub-reach 3 (wider floodplain)

Flow Event	Channel				Floodplain (Overbank)				Total			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
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
100-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)

Flow Event	Channel				Floodplain (Overbank)				Total			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
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
100-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

Table 4.7 illustrates that 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 would be expected in wider floodplain reaches with complete Arundo coverage than in narrower ones. It also appears that the threshold for

morphologic change from Arundo coverage is less in wider reaches. Examining the Scenario 4 stream power ratios shows that in the narrower reach that stream powers are slightly reduced compared to the native vegetation scenario and that the morphology of the main channel may be little affected. As discussed earlier, the model does not incorporate changes in channel width that occur as Arundo establishes on the floodplain, so the above observation may not be correct.

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 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 floods 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 different floodplain vegetation scenarios (modeled as ineffective flow areas and varying roughness) for the 1997 channel and floodplain topography suggested that the conversion from complete native vegetation coverage to complete coverage by mature Arundo stands has 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 channel 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 about equal that which passes through to downstream reaches and the Pacific Ocean.

5. STUDY STREAM ARUNDO RESPONSES

5.1 Introduction

This chapter applies the results of the literature review (Chapter 3) and the case study analysis (Chapter 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 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 3.

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 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 2.4 and 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 3), which is the ratio of the low flow channel width to the floodplain width (Table 5.1).

Table 5.1: 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 3.1. Table 5.1 shows the scores assigned to the different width ratios.

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 compared to native vegetation coverage. This percent coverage seemed to be between 28% and 45% Arundo coverage for the case study river (see Section 4.6). Table 5.2 shows the scoring that was developed based on the percent Arundo Coverage mapped for each reach in Chapter 3. Cut-off points of 25% and 40% were selected for scoring the impact of percent Arundo cover on river characteristics.

Table 5.2: 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 Chapter 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 establishment 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 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.

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 5.3.

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 5.4.

Table 5.3: 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 5.4: 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.

5.3 Santa Margarita River

Table 5.5 shows the Arundo impact scores for the Santa Margarita River study reaches. Note that the case study Sub-reaches 1 through 6 conform to Reaches 4 through 9 in the GIS mapping in Chapter 3.

Table 5.5: Santa Margarita River Arundo Impact Scores

Reach	Case Study Sub-Reach	<i>Total Score</i>	Arundo Impact Scores				
			Width Ratio	Arundo Coverage	Floodplain Width	Bed Slope	Other Features
1		<i>-1</i>	-1	0	0	1	-1
2		<i>-1</i>	-1	0	0	0	0
3		<i>0</i>	0	0	0	0	0
4	1	<i>2</i>	2	0	0	0	0
5	2	<i>6</i>	2	3	0	1	0
6	3	<i>2</i>	2	1	0	-1	0
7	4	<i>7</i>	2	3	1	1	0
8	5	<i>4</i>	0	3	0	0	1
9	6	<i>0</i>	-1	0	0	0	1
10		<i>0</i>	-1	0	0	0	1
11		<i>-1</i>	-1	0	0	0	0
12		<i>-1</i>	-1	0	n/a	n/a	0

Table 5.5 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 5.5 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 Chapter 4. Sub-reach 4 does show a rise in the water surface profile compared to the base case (Figure 4.8) and other modifications to the reach hydraulics occur. Sub-reach 2 shows no rise in the water surface profile (Figure 4.8); instead, the increased flow through the main channel is accommodated by increases in velocities.

5.4 San Luis Rey River

Table 5.6 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, eradication programs 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.

Table 5.6: San Luis Rey Arundo Impact Scores

Reach	<i>Total Score</i>	Arundo Impact Scores				
		Width Ratio	Arundo Coverage	Floodplain Width	Bed Slope	Other Features
1	<i>-1</i>	-1	0	0	1	-1
2	<i>3</i>	-1	3	0	1	0
3	<i>-1</i>	-1	0	0	0	0
4	<i>2</i>	0	1	0	1	0
5	<i>-1</i>	0	0	-1	0	0
6	<i>1</i>	0	0	1	0	0
7	<i>-2</i>	-1	0	-1	0	0
8	<i>0</i>	2	0	0	1	-3
9	<i>-1</i>	2	0	0	0	-3
10	<i>-5</i>	0	0	-1	-1	-3
11	<i>-1</i>	2	0	n/a	n/a	-3

5.5 Santa Ana River

Table 5.7 summarizes the Arundo Impact scores for the Santa Ana River 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.

Table 5.7: Santa Ana River Arundo Impact Scores

Reach	Total Score	Arundo Impact Scores				
		Width Ratio	Arundo Coverage	Floodplain Width	Bed Slope	Other Features
1	5	2	0	1	1	1
2	4	0	3	1	0	0
3	-1	-1	0	-1	1	0
4	0	-1	0	1	0	0
5	0	-1	0	0	1	0
6	-2	-1	0	-1	0	0
7	-1	-1	0	n/a	n/a	0

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. The scoring system may also be useful as a monitoring tool; those reaches with high combined scores might be monitored regularly to determine when further Arundo eradication may be necessary to avoid changes in river processes and morphology.

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 floods and re-establish mature stands on much of the floodplain in the typical time intervals 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 one 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 aggrade 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 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. Modeling of different floodplain vegetation scenarios suggested that the conversion from complete 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 to the 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.

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