Pajaro River Watershed Flood Prevention Authority

Phase 1 Final Report for the Pajaro River Watershed Study

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RMC
Raines, Melton & Carella, Inc.

in association with

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CONSULTING CIVIL ENGINEERS

Table of Contents

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Glossary

AMC (Antecedent Moisture Condition) – A measure of how wet the soil was prior to a rain event

Annual instantaneous maximum peak discharge – The greatest discharge value at a point during a water year

Annual maximum 3-day average discharge – The greatest average discharge value over three days during a water year

Attenuate – To reduce

Authority – The Pajaro River Watershed Flood Prevention Authority

Catch point – One of four locations at which PRO-FLO models discharge

CEQA (California Environmental Quality Act) – State law written to maintain a high quality environment

cfs (Cubic Feet per Second) – A measure of discharge where 1 cfs is approximately 450 gallons per minute

CN (Curve Number) – A scale to relate how much precipitation is absorbed by the soil to how much is converted to runoff

Corps – The Army Corps of Engineers

Design discharge **-** Discharges from the most severe combination of meteorological and hydrologic conditions that are considered reasonably characteristic of the geographical region involved

Design storm – A synthetic rainfall used in modeling to characterize rain events rather than model individual storms

Drainage area – The area in which all surface runoff is carried away by a single stream system

Exceedance probability – The chance that a given event will be equaled or surpassed in magnitude

FEMA (Federal Emergency Management Agency) – A federal organization created to prepare for, respond to, recover from, and mitigate against disasters

Flooding frequency – The number of times a flood occurs in any average interval of time

Flood plain – The area of land that has historically been covered by water during floods

GIS (Geographic Information System) – A spatial database

Groundwater recharge – The addition of water to subterranean water bodies

GUI (Graphical User Interface) – A method of interacting with a computer program

HEC-1 (Hydrologic Engineering Center Flood Hydrograph Package) – One of the software programs used to create PRO-FLO

HEC-RAS (Hydrologic Engineering Center River Analysis System) – One of the software programs used to create PRO-FLO

Hydraulic roughness – The resistance to flow due to channel characteristics

Hydrograph – A location specific graph showing some property of water with respect to time.

Hydrologic condition – A measure of factors that impact surface runoff and is used to determine the curve number

Impervious surface – A surface not allowing the absorption or seepage of water into the ground

Isohyets – Contours or lines of equal rainfall

Levee – An embankment constructed to prevent flooding outside of a confined space

MAP (Mean Annual Precipitation) – The average rainfall over one year for a specific point or area

NLCD (National Land Cover Dataset) – Data used to classify land uses

NRCS (Natural Resources Conservation Service) – Agency tasked with maintaining, conserving, and improving the nation's natural resources and environment

Orographic effect – Mountain impacts on processes such as precipitation

PRO-FLO (Pajaro River to the Ocean FLOod Model) – Model developed for the PRWS to simulate floods in various conditions

PRO-SED (Pajaro River to the Ocean SEDiment generation and transport model) – Model developed for the PRWS to simulate the effects of various conditions on sedimentation and erosion.

PRWS (Pajaro River Watershed Study) – A study authorized by the Authority to determine the causes of flooding and identify methods of flood protection

QAPP (Quality Assurance Project Plan) – Guidelines and protocols for data collection, handling, and analysis

Return period – The average amount of time between occurrences of an event of a given size

Riparian – Related to or situated on the bank of a river or other body of water

SCS (Soil Conservation Service) – The agency now known as the NRCS

SCVWD (Santa Clara Valley Water District) – One of the water districts impacting the PRWS

SSURGO (Soil Survey Geographic database) – Digitized soil maps

STATSGO (State Soil Geographic database) – Digital general soil association map

TDS Equation (Return Period-Duration-Specific equation) – A relationship used to determine the amount of rainfall for a location based on the MAP and the return period and duration of the event

Transposition mechanism – The basis of the design storm

TM (Technical Memorandum) – Documents cataloging technical decisions, methods, and results in support of the PRWS

USGS (United States Geological Survey) – A federal agency that collects information about and analyzes natural resources

Watershed – The area upstream of a point through which all surface water within that area flows

Water year – The period from October 1 through September 30

Executive Summary

Executive Summary

The purpose of Phase 1 of the Pajaro River Watershed Study was to model both the hydrologic and sediment regimes of the Pajaro River watershed, providing a foundation and stepping-stone for the development of flood protection solutions for the Pajaro Valley.

Several lessons can be gleaned from Phase 1 modeling results. The flooding effects of urbanization, agriculture, flood protection projects, in-stream channel conditions or vegetation, and in-stream sediment factors are summarized below:

Hydrology

- Since 1947, the addition of three reservoirs significantly reduced the probability of flooding in the lower Pajaro River.
- Neither current agriculture conditions nor potential agricultural changes have a significant effect on design discharge or flood impacts.
- Urbanization increases the runoff from frequent events (2-year to 25-year) but has little impact on runoff from large storms (50-year to 200-year).
- Soap Lake provides significant flow attenuation and flood storage benefits for the upper Pajaro River and is key to flood protection.

Sediment

- The small, predicted changes in peak design discharges should not significantly alter sedimentation conditions within the Pajaro River channel.
- Significant growth of shrubby vegetation could increase hydraulic channel roughness and could be expected to cause an increase in sediment deposition.
- Changes in sediment load may have localized impacts at the confluence of the San Benito and Pajaro Rivers but do not affect the system as a whole.
- Soap Lake limits sediment discharge from the upper to the lower Pajaro River.

As currently calibrated, both models meet the goals of Phase 1. The models can be further refined in future phases if required. Also, Soap Lake operation and flood protection capabilities could be examined in greater detail.

The Pajaro River is the largest coastal stream between the San Francisco Bay and the Salinas Watershed with a watershed of over 1,300 square miles.

The watershed covers portions of Santa Cruz, Santa Clara, San Benito, and Monterey Counties (Figure ES-1). The large size of the watershed contributes to the number of diverse environments, physical features, and land uses within its boundaries. Development within the watershed, both urban and rural, is clustered around the major cities of Watsonville, Gilroy, Morgan Hill, Hollister, and San Juan Bautista. Agriculture and grazing are the dominant land uses in these areas but represent a small portion of the total watershed land use. The majority of the watershed land cover is grassland, shrubland, and forest.

Four Watershed Conditions

Land use is one of the factors that affects flood frequency and magnitude. One of the major goals of Phase 1 of the study was to understand the potential flooding affects of land use changes over time. Four different land use conditions were chosen to span the extent of the reasonable land use changes and associated flooding affects. Modeling the watershed in different conditions gives insight into potential future flooding problems and allows the impacts of development trends to be identified.

Each of the four conditions was chosen based on both individual characteristics and patterns that can be established between them. First, the model was developed and calibrated using existing conditions. Then, the four conditions were selected and modeled. The following four conditions allow the model to explore watershed response to changes that might affect downstream flooding.

- **Back in Time to 1947:** The historical perspective provides a glimpse of how flooding has changed due to known shifts in land use. The year 1947 is significant because it was just before the Corps' levees were built and had conditions similar to when the 1955 flood occurred. In addition, three of the four existing reservoirs and some additional levees were not yet in place in 1947.

- **General Plan Buildout:** This scenario allows the model to predict the watershed flood potential using the urban and agricultural land uses for each city and county designated by the individual planning departments. This is the best estimate available for future conditions within the watershed. While the horizons of the individual general plans vary greatly, this scenario is intended to approximately represent the years between 2015 and 2020.

- **Ultimate Buildout in 2050:** This scenario represents a worst-case scenario, in terms of flooding, due to urbanization. The model predicts how the watershed would respond to significantly increased growth in the cities beyond what the general plans currently allow. The year 2050 is the approximate end of the economic life of a project started at the time of this report.

- **Changes in Agriculture:** Agriculture can play a large role in the amount of runoff and therefore flooding in an area. This scenario does not represent any particular time period but parallels the Ultimate Buildout scenario in that it represents a worst-case agricultural hydrologic conditions.

Hydrology Model Results of Four Watershed Conditions

- **Back in Time to 1947:** Peak and average design discharges were higher in 1947 than they are today. Reservoirs existing today in the upper reaches of the watershed provide some incidental flood protection in the lower Pajaro River area.

- **General Plan Buildout and Ultimate Buildout in 2050:** These two watershed scenarios have been grouped together due to similarities in both their goals and results. Both conditions were chosen to see the effects of urbanization on runoff but at different times in the future; consequently, results show similar trends.

  The model results indicate that urbanization affects small storm discharge more than it affects large storm discharge. For the General Plan Buildout scenario, all changes in storms larger than the 50-year event are less than 3% for both peak and 3-day average discharges. For the Ultimate Buildout

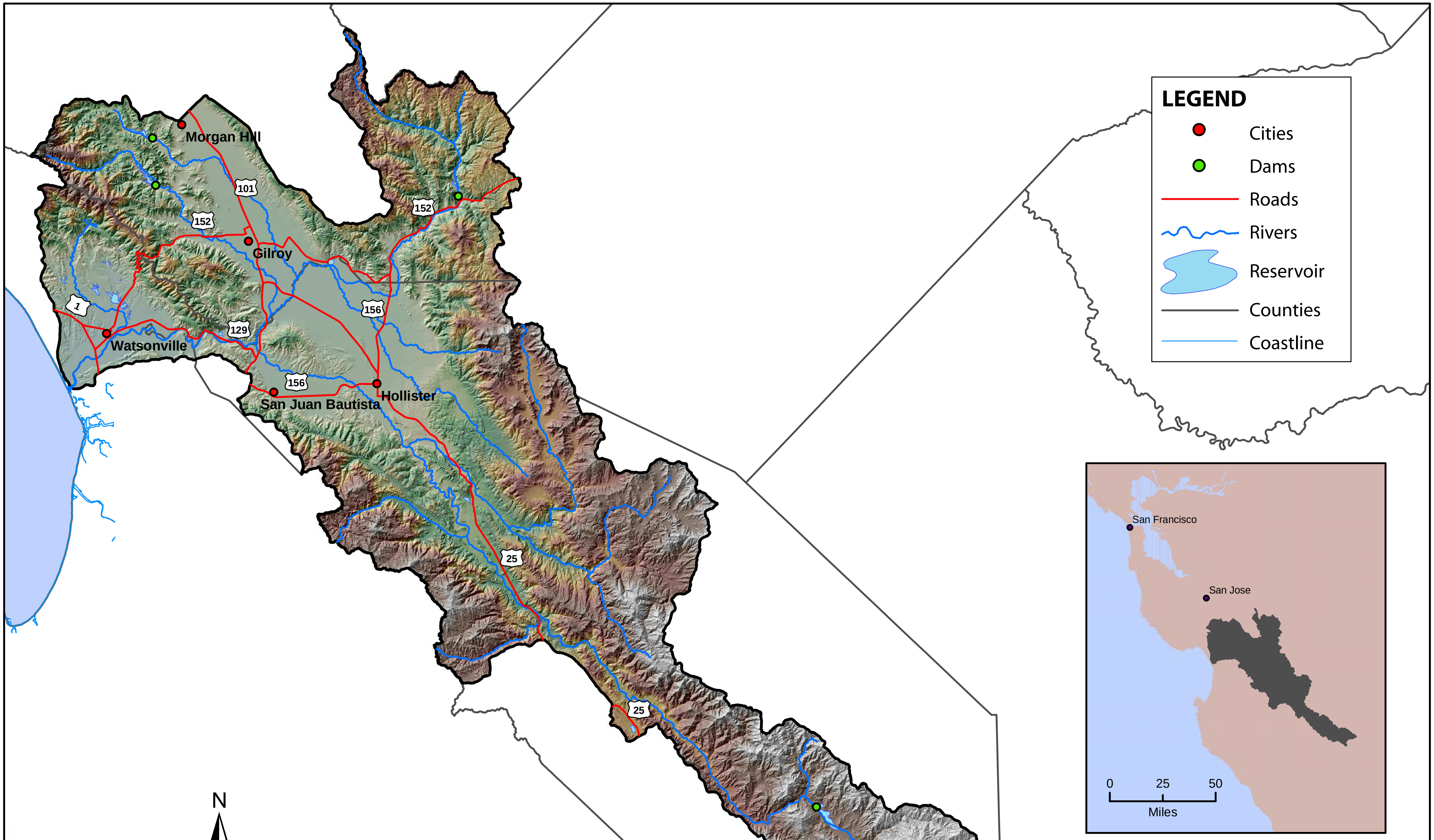

Figure ES-1

PAJARO RIVER WATERSHED

Pajaro River Watershed

scenario, the largest change is approximately a 5% increase in maximum annual peak discharge and 3-day average flow. The lack of significant changes is probably due to the small amount of urbanization upstream of the San Benito River modeling point.

Urbanization has a significant effect on the peak discharge of the smaller storms (2-year to 25-year). The impervious surfaces added by the development of urban areas generate more runoff and discharge in smaller events. The discharge frequency of a given storm will decrease with the additional urbanization. In other words, what was previously considered a 25-year storm would be expected to occur every 23 years.

- **Changes in Agriculture:** Model results indicate that even if all current agricultural uses in the watershed were converted to row crops under poor hydrologic conditions, the changes in peak discharge and 3-day discharge for the 50-year to 200-year return periods are well under a 2.5% increase from existing conditions. However, the 2-year to 25-year return periods show a much larger impact, increasing flows up to almost 9.5% in some locations. The major impact comes from the Lower Soap Lake watershed that includes agricultural uses in the South Santa Clara Valley, the Hollister Valley, and the Bolsa. Changes in the San Benito River watershed were very small, as only a small percentage of that watershed is currently used for agriculture.

Sediment Model Conditions

Additional scenarios were developed for the sediment model to expand the understanding of the sediment characteristics of the Pajaro River. The sediment model used the hydrology model results as one of several variables. Other variables included streamflow data, hydraulic roughness of the channel, and sediment data. Comparison between the current peak discharge and the Back in Time to 1947 peak discharge shows the effects of varying streamflow. Increasing the channel hydraulic roughness simulates additional vegetation and impacts the velocity and water depth in the channel, which increases sediment deposition. The other conditions are developed based on an increase or decrease in actual sediment load which could result from changes in upstream land use, instream gravel mining, incision and erosion of upstream channels, and reservoir construction.

Sediment Model Results

Neither the increased peak design discharge and flow nor the changes in sediment load affected the sedimentation or sediment transport in the river dramatically. Increasing the hydraulic roughness does increase sedimentation at the confluence of the Pajaro River and San Benito River. Over several large storms this sediment could move downstream into the leveed portion of the river.

Next Step

The products of Phase 1 will help guide and direct the next and future phases of the Pajaro River Watershed Study. The Pajaro River Watershed Flood Prevention Authority is beginning Phase 2 – Identification and Preliminary Evaluation of Alternatives in July 2002. Alternatives likely to be considered in Phase 2 are combinations of detention basins, various forms of levees, raised dams, and additional reservoirs. Evaluation criteria will be based on the interests of and inputs from the Authority and watershed stakeholders.

Introduction
CHAPTER 1

CHAPTER 1

INTRODUCTION

The Phase 1 Report outlines, summarizes, and explains the progress achieved to date within the Pajaro River Watershed Study. Phase 1 consisted of modeling both the hydrologic and sediment regimes of the watershed. These models provide a better understanding of the characteristics of the watershed and changes over time that affect flooding frequency and potential in the downstream reaches of the Pajaro River. This chapter gives background information on the project including the formation of the Pajaro River Watershed Flood Prevention Authority (Authority), the need for the Pajaro River Watershed Study (PRWS), and the physical setting and history of the watershed.

Purpose / Legal Authority

The Pajaro River Watershed Flood Prevention Authority was established in October 1999 in order to "identify, evaluate, fund, and implement flood prevention and control strategies in the Pajaro River Watershed, on an intergovernmental basis."[1] Since the watershed covers areas of four counties and four water districts, the board is comprised of one representative from each of the following agencies:

- County of Monterey
- County of San Benito
- County of Santa Clara
- County of Santa Cruz
- Monterey County Water Resources Agency
- San Benito County Water District
- Santa Clara Valley Water District
- Zone 7 Flood Control District

The Authority acts as a governing body through which each member organization can participate and contribute to finding a method to provide flood protection in the watershed and promote general watershed interests. In addition to flood protection, some identified benefits include:

- Municipal, agricultural, and industrial water supply
- Groundwater recharge
- Support of rare, threatened, or endangered species
- Migration and spawning of aquatic organisms
- Preservation of wildlife habitat[2]

Although efforts have been made in the past to prevent flooding, it has become apparent over the past decades that the magnitude of the problem was not properly established. Flooding throughout the lower Pajaro River reaches is a hazard to public and private property including residences, agriculture, highways, watercourses, and environmental resources. Recent floods have caused millions of dollars in damage. In addition, projects completed in the past may have caused environmental damage by removing riparian habitat and straightening the river's path.

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[1] Keeley, "Assembly Bill 807: Pajaro River Watershed Flood Prevention Authority Act." October 10, 1999.
[2] "Draft Water Quality Management Plan for the Pajaro River Watershed." Prepared for Association of Monterey Bay Area of Governments. March 1999.

As described in the enabling legislation State Assembly Bill 807, the goal of the Authority is to implement flood prevention and control strategies within the watershed. It is a further goal of the study to identify strategies and projects that will provide multiple benefits, such as drinking water, ground water recharge, or environmental restoration and protection.

Setting

The Pajaro River is the largest coastal stream between the San Francisco Bay and the Salinas Watershed in the County of Monterey.[3] The watershed is approximately 1,300 square miles.

The watershed covers portions of Santa Cruz, Santa Clara, San Benito, and Monterey Counties. The large size contributes to the number of diverse environments, physical features, and land uses within the watershed boundary. Tributaries to the Pajaro River, the largest of which is the San Benito River, originate throughout the watershed. A relief map of the watershed showing major highways, cities, dams, and rivers can be seen in Figure 1-1.

Soap Lake is an intermittent feature of the watershed but has been found to be an extremely important flood control feature. Upper Soap Lake is also known as San Felipe Lake and is a permanent body of water. Lower Soap Lake, or just Soap Lake, which is located between San Felipe Lake and the Highway 101 crossing, is created when flood events create a backup on the Pajaro River upstream of the San Benito River. This reach of the Pajaro River acts as a natural control for increased flows from the upper Pajaro River watershed. The lake effects disappear as the floodwaters recede.

Development within the watershed, both urban and rural, is clustered around the major cities. The major urban centers are Watsonville, Gilroy, Morgan Hill, Hollister, and San Juan Bautista. Agriculture and grazing are the dominant land uses in these areas but represent a small portion of the total watershed land use. Other industries outside of the urban setting include mining and timber harvesting. The majority of the land cover is grassland, shrubland, and forest. Figure 1-2 shows the spatial distribution of the land uses.

Brief History of the Watershed

To prepare for the future, it is necessary to understand current and past watershed conditions. The present is important because it is the reference point for future courses of action. The past is relevant because the ability to see how the watershed has changed over the years makes it possible to understand how different factors, taken individually or as a whole, affect flooding potential. The late 1940s are especially significant because of major flood protection work done at that time. The work radically changed the shape and function of the river and flood plain. It is important to see how the watershed has changed since that time.

Flood protection management entered the current era when the U.S. Army Corps of Engineers (Corps) initiated a study in 1936. However, it was not until 1949 that a complete levee was constructed from Murphy's Crossing to the river mouth, a distance of about 10.5 miles, (Figure 1-3) to improve flood protection for the lower Pajaro River flood plain.[4] In some locations, existing levees, which had straightened the river course somewhat, were

[3] Ibid.
[4] "Draft Environmental Impact Report: Pajaro River and Salsipuedes and Corralitos Creeks Management and Restoration Plan, Santa Cruz County, California." Prepared for County of Santa Cruz. September 2001.

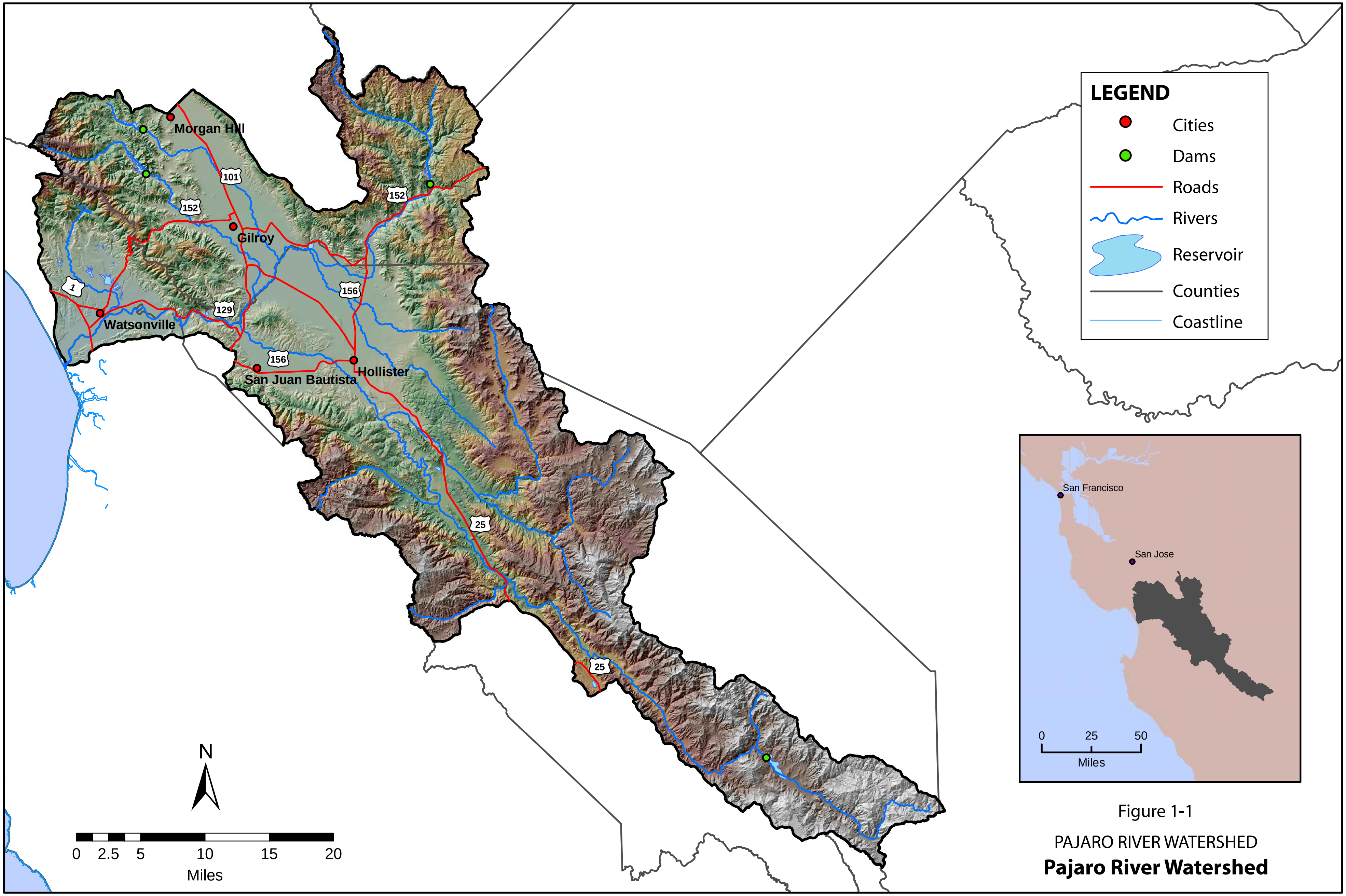


Figure 1-1

PAJARO RIVER WATERSHED

Pajaro River Watershed

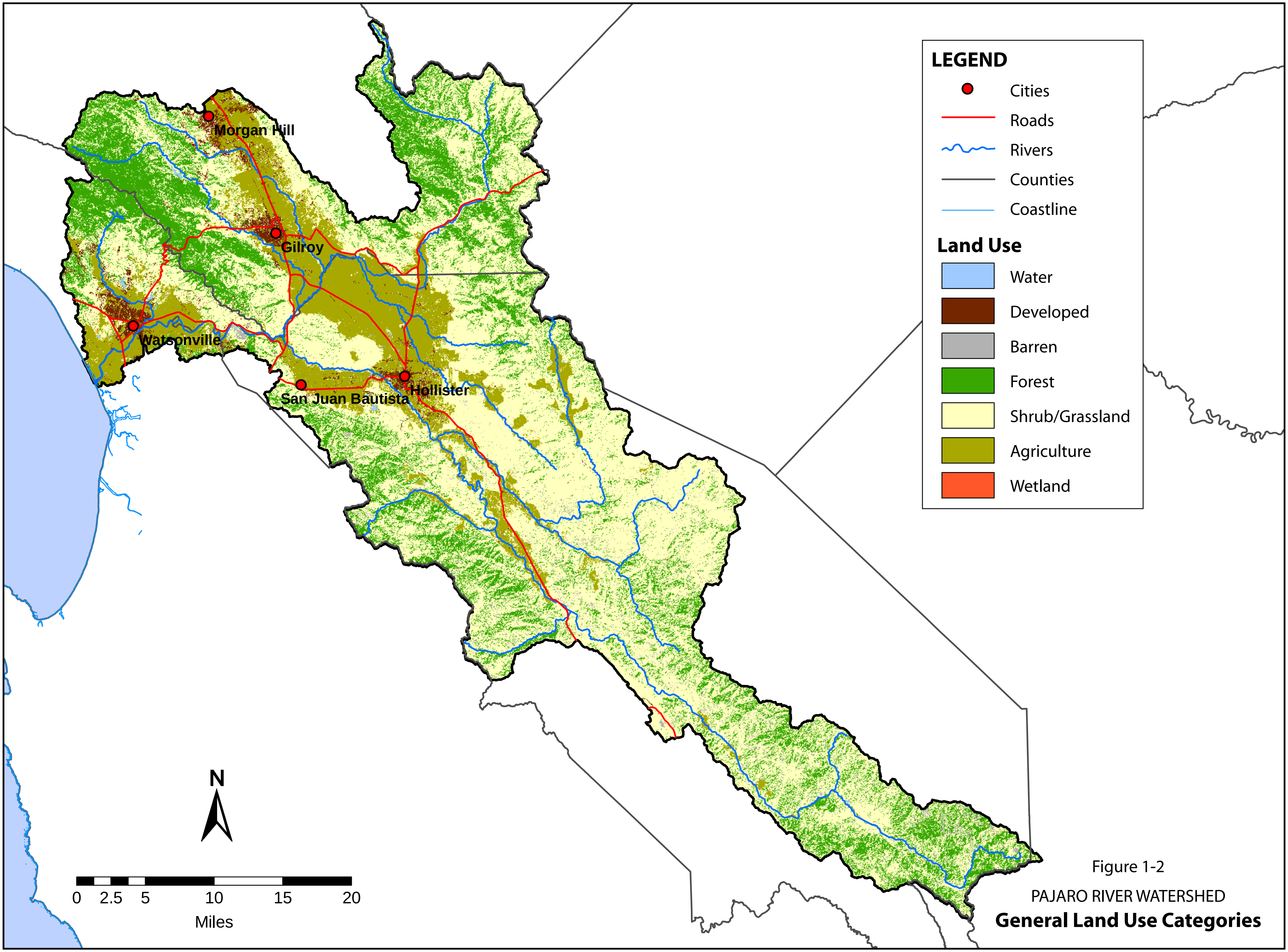


Figure 1-2

PAJARO RIVER WATERSHED

General Land Use Categories

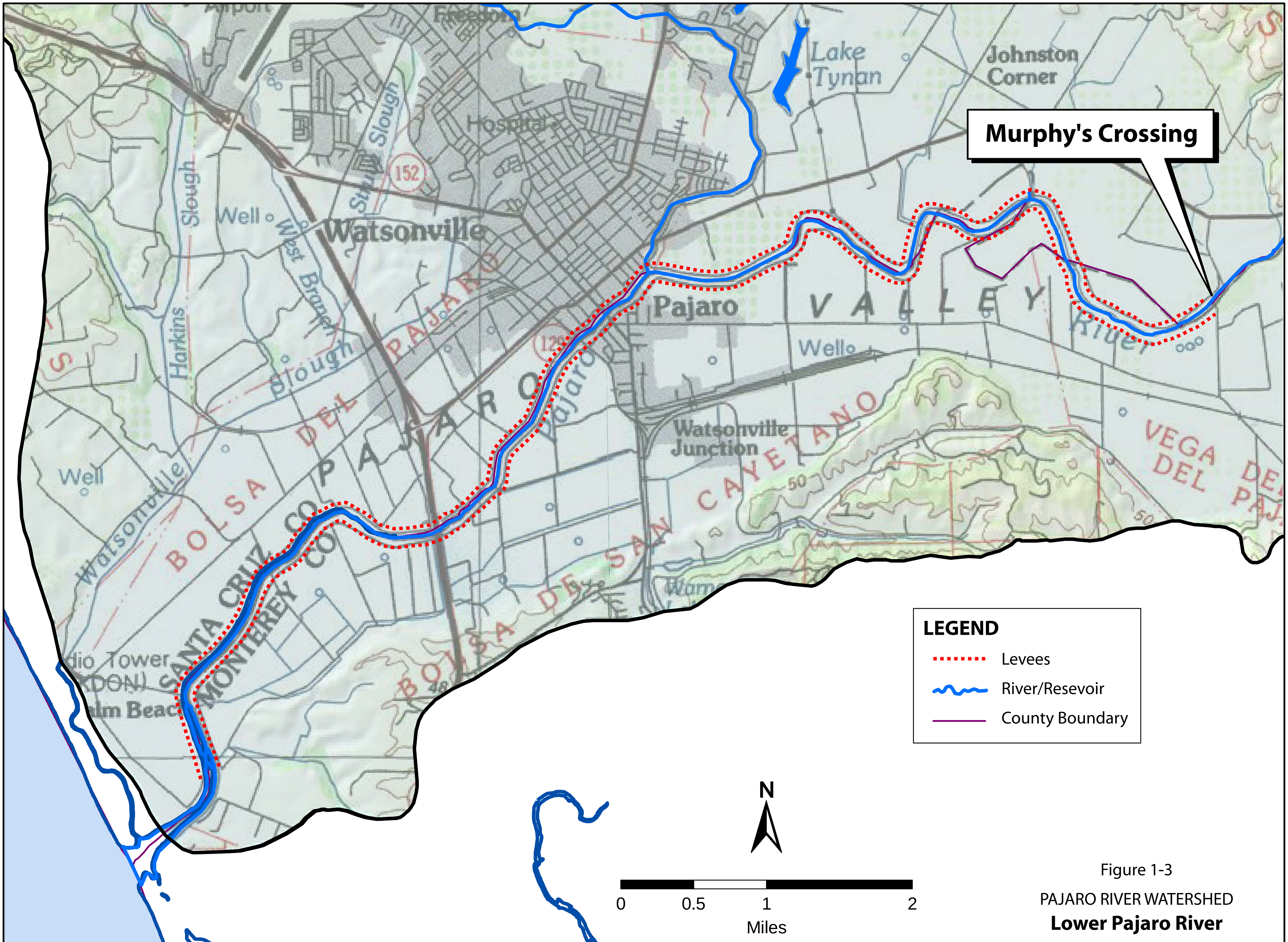


Figure 1-3
PAJARO RIVER WATERSHED
Lower Pajaro River

raised to provide additional protection. New levees filled in gaps and extended the coverage area. The current levee system provides protection against approximately a 25-year storm.

Based on streamflow records, flood discharges have exceeded the levee design discharge of roughly 19,000 cubic feet per second (cfs) four times to date. The first two high water periods, in 1955 and 1958, stimulated interest in further flood protection works but since no consensus could be reached regarding the type of project, the idea was abandoned. The droughts throughout the 1970s and early 1980s lowered public awareness of floods even further. Since then though, major floods occurred in 1995 and 1998. The flooding in 1995 caused Governor Pete Wilson to suspend Department of Fish and Game regulations and the California Environmental Quality Act (CEQA) to provide emergency flood protection.[5] This most often took the form of vegetation and sandbar removal.

The magnitude of flood protection is not the only aspect of the watershed that has changed since the early 1940s. There has been a shift in the type and extent of agricultural production within the watershed. Agriculture has been a huge part of the area's economy since the late 1800s, the magnitude of export due largely to the available transportation to ship the product, the development of refrigeration, and the availability of deep wells. Up to World War II, orchard crop production, especially of apples, apricots, and prunes, was increasing. Vegetables high in nutrition also experienced elevated demand. As the years passed, the local demand for staple crops lessened and the orchards passed their prime growing years. Sometime during the 1950s, a gradual transition was made to smaller crops, such as strawberries, which had a higher yield per acre in both tonnage and profit. Not all of the orchards were replaced, however, and those that remain are a significant part of the watershed's land use. Martinelli's Cider still maintains its fields in the Watsonville area. Many other agricultural products are still grown in great quantities for both domestic use and foreign export.[6,7,8]

Population has grown in the urban areas of the watershed (Figure 1-4). Most of the growth and urbanization has taken place around the five largest cities within the watershed: Watsonville, Gilroy, Morgan Hill, Hollister and San Juan Bautista. All five cities have grown recently as the area has become more popular due to the housing availability, regional agriculture and industry, and proximity to other major economic and industrial locales.

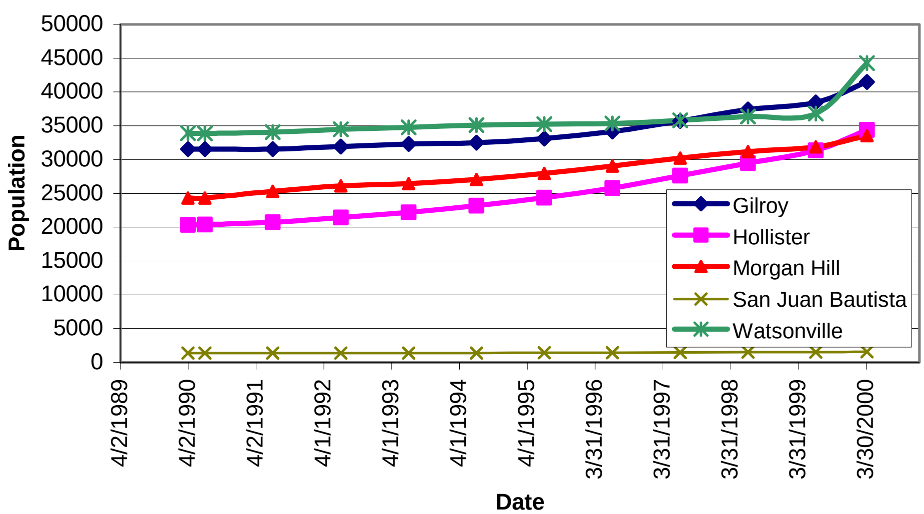


Figure 1-4
City Population

[5] Ibid.
[6] Personal communications. Pajaro Valley Historical Association. 2/26/02.
[7] County Crop Reports for Monterey, San Benito, and Santa Clara.
[8] Martinelli's Cider Electronic Brochure. Accessed on 4/29/02 at http://www.martinellis.com/Brochure/home.htm.

Individual agencies have worked on solutions to the flooding, erosion, loss of wildlife habitat, and threat to listed species such as the steelhead trout, the California red-legged frog, the tidewater goby, and the western pond turtle. In 1999, the Pajaro River Watershed Flood Prevention Authority was created by state law to encourage cooperation between agencies and promote regional flood solutions. The Authority's study began in late 2001. This report concludes the first phase.

Purpose of Report

As currently outlined by the state, there are four phases of the Pajaro River Watershed Study:

- Phase 1: Streamflow Modeling
- Phase 2: Identification and Evaluation of Alternatives
- Phase 3: Selection of Projects
- Phase 4: Preliminary Design of Projects

This report conveys the results of Phase 1.

This document summarizes the modeling process and reports the findings established by a literature review, field analysis, and quantitative modeling. The two models developed for the Pajaro River watershed are a hydrologic model PRO-FLO (Pajaro River to the Ocean FLOod model) and a sediment transport model PRO-SED (Pajaro River to the Ocean SEDiment generation and transportation model). Aspects of the models necessary to accurately represent watershed conditions and responses to rainfall, from theory to calibration, are explored and explained. Four watershed conditions were modeled during Phase 1. The rationale for each condition is explained and the results are summarized and analyzed.

A Quality Assurance Project Plan (QAPP) was also prepared for this project. The QAPP establishes guidelines and protocols for data collection, handling, and analysis. In addition, project roles are clearly defined within the consultant team, which is useful when individuals not directly associated with the project have questions regarding specific aspects of the study.

In addition to the above tasks, this report establishes an initial direction for the rest of the study. The intent of this report is not only to summarize the results of Phase 1, but also to provide a foundation and stepping-stone for the rest of the Pajaro River Watershed Study.

Modeling Process

CHAPTER 2

CHAPTER 2

MODELING PROCESS

Modeling the Pajaro River watershed's hydrologic and sediment frequency response is a crucial step for the success of the study for several reasons. The models themselves provide a tool to see how the flood potential at various locations changes with different land use conditions and rain intensities. One of the goals of the watershed study is to identify flood control projects. The models can be used to realize this goal and analyze the effect of various plans on downstream flooding. Even after the completion of the study, regional planners can predict the effects of various projects allowing them to minimize or reduce the flood risk in susceptible areas.

Creating a model also encourages the collection of the most recent data. Rather than relying solely on data collected around fifty years ago, models created for the Pajaro River Watershed Study rely on as much current data as is available, including field studies conducted exclusively for the PRWS. Current data leads to more accurate results and best represents current watershed flood potential.

The following sections examine the data collection processes and step through the creation of the two models. Strengths and weaknesses are identified as are limiting conditions.

Pajaro River to the Ocean Flood Model

The Pajaro River to the Ocean FLOod model (PRO-FLO) is designed to predict the frequency of 2-, 10-, 25-, 50-, 100-, 200-year floods at four catch points based on a synthetic design storm rainfall input. The rainfall is a normalized yet adjustable rainfall that is applied to the watershed surface. The watershed is divided into subwatersheds. The land use/soil type combinations for each sub-watershed are an indicator of the amount of runoff associated with a given amount of rainfall. The runoff is then routed through the streams and rivers to the catch points at which watershed discharge is predicted. Model outputs consist of annual peak flow and maximum average 3-day discharges at the four points.

PRO-FLO is a highly adaptable model. It is based on the most accurate data available to-date for rainfall, soil groups, land use, and subwatershed routing factors. Land use is one of the flooding factors that is sensitive to human influence and can have a rapid rate of change. The land use database is very flexible and the land uses within the sub-watersheds can be changed quickly and easily to reflect any scenario. PRO-FLO can also be altered to include routing changes such as dams and alternate channels.

The model is limited to the boundaries of the Pajaro River watershed. Calibrations for any model are individualized to fit particular settings or locales and PRO-FLO is no exception. Each sub-watershed has its own set of characteristics that sets it apart from others. The calibrations were done using data collected within those sub-watersheds and the model reflects their individuality. In addition to the unique calibration, the design storm and soil and land use datasets were created specifically for the Pajaro River watershed and are not applicable elsewhere.

The cornerstone of PRO-FLO is frequency analysis. This type of analysis allows a limited dataset to be substantially extrapolated using accepted methods to cover a wide range of flood events. In order for the probability and statistics to have any relevance to watershed flood control, the watershed must be homogeneous. A homogeneous watershed has not changed in a significant way over time. Small, natural changes occur constantly and average to no change across the watershed. Even man-made changes such as building a dam or urbanization, both considered to be irreversible, can occur without affecting the status of the watershed so long as they do not cause a significant change in the runoff. The watershed stream gage record was analyzed for homogeneity during the period of interest for this study, the 1940s through present. The watershed, while showing some minor trends, has been determined to be homogeneous. For specific details, please refer to Technical Memorandum (TM) 1.2.3 in the Appendix.

To understand how to apply and use the model, it is important to understand the model's major components and how they are put together. The following sections highlight and explain the most significant aspects of the model. The Appendix of this report contains further information regarding the models of the Pajaro River Watershed.

Establish Basis of Comparison

Establishing the basis of comparison is an absolutely crucial step in the modeling process. Models can be used to predict situations both quantitatively and qualitatively. The model outputs can be used quantitatively to size flood protection projects for specific flows or qualitatively to see varying effects of certain conditions or projects on watershed flooding. While results are not 100% accurate, they can be quite useful. These results are the best possible predictions and are also powerful tools when comparing results from several scenarios. The key watershed parameters and locations form the basis of comparison.

In general, the primary parameter used for comparing changes to watersheds is the annual instantaneous maximum peak discharge. This is the discharge in a stream channel and adjoining overbanks that is the greatest value at any time during a water year no matter how long the discharge lasts. A water year begins on October 1 and ends on September 30. Since the water year is split between two calendar years, it is assigned the calendar year corresponding to the September 30 date.

The secondary hydrologic parameter is the volume of flow in the stream. Generally the annual maximum 1-day average discharge value or 3-day average discharge is used in highlighting differences in runoff. For the Pajaro River watershed the annual maximum 3-day average discharge is used because the watershed is large and the 1-day average discharge would reflect the instantaneous peak discharge. Size is an issue because a larger watershed takes longer to drain and this affects the discharge measurement in the downstream reaches.

The use of both of these parameters allows for the characterization of the Pajaro River watershed. Key concepts are summarized in Table 2-1 below.

Table 2-1: PRO-FLO parameters and key concepts. Both parameters are annual maximum values within a water year.

Discharge Parameter	Key Concept
Instantaneous Peak	Duration does not matter
3-Day Average	Measured in consecutive 72-hour period

As mentioned before, the locations at which these parameters are to be predicted are essential to characterizing the watershed. Four points have been chosen to represent the watershed. Their locations and significance are listed below.

- San Benito River Upstream of Pajaro River Confluence: This point has historically been an important predictor for the flow conditions within the lower Pajaro River. The drainage area is approximately 664 square miles.
- Pajaro River Upstream at US Highway 101: Representing the other upper-watershed branch of the Pajaro watershed, this point predicts flow from 505 square miles including a significant storage area, Lower Soap Lake.
- Pajaro River at Chittenden: This critical point is the location of a long-term stream gage record and represents the discharge to the upper portions of the Corps flood control project. This point is two miles downstream of the Pajaro and San Benito confluence and the drainage area is 1,186 square miles.
- Pajaro River Downstream of Salsipuedes Creek: This flow represents the discharge along the lower portions of the Corps flood control project. The drainage area of this point is approximately 1,274square miles.

The locations are shown in Figure 2-1.

The wide range of frequencies, 2-, 10-, 25-, 50-, 100-, and 200-year return periods, spans the hydrologic spectrum of floods. The frequency given in terms of return period is the reciprocal of the annual exceedance probability. For example, a 50-year flood has a 2 percent chance of being equaled or exceeded in any given water year and a 100-year flood has a 1 percent chance. A more intuitive way to think of flood frequencies is, on average, a 50-year flood occurs once every fifty years. Similarly, a 100-year flood occurs every 100 years. This does not mean, however, that a storm of a given size cannot occur more than once in a given period, but only that the interval between occurrences will average that period.

Establish Rainfall

One of the most critical inputs to any hydrologic model is the rainfall. A synthetic rainfall is used in this study for several reasons. They include:

- To compensate for a lack of rainfall gages or missing data
- To apply rainfall to the entire watershed
- To normalize to average precipitation in an area and not to any particular storm, which leads to a characteristic storm
- To eliminate the need for many different storms to characterize watershed response

By establishing a balanced design storm with a variable intensity, it is possible to mimic rainfall depths depending on spatial location and rainstorm frequency. Drier areas will receive less rainfall than wetter areas and more frequent events will be smaller and less intense than huge, infrequent storms.

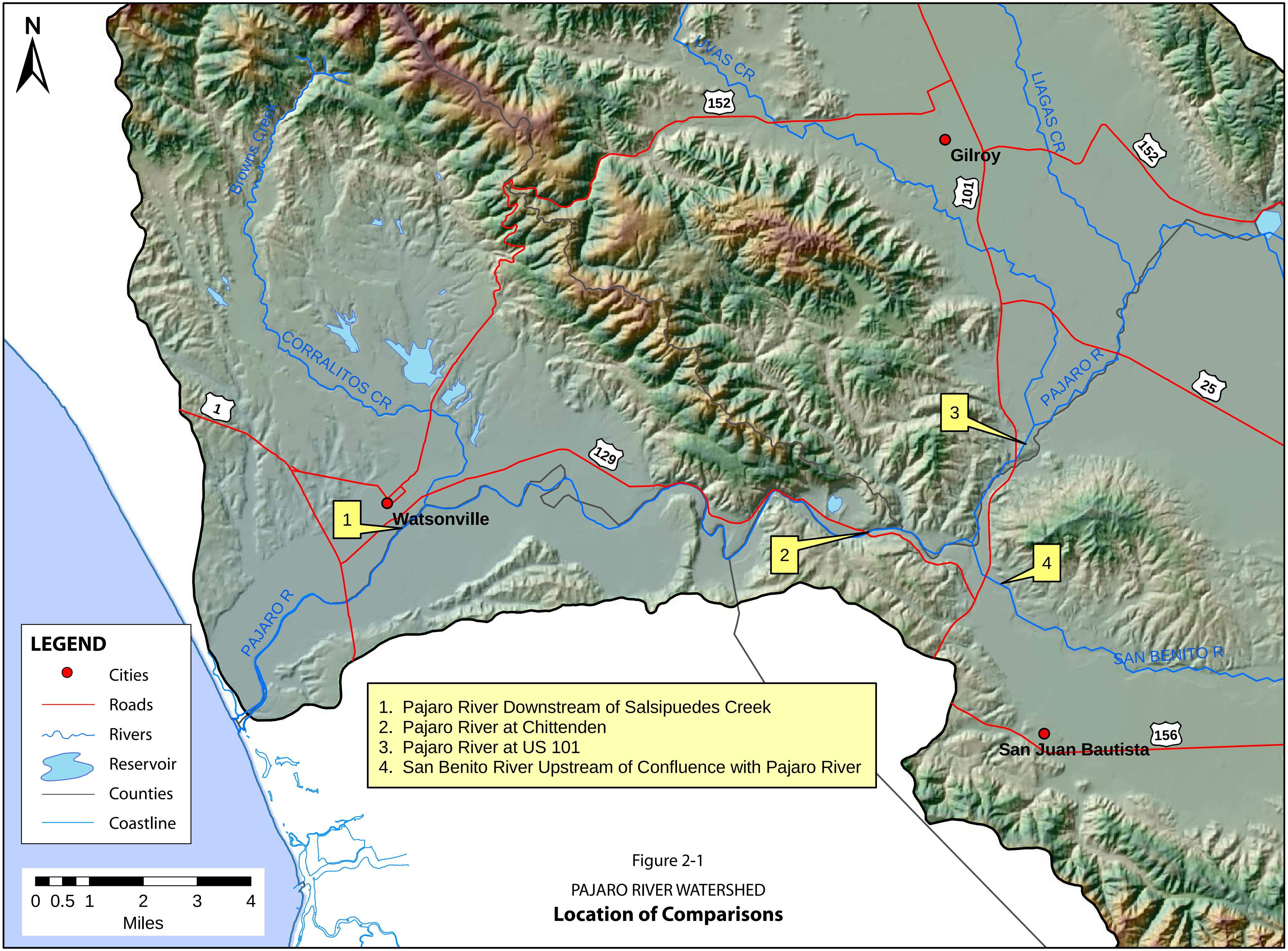


Figure 2-1

PAJARO RIVER WATERSHED

Location of Comparisons

The development of a design storm involves defining five elements:

- **Transposition mechanism:** the basis of the design storm which provides a reference point against which to scale the storm events
- **Duration of the design storm:** the time during which there is precipitation over the watershed
- **Depth - duration - frequency relationship:** the location-specific relationship that provides the depth of rain that falls in an event of a particular duration and frequency
- **Drainage area versus rainfall-reduction relationship:** a relationship that quantifies the lesser impact that a large storm has on a given point rather than a smaller, more focused event
- **Temporal distribution of the design storm's rainfall depth:** the progression of the storm across the watershed.

Incorporating all of these elements, the design storm structure can be summarized as follows: As the storm moves across the watershed according to the temporal distribution, the transposition mechanism and duration serve as inputs to a defined relationship by which the location specific depths of rainfall are known. That depth is reduced though based on the size of the watershed using the drainage area versus rainfall reduction relationship.

The above elements are discussed further in the paragraphs below. For further discussion, please refer to TM 1.2.2 in the Appendix.

Transposition Mechanism

The transposition mechanism is the basis of the design storm and serves as an input to the depth-duration-frequency relationship. Mean Annual Precipitation (MAP) is the transposition mechanism used for PRO-FLO. In 1989, Santa Clara Valley Water District (SCVWD) developed a set of isohyets, or lines of equal rainfall, for the counties of Santa Clara, San Benito, Monterey, Santa Cruz, and several other counties. Data from 255 stations was collected and analyzed. Isohyets account for orographic effects. The MAP map is shown in Figure 2-2. The area-weighted MAP for the watershed is approximately 19 inches.

Duration

The duration of the design storm is determined by an analysis of rainfall depth. 3-day and 5-day rainfall depths for precipitation gages throughout the watershed were compared. Extending the duration to 5 days does not significantly increase the depth of rainfall over that measured in 3 days. Therefore, the duration of the PRO-FLO design storm is 72 hours. The 72-hour duration is used rather than 3 days because the daily values recorded once a day are always less than or equal to the depths based on 72 consecutive hours regardless of where the midnight hour falls relative to the beginning of the storm event.

Depth-Duration-Frequency Relationship

The SCVWD has produced a set of equations to determine depth of rainfall given the MAP, duration, and frequency. The linear equation of interest is called the Return Period-Duration-Specific (TDS) Regional Equation given by

$$X_{T,D} = A_{T,D} + B_{T,D} * MAP \qquad \text{Eq. 2-1}$$

where $X_{T,D}$ is the rainfall depth in inches for a specific return period, T, and a specific duration, D. $A_{T,D}$ and $B_{T,D}$ are, respectively, the equation intercept and slope for the same period and duration. MAP is the mean annual precipitation for the point of interest. Values for $A_{T,D}$ and $B_{T,D}$ can be found in *Hydrology Procedures* published by the SCVWD in December 1998.

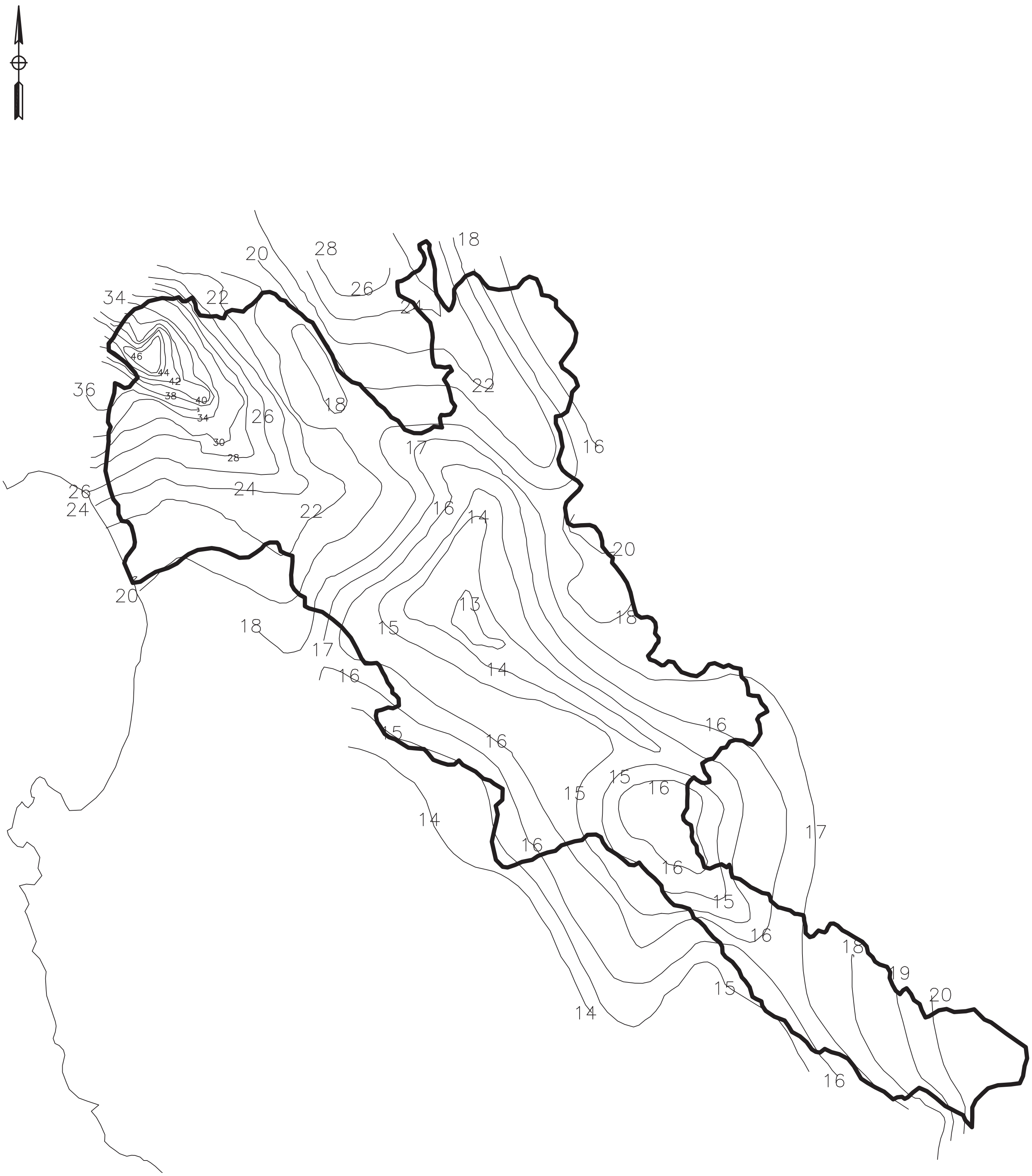


Figure 2-2

PAJARO RIVER WATERSHED

Mean Annual Precipitation
(in inches)

Source: SCVWD, 1989.

The design storm uses the SCVWD TDS equation to determine depths of rainfall as a function of MAP, duration, and frequency. TM 1.2.2 in the Appendices describes the procedure used to test the accuracy of these equations throughout the watershed.

Depth-Area Reduction Relationship

The relationship between normalized storm totals and area covered by the storm is important to quantify because it provides a historically based constraint on the size of flood-producing storms in the watershed. This relationship is normally shown as a ratio of rainfall at a point to rainfall over a range of areas. The depth-area reduction relationship is based on the Corps' analysis of the December 1955 storm. This particular analysis was chosen due to the aerial extent of the storm and the positioning of the 1955 storm. Figure 2-3 shows the depth-area reduction curve associated with the storm.

As the drainage area to any given catch point (or point of interest along the stream network) gets larger, the storm must be reduced to account for the fact that historic storms have decayed as larger and larger areas are considered. The storms have had centers of higher rainfall surrounded by areas of lower rainfall. Therefore, as larger drainage areas are considered, the storm is centered in one location and the Corps' depth-area relationship as shown in Figure 2-3 is used to adjust the rainfall depths to reflect the historic centering of large storms in the watershed.

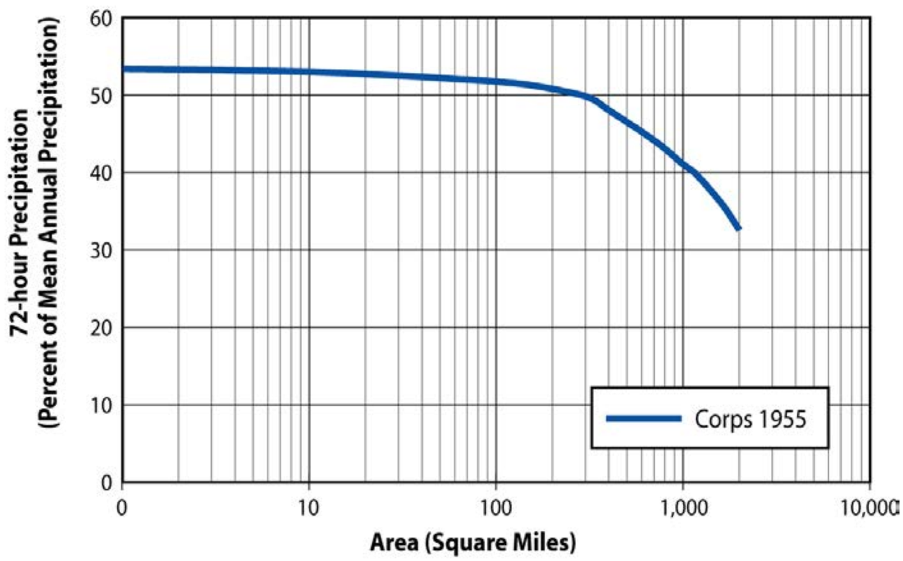


Figure 2-3
Depth-Area Curve
Pajaro River Basin

Temporal Distribution

The December 1955 storm was chosen as the basis of the temporal distribution due to the number of other analyses done for this particular storm. However, the pattern is adjusted so that it reflects the rain gage statistics predicted by the SCVWD TDS equation to produce a balanced storm. Balancing is normally done by scaling the rainfall pattern to fit specified values. In this case, the values specified were the percentages of the 72-hour rainfall that fell during the following durations: 48, 24, 6, and 3 hours. Although the design pattern is shifted somewhat for the balanced storms, it does reflect the rainfall statistics as represented by the SCVWD TDS equations.

DATA

The basis of comparison and the design storm are necessary for the model but neither represents the actual watershed condition. This section is a discussion of the three inputs to the model that represent individual characteristics of the watershed. They are soil group, land use, and river geometry.

Soil Group

Precipitation, once it lands on the earth, is to some degree absorbed by the soil. The excess rain creates puddles or ponds, or is transported away. The transported water is considered to be runoff. The amount of water absorbed, the drainage capacity of the soil, is one of the watershed characteristics that affects the amount of runoff.

Hydrologic soil groups are defined by the steady rate of infiltration into a unit area of soil. There are four general groupings, A through D. Descriptions of each can be found below in Table 2-2. The groupings are essentially a qualitative measurement of how quickly water on the ground will be absorbed by the ground. This directly affects the amount of runoff since the faster the water seeps into the ground, the less water remains on the surface to become runoff. When combined with the type of land use, the soil group leads to a runoff curve number. This will be discussed further in later sections.

Table 2-2: Natural Resources Conservation Service hydrologic soil groups.

Hydrology Class	Description
A	High infiltration rates. Soils are deep, well drained to excessively drained sands and gravels.
B	Moderate infiltration rates. Deep and moderately deep, moderately well and well-drained soils with moderately coarse textures.
C	Slow infiltration rates. Soils with layers impeding downward movement of water, or soils with moderately fine or fine textures.
D	Very slow infiltration rates. Soils are clayey, have a high water table, or are shallow to an impervious layer.

The Natural Resources Conservation Service (NRCS) has made public two levels of soil information. The more detailed Soil Survey Geographic (SSURGO) database has yet to be prepared in a digital format for Santa Clara County and San Benito County at the time this report is written. A similar data set, the State Soil Geographic (STATSGO) database is available for the entire watershed. STATSGO data has less detail than SSURGO data but was found to be adequate for this study. Figure 2-4 shows the distribution of the four soil groups over the entire watershed.

Land Use

Land use also affects runoff because it can affect how quickly water is absorbed by the soil. For example, a meadow will allow less runoff than a parking lot, which will sheet flow all of the water off of its surface.

Land use data was obtained from the United States Geological Survey (USGS) 1992 National Land Cover Dataset (NLCD). The NLCD was chosen as the basis for the land use data due to its format and source, its complete, consistent coverage across the entire watershed, and the fact that it is one of the most current data sets of its kind. The land uses are classified into 21 different groups. A list of these uses and a brief description can be found in the Appendix of TM 1.2.6. Two land use groups, ice and barren, are not found within the watershed. The distribution of land uses can be seen in Figure 2-5.

It has been determined that most of the watershed is accurately represented by the NLCD data. Since the set of data was obtained in 1992, the land use of some areas is different from what the dataset indicates, especially around the urban areas within the watershed. Some of the agriculture and open space land has been urbanized, resulting in a higher runoff factor. The dataset was not modified to reflect recent urbanization but the runoff coefficients were adjusted accordingly. TM 1.2.7 in the Appendix has details regarding this matter.

A simple analysis of the land use can provide some insight into the uses of the watershed and major factors that may or may not affect flooding. Table 2-3 shows the percentage of the major land use classes found within the Pajaro River watershed. Interestingly, only 10% of the total watershed area is developed, either by agriculture (7.5%) or by urban areas (2.4%), yet these uses are clearly the most visible from the road. The remaining 90% is natural area such as grassland, shrubland, or wooded areas. Even more interesting is the fact that only 1.8% of the watershed above the Chittenden Gap is currently urbanized.

Table 2-3: Percentage of major land use classes circa 1992-2002.

Land Use Classification	Percentage of Watershed Area
Urban	2.4
Forest	24.3
Grass	64.2
Agriculture	7.5
Other	1.6

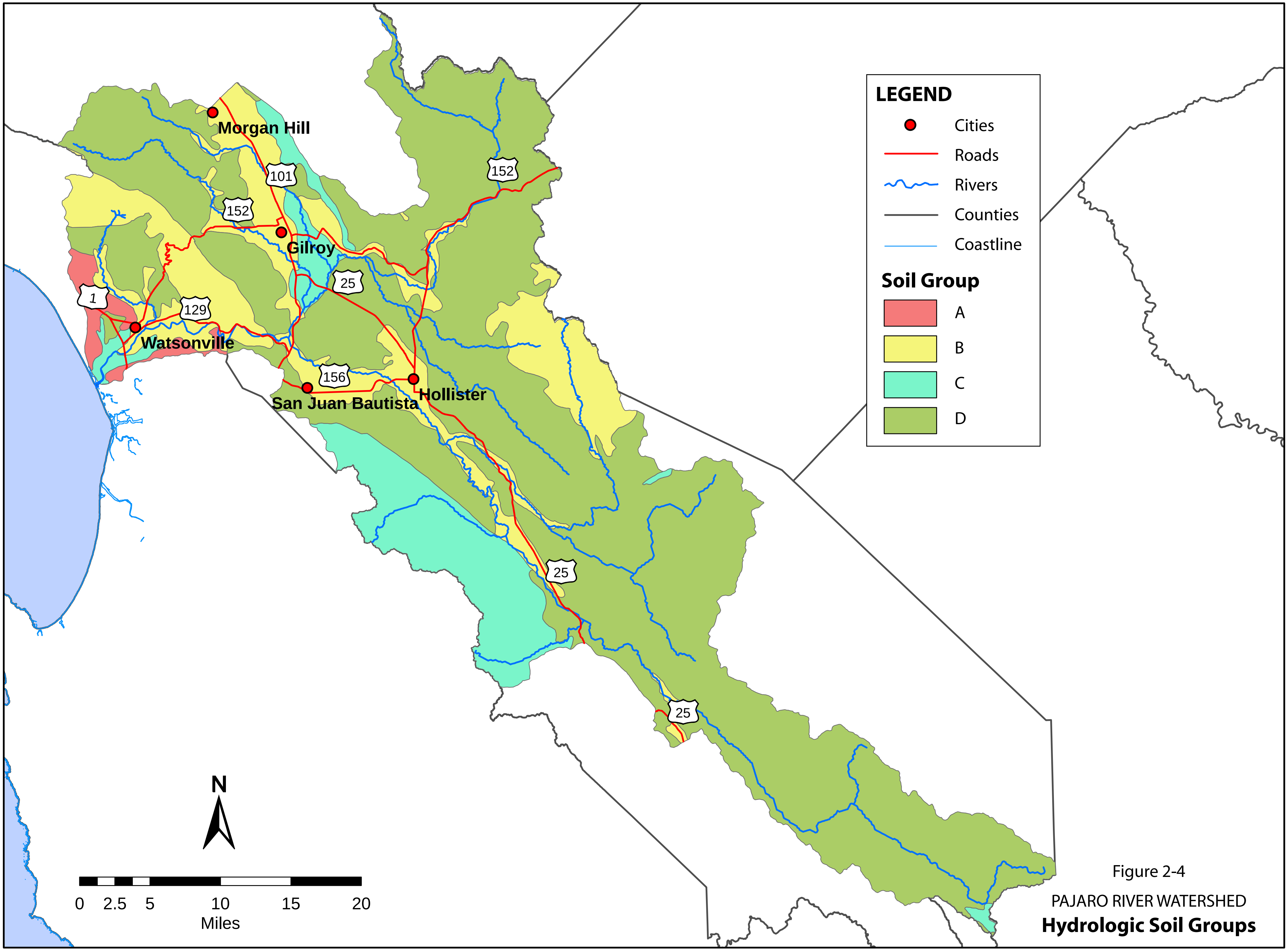


Figure 2-4
PAJARO RIVER WATERSHED
Hydrologic Soil Groups

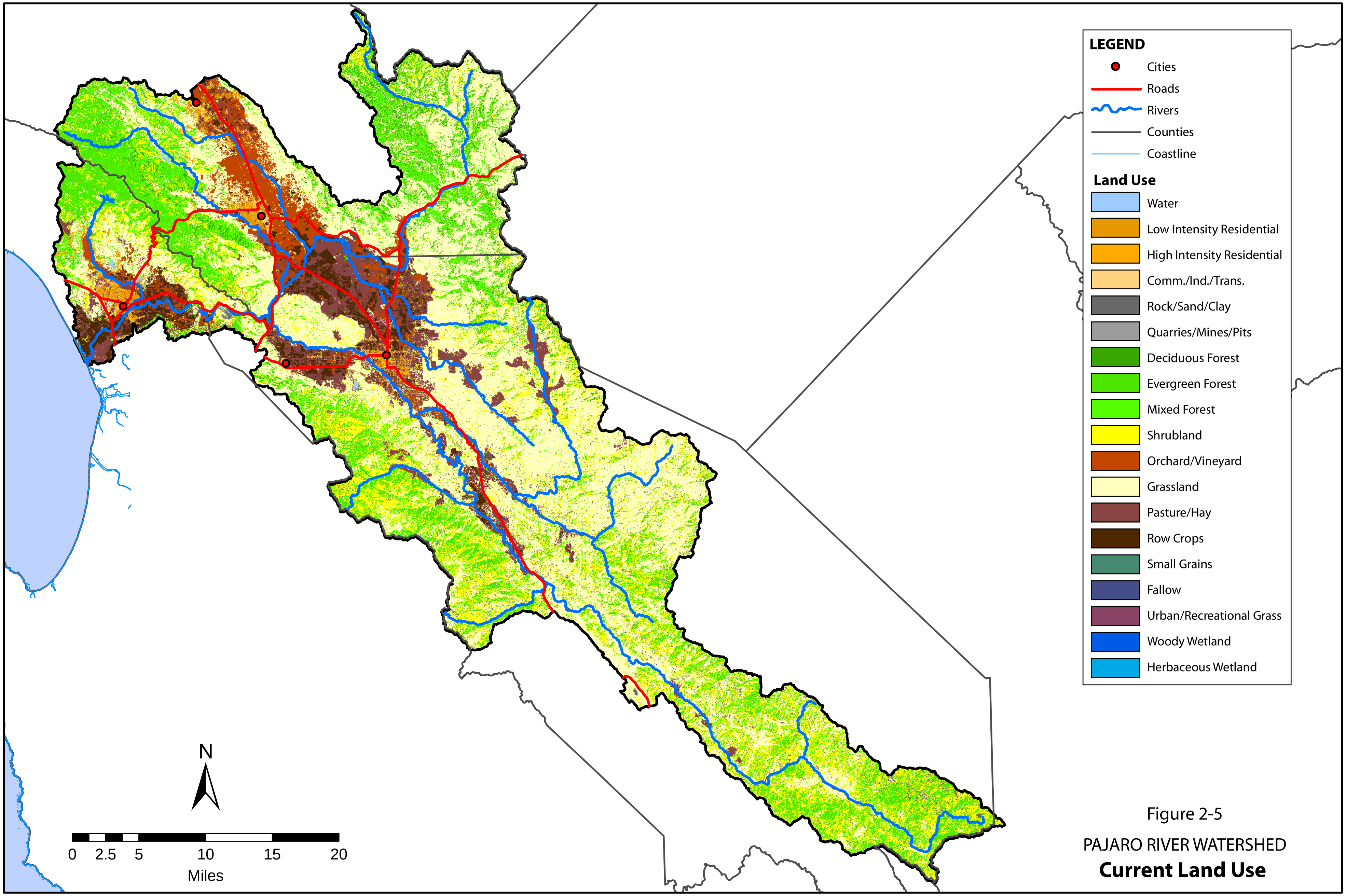


Figure 2-5
PAJARO RIVER WATERSHED
Current Land Use

River Geometry

River geometry is a necessary input that allows computations of flood wave travel through the lower reaches of the San Benito and the Pajaro Rivers. It is necessary to model how large and how quickly a flood wave will travel in order to be able to predict proximate effects and to design flood protection projects. The river geometry consists of cross sectional data for channel and adjoining overbank (flood plain) areas at a sufficient number of locations along the rivers to allow an unsteady-state, one-dimensional hydraulic model to compute the passage and attenuation of flood waves as they proceed through the channel system.

There are five sources of river geometry data used in these models. They include:

- Federal Emergency Management Agency (FEMA) HEC-2 model developed in the late 1970s
- US Army Corps of Engineers field measurements from 1995
- Flood Plain Information Report prepared by the US Army Corps of Engineers in 1974
- Flood Insurance Study by FEMA completed in the late 1980s
- CalTrans 5-foot topographic maps from 1988

The discrepancy in dates in some cases does affect the shape and depth of the Pajaro and San Benito Rivers. Streambed profiles from two of the more significant studies, the HEC-2 model and the 1995 Corps field measurements, can be seen in Figure 2-6. One of the reasons for the difference in streambed elevation between the two data sets, especially in the lower reaches, is the Corps measurements were made directly following a large flood event and a subsequent channel cleaning to remove vegetation and silt. The effects of sediment transport are considered in the second model of the PRWS and will be described in Chapter 3.

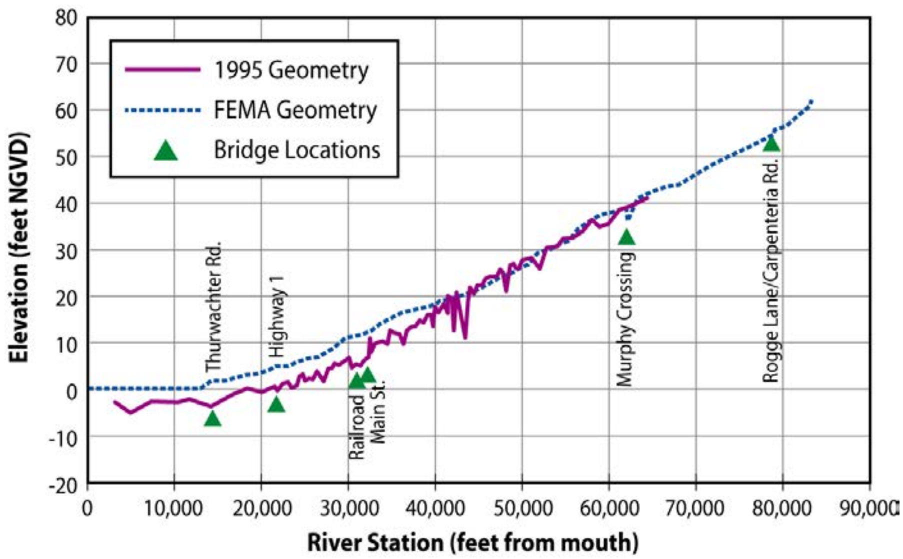


Figure 2-6
Pajaro River Channel Profile Comparison

When combined, these five data sources provide sufficient data with which to model both lower reaches with the addition of only two cross sections within Chittenden Gap. The first reach is on the Pajaro River from the Pacific Ocean upstream to the outlet of lower Soap Lake, approximately 2,000 feet upstream of US Highway 101, and is roughly 24 miles long. The second modeled reach is on the San Benito River from the confluence with the Pajaro River upstream to the Hospital Road crossing. This distance is approximately 13 miles.

Model Software

PRO-FLO is a combination of two existing models, Hydrologic Engineering Center Flood Hydrograph Package (HEC-1) and Hydrologic Engineering Center River Analysis System (HEC-RAS). These models were chosen for their proven track record as being appropriate tools in cases such as this study, for their general acceptance by the public, engineers and planning experts, and also because they are publicly available. This allows PRO-FLO to be freely distributed among and used by interested parties. The following paragraphs discuss some of their most significant characteristics

HEC-1 is a comprehensive flood hydrograph model that allows users to work with recorded or hypothetical storms. Some of the directly relevant features include:

- Computation of basin-average precipitation from gages or hypothetical storms
- Unit hydrographs via Soil Conservation Service (SCS) methods
- Hydrograph routing by Muskingum and Muskingum-Cunge methods.[9]

HEC-RAS is used to calculate surface water profiles and hydrographs in a one-dimensional, unsteady state environment. The program has the capability to analyze a very simple reach to a very complex, branching system at subcritical, supercritical, and mixed flow regimes. The default equation is the one-dimensional energy equation using Manning's equation to calculate friction losses and contraction/expansion energy equations using the change in velocity head. In cases where the surface profile is changing rapidly, such as bridge crossings and river confluences, the momentum equation is used.[10]

Model Theory

Although the software does most of the calculations, in order to understand the model and its results better some knowledge of relevant theory and methods is necessary. This section outlines the most important aspects of PRO-FLO that have not already been discussed. These include curve numbers, unit hydrographs, and routing techniques.

A curve number (CN) is used to quantify the amount of runoff created from a given amount of rainfall. Curve numbers for PRO-FLO are sourced from previously published works by the SCS, in a variety of textbooks on hydrology, and in local agencies' design handbooks. The curve number is a function of four variables: land use, hydrologic soil group, hydrologic condition, and antecedent moisture condition (AMC). The land use and hydrologic soil group were discussed in previous sections of this report. Hydrologic condition is a general measure of several different factors that may affect runoff. These can include artificial changes to the surface or natural blockage of precipitation. For example, a strawberry field can have a "poor" hydrologic condition due to the sheet plastic and grading to increase drainage. Shrub land was the only land use with a "good" hydrologic condition due to minimal soil blockage. All other land uses received a "fair" rating. CNs are also a function of AMC. AMC is a measure of how wet the ground was previously to the time period of interest. The SCS has developed a relationship for changing between AMC II and either AMC I (dry) or AMC III (wet). Values for CNs of an intermediate AMC were interpolated based on published values. Table 2-4 has an example of curve numbers used for PRO-FLO. The values are based on AMC II.

[9] US Army Corps of Engineers. "Computer Program Catalog." August 1997.
[10] Ibid.

Table 2-4: Curve Numbers used in PRO-FLO. Twelve numbers are needed for each land use type.

	Soil Group and Hydrologic Condition Good Fair Poor			
Land Use	**A**	**B**	**C**	**D**
Low Density Residential	35 44 64	48 58 68	66 71 78	70 74 79

A CN of zero indicates that all of the rainfall is absorbed into the soil while a CN of 100 indicates that all of the rainfall is converted to runoff.

As described above, the major component of PRO-FLO is HEC-1, which is based on unit hydrographs. The SCS, now known as the NRCS, unit hydrograph is shown in Figure 2-7. The hydrograph is expressed in unitless measures of flow relative to peak flow and time, or lag, relative to time to peak. Runoff from storms of differing magnitudes can therefore be scaled by the unit hydrograph. Further details regarding different types of lag and flow equations can be found in TM 1.2.7.

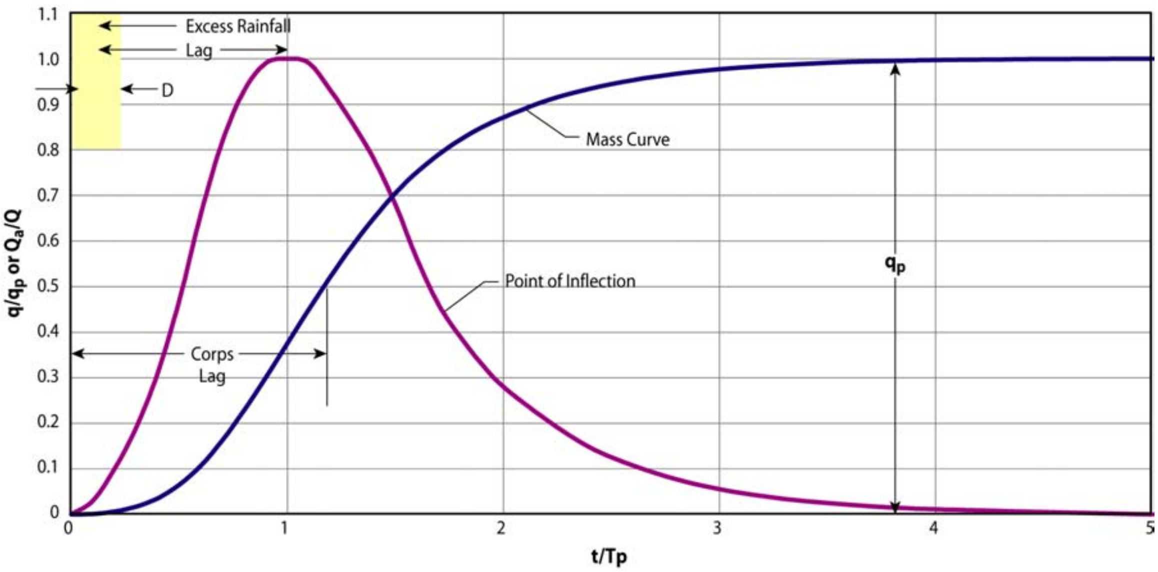


Figure 2-7
Unit Hydrograph

For purposes of this study, the Pajaro River watershed has been broken up into 32 sub-watersheds. Figure 2-8 shows the location, relative size, and shape of the sub-watersheds. Catch points, often at the location of a USGS stream gage, define these sub-watersheds. As a check of watershed delineation accuracy, drainage areas for PRO-FLO were compared to areas published by the USGS for some of their stream gages in the Pajaro watershed. Table 2-5, below, shows the results of this analysis.

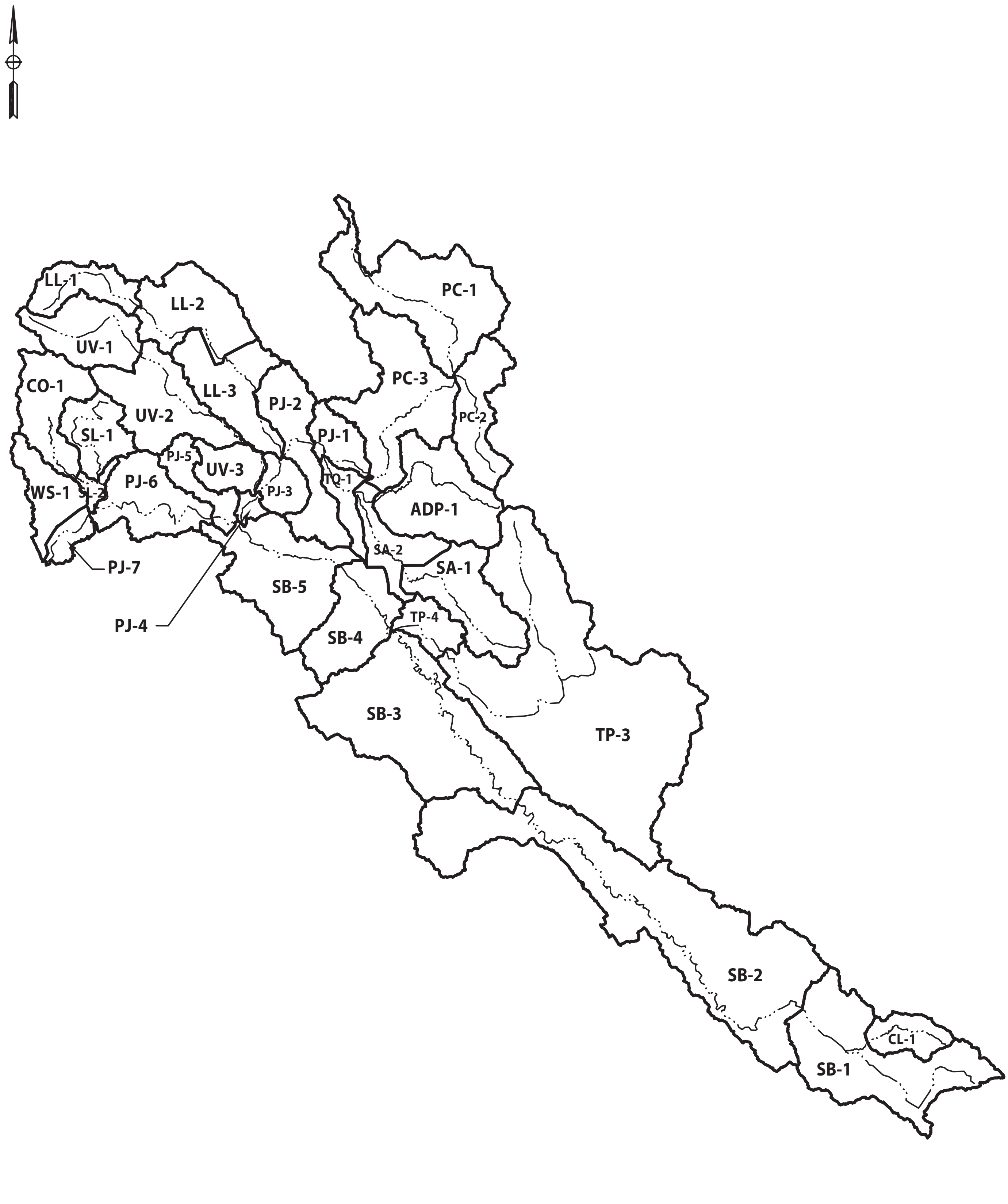


Figure 2-8

PAJARO RIVER WATERSHED

Sub-Watershed Layout

Table 2-5: Comparison between PRO-FLO sub-watershed areas and USGS areas. The differences are negligible: all are less than 10%, five of the seven are less than 1%, and the largest watershed difference is 0.03%.

Location	PRO-FLO (mi^2)	USGS Area (mi^2)
San Benito River nr. Willow Creek School	248.2	249
San Benito River at Highway 156	609.2	607
Tres Pinos Creek nr. Tres Pinos	209.2	208
Pacheco Creek at Dunneville	153.2	154
Pajaro River nr. Gilroy	406.3	399
Corralitos Creek at Freedom	29.9	27.8
Pajaro River at Chittenden	1186.4	1186

Hydrographs for each sub-watershed are created based on the amount of runoff (calculated using the curve number) created by the design storm. The hydrograph is not just based on rainfall and the runoff from individual sub-watersheds. Flow, both timing and magnitude, from watersheds upstream of the watershed of interest is added based on the previous hydrograph.

Routing techniques are used to combine the hydrographs of different subwatersheds. Routing is the quantification of storage within the river channels. The velocity, reach length, or time of travel of the flood wave down the river is not consistent between subwatersheds nor is the river geometry. The amount of water stored is usually expressed as a relationship between inflow to the reach, outflow from the reach, and the time taken to get through the reach. PRO-FLO relies on the Muskingum method to perform routing calculations for most of the reaches but uses the Muskingum-Cunge method for several. Please refer to the TMs and hydrology texts for additional detail regarding these methods and routing in general.

Model Calibration

The modeling is done with as many facts as are available regarding the attributes of the watershed. There are several conditions though that are not officially quantified or available and therefore assumptions must be made. The calibration phase of modeling provides the opportunity to fine-tune those assumptions and allows the model to truly represent the Pajaro River watershed.

The first step of the calibration process demonstrates the model functionality. The model is demonstrated by using actual storms as shown in TM 1.2.2 to attempt to reproduce stream hydrographs noted in TM 1.2.3. This part of the calibration process shows whether or not the model can reasonably reproduce actual storm events. The most important aspect of the reproduction is the timing of the peak discharges. This indicates whether or not the unit hydrograph provides approximately the right watershed temporal response to rainfall. Once this has been answered in the affirmative, the model is calibrated using design storms as discussed in TM 1.2.2 to match the frequency curves at stream gages as presented in TM 1.2.3. It is by comparing these frequency curves that the effect of watershed changes can be seen on the flooding potential.

TM 1.2.3 goes into some detail regarding the hydrographs available for the annual maximum flood events for the years 1994-1999 inclusive. The storms themselves are described in TM 1.2.2. The reconstitution is of the three-day stream gage responses at a number of stream gages in the watershed. The CN values determined for each sub-watershed were used as a starting point. The rainfall over each sub-watershed was taken from the isohyetal maps shown in TM 1.2.2. The pattern of rainfall was obtained by averaging the hourly patterns at the two nearest working rain gages during the three days considered.

Two calibration parameters were used in the reconstitution: Antecedent Moisture Condition and lag time through the sub-watershed roughness parameter. A higher AMC produces more runoff because the ground has a higher water content before the storm began and therefore cannot absorb as much water. AMC was varied by 0.5 (i.e. AMC I.5, AMC II, AMC II.5) and CNs were altered accordingly. The roughness parameter affects the lag time of the hydrograph and varies between 0.08 and 0.03. Higher values are used for natural channels while lower values represent hydraulic efficiency. They are estimated based on field reconnaissance for each sub-watershed.

The model hydrographs were compared to the recorded hydrographs. The AMC and roughness parameter were adjusted to best fit the available data. It is appropriate to note that the available calibration data is not error free. Most of the gages generating the data are given a poor rating by the USGS, meaning that 95% of the daily discharges are more than 15% from the true value of stream flow, or more simply that the standard deviation is at least 10%. Only three of the gages are rated as fair. A rating of fair means that 95% of the discharges are within 15% of the actual values, meaning that there is a 7.5% relative error. Although the data is not error free, PRO-FLO is calibrated to the best available estimate of discharge.

Reconstitution of the timing and magnitude of the peak discharge and discussion of the results can be found in TM 1.2.7 in the Appendix to this report.

The second phase of PRO-FLO fine-tunes the model to reproduce the frequency curves at stream gages as presented in TM 1.2.3 using the design storm developed in TM 1.2.2.

The model was calibrated based on five points within the watershed: Pajaro River at Chittenden, San Benito River at Highway 156, Pajaro River near Gilroy, Pacheco creek at Dunneville, and Uvas Creek near Morgan Hill. The AMC and base flow were the only two parameters that were changed to match the flow. The model was run using the 72-hour design storm at 2-, 10-, 25-, 50-, 100-, and 200-year return period storms.

The AMC was allowed to vary in increments of 0.25 between AMC I and AMC III. Storms in the first phase of calibration required individual AMC adjustments for the model output to match the hydrographs. Since a single storm is used for PRO-FLO the AMC value needs to be set only once for each storm magnitude. The AMC for the 200-year flood was AMC I.75 while all other return period floods fit best with the AMC I.5.

The second calibration parameter was base flow. Base flow was added on a “per square mile of drainage area” basis. The base flow varied between sub-watersheds. Sub-basins draining to Lower Soap Lake have a higher base flow component compared to those draining to the San Benito River based on the discharge to area ratio probably due to the soils and higher MAP in those subwatersheds. Base flow also varied with flood frequency and generally the more frequent events had lower base flows.

Calibration has produced a model that is adequate to use as a flood prediction tool. Figure 2-9 compares the model results at Chittenden with flooding frequencies developed in TM 1.2.3. An analysis of the five calibration stations yields a standard error of 20.4% for the peak discharges and 21.5% for the 3-day average discharge. While this error may seem high at first, the standard error of the frequency curves themselves is 31%, even greater than that of PRO-FLO. Model results are well within 90% confidence limits of the frequency curves. For all graphical and analytical model calibration results and associated discussion, please refer to TM 1.2.7 of this study.

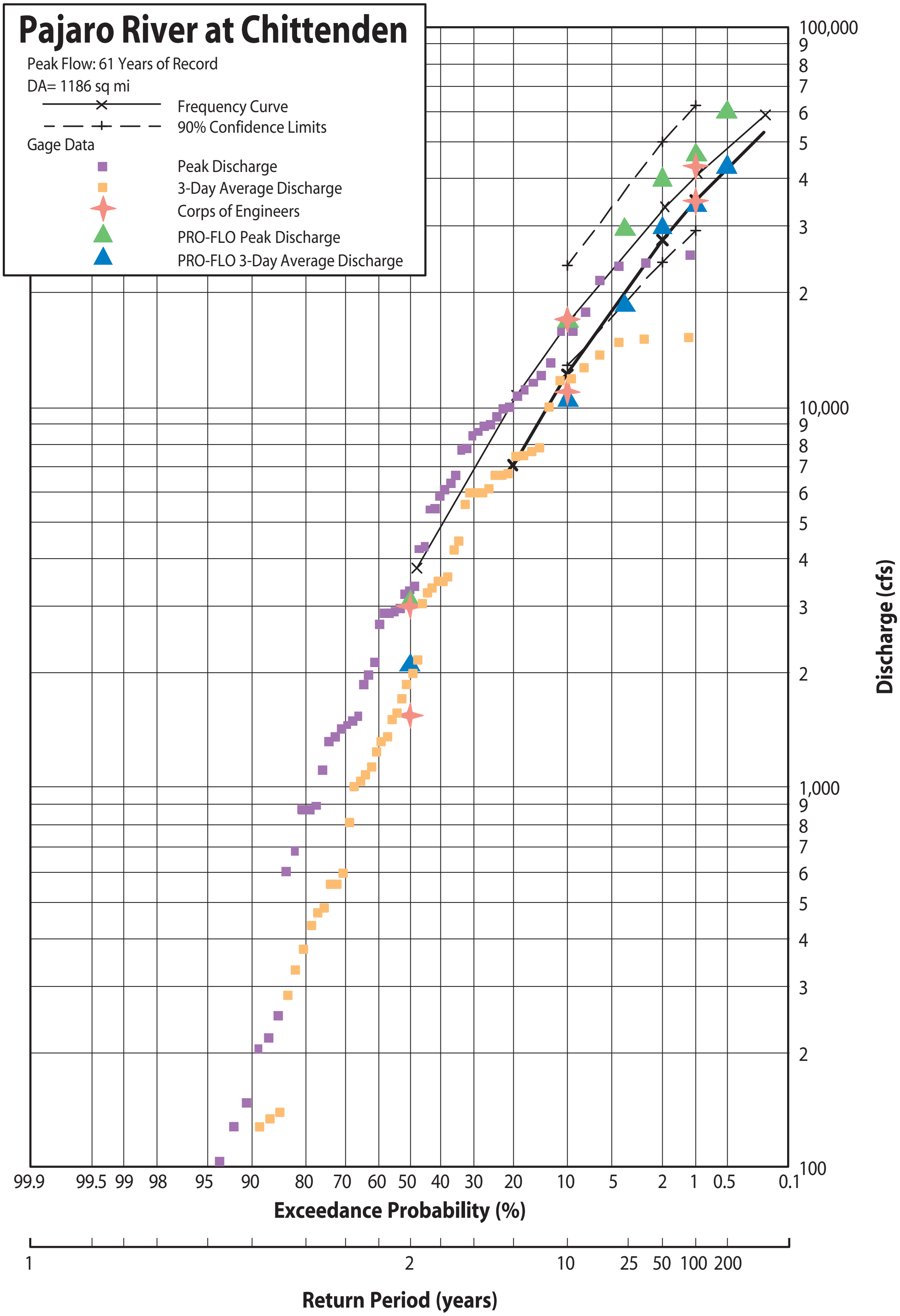


Figure 2-9

PAJARO RIVER WATERSHED

PRO-FLO Calibration

After calibrating the model, the effect of different storm centers was analyzed. It is possible that a storm centered in one area of the watershed would produce a greater discharge than a storm of the same magnitude but centered in a different location. The PRO-FLO results reported thus far have all been developed on the premise that the area reduction factor shown in Figure 2-3 applies uniformly to the entire watershed upstream of the catch point in question. To assess the impact of different storm centerings, three additional centerings were modeled. Adjusting the area reduction factor to account only for the watershed above the centering point simulated this effect. Table 2-6 shows the location and relative effect of the change in location on the overall output of the model.

Table 2-6: Location of different storm centerings and relative change in peak discharge and 3-day average discharge.

Location	% Change Peak Discharge	% Change 3-day Average Discharge
Pajaro River at Chittenden Gap (Base)	--	--
San Benito River Watershed	-2%	-12%
Lower Soap Lake	-3%	-6%
In-between Lower Soap Lake & San Benito River Watershed	-1%	-8%

As can be seen in Table 2-6, all of the alternate centerings produced slightly lower discharges. Since the primary goal of the study is to predict floods, it does not make sense to center storms over areas where the discharge, and therefore the flooding, would be less severe. It is therefore possible to conclude that the uniformly applied area reduction factor is the most appropriate way to apply the reduction factor.

The calibrated model produces current discharges similar to those predicted by the Army Corps of Engineers and close to the statistical representation of the data. Table 2-7 is a summary of the peak and 3-day average discharge results at the four positions for the six frequencies. This table can serve as a reference point for the results of other modeled scenarios.

Table 2-7: Modeled discharges using current land use. The "Area" values represent the drainage area, in square miles, at that point.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,270	10,700	18,700	26,100	31,500	44,600
3-Day Avg. Q		454	3,690	6,960	11,900	14,800	21,000
Lake Outlet	505						
Peak Q		3,390	14,400	19,800	24,500	26,100	29,600
3-Day Avg. Q		2,070	9,720	15,200	19,900	21,900	25,600
Chittenden	1,186						
Peak Q		3,070	16,400	27,900	38,100	44,600	59,900
3-Day Avg. Q		2,090	10,400	17,700	26,600	30,900	40,100
D/S Salsipuedes	1,274						
Peak Q		3,790	19,100	30,800	42,300	49,400	66,200
3-Day Avg. Q		2,680	12,400	20,000	29,200	33,900	43,900

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,270	10,700	18,700	26,100	31,500	44,600
3-Day Avg. Q		454	3,690	6,960	11,900	14,800	21,000
Lake Outlet	505						
Peak Q		3,390	14,800	21,200	26,900	30,300	35,200
3-Day Avg. Q		2,070	9,690	15,300	20,300	22,600	27,300
Chittenden	1,186						
Peak Q		3,070	16,900	28,600	37,900	43,700	57,600
3-Day Avg. Q		2,090	10,400	17,700	26,800	31,200	41,000
D/S Salsipuedes	1,274						
Peak Q		3,790	19,600	31,700	42,200	48,500	64,000
3-Day Avg. Q		2,680	12,400	20,100	29,400	34,200	44,800

Pajaro River to the Ocean Sediment Generation and Transport Model

The Pajaro River to the Ocean SEDiment generation and transport model (PRO-SED) is designed to generate river reach profiles to determine the effects of watershed and riverbed changes on sediment scour and deposition during flooding events of various intensities. The model creates a hydrograph and, based on initial sediment data, calculates the location and magnitude of the sediment transport.

As PRO-SED and PRO-FLO have been jointly developed, they have many of the same advantages and drawbacks. PRO-SED is based on the best available data, including published data as well as field studies conducted solely for this model. Geometric, streamflow, and sediment data inputs can be varied to create nearly any watershed condition or sediment type. Outputs are based on equations developed to model unsteady, non-uniform flow, which more accurately simulate actual conditions than those based on simplifying assumptions. PRO-SED is limited to the Pajaro River watershed, though, as the above data inputs have only been collected within the watershed boundaries. The one-dimensional nature of the model also makes it unsuitable to model sediment transport through large bodies of water such as a large reservoir or the ocean.

To understand how to apply and use PRO-SED, it is important to understand the model's structure and the data on which the model relies. The following sections explain the basics of the sediment model including the types of data that are required, where that data comes from, the software used, and the procedures performed to calibrate the model.

Model Software

PRO-SED uses MIKE11 software to model the sediment transport. MIKE11 consists of a one-dimensional, unsteady-flow hydrodynamic module coupled with a sediment transport module. The program was developed by the Danish Hydraulic Institute and is regarded as one of the best sediment modeling programs available. The model is widely accepted, both internationally and within California, and has been approved by FEMA for use in flood studies.

There are several important features of MIKE11 that make it the preferred software for PRO-SED. These include:

- Graphical User Interface (GUI) that facilitates data entry and result viewing
- Open channel flow equations to simulate flow across weirs, culverts, and control structures including dams
- Multiple transport equations to best fit the situation of interest
- Two-layer bed allows for geologic controls
- Shielding can be simulated. Shielding occurs when coarser material overlies fine material, which prevents scouring from occurring

The user specifies the volume of the inflowing sediment load and its grain size distribution, as well as the initial grain size distribution of the bed material. The model produces a variety of outputs via the graphical user interface, including animations showing the response of the river system over time as developed from the simulation.

DATA

Sediment transport models require three kinds of input data: geometric, streamflow, and sediment data. The following paragraphs will briefly describe each of the data types and provide some information about them. For further detail and analysis, please refer to the associated TMs in the Appendix.

Model Geometry and Boundary Conditions

Geometric data describes the channel features such as cross section shape, long section profile, flood plain and levee features, and the river's hydraulic roughness. The hydraulic roughness is used in simulation models to represent the effect of channel features, such as dunes and vegetation, on flow characteristics. High hydraulic roughness leads to slower flow velocities and deeper water than channels with low hydraulic roughness.

The cross section data that was used to develop the model is the same as that used to develop the HEC-RAS model within PRO-FLO. MIKE11 does not require as many cross sections to characterize the river, though. The unnecessary profiles are not included in the model.

PRO-SED models transport from just upstream of Chittenden Pass and the confluence between the Pajaro River and the San Benito River to 0.5 miles upstream of the Pacific Ocean. This stretch of river can be seen in Figure 2-10. Input hydrographs for discharge and sediment load were established for the upstream boundary. The downstream boundary uses normal flow depth as a boundary condition. Although tidal influence may be experienced at this point during low flows, during the high flow events important for sediment transport, the river discharge effects will dominate. Use of a normal depth downstream boundary condition is therefore appropriate.

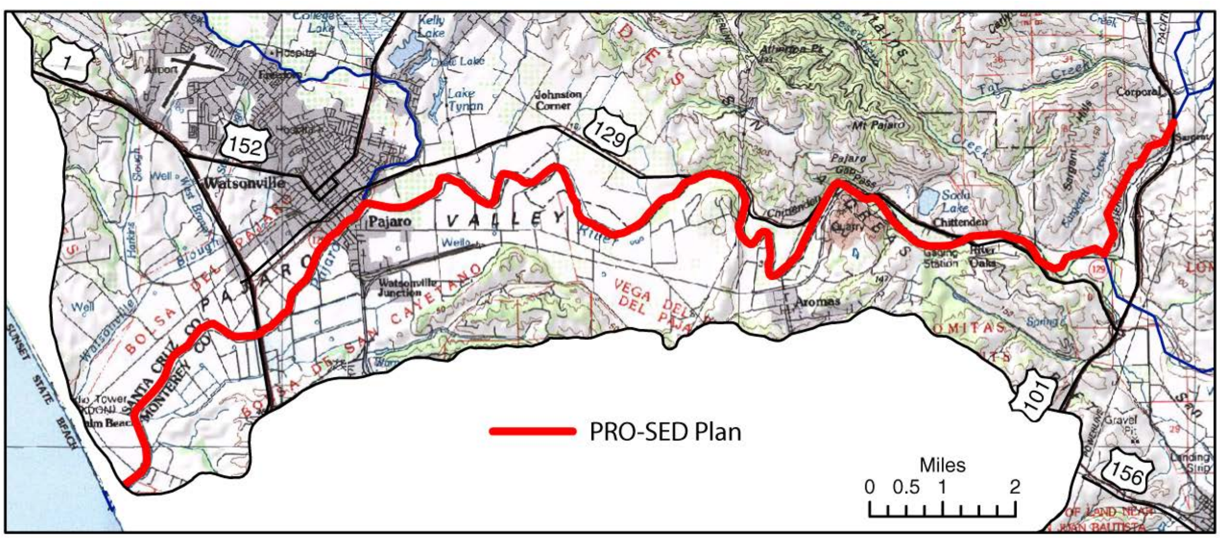


Figure 2-10
PRO-SED Plan

Streamflow

The streamflow data used in sediment transport modeling can either represent short duration, extreme flood events or long duration hydrographs. The short duration hydrographs may take place over a few days, whereas the longer duration flow hydrographs may represent flow over several years. Short duration hydrographs are often used to investigate the impact of an extreme flood event on the sediment transport characteristics of a stream. Long duration flow hydrographs may be used to simulate the long-term effect of river flow on sediment transport characteristics.

The long term flow record collected by the USGS at the Chittenden gage (11159000) is used to simulate long-term sediment transport in the river. This data has been recorded over the period 10/1/39 to 9/30/00.

Sediment

Sediment input forms a very important component of sediment transport modeling. It is also the most difficult to estimate because data are often lacking or represent short duration records. The characteristics of the sediment discharge records that were used to develop input for this model are presented in this section, and the method that was used to develop the inflow record is also briefly discussed.

The following data were used to determine inflowing sediment load at the USGS Chittenden gage:

- Streamflow data are available for 61 years, from 10/1/39 to 9/30/00
- Sediment load at this gage was reported on 46 different days between 1978 and 1990
- Of the available suspended sediment load data, on 37 days the percentage of the total sediment load which consisted of sand (>0.062 mm diameter) was reported.

It is necessary to establish the amount of sediment entering the upper boundary of the sediment transport model. Because the grain size of interest in the Pajaro River is coarse sediment, determined in TM 1.2.4 to be primarily sand, the inflowing load of coarse sediment must be determined and distinguished from the finer sediment load.

To establish a relationship between discharge and sediment load, the daily suspended sediment load was plotted as a function of daily discharge. Based on the plotted data, the total sediment load for any discharge can be predicted using the equation

$$\text{Load} = 0.033*\text{Qcfs}^{1.56} \qquad \text{Eq. 2-1}$$

and the coarse sediment load for any discharge can be predicted using the equation

$$\text{Load} = 0.007*\text{Qcfs}^{1.56} \qquad \text{Eq. 2-2}$$

where Load is the sediment load in tons/day and Qcfs is the mean daily discharge in cfs. These rating relationships can be seen in Figure 2-11. These equations can be applied to the entire streamflow record to estimate the inflowing load over time.

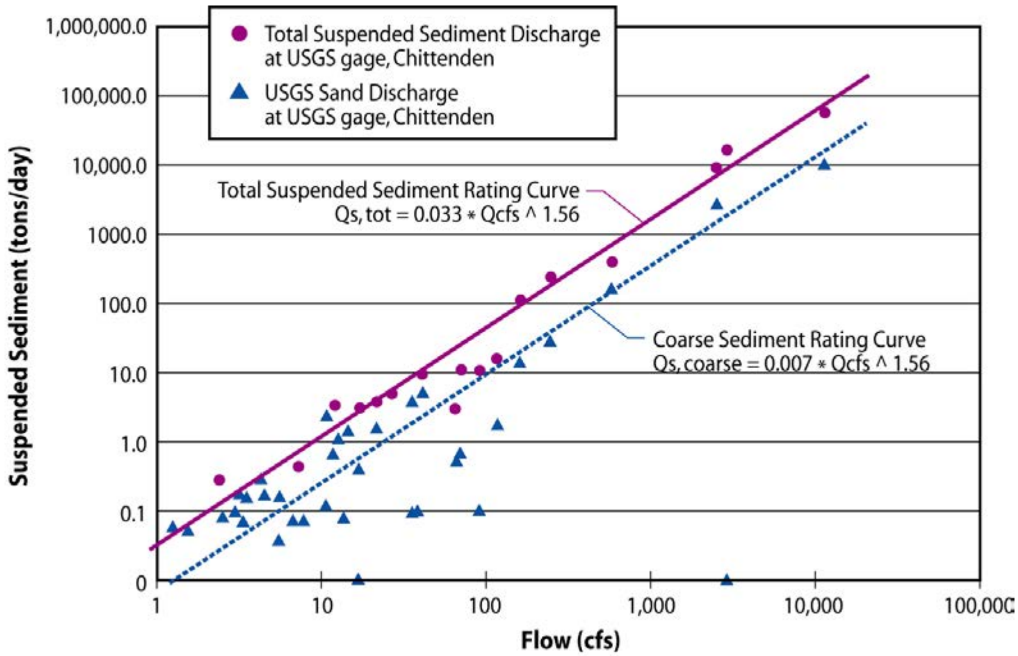


Figure 2-11
Pajaro River Suspended Sediment Transport Curve
USGS Chittenden Gage (11159000)

For additional information about temporal variation in sediment load and how the loading changes with discharge rate, please refer to TM 1.2.9.

CALIBRATION

PRO-SED is calibrated by adjusting four properties of the model until the accuracy of the model is adequate. The parameters and some discussion can be found below:

- Hydraulic roughness (Manning's n value) – This value affects the detention time of the water within the channel.
- Composition and thickness of the active bed layer – Only sediment in the active bed layer is available for transport.
- Flood plain divide where applicable – During flood events there is flow both in the channel and over the flood plain. Each has a different set of parameters affecting the velocity and volume of flow.
- Number of cross sections – There must be an adequate number of cross sections for the model to function properly.

PRO-SED can be run in either fixed-bed or movable-bed modes. When run in fixed-bed mode, the model resembles the HEC-RAS model. When run in movable-bed mode, PRO-SED simulates sediment movement in the river, with the riverbed changing as sediment is scoured or deposited with variation in the flow. Accuracy of the model is verified by comparing the model output in fixed-bed mode to two outputs from the HEC-RAS aspect of PRO-FLO. The two outputs are the 100-year event hydrograph at Chittenden and a longitudinal profile of peak water surface elevations for the 100-year event along the river. As can be seen in Figure 2-12a and 2-12b, there is a very high correlation between the two models.

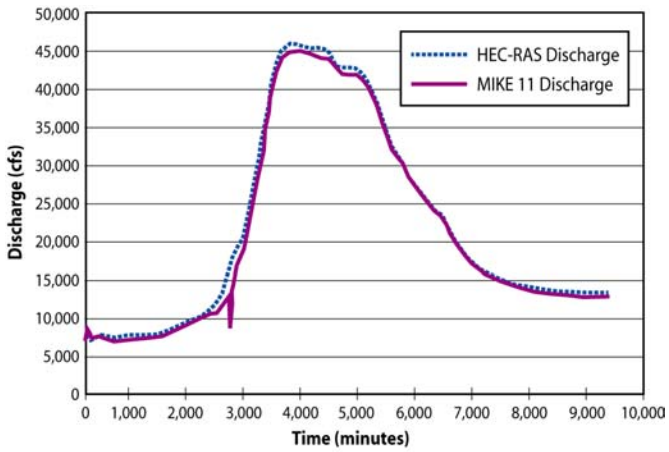


Figure 2-12a
PRO-SED Calibration Curve

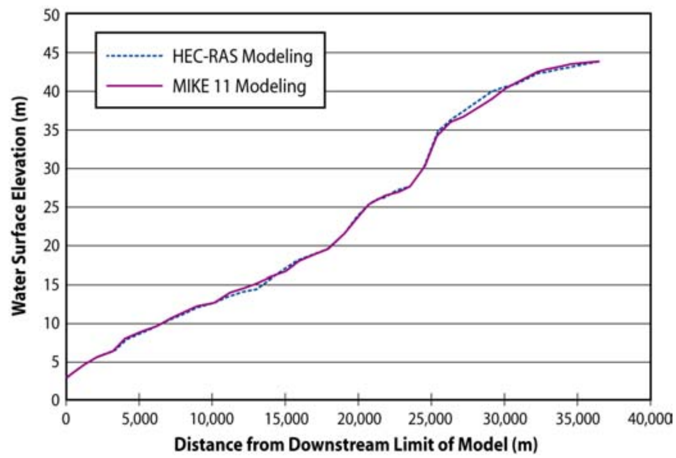


Figure 2-12b
Water Surface Elevation Comparison

As a check of the validity of the model and calibration, the model outputs were compared to field observations of the lower Pajaro River. The model predicts that net sediment deposition occurs in some locations, such as at the confluence with the San Benito River, at Carpenteria Road/Rogge Lane, and at Murphy's Crossing. For most of the rest of the river the simulation indicates that it is likely that the riverbed experiences net erosion. This means that it is reasonable to expect the riverbed to experience net degradation for most of its length during the course of the 100-year flood event. This finding is in agreement with the observations pertaining to the long-term behavior of the river that was summarized in TM 1.2.8.

Four Watershed Conditions

CHAPTER 3

CHAPTER 3
FOUR WATERSHED CONDITIONS

One of the major goals of Phase 1 of the PRWS is to see how land use affects flooding frequency and flooding intensity. Modeling the watershed in different conditions gives insight into future flooding problems and allows the impacts of development trends to be identified. As a starting point, four watershed conditions have been modeled with both PRO-FLO and PRO-SED. The conditions were chosen based on particular questions that needed to be answered and the four conditions comprehensively span the extent of reasonable land use changes. Other conditions can be modeled as needed at a later point.

The following paragraphs are split into three sections. The first describes the individual hydrologic watershed conditions and their possible impacts on future planning within the Pajaro River watershed. The second discusses the four sediment transport conditions modeled. The third summarizes lessons learned from the modeling exercise and provides some additional discussion regarding their impacts.

Hydrologic Model Scenarios and Results

Each of the four conditions was chosen based on both individual characteristics and patterns that can be established between all of them. The model was calibrated using existing conditions. The following four conditions allow the model to explore watershed response to changes that might affect downstream flooding.

1. **Back in Time to 1947**: It is important to be able to compare current and future conditions to those of the past. The historical perspective provides a glimpse of how flooding has changed due to known shifts in land use. The year 1947 is significant because it was just before the Corps' levees were built in 1949 and had conditions similar to when the 1955 flood occurred. In addition, three of the four existing reservoirs and some additional levees were not yet in place in 1947.
2. **General Plan Buildout**: This scenario allows the model to predict the watershed flood potential using the urban and agricultural land uses for each city and county designated by the individual planning departments. This is the best estimate available for future conditions within the watershed. While the horizons of the individual general plans vary greatly, this scenario is intended to approximately represent the years between 2015 and 2020.
3. **Ultimate Buildout in 2050**: This scenario represents a worst-case scenario, in terms of flooding, for urbanization. The model predicts how the watershed would respond to unchecked growth in the cities beyond what the general plans allow. The year 2050 is the approximate end of the economic life of a project started at the time of this report.
4. **Changes in Agriculture**: Agriculture can play a large role in the amount of runoff and therefore flooding in an area. This scenario does not represent any particular time period but parallels the Ultimate Buildout scenario in that it represents a worst-case agricultural condition.

The next sections go into greater detail for each scenario, including how the data was developed for the condition and the results of each HEC-1 and HEC-RAS model run. HEC-RAS peak discharges on the lower reaches are slightly lower than those calculated by HEC-1 due to HEC-RAS's ability to model attenuation within the river system. The discharge and relative change for each condition and frequency between the two model structures is similar. Either model could be considered representative of the actual discharges and both support conclusions based on this study. Figure 2-1 shows the locations of the comparison points highlighted in the tables displaying model results.

BACK IN TIME TO 1947

Watershed Condition and Data

This simulation represents flooding conditions that the Corps was using to design the levees on the lower Pajaro River. Data used to represent the historic watershed condition are the same except for the land use and some routing changes.

The routing changes were necessary because of post-1947 upstream flood control and water supply projects. Uvas Dam, Chesbro Dam, and Hernandez Dam have all been built since 1947. The only major dam in the watershed before 1947 was the Pacheco Dam. Since the dams did not exist prior to 1947 and the Corps did not have any way to predict their existence, storage and attenuation effects were removed from the model, allowing the water to flow through the reaches uninhibited. Also, in 1947, Llagas Creek did not have the existing leveed channel in its lower reaches. To account for this pre-channel condition, the routing in this reach was changed to include the additional attenuation that would be expected with a smaller channel and a larger flood plain.

Historic land use was obtained from several different sources. The extent of the cities is determined from an interpolation of USGS topographic maps. Every few years, the USGS remaps any given quad at the 7.5 minute and 15 minute scale. All USGS maps for each 15-minute quad impacting the Pajaro River watershed around 1947 were obtained. Maps developed before and after 1947 were used as guides for the actual area of urbanization within the watershed in 1947. The new urban areas were mapped on the land use Geographic Information System (GIS) database.

Agricultural information for this time period is not available in a graphical format. Instead, the historic agriculture land use is derived from a combination of resources. Agricultural data was obtained by combining information from historic aerial photos from the early 1940s, county crop reports from that era, and conversations with local farm bureau and historic society representatives.

Figure 3-1 shows the distribution of the land uses used by PRO-FLO that were found in the Pajaro River watershed in 1947. Comparison with Figure 2-5 shows the type and size of the changes made to arrive at the historic land use.

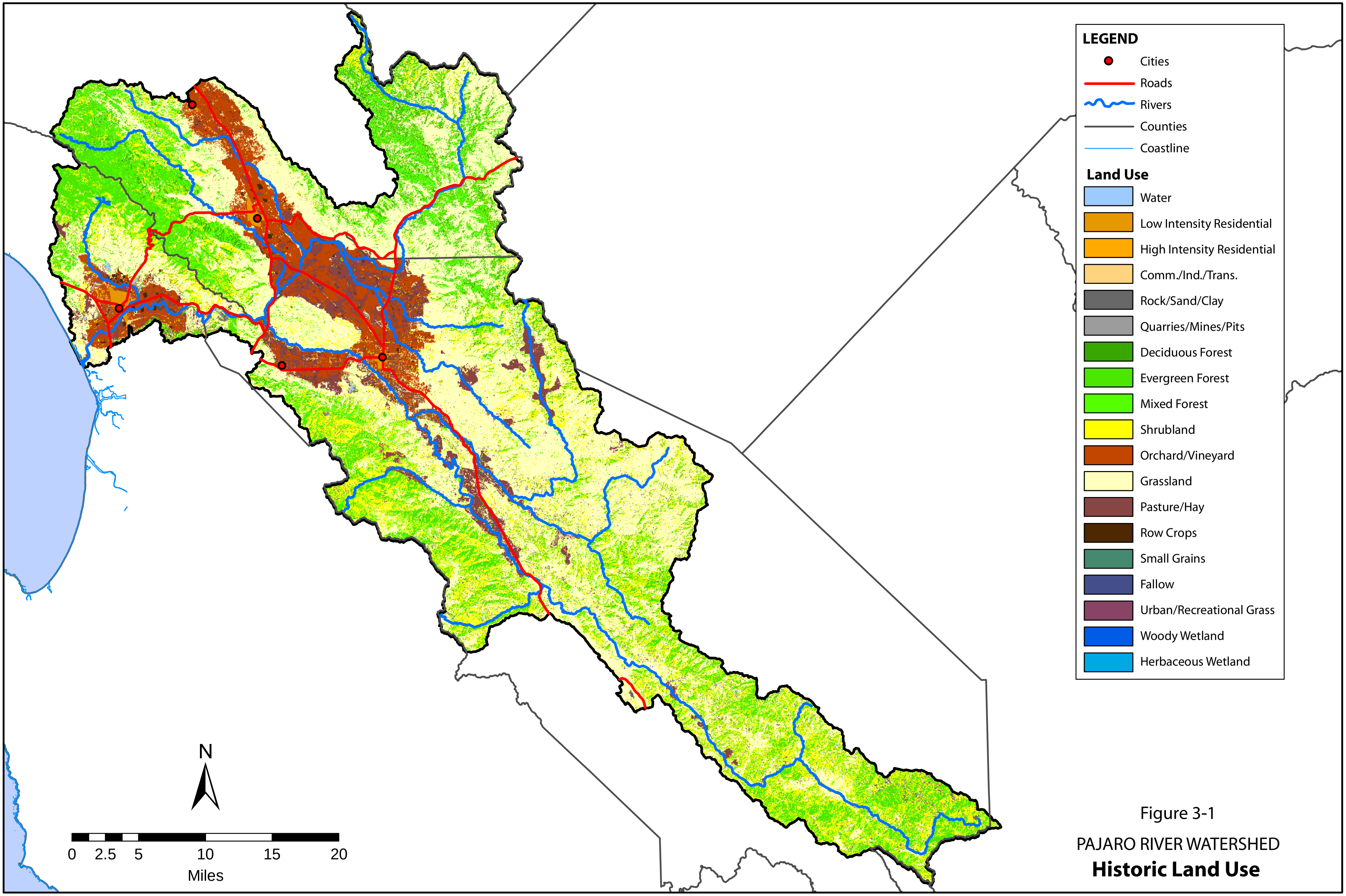


Figure 3-1

PAJARO RIVER WATERSHED

Historic Land Use

Model Results

With the routing changes in place and the impermeability and curve numbers adjusted to match the land use, PRO-FLO produced the following results. For each comparison point and return period, Table 3-1 contains the peak and 3-day average modeled flows and Table 3-2 contains the relative change from existing conditions. Discussion of the results follows.

Table 3-1: Model output for historical watershed condition. It is important to note that runoff has decreased since 1947. The sub-watershed areas are square miles and the discharge units are cfs.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,880	13,300	21,500	30,500	37,300	52,200
3-Day Avg. Q		602	4,540	8,010	12,800	15,700	21,900
Lake Outlet	505						
Peak Q		4,470	15,200	20,300	24,800	26,400	30,000
3-Day Avg. Q		2,340	10,200	15,600	20,100	22,100	25,900
Chittenden	1,186						
Peak Q		3,720	19,500	31,300	42,000	50,200	68,800
3-Day Avg. Q		2,150	11,300	19,000	27,800	32,100	41,300
D/S Salsipuedes	1,274						
Peak Q		4,310	21,500	33,800	45,100	53,500	73,500
3-Day Avg. Q		2,710	13,300	21,400	30,500	35,200	45,300

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,880	13,300	21,500	30,500	37,300	52,200
3-Day Avg. Q		602	4,540	8,010	12,800	15,700	21,900
Lake Outlet	505						
Peak Q		4,470	15,400	21,500	27,000	30,300	35,300
3-Day Avg. Q		2,340	10,200	15,600	20,600	22,800	27,600
Chittenden	1,186						
Peak Q		3,720	19,200	31,600	41,500	48,500	63,100
3-Day Avg. Q		2,150	11,300	19,100	28,000	32,500	42,200
D/S Salsipuedes	1,274						
Peak Q		4,310	21,600	35,000	45,100	52,400	69,400
3-Day Avg. Q		2,710	13,300	21,500	30,700	35,500	46,200

Table 3-2: Relative change in model output for historical watershed condition. It is important to note that runoff has decreased since 1947. The sub-watershed areas are square miles and the percentages represent change from the current model flow at that return period.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		48.1%	24.4%	14.7%	16.9%	18.4%	17.2%
3-Day Avg. Q		32.6%	23.2%	15.0%	7.5%	5.9%	4.4%
Lake Outlet	505						
Peak Q		32.0%	4.9%	2.7%	1.0%	1.1%	1.1%
3-Day Avg. Q		12.7%	5.1%	2.5%	1.4%	1.2%	0.9%
Chittenden	1,186						
Peak Q		21.3%	19.2%	12.0%	10.2%	12.5%	14.8%
3-Day Avg. Q		2.6%	8.3%	7.4%	4.5%	3.9%	3.0%
D/S Salsipuedes	1,274						
Peak Q		13.9%	12.6%	9.6%	6.4%	8.4%	11.0%
3-Day Avg. Q		1.4%	6.9%	7.0%	4.5%	3.9%	3.1%

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		48.1%	24.4%	14.7%	16.9%	18.4%	17.2%
3-Day Avg. Q		32.6%	23.2%	15.0%	7.5%	5.9%	4.4%
Lake Outlet	505						
Peak Q		32.0%	4.0%	1.3%	0.4%	-0.2%	0.4%
3-Day Avg. Q		12.7%	5.2%	2.5%	1.4%	1.2%	0.9%
Chittenden	1,186						
Peak Q		21.3%	13.6%	10.5%	9.5%	11.0%	9.6%
3-Day Avg. Q		2.6%	8.4%	7.5%	4.5%	3.9%	3.0%
D/S Salsipuedes	1,274						
Peak Q		13.9%	9.8%	10.2%	7.0%	8.0%	8.4%
3-Day Avg. Q		1.4%	7.0%	6.9%	4.4%	3.9%	3.1%

As can be seen in Table 3-2 by the positive percentage change or by comparing Tables 3-1 and 2-7, both peak and average discharges were higher in 1947 than they are today. For the San Benito River, it was discovered that Hernandez Reservoir detains and significantly attenuates the runoff hydrograph from the 85 square mile watershed for the reservoir. Not having the reservoir not only increases the discharges, but equally important for downstream effects, it moves the peak discharge up about eight hours. With this shift the San Benito River flood wave adds almost directly to the peaks of other sub-watershed hydrographs. The effects can be seen in the increases at the Chittenden and downstream of the Pajaro River confluence with Salsipuedes Creek.

Removing the Uvas and Chesbro Reservoirs had similar effects on peak discharges that can be seen at the Lake Outlet location. The model hydrographs indicate that the peaks were increased significantly on both creeks. When the Llagas peak met the Pajaro River peak though, the established Pajaro peak dominated. The Llagas peak was slightly smaller and arrived sooner than the Pajaro peak, which was delayed due to the attenuation effects of Pacheco Reservoir and Upper Soap Lake. At the confluence with the Uvas Creek however, the combination of the Uvas and Llagas peaks overwhelmed the Pajaro peak and became dominant. This complex interaction results in a slight increase at the larger return period and much greater increases at higher frequencies.

The 3-day average discharges were greater than existing because the water supply dams were not there to trap part of the flood flows and keep them in the reservoirs for later release.

General Plan Buildout and Ultimate Buildout in 2050

These two watershed scenarios have been grouped together due to similarities in both their goals and results. Both conditions were chosen to see the effects of urbanization on runoff but at different times in the future. Consequently, results show similar trends.

Watershed Condition and Data

Land uses for the General Plan Buildout were obtained from the general plans of the four counties (Monterey, San Benito, Santa Clara, and Santa Cruz) and five cities in the watershed (Gilroy, Hollister, Morgan Hill, San Juan Bautista, and Watsonville). The land uses defined by the general plans were overlaid on the current land uses. The effect is that only those areas with land uses other than what is currently defined were changed. The goal of this modeling scenario was to identify future downstream flooding based on planned development, both in terms of urbanization and agricultural expansion. For this reason, no additional sources of data were necessary.

Figure 3-2 shows the distribution of the land uses used by PRO-FLO that could be found at the outer limit of the communities' general plans.

An extrapolation of urban area land use percentage was used to predict city growth through the year 2050. City sprawl for this scenario is based on the percentage of urbanized areas from the historical, current, and general plan watershed conditions representing, respectively, the years 1947, 1992, and about 2015. As mentioned earlier, 1992 land use can be assumed to represent current conditions. The Ultimate Buildout scenario was applied to the General Plan Buildout land use since it would be the most similar and would reduce any error assumed in this method. The increase in percentage urbanized was applied equally to the three types of urban land use, those being low intensity residential, high intensity residential and commercial/industrial/transportation, within sub-watersheds that would be affected by the cities' growth. The remaining area of sub-watershed unaffected by urbanization was redistributed among the other land use categories, including agriculture, based on the original ratio of land uses. Sub-watersheds not affected by urban growth were left the same as those in the General Plan Buildout scenario.

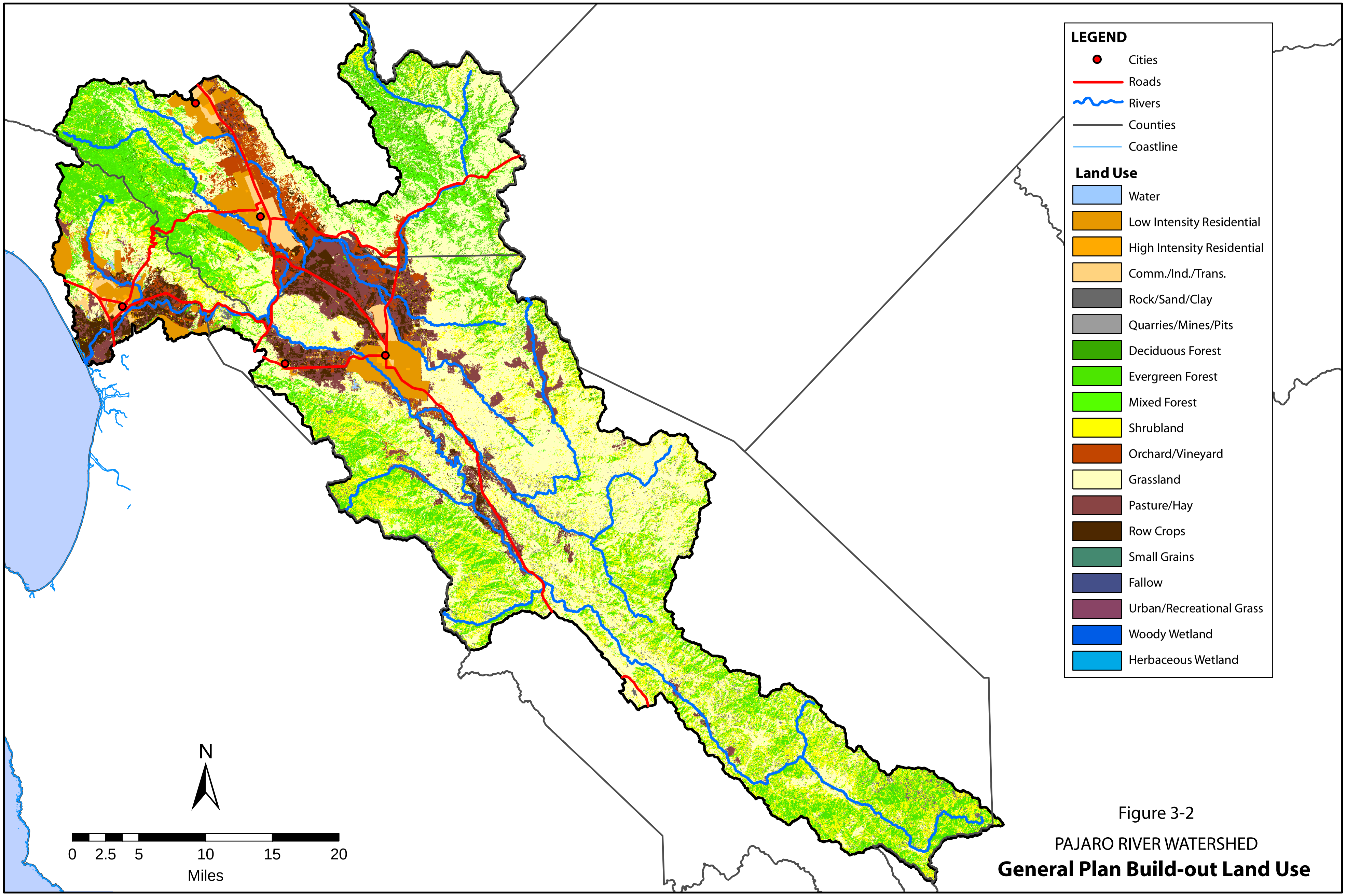


Figure 3-2

PAJARO RIVER WATERSHED

General Plan Build-out Land Use

Figure 3-3 shows the urbanization of the entire watershed and serves as an example of the analysis used to develop the land use for the Ultimate Buildout condition. Figure 3-4 shows the distribution of the land uses used by PRO-FLO that is predicted in the year 2050 if city growth continues as expected based on city and county general plans.

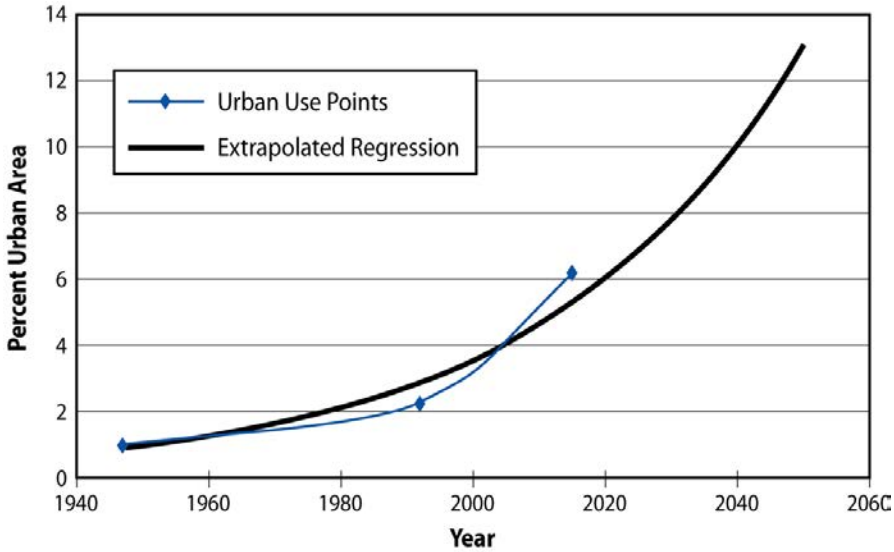


Figure 3-3
Watershed Urban Expansion

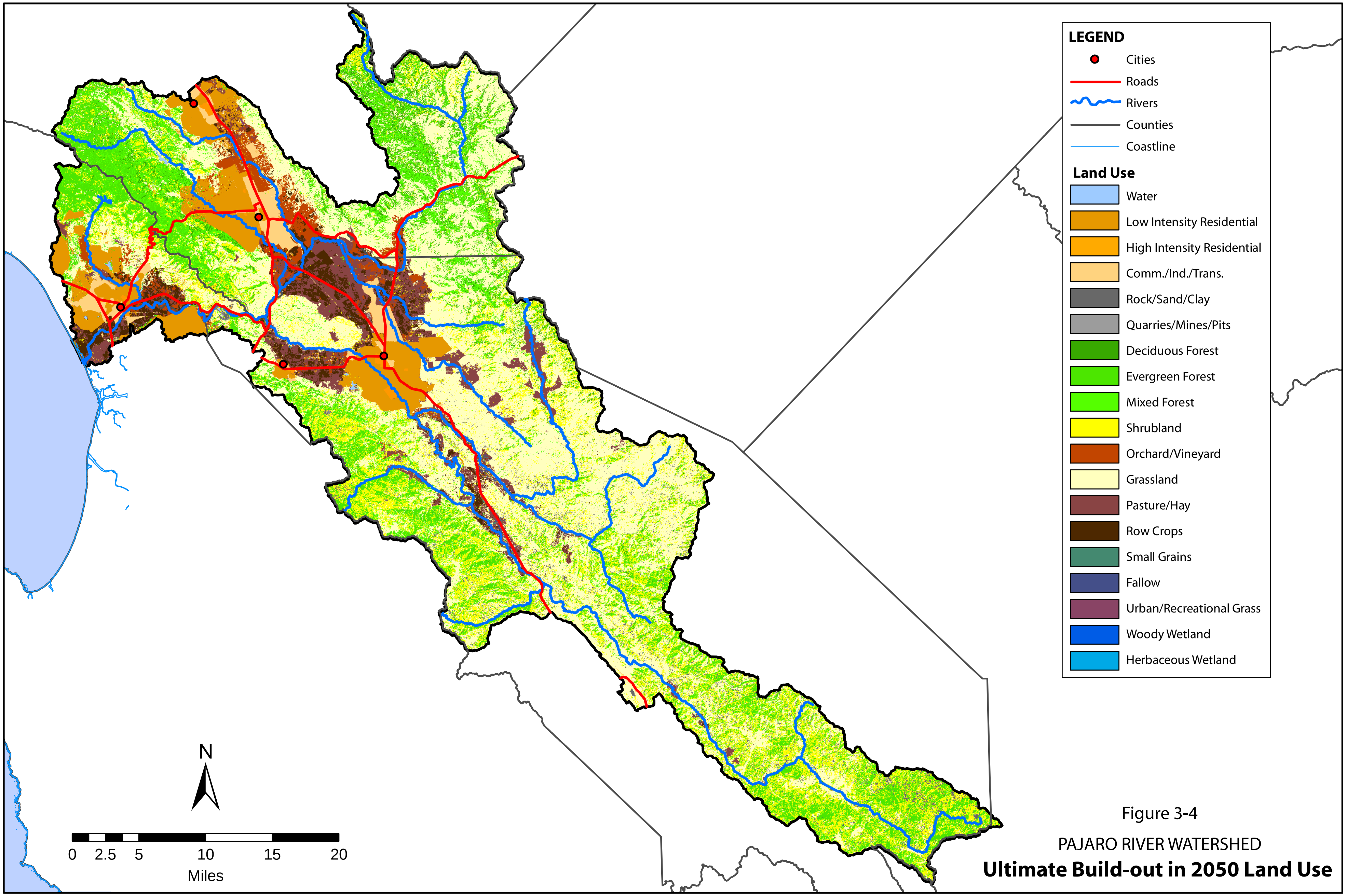


Figure 3-4

PAJARO RIVER WATERSHED

Ultimate Build-out in 2050 Land Use

Model Results

The appropriate model parameters were adjusted to account for the new land uses in both conditions. The major changes due to urbanization are the changes in impermeability, which are summarized below in Table 3-3. For each location and return period, Table 3-4 contains the peak and 3-day average modeled flows and Table 3-5 contains the percent change for the General Plan Buildout scenario. Similarly, Table 3-6 contains the peak and 3-day average modeled flows and Table 3-7 contains the percent change for the Ultimate Buildout in 2050 watershed condition. Discussion of both model results follows the tables.

Table 3-3: Impermeability of the Pajaro River Watershed. The impermeability increase nearly parallels urban development. The values in this table are percentages of total watershed area.

Watershed Condition	Percent Urban Area	Percent Impermeable
Existing	2.4	1.3
General Plan	6.2	3.0
Ultimate	9.6	4.1

Table 3-4: Model output for General Plan Buildout condition. The sub-watershed areas are square miles and the discharge units are cfs.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,280	10,800	18,800	26,200	31,600	44,700
3-Day Avg. Q		467	3,720	7,000	11,900	14,900	21,100
Lake Outlet	505						
Peak Q		4,020	14,900	20,200	24,800	26,400	29,900
3-Day Avg. Q		2,290	10,100	15,600	20,200	22,200	25,900
Chittenden	1,186						
Peak Q		3,610	16,900	28,700	38,600	45,200	60,500
3-Day Avg. Q		2,300	10,800	18,100	27,000	31,400	40,500
D/S Salsipuedes	1,274						
Peak Q		4,340	19,800	32,000	43,300	50,500	67,400
3-Day Avg. Q		2,990	13,000	20,700	29,900	34,600	44,600

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,280	10,800	18,800	26,200	31,600	44,700
3-Day Avg. Q		467	3,720	7,000	11,900	14,900	21,100
Lake Outlet	505						
Peak Q		4,020	15,300	21,600	27,400	30,700	35,600
3-Day Avg. Q		2,290	10,100	15,700	20,700	23,000	27,700
Chittenden	1,186						
Peak Q		3,610	17,300	29,300	38,400	44,400	58,200
3-Day Avg. Q		2,300	10,800	18,200	27,300	31,700	41,400
D/S Salsipuedes	1,274						
Peak Q		4,340	20,300	32,700	43,100	49,600	65,300
3-Day Avg. Q		2,990	13,000	20,800	30,200	35,000	45,600

Table 3-5: Relative change for the General Plan Buildout condition. The sub-watershed areas are square miles and the percentages represent change from the current model flow at that return period.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1.0%	0.5%	0.4%	0.3%	0.3%	0.3%
3-Day Avg. Q		2.9%	0.9%	0.5%	0.3%	0.3%	0.2%
Lake Outlet	505						
Peak Q		18.7%	3.4%	2.0%	1.0%	1.1%	1.0%
3-Day Avg. Q		10.7%	4.0%	2.7%	2.0%	1.6%	1.2%
Chittenden	1,186						
Peak Q		17.8%	3.1%	2.9%	1.3%	1.3%	1.0%
3-Day Avg. Q		10.2%	3.6%	2.3%	1.6%	1.4%	0.9%
D/S Salsipuedes	1,274						
Peak Q		14.6%	4.1%	3.9%	2.2%	2.2%	1.8%
3-Day Avg. Q		11.8%	4.8%	3.4%	2.4%	2.1%	1.6%

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1.0%	0.5%	0.4%	0.3%	0.3%	0.3%
3-Day Avg. Q		2.9%	0.9%	0.5%	0.3%	0.3%	0.2%
Lake Outlet	505						
Peak Q		18.7%	3.5%	2.0%	2.0%	1.2%	1.1%
3-Day Avg. Q		10.7%	4.1%	2.8%	2.1%	2.0%	1.4%
Chittenden	1,186						
Peak Q		17.8%	2.6%	2.7%	1.4%	1.5%	1.0%
3-Day Avg. Q		10.2%	3.7%	2.4%	1.6%	1.5%	1.0%
D/S Salsipuedes	1,274						
Peak Q		14.6%	3.5%	3.0%	2.2%	2.2%	1.9%
3-Day Avg. Q		11.8%	5.0%	3.6%	2.6%	2.4%	1.9%

Table 3-6: Model output for Ultimate Buildout condition. The sub-watershed areas are square miles and the discharge units are cfs.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,330	10,800	18,900	26,300	31,600	44,700
3-Day Avg. Q		528	3,800	7,080	12,000	14,900	21,100
Lake Outlet	505						
Peak Q		4,700	15,000	20,500	25,000	26,600	30,100
3-Day Avg. Q		2,490	10,200	15,900	20,500	22,500	26,100
Chittenden	1,186						
Peak Q		4,270	17,400	29,500	39,000	45,700	61,000
3-Day Avg. Q		2,520	11,200	18,500	27,400	31,700	40,800
D/S Salsipuedes	1,274						
Peak Q		5,300	20,600	33,300	44,400	51,700	68,700
3-Day Avg. Q		3,380	13,700	21,400	30,600	35,400	45,400

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,330	10,800	18,900	26,300	31,600	44,700
3-Day Avg. Q		528	3,800	7,080	12,000	14,900	21,100
Lake Outlet	505						
Peak Q		4,700	15,400	21,900	27,800	30,900	35,900
3-Day Avg. Q		2,490	10,200	16,000	21,100	23,400	28,000
Chittenden	1,186						
Peak Q		4,270	17,700	29,900	38,900	44,900	58,600
3-Day Avg. Q		2,520	11,200	18,600	27,600	32,100	41,700
D/S Salsipuedes	1,274						
Peak Q		5,300	21,000	33,500	44,200	50,900	66,500
3-Day Avg. Q		3,380	13,600	21,500	30,900	35,800	46,400

Table 3-7: Relative change for the Ultimate Buildout condition. The sub-watershed areas are square miles and the percentages represent change from the current model flow at that return period.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		5.0%	1.3%	0.7%	0.5%	0.5%	0.4%
3-Day Avg. Q		16.3%	3.2%	1.6%	0.9%	0.8%	0.5%
Lake Outlet	505						
Peak Q		38.6%	4.2%	3.5%	1.7%	1.9%	1.7%
3-Day Avg. Q		20.1%	5.3%	4.8%	3.4%	2.9%	2.0%
Chittenden	1,186						
Peak Q		39.3%	6.0%	5.7%	2.4%	2.3%	1.8%
3-Day Avg. Q		20.7%	7.1%	4.5%	2.9%	2.6%	1.6%
D/S Salsipuedes	1,274						
Peak Q		39.9%	8.1%	7.9%	5.0%	4.8%	3.7%
3-Day Avg. Q		26.3%	10.2%	7.0%	4.9%	4.4%	3.2%

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		5.0%	1.3%	0.7%	0.5%	0.5%	0.4%
3-Day Avg. Q		16.3%	3.2%	1.6%	0.9%	0.8%	0.5%
Lake Outlet	505						
Peak Q		38.6%	4.2%	3.5%	3.5%	2.0%	2.0%
3-Day Avg. Q		20.1%	5.4%	5.0%	3.7%	3.5%	2.5%
Chittenden	1,186						
Peak Q		39.3%	4.8%	4.5%	2.6%	2.7%	1.8%
3-Day Avg. Q		20.7%	7.3%	4.6%	3.1%	2.8%	1.9%
D/S Salsipuedes	1,274						
Peak Q		39.9%	6.8%	5.7%	4.8%	4.8%	3.9%
3-Day Avg. Q		26.3%	9.7%	7.1%	5.0%	4.6%	3.5%

Urbanization has a relatively small impact on the design flows, i.e. 100-year floods, for flood control projects. Urban land uses do affect the amount of runoff created in more frequent storms.

The change due to urbanization in design discharge at the longer return periods, 50- to 200-year, is not as large as one might have expected. For the General Plan Buildout scenario in both models, all changes in storms larger than 50-year floods are 2.6% or less for both peak and 3-day average discharges. The smallest change is 0.2% change in the 3-day average discharge of the 50- and 200-year storm. For the Ultimate Buildout scenario, the largest change, a 5.0% increase in peak discharge (HEC-1) and a 5.0% increase in 3-day average flow (HEC-RAS), is at the position downstream of the confluence of the Pajaro River and Salsipuedes Creek. The smallest changes come in the San Benito Watershed with less than 1% change in peak and 3-day average discharges over the spectrum of 50- to 200-year floods for both models. These changes, or lack thereof, are probably due to the small amount of urbanization upstream of the San Benito River modeling point.

Urbanization has a significant effect on the peak discharge of the smaller storms (2- to 25-year). The impervious surfaces added by the development of urban areas generate more runoff and discharge in smaller events. The discharge frequency of a given storm will decrease with the additional urbanization. In other words, what was previously considered a 25-year storm would be expected to occur every 23 years.

Changes in Agriculture

Watershed Condition and Data

Agribusiness in the area has transitioned from subsistence farming to a very lucrative industry. The progression has been partially due to a higher crop yield per acre and an increased percentage of cash crops such as strawberries. Advances in agriculture technologies have made these shifts possible. One of the most important technologies has been the development and use of sheet plastic and additional grading, both of which increase runoff.

This modeling condition assesses the hydrologic impact of agriculture in the watershed. It represents a change in all existing agriculture, transforming the landscape from a mixture of orchards and vineyards, pasture and hay, row crops, small grains, and fallow agricultural land to only row crops. This scenario gives no consideration to the availability of water to convert the land to row crops nor thought to the soil conditions or any other consideration a farmer might make before changing one type of crop to another.

As discussed in the section of this report about the calibration of PRO-FLO, land use is not the only factor affecting runoff. The other most relevant factor to this scenario is the hydrologic condition. The most profitable row crops such as strawberries utilize the plastic sheeting that increases runoff. Therefore, this watershed condition also assumes that there is a poor hydrologic condition.

These two conditions, row crops and a poor hydrologic condition, while maximizing the profitability of agriculture in the watershed also create a maximum amount of runoff thereby increasing the flood risk.

Figure 3-5 shows the land use distribution used by PRO-FLO in this watershed condition. All of the agriculture is considered as row crops with a poor hydrologic condition. All other land uses are the same as the land use established earlier as the current land use.

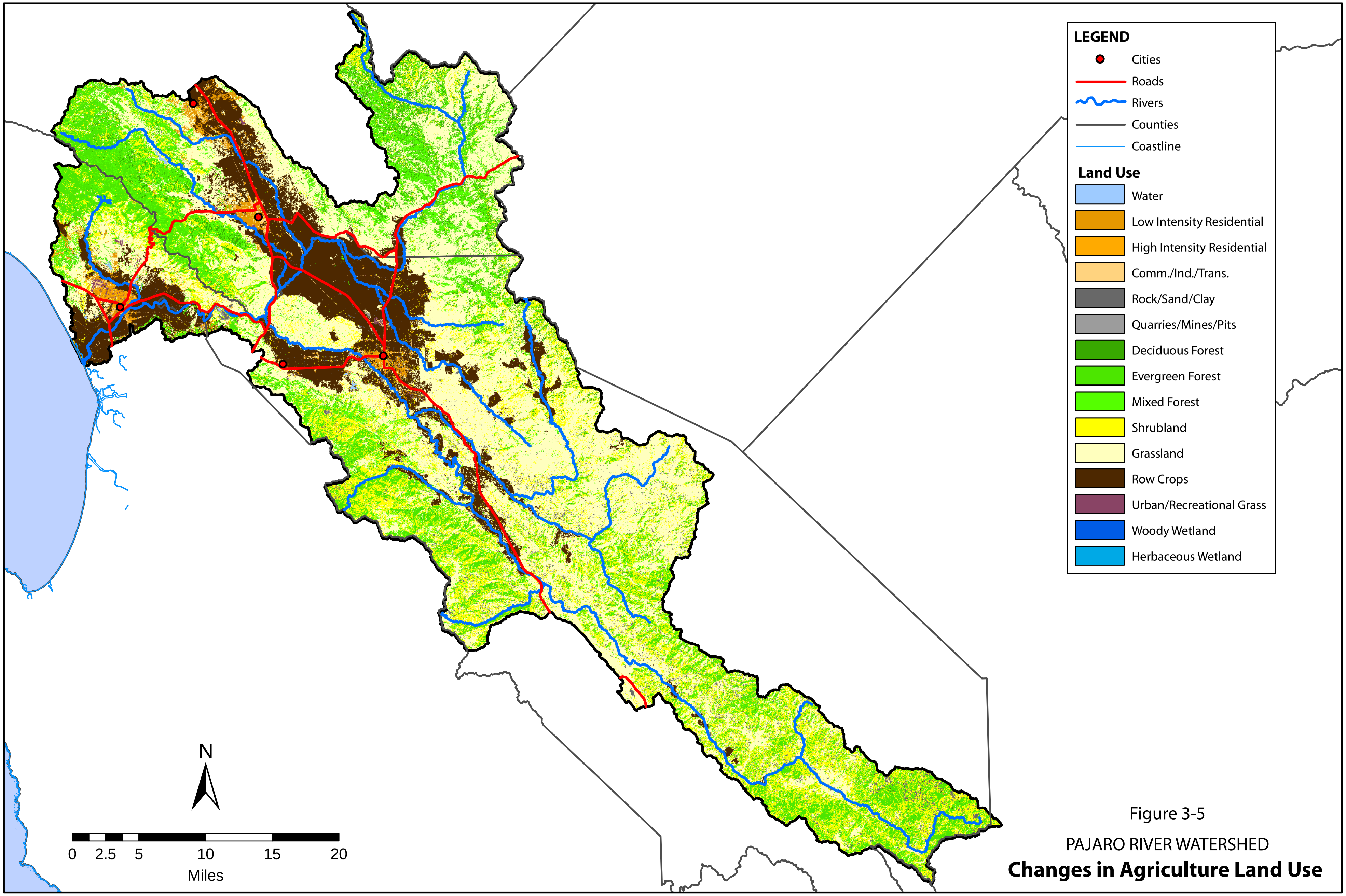


Figure 3-5

PAJARO RIVER WATERSHED

Changes in Agriculture Land Use

Model Results

To set the model for the Changes in Agriculture condition only curve numbers were changed where agriculture plays a role in the sub-watershed. All other conditions match the parameters for current land use. There are no changes to the percent impervious for any sub-watershed since this scenario assumes that only agricultural uses change. For each location and return period, Table 3-8 contains the peak and 3-day average modeled flows and Table 3-9 contains the percent change for the Changes in Agriculture scenario.

Table 3-8: Model output for Changes in Agriculture condition. The sub-watershed areas are square miles and the discharge units are cfs.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,270	10,700	18,700	26,100	31,500	44,600
3-Day Avg. Q		454	3,690	6,970	11,900	14,800	21,000
Lake Outlet	505						
Peak Q		3,710	14,800	20,100	24,700	26,300	29,900
3-Day Avg. Q		2,180	9,980	15,500	20,100	22,100	25,900
Chittenden	1,186						
Peak Q		3,270	16,600	28,400	38,400	45,000	60,300
3-Day Avg. Q		2,180	10,700	18,000	26,900	31,200	40,400
D/S Salsipuedes	1,274						
Peak Q		4,000	19,400	31,400	42,700	49,900	66,800
3-Day Avg. Q		2,760	12,700	20,300	29,500	34,200	44,300

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		1,270	10,700	18,700	26,100	31,500	44,600
3-Day Avg. Q		454	3,690	6,970	11,900	14,800	21,000
Lake Outlet	505						
Peak Q		3,710	15,100	21,500	27,300	30,600	35,600
3-Day Avg. Q		2,180	10,000	15,500	20,600	22,900	27,700
Chittenden	1,186						
Peak Q		3,270	17,200	29,500	38,600	44,600	58,400
3-Day Avg. Q		2,180	10,800	18,300	27,400	31,900	41,600
D/S Salsipuedes	1,274						
Peak Q		3,970	19,900	32,300	42,600	49,100	64,700
3-Day Avg. Q		2,760	12,700	20,400	29,800	34,600	45,200

Table 3-9: Relative change for the Changes in Agriculture condition. The sub-watershed areas are square miles and the percentages represent change from the current model flow at that return period.

a) HEC-1

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
3-Day Avg. Q		0.0%	0.1%	0.1%	0.0%	0.0%	0.0%
Lake Outlet	505						
Peak Q		9.4%	2.2%	1.4%	0.7%	0.9%	0.9%
3-Day Avg. Q		5.4%	2.6%	1.9%	1.5%	1.3%	1.0%
Chittenden	1,186						
Peak Q		6.7%	1.5%	1.8%	0.7%	0.7%	0.7%
3-Day Avg. Q		4.0%	2.1%	1.4%	1.0%	0.9%	0.7%
D/S Salsipuedes	1,274						
Peak Q		4.8%	1.5%	1.8%	0.9%	1.0%	0.9%
3-Day Avg. Q		3.2%	2.0%	1.5%	1.1%	1.0%	0.8%

b) HEC-RAS

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
San Benito R.	664						
Peak Q		0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
3-Day Avg. Q		0.0%	0.1%	0.1%	0.0%	0.0%	0.0%
Lake Outlet	505						
Peak Q		9.4%	2.2%	1.4%	1.5%	0.9%	1.0%
3-Day Avg. Q		5.4%	2.7%	2.0%	1.6%	1.5%	1.2%
Chittenden	1,186						
Peak Q		6.7%	2.1%	3.4%	1.9%	2.0%	1.5%
3-Day Avg. Q		4.0%	3.5%	3.3%	2.3%	2.1%	1.6%
D/S Salsipuedes	1,274						
Peak Q		4.8%	1.4%	1.6%	0.9%	1.1%	1.1%
3-Day Avg. Q		3.2%	2.0%	1.5%	1.2%	1.1%	0.9%

From Table 3-9, it is evident that even if all current agricultural uses in the watershed were converted to row crops under poor hydrologic conditions the changes in peak discharge and 3-day discharge for the 50-year to 200-year return periods is well under a 2.5% increase from existing conditions in the watershed at the four comparison points. One can therefore conclude that any impact agricultural practices may have on the peak and 3-day average discharge would be small.

At the 2-year through 25-year return periods the changes in agricultural practices have a much larger impact, increasing flows up to almost 9.5% at the outlet of Lower Soap Lake. The major impact comes from the Lower Soap Lake watershed that includes agricultural uses in the South Santa Clara Valley, the Hollister Valley, and the Bolsa. Changes in the San Benito River watershed were very small as only a small percent of that watershed is currently used for agriculture.

Sediment Transport Model Scenarios and Results

The scenarios modeled for sediment transport are somewhat different than those modeled with PRO-FLO. The HEC-RAS modeling done for the PRO-SED model yielded very similar peak 100-year discharges at Chittenden for three of the four scenarios and the existing discharge (Table 3-10). The similarities in peak discharges and hydrographs for the different scenarios would create nearly identical results within the PRO-SED models and little benefit would be gained. For this reason, additional scenarios with direct relevance to the issues being studied for the PRWS have been developed and are described in the following section.

Table 3-10: Modeled peak 100-year flood discharges at Chittenden. The General Plan Buildout, Ultimate Buildout, and Changes in Agriculture discharges are too similar to the existing discharges to be considered distinct.

	Chittenden Peak Discharge (cfs)	
Condition	HEC-RAS	HEC-1
Existing	42,501	44,627
Back in Time to 1947	47,103	50,200
General Plan Buildout	43,151	45,210
Ultimate Buildout in 2050	43,675	45,659
Changes in Agriculture	42,921	44,956

Model Scenarios

Conditions that can be modeled must be based on available inputs to the model. PRO-FLO uses land use as an input while PRO-SED uses streamflow data, hydraulic roughness, and sediment data. The four conditions modeled with PRO-SED are variations of those inputs, the results of the model runs giving a good picture of what affects sediment transport.

Although the others have similar peak discharges, important lessons can be learned from the Back in Time to 1947 condition described in previous sections. The PRO-FLO hydrographs for the Back in Time scenarios can be considered distinct. Modeling these conditions will show how streamflow affects sediment transport, deposition, and scour.

An additional scenario was constructed by altering the existing condition model to examine the possible impact of additional shrubby vegetation growth in the channel. Increasing the value for hydraulic roughness (Manning's n-value) in the model simulated the addition of vegetation. For this scenario channel hydraulic roughness values were increased by 50% over the existing condition model. Flood plain hydraulic roughness was unchanged. In addition to impacting the velocity and water depth in the channel, vegetation will also mechanically trap coarse sediment and reduce flow velocities at the sediment-water interface on the channel bed. Although these mechanisms increase sedimentation, they are not accounted for in the model. Therefore, actual sediment deposition in the channel could be greater than simulated.

Changes in the inflowing sediment load can result from changes in upstream land use, instream gravel mining, incision and erosion of upstream channels, and reservoir construction. Current sediment yield estimation does not allow exact estimation of the impact of watershed changes on sediment delivery to the river. It was therefore decided to determine the sensitivity of the model to changes in inflowing sediment load. A 20% change in incoming sediment load in rivers as large as the Pajaro River is considered significant. Therefore, should the model indicate little sensitivity to a change of 20% in incoming sediment load, it would be an indication that the changes in sediment delivery from the upper river sub-watershed would probably have an insignificant effect of riverbed response during extreme flood events. Increasing or decreasing the factor in Equation 2-1 adjusts the amount of sediment entering the modeled reach. For a 20% increase, Equation 2-1 becomes

$$\text{Load} = 0.040 * \text{Qcfs}^{1.56} \qquad \text{Eq. 3-1}$$

And for a 20% decrease, Equation 2-1 becomes

$$\text{Load} = 0.026 * \text{Qcfs}^{1.56} \qquad \text{Eq. 3-2}$$

The conditions modeled with PRO-SED are summarized in Table 3-11.

Table 3-11: Summary of PRO-SED modeled scenarios. Simulation #1 provides a baseline for comparison while simulations #2-5 test the watershed's sediment sensitivity to discharge, hydraulic roughness, and sediment load.

Simulation Number	Hydrograph Scenario	Peak Discharge (cfs)	Hydraulic Roughness	Sediment Input Rating Curve
1	Existing Condition	**42,501**	Existing	Existing
2	Historic Condition	**47,103**	Existing	Existing
3	Existing Condition	42,501	**50% Higher**	Existing
4	Existing Condition	42,501	Existing	**20% Increase**
5	Existing Condition	42,501	Existing	**20% Decrease**

MODEL RESULTS

The five conditions described in the previous section were modeled based on a 100-year storm event which makes the results more meaningful for planning and project design. The following paragraphs summarize the results of Simulations #1-5. TM 1.2.10 contains specific result details for each simulation.

Simulation #1: In the first simulation, current conditions are exposed to a 100-year storm event. Very little net change occurs in the bed profile over the duration of the flood event. Scour and refilling of holes may occur during the event, but cannot be seen at the end of the simulation.

Simulation #2: The increase in peak discharge for this scenario results in an increase in sediment input at the peak of the flood. This results in about 5 inches (0.12 m) of additional bed material deposition in the vicinity of the confluence of Pajaro and San Benito Rivers but along the remainder of the river the changes in bed profile are essentially insignificant and no net change is evident. These results indicate that the change in discharge between the 1947 Condition and the existing condition does not significantly impact sedimentation conditions along the Pajaro River, as long as the sediment yield relationship remains unchanged.

Simulation #3: As might be expected, a 50% increase in hydraulic roughness leads to a greater deposition of sediment due to reduced velocities. The maximum deposition is about 6 inches (0.15 m) while maximum scour is about 10 inches (0.25 m). Most of the additional deposition is in the upstream area of the model with virtually no change in bed material downstream in the vicinity of Watsonville. Over multiple storm events though, the deposition could move further downstream. Growth of in-channel vegetation, which increases hydraulic roughness, would increase sediment deposition.

Simulation #4/5: A 20% increase in sediment load raises the bed elevation about 17 inches (0.43 m) and a 20% decrease lowers the bed by the same amount. Most of the deposition occurs at the upstream end of the model in a single event but could move downstream over multiple events. Scour in the Chittenden area is limited by geologic controls. As the change in riverbed elevation at the upstream end is relatively minor compared to the total increase in sediment load, the absence of change in riverbed elevation over the rest of the model indicates that the sediment transport capacity in the downstream river may be adequate to convey relatively large changes in sediment input to the model.

Conditions Summary

A simple analysis of the hydrologic model results of these four watershed conditions regarding the effects of urbanization, agriculture, and some flood control projects leads to several conclusions. To simplify the results, discharges are grouped by return periods. Floods with a return period of less than 50 years form one group and the other group consists of floods with return periods greater than 50 years. The lessons can be summarized as:

- For 50- to 200-year floods, neither urbanization nor agriculture has a significant impact on runoff
- For 2- to 25-year floods, both urbanization and agriculture have an impact on runoff, but urbanization plays a much larger role
- Since 1947, the addition of three reservoirs significantly reduced the probability of flooding in the lower Pajaro River

These points are developed further in the paragraphs that follow. Please refer to Figures 3-6a through 3-6h at the end of this section for graphical summaries of the model results that support the above lesson summaries. Only the HEC-1 results are plotted here to serve as an example of the watershed change effects due to the similarities in the discharge results between HEC-1 and HEC-RAS,

Agriculture does not affect storm runoff very much in either frequency group. Some slight effects are noticed in the lowest reaches as agriculture becomes one of the dominant land uses proximate to the Pajaro River. The nearly negligible effect, even under the worst conditions, is probably due to the small amount of existing agriculture in the upper reaches of the watershed. It appears that, overall, agricultural effects are not factors in the flooding of the lower Pajaro River.

As discussed earlier, urbanization does not affect runoff from larger storms as much as one might have expected. On the other hand, it does create a significant increase in runoff from the more frequent 2- to 25-year floods. Urbanization has a relatively smaller impact on the larger storms because of the amount of runoff predicted for current conditions. The larger storms currently produce a great deal of runoff since the earth is not able to absorb as much water as is precipitated. The ground quickly becomes saturated once the rain starts falling. Additional urban landscape simply replaces a saturated surface with an impermeable surface. The difference between the sheeting effect of saturated earth and an urban landscape is not significant. Since there is less rain in the more frequent events though, the ground is generally able to absorb a significant portion of the rainfall, reducing the amount available for runoff.

The increases in discharge due to urbanization, while not having a significant impact on future projects, could reduce the level of protection of the existing flood control levees. For example, changing the peak discharge at the Chittenden gage for Ultimate Buildout conditions as shown in Table 3-6a would result in the return period of the 18,000 cfs design capacity being reduced from its current 12-year capacity to an 11-year capacity, which equates to a reduction in protection of approximately 10%. In 1998 the levees were able to contain flows up to 25,000 cfs, flows equivalent to a 25-year flood. The decreased capacity in the Ultimate Buildout scenario again reduces the level of protection by about 10% to 23-years.

In the past, both the cities and area of land dedicated to agriculture were smaller. Based on three of the four scenarios in this study, this would lead one to believe that floods were less frequent in the mid-1900s. The historical scenario shows that this is not the case. The major difference between the Historical and other urban and agricultural scenarios is the lack of dams in 1947. The three large reservoirs, Hernandez, Uvas, and Chesbro, created since 1947 have been shown to be quite effective in reducing discharges of the more frequent events. Hernandez Reservoir has reduced peak discharges across the flood frequency spectrum.

Lessons learned from the sediment model results are much more intuitive. For 100-year flood events, they can be summarized as:

- Reasonable changes in peak discharges, as modeled by PRO-FLO, should not significantly alter sedimentation conditions within the Pajaro River channel.
- Significant growth of shrubby vegetation would be expected to cause an increase in sediment deposition.
- A significant change in sediment load has a relatively minor impact on sedimentation in the Pajaro River except potentially at the confluence with the San Benito River. If the simulated deposition is created due to a boundary condition within the model, the sediment transport capacity of the lower Pajaro River could be adequate to convey relatively large changes in sediment load without significant changes in the deposition pattern.

One of the aspects of the Pajaro River watershed that affects both hydrologic and sediment processes is Soap Lake. As the flood waves travel down both the Pajaro and San Benito Rivers, the Pajaro flow is limited by Chittenden Gap and Lower Soap Lake forms. The water levels at the confluence of the two rivers can therefore be higher than the level in Lower Soap Lake, which causes the current to reverse directions. Not only is this an interesting hydrologic phenomenon, it has impacts on flooding downstream. Flow from the upper Pajaro River is limited by a control that acts as a natural detention pond. Much of the peak discharge must therefore come through the San Benito River based solely on the path of the river. The peak discharge from the upper Pajaro River is attenuated by the formation of Soap Lake. Since the lake diminishes the current as well, there are sediment effects. A great deal of the sediment is able to fall out of the water column since the turbulence is decreased and the detention time is increased. Observations noted in TM 1.2.4 support this theory.

Figure 3-6a

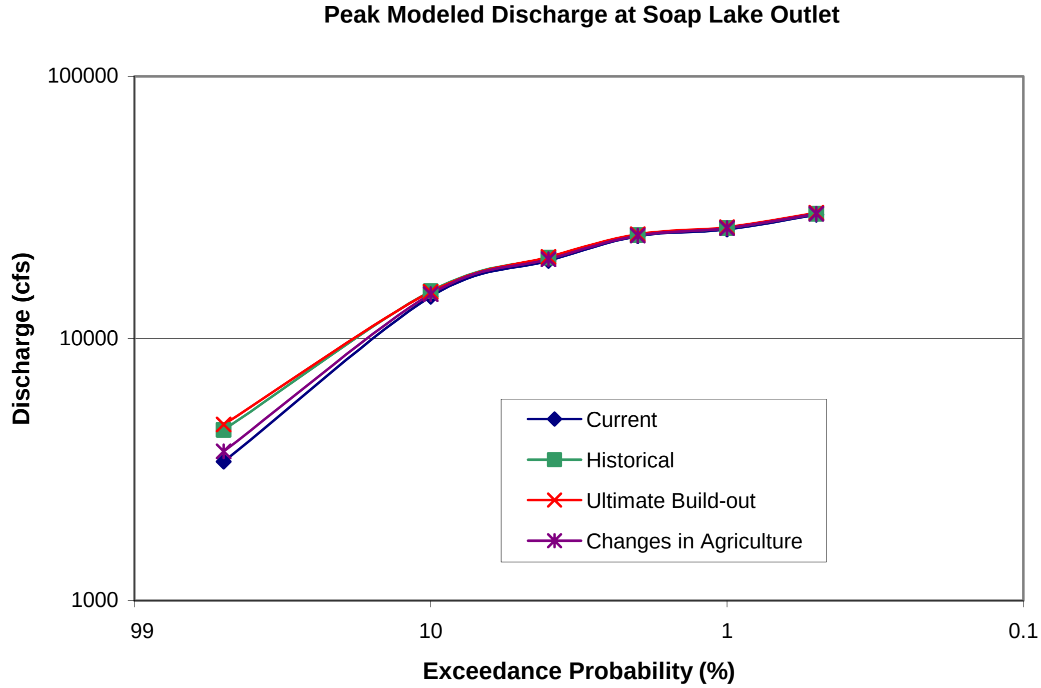


Figure 3-6b

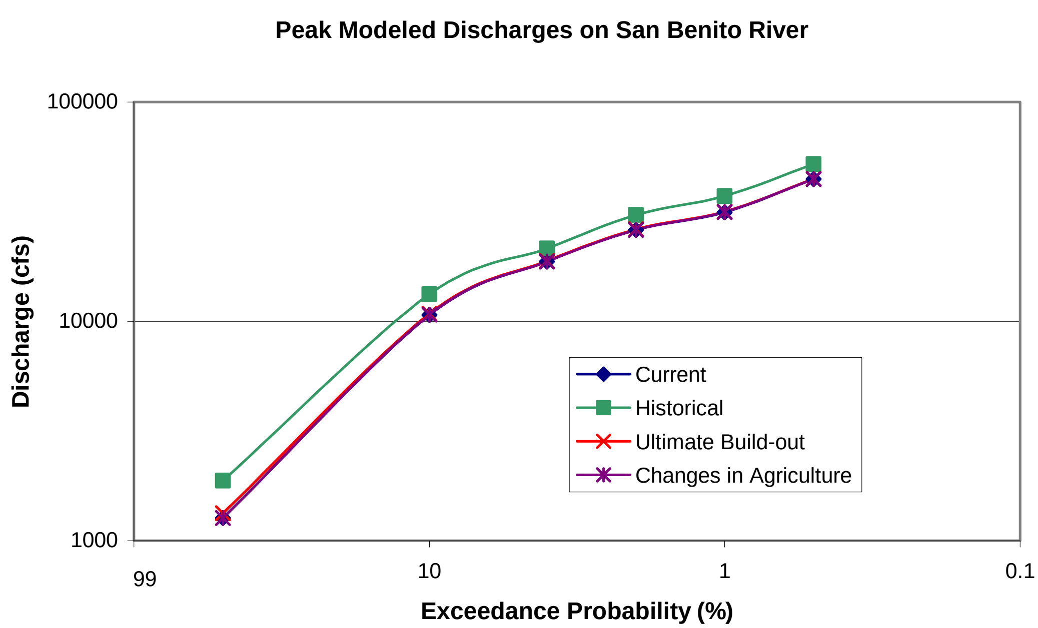


Figure 3-6c

Peak Modeled Discharges at Chittenden

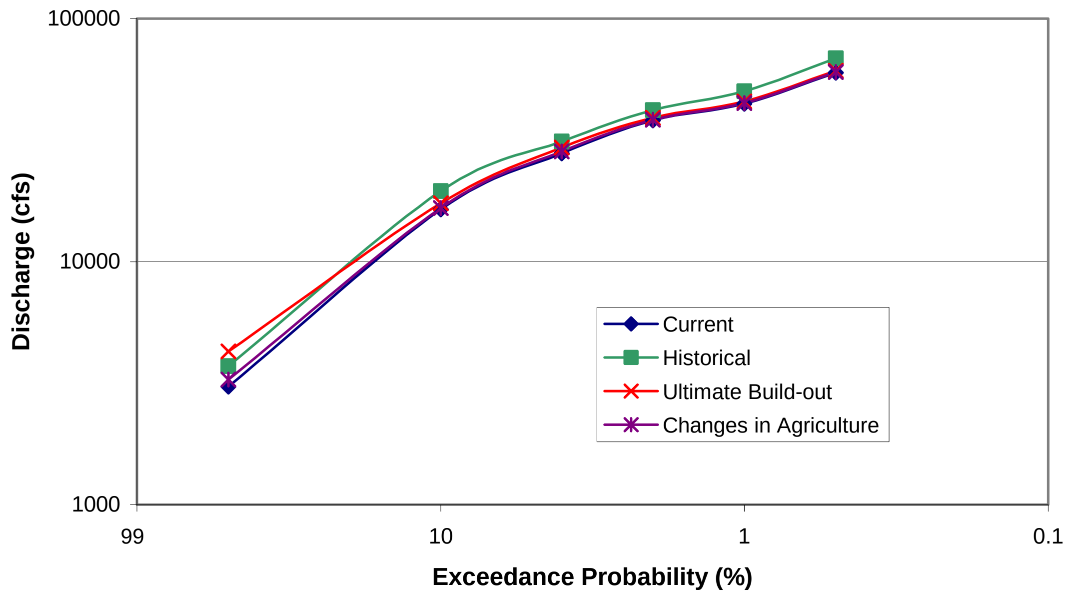


Figure 3-6d

Peak Modeled Discharge Downstream of Salsipuedes Confluence

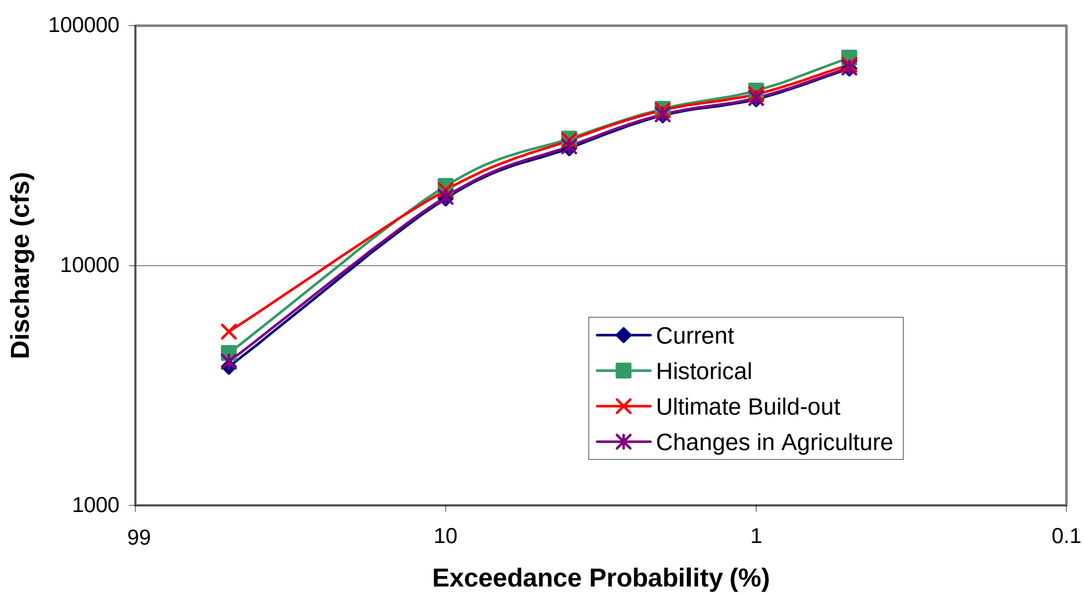


Figure 3-6e

Maximum 3-day Average Discharge at Soap Lake Outlet

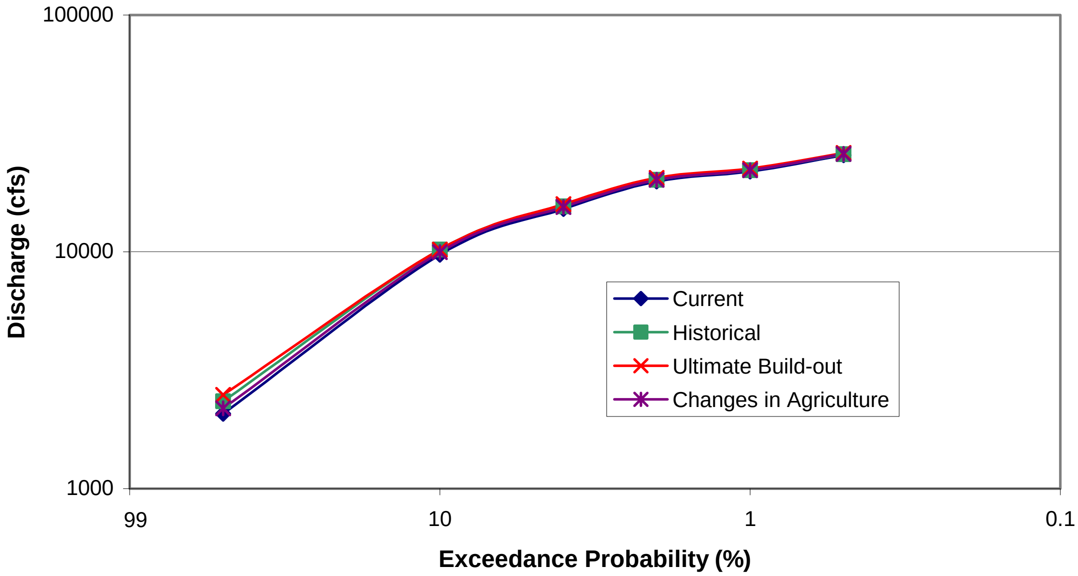


Figure 3-6f

Maximum 3-day Average Discharge on San Benito River

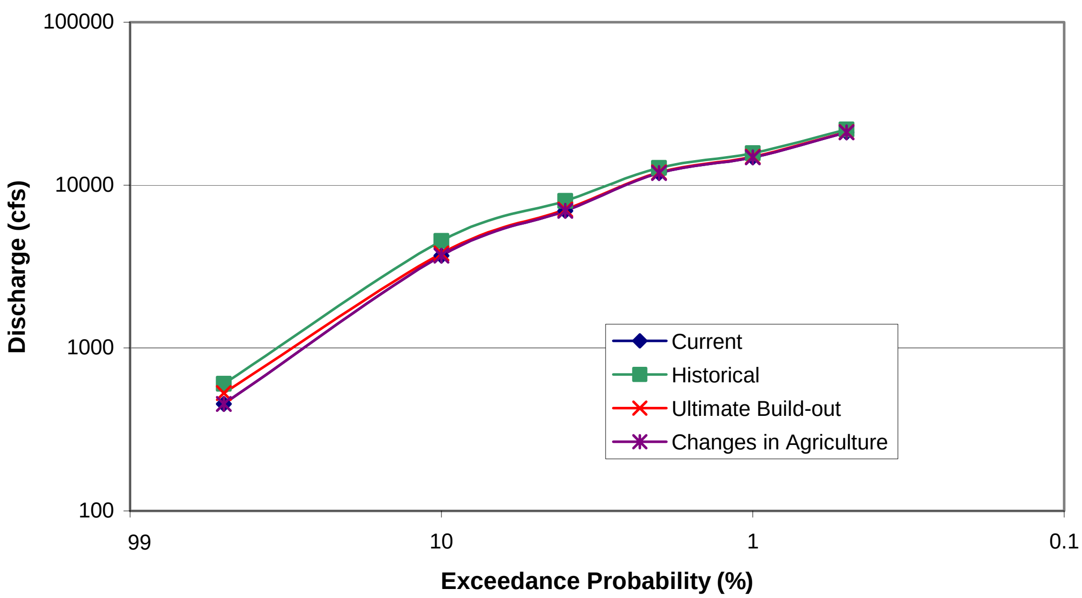


Figure 3-6g

Maximum 3-day Average Modeled Discharge at Chittenden

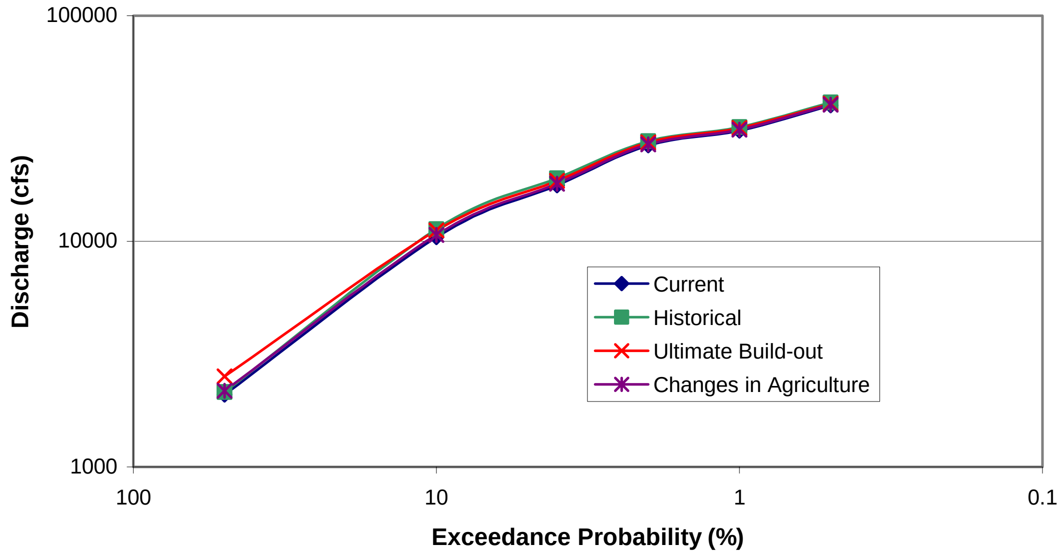
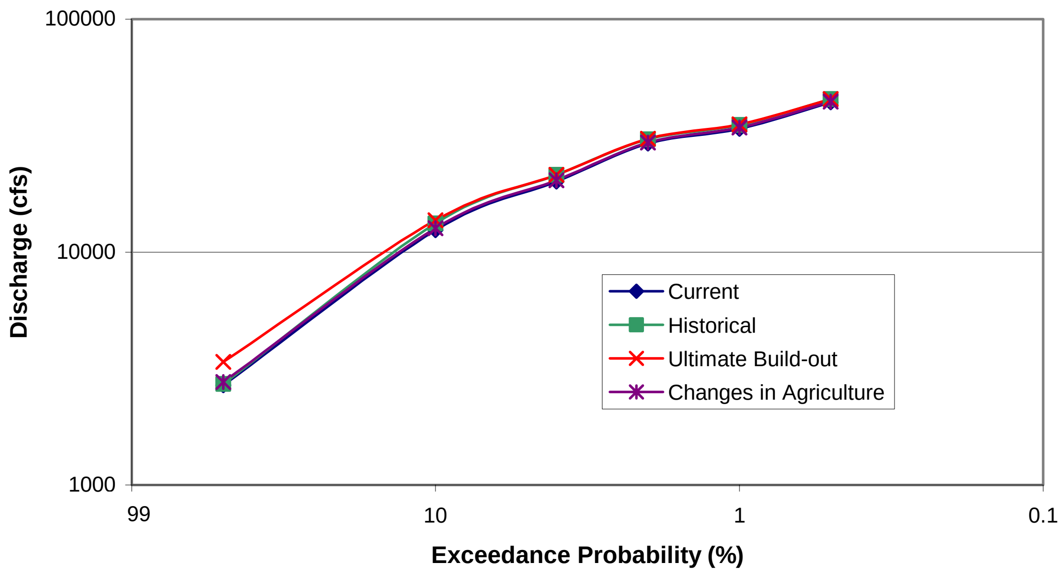


Figure 3-6h

Maximum 3-day Average Discharge Downstream of Salsipuedes Confluence



Phase 1 Conclusions

CHAPTER 4

CHAPTER 4

PHASE 1 CONCLUSIONS

The body of this report has focused on the following items:

- The creation and calibration of a hydrologic model (PRO-FLO) and a sediment transport model (PRO-SED)
- The model results for four watershed conditions

The following sections will highlight the key steps, issues, and conclusions of each of these aspects of Phase 1.

Models

The two models developed in this phase are Pajaro River to the Ocean FLOod model (PRO-FLO) and Pajaro River to the Ocean SEDiment generation and transport model (PRO-SED). PRO-FLO is designed to predict annual maximum peak and 3-day average river discharges at four separate points based on a design storm adjustable to a range of event frequencies. PRO-SED analyzes the impact of sediment changes such as sediment load, gradation, and changes in riverbed properties on the lower Pajaro River. It can also be used to investigate different channel maintenance options. As currently calibrated, both models are more than adequate to meet the goals of Phase 1 of the Pajaro River Watershed Study. They can be further refined however if future phases require a greater degree of accuracy.

The hydrologic model PRO-FLO uses river geometry, rainfall patterns, soil groups, and land use data to represent watershed flooding conditions. Rainfall patterns are used to create a design storm that is representative of storms that have caused flooding in the past and can be applied to the model. The soil groups and land use data are analyzed to yield a runoff indicator known as a curve number. Rainfall will either be absorbed by the earth, be retained and create puddles or ponds, or create runoff. The curve number represents the amount of runoff that could be expected with a given amount of rain. River geometry is used to simulate routings to perform dynamic simulations of flood waves that might impact agricultural or urban land. All of these inputs are used in two software packages, HEC-1 and HEC-RAS, which produce both peak and 3-day average discharges based on various storm frequencies. The model is calibrated based on the timing and magnitude of maximum annual peak flows as well as matching exceedance probability graphs of long-standing USGS stream gages. An analysis of five calibration stations yields a standard error of approximately 20% for peak discharge and 3-day average discharge.

The sediment transport model PRO-SED uses the dynamic modeling results from PRO-FLO, river geometry, and sediment data to produce a variety of outputs. These include sedimentation and scour location and evolution of the river shape over time. The software used for this model, MIKE11, was developed by the Danish Hydraulic Institute and is regarded as one of the best sediment modeling programs available. PRO-SED is calibrated to match HEC-RAS outputs developed within PRO-FLO by adjusting hydraulic roughness, composition and thickness of the active bed layer, the flood plain divide, and the number of cross sections used within the model.

Four Watershed Conditions

Four watershed conditions were designed by the Staff Working Group to better understand the impacts that certain factors had as well as to get a feeling for the range of flood discharges that are possible. Those factors include urbanization, agriculture, and existing flood protection structures. The four watershed conditions, along with a brief discussion of the rationale behind each scenario, can be found below.

1. **Back in Time to 1947**: It is important to be able to compare current and future conditions to those of the past. The year 1947 is significant because it is just before the Army Corps of Engineers' levees were built in 1949 and has similar conditions to when the 1955 flood occurred. In addition, three of the four existing reservoirs and some additional levees were not yet in place in 1947.
2. **General Plan Buildout**: This scenario allows the model to predict the watershed flood potential using the urbanization and land use for each city and county based on the efforts of the individual planning departments. This is the best estimate available for future conditions within the watershed.
3. **Ultimate Buildout in 2050**: This scenario represents a worst-case scenario, in terms of flooding, for urbanization. The model predicts how the watershed responds to unchecked growth in the cities beyond what the general plans allow. The year 2050 is the approximate end of the economic life of a project started at the time of this report.
4. **Changes in Agriculture**: Agriculture can play a large role in the amount of runoff and therefore flooding in an area. This scenario parallels the urbanization scenario and acts as a worst-case agricultural condition.

Flooding Impacts

Several conclusions can be drawn based on the General Plan Buildout, Ultimate Buildout, and Changes in Agriculture scenario model results. One of the most significant and relevant to this study is the impact of land use on flooding. The type of agriculture might impact local runoff but on a watershed scale there is a minimal effect, probably due to the small percentage of agricultural land. Urbanization plays a larger role but for larger storm events, such as the 50- to 200-year storms, land use does not impact the amount of runoff created as much as one might expect. These large storms will saturate the ground quickly, effectively creating an impermeable surface for any additional rain. Therefore, the amount of runoff created by an urban surface or a natural yet saturated surface is nearly the same. For smaller storms, such as 2- to 25-year storms, land use and urbanization plays a more significant role. The discharges from these storms can have environmental effects if not managed properly. Since the storms and discharges are small however, existing downstream flood protection structures should be sufficient to handle any increases due to urbanization within the next 50 years for the 2- to 10-year floods. Existing control structures should be upgraded to protect against future 25-year floods. Overall, land use, either agricultural or urban, does not greatly affect the probability of flooding in the lower Pajaro River, probably since the total area for these two land use groups within the watershed is much smaller than the rural areas.

The Back in Time condition model results seem to contradict the above conclusions. Since there was less urbanization and less agriculture with far fewer row crops, the above conclusions would lead to the prediction that flooding potential was less significant in 1947 than it is now. However, the model results indicate that flooding potential was worse in 1947. The only other significant change in the watershed since 1947 is the addition of three dams, the Hernandez, Uvas, and Chesbro dams. The addition of these dams significantly reduced the peak flows and somewhat reduced the 3-day average volume. For example, Figure 3-6b shows the peak and Figure 3-6f shows the 3-day average discharge on the lower San Benito River. The historical line represents discharges before the Hernandez Dam while the other three are discharges with the Hernandez Dam in place and functioning. Existing runoff detention is key to downstream flood mitigation.

SEDIMENTATION IMPACTS

Sediment transport within the lower Pajaro River was tested using five simulations based on the results of the HEC-RAS model within PRO-FLO. Changes in peak discharge are unlikely to affect sedimentation patterns based on single storms. Larger storms increase the sediment load deposited at the confluence of the Pajaro and San Benito Rivers but yield little change in bed elevation as most of the additional sediment is transported downstream and out of the river reaches.

Growth of vegetation in the river channel could increase sediment deposition in several ways. As discussed earlier, vegetation increases hydraulic roughness. This slows the current, which allows sediment to settle out of the water column. There is also a mechanical trap on the vegetation itself but this is not accounted for in the model. Over time, the amount of sediment in the river channel will likely be significantly higher than what is modeled by PRO-SED. The sediment build-up could lead to increased opportunity for flooding if not controlled.

Changes in sediment load can be caused by many upstream changes. These include changes in land use, instream gravel mining, incision and erosion of upstream channels, and reservoir construction. Model results indicate, however, that the lower Pajaro River is relatively insensitive to changes in sediment load. The river is able to transport significantly more sediment than it is currently carrying without increasing local deposition.

Based on the above sediment model results, the four conditions modeled with PRO-FLO would have had little, if any, impact on sedimentation in the lower Pajaro River.

Both Upper and Lower Soap Lake play significant roles in limiting runoff peak discharge and sediment input to the lower Pajaro River from the upper reaches.

Future Phases
CHAPTER 5

CHAPTER 5

FUTURE PHASES

As discussed earlier, the goal of the first phase of the Pajaro River Watershed Study is to develop tools to model the watershed and gain an understanding of the effects that human processes and projects have had and could continue to have on flooding in the lower Pajaro River reaches. As outlined, the next phases of the study will identify, select, and begin to design projects that will "implement flood prevention and control strategies within the watershed"[11] as well as enhance opportunities for water supply, environmental restoration, groundwater protection, and intergovernmental participation. This section of the report provides a glimpse at some key issues that will arise and identify some preliminary alternatives that have worked in other watersheds with similar problems.

Key Issues

Certain topics and items of concern tend to be common among most projects. These include consensus, coordination with other studies, environmental matters, and funding. At this point in the PRWS, a strong foundation has been laid for most of these matters. For the others, being aware of the concerns and complying with any laws or regulations is the best preparation. Below is a brief description of some of these issues, why they are important, and any work that has been done to minimize their possible effects on the study.

CONSENSUS

One of the keystones of a successful program is being sure that people agree on its value and believe that the best possible projects have been developed. In addition to providing flood protection, the PRWS can produce a product with multiple benefits for individual projects or include several projects in the final designs so that all stakeholders benefit from the study.

Consensus within two groups is important for the PRWS. One is consensus within the Authority. Agency representatives meet at least once a month to discuss progress on the study and answer any questions that arise. With all eight agencies discussing issues of concern and working together, it is possible to arrive at a solution that is both technically feasible and politically friendly.

The other aspect of consensus is the public opinion. Through outreach efforts, it is possible to both educate the public and obtain their input for the study. It is important to learn what matters to the stakeholders since they are the ones who will be directly impacted by any projects or conclusions that come out of the study. The Phase 2 Outreach Plan has details regarding this important aspect of the Pajaro River Watershed Study including developing a graphic identity, outreach meetings, media awareness, and a website.

COORDINATION

Coordination with past, current, and future projects affecting the Pajaro River watershed is crucial to the success of the study. Past projects have identified areas of concern for the local residents and collected a great deal of

[11] Keeley, "Assembly Bill 807: Pajaro River Watershed Flood Prevention Authority Act." October 10, 1999.

data for the watershed. Project alternatives have been identified, as have benefits and drawbacks for each. Current projects are accomplishing the same feats as past projects but are more relevant. Aspects of the study such as project identification and outreach can be combined in order for both projects to be more efficient. Future studies should be able to dovetail with ongoing efforts for this study.

Current relevant projects and studies include:

- Lower Pajaro River Flood Protection Project
- San Luis Reservoir Low Point Improvement Project
- Various Sediment Projects with the Regional Water Quality Control Board
- Pajaro Valley Water Management Agency Water Supply Project
- Llagas Creek Flood Protection Project

Environment

Impacts to the environment are very important considerations when planning any project or developing an area. Threatened and endangered species such as the steelhead trout, the California red-legged frog, the tidewater goby, and the western pond turtle must be protected and their habitats preserved. The PRWS will be in compliance with the Endangered Species Act (ESA). In addition to the ESA and biological environmental impacts, the Clean Water Act must be adhered to as well. For example, the Pajaro River was listed on the 303(d) list as a high priority site for nutrients and Llagas Creek is listed for both nutrients at a high priority and sedimentation at a medium priority. San Benito River was listed on the 1998 list as a medium priority for sedimentation and Hernandez Reservoir was a medium priority for mercury.[12,13]

Funding

At this point, funding for final project design, any construction work, and all follow-up work has yet to be identified. Some money sources that could be applied to this project include:

- Army Corps of Engineers funding through Civil Works program and continuing authorities
- Natural Resources Conservation Service PL-566 program (Watersheds and Flood Prevention)
- FEMA Highway Bridge Rehabilitation and Replacement and T21 programs
- State water bonds

[12] Central Coast Regional Water Quality Control Board. "2002 Revision of the Clean Water Act Section 303(d) List of Water Quality Limits: Section 303(d) List Proposals."
[13] Central Coast Regional Water Quality Control Board. "1998 303(d) List and TMDL Priority Schedule."

Preliminary Projects

Several flood control options have already been identified based on work done in other watersheds. This section identifies the rationale behind each project and the project benefits and drawbacks. Based on physical geography and urban development patterns, the ideas can be divided into two groups.

The following descriptions do not relate any project preference or detailed feasibility study. It is simply a list of ideas that have been used in other places and shown to meet the goals and objectives of this study.

Downstream Projects

The Lower Pajaro River Flood Protection Project has been studying since June of 2001 possible solutions to reduce the threat of flooding in the Watsonville area. It appears that a combination of projects that would maximize stakeholder satisfaction will be the best alternative. The flood protection elements will probably include:

- Some floodwall/levee raise
- Bridge modifications and replacements
- Vegetation management
- Some dredging
- Some set-back onto agricultural land[14]

These options are classic flood protection solutions and have proven to be effective at reducing flood risk. Drawbacks include environmental implications and loss of usable land along the riverbanks.

The PRWS will also consider implementation alternatives for an overflow bypass channel. A reasonable flow for the existing flood protection structures would need to be established. Any excess flow would be diverted into a separate channel. The channel would nearly parallel the river until a point downstream of the flood danger zone where the water would either be reintroduced to the river or flow into the ocean. This project could provide valuable protection and minimizes environmental impacts and loss of land. An open channel bypass does use some agricultural land though and the cost can be high. To eliminate lost agricultural land it is possible to dig a subterranean channel. The excavation cost may make this option prohibitive though.

Upstream Projects

Local detention basins would provide some relief from frequent storm events and mitigate water quality problems such as the sedimentation and erosion caused by those events. Since the impact of the low return period storm is raised significantly by urbanization, it is logical to place these ponds in areas just downstream of urban areas. The basins can be associated with any major stream and can provide other benefits such as ground water recharge. Drawbacks include loss of land that could be used for other purposes and possible loss of habitat.

[14] "Draft Pajaro River Flood Protection Community Planning Process Newsletter". May 2002.

Building on the idea of detention basins, it is also possible to implement regional detention basins. These larger off-stream storage sites provide a greater degree of flood protection due to their larger capacity. As Soap Lake does, they act as natural, temporary reservoirs. The benefits and drawbacks are the same as for the local detention basins but on a larger scale.

As was shown and discussed in previous sections, the upstream dams, Hernandez, Pacheco, Uvas, and Chesbro, have provided a great deal of flood protection. One possibility for additional protection is to increase the capacity of these dams. Some land next to the reservoir would be affected during large storms. Another possibility is to build a new dam. The new dams would not only provide the greatest amount of flood protection but also provide water quality benefits, a possible water supply, groundwater recharge, new wetlands, and recreation. The drawbacks are large however. Usable land is lost, habitat is destroyed, species might be impacted, and the project is very expensive.

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Appendices

APPENDICES

The appendices for this report consist of a digital copy of this report, the executive summary, and eleven technical memoranda written to document progress on the Pajaro River Watershed Study. They can be found in PDF format on the CD attached to this report.

Folder	Filename	Contents
Report	Phase_1_Report.pdf	Complete PRWS Phase 1 Report
	Exec_Summ.pdf	PRWS Phase 1 Executive Summary
	Chapter_1.pdf	Chapter 1
	Chapter_2.pdf	Chapter 2
	Chapter_3.pdf	Chapter 3
	Chapter_4.pdf	Chapter 4
	Chapter_5.pdf	Chapter 5
	Support.pdf	Cover, Table of Contents, Glossary, References, Appendices
TMs	TM_1-2-1.pdf	Basis of Comparison
	TM_1-2-2.pdf	Rainfall Data Analysis
	TM_1-2-3.pdf	Runoff Data Analysis
	TM_1-2-4.pdf	Sediment Data Analysis
	TM_1-2-5.pdf	River Geometry Data Analysis
	TM_1-2-6.pdf	Land Use Data Analysis
	TM_1-2-7.pdf	Hydrologic Model Description
	TM_1-2-8.pdf	Qualitative Sediment Analysis
	TM_1-2-9.pdf	Sediment Model Description
	TM_1-2-10_hydro.pdf	Hydrologic Model Conditions
	TM_1-2-10_sed.pdf	Sediment Model Conditions

Raines, Melton & Carella, Inc. Consulting Engineers/Project Managers *in association with* Schaaf & Wheeler Consulting Civil Engineers

Technical Memorandum No. 1.2.1 – Basis of Comparison

Task:	Basis of Comparison
To:	PRWFPA Staff Working Group
Prepared by:	J. Schaaf
Reviewed by:	R. Raines
Date:	October 8, 2001

Introduction

The purpose of this Technical Memorandum (TM) is to establish the basis upon which Pajaro River watershed conditions will be compared. The basis could be peak discharge or volume of discharge. The staff working group of the Pajaro River Watershed Flood Prevention Authority will be the selector of the basis of comparison for this project. The basis of comparison will allow decision makers to determine which course or courses of action to pursue to improve the level of flood protection to the residents of the Pajaro River valley.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a streamflow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1, the watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by a Corps of Engineers levee project constructed between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at the outlet to Soap Lake – a low-lying area of Santa Clara and San Benito Counties – has a drainage area of approximately 500 square miles.

Previous Hydrologic Reports

Two federal agencies, the US Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA), have been responsible for all previous hydrologic reports. The USACE, San Francisco District, has authored:

Flood Control Survey Report for the Pajaro River, 1942,
Office Report on Standard Project Flood, Pajaro River Basin, 1961
Interim Report for Flood Control, Pajaro River Basin, 1963
Flood Plain Information Report – Uvas-Carnadero Creek, 1973
Flood Plain Information Report - San Felipe Lake and Pacheco Creek, 1973
Flood Plain Information Report - San Benito River, 1974
Flood Plain Information Report – San Felipe Lake Unit 2

FEMA has prepared the following Flood Insurance Study reports in which peak discharges are presented for the Pajaro River and tributary watercourses:

Santa Clara County, 1981
Santa Cruz County, 1986
San Benito County, 1991

The FEMA discharges listed for the 100-year flood have particular meaning for a number of federal agencies and agencies insured or guaranteed by the federal government. These discharges are to be used in planning facilities that use federal monies or for projects that are insured or backed by federal monies. While USACE discharge values art the ones that agency will utilize for analysis, design and construction of flood control projects done under its jurisdiction, the FEMA discharges take on a wider area of jurisdiction because of federal regulations.

Basis of Comparison

The Pajaro River watershed is large and the land uses are varied from dense urban to intensive agricultural to grazing lands to unused acreage. Changes in land use and management plans can affect watershed behavior. To be sure the hydrologic model will address the needs of decision makers and planners, three questions must be addressed: what hydrologic parameters are necessary for comparison, where in the watershed should these parameters be predicted, and at what exceedence frequencies should these parameters be predicted.

Parameters to be used

The most widespread parameter used for comparing changes to watersheds is "the annual instantaneous maximum peak discharge." This is the discharge (rate of flow) in a stream channel and adjoining overbanks that is the greatest value at any time during a water year no matter how long the discharge lasts. A water year is the year ending September 30 and beginning the previous October 1. It is assigned the calendar year corresponding to the September 30 date.

The second most prevalent hydrologic parameter is the volume of flow in the stream. Generally the annual maximum 1-day average discharge value or 3-day average discharge is used in highlighting differences in runoff. For the Pajaro River watershed the annual maximum 3-day average discharge is recommended because the watersheds are generally large and the 1-day average discharge is often reflective of the instantaneous peak discharge.

Two parameters are recommended – instantaneous peak discharge and 3-day average discharge. Both parameters are to be annual maximum values.

Parameters to be predicted

Shown in Table 1 are annual instantaneous maximum peak discharges from two long-term stream gages – one on the San Benito River near the City of Hollister and one on the Pajaro River at Chittenden just upstream of the end of the Corps of Engineers Flood Control project.

The San Benito River near Hollister gage had a drainage area of 586 square miles, while the current gage located at Highway 156 has a drainage area of 607 square miles. The drainage areas at the two gage locations are within 3.5 percent of one another and the combined record can be considered as one continuous record since 1950.

The drainage area at the San Benito stream gage is approximately half of that at the Pajaro River at Chittenden gage.

Data has been collected on the Pajaro River continuously since 1940. The four largest instantaneous peak events shown on Table 1 are in the 1956, 1958, 1995 and 1998 water years.

The ratios for the peak discharges at the Chittenden gage divided by the peak discharges at the San Benito River gage for the four major flood years are:

YEAR – Ratio

1956 – 3.217

1958 – 2.026

1995 – 1.287

1999 – 0.728

Because the ratio of the drainage areas at the gages is approximately 2.0, one might expect that the peak discharges maintain about that same ratio. However, the 1956 event, the Christmas 1955 flood, shows much more of the peak discharge attributable to the Soap Lake portion of the Chittenden gage's drainage area. The April 1958 flood was fairly evenly distributed.

The two most recent floods, the March 1995 flood and the February 1998 flood, had much more of their peak discharge coming from the San Benito River portion of the overall watershed at the Chittenden gage site.

Table 2 shows the average daily discharges on the two rivers for the four largest flood recorded at the Chittenden gage. The ratios of the sum of the average flows for the maximum three consecutive days are shown below:

12/1955	Chittenden 45,300 cfs-days;	San Benito 10,040 cfs-days;	Ratio = 4.512
4/1958	Chittenden 44,480 cfs-days;	San Benito 12,580 cfs-days;	Ratio = 3.536
3/1995	Chittenden 41,120 cfs-days;	San Benito 19,170 cfs-days;	Ratio = 2.145
2/1998	Chittenden 45,800 cfs-days;	San Benito 25,790 cfs-days;	Ratio = 1.776

Interestingly, the maximum consecutive 3-day flow volume was approximately the same for all four major floods on the Pajaro River. The amount of volume contributed by the San Benito River watershed, however, has grown from around a quarter in the 1950's floods to around a half in the 1990's floods. This means that the rest of the 1,186 square mile watershed at the Chittenden gage contributed less volume in the 1990's floods than it did in the 1950's floods.

The instantaneous peak discharge and the maximum average discharge for a three contiguous day period are the two parameters selected as a basis of comparison.

Locations of Parameters

The stream gage data presented in the preceding section indicate that the San Benito River can be an important predictor of what the peak discharge and the volume of flow will be for the lower Pajaro River (that portion downstream of the Chittenden stream gage location.) Thus there needs to be a comparison point located on the river just upstream of the confluence with the Pajaro River – a drainage area of approximately 661 square miles.

A comparison point must also be at the Chittenden gage location. With a drainage area of 1,186 square miles, this point is critical because it is the location of a long-term stream gage record. The flow at this point represents the discharge to the upper portions of the Corps flood control project.

A final upper watershed comparison location will be on the Pajaro River just upstream of US Highway 101. The discharge at this point represents the flow from a drainage area of approximately 500 square miles. It also represents the outflow from what a significant storage area upstream of US Highway 101 in Soap Lake.

A fourth and final comparison point will be on the Pajaro River just downstream of the confluence with Salsipuedes Creek. This flow represents the discharge along the lower portions of the Corps of Engineers flood control project. The drainage area of this point is approximately 1,273 square miles.

These four comparison points are shown in Figure 1.

Frequencies to be used

The frequencies used for comparison purposes should span the hydrologic spectrum of floods. To provide results over this spectrum the following frequencies should be used: 2-, 10-, 25-, 50-, 100- and 200-year return periods.

The frequency given in terms of return period is simply the reciprocal of the annual exceedance probability. For example the 50-year flood has a 2 percent chance of being equaled or exceeded in any given water year. A 2-year flood has a 50 percent chance of being equaled or exceeded in any given water year. The annual exceedance probability is the more correct way to think about risk but the return period concept is more commonly used.

The use of frequency curves is preferred over use of the six annual maximum flood events from 1994 to 1999 because the six flood events only represent the rainfall patterns that occurred and may not give a proper accounting for those patterns, which may occur. The frequency curves have an inherent statistically probable rainfall pattern and depth-duration relationship.

Conclusion

The basis for comparison will be done with a series of eight frequency curves. Four curves will be for instantaneous peak discharge and four for average 3-day discharge. There will be two frequency curves, peak and 3-day discharge, at each of four locations: Pajaro River downstream of Salsipuedes Creek near Watsonville; Pajaro River at Chittenden; Pajaro River upstream of US Highway 101; and the San Benito River at the confluence with the Pajaro River.

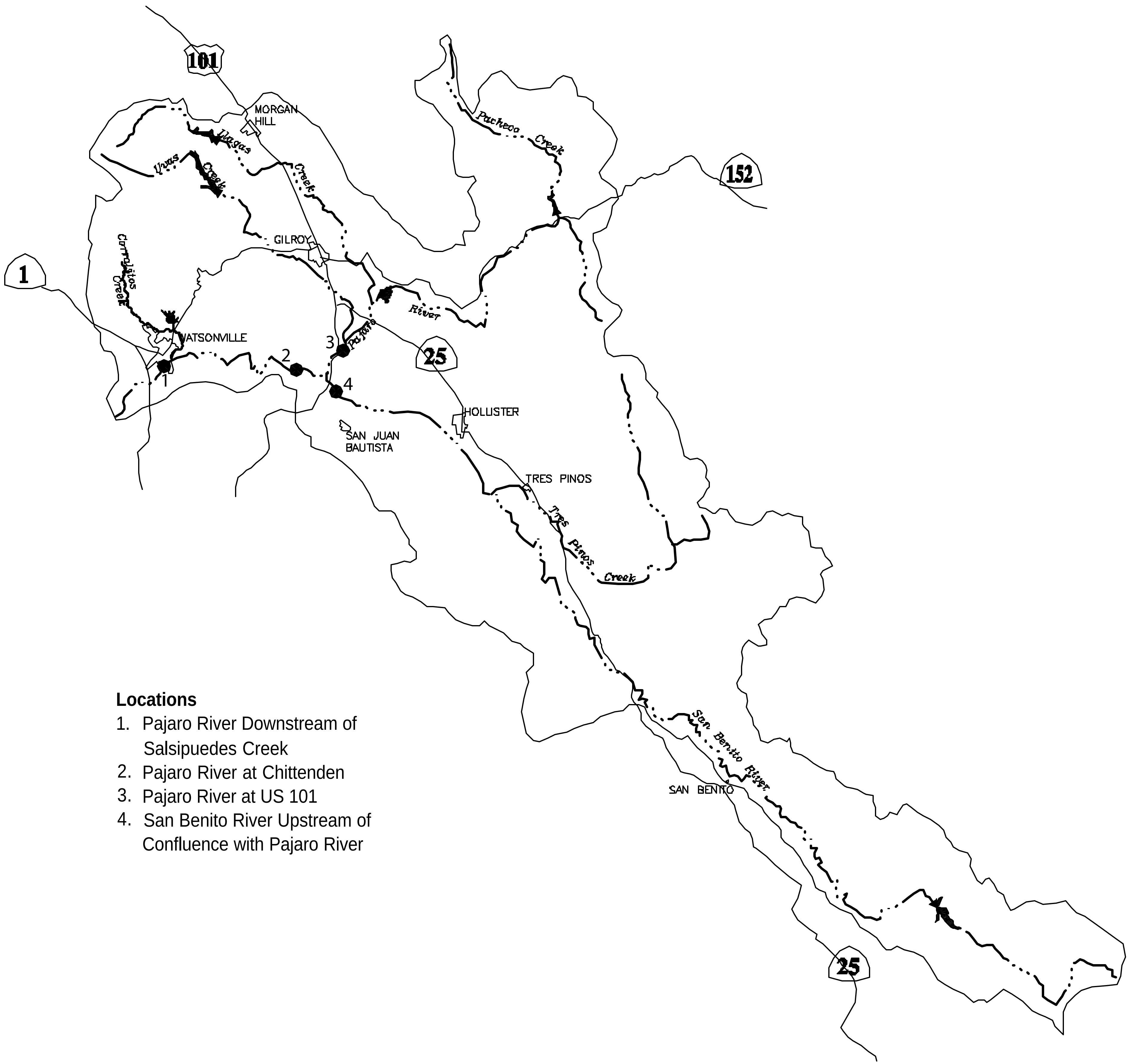
TABLE 1
Annual Maximum Peak Discharges (in cfs)

Water YEAR	Pajaro River @ Chittenden 11159000	San Benito River nr. Hollister 11158500	San Benito River @ Hwy 156 11158600
1940	**9880**		
1941	11100		
1942	5390		
1943	9000		
1944	6080		
1945	10700		
1946	1500		
1947	896		
1948	220		
1949	1980		
1950	**1430**	**108**	
1951	7810	1490	
1952	1000	5490	
1953	2870	835	
1954	682	595	
1955	871	347	
1956	24000	7460	
1957	1110	489	
1958	23500	11600	
1960	**3390**	**1740**	
1960	2880	430	
1961	23	26	
1962	2910	1350	
1963	11600	339	
1964	1480	44	
1965	3300	906	
1966	1320	912	
1967	7720	1900	
1968	205	62	
1969	17800	8900	
1970	**5820**	**1110**	
1971	874	521	514
1972	128	325	300
1973	8610	7400	8030
1974	5400	3970	2080
1975	3230	6880	3430
1976	104	37	49
1977	16	47	0
1978	9420	6190	5460
1979	2130	931	781
1980	**8890**	**3250**	**2550**
1981	2680	142	93
1982	12100	2320	1700
1983	15800	11600	13900
1984	4240		840
1985	1360		103
1986	13100		2930
1987	1870		209
1988	51		33
1989	251		7
1990	**148**		**13**
1991	2960		152
1992	1540		676
1993	6630		1960
1994	600		334
1995	21500		16700
1996	8430		1930
1997	15800		6850
1998	25100		34500
1999	4300		1640

TABLE 2
Average Daily Discharges (in cfs)

Date	(Peak)	Pajaro R. @Chittenden	San Benito R. (Active Gage)
12/22/1955		1210	0
12/23/1955		11500	2870
12/24/1955	pk 24,000	21700	5980
12/25/1955		12100	1190
12/26/1955		4220	600
4/1/1958		5560	2650
4/2/1958		7800	1620
4/3/1958	pk 23,500	19200	7840
4/4/1958		16600	3120
4/5/1958		8680	1540
3/10/1995		8120	6660
3/11/1995	pk 21,500	19400	8030
3/12/1995		13600	4480
3/13/1995		7450	2080
3/14/1995		3590	1410
2/1/1998		952	216
2/2/1998		4280	2120
2/3/1998	pk 25,100	18300	19800
2/4/1998		17300	3870
2/5/1998		10200	550

Figure 1



Locations of Comparisons

Pajaro River Watershed

SCALE: 1" = 40,000'

FILE NAME: RMCI/02/dwgs/Figure1.dwg

Schaaf & Wheeler

Pajaro River Watershed Study

Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers

in association with

Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.2 – RAINFALL

Task: Collection and Analysis of Rainfall Data

To: PRWFPA Staff Working Group

Prepared by: J. Schaaf

Reviewed by: R. Raines

Date: November 13, 2001

Introduction

This Technical Memorandum (TM) deals with the rainfall aspects of the proposed hydrologic model. Rainfall is a necessary input into any hydrologic model. This TM will describe the rainfall data collected in and near the Pajaro River watershed, present precipitation totals and temporal distributions for specific storms from 1994 to 1999, establish statistical relationships for rainfall in the watershed, and show the development of the elements for the design storm to be used as part of the hydrologic model.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a stream flow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1 (previously submitted with TM1.2.1) the watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by a Corps of Engineers levee project constructed between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at the outlet to Soap Lake – a low-lying area of Santa Clara and San Benito Counties – has a drainage area of approximately 500 square miles.

Objectives of this TM

Rainfall data from twenty nine gages (twelve recording and seventeen non-recording) in or near the Pajaro River watershed are reported by the National Weather Service (NWS) and thus are included in the NWS publications and data sets. The Santa Clara Valley Water District (SCVWD) collects data from seven recording gages in and near the watershed. Of those gages six are in the watershed. The locations of all the gages are shown in Figure 2.1.

Given the wealth and yet paucity of rainfall data, the first objective of this TM is to establish a Mean Annual Precipitation (MAP) relationship for the watershed. This relationship is usually in the form of a map showing the watershed area along with accompanying isohyets (in inches) of MAP. MAP will be used to transpose storm amounts from gaged locations to those locations in the watershed, which have no gages.

The second objective is to establish rainfall patterns and depths in the watershed for use by the hydrologic model when calibrating to 1994 to 1999 high water events at the Chittenden stream gage.

The third objective is to establish a design storm for the watershed. TM 1.2.1 (Establish a Basis of Comparison) recommends using frequency curves to form the basis upon which to compare watershed changes. Therefore, a design storm must be established as input to the hydrologic model. The model's predicted runoff from the design storms of various frequencies will then be used to formulate the information needed to enable comparisons of the flood control consequences of selected watershed conditions.

The development of a design storm involves defining five elements:

a transposition mechanism (like MAP),
the duration of the design storm,
a depth versus duration versus frequency relationship,
a drainage area versus rainfall reduction relationship, and
the temporal distribution of the design storm's rainfall depth.

Mean Annual Precipitation

Three existing maps were considered for the MAP map. The first was a San Francisco District US Army Corps of Engineers Normal Annual Precipitation Map with rainfall from 1906 to 1956. The series of three maps which covered the entire San Francisco District's jurisdiction was at an approximate scale of 1" = 8 miles.

The second map was produced by the United States Geological Survey in 1969 and covered the State of California at an approximate scale of 1" = 16 miles.

The final map was from the SCVWD. This map was produced in 1989 and covered much of the Counties of Santa Clara, San Benito, Monterey, Santa Cruz, Alameda, San Mateo, San Francisco, Contra Costa and Marin. The map was produced at an approximate scale of 1" = 4 miles.

As outlined in the October 1989 *Hydrology Open File Report*, the SCVWD used data from 255 recording and non-recording stations to prepare the MAP map. A careful analysis of the data was performed. This included a double mass analysis to ensure consistency between stations.

It is well known that annual rainfall totals in the region vary with elevation. Higher elevations exhibit higher MAP. According to the SCVWD report this orographic effect was considered when drawing the MAP isohyets. The report states that care was taken to conform to general topographic features particularly in areas of sparse recorded rainfall data.

Because the SCVWD map was the most recent it was decided to use this MAP map for future rainfall transpositions needed for this hydrologic model. The MAP map is shown in Figure 2.2.

Using Figure 2.2 it was determined that the overall, area-weighted MAP for the entire watershed is approximately 19 inches.

Rainfall Depths and Patterns 1994 to 1999

Rainfall Depths

The maximum instantaneous peak discharge at the Pajaro River at Chittenden stream gage for water years 1994 to and including 1999 were determined from USGS stream gage records. The rainfall depths from all gages shown in Figure 2.1 were totaled for storms that produced the annual maximum peak discharges on the Pajaro River. Shown in Figures 2.3 to 2.8 are the accumulations of rainfall as a function of time at the recording stations as well as the non-recording stations. The data from recording stations are shown with continuous lines but the non-recording stations are shown as a series of symbols representing the cumulative depth of rainfall after each daily reading of the non-recording gages.

The MAP of each station was estimated and the 3-day and 5-day rainfall totals were normalized to MAP. The results are shown in Table 2.1. Extending the duration to 5 days does not significantly increase the depth of rainfall over that measured in 3 days. Therefore, only the 3-day duration will be used in the remainder of the analysis of the six rainfall events.

Figures 2.9 to 2.14 show isohyets of 72-hour rainfall normalized by MAP for each of the six storm events. It can be readily seen that 1995 and 1998 were much greater storms than the other four and that of the six storms considered, the 1994 and 1999 storms contained the least amounts of rainfall.

Figure 2.15 is a normalized isohyetal map of the December 1955 storm. The isohyets were based on published Corps of Engineers maps showing the isohyets to the north of Hollister. Isohyets in the areas south of Hollister were added to 2.15 by determining the depths that fell in December 1955 at stations in and very near the watershed and normalizing those depths by MAP.

It is quite clear when viewing the normalized rainfall totals that the 1955 storm produced greater depths of rainfall over larger areas of the watershed than did the February 1998 storm or the March 1995 storm. Even though the 1995 and 1998 storms were large they were not as large as the “Christmas storm” of December 1955.

The relationship of normalized storm totals to area covered by the storm is important to quantify because it provides a constraint on just how large flood-producing storms are likely to be in the watershed. This relationship is normally shown as a ratio of rainfall at a point (for instance a rain gage) to rainfall over larger and larger areas. A typical relationship is shown in Figure 2.16 taken from the NWS Precipitation-Frequency Atlas for the Western United States. Note that the shorter the duration the quicker and more rapidly the point rainfall drops off with area. The NWS Depth-Area curve only extends to 400 square miles, an area too small for use in the Pajaro watershed with a total drainage area of approximately 1300 square miles.

Figure 2.17 shows the Corps of Engineers depth-area curve for the December 1955 storm centered in the watershed. The depths are 72-hour maximum depths that have been normalized to MAP. Superimposed on Figure 2.17 are the NWS Depth-Area relationships set to a point value of 53.4 percent so that the curves all can start at the same y-axis value. The overlaying of the curves provides an indication of how rapidly (or how slowly) storm centers have historically dissipated over larger and larger watershed areas.

Figure 2.17 also superimposes the depth-area curves restricted to Pajaro River watershed areas for the 1994 to 1999 storms and the December 1955 storm as shown in Figure 2.15. It is clear that the December 1955 storm was far greater in areal extent than were the storms of 1995 and 1998. It is also clear that the December 1955 storm was centered over only a part of the Pajaro River watershed. Use of the Corps of Engineers depth-area curve for the Pajaro River watershed hydrologic model means that the model will assume that more of the storm is centered in the watershed than actually occurred during the large December 1955 storm

The Corps of Engineers depth-area curve for the 1955 storm will be used as part of the hydrologic model.

Rainfall Patterns

Seventy-two-hour rainfall patterns are shown in Figure 2.18 for the December 1955, March 1995 and February 1998 storms. All three patterns show hourly precipitation as a percent of 72-hour total rainfall. The December 1955 pattern is from Corps of Engineers reports and is based on the December 21 to 24, 1955 rainfall. Hourly depths at three recording stations – Freedom 8NNW, Hollister and Stayton Mine - were averaged to produce this pattern. The rainfall pattern from the April 10 to 12, 1995 storm was recorded at the Hollister 2 recording rain gage. The rainfall pattern from February 1 to 3, 1998 was recorded at the San Benito recording rain gage.

All patterns are similar and any one could be used as a design storm pattern. Since the December 1955 storm has been used so extensively by the Corps of Engineers in all its past work in the watershed, this same pattern will be used as the basis for the design storm for the hydrologic model.

Rainfall Statistics

The SCVWD has produced a set of equations to determine depth of rainfall given the MAP, the duration and the frequency. These equations are shown in *Hydrology Procedures* published in December 1998.

The equation of interest is called the Return Period-Duration-Specific (TDS) Regional Equation. The basic form of the TDS equation is:

$$X_{T,D} = A_{T,D} + B_{T,D}\ MAP$$

where: $X_{T,D}$ = Rainfall depth in inches for a specific return period, T, for a Specific duration, D
$A_{T,D}$ = Equation intercept for return period T and duration D
$B_{T,D}$ = Equation slope for return period T and duration D
MAP = Mean Annual Precipitation

Hydrology Procedures contains tables of slopes and intercepts for durations ranging from 5-minutes to 60-days. The return periods included in the tables are: 2-, 5-, 10-, 25-, 50-, 100-, 200-, 500-, 1000-, and 10000-years.

The TDS equation appears to be useful for the hydrologic model because it uses MAP as an independent variable, a quantity that has been mapped for the Pajaro River watershed.

To determine how well the SCVWD TDS equations fit the rain gage data in the Pajaro River watershed a comparison was made between recorded data and TDS results. Three stations were used for the comparison: Morgan Hill, Hollister 2 and Hernandez 7SE. These three stations were selected because they were recording stations, were well distributed throughout the watershed and varied in MAP from 13 inches at Hollister 2 to 20 inches at Hernandez 7SE and 21 inches at Morgan Hill.

Shorter Durations

Figures 2.19, 2.20 and 2.21 show the 1-, 2-, 3-, and 6-hour rainfall depths measured at the gages and the corresponding predicted depths of rainfall from the TDS equation. The data from the gages was plotted using the Median Plotting Position formula.

As can be seen in the figures, the TDS equation fits the data well. The worst fit is that for the Morgan Hill gage where the data between exceedance probabilities of 10 to 50 percent seem a little high compared to the TDS frequency curve. The SCVWD report contains information on the measure of "the goodness of fit" for the TDS equation. For the 6-hour duration the Standard Error for the 100-year depth (1 percent exceedance probability) is 0.28 inches. This means that the "true" 100-year six-hour depth is within the value predicted by the TDS equation plus or minus 0.28 inches 67 percent of the time. Or it is within plus or minus 0.56 inches 90 percent of the time. The Standard Errors for the 10-year and 2-year depths are 0.31 inches and 0.18 inches respectively. It appears that all data points are within plus or minus one Standard Error for the 6-hour duration.

The comparison between station data and the TDS equation shows that for the shorter durations the equation provides an adequate representation of the frequency response of rainfall in the Pajaro River watershed.

One interesting feature of the TDS equation is that the longer the duration the faster rainfall depths increase with MAP. Referring to Figures 2.20 and 2.21 the 1 percent 1-hour depth only changes from 0.9 to 1.0 inches (an 11 percent increase) as MAP varies from 13 to 20 inches. However, the 6-hour, 1 percent depth changes from 2.1 to 2.8 inches for these two stations (a 33 percent increase) for the same 54 percent increase in MAP. The TDS equation indicates that the variation of rainfall depth is more dependent upon MAP with increasing duration.

Longer Durations

Longer durations were represented by curves for 1-day, 2-day and 3-day rainfall depths. The same three stations were used: Morgan Hill, Hollister 2 and Hernandez 7SE. The TDS frequency curves and the data plotted using the Median Plotting Position formula are shown in Figures 2.22, 2.23 and 2.24.

The Morgan Hill data as shown in Figure 2.22 appear to be under-predicted by the TDS equation. The fit seems much improved when viewing Hollister 2 in Figure 2.23 or Hernandez 7SE in Figure 2.24.

The Standard Error for the 3-day duration for the 100-year return period is 1.79 inches. For the 10-year return period the Standard Error is 1.01 inches. Most, but not all the 3-day depths would fit within plus one Standard Error above the TDS curve. The Morgan Hill data appears to be under-predicted by the equations.

Because the fit of the Morgan Hill data was less than preferred, the test was extended to other recording stations at: San Benito in Figure 2.25, Hollister 9ENE in Figure 2.26, Gilroy 8NE in Figure 2.27 and Sunset State Beach in Figure 2.28. The data fits relatively well with some over-predictions and some under-predictions. Based on the data as a whole the TDS equation fits the longer duration data adequately.

The conclusion, then, is that the SCVWD TDS equation and accompanying coefficients are adequate to determine depth of rainfall as a function of return period (exceedance probability or frequency), duration and MAP.

Design Storm

Duration

The duration of the design storm is 72 hours. The 72-hour duration is used rather than 3 days because the daily values read once a day are always less than or equal to the depths based on 72 consecutive hours regardless of where the midnight hour falls.

Depth-Duration-Frequency

The design storm will use the SCVWD TDS equation and tables of intercepts and slopes to determine depths of rainfall as a function of MAP, duration and frequency (or return period.) This equation was shown to adequately match the frequency plots of data collected for 25 to 50 or so years at rainfall stations in and near the watershed.

Depth-Area Reduction

The depth-area reduction factor will be based on the Corps of Engineers analysis of the December 1955 storm. As the drainage area to any given catch point (i.e. point of interest along the stream network in the watershed) gets larger the storm must be reduced to account for the fact that historic storms have decayed as larger and larger areas are considered. The storms have had centers of higher rainfall surrounded by areas of lower rainfall. For example, Figure 2.29 is a cel from radar images that shows the relative amount of rain that fell during the hour ending at 7 a.m. on February 3, 1998. The storm totals for that hour were greatest just east of the Tres Pinos Creek watershed over the hills in Fresno County. This can be seen in Figure 2.29 by focusing on the area in red where the storm was most intense for that hour. As larger and larger areas are considered in Figure 2.29, it can be seen that the storm totals drop off. This same centering concept will be used in the hydrologic model. As larger and larger drainage areas are considered, the storm will be centered in one location and the Corps of Engineers depth-area relationship as shown in Figure 2.17 will be used to adjust the rainfall depths to reflect the historic centering of large storms in the watershed.

Pattern

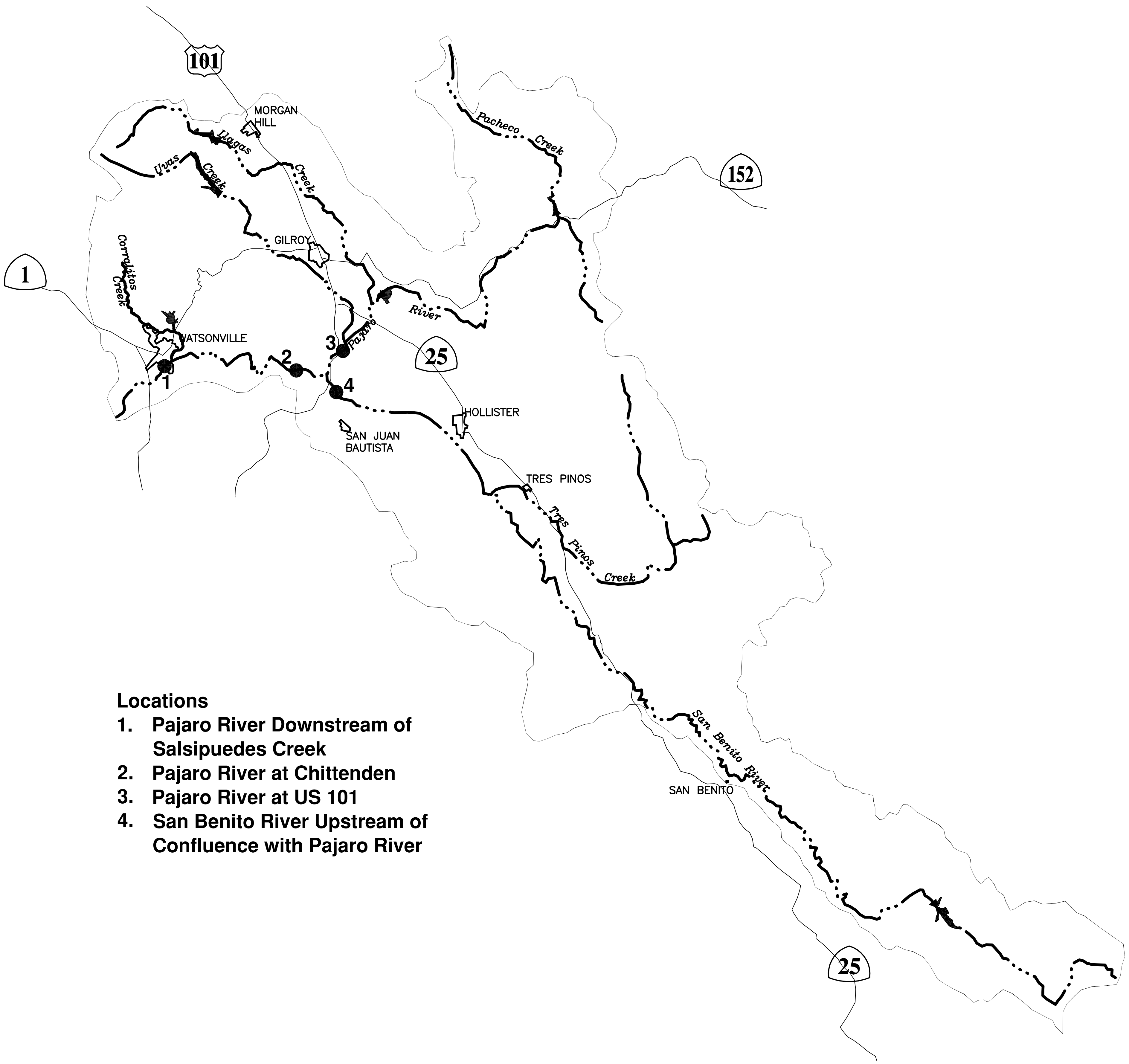
The December 1955 storm pattern is to be used for the temporal distribution for all designated storm return periods from 2 years to 200 years. However, the pattern will be adjusted so that it reflects the rain gage statistics predicted by the SCVWD TDS equations. Figure 2.30 shows the original 1955 pattern as presented by the Corps of Engineers along with the "balanced" patterns at Hollister 2 (13 inches MAP) and Morgan Hill (21 inches MAP) for the 100-year storm. Balancing is normally done by "rubberbanding" the rainfall patter to fit specified values. In this case the values specified were the percentages of 72-hour rainfall that fell during the following durations: 48, 24, 6 and 3 hours. Depths of rainfall for each duration were predicted by using the SCVWD TDS equations. As can be seen in Figure 2.30 the design pattern is shifted somewhat for the balanced storms. However, the "balanced" storm reflects the rainfall statistics as represented by the SCVWD TDS equations.

Conclusion

A balanced design storm has been developed for the hydrologic model. That storm is 72 hours in duration, uses MAP to predict the depth of rainfall for any frequency storm from the SCVWD TDS equation, uses a pattern based on the December 1955 storm but is "balanced" to reflect probabilities of rainfall depths, and uses the Corps of Engineers December 1955 storm depth-area curve as an areal reduction coefficient for rainfall depth.

Locations of Comparisons

Pajaro River Watershed



Locations

1. **Pajaro River Downstream of Salsipuedes Creek**
2. **Pajaro River at Chittenden**
3. **Pajaro River at US 101**
4. **San Benito River Upstream of Confluence with Pajaro River**

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Figure 2.1

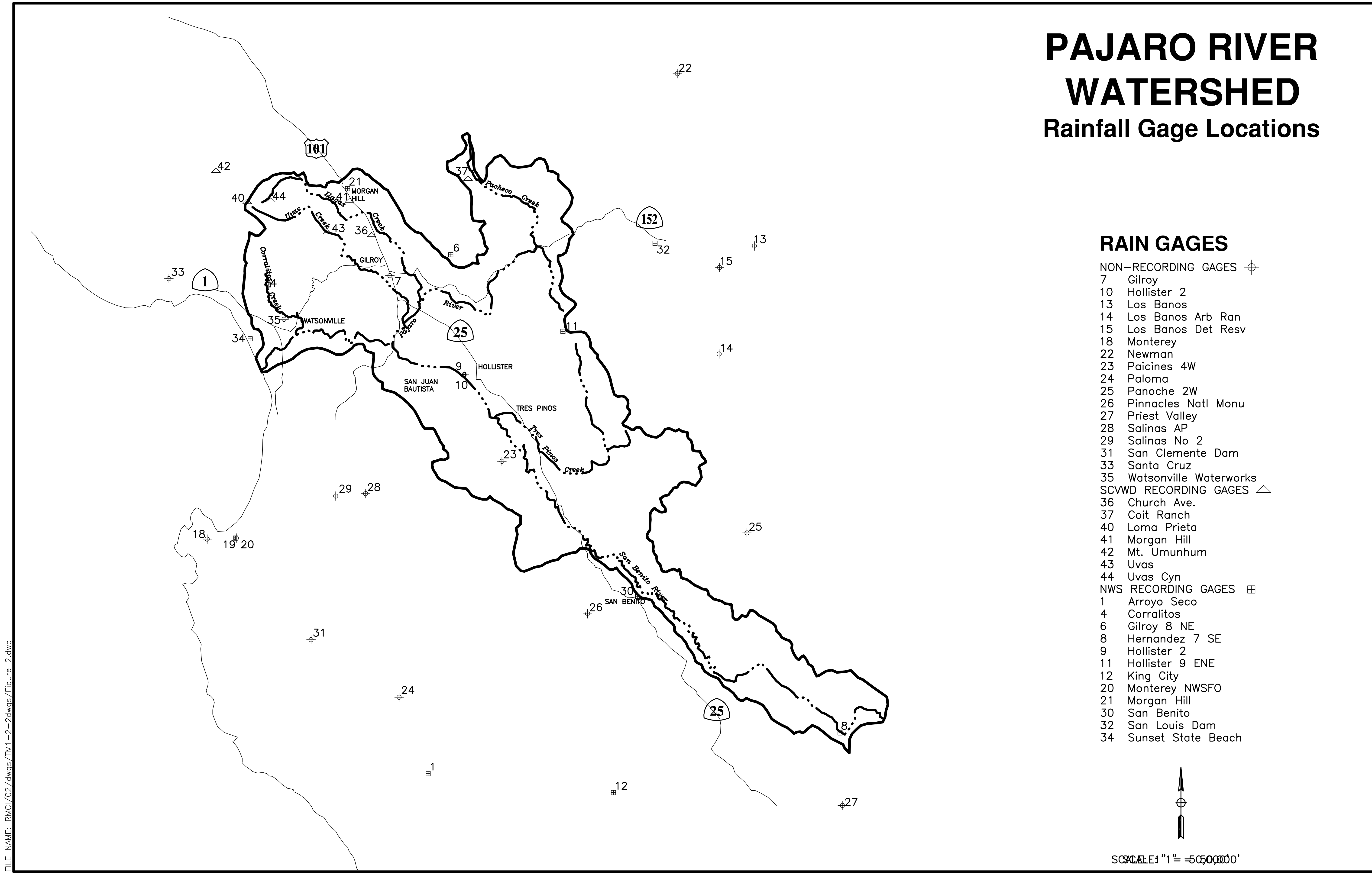

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Figure 2.2

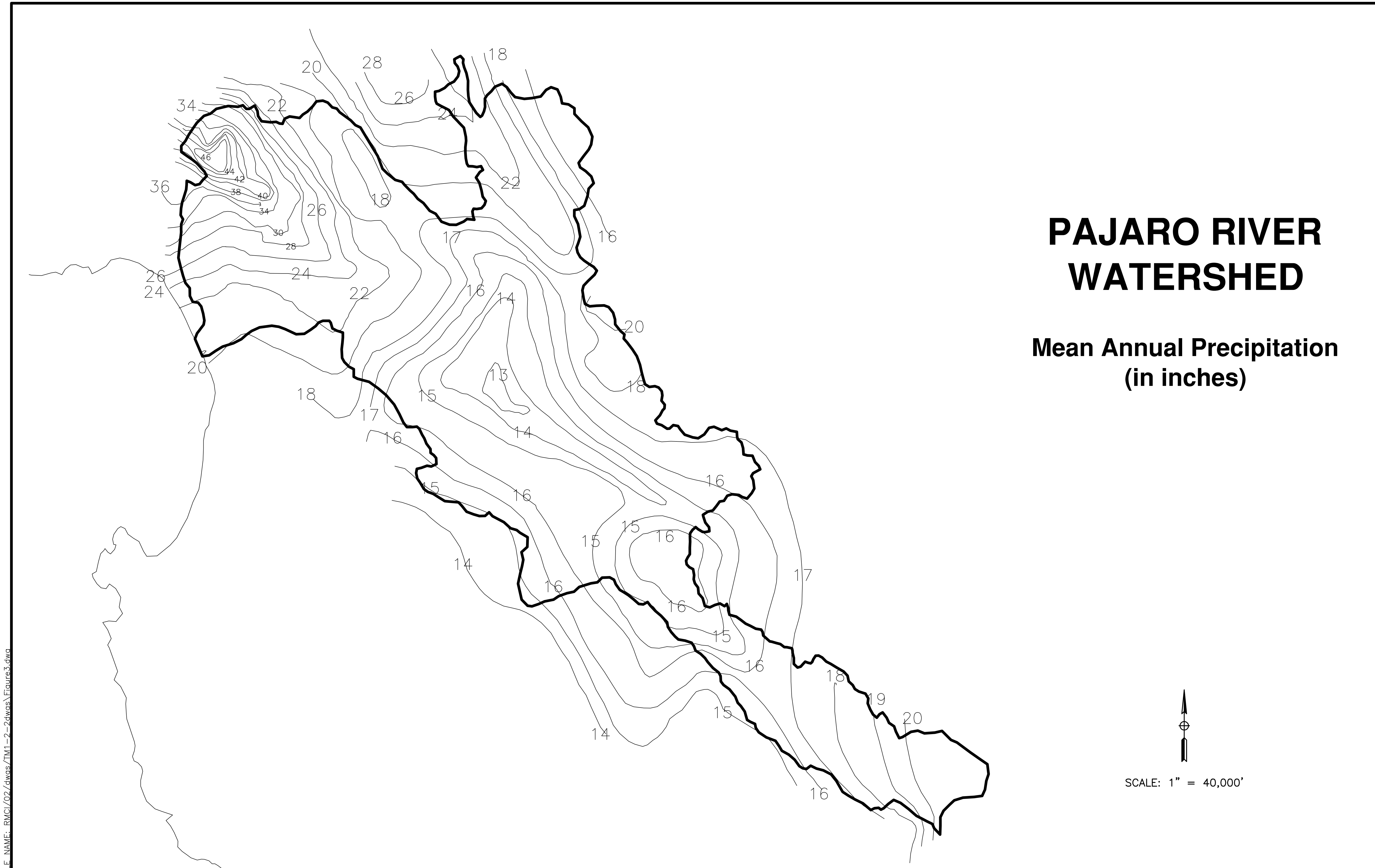
PAJARO RIVER
WATERSHED
Mean Annual Precipitation
(in inches)
SCALE: 1" = 40,000'

Figure 2.3

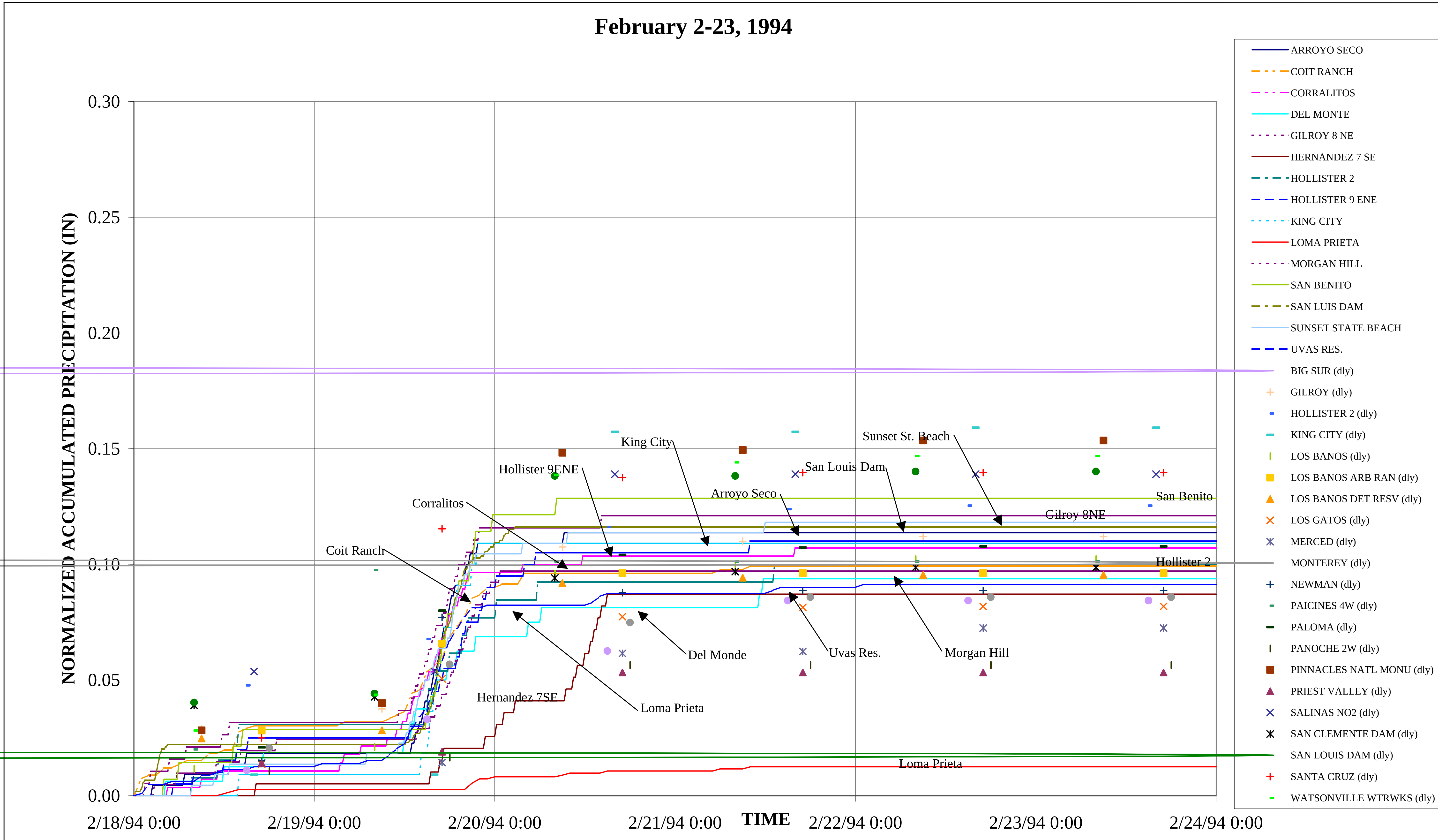

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Figure 2.4

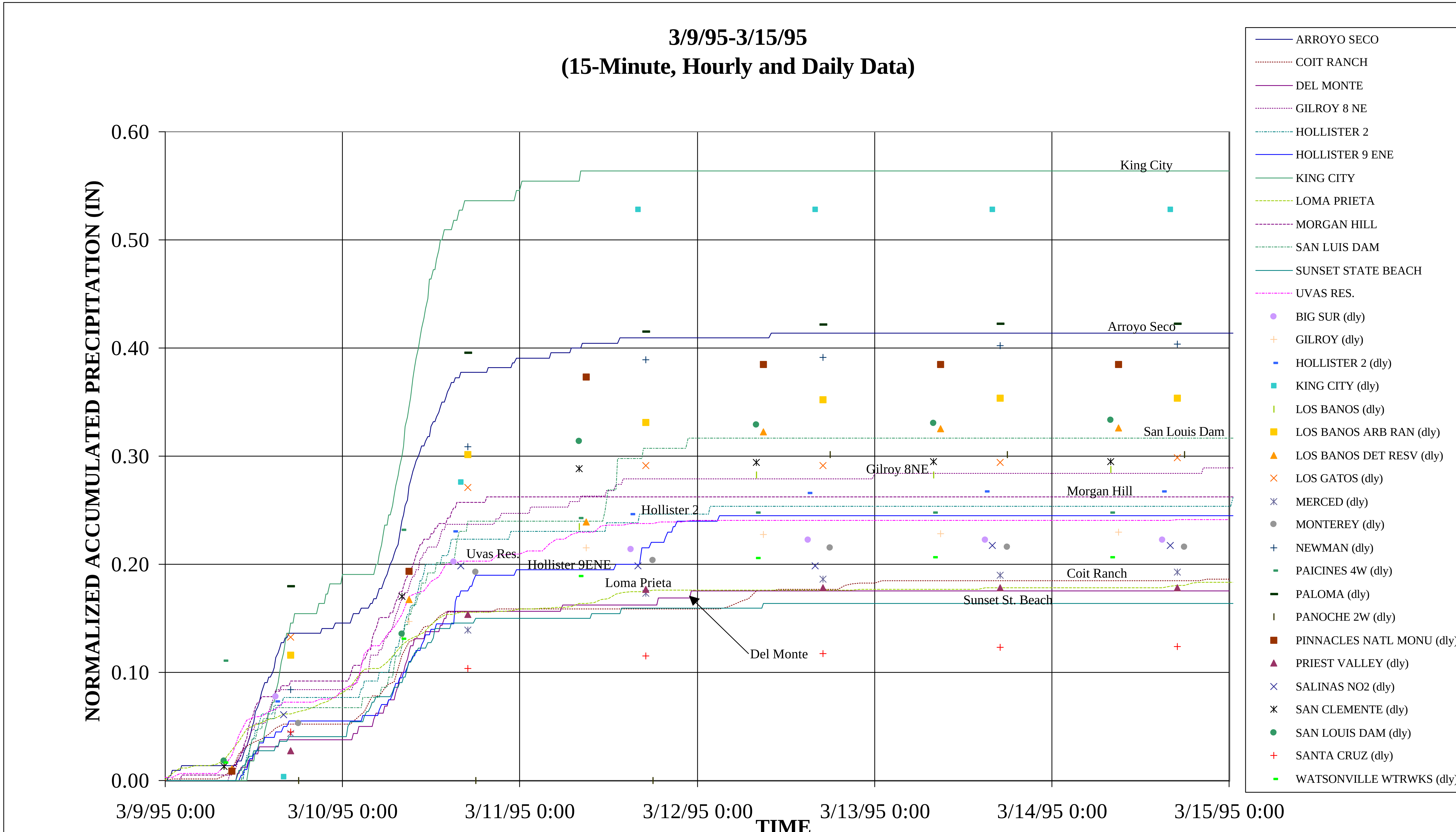

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Figure 2.5

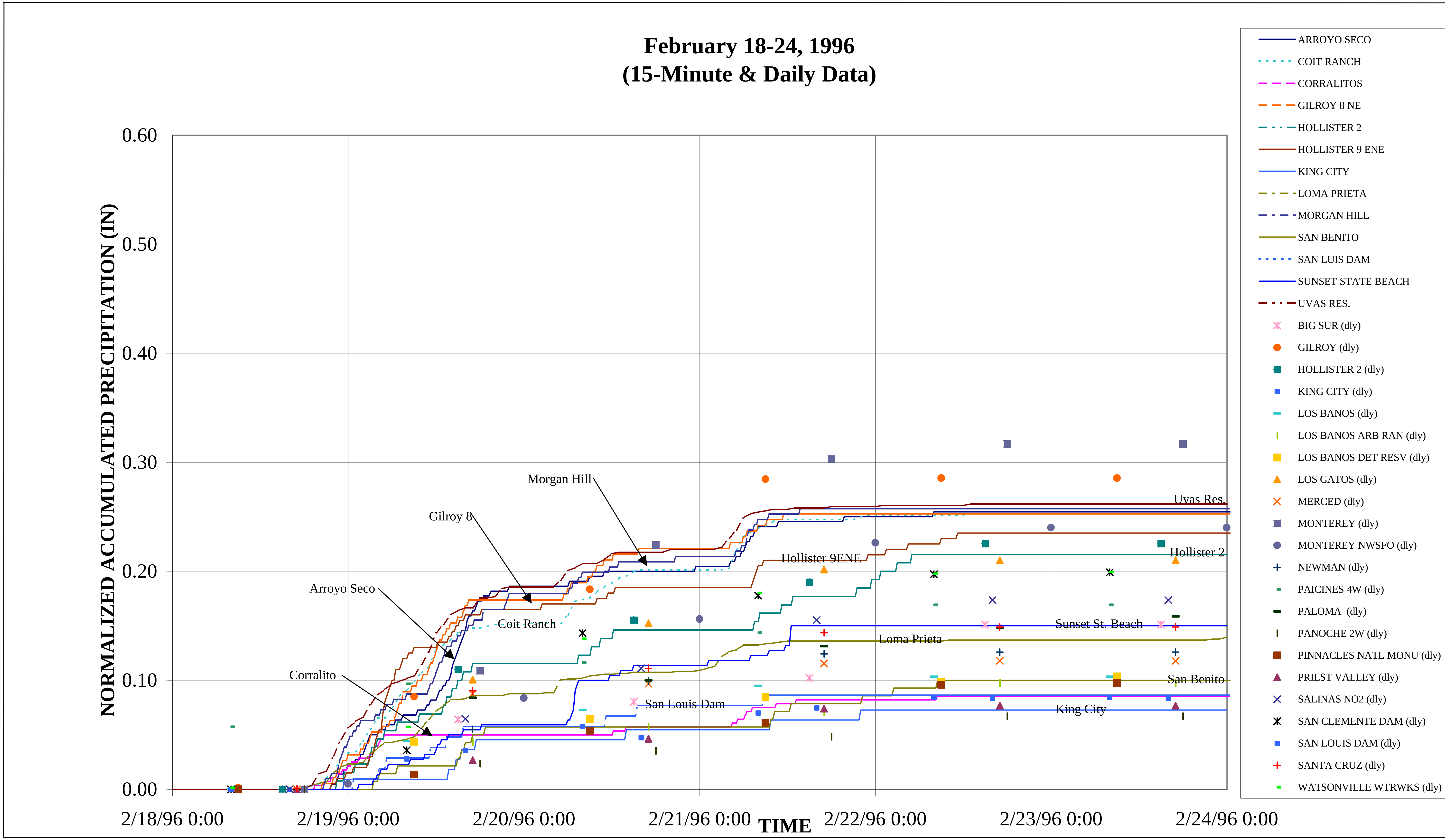

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Figure 2.6

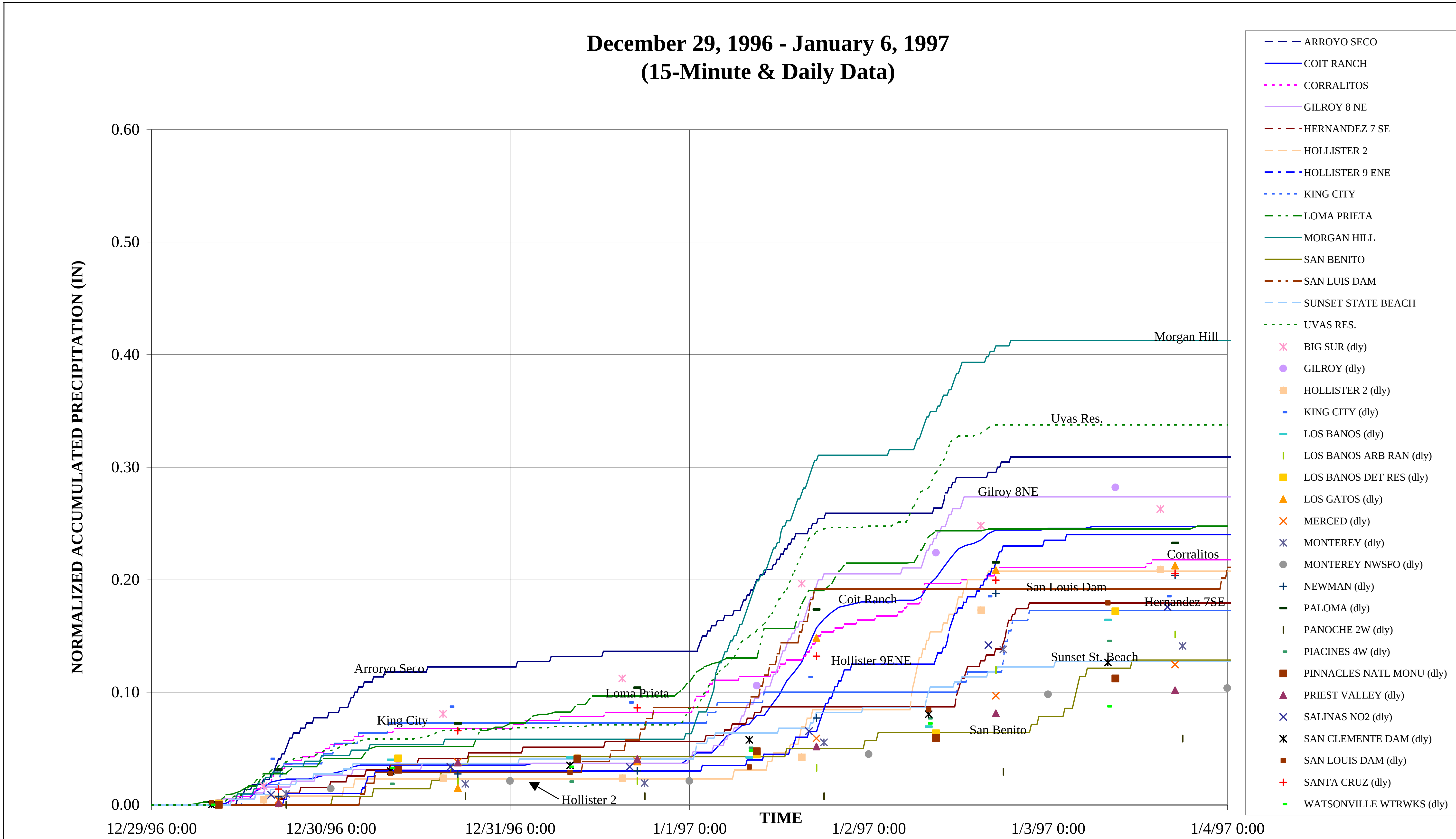

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Figure 2.7

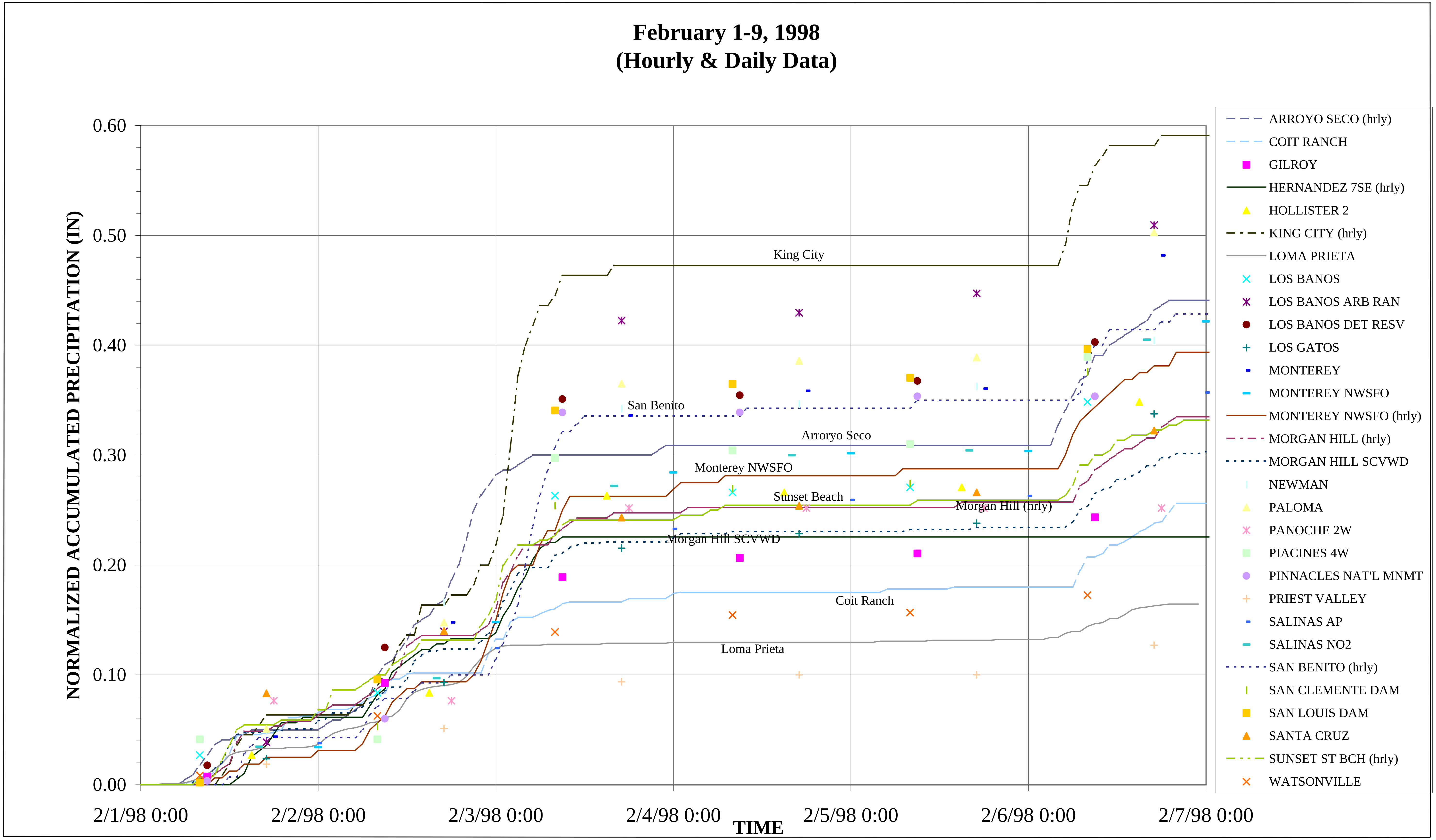

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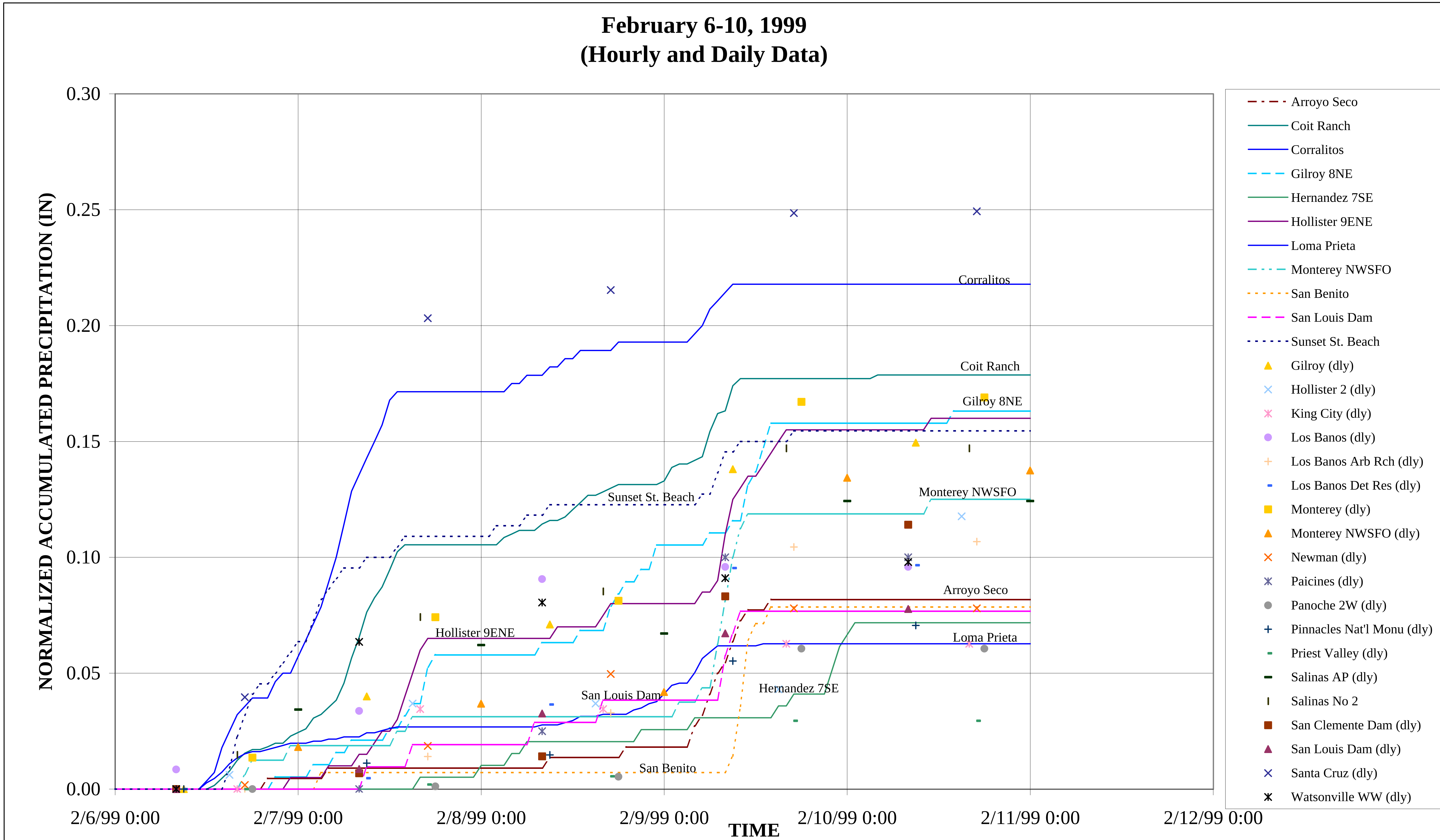
Figure 2.8



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Storm Totals
Normalized by Mean Annual Precipitation

Table 2.1

			3-Day Maxima						5-Day Maxima					
Number	Station Name	M.A.P.	94 Storm	95 Storm	96 Storm	97 Storm	98 Storm	99 Storm	94 Storm	95 Storm	96 Storm	97 Storm	98 Storm	99 Storm
1	Arroyo Seco	22	0.11	0.41	0.20	0.19	0.31	0.08	0.11	0.41	0.25	0.19	0.31	0.08
4	Corralitos	28	0.10	-	0.08	0.14	-	0.22	0.11	-	0.09	0.16	.--	0.22
6	Gilroy 8 NE	19	0.12	0.28	0.25	0.24	-	0.16	0.12	0.28	0.25	0.24	-	0.16
7	Gilroy	20	0.10	0.22	0.18	0.18	0.19	0.08	0.11	0.23	0.29	0.28	0.21	0.15
8	Hernandez 7 SE	20	0.09	-	-	0.13	0.23	0.07	0.09	-	-	0.14	0.23	0.07
9	Hollister 2	13	0.10	0.25	0.16	0.15	0.26	0.04	0.13	0.27	0.23	0.19	0.27	0.12
10	Hollister 2	13	0.09	0.25	0.18	0.18	-	-	0.10	0.25	0.22	0.22	-	-
11	Hollister 9 ENE	20	0.11	0.24	0.21	0.21	-	0.16	0.11	0.25	0.24	0.24	-	0.16
12	King City	11	0.15	0.56	0.06	0.10	0.47	0.03	0.16	0.56	0.08	0.12	0.47	0.06
13	Los Banos	9	0.08	0.23	0.07	0.03	0.30	0.10	0.10	0.28	0.10	0.16	0.34	0.10
14	Los Banos Arb Ran	9	0.09	0.33	0.06	0.11	0.42	0.03	0.10	0.35	0.10	0.15	0.45	0.11
15	Los Banos Det Resv	8	0.08	0.24	0.06	0.02	0.35	0.04	0.10	0.33	0.10	0.17	0.37	0.10
18	Monterey	16	0.06	0.20	0.23	0.12	0.34	0.08	0.09	0.22	0.33	0.14	0.36	0.17
20	Monterey NWSFO	16	-	-	0.21	0.08	0.26	0.12	-	-	0.24	0.08	0.29	0.13
21	Morgan Hill	21	0.10	0.26	0.26	0.35	0.25	-	0.10	0.26	0.26	0.36	0.26	-
22	Newman	11	0.08	0.39	0.10	0.16	0.34	0.05	0.09	0.40	0.13	0.20	0.36	0.08
23	Paicines 4W	16	0.08	0.24	0.10	0.06	0.30	0.03	0.10	0.25	0.17	0.14	0.31	0.10
24	Paloma	22	0.10	0.41	0.10	0.14	0.37	-	0.11	0.42	0.15	0.22	0.39	-
25	Panoche 2w	17	0.05	-	0.04	0.06	0.25	0.00	0.06	0.30	0.07	0.06	0.25	0.06
26	Pinnacles Natl Monu	17	0.14	0.37	0.05	0.06	0.34	0.02	0.15	0.38	0.10	0.11	0.35	0.07
27	Priest Valley	40	0.05	0.18	0.05	0.04	0.09	0.01	0.05	0.18	0.08	0.10	0.10	0.03
28	Salinas AP	14	0.09	0.20	-	-	0.23	0.07	0.09	0.20	-	-	0.26	0.12
29	Salinas No 2	14	0.12	0.20	0.05	0.11	0.21	0.09	0.14	0.22	0.17	0.17	0.30	0.15
30	San Benito	14	0.13	-	0.06	0.11	0.34	0.08	0.13	-	0.10	0.12	0.35	0.08
31	San Clemente Dam	22	0.08	0.29	0.14	0.05	0.25	0.01	0.10	0.30	0.20	0.13	0.27	0.11
32	San Louis Dam	10	0.12	0.32	0.09	0.16	0.34	0.08	0.14	0.32	0.09	0.20	0.37	0.08
33	Santa Cruz	28	0.13	0.12	0.11	0.14	0.24	0.21	0.14	0.12	0.15	0.20	0.27	0.25
34	Sunset State Beach	19	0.11	0.16	0.15	0.09	0.24	0.15	0.12	0.16	0.15	0.11	0.26	0.15
35	Watsonfille Waterwo	22	0.13	0.18	0.14	0.08	0.30	0.15	0.15	0.21	0.20	0.16	0.28	0.18
36	Church Ave Perc. Ponds	20	0.12	0.22	0.20	0.30	0.22	0.10	0.12	0.22	0.24	0.34	0.23	0.11
37	Coit Ranch	26	0.14	0.18	0.22	0.21	0.17	0.15	0.14	0.19	0.25	0.24	0.18	0.18
40	Loma Prieta	44	0.05	0.18	0.12	0.18	0.13	0.04	0.06	0.18	0.14	0.25	0.13	0.04
41	Morgan Hill	22	-	-	-	-	0.23	0.10	-	-	-	-	0.23	0.10
42	Mt. Umunhum	42	0.09	0.33	0.19	0.26	0.18	0.17	0.10	0.38	0.24	0.37	0.20	0.20
43	Uvas	31	0.12	0.24	0.22	0.27	0.13	0.11	0.13	0.26	0.26	0.34	0.13	0.13
44	Uvas Cyn County Park	41	0.13	0.24	0.21	0.25	0.17	0.14	0.14	0.28	0.26	0.37	0.20	0.16

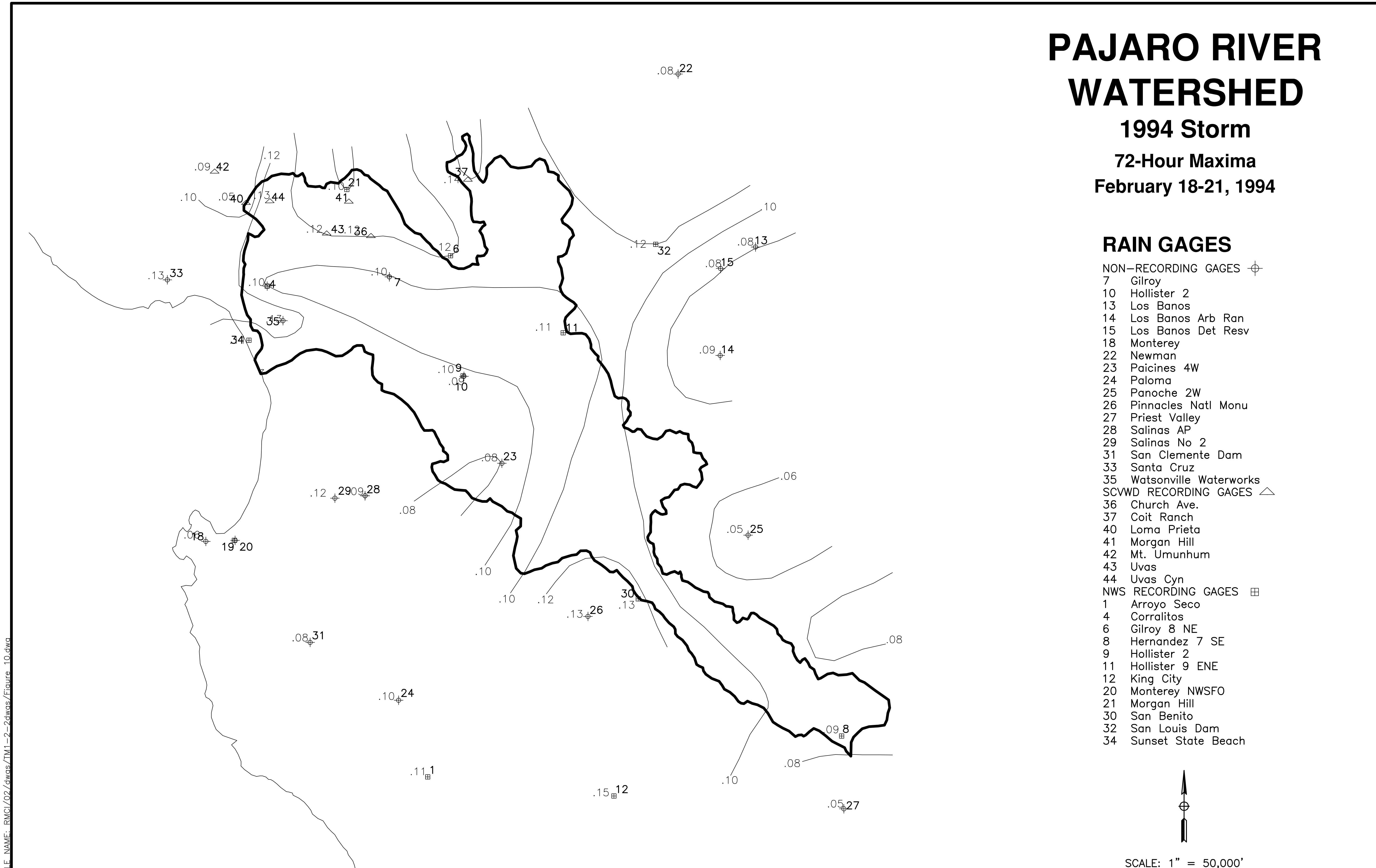

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Figure 2.10

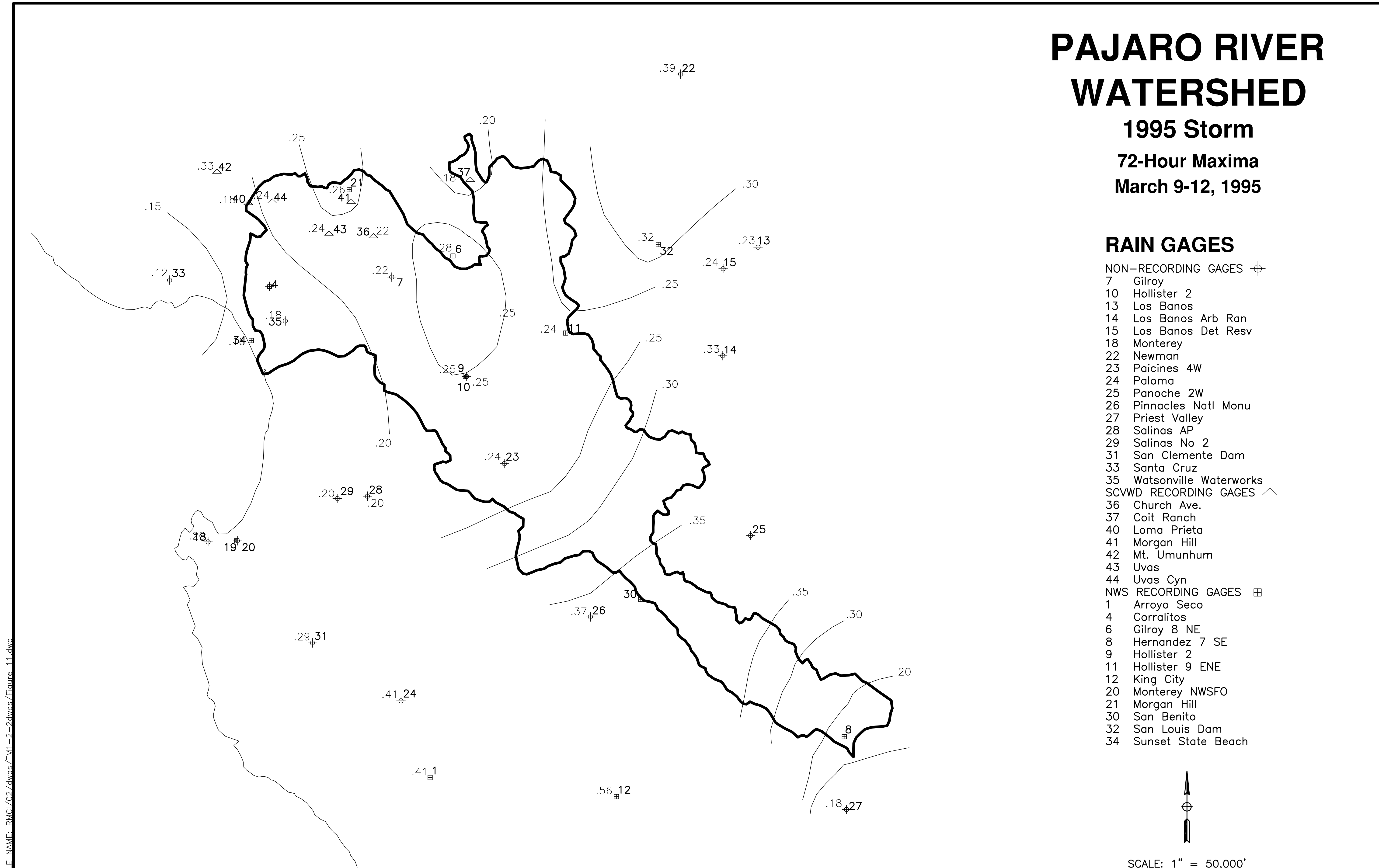

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Figure 2.11

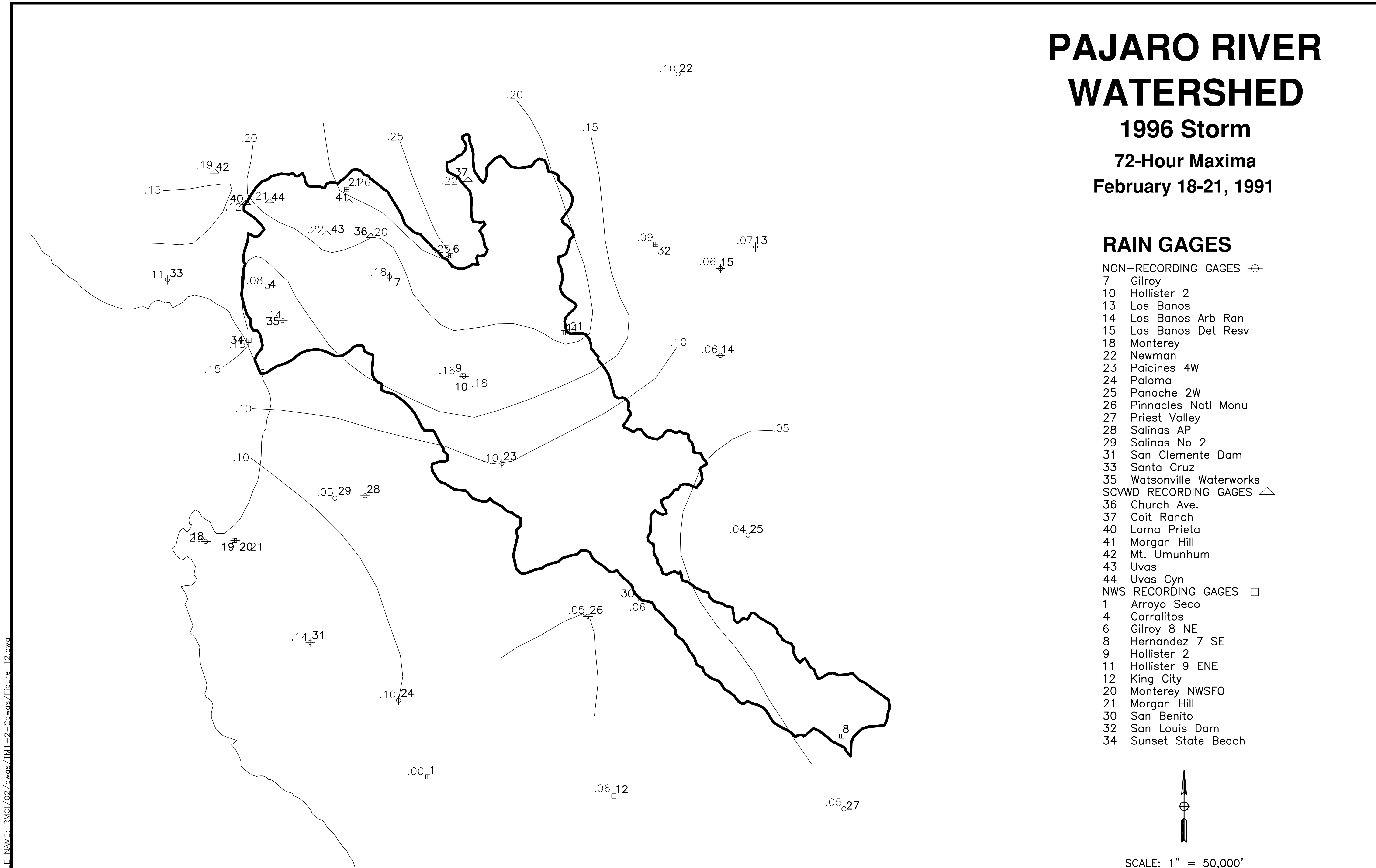

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Figure 2.12

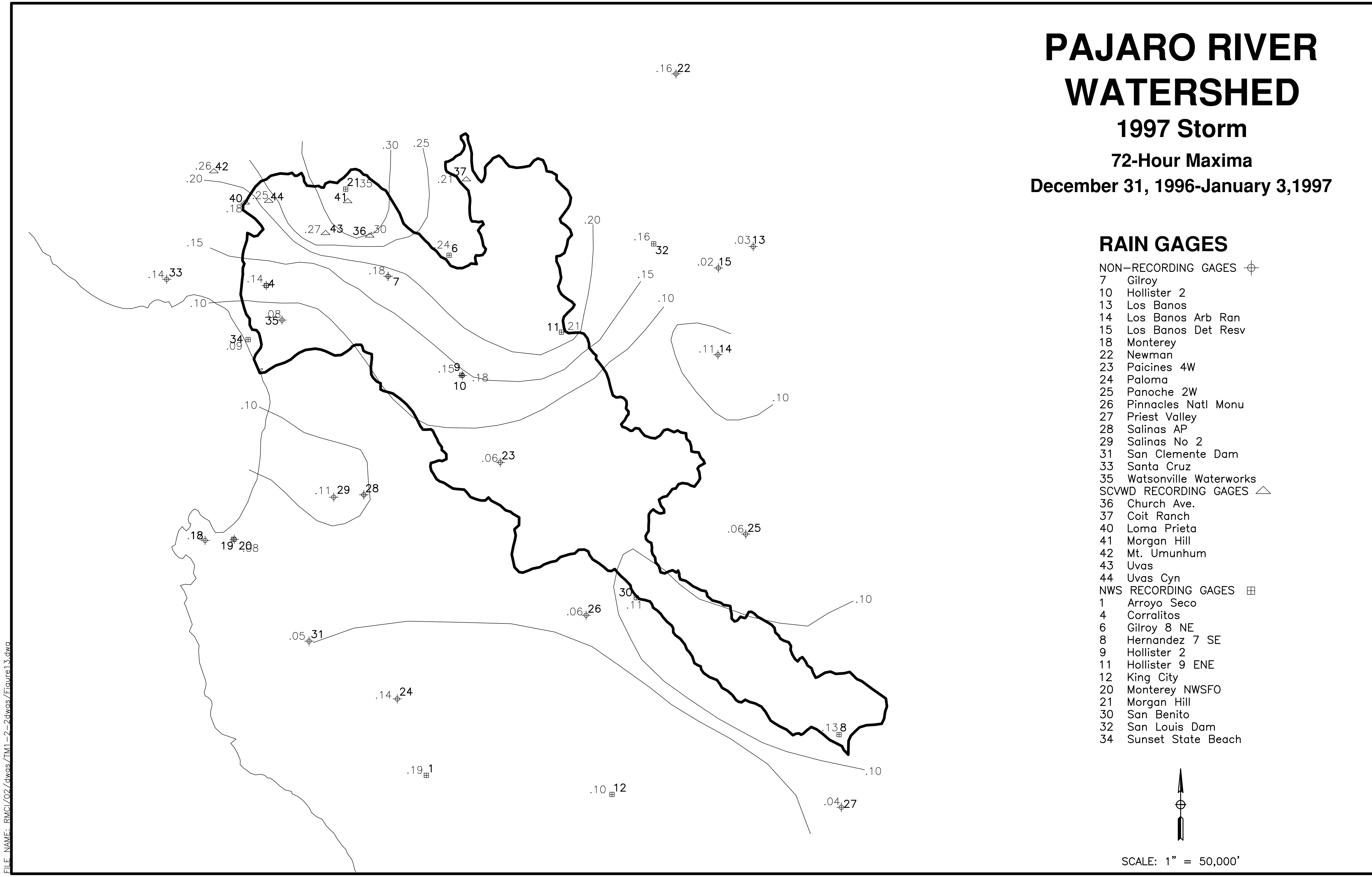

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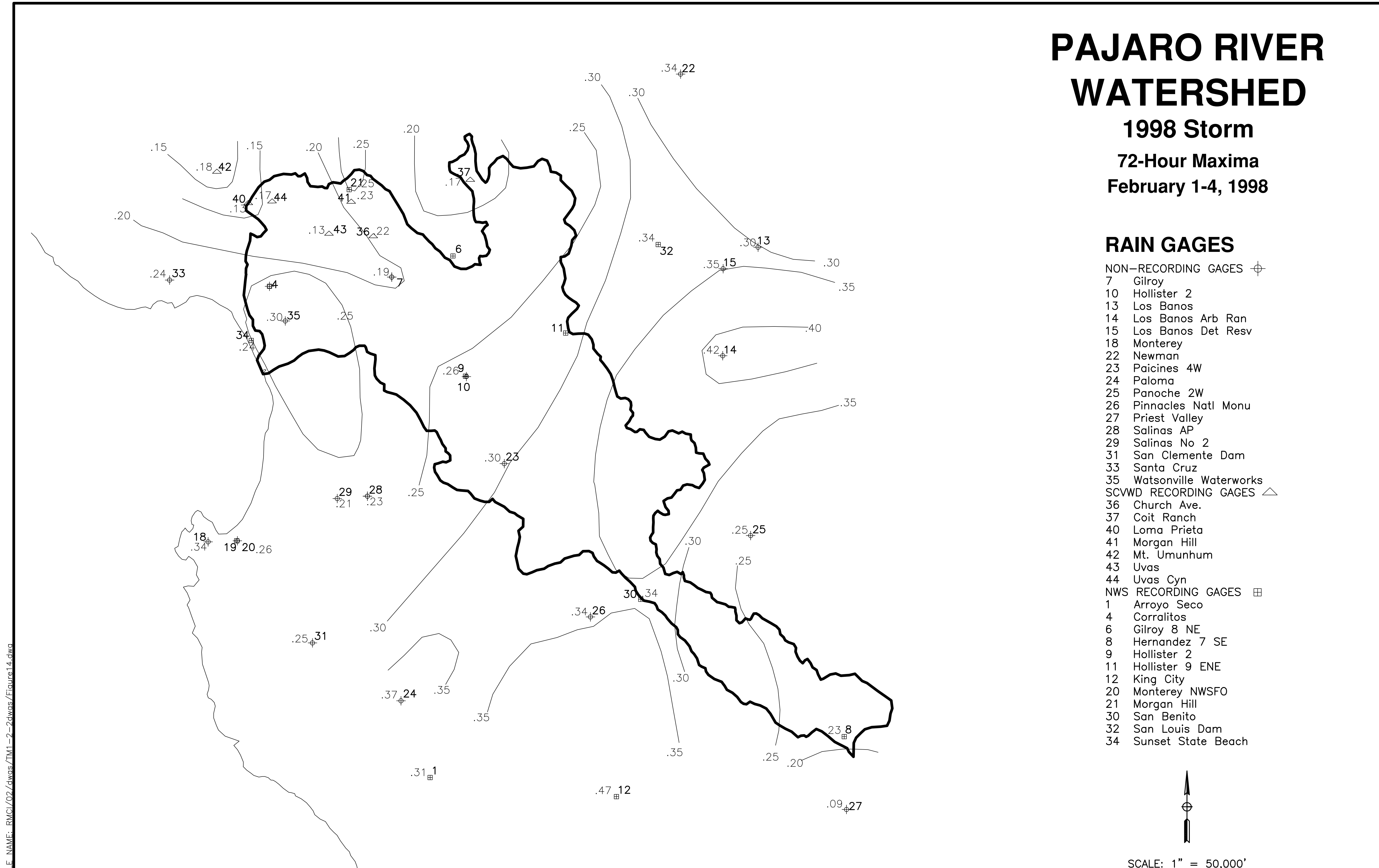
Figure 2.13



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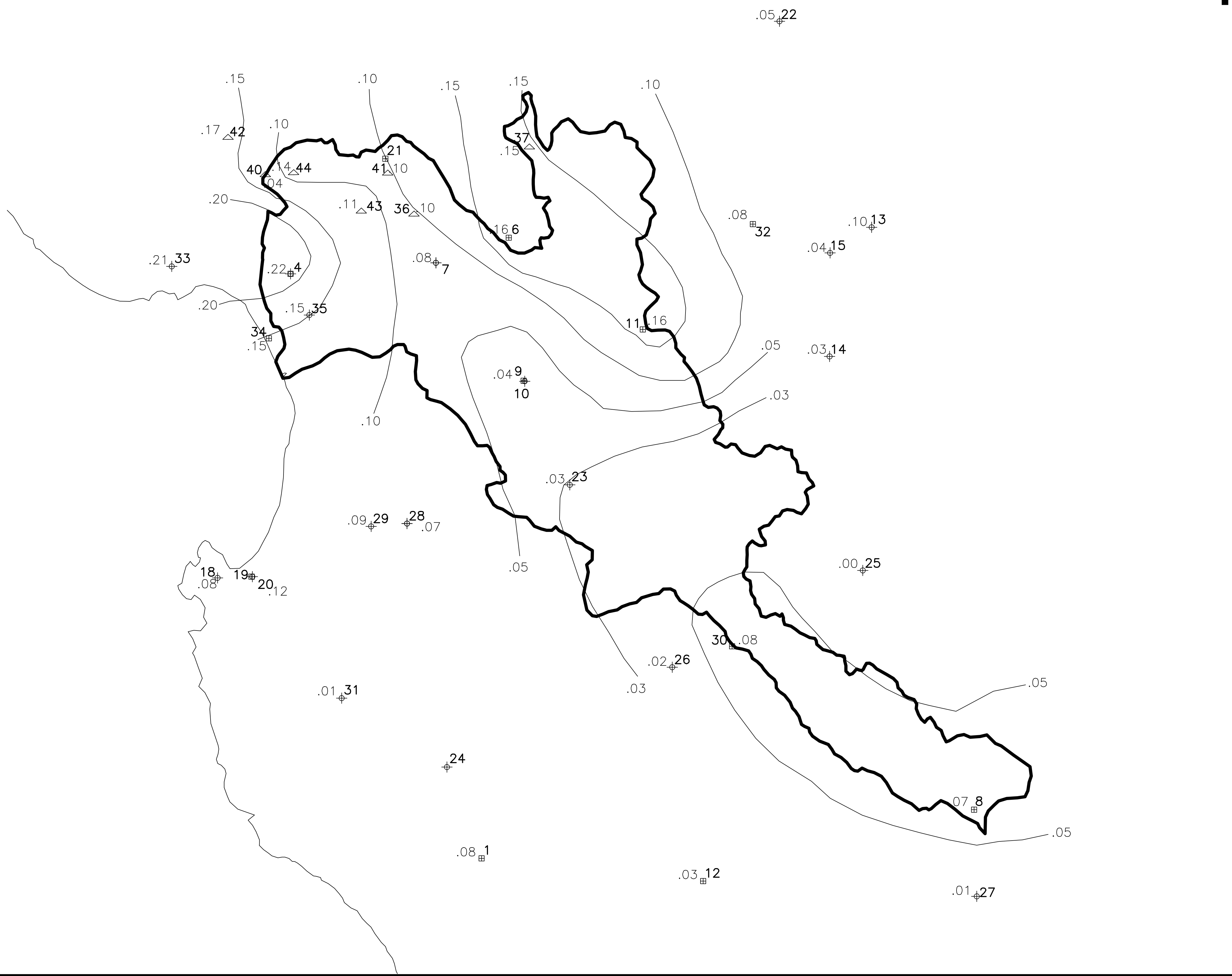
PAJARO RIVER WATERSHED

1999 Storm

72-Hour Maxima

February 6-9, 1999



RAIN GAGES

NON–RECORDING GAGES

7 Gilroy
10 Hollister 2
13 Los Banos
14 Los Banos Arb Ran
15 Los Banos Det Resv
18 Monterey
22 Newman
23 Paicines 4W
24 Paloma
25 Panoche 2W
26 Pinnacles Natl Monu
27 Priest Valley
28 Salinas AP
29 Salinas No 2
31 San Clemente Dam
33 Santa Cruz
35 Watsonville Waterworks

SCVWD RECORDING GAGES

36 Church Ave.
37 Coit Ranch
40 Loma Prieta
41 Morgan Hill
42 Mt. Umunhum
43 Uvas
44 Uvas Cyn

NWS RECORDING GAGES

1 Arroyo Seco
4 Corralitos
6 Gilroy 8 NE
8 Hernandez 7 SE
9 Hollister 2
11 Hollister 9 ENE
12 King City
20 Monterey NWSFO
21 Morgan Hill
30 San Benito
32 San Louis Dam
34 Sunset State Beach

SCALE: 1" = 50,000'

FILE NAME: RMCI/02/dwgs/TM1-2-2dwgs/Figure15.dwg

Figure 2.15

PAJARO RIVER WATERSHED

1955 Storm

72-Hour Maxima

December 21-24, 1955

RAIN GAGES

NON–RECORDING GAGES
7 Gilroy
10 Hollister 2
13 Los Banos
14 Los Banos Arb Ran
15 Los Banos Det Resv
18 Monterey
22 Newman
23 Paicines 4W
24 Paloma
25 Panoche 2W
26 Pinnacles Natl Monu
27 Priest Valley
28 Salinas AP
29 Salinas No 2
31 San Clemente Dam
33 Santa Cruz
35 Watsonville Waterworks

SCVWD RECORDING GAGES
36 Church Ave.
37 Coit Ranch
40 Loma Prieta
41 Morgan Hill
42 Mt. Umunhum
43 Uvas
44 Uvas Cyn

NWS RECORDING GAGES
1 Arroyo Seco
4 Corralitos
6 Gilroy 8 NE
8 Hernandez 7 SE
9 Hollister 2
11 Hollister 9 ENE
12 King City
20 Monterey NWSFO
21 Morgan Hill
30 San Benito
32 San Louis Dam
34 Sunset State Beach

SCALE: 1" = 50,000'

FILE NAME: RMCI/02/dwgs/TM1-2-2dwgs/Figure16.dwg

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Figure 2.16

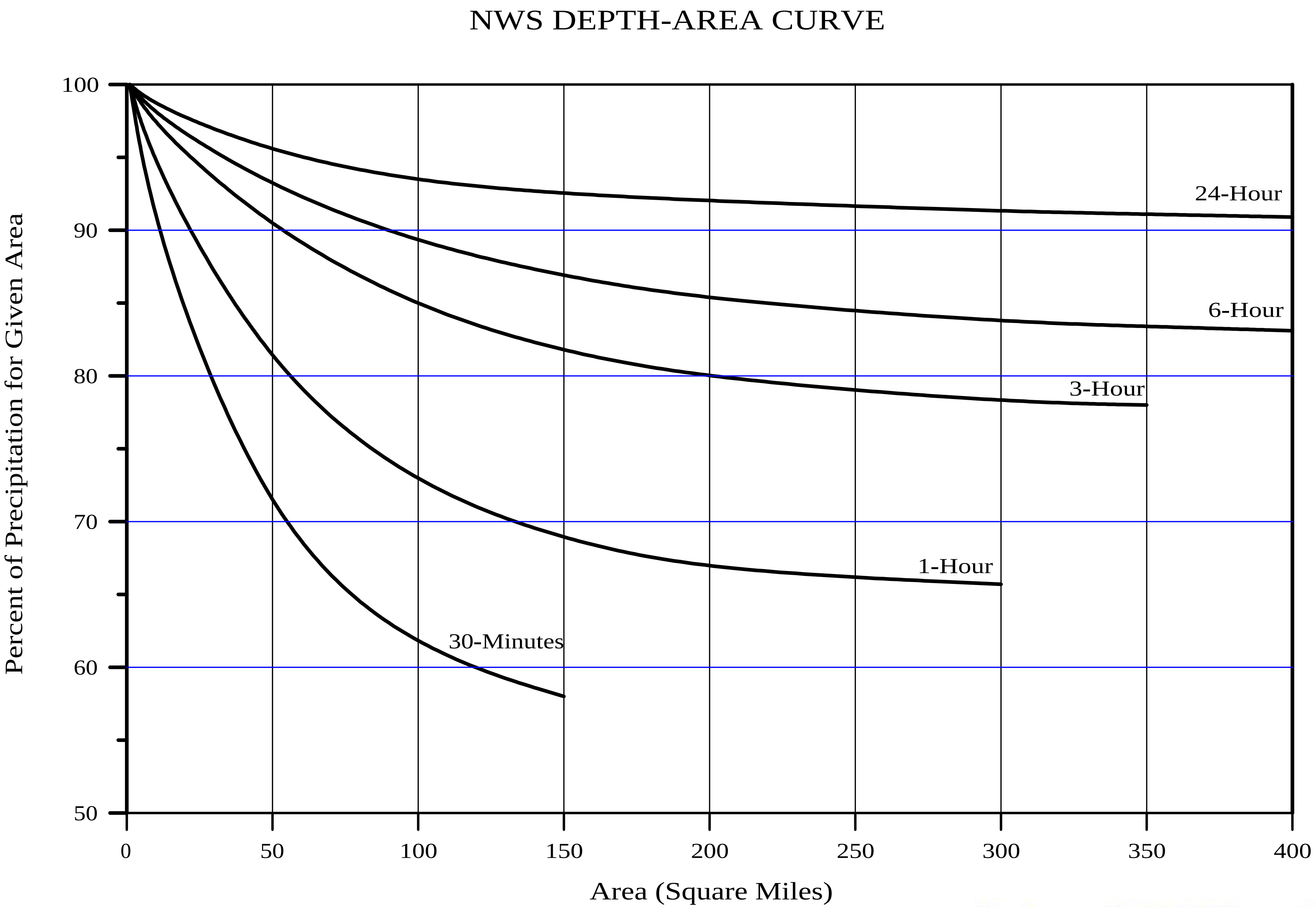

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Figure 2.17

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Figure 2.18

72-Hour Rainfall Patterns Normalized to 72-Hour Depth

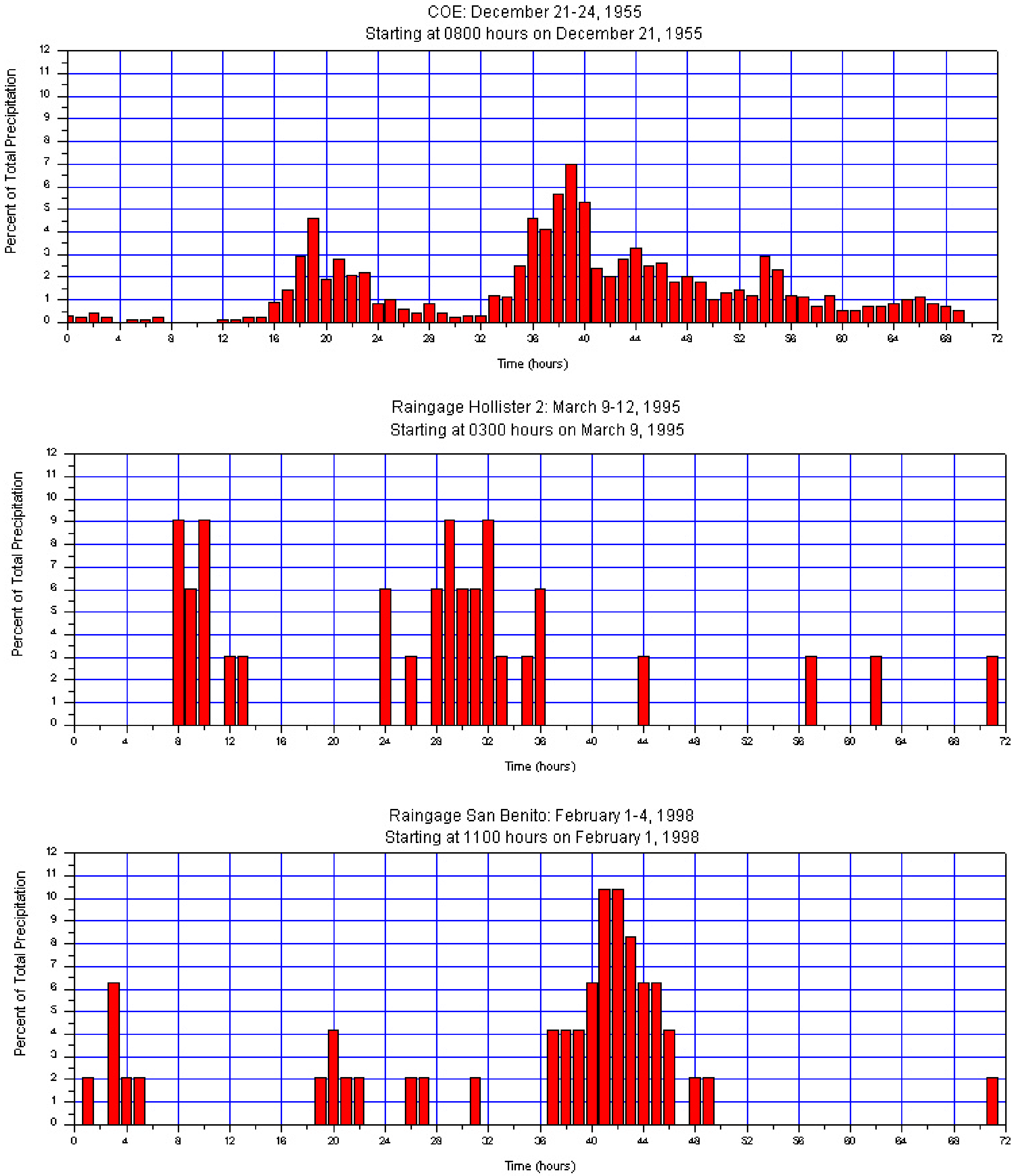

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Figure 2.19

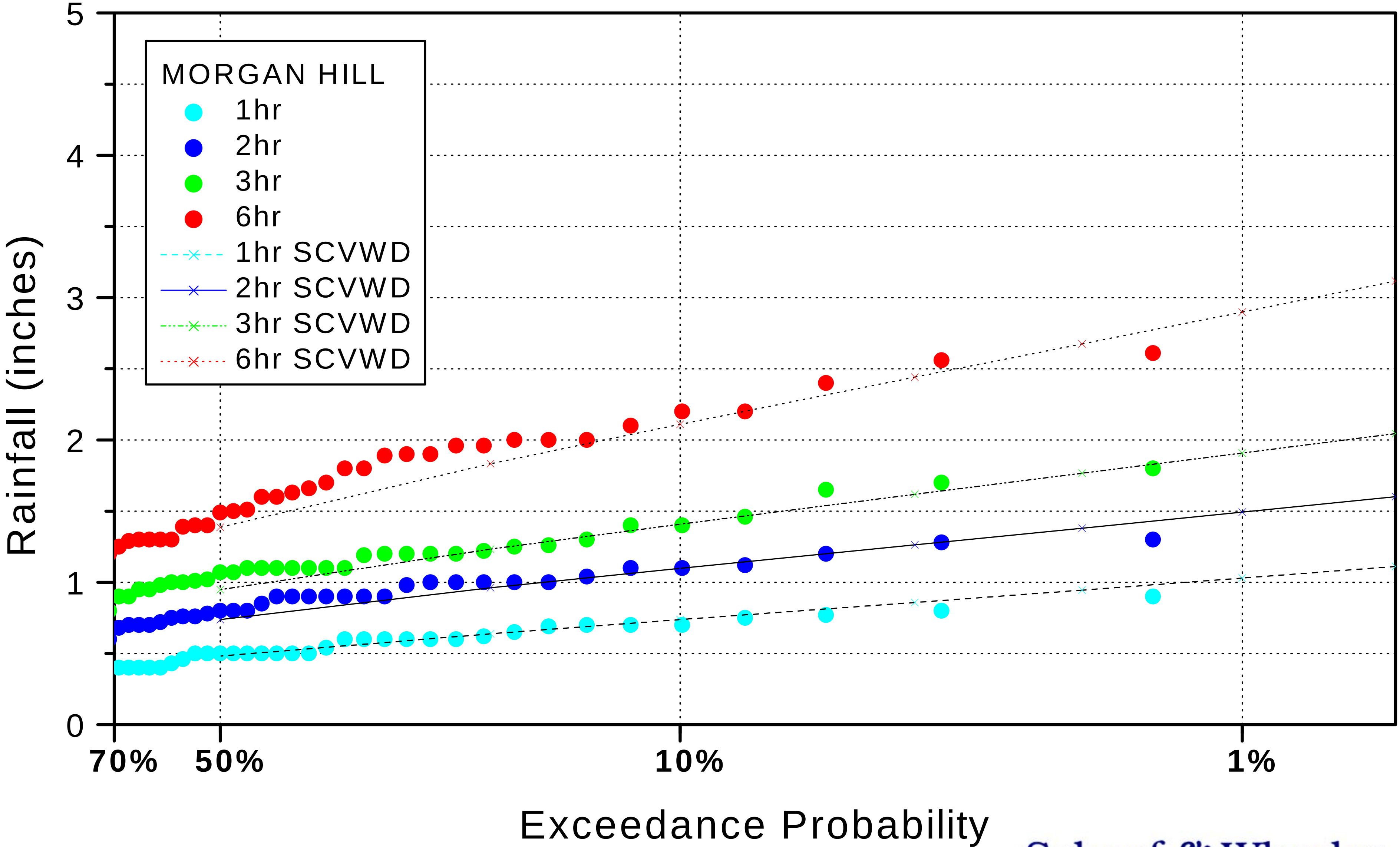

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Figure 2.20

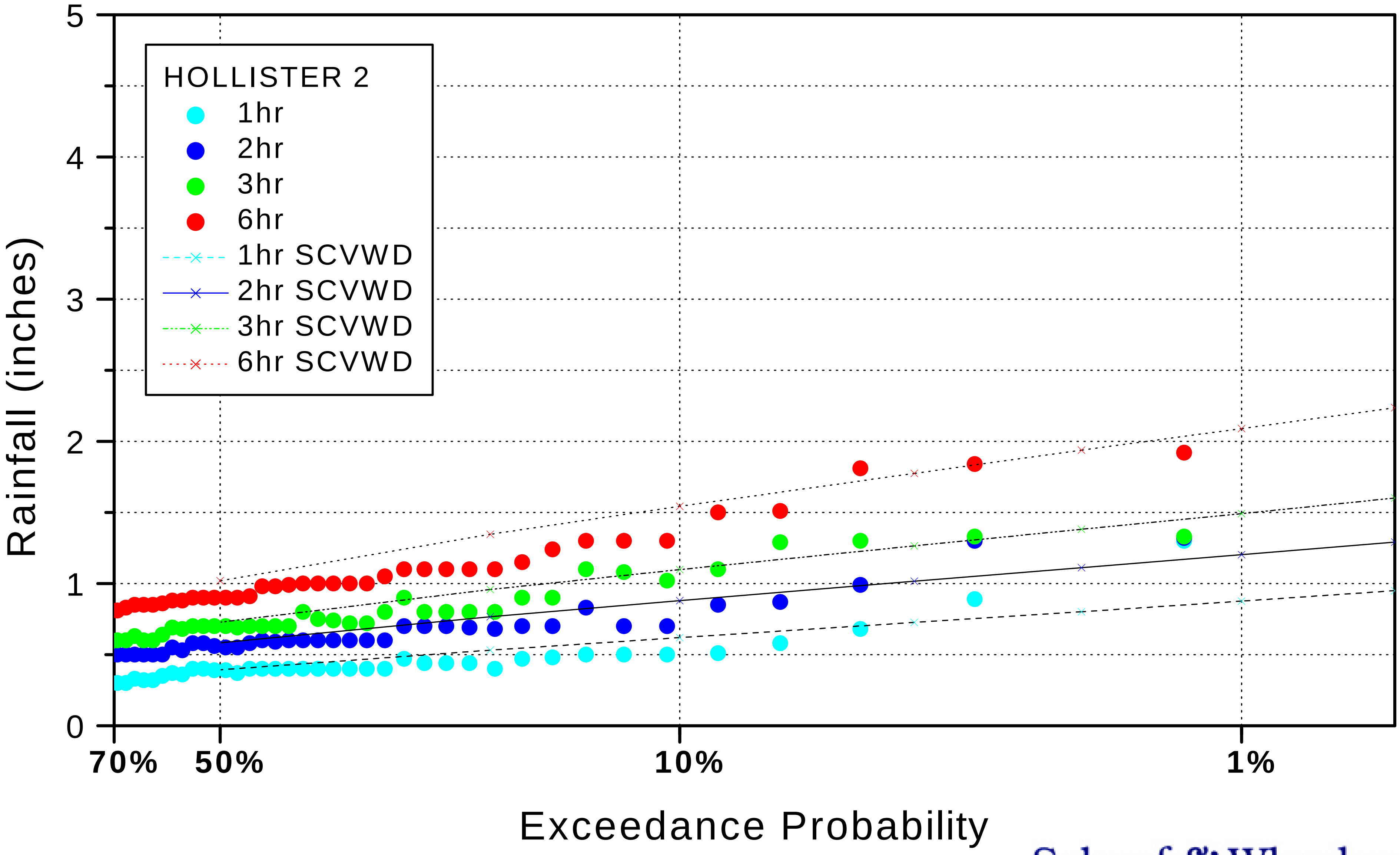

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Figure 2.21

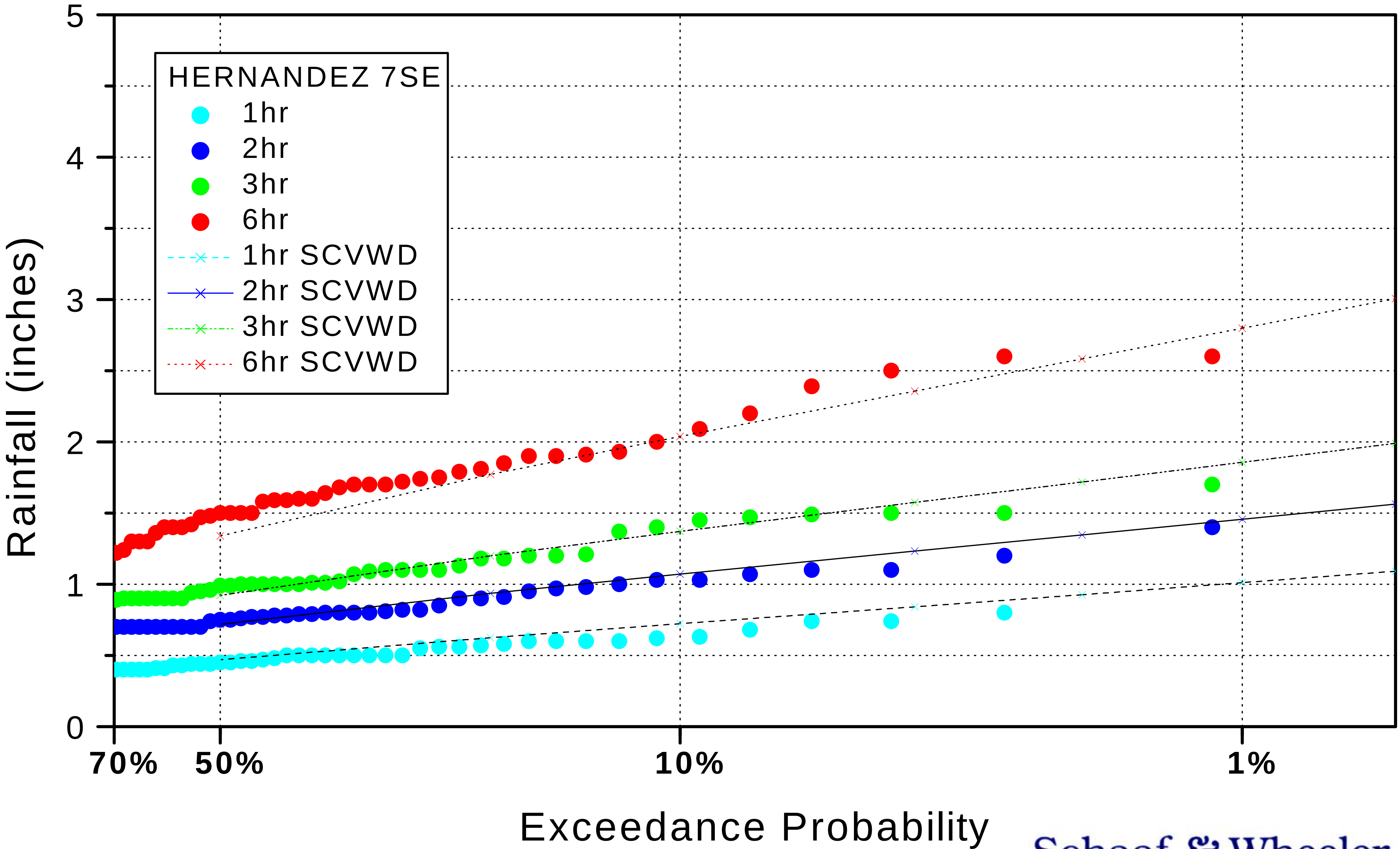

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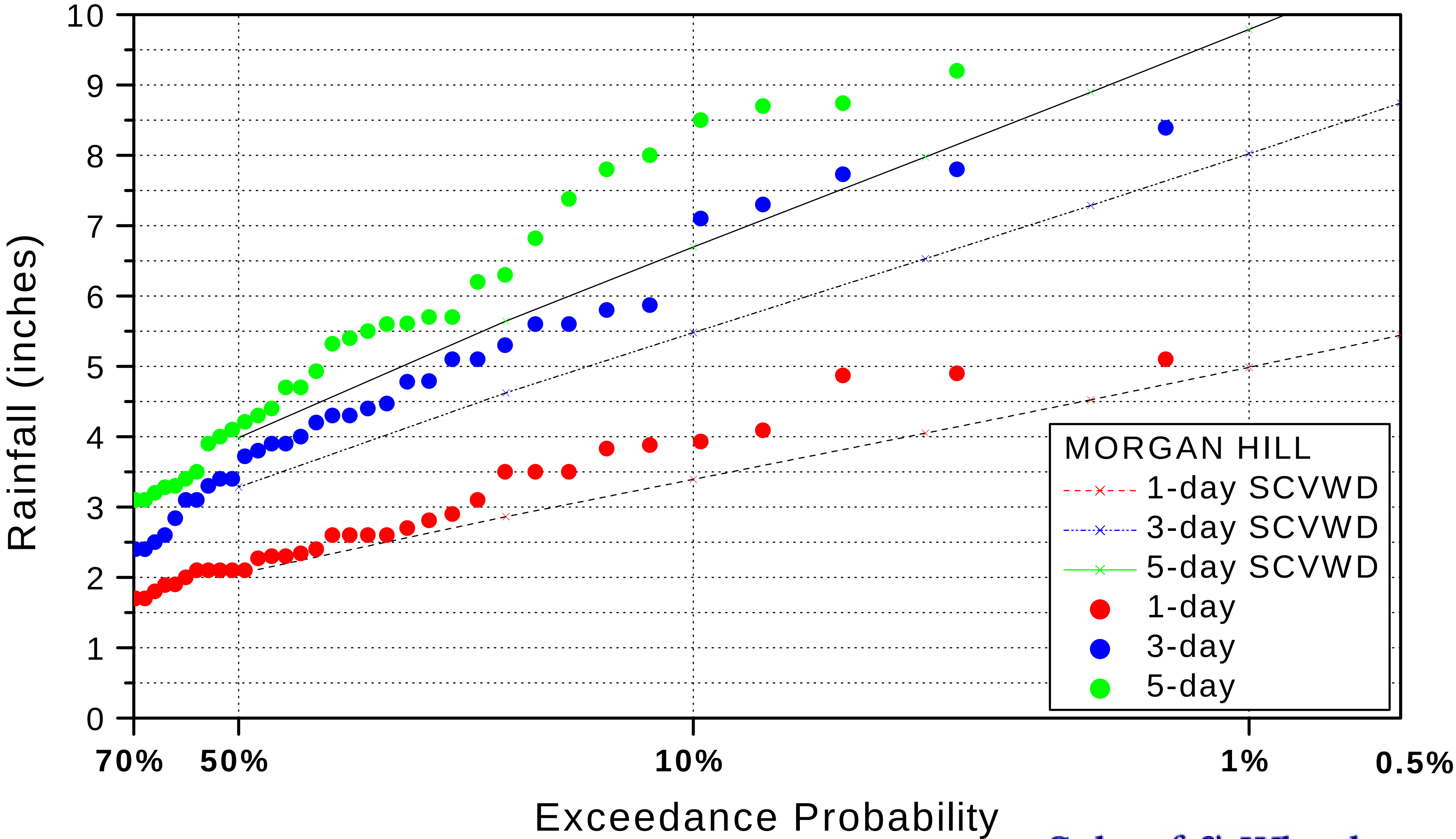
Figure 2.22



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Figures 2.23

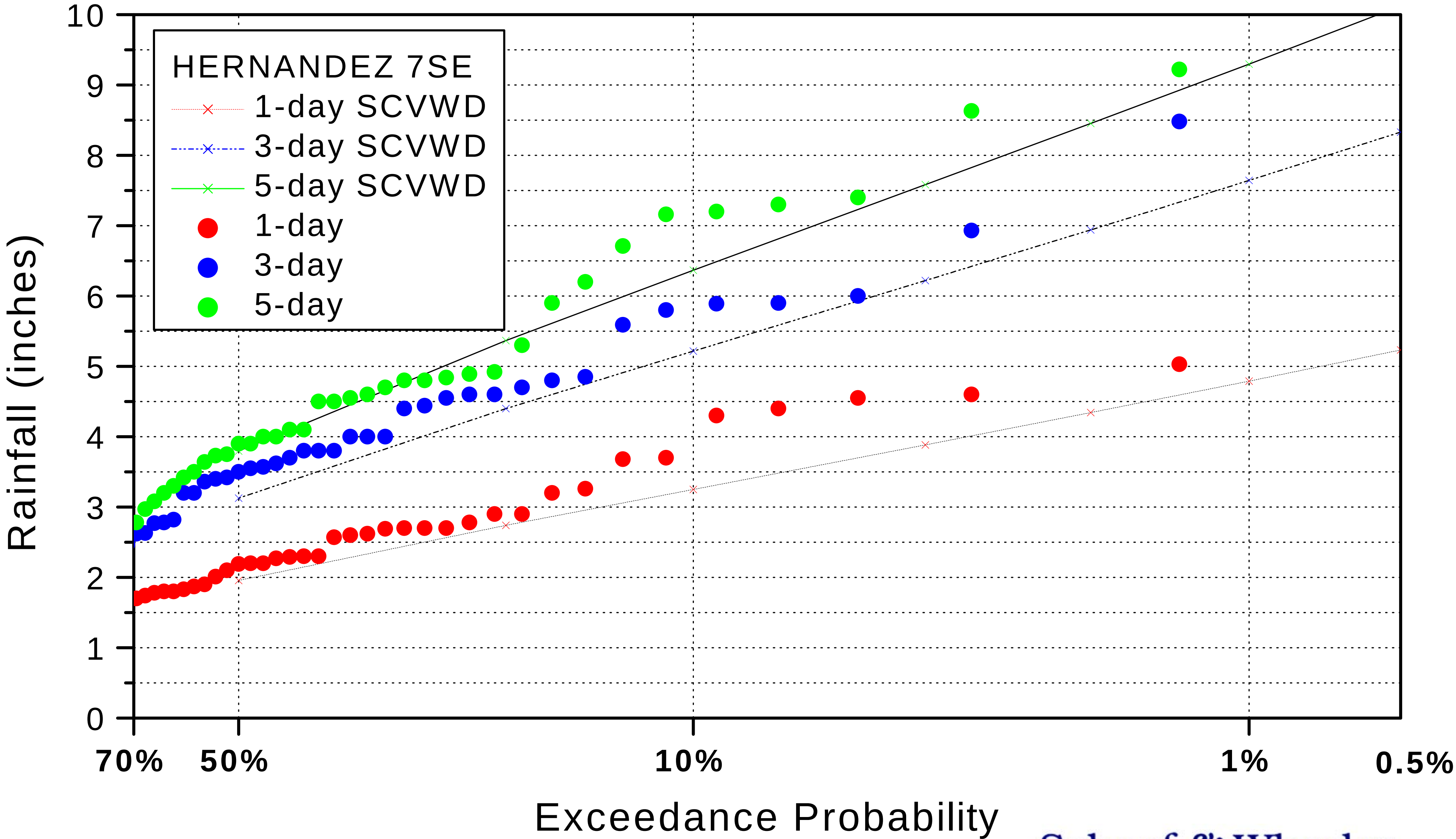

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Figure 2.24

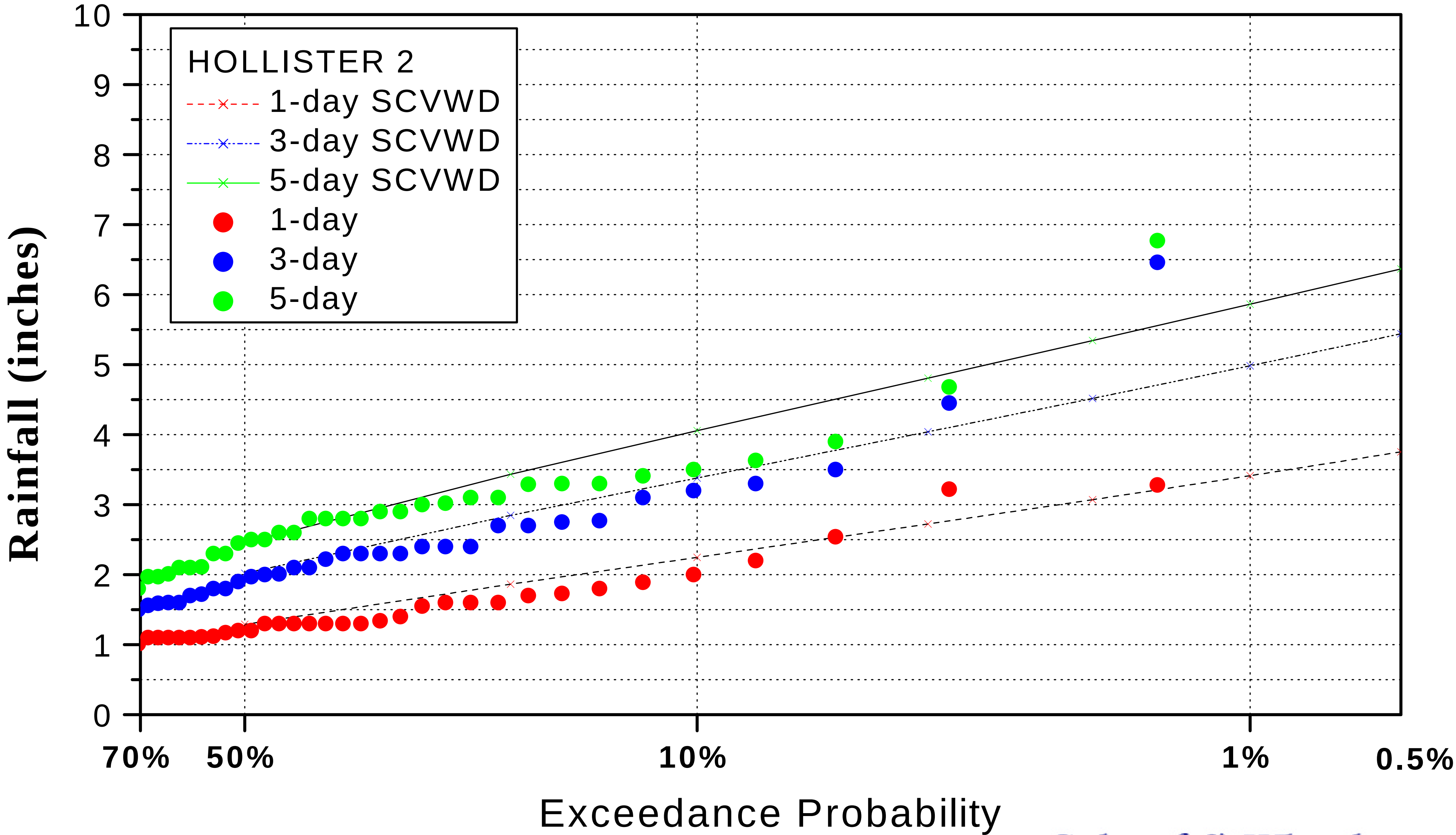

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Figure 2.25

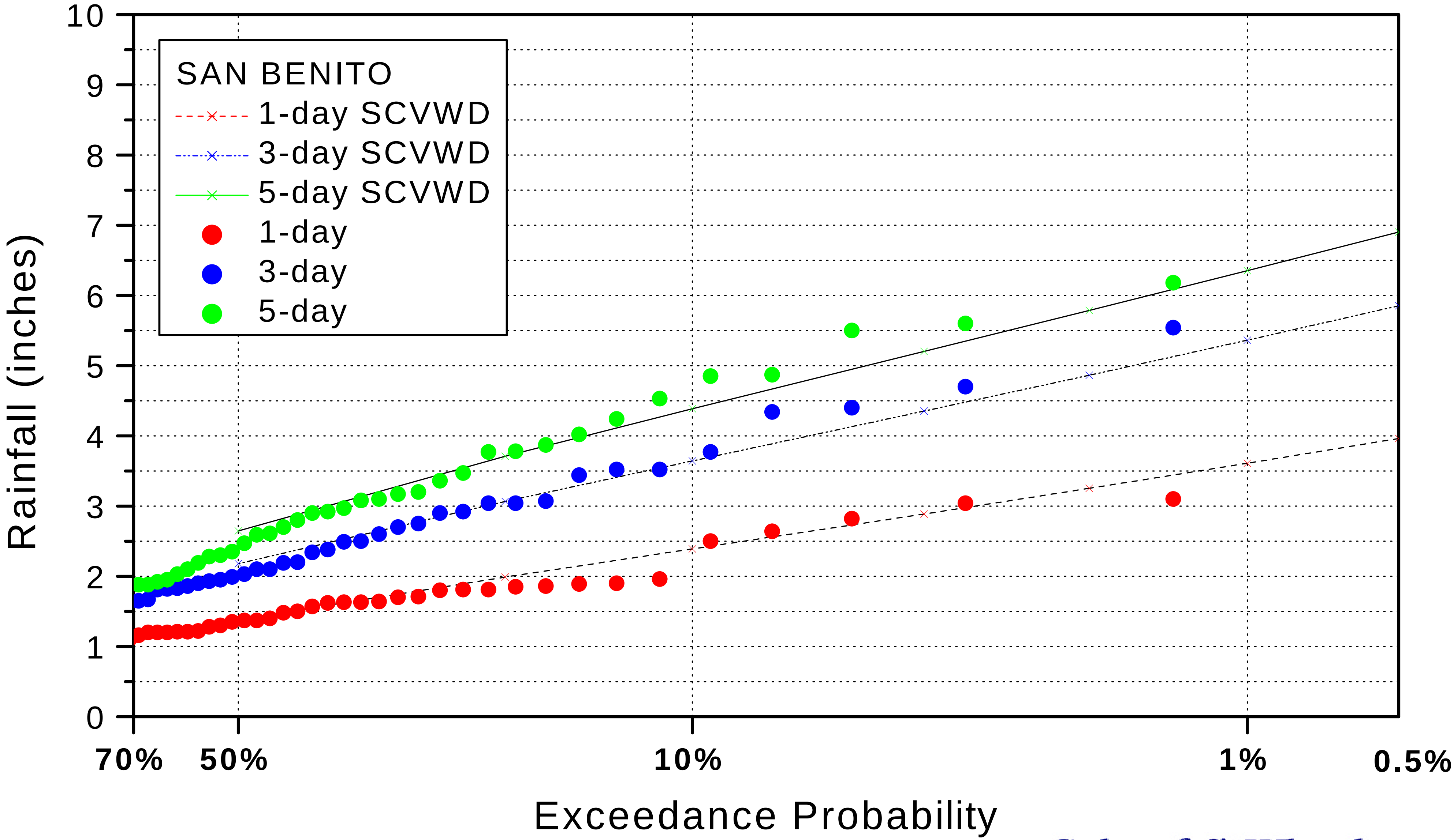

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Figure 2.26

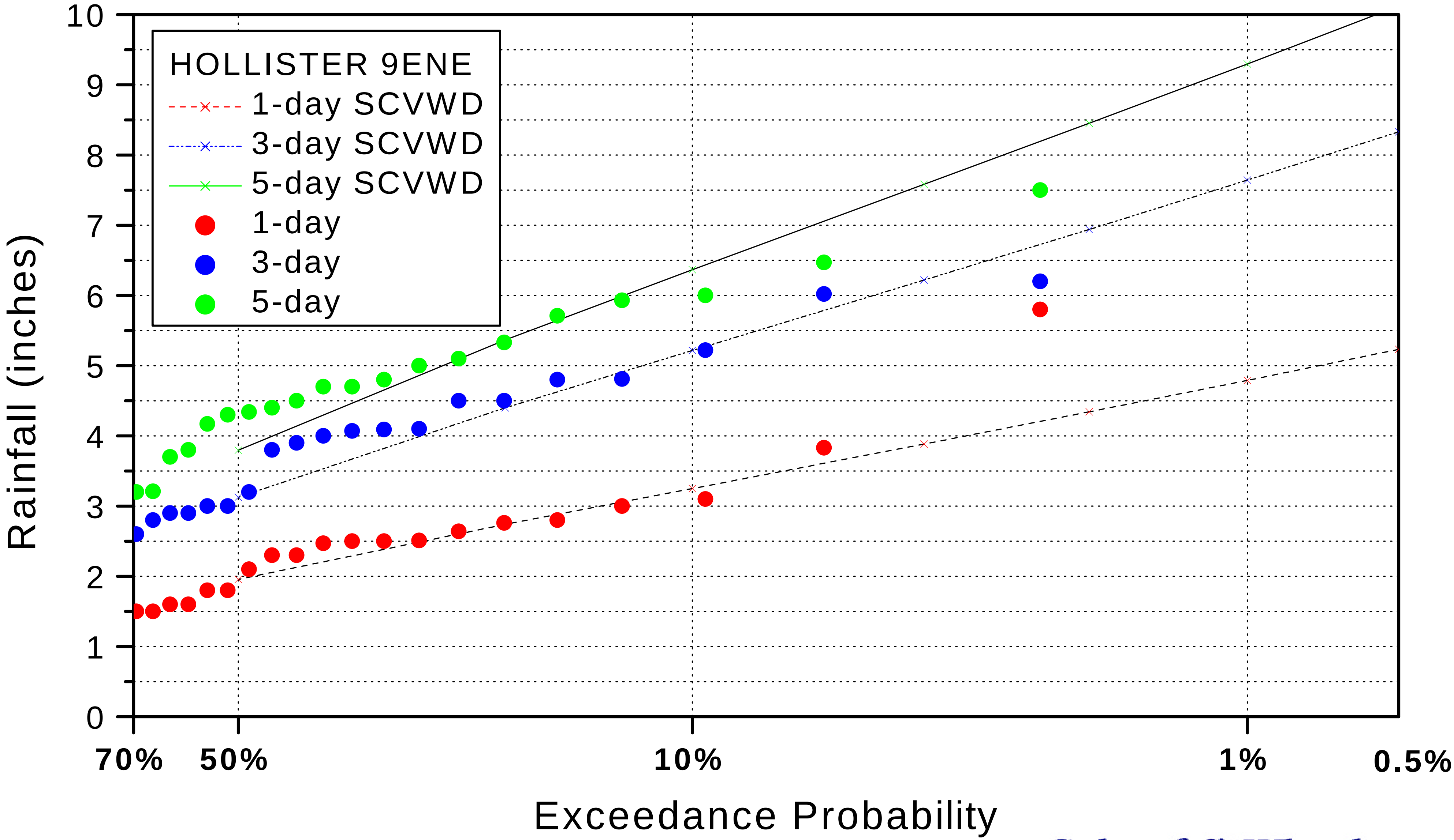

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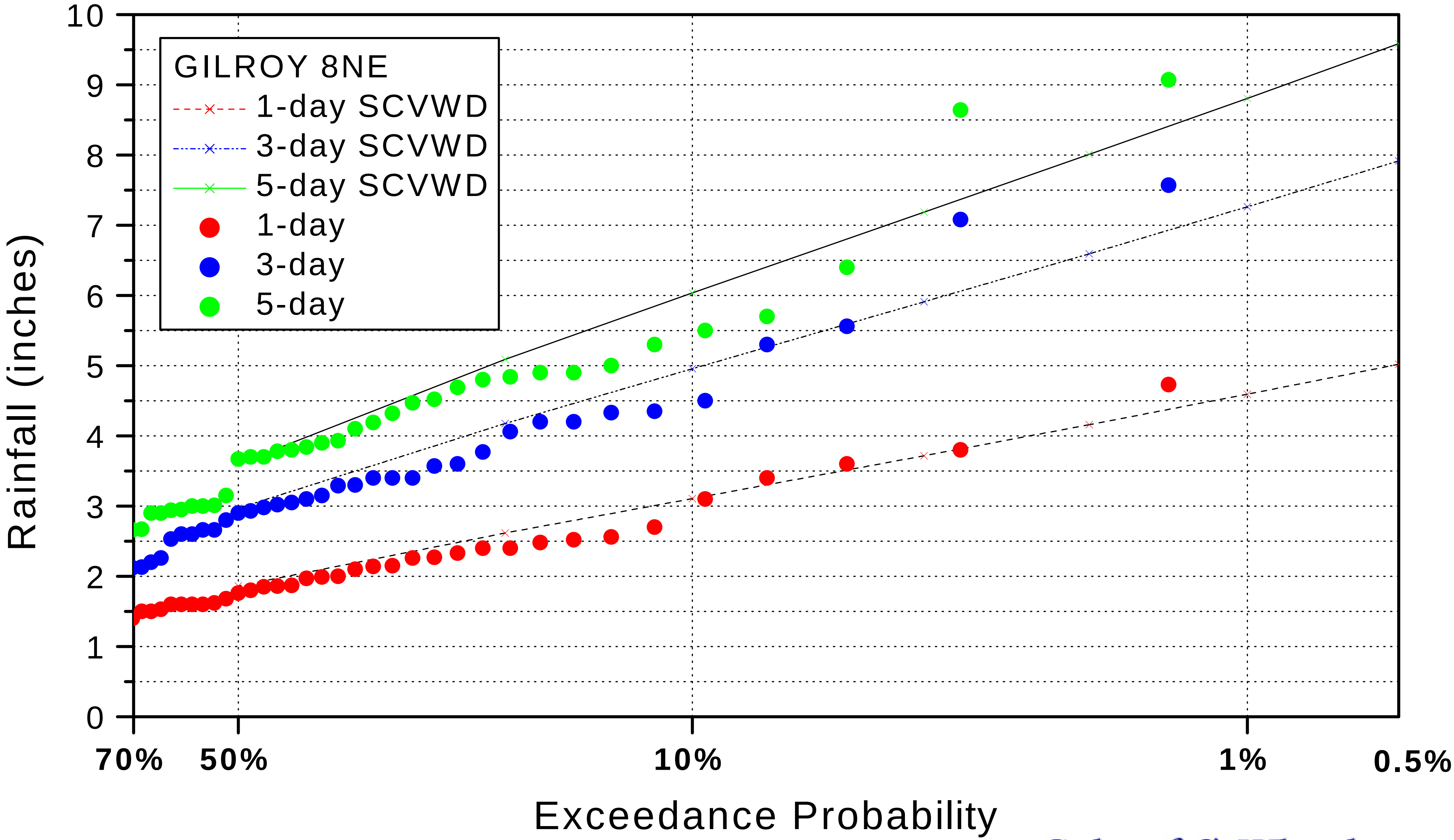
Figure 2.27



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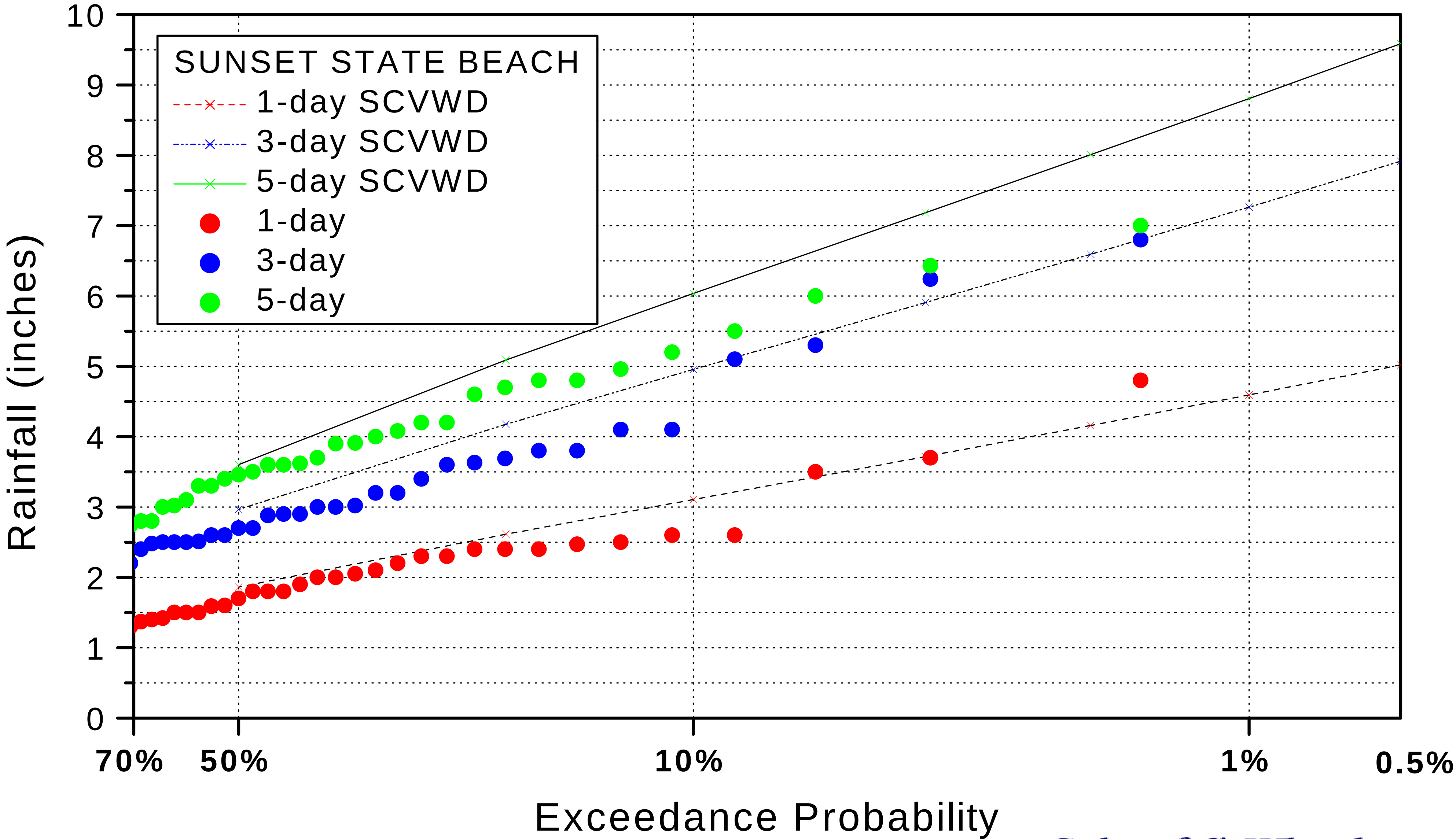

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Figure 2.29

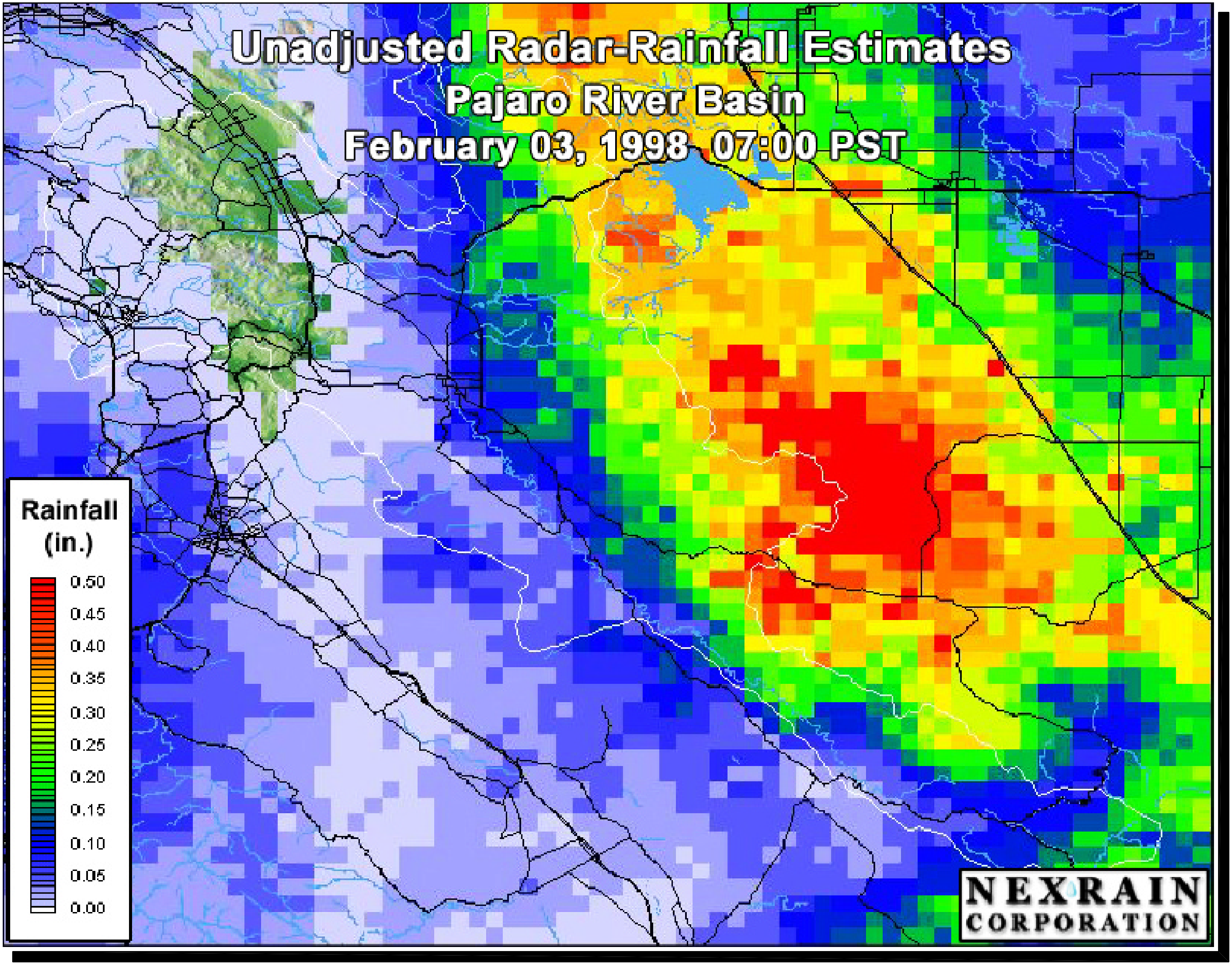

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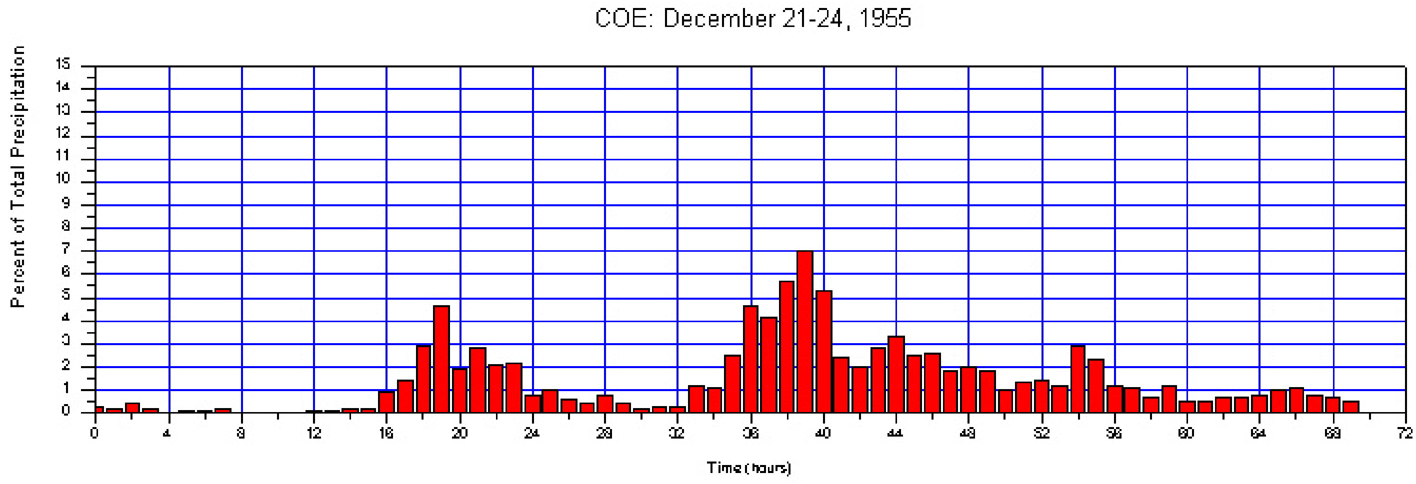
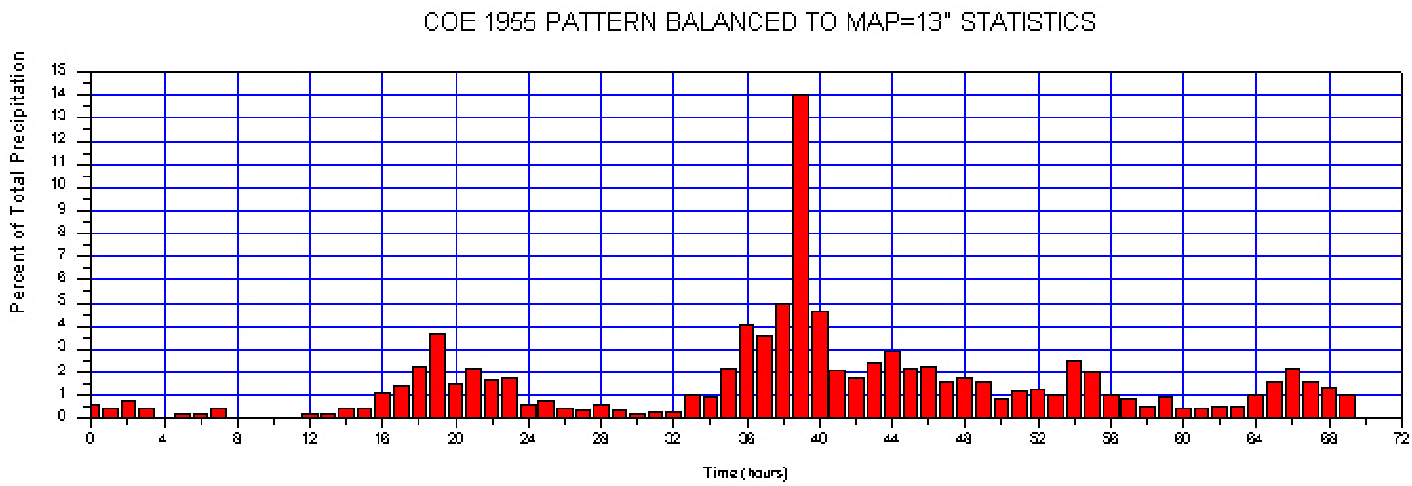
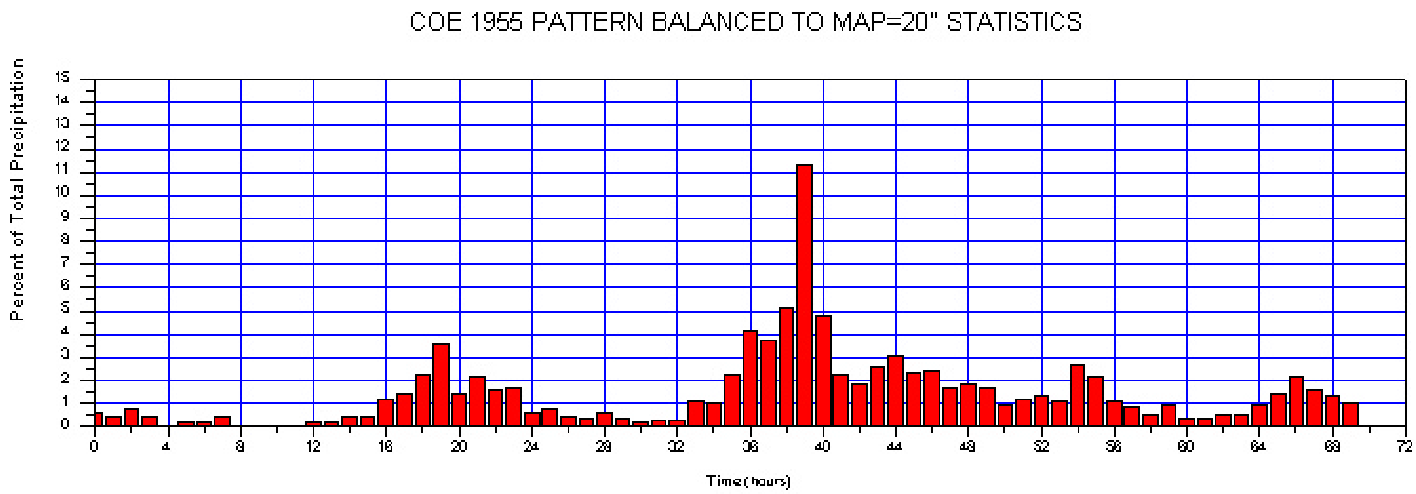
Figure 2.30

72-Hour Rainfall Patterns Normalized to 72-Hour Depth







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Consulting Engineers/Project Managers
in association with
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Technical Memorandum No. 1.2.3 – Runoff

Task: Collection and Analysis of Runoff Data

To: PRWFPA Staff Working Group

Prepared by: J. Schaaf

Reviewed by: R. Raines

Date: December 12, 2001

Introduction

This Technical Memorandum (TM) addresses runoff. Runoff entails both the instantaneous rate of discharge in a watercourse as well as the volume of discharge over a period of time. This TM discusses runoff that was measured at stream gage locations in the watershed. This data will be used in the modeling effort to calibrate and validate the hydrologic model.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a stream flow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. The watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by levees constructed by the Corps of Engineers between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at the outlet to Soap Lake – a low-lying area of Santa Clara and San Benito Counties – has a drainage area of approximately 500 square miles.

Objectives of this TM

Two types of runoff data will be presented in this TM. The first type is the measured runoff hydrograph from 1994 to 1999 at each active stream gage for which data is available. The second type is historical data at each stream gage in the Pajaro River watershed. The historic data will be used as the input for statistical analysis of both peak discharge and volume of runoff.

The hydrograph data from 1994 to 1999 will be used to help calibrate and validate the hydrologic model by showing that the model predicts recent runoff events in terms of the timing of peak discharge and in total amount of runoff. The statistical results of the historical data analysis will be used to calibrate the hydrologic model so that it can effectively reproduce the frequency response of a gauged watershed. Once the model can reasonably replicate the runoff events from the six-year period and the frequency curves at stream gage locations, the model will be ready to assess a variety of watershed changes and the impacts those changes would have on downstream frequencies of peak discharge and volume of discharge.

Hydrographs at Active Stream Gages

The USGS has been collecting data in the Pajaro River watershed since the 1930's. Table 3.1 and Figure 3.1 show the 27 stream gage locations at which data has been collected since 1930. Lengths of record at the gages vary from 1 year to 60 years.

Of the 27 historic gages only seven are currently active. These include six gages operated by the USGS: Clear Creek near New Idria, San Benito River near Willow Creek School, Tres Pinos Creek near Tres Pinos, San Benito River at Highway 156, Pajaro River at Chittenden, and Corralitos Creek at Freedom. In addition, the Santa Clara Valley Water District (SCVWD) maintains the Pacheco Creek at Dunneville gage.

Table 3.1: USGS Stream Gages within the Pajaro River Watershed.

Station	Station Name	Begin	End	Total Years	Area (mi^2)
11152900	Cedar Creek Near Bell Station	10/1961	09/1982	21	13
11153000	Pacheco Creek Near Dunneville	10/1939	09/1982	43	146
11153040	Pacheco Creek at Dunneville	10/1981	09/1985	4	154
11153470	Llagas Creek Above Chesbro Res.	10/1971	09/1982	11	10
11153500	Llagas Creek Near Morgan Hill	10/1951	11/1971	21	20
11153700	Pajaro River Near Gilroy	03/1959	09/1982	24	399
11153790	Uvas Creek at Sveadal	10/1972	10/1974	3	3
11153800	Alec Canyon Creek Near Morgan Hill	11/1969	05/1972	3	1
11153900	Uvas Creek Above Uvas Reservoir	08/1961	09/1982	22	21
11154000	Uvas Creek Near Morgan Hill	10/1930	03/1957	27	30
11154100	Bodfish Creek Near Gilroy	10/1959	09/1982	23	7
11154200	Uvas Creek Near Gilroy	01/1959	09/1992	34	71
11154500	Pajaro River at Sargent	10/1940	09/1941	1	505
11154700	Clear Creek Near New Idria	10/1993	09/1999	6	14
11156000	San Benito River Below Hernandez	10/1949	09/1963	8	108
11156450	Willow Creek Trib. Nr. San Benito	07/1964	09/1969	6	1
11156500	San Benito R. Nr. Willow Cr. School	10/1939	09/1999	60	249
11156700	Pescardero Creek Near Paicines	07/1959	10/1970	13	38
11157500	Tres Pinos Creek Near Tres Pinos	10/1940	09/1999	46	208
11158500	San Benito River Near Hollister	10/1949	09/1983	34	586
11158600	San Benito River at Highway 156	10/1970	09/1999	29	607
11158900	Pescadero Creek Near Chittenden	09/1970	09/1981	12	10
11159000	Pajaro River at Chittenden	10/1939	09/1999	60	1186
11159150	Corralitos Creek Near Corralitos	10/1957	10/1972	16	11
11159200	Corralitos Creek at Freedom	10/1956	09/1999	43	28
11159400	Green Valley Creek Near Corralitos	10/1963	09/1967	4	7
11159500	Pajaro River at Watsonville	10/1911	09/1973	4	1272

The SCVWD keeps up other USGS gages in the watershed. However, these gages drain small areas or are under severe regulation by nearby upstream water supply reservoirs and are therefore not included in this study.

Hydrographs from active stream gages were obtained from the USGS and the SCVWD. Typical hydrographs are shown in Figures 3.2 to 3.7. These and other measured stream flows will be compared to the runoff predicted by the hydrologic model. This comparison will be discussed in the upcoming TM 1.2.7.

Historic Stream Gage Data

The 27 stream gages shown in Table 3.1 and Figure 3.1 were analyzed for length of record. Statistical analysis on records of 20 or fewer years was considered less desirable than on gages with more than 20 years of record. All stations with less than 20 years of record were eliminated from Table 3.1.

Stream gage records for discharges from smaller watersheds were considered less desirable for the model as the major comparison points decided on in TM 1.2.1 were for drainage areas in excess of 500 square miles. Only those stream gages with drainage areas in excess of 20 square miles were considered appropriate for this statistical analysis.

Several stream gages were combined in order to meet the time and drainage area requirements. The first combination involves the two gages on the San Benito River near Hollister. Their records were combined to create one long record from 1949 to 1999. Since the drainage areas of the two gages is only 3.5% different, the data was not corrected to account for this small variation. The two gages on Pacheco Creek near Dunneville were similarly combined to create one long record. The difference in drainage area was only 5.5 percent. Again no correction was made to account for this small difference. This gage was abandoned by the USGS in 1985. The SCVWD took over operation of the gage when the USGS abandoned it. Data is current but not all is readily available.

Uvas Creek has three stream gages. The one farthest downstream has been influenced by Uvas Reservoir and as such a statistical analysis may not be appropriate. However, for now, the data will be retained for analysis until it is shown to be inappropriate. The remaining two gages on Uvas Creek both reflect the runoff from the watershed above the reservoir. The upper gage only drains 20 square miles of the 30 that drain to the reservoir. The lower of the two gages was located near the site of the existing dam. It had a slightly longer record 27 years as opposed to 22 years and drained 30 square miles. Because of the similarity of these gages it was decided to use the lower of the two and to disregard the upper gage.

Only nine stream gages remain after the above steps that can be analyzed statistically. The locations of these gages are summarized in Table 3.2 and shown in Figure 3.8.

Table 3.2: USGS Stream Gages Used for Statistical Analysis.

Station	Station Name	Begin	End	Total Years	Area (mi^2)
11153040	Pacheco Creek at Dunneville	10/1939	09/1995	55	154
11153700	Pajaro River Near Gilroy	03/1959	09/1982	24	399
11154000	Uvas Creek Near Morgan Hill	10/1930	03/1957	27	30
11154200	Uvas Creek Near Gilroy	01/1959	09/1992	34	71
11156500	San Benito R. Nr. Willow Cr. School	10/1939	09/1999	60	249
11157500	Tres Pinos Creek Nr. Tres Pinos	10/1940	09/1999	46	208
11158600	San Benito River at Highway 156	10/1949	09/1999	49	607
11159000	Pajaro River at Chittenden	10/1939	09/1999	60	1186
11159200	Corralitos Creek at Freedom	10/1956	09/1999	43	28

Stream Gage Statistics

The standard method used in the United States for analysis of stream gage data involves the use of the log Pearson Type III probability distribution. This distribution is mandated for use by federal agencies in Bulletin 17B, published by the United States Water Resources Council in 1982. That Bulletin provides the guidelines for application of the log Pearson Type III distribution to stream gage data. Because of the wide spread use, most local and state agencies throughout the country use the same distribution to analyze stream gage data.

The log Pearson Type III distribution requires an estimation of the mean, the standard deviation and the skew of the probability distribution for each station. The data from station records provide good estimates of both mean as well as standard deviation. The skew, however, is a statistic that is more difficult to estimate accurately because the computation involves the cube of the distance of each data point from the mean value. Very high or very low data can influence the skew coefficient significantly.

To account for this difficulty, Bulletin 17B allows for the weighting of individual gage station skews with an estimate of the regional skew. In the central coast region, the stream gage station Arroyo Seco Near Soledad has been continuously collecting data for 98 years. The associated 244 square mile watershed drains an area that includes the Ventana Wilderness Area and has neither dams nor any significant urbanization. Therefore we assume that the area has remained hydrologically unchanged since the station was established. The skew computed using this station's data was used as the regional skew coefficient in analysis of stream gage data in the Pajaro River watershed. Statistics based on this data best reflect the long-term skew in the region.

The peak discharge frequency curve and the 3-Day average discharge frequency curve are shown in Figure 3.9 for the Arroyo Seco watershed. An exceedance probability of 1% indicates that there is a one percent chance each year that the associated discharge value may be equaled or exceeded and is called a 100-year flood. The 10 percent exceedance probability corresponds to a 10-year flood and the 50 percent exceedance probability corresponds to a 2-year flood.

There is a statistical chance that the data-based frequency curve is not completely accurate. The data may have been affected by long term weather patterns, not enough time to adequately sample the series, or some other unknown influence. The 90% confidence curves included in Figure 3.9 represent the area in which the actual frequency curve is 90% likely to fall. A longer period of record generally yields tighter confidence curves.

The large circles on Figure 3.9 show estimates of the 100-year and 10-year peak discharge and 3-Day average discharge made by the SCVWD and published in the 1998 *Hydrology Procedures*. The SCVWD values are very close to those predicted by this current statistical analysis.

The data plotted on Figure 3.9 was done using the Median Plotting Position method. The data and the log Pearson Type III curve seem to be close to one another for both the peak discharge as well as for the 3-Day average discharge curves until the lower frequency events. At these less frequent events the log Pearson Type III analysis predicts values greater than those observed. For example, the data itself might lead one to predict a 100-year peak discharge value of approximately 28,000 cfs. The log Pearson Type III analysis predicts a 100-year value of 37,000 cfs. Thus even with almost 100-years of record the data and the statistically generated frequency curve can vary significantly for the less frequent events. However, the log Pearson Type III analysis provides the current best estimate of the frequency of runoff events.

Figures 3.10 to 3.18 contain the frequency curves for the nine stream gages in the watershed. Estimates from the SCVWD and from the US Army Corps of Engineers are also shown on the frequency curves. The two stations where previous estimates are significantly different than current frequency curves were Figures 3.15 – Tres Pinos at Tres Pinos; and 3.16 – San Benito River at Highway 156. The 1998 peak discharge values at those two stations are more than double the next largest value in the 50 or so years the record at the two locations. These very large values pull the frequency curves up relative to older estimates that were done prior to the 1998 data.

Watershed Changes

One of the cornerstones of statistics and probability as applied to flood control hydrology and frequency analysis is that the data comes from homogeneous watershed. A homogeneous watershed does not permanently change in a significant way over time. All natural watersheds are constantly undergoing small changes. These changes, however, are natural and are generally assumed to be random. They average out over time such that no trend is embedded in the data. A change in a watershed that may make the stream gage data non-homogeneous would be the construction of a dam that regulates downstream discharges. However, construction of a dam that controls ten percent of the watershed above a gage may have only a little, if any effect on the runoff at the gage. Large-scale urbanization could also have a significant effect on the homogeneity of the stream gage data. Like the dam though, if the urbanization covers only a small portion of the watershed its effects may not be discernable at the measuring station.

The effects of urbanization may be seen in the stream gage record. Because the Pajaro River at Chittenden stream gage has been recording data for a significant period, it was decided to check the data at this gage to see if any trends were present. This gage has recorded 60 years of data from October 1939 to September 1999.

Volume runoff is used for this analysis rather than peak discharge for several reasons. First, peak discharges can be mitigated by use of detention basins which have become commonplace in the watershed. Also, conversion of permeable to impermeable surfaces creates an increase in runoff volume, particularly so at the smaller, more common events. Rather than focus on infrequent events, emphasis is placed on the more common events, especially the 2-year event which has a 50 percent chance of being equaled or exceeded in any year.

Table 3.3 summarizes the results for the 1-Day, 3-Day and 5-Day average discharges of 2-year storms. The two data sets, 1940 to 1969 and 1970 to 1999, each have 30 years of continuous data. The 2-year discharges are products of the log Pearson Type III analysis.

Table 3.3: Pajaro River at Chittenden Stream Gage.

Flow Duration	1940-1969	1970-1999
1-Day	2,866 cfs	2,113 cfs
3-Day	2,130 cfs	1,655 cfs
5-Day	1,639 cfs	1,336 cfs

The table shows that the 2-year discharges have decreased within this particular watershed in the last 30 years compared to the preceding 30 years. These results do not show any evidence of urbanization in the watershed. These results, however, could be showing that the reservoirs built in the watershed since 1940 have reduced the maximum annual 1-, 3-, and 5-Day average discharges. These reservoirs and their dates of construction are: Chesbro, 1955; Uvas, 1957; and Hernandez, 1961. The Pacheco Reservoir was constructed prior to 1940.

The same analysis was done for the San Benito near Hollister stream gage. The comparison is more complicated though because the gage was moved during the period of record. As mentioned earlier, two gage records were combined to form this one. From October 1949 until September 1983 the gage site had a drainage area of 586 square miles. From October 1970 until September 1999 the new gage site had a drainage area of 607 square miles – a 3.5 percent increase in drainage area. For purposes of this comparison the differences in drainage area were ignored. Table 3.4 below shows the 2-year storm results from 1950 to 1974 and from 1975 to 1999. The 1950 to 1974 data are from the first gage location while the 1975 to 1999 data are from the second and current gage location.

Table 3.4: San Benito River Near Hollister Stream Gage

Flow Duration	1950-1974	1975-1999
1-Day	407 cfs	408 cfs
3-Day	251 cfs	297 cfs
5-Day	183 cfs	228 cfs

The results show more discharge in the second 25-year period than in the first. The only significant change in this watershed has been the construction of Hernandez Reservoir and Dam in 1961. There is very little urbanization in this watershed.

The 2-year runoff volumes change, less than 30 percent in both cases, does not indicate any trend in the runoff data. At present, there is no reason to believe that the data needs to be de-trended before it can be used for statistical analysis. While it cannot be definitely stated that the gage records are indeed homogeneous, the data fails to show any trend due to urbanization. The data may show a change in volume of runoff due to the construction of upstream water supply reservoirs.

Conclusion

The stream gage data for the Pajaro River watershed has been collected and analyzed. The data shows the response of the watershed to rainfall as presented in TM 1.2.2 – Rainfall. The statistical analysis of the data shows how the watershed behaves from a probabilistic viewpoint. Both the data and the statistical analysis will be used in the calibration of the hydrologic model.

While the watershed has undergone changes due to construction of dams, changes of use from grassland to agricultural or from agricultural to urban or from low density urban to higher density urban, there is, at present, insufficient evidence in the stream gage record at Chittenden to indicate that these watershed changes have altered the statistical nature of the risk of floods along the lower Pajaro River.

Figure 3.1

PAJARO RIVER WATERSHED

Stream Flow Gages

11152900	Cedar Crk Nr Bell Station
11153000	Pacheco Crk Nr Dunneville
11153040	Pacheco Crk @ Dunneville
11153470	Llagas Crk Abv Chesbro Res
11153500	Lagas Crk Nr Morgan Hill
11153700	Pajaro Rvr Nr Gilroy
11153790	Uvas Crk @ Sveadal
11153800	Alec Cnyn Crk Nr Morgan Hill
11153900	Uvas Crk Abv Uvas Res.
11154000	Uvas Crk Nr Morgan Hill
11154100	Bodfish Crk Nr Gilroy
11154200	Uvas Crk Nr Gilroy
11154500	Pajaro Rvr @ Sargent
11154700	Clear Crk Nr New Idria
11156000	San Benito Rvr Blw MC Nr Hernandez
11156450	Willow Crk Trib Nr San Benito
11156500	San Benito Rvr Nr Willow Crk School
11156700	Pescadero Crk Nr Paicines
11157500	Tres Pinos Crk Nr Tres Pinos
11158500	San Benito Rvr Nr Hollister
11158600	San Benito Rvr @ Hwy 156 Nr Hollister
11158900	Pescadero Crk Nr Chittenden
11159000	Pajaro Rvr @ Chittenden
11159150	Corralitos Crk Nr Corralitos
11159200	Corralitos Crk @ Freedom
11159400	Green Valley Crk Nr Corralitos
11159500	Pajaro Rvr @ Watsonville

SCALE: 1" = 40,000'

FILE NAME: RMCI/07/dwgs/Fig3_1.dwg

Schaaf & Wheeler

Figure 3.2

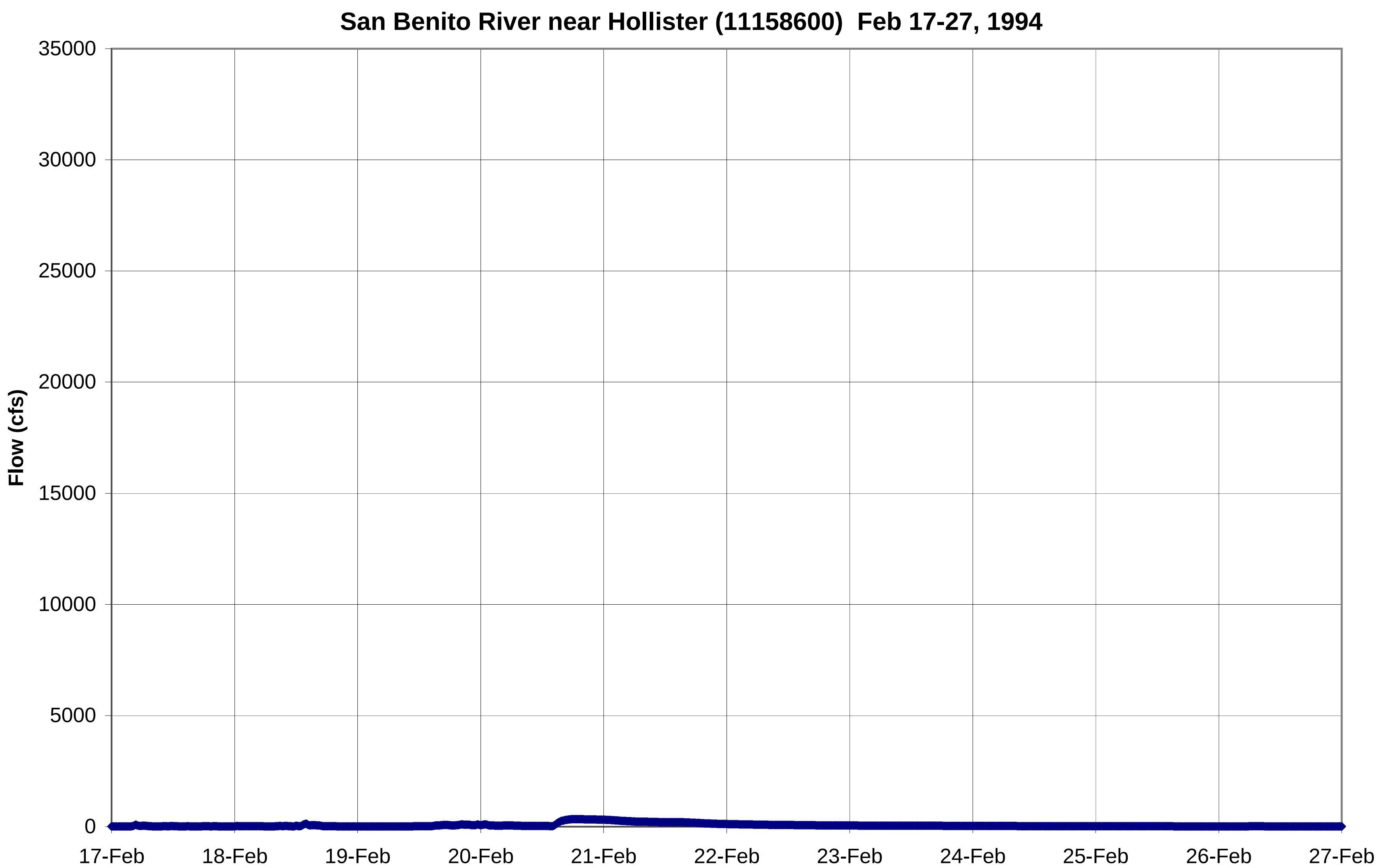

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Figure 3.3

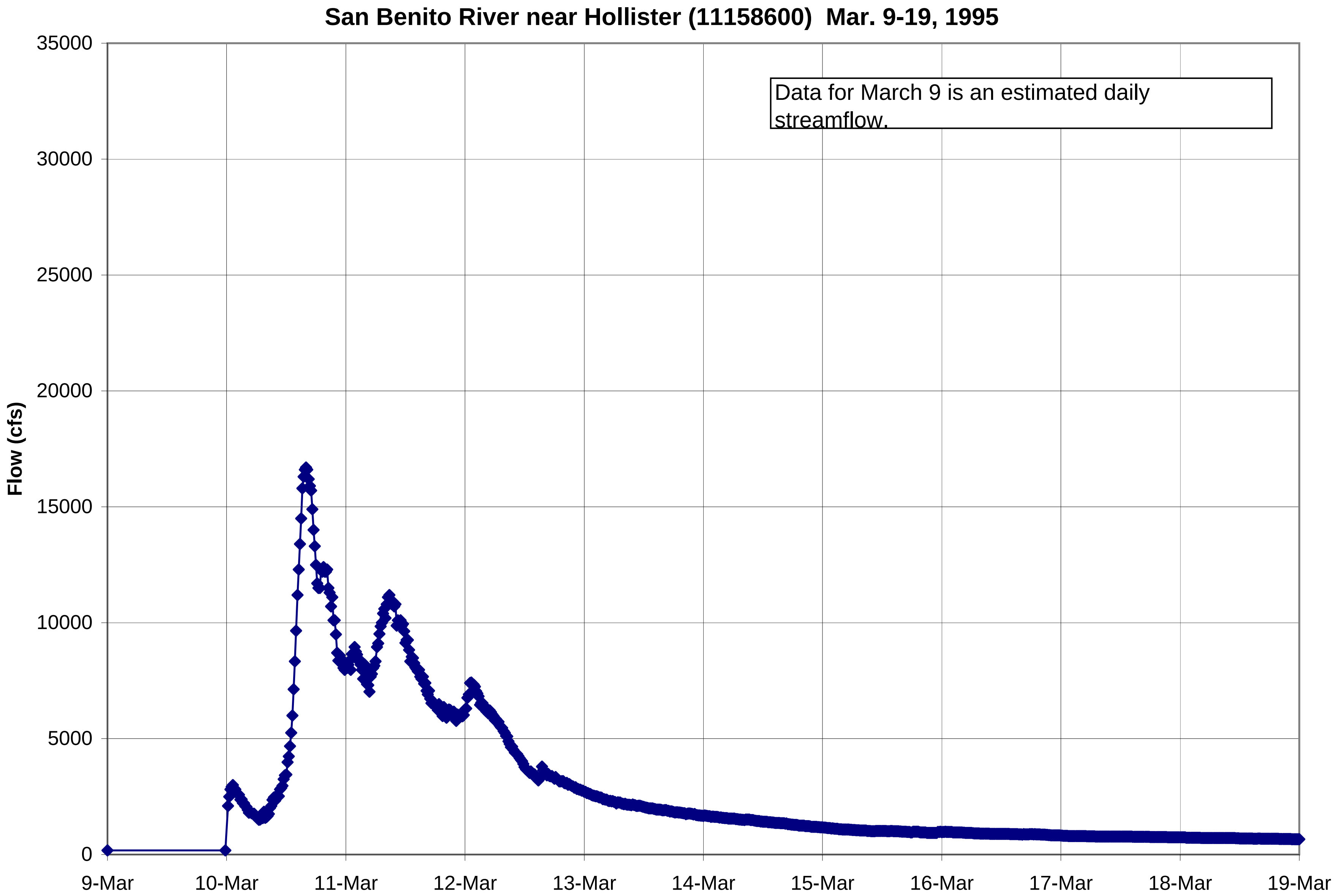

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Figure 3.4

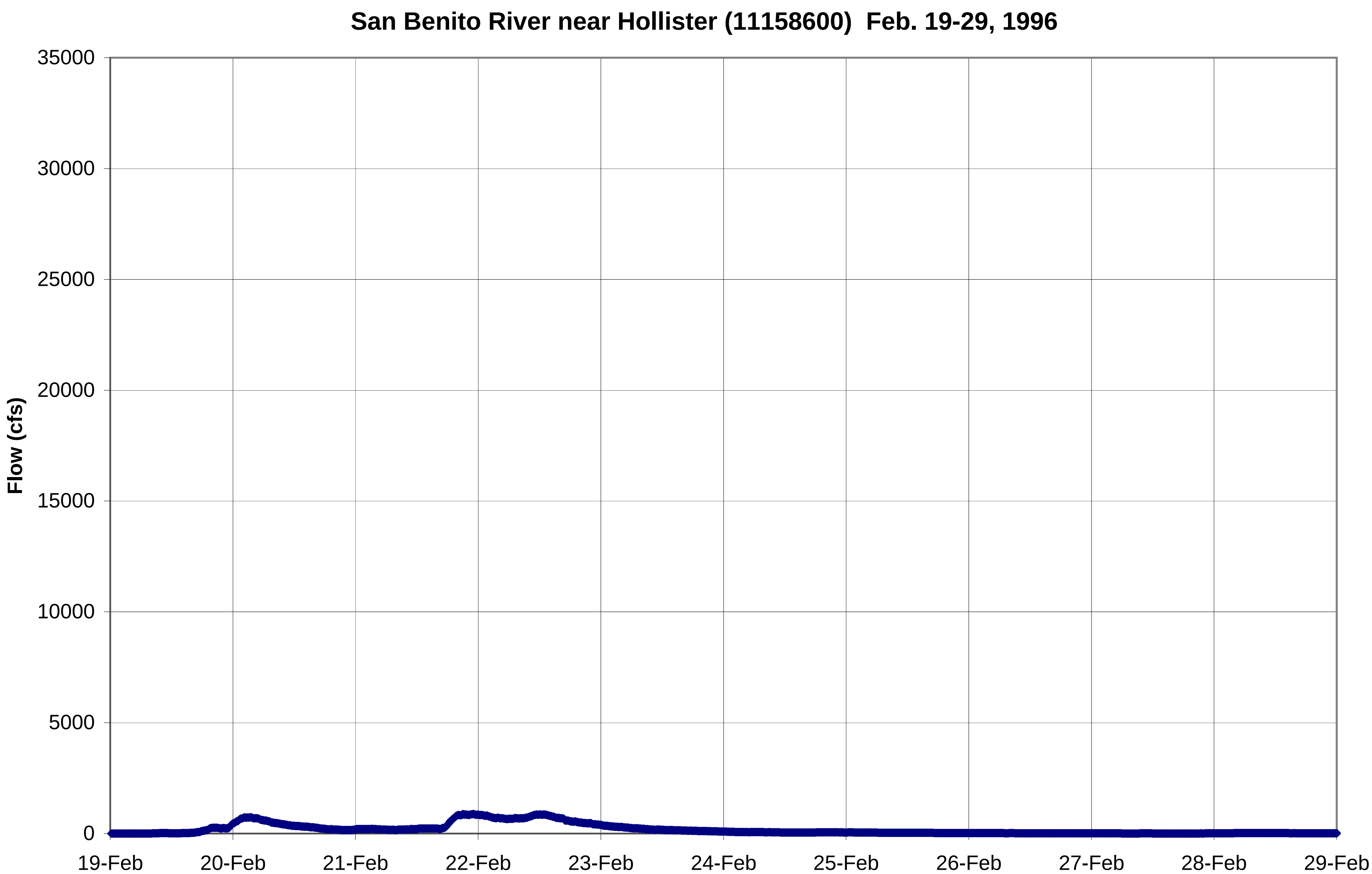

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Figure 3.5

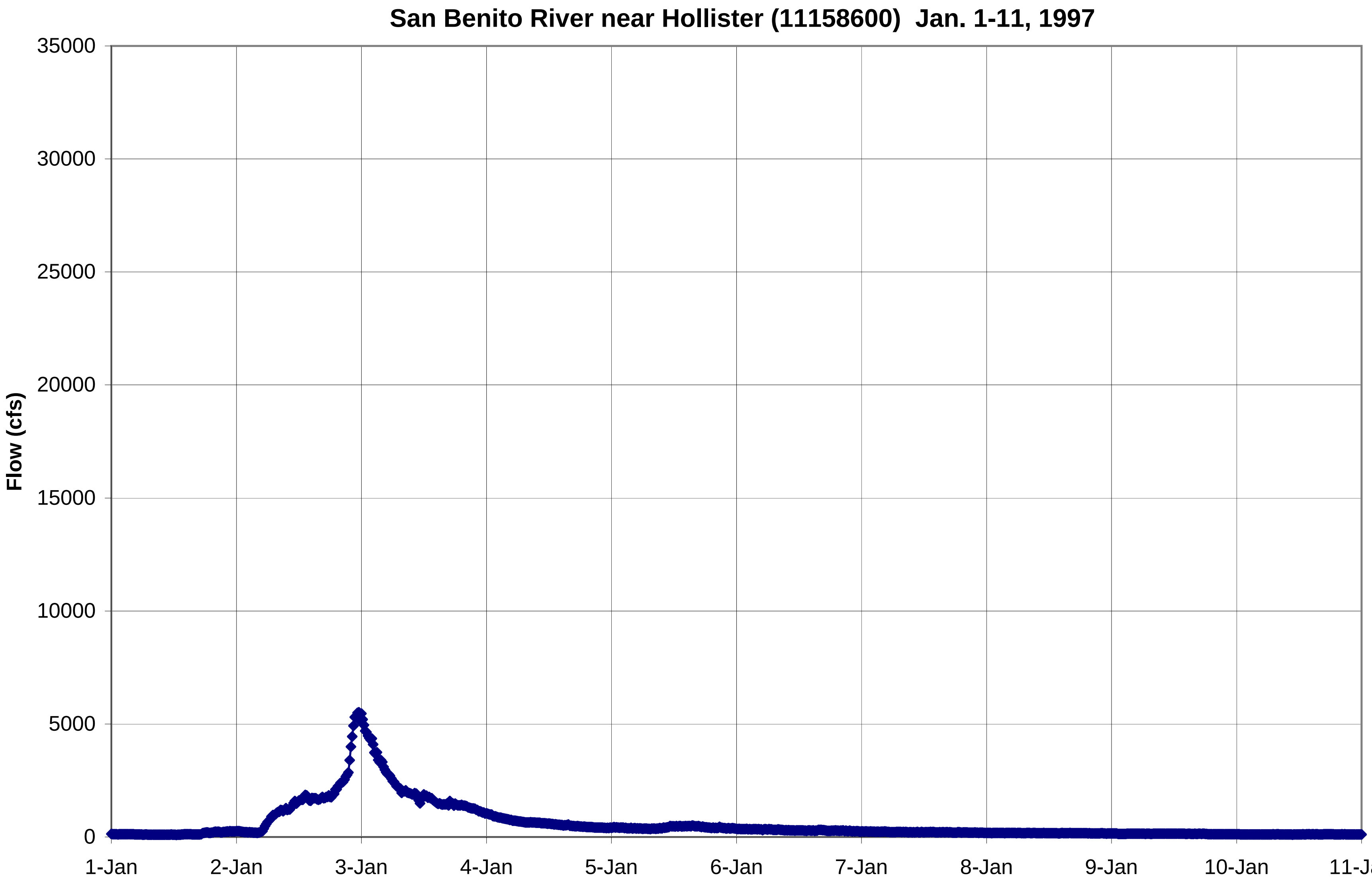

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Figure 3.6

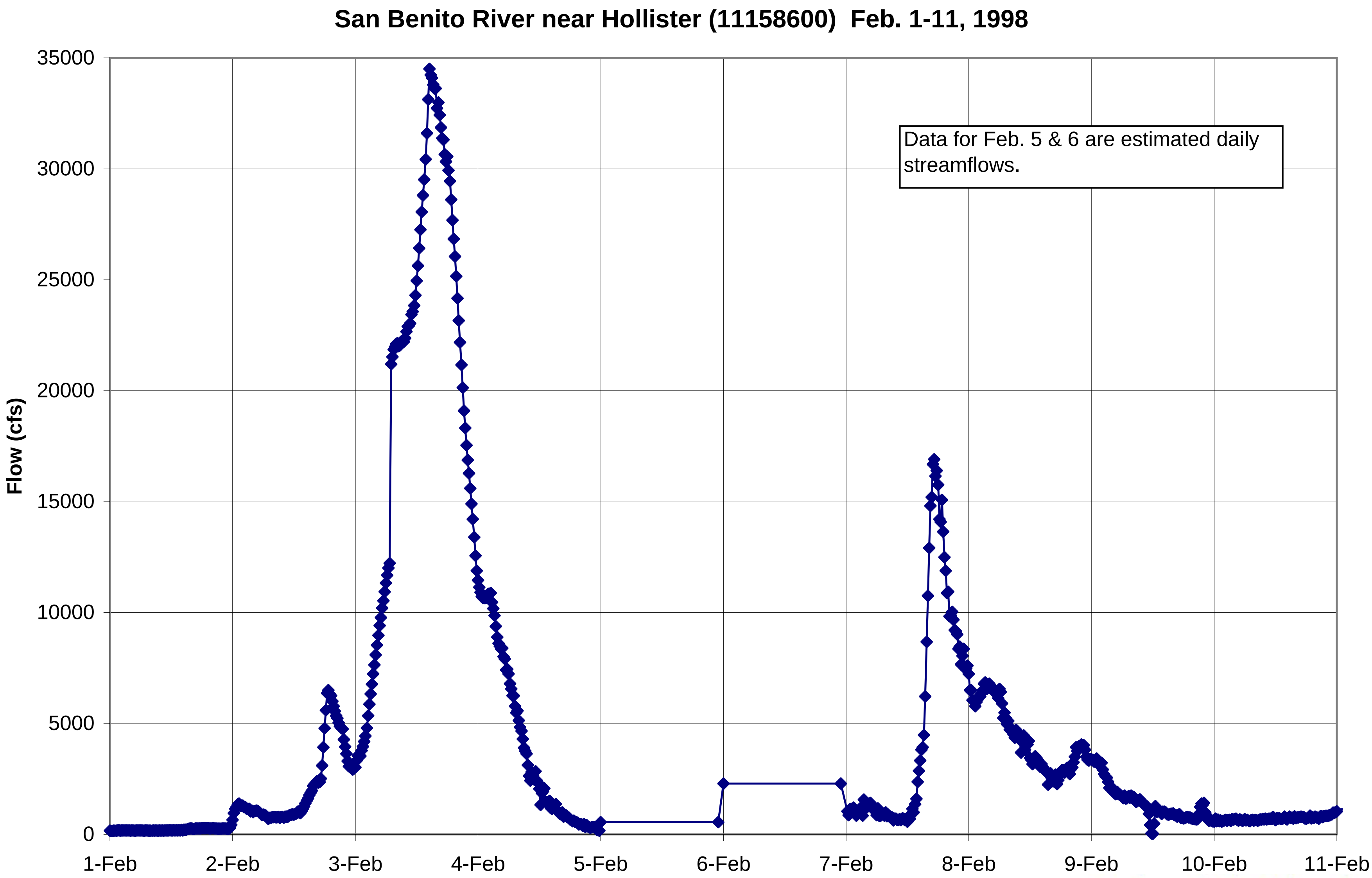

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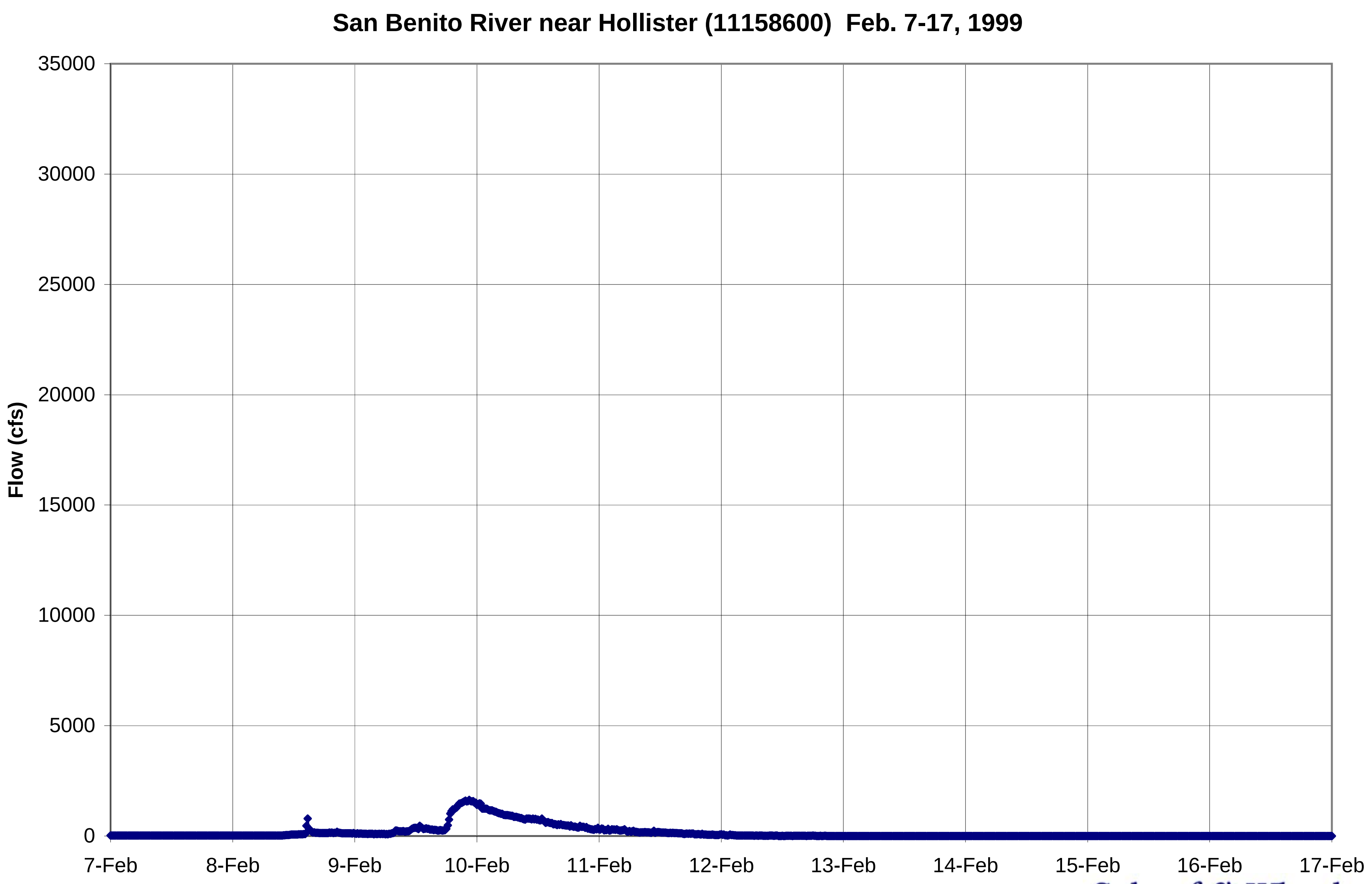
Figure 3. 7



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PAJARO RIVER WATERSHED

Final USGS Stream Flow Gages

11153040	Pacheco Crk @ Dunneville
11153700	Pajaro Rvr Nr Gilroy
11154000	Uvas Crk Nr Morgan Hill
11154200	Uvas Crk Nr Gilroy
11156500	San Benito Rvr Nr Willow Crk School
11157500	Tres Pinos Crk Nr Tres Pinos
11158600	San Benito Rvr @ Hwy 156 Nr Hollister
11159000	Pajaro Rvr @ Chittenden
11159200	Corralitos Crk @ Freedom

SCALE: 1" = 40,000'

FILE NAME: RMCI/07/dwgs/Fig3_8.dwg

Figure 3.9

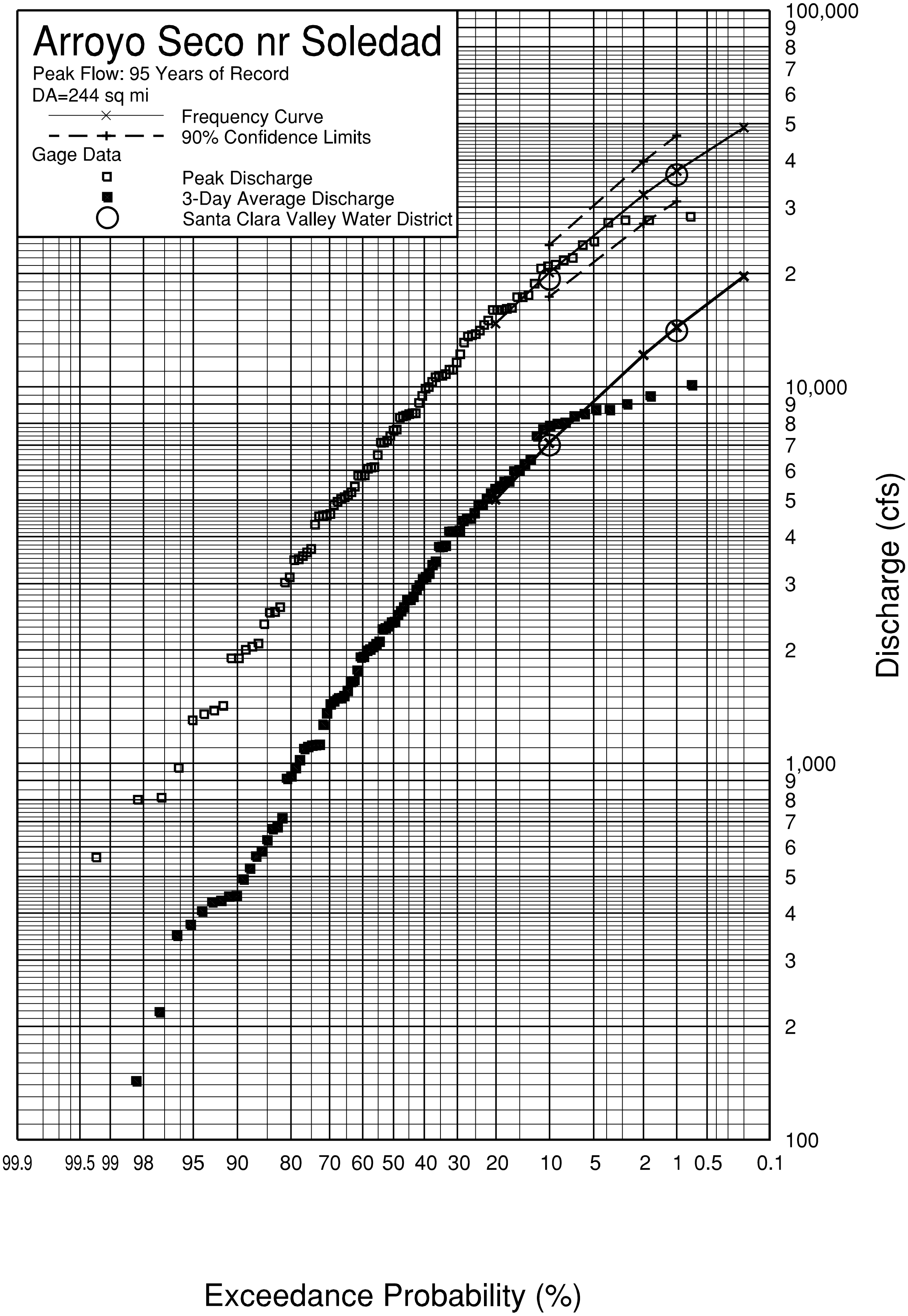

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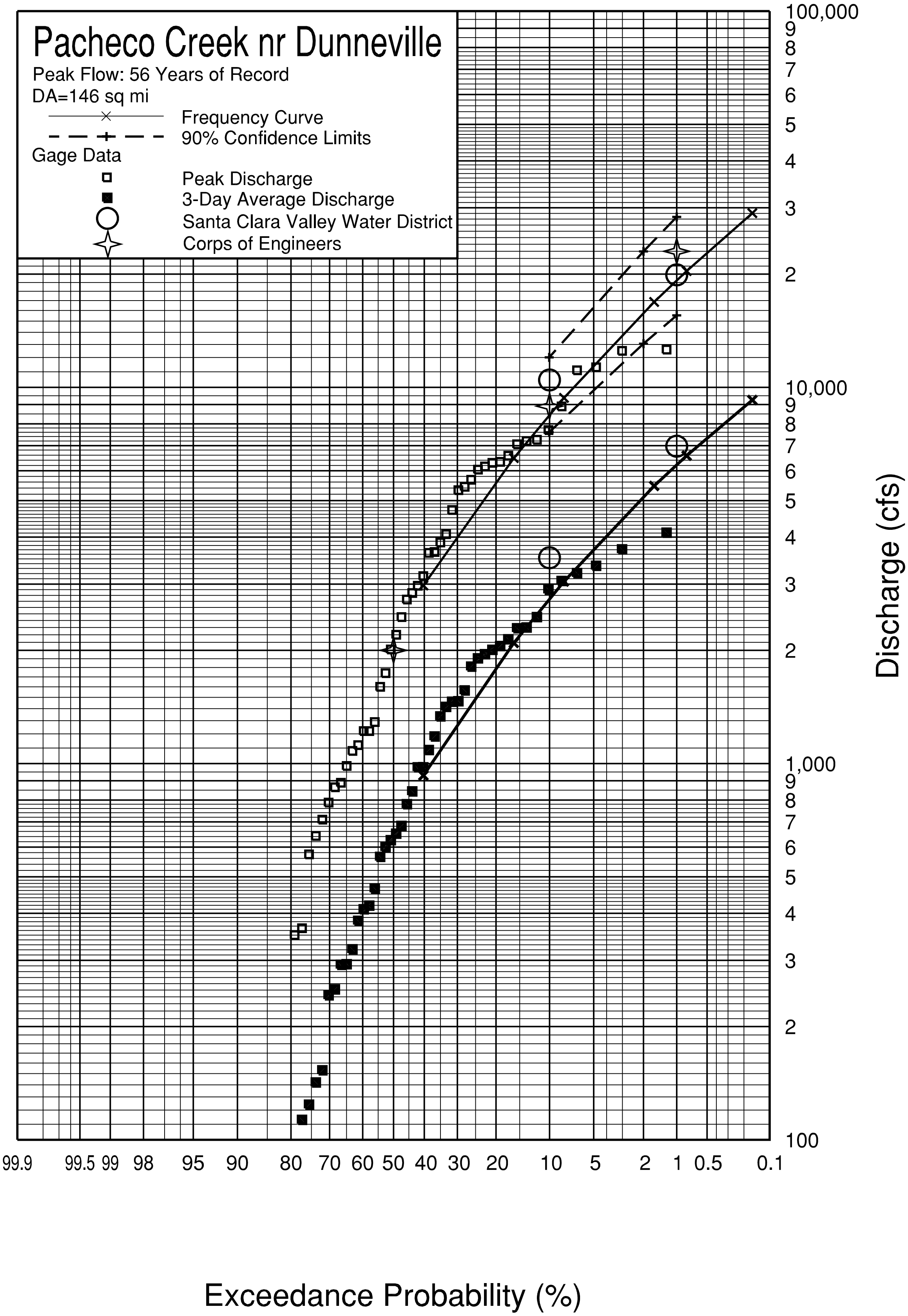
Figure 3.10



Schaaf & Wheeler

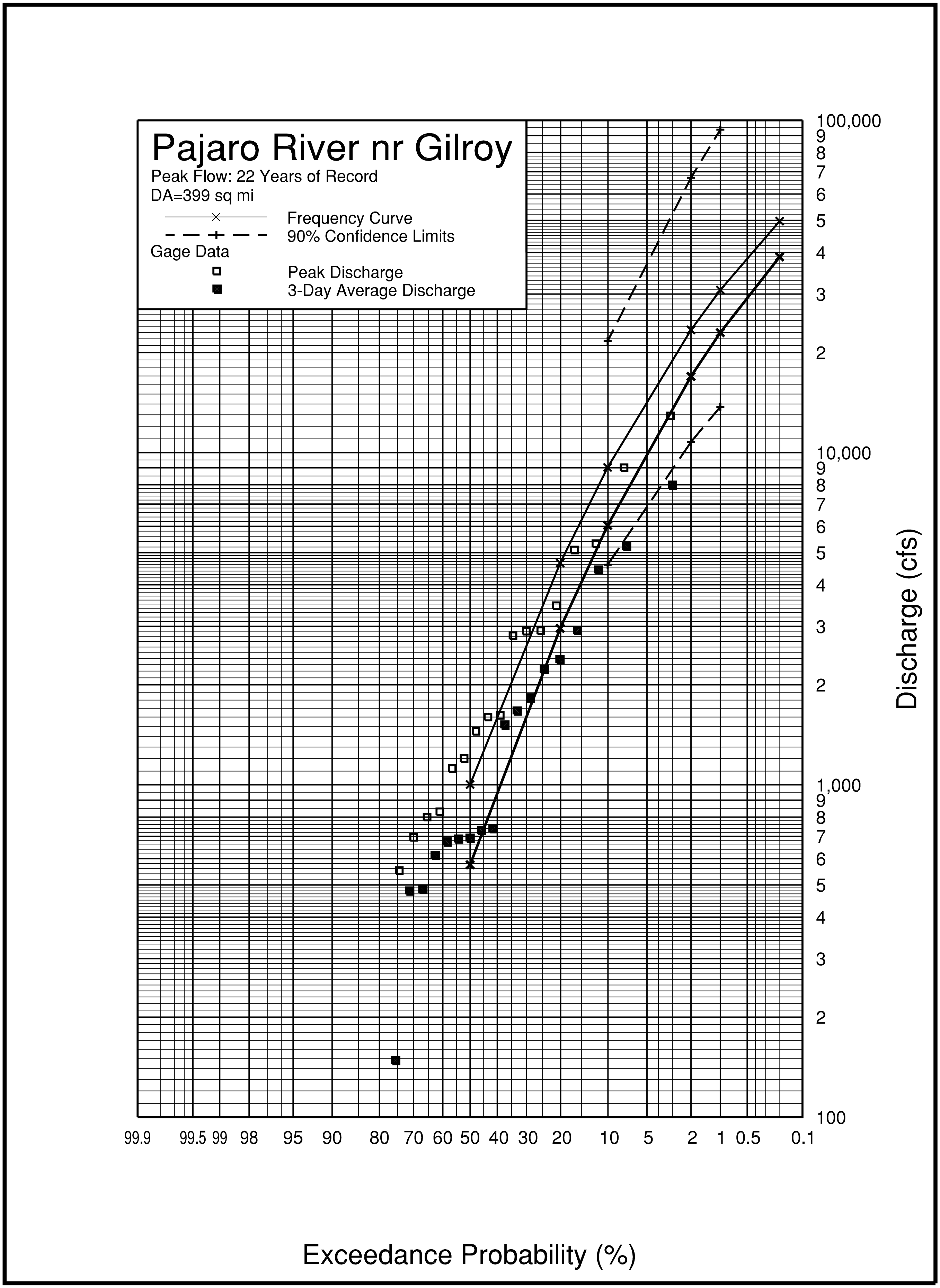
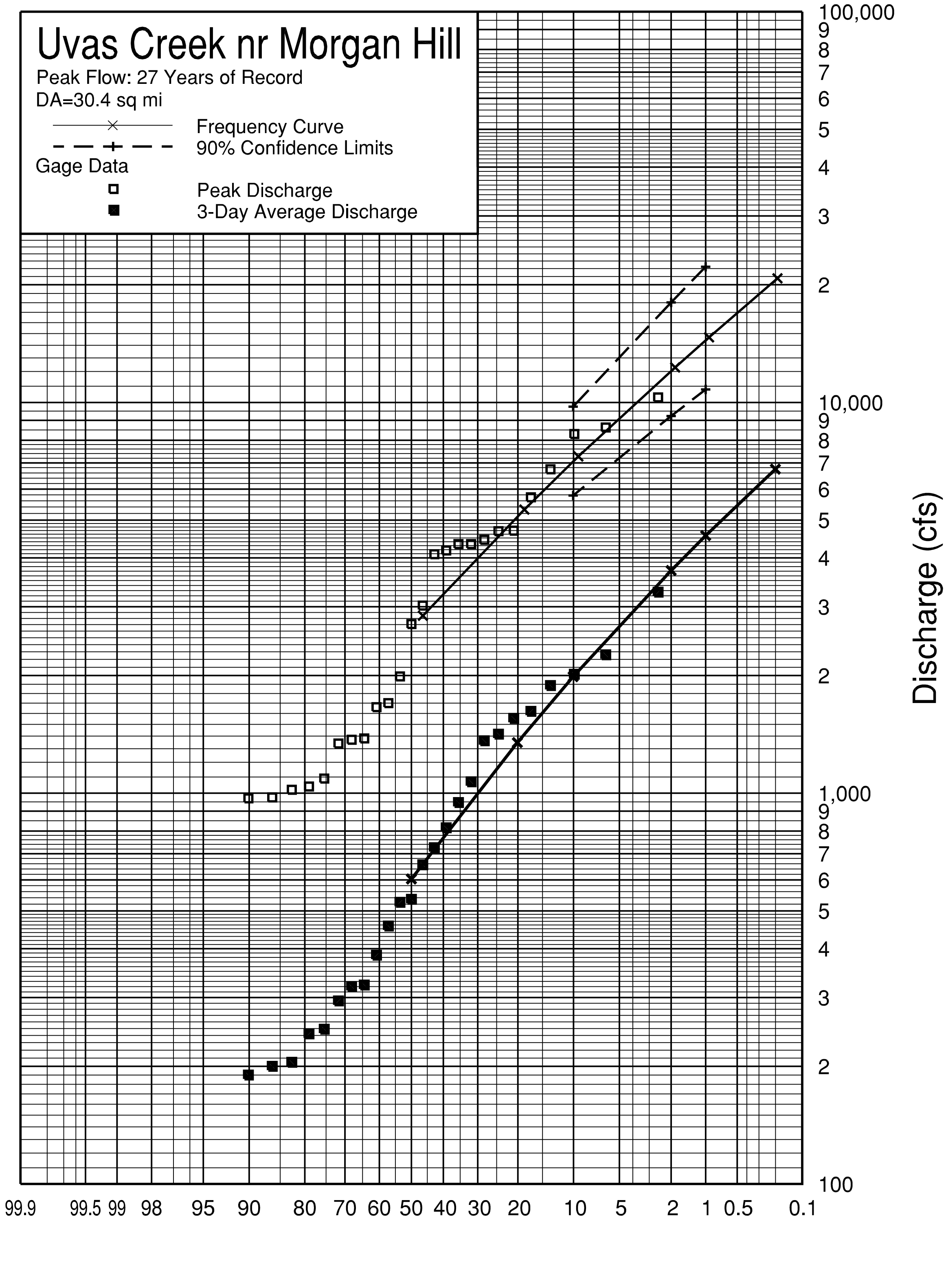
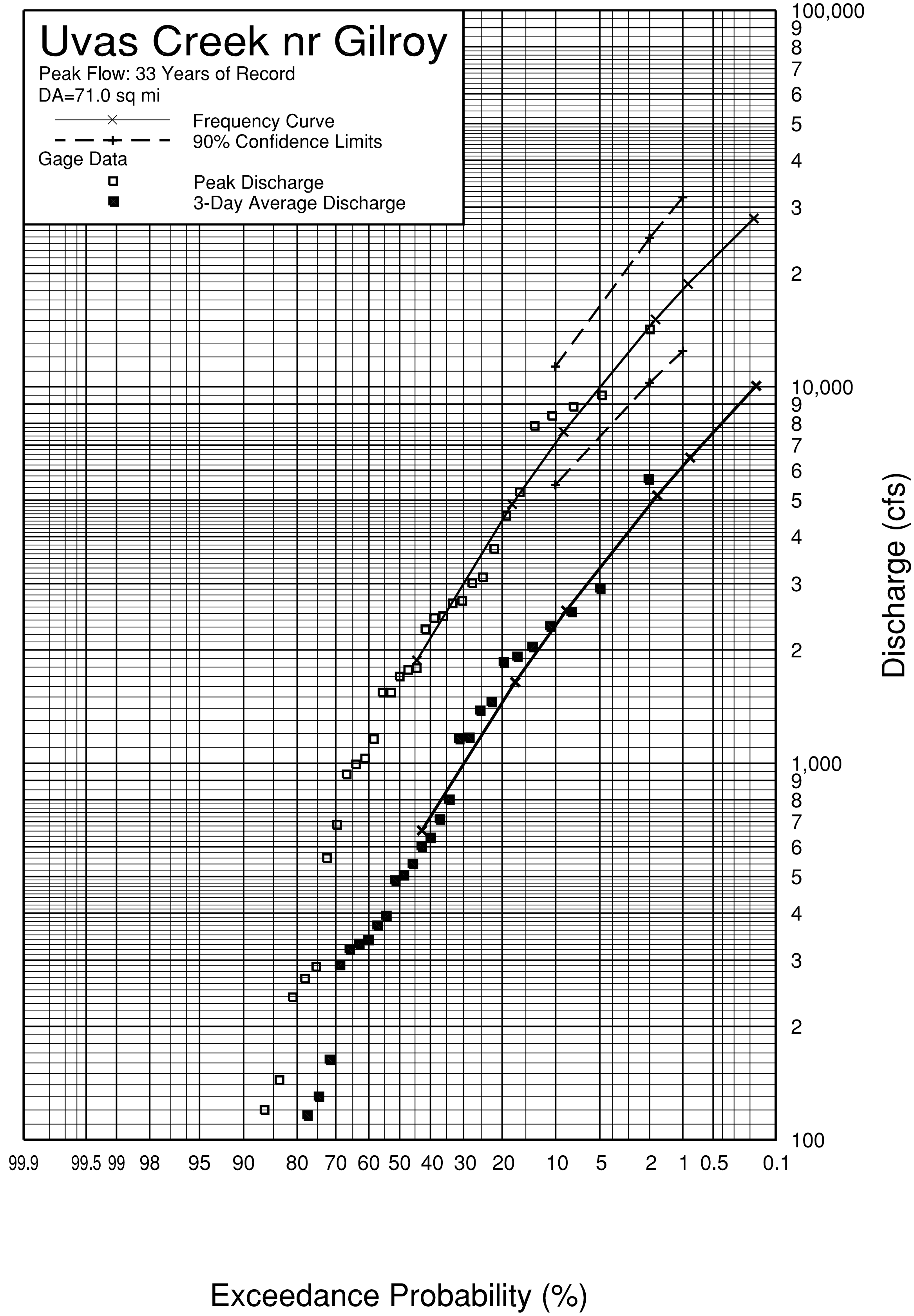

Pajaro River nr Gilroy
Peak Flow: 22 Years of Record
DA=399 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
100,000
9
8
7
6
5
4
3
2
10,000
9
8
7
6
5
4
3
2
1,000
9
8
7
6
5
4
3
2
100
99.9
99.5 99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.1
Discharge (cfs)
Exceedance Probability (%)

Figure 3.12



Schaaf & Wheeler

Figure 3.13



Schaaf & Wheeler

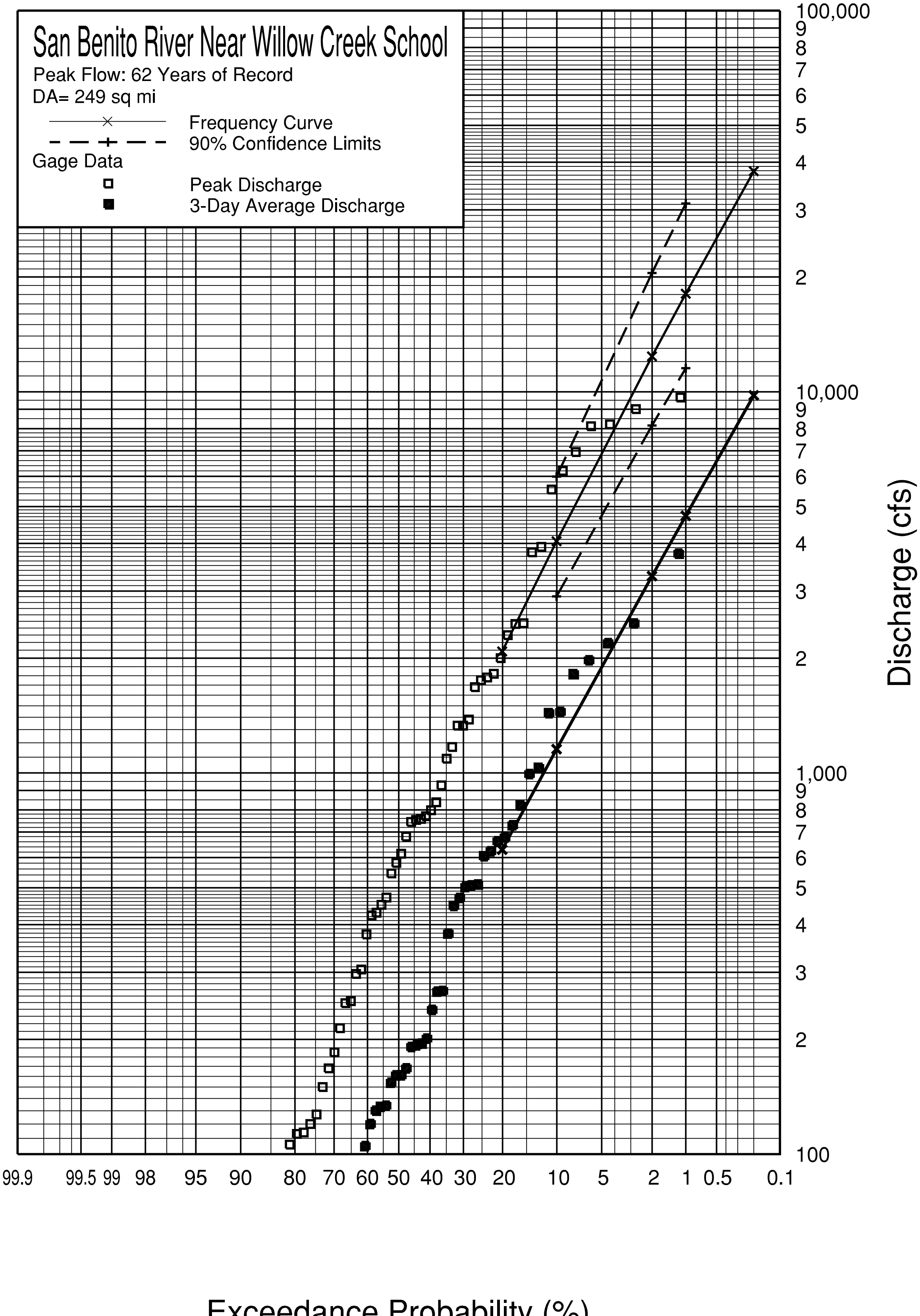
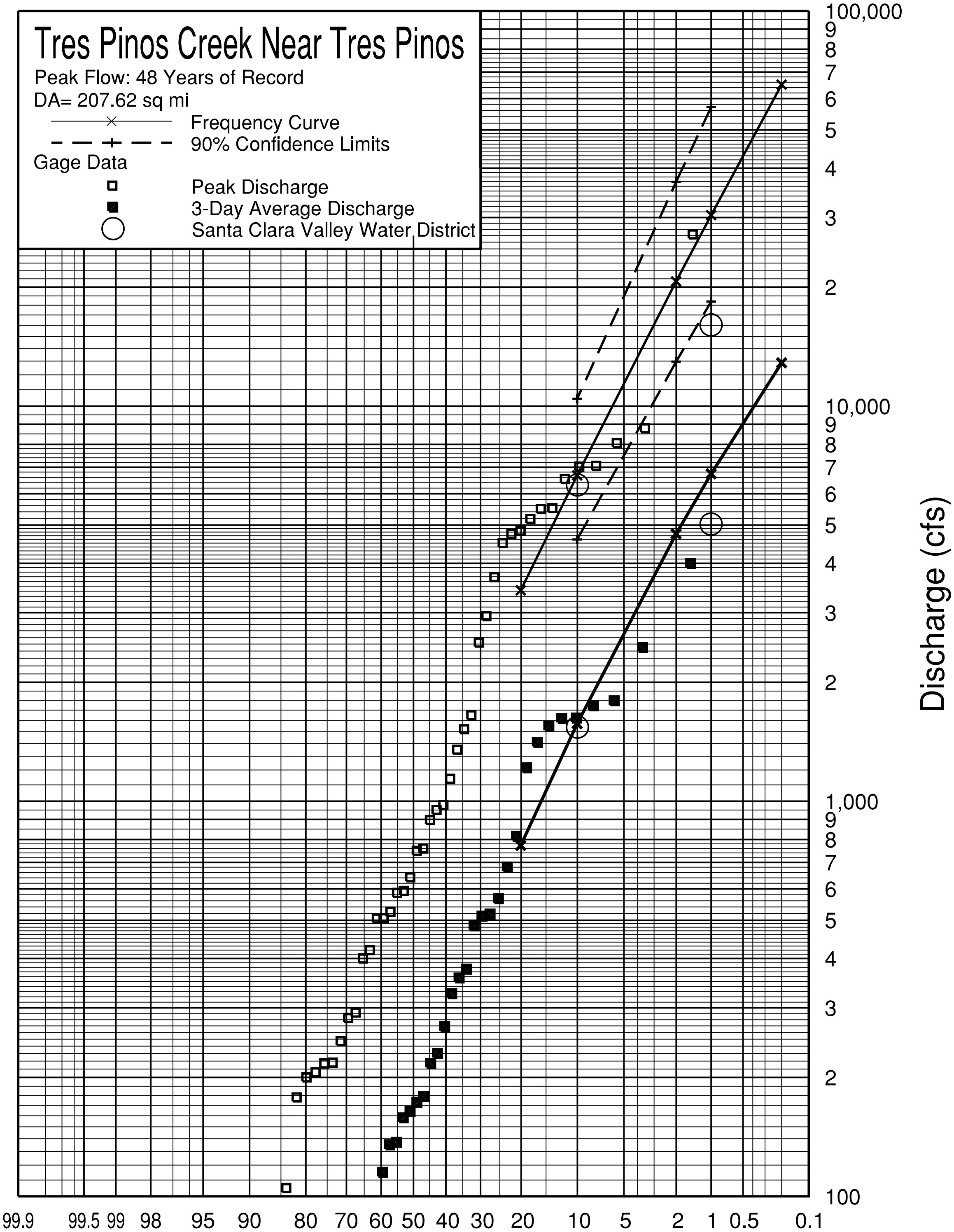
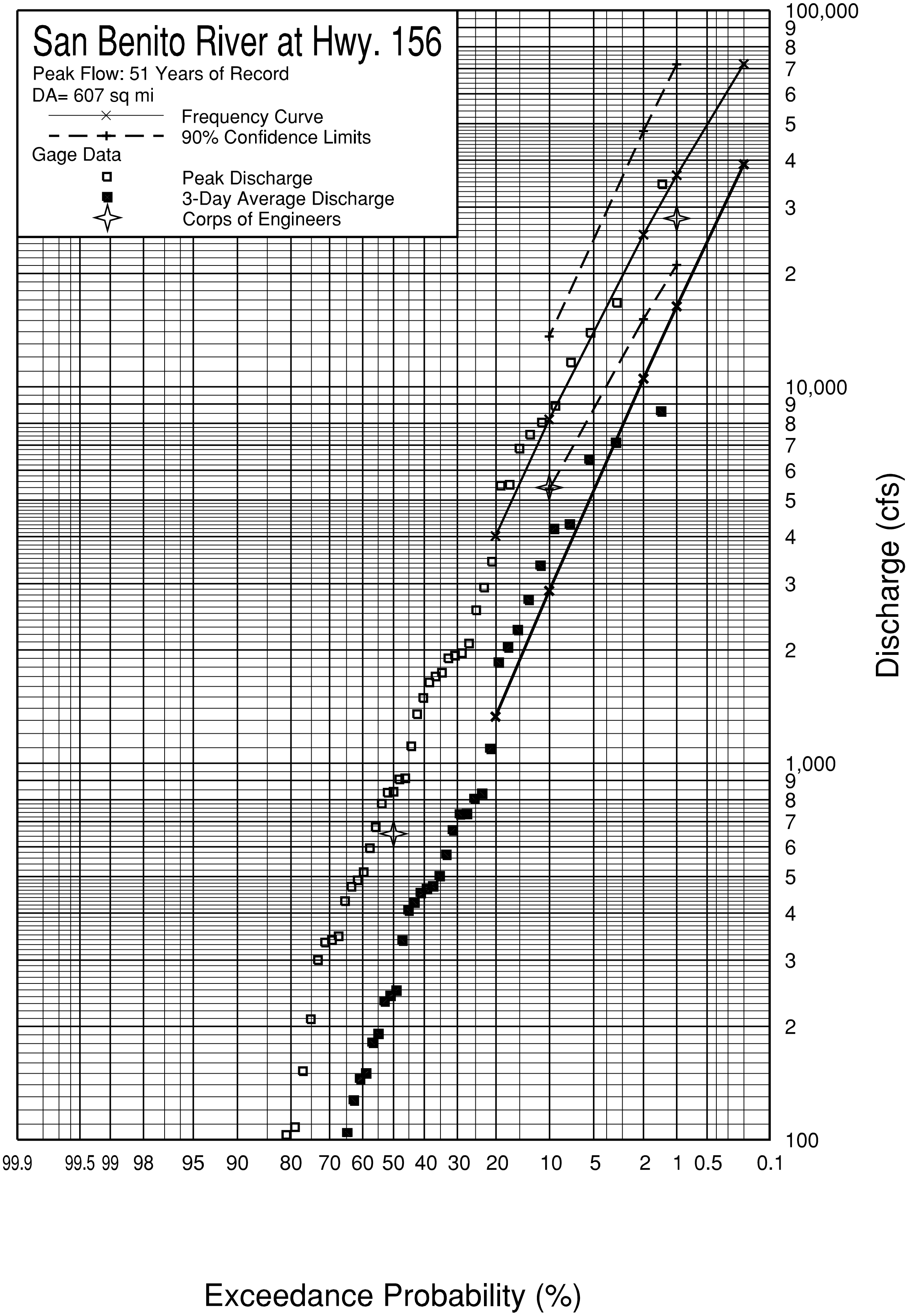
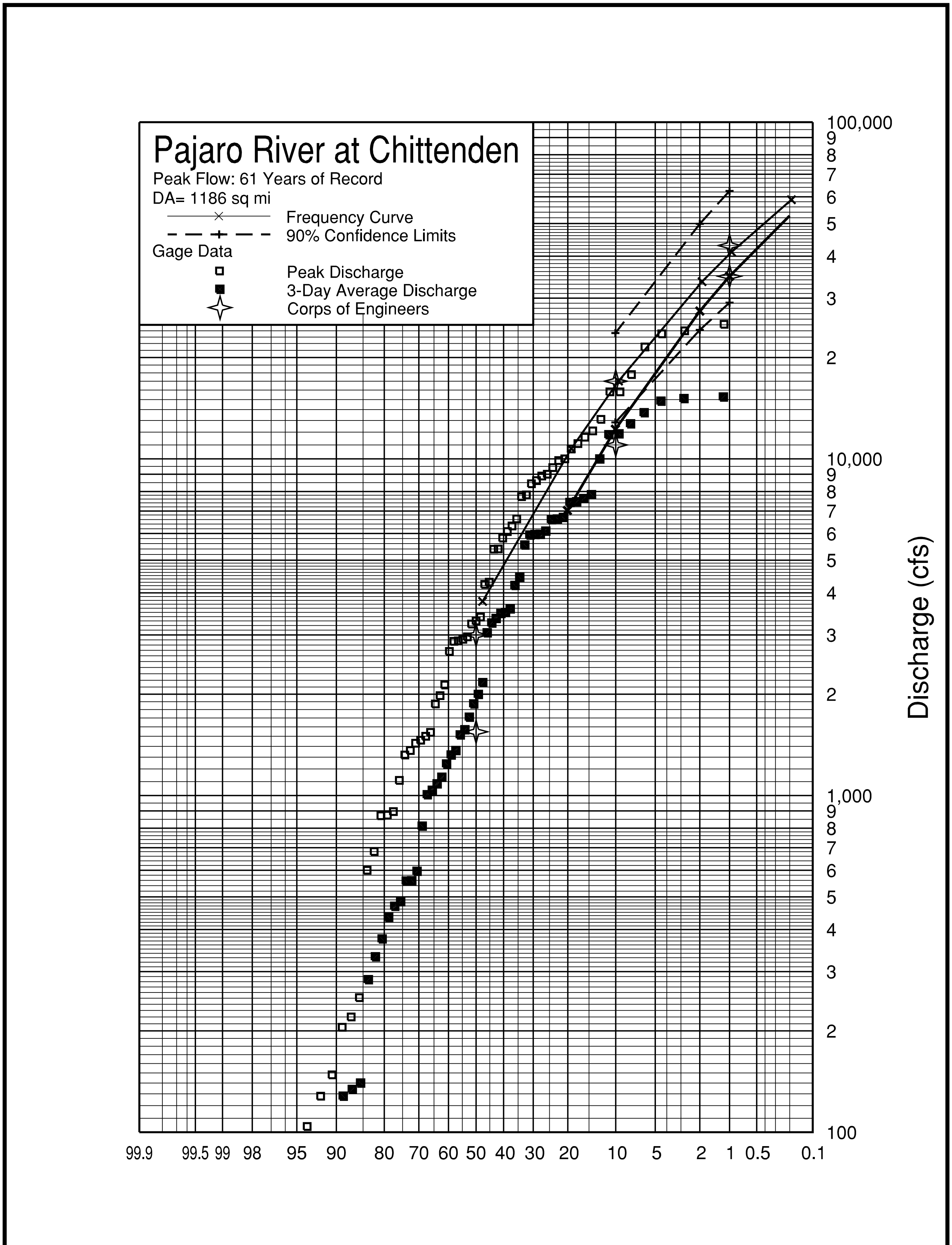

San Benito River Near Willow Creek School
Peak Flow: 62 Years of Record
DA= 249 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
100,000
10,000
1,000
100
Discharge (cfs)
99.9 99.5 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.1
Exceedance Probability (%)

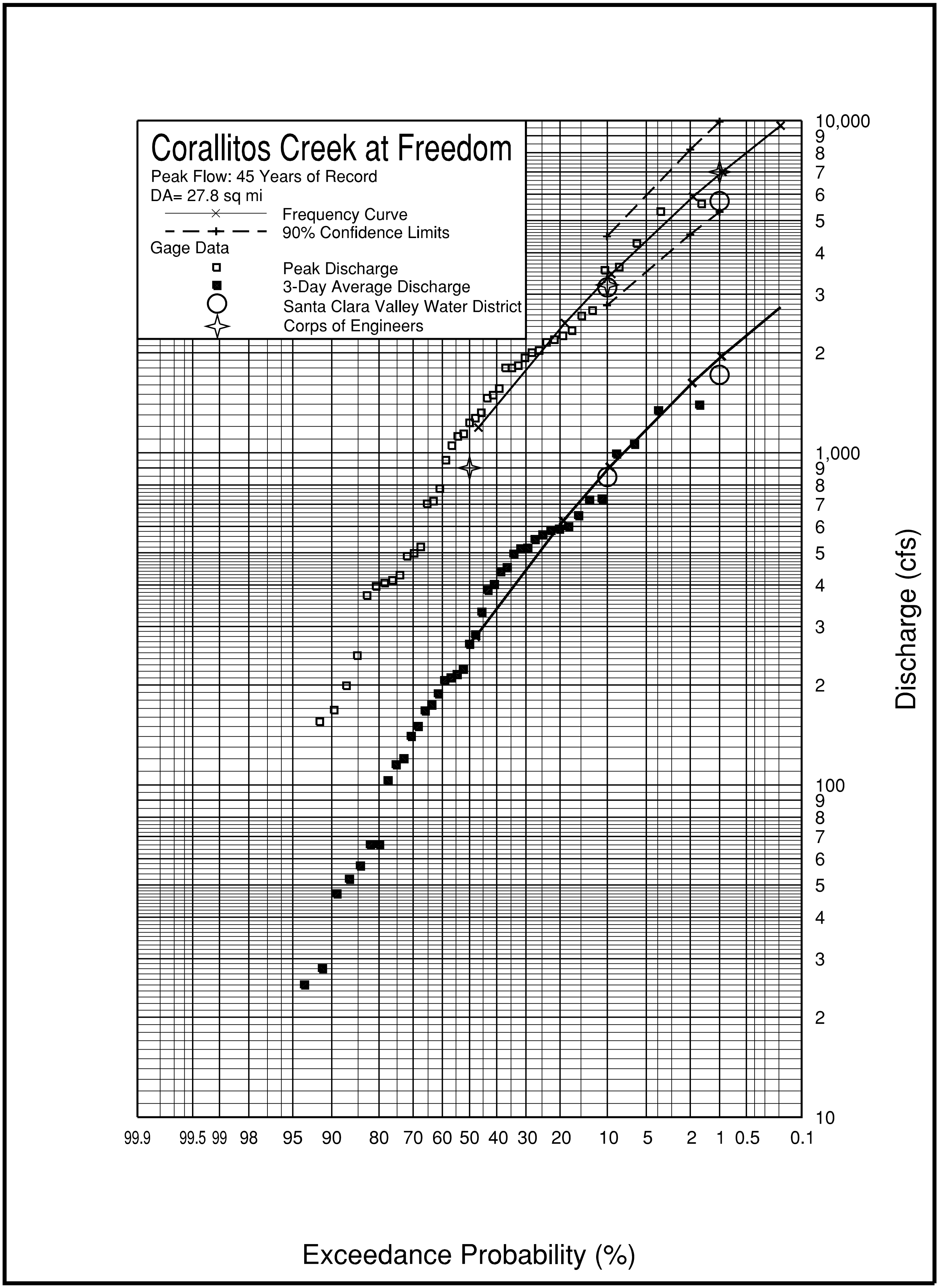
Figure 3.15



Tres Pinos Creek Near Tres Pinos
Peak Flow: 48 Years of Record
DA= 207.62 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
Santa Clara Valley Water District
100,000
9
8
7
6
5
4
3
2
10,000
9
8
7
6
5
4
3
2
1,000
9
8
7
6
5
4
3
2
100
Discharge (cfs)
99.9 99.5 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.1
Exceedance Probability (%)


San Benito River at Hwy. 156
Peak Flow: 51 Years of Record
DA= 607 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
Corps of Engineers
100,000
10,000
1,000
100
Discharge (cfs)
99.9 99.5 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.1
Exceedance Probability (%)


Pajaro River at Chittenden
Peak Flow: 61 Years of Record
DA= 1186 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
Corps of Engineers
100,000
10,000
1,000
100
Discharge (cfs)
99.9 99.5 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.1
Exceedance Probability (%)



Corallitos Creek at Freedom
Peak Flow: 45 Years of Record
DA= 27.8 sq mi
Frequency Curve
90% Confidence Limits
Gage Data
Peak Discharge
3-Day Average Discharge
Santa Clara Valley Water District
Corps of Engineers
10,000
9
8
7
6
5
4
3
2
1,000
9
8
7
6
5
4
3
2
100
9
8
7
6
5
4
3
2
10
99.9
99.5 99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.1
Discharge (cfs)
Exceedance Probability (%)

Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers

in association with

Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.4

Task: Collection and Analysis of Sediment Data

To: PRWFPA Staff Working Group

Prepared by: George W. Annandale

Reviewed by: Randy Raines

Date: February 13, 2002

Introduction

Sediment transport models require hydrologic input, sediment properties, an estimate of sediment yield and the physical geometry of the river channel. The physical geometry of the river is determined from surveys or topographic maps. The hydrologic input is in the form of a hydrograph, representing either a flood event such as the 100-year flood or a historic flood. It can also represent a flow sequence over a longer period of time, perhaps several years.

The bed of the Pajaro River consists mainly of non-cohesive sandy material. The properties that are required to characterize the sediment in the river are represented by the sediment gradations that were collected during the field reconnaissance. In addition to the sediment properties, a sediment transport model also requires an estimate of the sediment load that is discharged into the river from upstream or laterally from tributaries.

The sediment load estimate is derived from the sediment yield of a watershed. All of the water that reaches a stream carries sediment eroded from the drainage basin. The total amount of eroded sediment exported from such a drainage basin is known as its sediment yield. In order to adjust for different drainage basin sizes, the yield is expressed as a mass per unit area of drainage basin per year, i.e. tons per square mile per year ($t/mi^2/yr$) or tons per square kilometer per year ($t/km^2/yr$).

This Technical Memorandum (TM) presents the results of the sediment data analysis for the Pajaro River that was collected for the purposes of this project as well as the identification of sediment sources. It also provides an estimate of sediment yield.

Objectives of this TM

The objectives of this TM are to:

- Characterize bed and suspended sediment
- Identify sediment sources
- Estimate sediment yield

Project Scope and Background

A sediment transport model should be developed concomitantly with a hydrologic flow model to assist in the development of flood control strategies in the Pajaro River Watershed. The overall project objectives are to address the following issues:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Have the improvement and / or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?

The sediment transport model will be used in tandem with the hydrologic model to address these issues.

Setting

From a sediment transport and yield point of view, the watershed of the Pajaro River upstream of the Pacific Ocean can be divided into three principal components. The Upper Pajaro River and the San Benito River, the two upstream components, flow through Chittenden Pass to the Lower Pajaro River, the downstream watershed component.

Upper and Lower Soap Lake is an important feature that shapes the hydrologic and sediment transport response of the Upper Pajaro River. Lower Soap Lake is located just upstream of Chittenden Pass, with Upper Soap Lake even further upstream from Lower Soap Lake. All of the streams in the Upper Pajaro Basin upstream of Chittenden Pass first flow into Soap Lake before passing through to Chittenden Pass, and eventually downstream to the Lower Pajaro River. The Upper and Lower Soap Lake merges into one water body under high flow conditions.

Upper and Lower Soap Lake plays an important role in attenuating upstream floods and, as flow velocities decrease in the lake, depositing sediment. Interpretation of field data and the hydrologic and hydraulic modeling studies conducted for this project indicates that Soap Lake is very effective in trapping sediment that is generated from the Upper Pajaro River and its tributaries.

The San Benito River flows into the Pajaro River just downstream of the Soap Lake area on the upstream end of Chittenden Pass. The San Benito River has historically been subject to significant gravel mining operations. The mining in the riverbed and on its banks lead to degradation of the river, which resulted in a riverbed with negligible armoring, and with exposed riverbanks. Armoring, which often occurs in natural riverbeds, is a coarse layer of gravel and cobbles located on the top of a riverbed protecting the finer material below. The absence of an armor layer can lead to degradation of a riverbed if the incoming sediment load from upstream is less than the sediment load that is transported by the river in a downstream direction.

A previous study by Golder Associates Inc. (1997) concluded that the San Benito River has degraded significantly since the early 1950's. It was found that the San Benito River currently behaves like a compound channel in certain reaches. When the water discharge is low some sections of the channel are braided; with the same section changing to meandering flow when the water flow increases. This observation implies that the San Benito River is in a state of transition and that it is currently still seeking a state of quasi-equilibrium. A river is in a state of quasi-equilibrium when its behavior and fluvial geomorphology are relatively consistent over long periods of time. The San Benito River is currently still adjusting its fluvial geomorphology to accommodate the impacts of gravel mining that took place over many years.

The Lower Pajaro River receives sediment flowing from Chittenden Pass and contributes additional sediment from its own watershed. Row crops, in some cases having replaced orchards, cover large areas of the Lower Pajaro River watershed and contribute to the sediment load in the river.

Data collection

Field reconnaissance of the Pajaro River was executed on August 15 to 17, 2001, November 26 to 30, 2001 and at the end of January, 2002. Notes of field observations were made, digital photos were taken and sediment samples were collected for analysis. The locations of the 24 sediment samples that were taken from the riverbed and riverbanks of the Pajaro River were determined by means of GPS and are shown in Table 1.

Soil type data for the watershed as a whole was collected and plotted on a GIS map (see Technical Memorandum 1.2.8). In addition to this data, suspended sediment data that was collected by the USGS over the period 1978 to 1992 (14 years) was also obtained (Figure 1).

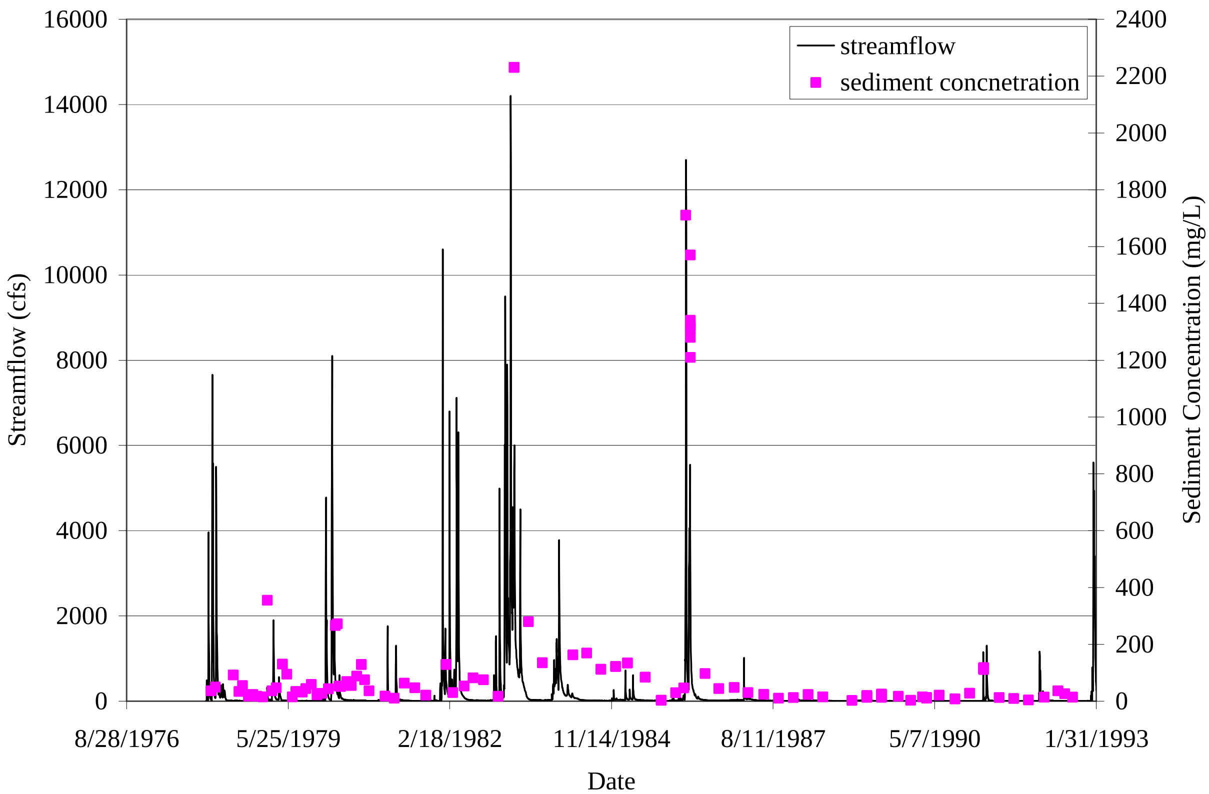


Figure 1. Sediment and Water Discharge at Chittenden gauge.

Sediment Sources

Bank Instability

As riverbanks fail under high flow conditions they add to the sediment load of the river. Unstable riverbanks were identified in a number of reaches of the Upper and Lower Pajaro River, and in the San Benito River. The locations of a number of bank failures that occurred during flood conditions within the levee portion of the Lower Pajaro River have been identified.

Riverbanks that are in the process of failing have also been identified in the Pajaro River through Chittenden Pass (Figure 2). These photos show trees leaning into the river, which are signs of bank failure in process. Bank failure in river reaches in the Upper Pajaro River has also been identified, but with the controlling effect of Soap Lake on this portion of the watershed the sediment that is produced by such failures is not contributed to the Lower Pajaro River. Bank failure in the degraded portion of the San Benito River under flood conditions is quite common in certain reaches (Figure 3). However, such failure also occurs in portions of the river upstream of the degraded reach (Figure 4).

Figure 2. Leaning trees in the Pajaro Gap in Chittenden Pass are an indicator of riverbanks that are in the process of failure.

Figure 3. San Benito River, showing braiding, mobile riverbed and bank erosion.

Figure 4. Bank failure in the upper, non-degraded reaches of the San Benito River.

Riverbed

The riverbeds of the San Benito, and Lower and Upper Pajaro Rivers generally lack armoring. Armoring is a layer of gravel and cobbles that often form in riverbeds where such material is present. This upper layer of coarse material usually protects the finer material beneath it against the erosive power of flowing water. The general absence of armor layers in the riverbeds of the rivers under investigation allows the riverbeds to possibly be mobilized by the erosive power of water flowing in these river channels during flood events. Mobilization of this material results in it being either suspended in the water or conveyed along the riverbed as bedload. As such the loose riverbed material is a source of sediment. Table 1 contains a list of sediment sample locations and median grain sizes (D_{50}) for samples taken by E&H on the Pajaro River.

Land Use

Various land uses occur in the watershed of the Pajaro and San Benito Rivers. By categorizing the known land use it is found that urban, industrial and mining land use occupies approximately 2% of the area, natural land (forest, grassland, etc.) occupies approximately 83%, and agricultural activities (orchards, row crops, hay) approximately 15%. This data is based on TM 1.2.6 completed by RMC.

Table 1. Sampling Locations and Median Particle Diameter (D_{50}).

Sample	Location	Distance from Bay (miles)	Median Grain Size (mm)
S20	W09	24.5	0.08
S19	W04	22.9	11.68
S18	W04	22.9	0.47
S27	W20	22	< 0.08
S25	W16	21.2	< 0.08
S24	W14	20.9	2.71
S26	W18	20.1	1.04
S17	W03	18.7	0.58
S16	W02	16.6	0.79
S12	WP15	15.1	0.22
S13	WP15	15.1	0.39
S14	WP15	15.1	0.41
S29	W22	13	< 0.08
S28	W21	11.6	0.17
S9	9R3	9.4	0.56
S8	13R3	9.3	2.18
S7	13R3	9.3	17.55
S6	14R3	9.2	0.16
S31	W24	8.4	1.46
S4	7R3	6.5	0.56
S3	6R3	6.4	1.46
S2	2R3	4.5	0.62
S1	2R3	4.5	0.76
S30	W23	2.6	0.11

Urban Development

The percentage area occupied by urban development is small relative to the other land uses (Figure 5) and is not considered to contribute significant volumes of sediment relative to the remainder of the watershed land uses.

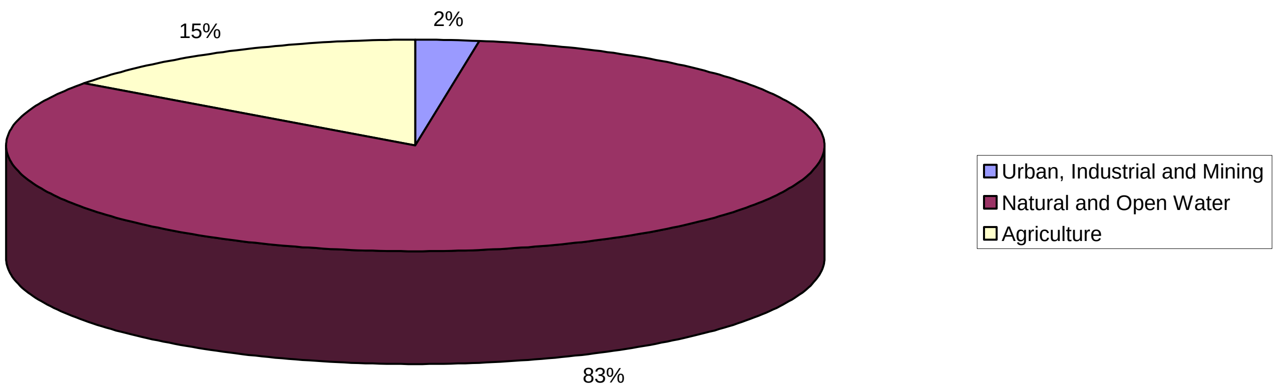


Figure 5. Land Use Summary for the Pajaro and San Benito River Watershed (TM 1.2.6, Pajaro River Watershed Study)

Agriculture

Agriculture is a dominant land use (aside from natural land) in the watersheds of the Pajaro and San Benito Rivers, occupying approximately 15% of the total watershed area and potentially producing significant volumes of sediment in certain locations. Observations made during the field reconnaissance did not reveal any significant efforts to control sediment production that originates from agricultural lands.

In the upper reaches of the Lower Pajaro River significant sediment loads are contributed by Coward Creek and by Corralitos Creek, which flows into Salsipuedes Creek and eventually into the Lower Pajaro River. The watersheds serving both of these creeks into the Lower Pajaro River are heavily farmed with row crops, often right to the edges of streams and drainage ditches adjacent to roads. The road ditches drain into streams, with the water eventually flowing into the Pajaro River (Figures 6 (a) and (b)).

The row crops in the levee portion of the Lower Pajaro River also drain into the Pajaro River through valves in the levees. The water flowing in the drainage ditches from the lands entrain sediment that is transported to the Pajaro River.

Figure 6. (a) Cultivation up to the edge of the stream, upstream of Coward Creek.

Figure 6. (b) Cultivation up to the edge of the road upstream of Salsipuedes Creek.

Grazing is practiced in the watershed but appears well managed. Sloughing of hill-sides has been observed in the San Benito River watershed, but usually does not contribute to the sediment load of the river because the sloughs are too far from the river banks and do not contribute to tributaries flowing into the San Benito River. Sloughing of material occurs higher up on the hill slopes, as is often observed in Northern California (Figure 7). In 1998, however, landslides in the Tres Pinos tributary to the San Benito River were significant. The sediments were carried into the San Benito River where they deposited near Hollister, apperently increasing the bed levels in that localized area (Paxton 2002).

Figure 7. (a) Sloughing in grazed land but located far away from the river, resulting in no significant contribution to sediment load in the San Benito River.

Figure 7. (b) Cows grazing in the San Benito River bed, close to the confluence with the Pajaro River.

Mining

Historic mining activity, dominant in the San Benito River for a long period of time, caused the river to degrade. The degraded condition of the river exposes river banks to erosion and removed the armor layers from the river, should that have existed previously. The exposed banks and bed of the river contributes to the sediment load under high flow conditions. Failing river banks increase sediment load, as does riverbed mobilization.

The exposed riverbed and riverbanks in the San Benito River are subject to erosion during high flood events. Mobilization of the riverbed and failure of the riverbanks under such conditions contribute to the sediment load in the water that is discharged from the San Benito River through Chittenden Pass to the Lower Pajaro River. According to the San Benito County Planning Department, two of the four permitted gravel mining companies in the San Benito watershed have not been mining since 1996 and 1998 (Paxton 2002). As the mining companies discontinue operations, it is possible that the San Benito River could converge towards a quasi-equilibrium condition in the future, possibly with the additional assistance of some stabilization activities.

Relative Contribution to Sediment Load

Interpretation of data collected during the field reconnaissance and of discussions with Schaaf & Wheeler pertaining to the hydrologic and hydraulic modeling of the San Benito and Upper and Lower Pajaro Rivers (other TMs) lead to the following conclusions:

- Most, if not all of the sediment flowing into the Lower Pajaro River through Chittenden Pass originates from the San Benito River.

- The sediment load that originates from the Upper Pajaro River is mostly trapped in the Lower and Upper Soap Lake area, resulting in negligible contribution of sediment load to the Lower Pajaro River.
- Large volumes of sediment appear to originate from Salsipuedes and Coward Creeks in the Lower Pajaro River, originating from farmland with little, if any, erosion control. Some of the sediment in the Lower Pajaro River also originates from the farmland adjacent to the levee. These loads are introduced into the river from the lands through drainage canals.

It is reasonable to assume that most of the suspended sediment load that has been measured by the USGS at the Chittenden gauge originates from the San Benito River Watershed.

Conclusions made from the field observations in both the Upper Pajaro River and the San Benito River watersheds indicate that the sediment load that is discharged into the Lower Pajaro River through Chittenden Pass mainly originates from the San Benito River. However, the riverbanks in Chittenden Pass itself are unstable in many locations, as evidenced by trees that are located on the banks leaning into the stream. When trees that are located on a riverbank lean towards a stream it usually indicate that the riverbank is in a process of failure. As flows increase the erosive power of the water in contact with the riverbank can destabilize the bank further and cause failure. The sediment that is generated from such failures adds to the sediment load of a river.

Sediment Yield

Estimates of sediment yield were made by using a number of techniques and comparing the results with estimates by others in the Pajaro River and surrounding areas. The methods of Denby and Bolton (1976) and the PSIAC method (PSIAC, 1968) were used to estimate sediment yield. These estimates were compared with the results of two sets of analyses of field data. The analyzed field data includes an analysis of the volume of sediment that was deposited in Hernandez Reservoir over a period of 39 years. In addition, an estimate of sediment yield was also made by analyzing the suspended sediment data that was collected at the USGS gauge at Chittenden over a period of 14 years.

Hernandez Reservoir

Hernandez Reservoir was commissioned in 1958 and was surveyed in 1988 and 1997. The estimated volume of sediment that was deposited in the reservoir over the periods 1958 to 1988, and 1988 to 1997 were used to calculate sediment yield from the 221 km^2 watershed upstream of the reservoir. It is estimated that the average sediment yield upstream of Hernandez Reservoir ranges between 250 to 290 $t/km^2/yr$.

USGS Chittenden Gauge Data

The sediment data collected by the USGS at Chittenden Gauge has been analyzed to develop a rating curve that was used to estimate the average annual suspended sediment load at Chittenden

Gauge. The estimated sediment load was multiplied by a factor of 1.05 to account for an estimated 5% bedload that should be added to the suspended load to calculate the total load.

The relationship between sediment discharge and concentration as a function of water discharge is called sediment rating curve or sediment transport curve. Two types of relationships are commonly used: (i) concentration versus discharge and (ii) load versus discharge.

Mathematical curve fitting was used to fit a curve between the suspended sediment load and water discharge for Chittenden Gage. A particular weakness of mathematically fitted curves in the log-domain is the potentially poor fit at the high extreme, which are often represented by few data points only (Morris and Fan, 1998). The appropriateness of a rating curve can be determined by using the curve and the measured instantaneous flows to calculate sediment loads. The calculated sediment loads are then compared with the measured loads and an error is determined. If the error is large, the rating curve should be modified because it is not considered representative of the actual conditions at the gauge. In the case of Chittenden Gauge it was found that the error between calculated and measured sediment loads was 52%.

The error can be reduced by developing a modified rating curve. This was done by dividing the data into discharge classes and computing the mean sediment load within each discharge class. The average flows, representing classes, and the average sediment load, representative of the same classes, were used to develop a new rating curve. The comparison between sediment loads calculated with the revised rating curve and the measured sediment loads was only 17%, significantly less than the error of 52% found with the original sediment rating curve.

Using this information and allowing for a bedload that is equal to 5% of the suspended load, it is estimated that the total average annual suspended sediment load from the San Benito River is approximately 443 t/mi^2/yr (155 t/km^2/yr).

Dendy and Bolton (1976)

Dendy and Bolton (1976) developed two equations to estimate sediment yield. They related specific sediment yield to drainage area using resurvey data from 800 reservoirs in the United States (excluding Florida) for drainage areas from 2.5 to 78,000 km^2 and runoff depths up to 330 mm/yr. The first method is based on surface area only, and the second method requires surface area and runoff in terms of depth per year (Morris and Fan 1997).

By using these methods it is estimated that the sediment yield could range between 80 and 230 t/km^2/yr (240 to 660 t/mi^2/yr).

PSIAC Method

The Pacific Southwest Interagency Committee (PSIAC) method estimates watershed specific sediment yield by evaluating the condition of the watershed with regard to several factors (Morris & Fan, 1997). These factors include surface geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and sediment transport. Each factor is assigned a yield level of high, moderate, or low. The watershed is assigned a predetermined score based on each factor; the total score then corresponds to a range for the specific sediment yield of the watershed. The sediment yield is estimated at 290 $t/km^2/yr$ (820 $t/mi^2/yr$) by using this method.

Comparison with other estimates

Table 2 contains a listing of the estimates made by E&H and by others in the Pajaro Watershed and surrounding areas.

Table 2. Comparison of sediment yield estimates by E&H and others.

Method	Location	Sediment Yield ($t/mi^2/yr$)	Sediment Yield ($t/km^2/yr$)	Source
Sediment Transport Measurements	Pajaro River at Chittenden (1978-91)	93		PWA (1996)
	Pajaro River at Chittenden (1979-92)	100		CH2MHill and NHC (1996)
	Corralitos Creek at Freedom (1976, 1977, 1981, 1982)	1,865		PWA (1996)
	Pajaro River at Chittenden – USGS data (1978 – 1992)	443	155	E&H (2002) – this report
Long-term Alluvial Deposition	Pajaro Valley	>126		Balance Hydrologics (1990)
Reservoir Sedimentation	Williams Reservoir (Los Gatos Creek)	500-800		Ritter and Brown (1972)
	Crystal Springs Reservoir (San Mateo County)	2,300		Brown and Jackson (1973)
	Hernandez Reservoir (San Benito River Watershed)	730	250 to 290	E&H (2002) – this report
Dendy and Bolton	800 Reservoirs in Continental U.S.	1,000		CH2MHill and NHC (1996)
	Applied to Pajaro River Watershed Mean	240-660	80 - 230	E&H (2002) – this report
Regional Correlation	Western U.S.	196-392		SCS (1969)
	California	1,300		Dunne and Leopold (1978)
PSIAC	Pacific Southwest	980-1,950		PWA (1996)
	Applied to Pajaro River Watershed Mean	820	290	E&H (2002) – this report
USLE*	Pajaro Valley	250		PWA (1996)

Summary and Recommendations

Sediment Properties

The D_{50} particle sizes of the 24 samples that were taken from the Pajaro River are shown in Table 1. Except for two locations where armored layers were present and sampled, most of the bed material can be described as a medium to coarse sand. The sediment generally decreases in size from upstream to locations closer to the Pacific Ocean, as is normal in most rivers.

Sediment Sources

The fluvial geomorphologic interpretation of the watershed indicates that the Upper Pajaro River watershed does not contribute any significant volume of sediment to the Lower Pajaro River. The principal sources of sediment to the Lower Pajaro River originate in the San Benito River, and Coward and Salsipuedes Creeks (both tributaries to the Lower Pajaro River). The San Benito River is degraded, with sediment originating from the riverbed and from riverbank failures. Riverbank failures in Chittenden Pass and the same in the Lower Pajaro River during floods also contribute to the sediment load. In addition, the mobile bed of the Lower Pajaro River is also a source of sediment.

Sediment Yield

It is recommended to use average sediment yields in the range of 200 to 300 $t/km^2/yr$ (570 to 850 $t/mi^2/yr$) for sediment transport modeling purposes for this project. Modeling of the four watershed scenarios required by this project should use this range as the average sediment yield and formulate sediment yields below and above this, up to the maximum estimate shown in Table 2 for modeling purposes.

The sediment yield from the Pajaro River is considered to be relatively low. Low sediment yields are generally considered to range between 100 to 300 $t/km^2/yr$ (approximately 300 to 850 $t/mi^2/yr$). High sediment yields are generally considered to be on the order of 1,000 $t/km^2/yr$ (approximately 3,000 $t/mi^2/yr$) or higher.

The sediment yield estimates made during the course of this study are, except for one, considered to be representative of sediment yield conditions of this watershed. The estimate of 80 $t/km^2/yr$ (240 $t/mi^2/yr$) made with one of the Dendy and Bolton (1976) methods is considered to underestimate actual sediment yield. The other estimates agree reasonably well. Two of these are based on field measurement, and the other two on sediment yield estimation methods. These four estimates, based on the Hernandez Reservoir surveys, data collected by the USGS and the Dendy and Bolton (1976) and PSIAC methods are representative of the recommended sediment yield range.

References

Dendy F.E. and Bolton G.C. 1976. Sediment Yield-Runoff-Drainage Area Relationships in the United States, J. Soil and Water Conservation, 31, (6), pp. 264-266.

Golder Associates Inc., (1997), Qualitative and Quantitative Analysis of Degradation of the San Benito River, Project Number 973-2236, Lakewood, Colorado.

Paxton, Mary. 2002. Telephone Interview with representative of San Benito County Planning Department. March 1, 2002.

PSIAC (Pacific Southwest Interagency Committee). 1968. Report of the Water Management Subcommittee, "Factors Affecting Sediment Yield and Measures for Reduction of Erosion and Sediment Yield", mimeo.

Appendices

Dendy & Bolton Calculations

PSIAC Calculations

Sediment RC Write-up

Hernandez Reservoir Calculations

OBJECTIVE:

The purpose of these calculations was to estimate watershed specific sediment yield in the Pajaro River watershed using the Dendy and Bolton (1976) method.

ASSUMPTIONS:

- The regression equations apply to conditions in the study area.
- Accurate runoff data was available from past USGS studies.

CALCULATIONS:

Dendy and Bolton (1976) developed two equations to estimate sediment yield. These equations related specific sediment yield to drainage area using resurvey data from 800 reservoirs in the United States (excluding Florida) for drainage areas from 2.5 to 78,000 km^2 and runoff depths up to 330 mm/yr (Morris and Fan 1997). The first equation is based on surface area only (Morris and Fan 1997):

$$\frac{S}{S_R} = \left(\frac{A}{A_R}\right)^{-0.16} \qquad (1)$$

where: S = specific sediment yield (t/km^2/yr or ton/mi^2/yr),
S_R = reference specific sediment yield value = (576 t/km^2/yr) = 1645 (ton/mi^2/yr),
A = watershed area (km^2 or mi^2),
A_R = reference watershed area value = 2.59 (English) = 1.0 (metric).

The second equation requires surface area and runoff in terms of depth per year(Morris and Fan 1997):

$$\frac{S}{S_R} = C_1 \cdot \left(\frac{Q}{Q_R}\right)^{0.46} \cdot \left[1.43 - 0.26 \cdot \log\left(\frac{A}{A_R}\right)\right] \qquad (2)$$

where: C_1 = coefficient = 0.375 (English) = 1.07 (metric)
Q = runoff depth (mm/yr or in/yr),
Q_R = reference runoff depth value = 508 (mm/yr) = 2 (in/yr).

The Pajaro River watershed was divided into five areas based on topography and land use. Runoff was estimated using USGS runoff map data for the San Francisco Bay region. Figure 1 shows the areas delineations within the Pajaro River watershed. Runoff values were obtained by averaging tabular runoff data for applicable stations or analyzing lines of equal runoff on the map. Specific sediment yield was calculated for each area within the Pajaro River watershed, then a weighted average based on area was used to estimate sediment yield for the entire watershed using equations (1) and (2).

CONCLUSIONS/RESULTS:

The specific sediment yield for the Pajaro watershed was estimated as 80 t/km^2/yr (240 tons/mi^2/yr) using surface area and runoff data with equation (2); the specific sediment yield was estimated to be 230 t/km^2/yr (660 tons/mi^2/yr) using the surface area of the watershed with equation (1). Because the Dendy and Bolton (1976) equations were developed using data from across the United States, these estimates should be considered for preliminary planning purposes only and as a rough check to compare with other estimates (Morris and Fan 1976).

Subject	Pajaro River Watershed Study Collection and analysis of sediment data	Executed by JJS	Client/ Project/ Task	RMC Pajaro River 1.2.4
Specific Sediment Yield Estimate Dendy & Bolton (1976)		Checked by TLB	Date	5/8/2002
		Approved by	Sheet No	2 of 2

REFERENCES:

Morris, Gregory and Fan, Jiahua. Reservoir Sedimentation Handbook. 1997.

Rantz, S.E., USGS. Mean annual runoff in the San Francisco Bay Region, California, 1931-70. Pamphlet to accompany map MF-613.

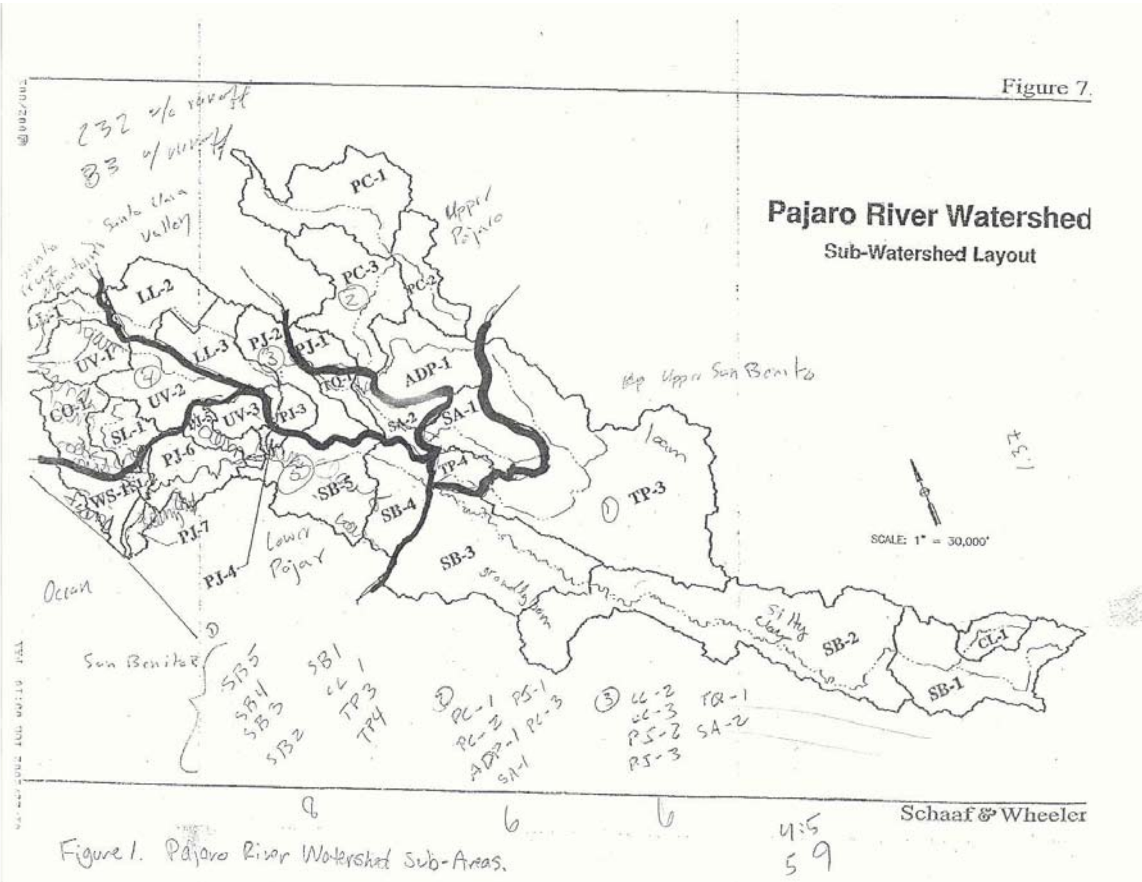


Figure 1. Pajaro River Watershed Sub-Areas.

OBJECTIVE:
Sediment yield of the Pajaro River watershed is estimated using the PSIAC method.

ASSUMPTIONS:
- Factors contributing to sediment yield may be estimated from topographic maps, soil maps, and land use information.
- Sub-basin names are those used in hydrologic modeling and provided by Schaaf and Wheeler (2001).

CALCULATIONS:
The Pacific Southwest Interagency Committee (PSIAC) method estimates watershed specific sediment yield by evaluating the condition of the watershed with regard to several factors. These factors include surface geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and sediment transport. Each factor is assigned a yield level of high, moderate, or low. The watershed is assigned a predetermined score based on each factor; the total score then corresponds to a range for the specific sediment yield of the watershed.

The Pajaro River watershed was divided into five areas based on topography and land use using pre-designated sub-basins (Schaaf & Wheeler 2001). The sediment yield factors that are estimated in the PSIAC method were assigned a sediment yield level of low, medium or high. These levels were then assigned a score and the total numerical score was used to estimate sediment yield. A weighted average sediment yield for the entire watershed was estimated based on the surface area of each area.

Surface geology was categorized using various reports on Pajaro River watershed geology.

Soils were categorized using NRCS soil component descriptions (NRCS 2002) for the watershed sub-areas and GIS maps (RMC 2001) of the watershed's categories. The PSIAC soils categories were assigned based on soil texture and chemical nature of the soils in each sub-area.

Climate was categorized by frequency, intensity, and duration of storm events for each of the sub-areas. Various reports on Pajaro River watershed hydrology were consulted for this condition estimate.

Runoff was categorized for each sub-area based on peak flows per unit area and volume of flow per unit area using various hydrology reports for the Pajaro River watershed.

For topography categorization, floodplain extent was considered. Also, upland slopes provided by Schaaf & Wheeler (2001) were considered for each sub-area.

Ground cover was categorized based on density of vegetation, presence of litter and/or rock in surface soil. These estimations for sub-areas were based on site reconnaissance of the area.

Land use was categorized based on site reconnaissance, aerial photography, and GIS mapping of land use provided by RMC (2001).

Notes and photographs from site reconnaissance were used to categorize the sub-areas for upland erosion.

Channel erosion and sediment transport was categorized by channel hydraulic geometry, flow duration, and erosion extent on bed and/or banks.

CONCLUSIONS/RESULTS:
Based on a total surface area of 3370 km^2, an average sediment yield for the entire watershed was computed to be 290 t/km^2/yr (820 tons/mi^2/yr).

REFERENCES:

Morris and Fan. Reservoir Sedimentation Handbook. 1997.

NRCS. 2002. http://www.statlab.iastate.edu/cgi-bin/osd/osdnamequery.cgi. January, 2002.

RMC. 2001. GIS Component Name Map Figure. Provided Electronically.

	Subject	Pajaro River Watershed Study Collection and analysis of sediment data	Executed by	BC	Client/ Project/ Task	RMC/ Pajaro River/ 1.2.4
E&H Engineering & Hydrosystems Inc	Suspended sediment discharge curve & sediment yield estimate using curve		Checked by	TLB	Date	5/8/2002
			Approved by		Sheet No	1 of 1

OBJECTIVE:

Develop regression equation using USGS data for Chittenden Gage for suspended sediment discharge versus flow. Using the regression equation developed, estimate sediment yield for the Pajaro River Watershed upstream of the gage for the entire flow record.

ASSUMPTIONS:

- Bedload is 5% of suspended load; thus total load is 105% of suspended load.
- Contributing area at Chittenden gage is 596 mi^2 which includes the San Benito watershed and Pajaro sub-areas between the outlet of Soap Lake and Chittenden. The upper Pajaro and the Hernandez Reservoir sub-areas were considered to produce negligible sediment at Chittenden (considering a 95% or greater trap efficiency).

CALCULATIONS:

The relationship between sediment discharge and concentration as a function of water discharge is called sediment rating curve or sediment transport curve. Two types of relationships are commonly used: (i) concentration versus discharge and (ii) load versus discharge.

Mathematical curve fitting was used to fit a curve between the suspended sediment load and water discharge for Chittenden Gage. A particular weakness of mathematically fitted curves is the potentially poor fit at the high extreme, which will be represented by few datapoints (Morris and Fan, 1998). This problem can be solved by dividing the data into discharges classes, computing the mean sediment concentration or load within each discharge class and then running the regression model again using the means.
In this problem, discharges were dividing into 5 cfs discharge intervals and the resulting mean sediment discharges were computed. Then the resulting data points were plotted and fitted with a regression equation.

Sediment yield was estimated using the reguession equation to calculate daily suspended sediment load for the period of record (October, 1939 to September, 2000). Each year's daily flows were summed to produce a mass per year. Then the average of the yearly loads was calculated. Bedload was added to the annual average load to get the total sediment yield at Chittenden per year.

The specific sediment yield was estimated by dividing sediment yield by contributing area.

CONCLUSIONS/RESULTS:

The regression equation developed for the suspended sediment discharge curve is: Qs = 0.026*Qw^1.5591, where Qs suspended sediment discharge (cfs) and Qw is water discharge (cfs).

The estimated specific sediment yield is 443 tons/mi^2/yr (155 t/km^2/yr).

REFERENCES:

Morris, Gregory L. and Fan, Jiahua. 1997. Reservoir Sedimentation Handbook. McGraw-Hill: New York.

USGS. 2001. Mean Daily Flows for Pajaro River at Chittenden, Gage 11159000.
http://water.usgs.gov/nwis/qwdata&introduction.

OBJECTIVE:

The purpose of these calculations is to quantify the sediment loading into Hernandez Reservoir based on reservoir storage loss, then approximate the sediment yield of the watershed. The sediment loading into the Pajaro River from the San Benito River is then approximated using the calculated sediment yield.

ASSUMPTIONS:

- The surveys conducted on Hernandez Reservoir accurately reflect field conditions.
- The off-road recreational vehicle area that operated in the early 1990's contributed additional sediment that was not representative of overall field conditions.
- The loss of storage in Hernandez Reservoir is due to sediment trapped from the contributing watershed since the original survey in 1958.
- The sediment in the reservoir has a density of 1.3 t/m^3.
- The watershed contributing to the Pajaro River has the same sediment yield per unit area as the sub-watershed draining into Hernandez Reservoir.

CALCULATIONS:

Sediment yield can be estimated for watershed by surveying the volume of accumulated sediment in a reservoir downstream over time. Hernandez Reservoir has lost a storage capacity of 1,000 and 1,500 acre-feet based on reservoir resurveys conducted in 1988 and 1997, respectively. The volume of sediment was converted to mass of sediment accumulation, then a rate per year was estimated based on time between surveys.

The trapping efficiency was estimated as approximately 95% using the Brune Curve and the capacity inflow ratio as shown in Figure 1.

The area of the Hernandez Reservoir watershed is 221 km^2. The specific sediment yield for the Hernandez watershed is the sediment mass entering per year divided by the trapping efficiency and divided by the area of the watershed.

Considering that the 221 km^2 contributing to Hernandez Reservoir results in sediment discharge of only 5% of sediment yield, only 1,498 km^2 of the 1,719 km^2 San Benito River watershed contributes 100% of its sediment yield to the Pajaro River. Thus, the sediment loading into the Pajaro River from the San Benito River watershed is specific sediment yield times 1,498 km^2 plus the mass entering the reservoir per year times 5%.

Based on sedimentation over a 30 year period (1958-1988), volumes indicate that the annual sediment loading from the watershed upstream of Hernandez Reservoir is 56,300 t/yr.

CONCLUSIONS/RESULTS:

The specific sediment yield of the Hernandez Reservoir watershed is estimated as 250 $t/km^2/yr$ (730 $tons/mi^2/yr$); this is assumed to be applicable for the entire San Benito River watershed. The watershed of the San Benito River at the confluence with the Pajaro River contributes approximately 428,800 t/year.

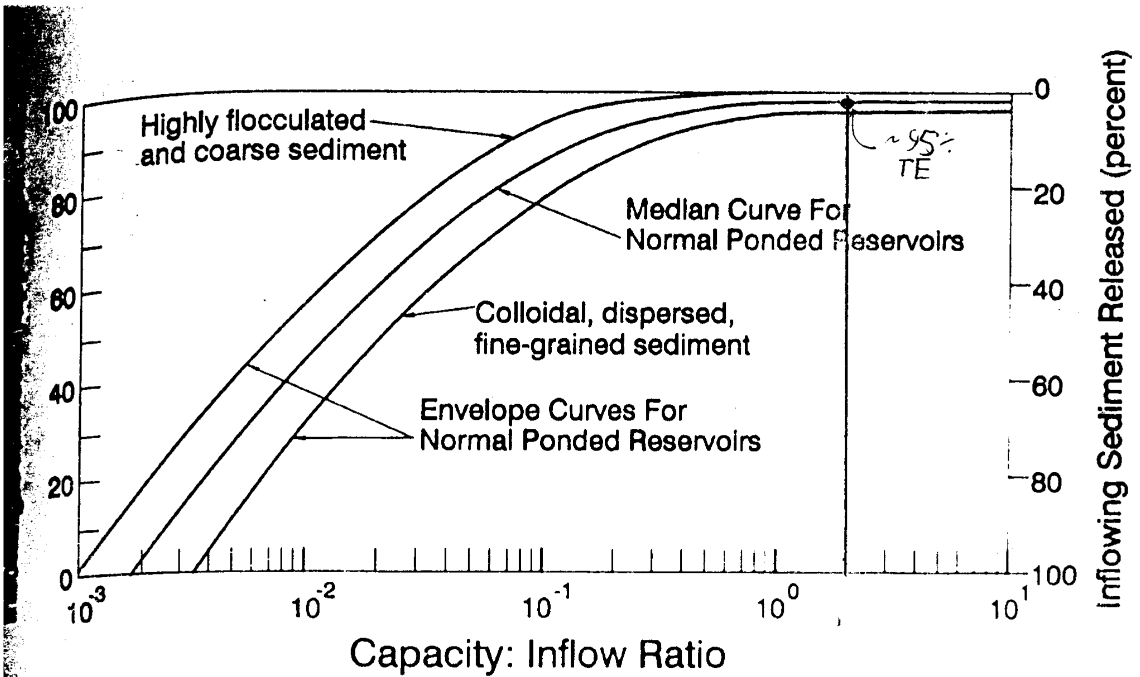
REFERENCES:

Morris, Gregory and Fan, Jiahua. Reservoir Sedimentation Handbook. 1997.

Rupert, Bill. Memorandum: Silting of the Hernandez Reservoir. Sullivan Engineers. 1988

Henze, Mark. Memorandum: Hernandez Reservoir Storage Capacity. San Benito County Water District. 1998

FIGURES:



IGURE 10.15 Brune curve for estimating sediment trapping or release efficiency in conventional mpounding reservoirs (*adapted from Brune, 1953*).

Figure 1. Brune Curve estimation of Hernandez Reservoir Trap Efficiency.

Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers

in association with

Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.5 – River Geometry

Task: Collection and Analysis of River Geometry Data

To: PRWFPA Staff Working Group

Prepared by: J. Schaaf

Reviewed by: R. Raines

Date: November 13, 2001

Introduction

This Technical Memorandum (TM) deals with the river geometry aspect of the proposed hydrologic model. River geometry is a necessary input that will allow computations of flood wave travel through the lower reaches of the San Benito and the Pajaro Rivers. The river geometry consists of cross sectional data for channel and adjoining overbank (floodplain) areas at a sufficient number of locations along the rivers to allow an unsteady-state, one-dimensional hydraulic model to compute the passage and attenuation of flood waves as they proceed through the channel system.

This TM describes the location of channel cross sectional data believed necessary to operate the unsteady-state, open channel hydraulic model. This TM also describes other principal hydrologic routing parameters that may be critical elements of the flood wave transport system in the Pajaro River watershed.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a stream flow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?

- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1 (previously submitted with TM1.2.1) the watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by a Corps of Engineers levee project constructed between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at the outlet to Soap Lake – a low-lying area of Santa Clara and San Benito Counties – has a drainage area of approximately 500 square miles.

Objectives of this TM

There are two reaches where the unsteady-state, open channel hydraulic model is to be used. The first is along the Pajaro River from the Pacific Ocean upstream to the outlet from Soap Lake. Soap Lake, which is normally dry and used for agriculture but which has flooded historically, is a low-lying area in Santa Clara and San Benito Counties that is situated upstream of the confluence with the San Benito River. The outlet to Soap Lake is approximately 2000 feet upstream of the US Highway 101 bridge over the Pajaro River. This reach is approximately 24 miles long.

The second reach to be included in the hydraulic model is the San Benito River from the confluence with the Pajaro River upstream to the Hospital Road crossing. This distance is approximately 13 miles.

This TM describes existing cross sections along these reaches and determines the need to obtain additional cross sections to enable a comprehensive model to be constructed along both river reaches. Both reaches have a number of bridge crossings. The crossings are both vehicular as well as heavy rail. These bridge crossings may impact channel or floodplain discharges and water surface elevations. This TM determines whether additional geometry is needed at existing bridge crossings.

There are a number of places in the watershed where storage may impact the flood hydrology. There are four major water supply reservoirs in the watershed: Chesbro on Llagas Creek, Uvas on Uvas Creek, Pacheco on the North Fork of Pacheco Creek, and Hernandez on the San Benito River. In addition to these engineered dams/reservoirs there are major flood storage areas located in Soap Lake, San Felipe Lake and College Lake.

San Felipe Lake is located immediately upstream of Soap Lake on the Pajaro River. In fact, the outlet from San Felipe Lake is the headwaters of the Pajaro River. The lake is also the terminus of Pacheco Creek and the Santa Ana/Los Viboras/Dos Pichachos Creeks system.

College Lake is located on the Salsipuedes Creek just upstream of the conflulence of Corralitos Creek. The lake is located upstream of the City of Watsonville. This natural lake, along with a number of other lakes in the area such as Tyman, Drew, Kelly, Pinto and Freedom provide water supply as well as some incidental flood storage.

This TM presents an initial exploration of the flood storage potential at these seven locations.

Pajaro River Model

There are five sources of river geometry data for the Pajaro River. The first was the HEC-2 model developed by FEMA for the Flood Insurance Study done for Santa Cruz and Monterey Counties in the late 1970’s. The steady state hydraulic model used by FEMA extended from the Pacific Ocean to just upstream of the Rogge Lane/Carpenteria Road bridge. (The bridge crosses the river at the junction between Santa Cruz, Monterey and San Benito Counties. The road is named Rogge Lane in Santa Cruz County and Carpenteria Road in San Benito and Monterey Counties.) The length of this reach is approximately 15.5 miles. According to the FEMA Flood Insurance Study Report for Santa Cruz County, the cross sections along the Pajaro River were obtained from three sources: a series of Corps of Engineers 2-foot contour topographic maps of the Pajaro River done in 1971; 4-foot contour maps done in 1978; and field measurements for portions below water.

The second source of data was from the US Army Corps of Engineers in 1995. Aerial photogrammetry was used to produce topographic maps but field measurements were done to obtain channel cross sections. The field work was done in August 1995 after the flood control channel had been restored to project conditions by removal of vegetation and silt. These sections extended from the Pacific Ocean to Murphy Crossing a distance of approximately 12 miles.

The inverts of the two sets of geometry along the river are shown in Figure 5.1. The 1995 inverts are lower than the FEMA inverts from approximately 2 miles upstream of the Main Street bridge crossing to the Ocean. The 1995 flood control project restoration work was limited to areas between the Main Street bridge crossing and the Murphy Road crossing.

A comparison was made between the two sets of channel geometry data. Cross sections from the two sets of geometry data were selected at roughly corresponding locations. The locations were not co-incident but were located close to one another.

Figure 5.2 shows the cross sections at channel station 10420 – a location downstream of the Thurwachter/McGowan Road bridge crossing. The sections are viewed looking downstream. From Figure 5.2 it appears that the FEMA section stopped at the water's edge and did not locate the channel invert. In terms of hydraulic properties, however, this omission would not be of any significance. The use by FEMA of the water surface rather than the invert of the channel (or channel thalweg) may explain the higher inverts shown in Figure 5.1 in the lower portions of the river. The rest of the cross sections are fairly consistent with the exception of the smaller area along the left bank as shown in the 1995 section.

Figure 5.3 shows the cross sections at channel station 28240 – located upstream of Highway 1 but downstream of the railroad bridge crossing. The sections are very similar with the exception of the lower end of the channel where the 1995 section reflects about a 5-foot lowering of the bottom portion of the channel.

Figure 5.4 shows the cross sections at channel station 35870 – located less than a mile upstream of the Main Street bridge crossing. The 1995 channel section appears slightly more constricted than the FEMA section but the bottom of the 1995 channel is approximately 5 feet lower than the FEMA invert. The FEMA invert may reflect a water elevation because there are no data points in the center of the bottom portion of the channel.

Figure 5.5 shows the cross section at channel station 49690 – located approximately 3 miles upstream of the Main Street bridge crossing. Here the inverts are quite similar but the 1995 section appears slightly more restrictive than the FEMA cross section.

Figure 5.6 shows the cross section at channel station 57920 – located approximately 1 mile downstream of Murphy Crossing. Here the 1995 section appears to be significantly larger than the FEMA cross section. The difference is probably due to two factors: slightly different angles of the sections crossing the river, and slightly different locations along the river. To understand how different channel locations can effect the cross section look at the little levee on the left bank on the 1995 cross section in Figure 5.6. This levee is not there on the FEMA cross section. The Corps project levees on the left bank start in just about the location of the cross section. Obviously the 1995 section was slightly downstream of the FEMA cross section. This may make some slight differences like the presence or absence of the little levee but it should not make the large difference in channel section in at the lower elevations and may indicate that the channel was wider in this reach in late 1995 than it was in the 1970's.

The hydraulic model will use the 1995 cross sections from the Pacific Ocean up to Murphy Crossing as these data reflect the most current condition of the flood control channel. From Murphy Crossing to approximately 500 feet upstream of Rogge Lane/Carpenteria Road, the FEMA cross sections will be used.

Upstream of this location on the Pajaro River there are three additional sources of channel geometry data.

The US Army Corps of Engineers prepared a Flood Plain Information Report in 1974 for the San Benito River from the Pajaro River to Tres Pinos Creek. That report presented data on the Pajaro River from the USGS stream gaging station at Highway 152 upstream to the confluence with the San Benito River. The report contains an invert profile of the Pajaro River in this reach and presents a cross section on the river downstream of the San Benito River confluence. Three other cross sections are indicated on the river profile but this information cannot be recovered from the Corps of Engineers. The one published cross section, however, does indicate the basic nature of the deep channel and the rather narrow, flat overbank areas in this reach.

Upstream of the confluence with the San Benito River, FEMA did a Flood Insurance Study from the confluence upstream to US Highway 101. Cross sections were surveyed in the field for that study. These sections are available for use in the hydraulic model.

Upstream of US Highway 101, 1988 CalTrans topographic maps with 5-foot contour intervals were used to develop cross sections from the highway bridge into Soap Lake a distance of a little less than one mile. The channel cross-section 50-feet upstream of US Highway 101 from the FEMA field survey was compared to the section taken from the CalTrans topographic map. An adjustment for the low flow areas of the channel was made to make the two sections compatible. In this flat section of the Pajaro River ponded water is consistently present. The CalTrans topography reflected the surface of the water. The field cross section was used to estimate the channel section below water. Where the CalTrans topography indicated no standing water the CalTrans topography was used uncorrected.

The locations of cross sections to be used in the hydraulic model of the Pajaro River from the Pacific Ocean to the outlet from Soap Lake are shown in Figure 5.7. The invert of the channel is shown, as are the locations of crossings, stream gages and major confluences. There is a gap in the data from upstream of Rogge Lane/Carpenteria Road to the Highway 129 crossing. This reach traverses the Chittenden gap, a narrow canyon with river channel, highway and little if any overbank area. One or two field cross sections are needed in this area to provide the proper hydraulic characteristics through this narrow gap. In this reach there appears to be one railroad crossing of the river. The geometry of this crossing must be determined during the field investigation. All other sections of the river appear to have adequate coverage of channel geometry.

San Benito River Model

The river geometry for the San Benito River will be taken from the HEC-6 model used in the August 1997 Golder Associates report *Qualitative and Quantitative Analyses of Degradation of the San Benito* River. The HEC-6 model uses river geometry cross-sections along with information concerning sediment properties to predict water surface elevations as well as sediment transport in a stream. For the flood wave routing portion of the hydrologic model, the channel cross sections used in the HEC-6 model adequately define the channel geometry in the San Benito River.

A profile of the invert of the San Benito River from its confluence with the Pajaro River upstream to the confluence with Tres Pinos Creek is shown in Figure 5.8.

Critical Routing Reaches

There are a number of locations in the Pajaro River watershed where storage of water may significantly affect flood flows to downstream areas. There are four major reservoirs in the upper watershed, i.e., the watershed upstream of the USGS stream gage at Chittenden. These are all water supply reservoirs and as such are generally operated to maximize the water supply of their particular hydrologic settings. Flood control storage is generally small or is only incidental at these facilities. Incidental flood storage occurs when a reservoir is not full and a flood occurs. The unfilled storage volume is filled with flood runoff thereby decreasing the volume of flood flow released to downstream areas. However, should the reservoir be full, only above spillway peak flow attenuation is available to modify downstream flood discharges.

The four major water supply reservoirs, their date of construction and their below spillway storage (their water supply storage) is shown below.

Reservoir	Storage acre feet	Year Constructed
Pacheco Lake	6,150	Pre-1940
Chesbro	8,090	1955
Uvas	9,950	1957
Hernandez	18,700	1961

The total of all water supply storage in the watershed is just less than 43,000 acre feet.

Another location in the watershed where storage could be a significant flood control hydrology factor is at Soap Lake/San Felipe Lake. Soap Lake is a low-lying area in San Benito and Santa Clara Counties. The outlet of the lake is on the Pajaro River just upstream of US Highway 101. San Felipe Lake is located at the headwaters of the Pajaro River just east of Soap Lake. At high storage levels the two lake could become one large flood control storage facility.

A topographic map of the Soap Lake and San Felipe Lake area was obtained from an April 1975 SCVWD report *Flood Damage: Pajaro River Basin*. A Corps of Engineers topographic map dated May 1940 was included in that report. Based on that May 1940 topographic map, there is an estimated 77,500 acre feet of flood storage in the lakes at elevation 150 feet. The combined lake would encompass 11,500 acres at that elevation. Five feet lower the storage in the combined lakes is estimated at 31,300 acre feet with a surface area of approximately 7,000 acres.

Corps of Engineers documents have estimated the 100-year flood elevation in the combined lakes at somewhere in the 145.5 feet to 147 feet range. These two lakes have the potential to significantly attenuate flood peaks as they come down the Pacheco Creek, Santa Ana Creek, Llagas Creek and Uvas Creek systems into the lakes.

Once the unsteady-state channel hydraulics model is established for the two rivers the outflow from Soap Lake will be determined as a function of the water level in the lake itself as well as the water level in the Pajaro River downstream of Soap Lake. As the Pajaro River leaves Soap Lake it is joined by the San Benito which together drop into the Chittenden gap with it narrow, constrictive channel section. The flow in the portions of the Pajaro River at and near the Highway 129 bridge may impact the flow coming from Soap Lake and therefore may impact the amount of flood storage available in that Lake.

For smaller flood events, Soap Lake and San Felipe Lake are two separate storage bodies. However, the relative water surface elevations in the two lakes control the discharge between the lakes via the Miller Canal. As the elevations become more identical the discharge between the lakes is reduced until the two lake combine water surface elevations and become one large flood storage area.

College Lake and its neighboring lakes provide storage in the lower watershed, i.e., the watershed downstream of the Chittenden stream gage. These lakes, too, appear to be operated to maximize water supply benefits. The flood storage in College Lake, by far the largest of the lakes in the Salsipuedes Creek watershed, has been estimated to be as great as 10,000 acre-feet. These local lakes, even if filled to water supply upper limits are expected to have significant impacts on the attenuation of peak runoff events and to lag the response from these local watersheds. The Corps of Engineers hydrologic modeling will be used for the Corralitos Creek and Salsipuedes Creek watershed to develop runoff hydrographs. No additional hydraulic modeling is planned for these tributaries of the Pajaro River.

Along all other reaches in the hydrologic model the translation and attenuation of flood wave discharges will be computed with the Muskingum routing method or the Muskingum-Cunge routing method. These methods are classified as hydrologic routing procedures and are not as hydraulically rigorous as the unsteady-state hydraulic model proposed for the lower reaches of the Pajaro and San Benito Rivers or for the storage-elevation-discharge routings planned for the Soap Lake and San Felipe Lake areas.

Conclusion

There are sufficient existing cross sections along the San Benito River and the Pajaro River to develop an unsteady hydraulic model to perform flood wave routings in the lower reaches of both rivers. The only minor exception to this statement is that two cross sections need to be obtained using field techniques for the Pajaro River downstream of Highway 152 but upstream of Rogge Lane/Carpenteria Road, i.e. within the Chittenden gap.

The storage in Soap Lake and San Felipe Lake can be significant during flood events. This storage will be used in the routing of flood waves through the lakes. The storage will be combined with the unsteady state hydraulic model to account for the effects of that storage on downstream flood discharges.

The storage in College Lake and neighboring lakes will be considered in the hydrologic model. The Corps of Engineers routing procedures that include storage effects will be used as part of the hydrologic model.

Figure 5.1

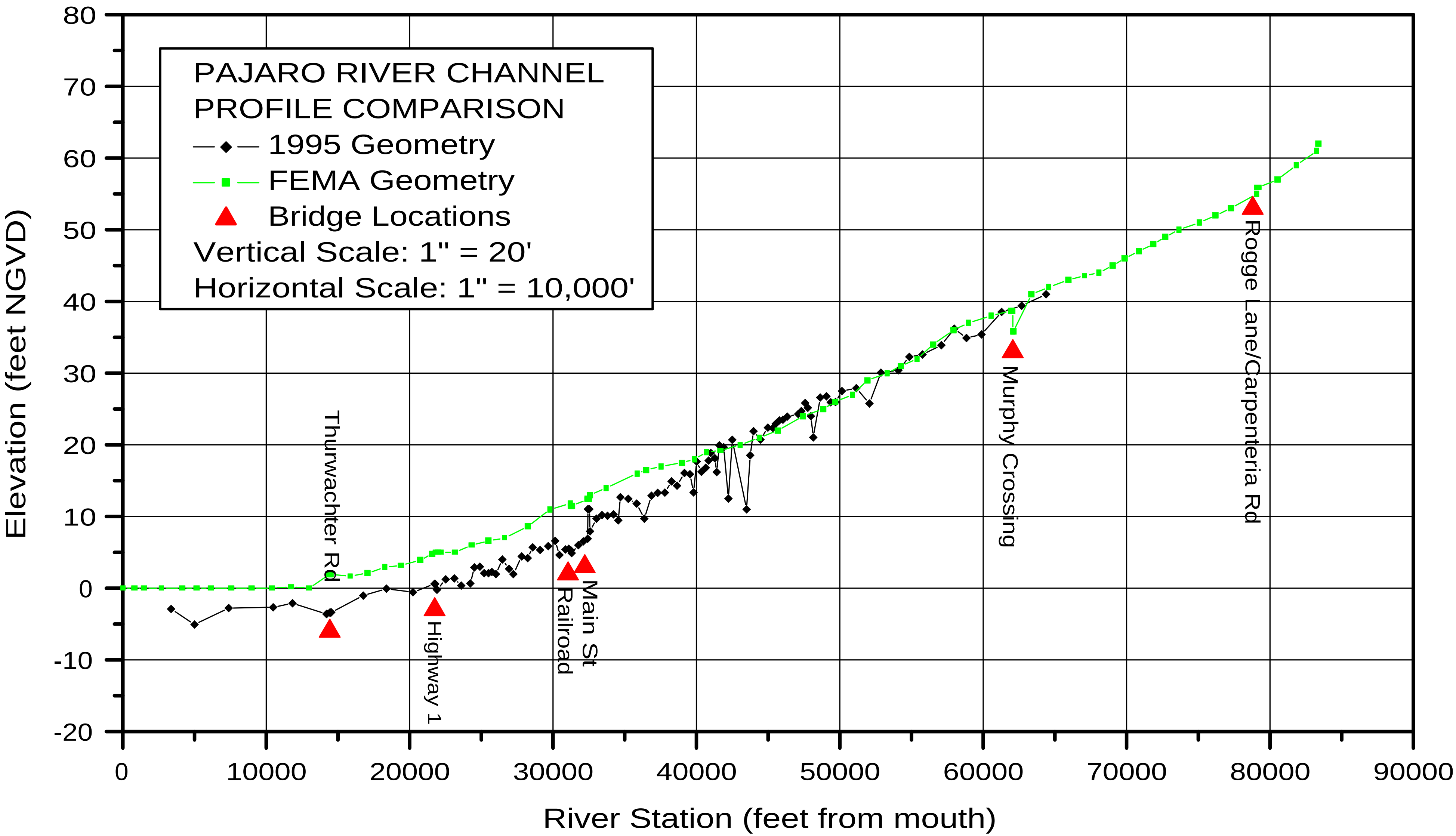


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Figure 5.2

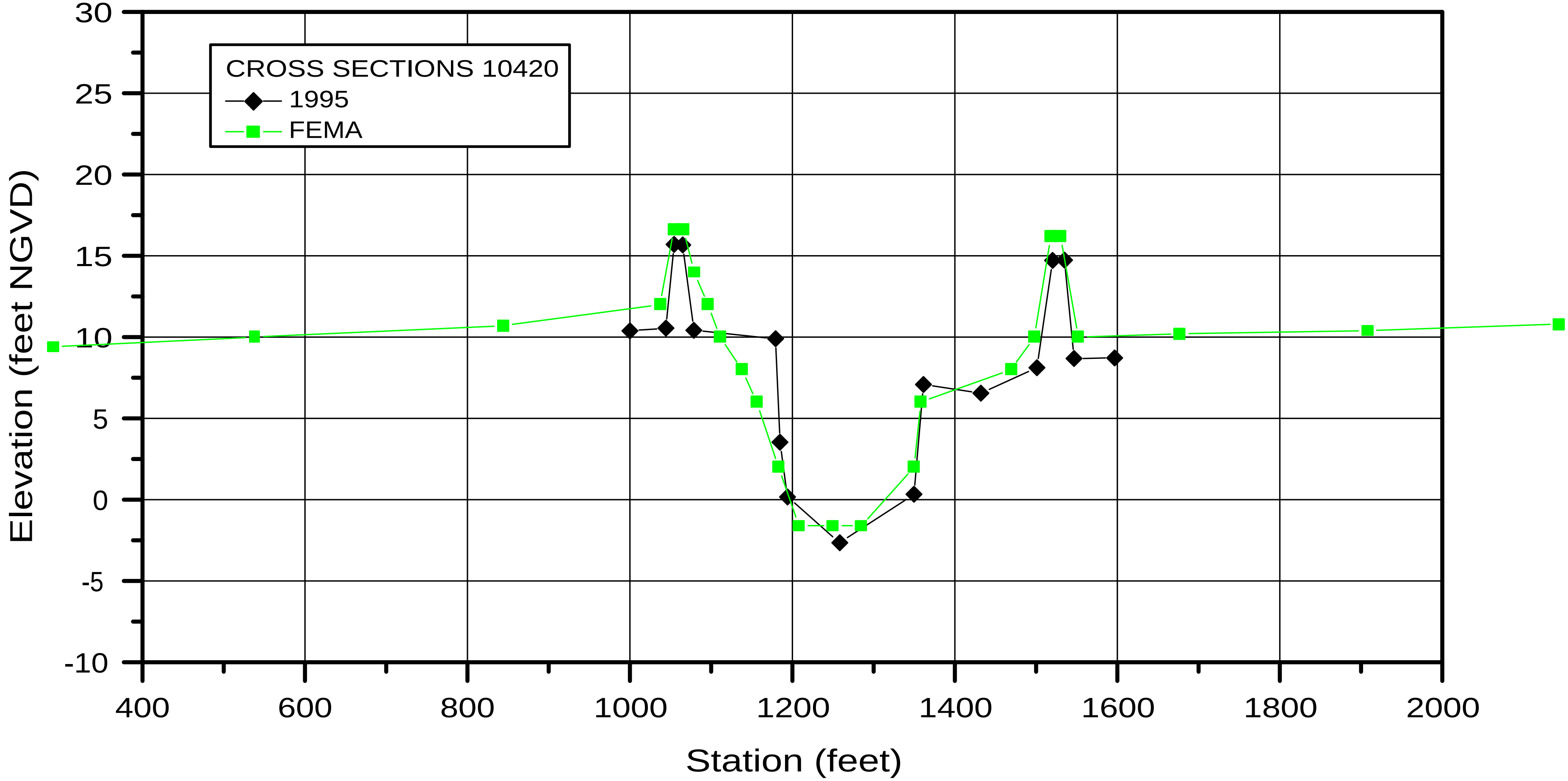

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Figure 5.3

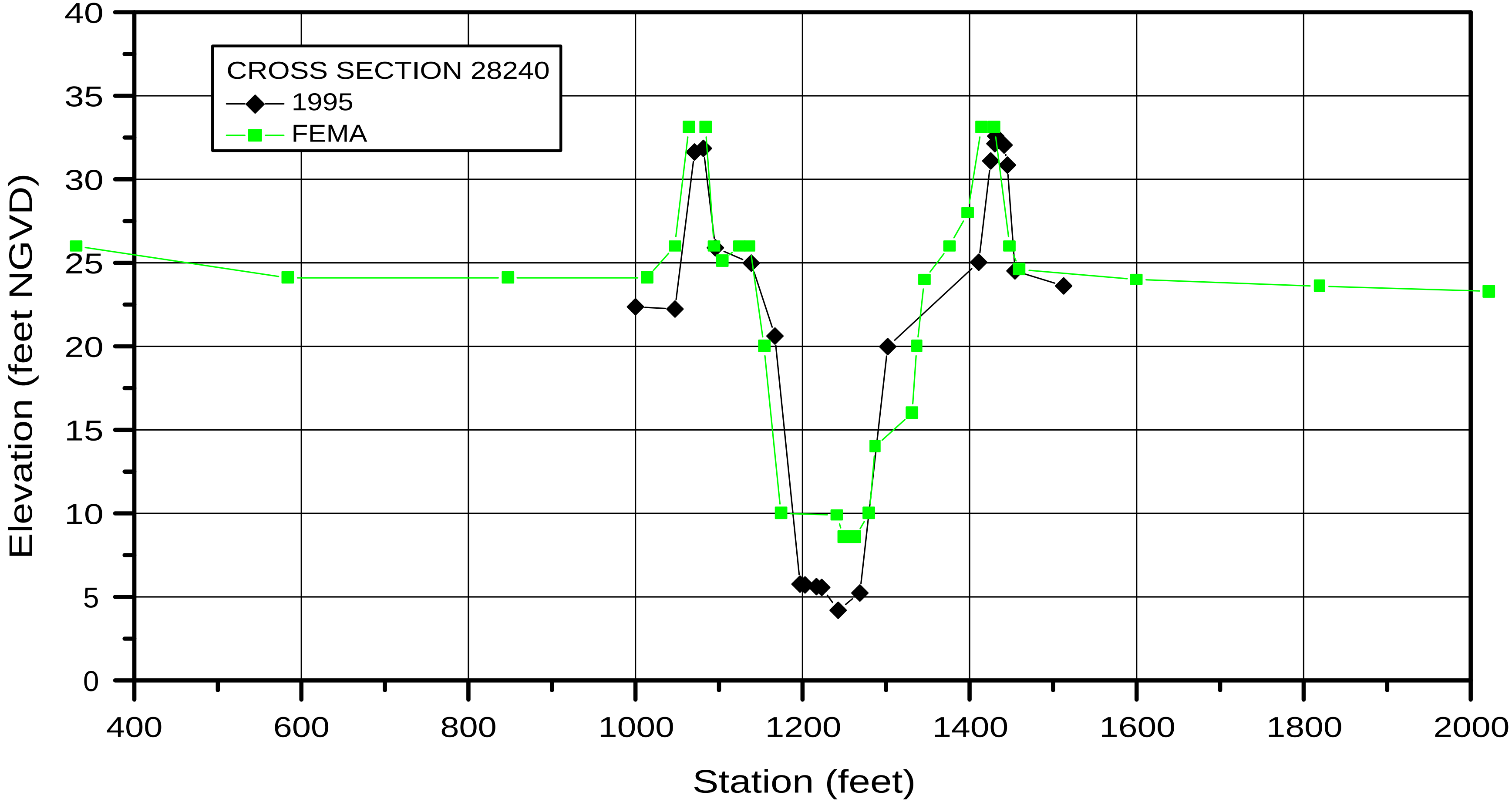

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Figure 5.4

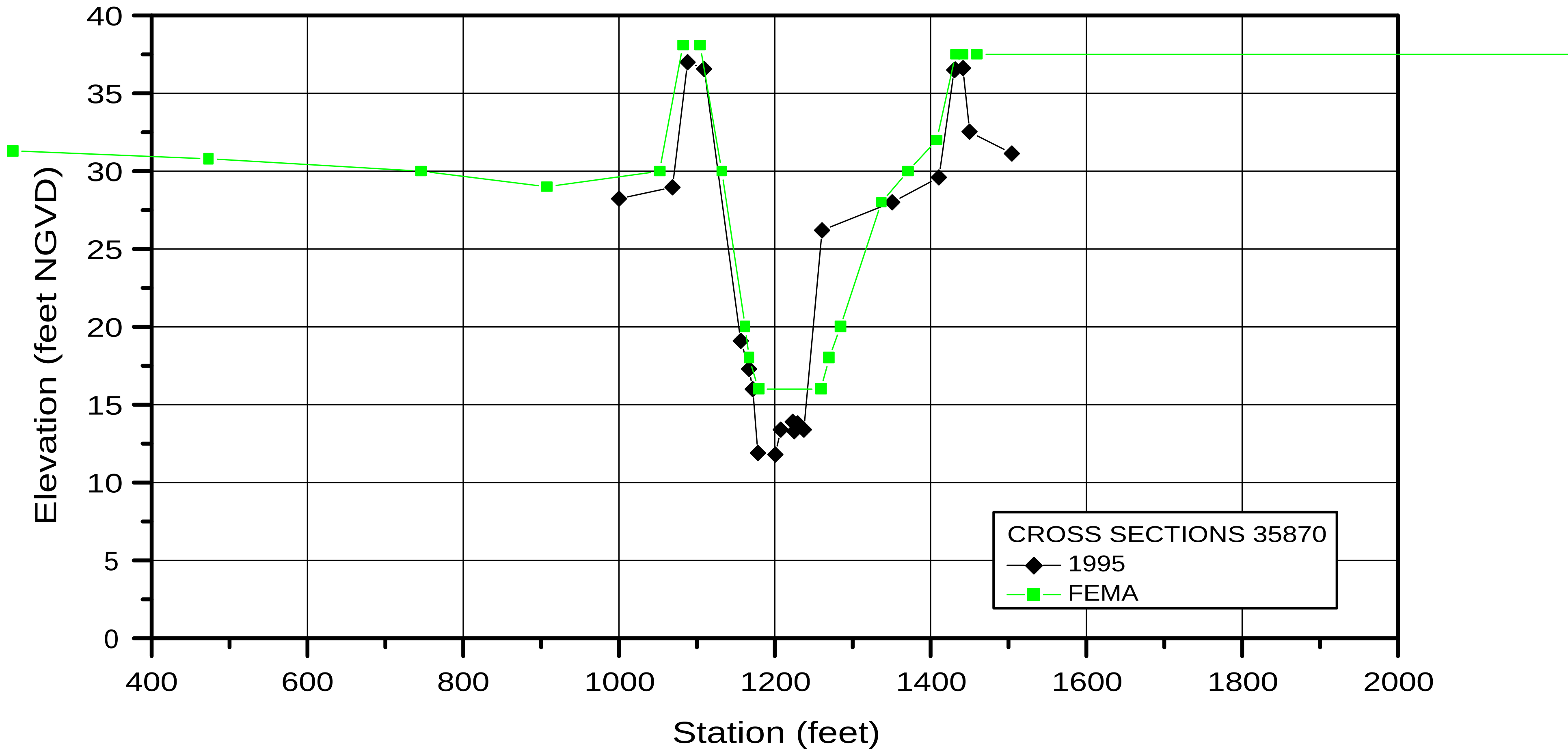

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Figure 5.5

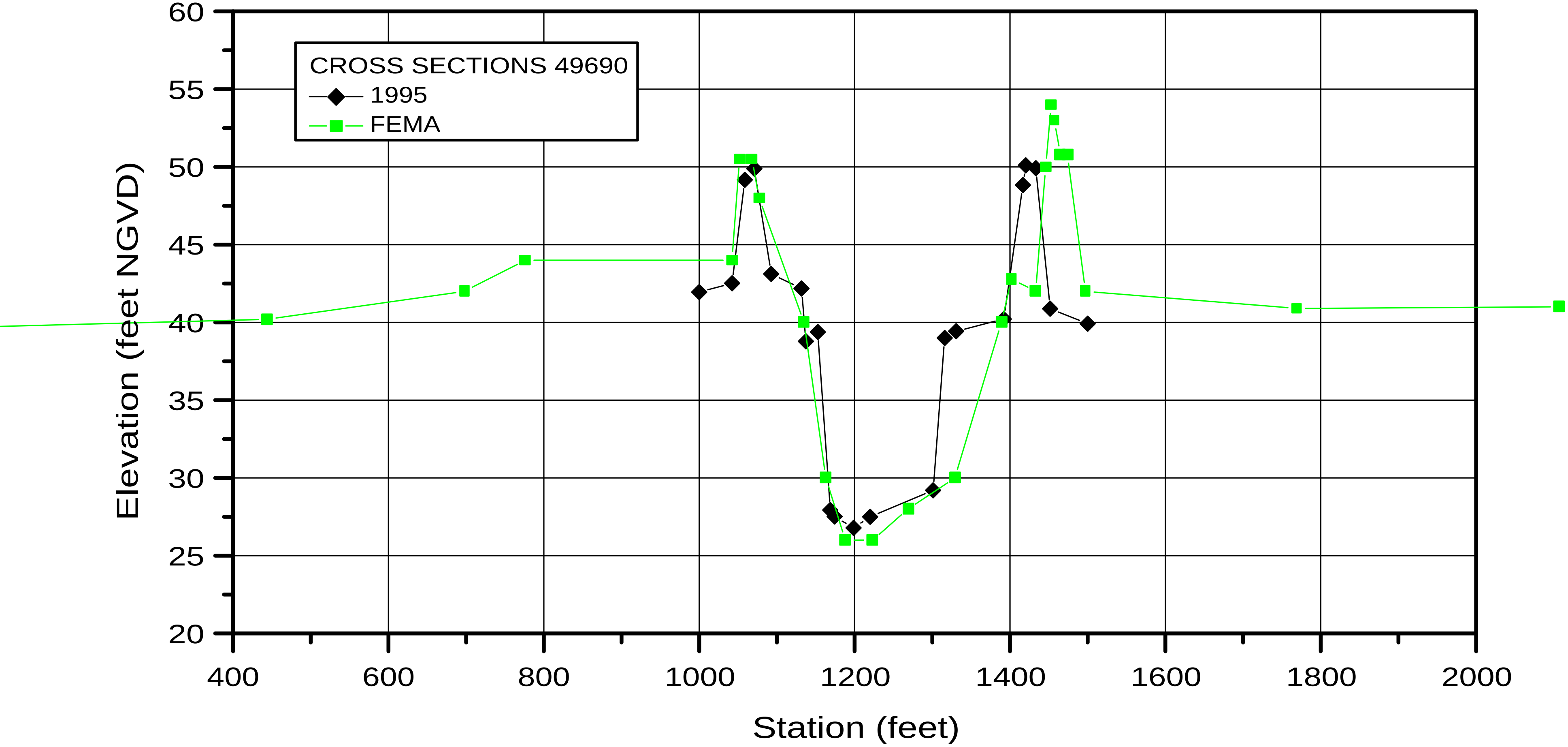

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Figure 5.6

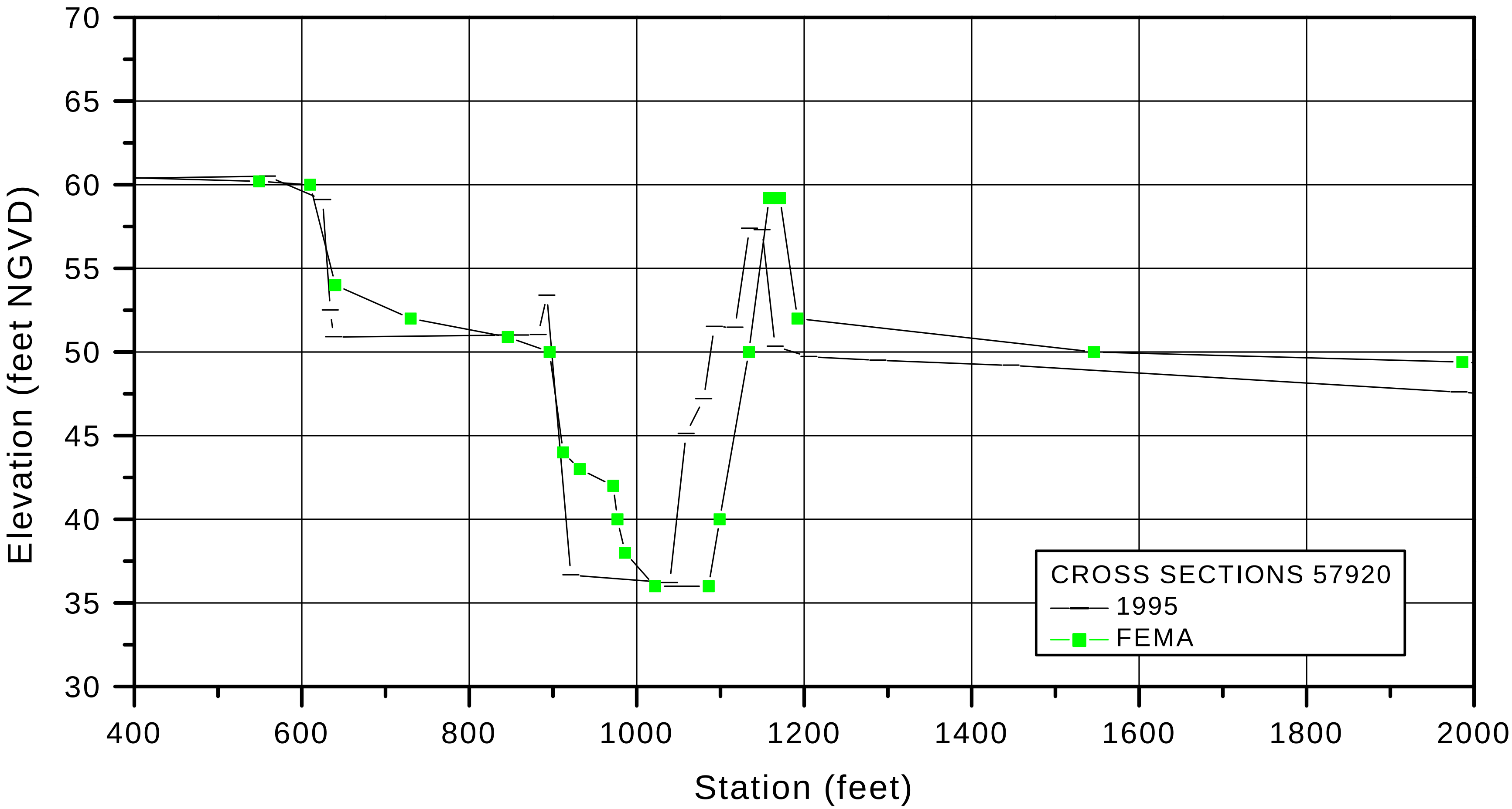

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Figure 5.7

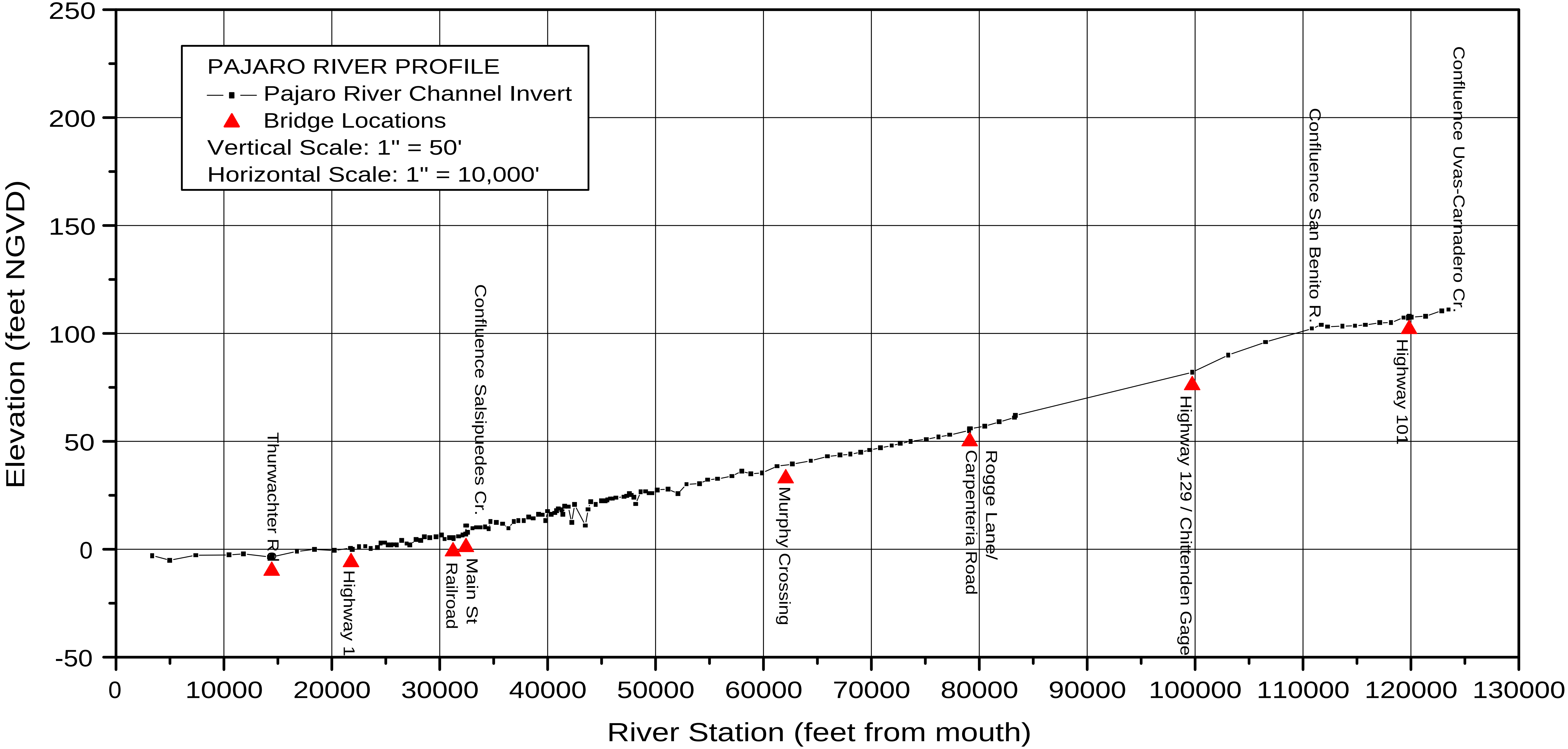

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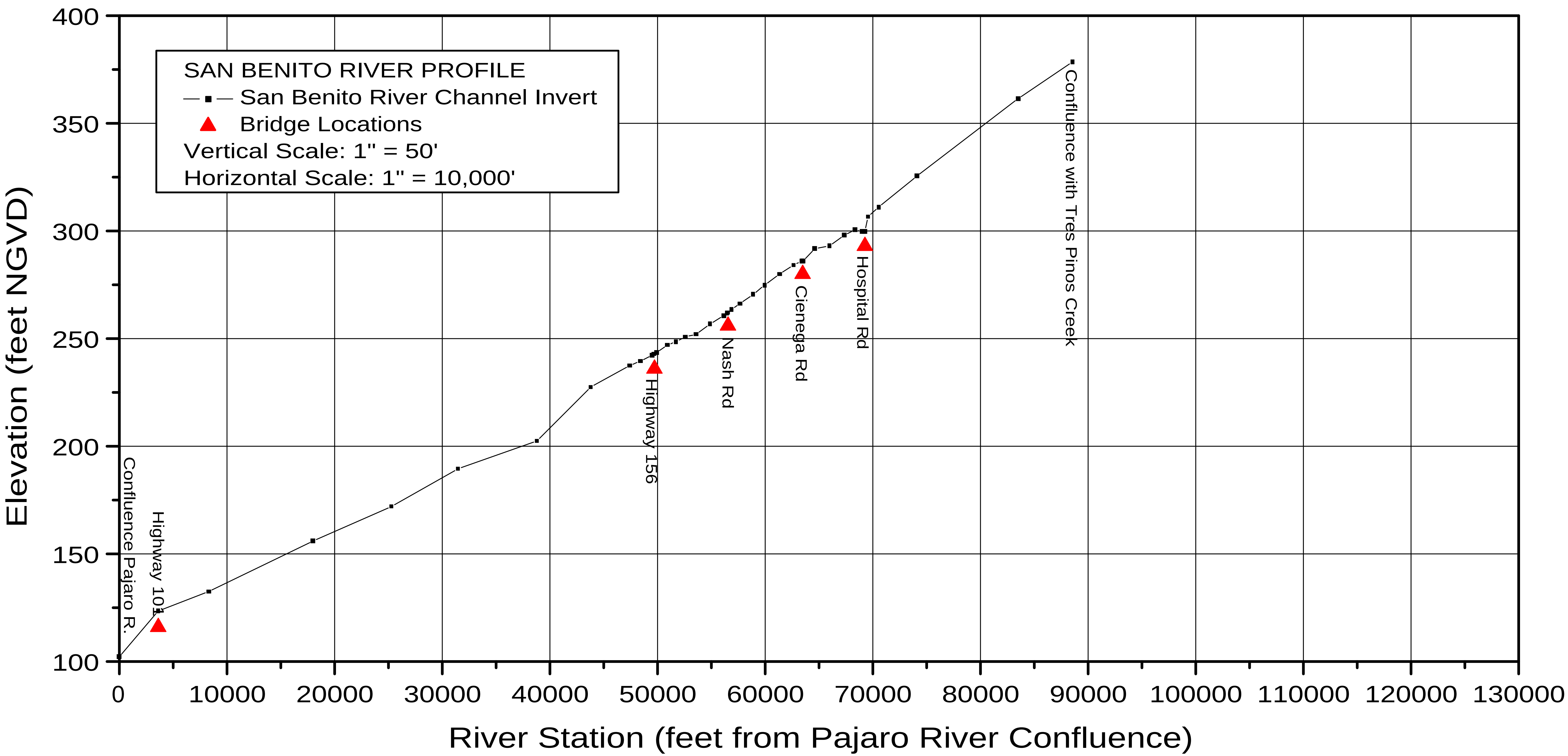
Figure 5.8



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RMC Raines, Melton & Carella, Inc. Consulting Engineers/Project Managers

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Technical Memorandum No. 1.2.6

Task: Land Use and Soils

To: PRWFPA Staff Working Group

Prepared by: T. Harrison

Reviewed by: L. Gutierrez

Date: December 12, 2001

Introduction

The purpose of this Technical Memorandum (TM) is to establish current land use and land cover (LULC) and soil conditions within the Pajaro River Watershed. Particularly relevant to the hydrologic runoff model is the percentage of the land use for each hydrologic soil group. The soil groups are based on NRCS A-D rating system.

Once the current conditions are defined, they can be used as a baseline to which other watershed conditions can be compared. This ability to compare past, future, and hypothetical conditions will allow decision makers to determine which course or courses of action to pursue to improve the level of flood protection for the residents of the Pajaro River valley.

After a brief summary of the scope, background, and setting of the Pajaro River Watershed Study, this TM will address land use and land cover as well as hydrologic soil groups found within the watershed. The source of the data will be discussed, as will the qualities and limitations of the data. Quality checks for both the soils and LULC data will be described and any necessary changes made. Current conditions will be presented and explained. At the end of the technical memorandum, a concise and direct conclusion will be drawn from the data and analysis presented within this document.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a streamflow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1, the watershed is somewhat elongated toward the southeast.

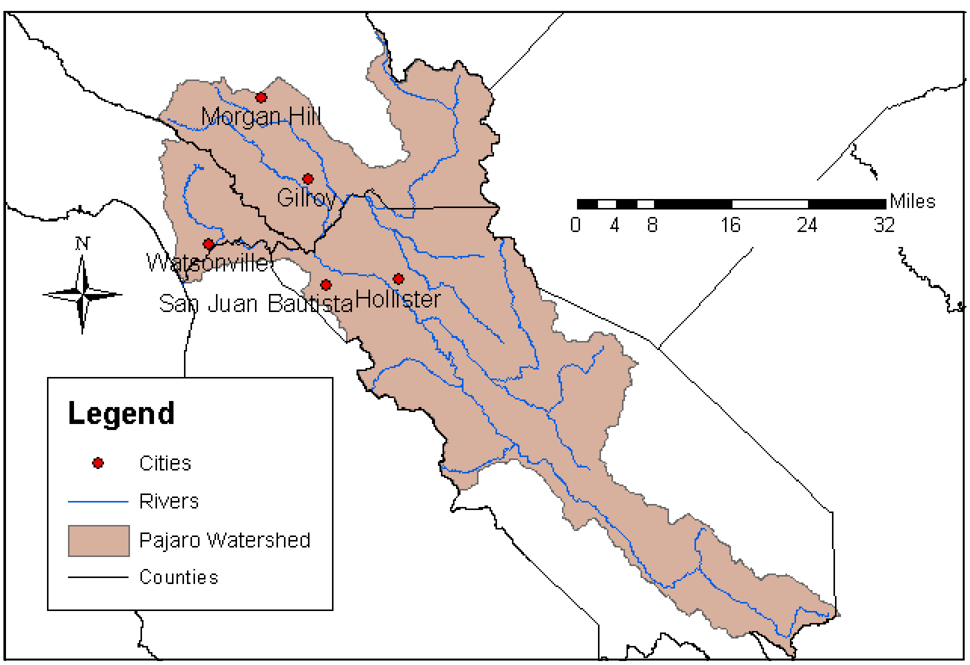

Figure 1: General map of Pajaro River Watershed.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by levees constructed by the Corps of Engineers between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at the outlet to Soap Lake – a low-lying area of Santa Clara and San Benito Counties – has a drainage area of approximately 500 square miles.

Sources of Data

Although there are many sources of data, it is important for this study to use the most current and most accurate data available. It is also important that the data cover the entire watershed. Some sources of data examined, although otherwise excellent, pertained only to portions of the watershed. It was found to be too difficult to collect pieces of the watershed and assemble them.

LULC

Appropriate data was found for both the LULC and soil aspects of this technical memorandum. LULC data was taken from the USGS website. The 1992 National Land Cover Dataset (NLCD) is available free of charge for the entire United States. It was generated using satellite imagery supported by topography, census, agricultural statistics, soil characteristics, other land cover maps, and wetlands data. The land uses are classified into 21 different groups. A list of these groups and associated descriptions can be found at the end of the technical memorandum in Appendix A. The website also mentions an updated dataset for the year 2000, but due to the data processing requirements this data will not be available for several years. Datasets from mid-1970 are available, but would not represent the current land use as well as the more recent data.

Although the 1992 NLCD data is the best available LULC information for this project, there is a drawback to using this data. Although the data has been checked for initial quality, a final accuracy assessment from USGS or EPA is not yet available. GIS coordinators at the USGS EROS Data Center maintain that the data is generally quite good without the final assessment, but recommended an independent verification of the data. Steps taken to do this are discussed below.

Hydrologic Soil Groups

Soils data was obtained directly from the Natural Resources Conservation Service (NRCS). Digitized soil surveys, also known as SSURGO data, were not available for both Santa Clara County and San Benito County. SSURGO data is recognized as the most accurate soils data offered for public access and use. Another dataset, STATSGO, is also available but is intended for large scale planning. The NRCS State Office was able to provide STATSGO level data with the information necessary for this study.

The hydrologic soil group is the most important soil property for runoff potential. Since this property changes quickly across small distances that are not measurable at the STATSGO level, soil scientists at the NRCS office recommended that the data provided be verified to confirm adequate accuracy for the modeling needs of the study. As with LULC data, steps taken to provide this confidence are described below.

Quality Checks

Data quality checks are essential to any study, but are especially important when the data is provided with warnings. Below are checks and processes used to address any concerns regarding the accuracy of the data obtained for this aspect of the study.

LULC

Since the LULC dataset is computer generated using satellite images, it might be expected that any mistake in classifying land use and land cover would be made consistently. It is therefore necessary to check only one representative piece of the dataset for accuracy in defining land use and land cover. The land use in Santa Clara County was cross-checked using SCVWD land use parcel data from 1999. As can be seen in Figure 2a and 2b, land use patterns in the two datasets are remarkably similar. While the land use types may be different, further examination reveals that SCVWD's data can be aggregated to fit into the land types represented in the 1992 USGS dataset. For example, the public open space and scenic forest classifications of the parcel dataset might be combined to represent evergreen forest in the USGS dataset. Because the correlation between the two datasets is extremely high, it is possible to assume that the data will be as accurate throughout the entire watershed as it is in this case.

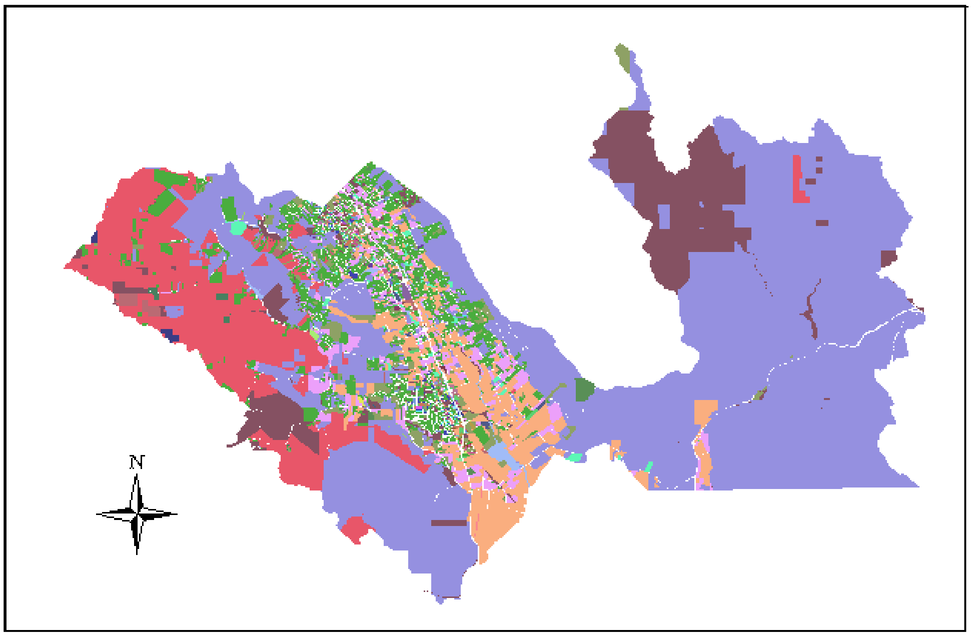

Figure 2a: SCVWD 1999 land use parcel data.

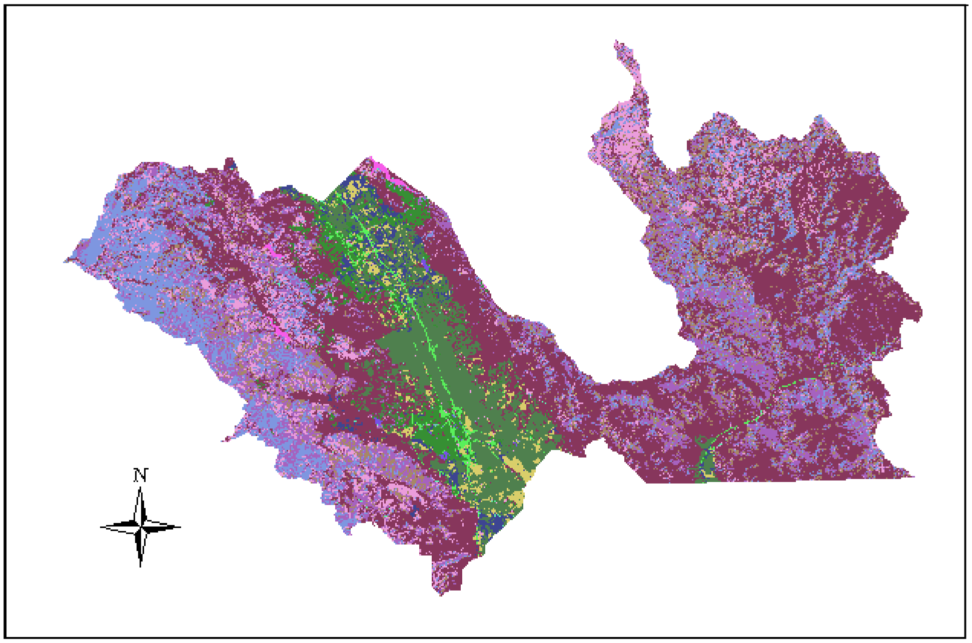

Figure 2b: 1992 USGS NLCD land use data.

Since the land use parcel dataset is much more current than the 1992 dataset, it is possible to compare how the land use has changed over those seven years. The similarity between the two suggests that the LULC changed little in this time span, with the exception of some residential and urban areas. These are likely to spring up as the population grows and cannot be expected to appear in the 1992 USGS data. The likeness of the two is strong evidence to support the use of the 1992 data as representative of current conditions.

To address the population growth and urban development, as well as further check the accuracy of the USGS dataset, visits to and around the urban centers were made. While this fieldwork verified the accuracy of most of the dataset, urban development was noted in several areas not indicated on a map generated using the USGS data. These were mostly in the vicinity of Gilroy, Morgan Hill, Watsonville, Hollister, and San Juan Bautista, all of which can be seen in Figure 1. The locations of the unmarked urban areas were noted. How this problem is addressed is discussed in a future section.

Another check of the 1992 USGS data, the general plans of the four counties and five cities included in the study were examined. No indication was found within those general plans that the suggested dataset would be unacceptable for this watershed study.

In 1999, AMBAG published a report of which a section was dedicated to land use. Through simplifying the Pajaro River Watershed Study land use definitions to match those used by AMBAG, the land use statistics became similar. For example, the AMBAG report states that about 76% of the watershed is used for agriculture and grazing. A summation of agriculture and grazing land uses in this study gives a total of about 72%. This difference is well within the acceptable standards of error.

Soils

Taking the recommendation of the NRCS soil scientist, the precision of the STATSGO hydrologic grouping was checked to determine whether it was adequate for a runoff model. A comparison was made between the provided data and the soil surveys for the four counties. Although there were small-scale differences between the surveys and soil data, based on the size of the watershed and qualitative nature of the ranking system it was decided that the digital STATSGO data would be sufficient for the modeling needs.

Data Updates

The quality checks described above demonstrated that the 1992 USGS LULC and the STATSGO soils data are reliable. The STATSGO data can be imported into the runoff model without any alterations. The LULC data has been shown to be more than adequate for most of the watershed. The only areas that are lacking are those that have been developed since 1992. In these areas, land uses marked as rural have become urban and are therefore more impervious to any rainfall or waterflow.

Rather than alter the LULC data file, the change in land use will be accounted for directly in the runoff model. Subwatersheds will have an artificially increased runoff coefficient if they have recently urbanized areas within the boundaries. Not only is this more time efficient but also might be more accurate and allow for better calibration. Since the exact extent of the urbanized area is unknown, additional calibration would be necessary anyway. Leaving the LULC data intact in its original form reduces errors that could be generated while changing the data attributes and provides a reference point for future modeling efforts.

Current Conditions

Population Growth

With a growing population come changes in land use. Perhaps the most important and obvious difference is the development of rural and agricultural areas. The additional population, housing, and community expansion such as parking lots and roads affect the percentage of pervious soil over an area. This is reflected in the runoff coefficient. For further explanation and description, please refer to TM 1.2.3.

Assuming that there is sufficient space and resources, existing urban areas tend to expand more rapidly than undeveloped areas. Based on field observations, this appears to be the case within the Pajaro River Watershed. There has been significant development associated with the sudden increase with population in the five major cities of the watershed, those being Gilroy, Hollister, Watsonville, Morgan Hill, and San Juan Bautista. While the raw land use data has not be altered to reflect these changes, the runoff coefficient within the runoff model is changed to reflect the population increase shown in Figure 3.

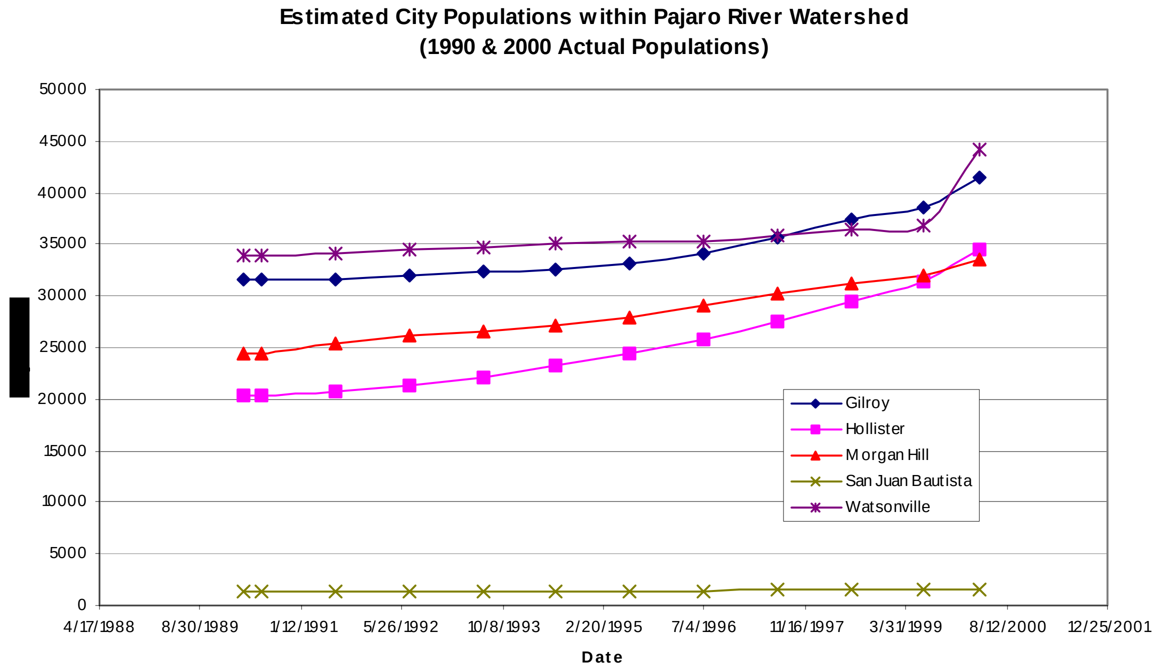

Figure 3: Population growth curves for five cities within the Pajaro River Watershed.

Land Use, Land Cover, and Hydrologic Soil Groups

As described in previous sections of this technical memorandum, the 1992 land use and land cover data obtained from the USGS adequately represents current conditions. Figure 4 shows land use and land cover trends across the entire watershed. It is apparent that a grassy land cover is the most prevalent classification. With further analysis it can be shown that about 40% of the watershed is grass or other herbaceous species. The next most common land covers are shrubland at 16% and evergreen forest at 13%. As can be seen in the Figure 4, high and low intensity residential land uses are not very influential as they combine for less than 2% of the total watershed land use. A percentage breakdown of all of the land uses found in Figure 4 can be found at the end of this technical memorandum in Appendix B.

Figure 5 represents the hydrologic soil groupings based on NRCS data. Soil type D is the most widespread classification across the watershed. Type B is fairly common in the urbanized areas in the northwest as well. The balance between all four types, A through D, within the subwatersheds can be found below. For a more thorough description of the effects of this balance please refer to TM 1.2.3. A qualitative description of the differences between the soil types can be found at the end of this technical memorandum in Appendix C.

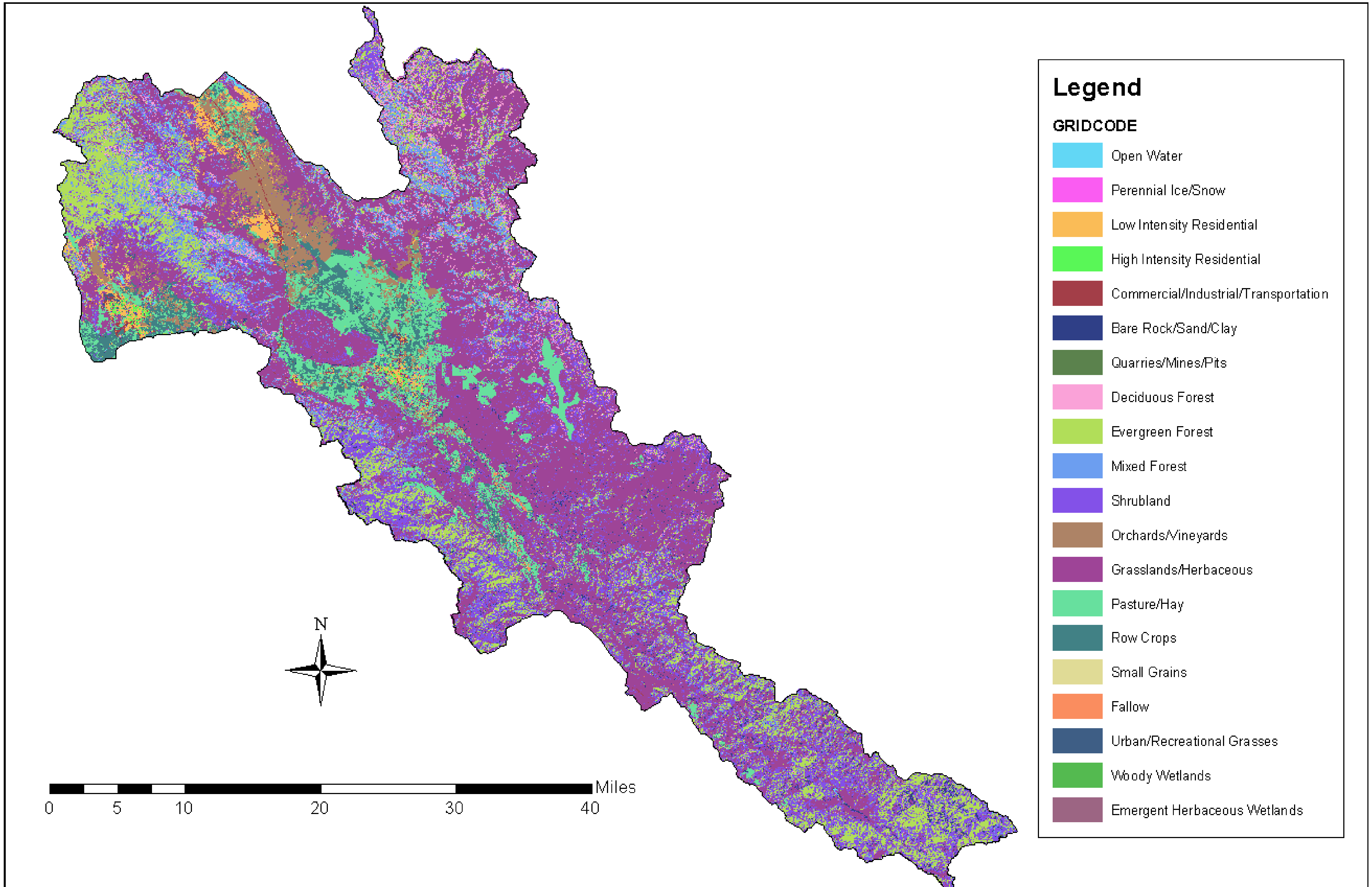

Figure 4: USGS land use and land cover for the Pajaro River Watershed.

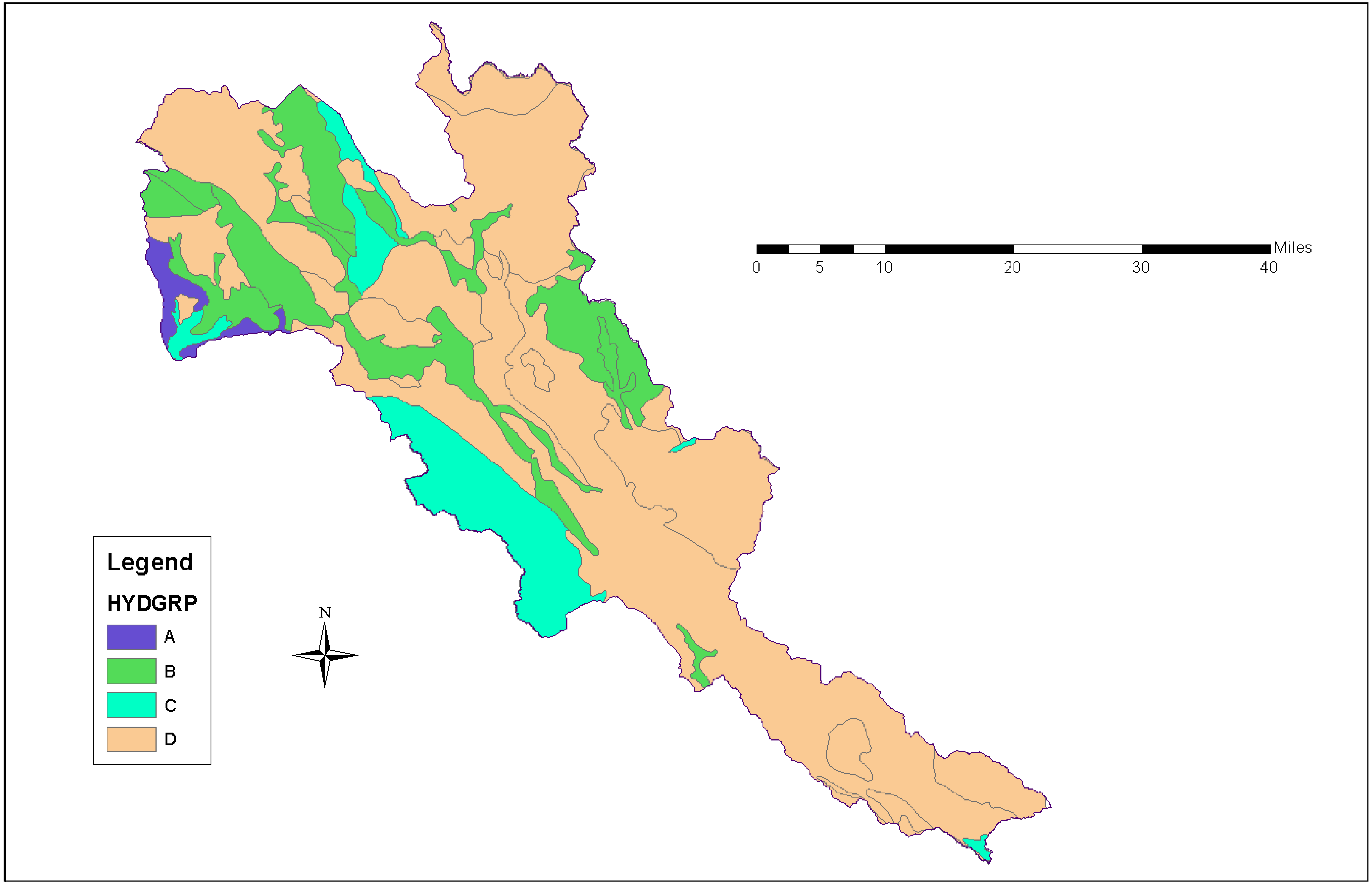

Figure 5: NRCS hydrologic groups of the Pajaro River Watershed.

Curve Numbers

Using GIS tools, the USGS land use and the NRCS soils data wered merge together. This data was then spatially partitioned to each subwatershed. The percent of the various land use types was computed for each hydrologic soil group in individual subwatersheds. Runoff curve numbers (CN), derived from the soil-land use percentages, can be applied to the runoff model to determine the effects of soil infiltration potential and land use on flood events.

Conclusion

This technical memorandum has shown that the land use and soils data presented here adequately represents the current conditions of the watershed. This data can be used within the hydrologic runoff model for baseline conditions and be adjusted to represent past, future, and hypothetical watershed conditions.

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Appendix A

Land Cover Class Definitions

from http://landcover.usgs.gov/classes.html

Water - All areas of open water or permanent ice/snow cover.

Open Water - all areas of open water, generally with less than 25% cover of vegetation/land cover.
Perennial Ice/Snow - all areas characterized by year-long surface cover of ice and/or snow.

Developed - Areas characterized by a high percentage (30 percent or greater) of constructed materials (e.g. asphalt, concrete, buildings, etc).

Low Intensity Residential - Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.
High Intensity Residential - Includes highly developed areas where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80 to100 percent of the cover.
Commercial/Industrial/Transportation - Includes infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential.

Barren - Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the "green" vegetated categories; lichen cover may be extensive.

Bare Rock/Sand/Clay - Perennially barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, beaches, and other accumulations of earthen material.
Quarries/Strip Mines/Gravel Pits - Areas of extractive mining activities with significant surface expression.
Transitional - Areas of sparse vegetative cover (less than 25 percent of cover) that are dynamically changing from one land cover to another, often because of land use activities. Examples include forest clearcuts, a transition phase between forest and agricultural land, the temporary clearing of vegetation, and changes due to natural causes (e.g. fire, flood, etc.).

Forested Upland - Areas characterized by tree cover (natural or semi-natural woody vegetation, generally greater than 6 meters tall); tree canopy accounts for 25-100 percent of the cover.

Deciduous Forest - Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen Forest - Areas dominated by trees where 75 percent or more of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed Forest - Areas dominated by trees where neither deciduous nor evergreen species

represent more than 75 percent of the cover present.

Shrubland - Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall, with individuals or clumps not touching to interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included.

Shrubland - Areas dominated by shrubs; shrub canopy accounts for 25-100 percent of the cover. Shrub cover is generally greater than 25 percent when tree cover is less than 25 percent. Shrub cover may be less than 25 percent in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25 percent and shrubs cover exceeds the cover of the other life forms.

Non-Natural Woody - Areas dominated by non-natural woody vegetation; non-natural woody vegetative canopy accounts for 25-100 percent of the cover. The non-natural woody classification is subject to the availability of sufficient ancillary data to differentiate non-natural woody vegetation from natural woody vegetation.

Orchards/Vineyards/Other - Orchards, vineyards, and other areas planted or maintained for the production of fruits, nuts, berries, or ornamentals.

Herbaceous Upland - Upland areas characterized by natural or semi-natural herbaceous vegetation; herbaceous vegetation accounts for 75-100 percent of the cover.

Grasslands/Herbaceous - Areas dominated by upland grasses and forbs. In rare cases, herbaceous cover is less than 25 percent, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing.

Planted/Cultivated - Areas characterized by herbaceous vegetation that has been planted or is intensively managed for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Herbaceous vegetation accounts for 75-100 percent of the cover.

Pasture/Hay - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops.
Row Crops - Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.
Small Grains - Areas used for the production of graminoid crops such as wheat, barley, oats, and rice.
Fallow - Areas used for the production of crops that do not exhibit visable vegetation as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage.
Urban/Recreational Grasses - Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses.

Wetlands - Areas where the soil or substrate is periodically saturated with or covered with water as defined by Cowardin et al.

Woody Wetlands - Areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.
Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.

Appendix B

Pajaro Watershed LULC Breakdown

LULC Classification	Percentage of Watershed Area
Open Water	0.11%
Perennial Ice/Snow	0.0%
Low Intensity Residential	1.5%
High Intensity Residential	0.14%
Commercial/Industrial/Transportation	0.58%
Bare Rock/Sand/Clay	1.5%
Quarries/Strip Mines/Gravel Pits	0.04%
Transitional	0.0%
Deciduous Forest	3.6%
Evergreen Forest	13.0%
Mixed Forest	7.7%
Shrubland	16.4%
Orchards/Vineyards/Other	3.9%
Grasslands/Herbaceous	40.4%
Pasture/Hay	7.4%
Row Crops	3.4%
Small Grains	0.05%
Fallow	0.13%
Urban/Recreational Grasses	0.19%
Woody Wetlands	0.0%
Emergent Herbaceous Wetlands	0.0%

Appendix C

NRCS Hydrologic Soil Groups

from the State Soil Geographic Database

Hydrology Class	**Description**
A	High infiltration rates. Soils are deep, well drained to excessively drained sands and gravels.
B	Moderate infiltration rates. Deep and moderately deep, moderately well and well drained soils with moderately coarse textures.
C	Slow infiltration rates. Soils with layers impeding downward movement of water, or soils with moderately fine or fine textures.
D	Very slow infiltration rates. Soils are clayey, have a high water table, or are shallow to an impervious layer.

Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers
in association with
Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.7 – Hydrologic Model

Task: Develop Hydrologic Model

To: PRWFPA Staff Working Group

Prepared by: J. Schaaf

Reviewed by: R. Raines

Date: March 13, 2001

Introduction

This Technical Memorandum (TM) describes the components of the hydrologic model and the data used to establish the parameters for the model. The TM goes on to compare model results with actual stream gage discharge hydrographs that occurred in the watershed from 1994 to 1999. The TM then demonstrates how the model is calibrated to reproduce frequency curves for peak discharge and 3-day volume at stream gages in the watershed.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a stream flow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1 (previously submitted with TM 1.2.1) the watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by a Corps of Engineers levee project constructed between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at US Highway 101 is just downstream of the outlet of "Lower Soap Lake" – a low-lying area of Santa Clara and San Benito Counties. This outlet has drainage area of approximately 500 square miles and includes such tributary watercourses as: Uvas Creek, Llagas Creek, Pacheco Creek and Santa Ana Creek.

The Hydrologic Model

The hydrologic model for the Pajaro River watershed is called PRO-FLO, which stands for Pajaro River to the Ocean – FLOod hydrology model. PRO-FLO is a traditional unit hydrograph model that uses a Curve Number (CN) to convert rainfall into runoff and loss. The model will be demonstrated by using actual storms as shown in TM 1.2.2 to attempt to reproduce stream hydrographs noted in TM 1.2.3. This part of the calibration process will show whether or not the model can reasonably reproduce actual storm events. Once this has been answered in the affirmative, the model will be calibrated using design storms as discussed in TM 1.2.2 to produce the frequency curves at stream gages as presented in TM 1.2.3.

The discussion below describes the elements of the model, the data needed for the model and the sources of those data.

The Watershed

Figure 7.1 shows the watershed of the Pajaro River broken into 32 sub-watersheds. The sub-watersheds are given a three- or four-character designation as shown on Figure 7.1. Table 7.1 shows some physical attributes of each of the sub-watersheds.

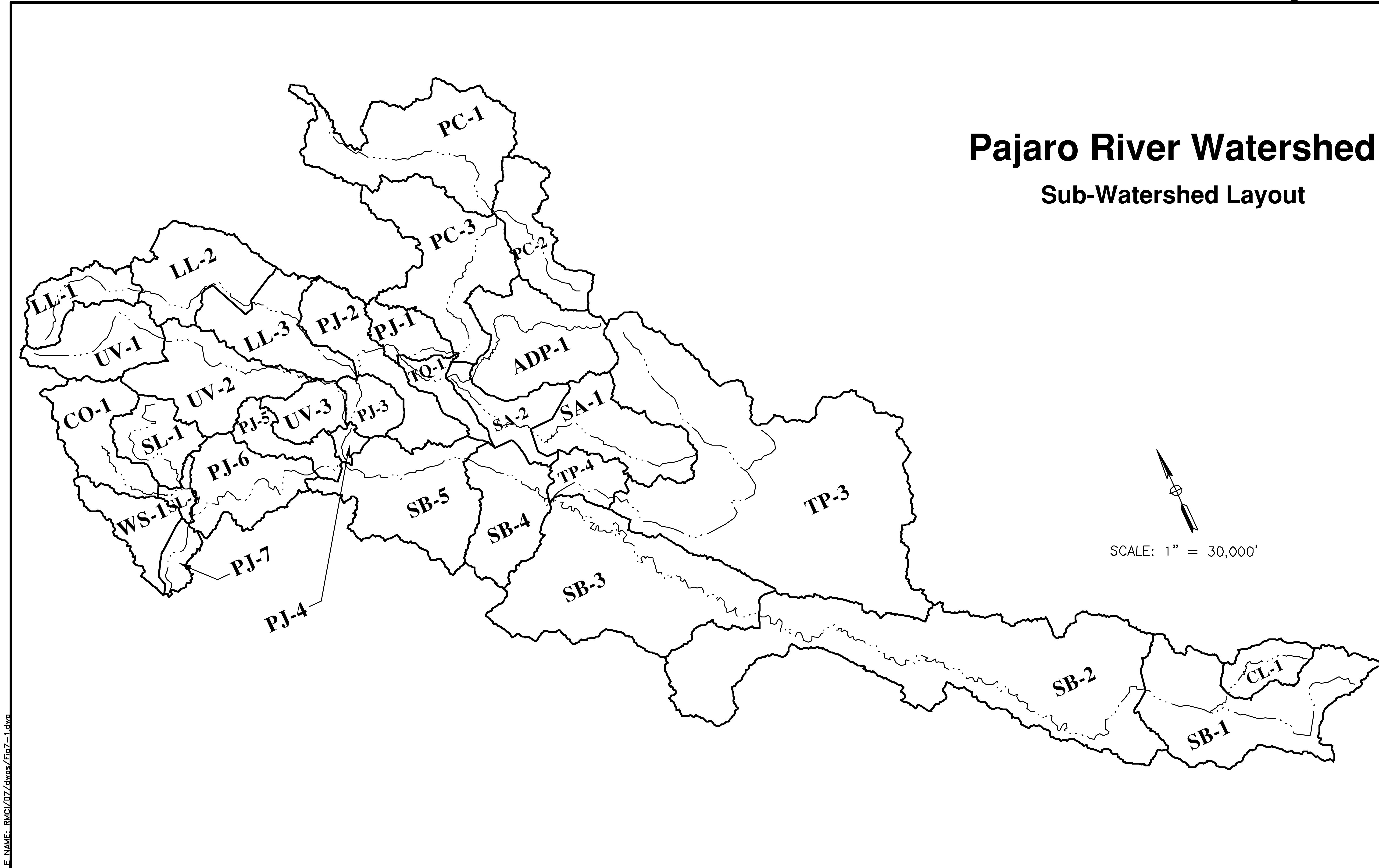

Pajaro River Watershed
Sub-Watershed Layout
PC-1
PC-3
PC-2
LL-2
LL-1
LL-3
PJ-2
PJ-1
TQ-1
ADP-1
UV-1
UV-2
UV-3
PJ-3
SA-2
SA-1
CO-1
PJ-5
SL-1
PJ-6
TP-4
TP-3
SB-5
SB-4
WS-1
SL-2
PJ-7
PJ-4
SB-3
SB-2
CL-1
SB-1
SCALE: 1" = 30,000'
FILE NAME: RMCI/07/dwgs/Fig7-1.dwg

Table 7.1

Pajaro River Watershed
Sub-Watershed Hydrologic Parameters

Sub-Watershed	Basin Roughness	Basin Length	Length to Centroid	Slope	SCS Lag	Area	Mean Annual Precip.
	N	L	Lc	S	LAG	A	MAP
		(mi)	(mi)	(ft/mi)	(hours)	(mi^2)	(in)
CL-1	0.07	7.79	3.95	126.30	2.04	14.12	20.4
SB-1	0.07	21.78	6.86	78.32	3.74	71.29	19.4
CL+SB1	0.07	21.78	7.71	78.32	3.74	85.41	19.4
SB-2	0.04	46.48	19.50	20.83	6.67	163.74	15.3
SB-3	0.07	29.56	17.82	19.98	8.38	102.15	16
TP-3	0.07	29.05	13.55	25.41	7.09	209.22	15.5
TP-4	0.06	6.71	3.28	42.06	1.48	13.28	13
SB-4	0.07	15.27	9.50	53.95	4.00	35.37	14.5
SB-5	0.06	12.79	5.90	62.84	2.42	54.69	16.1
SA-1	0.06	13.27	4.73	63.03	2.22	38.16	14.8
SA-2	0.05	9.91	4.82	13.24	2.25	19.46	13.4
ADP-1	0.07	14.21	8.93	98.38	3.32	46.83	15.4
PC-1	0.06	19.67	7.75	76.05	3.19	66.83	19.5
PC-2	0.06	9.77	3.46	135.06	1.36	27.77	20.2
PC-3	0.06	19.83	7.34	29.78	3.83	58.58	18.7
TQ-1	0.05	8.36	3.86	14.52	1.83	10.84	16.7
PJ-1	0.06	5.45	2.08	177.45	0.67	13.73	17.2
PJ-2	0.05	12.64	1.75	12.72	1.57	33.97	19.8
LL-1	0.08	11.98	6.45	58.89	3.48	19.24	34.4
LL-2	0.05	9.28	4.41	17.68	1.96	36.91	19.7
LL-3	0.05	13.71	7.38	12.92	3.18	34.01	19.3
UV-1	0.08	11.39	5.55	28.80	3.73	30.67	41
UV-2	0.07	14.48	8.09	24.92	4.31	41.14	28.1
UV-3	0.06	7.67	2.84	84.24	1.23	14.67	23.8
PJ-3	0.05	7.40	2.48	11.08	1.48	12.03	20.5
PJ-4	0.06	3.54	1.60	100.10	0.50	3.51	20.8
PJ-5	0.07	9.39	4.14	87.33	1.99	14.14	23.4
PJ-6	0.05	12.17	4.98	8.36	2.79	32.44	22
CO-1	0.08	11.83	6.59	63.78	3.44	29.95	29.3
SL-1	0.07	10.98	5.41	43.32	2.84	20.62	26.5
SL-2	0.03	4.53	2.80	31.12	0.35	4.25	21.6
WS-1	0.06	11.11	5.71	17.71	2.98	19.47	22.1
PJ-7	0.05	5.53	3.01	1.19	2.41	7.74	20.4

The drainage areas from Table 7.1 were summed at the location of each active USGS stream gage. This summed area was then compared to the area published by the USGS. As can be seen in Table 7.2 there is a good correspondence between the two.

Table 7.2

Comparison of Drainage Areas
(square miles)

Location	From Table 7.1	From USGS
San Benito R. Nr. Willow Creek School	248.2	249
San Benito R. at Highway 156	609.2	607
Tres Pinos Creek Nr. Tres Pinos	209.2	208
Pacheco Creek At Dunneville	153.2	154
Pajaro River Nr. Gilroy	406.3	399
Corralitos Creek At Freedom	29.9	27.8
Pajaro River At Chittenden	1,186.4	1,186

The Computations

The software program HEC-1, developed by the US Army Corps of Engineers, is used to do the hydrologic computations. This software package is readily available, in the public domain and has been used for many years by engineers all over the world to develop flood control hydrology for a variety of projects for very small to very large watersheds.

Unit Hydrograph

The unit hydrograph is the response of a watershed to one inch of excess precipitation generated uniformly over a unit of time. For PRO-FLO the unit of time is one hour. All design storms used in this model are divided into depths of rainfall each hour. Since this is the definition of the basic input to the model, the runoff (or excess precipitation) will be computed for each hour. As the computations are done hourly, the unit hydrograph is defined with a one-hour unit of time.

There are two ways of defining unit hydrographs: reconstitution of actual rainfall-runoff events, and synthetic unit hydrographs. The US Army Corps of Engineers has developed a unit hydrograph for the Corralitos Creek at Freedom gage site and for Salsipuedes Creek above College Lake. The Corps of Engineers one-hour unit hydrographs are used for sub-watersheds CO-1 and SL-1.

The remaining 30 sub-watersheds had their unit hydrographs defined using the synthetic unit hydrograph as defined by the US Department of Agriculture Soil Conservation Service (SCS.) The SCS is now named the National Resources Conservation Services (NRCS) but for purposes of this report the old acronym, SCS, will be used.

The SCS synthetic unit hydrograph is shown in Figure 7.2 in dimensionless form. The dimensionless discharge axis is in percent of peak discharge. The dimensionless time axis is in percent of time to peak. The SCS has an equation for computation of peak discharge. Computation of time to peak will be based on "lag" as defined in Figure 7.2.

The equation for the peak discharge, q_p (in cfs), of the unit hydrograph is:

$$q_p = 484\ A / T_p$$

Where: A is the drainage area in square miles
T_p is the time to peak in hours.

Once the peak discharge is computed the hydrograph can be scaled in both directions.

To compute the time to peak, the procedure used in PRO-FLO is to define the lag of the sub-watershed using the Corps of Engineers procedures and then convert that lag time into the lag time as defined by the SCS unit hydrograph.

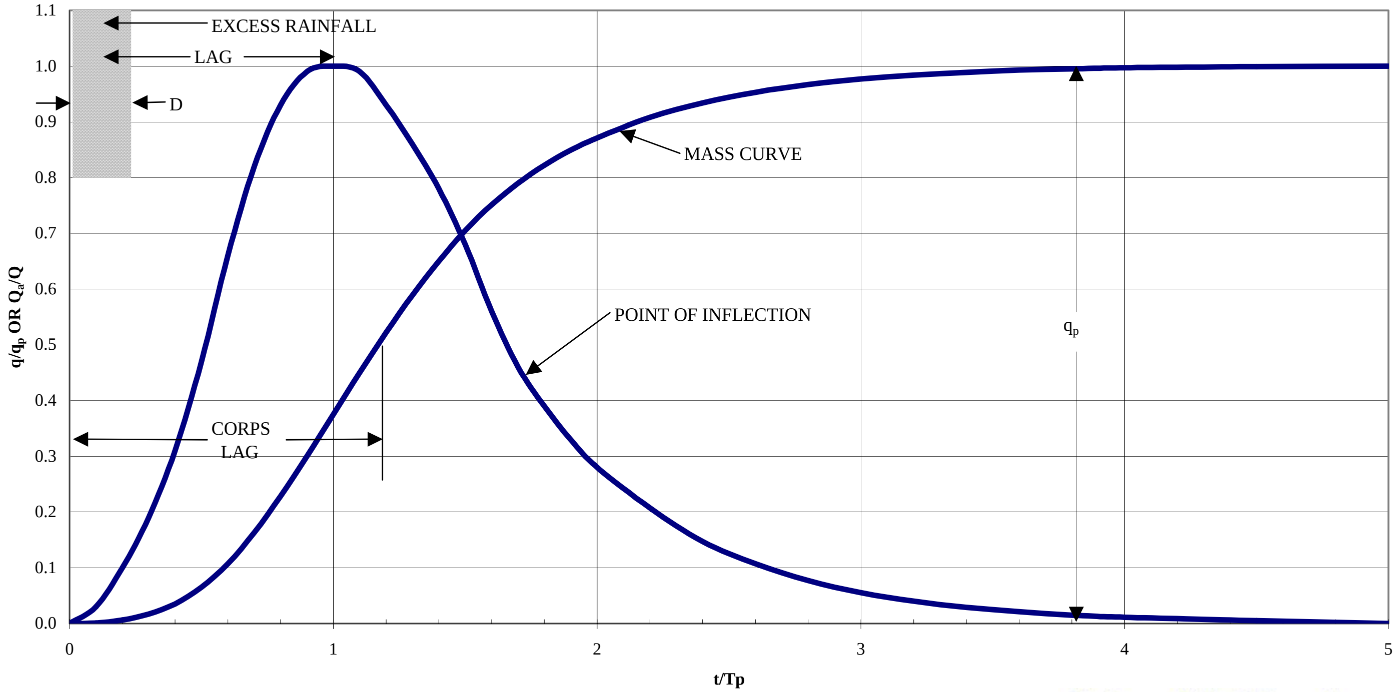
The Corps of Engineers formula for the lag of a sub-watershed is:

$$\text{Lag} = 24\ N\ [\ L\ L_{ca} / S^{0.5}]^{0.38}$$

Where: Lag is in hours and is defined by the Corps as the time between the beginning of the excess precipitation and the point where 50 percent of the volume has discharged from the watershed
N is the sub-watershed roughness factor
L is the length in miles of the longest watercourse in the sub-watershed
L_{ca} is the length in miles along the longest watercourse to the centroid of the sub-watershed
S is the average slope in feet per mile along the longest watercourse

Figure 7.2

Unit Hydrograph



The SCS definition of lag is shown graphically in Figure 7.2. It is different than the one the Corps uses. For use in the PRO-FLO model, the Corps of Engineers lag is converted to the SCS lag by multiplying the results of the above equation by 0.8625 and subtracting half of the one-hour unit time of the unit hydrograph.

The roughness values in the sub-watersheds varied from 0.08 to 0.03. They were estimated based on field reconnaissance. Generally the higher values are used for natural channels whereas the lower values are used for urban areas that not only have paved surfaces but also hydraulically more efficient, engineered interior drainage facilities. Basin roughness is one parameter that can be changed to achieve a better fit between predicted and actual runoff hydrographs.

Rainfall-Runoff

The SCS method uses a Curve Number (CN) to divide rainfall into: loss and excess. Excess precipitation is also called runoff. The procedure used to do this is embedded in the HEC-1 computer model but follows the traditional equations and procedures developed by the SCS. CN, a dimensionless number that varies from 0 (no runoff, all loss) to 100 (all runoff, no loss), depends upon four factors: hydrologic soil group (HSG), land use, hydrologic condition, and antecedent moisture condition (AMC.) In the discussion that follows the AMC is fixed at II – the standard condition for reporting CN values. A more detailed discussion of AMC and how it impacts peak discharge and volume of runoff will be found in a later section. For the present, however, the description of the rainfall-runoff portions of the model will be restricted to discussing only three of the four factors that influence CN.

As discussed in TM 1.2.6 there are only four HSG designations. The definitions of the four are shown in the appendix to that TM. The HSG distribution over the Pajaro River watershed is available in GIS format and has been used for this modeling effort.

Twenty-one categories of land use were discussed in TM 1.2.6. These land uses were defined by the USGS and are available in GIS format. The land use defined was as existed in 1992. A field reconnaissance led to changes in land uses of a few sub-watersheds as shown in Table 7.3. The sub-watersheds where changes were made were in the vicinity of Morgan Hill, between Morgan Hill and Gilroy and downstream of Chittenden. The principal problem upstream of Chittenden was that it appeared that a substantial portion of the large number of orchards shown in the 1992 land use GIS had been converted to row crops and/or low-density residential uses. In the sub-watersheds down stream of Chittenden a large percentage of the orchards shown in the 1992 land use GIS have been converted to row crops.

Table 7.3

Changes to USGS Land Use Data

Sub-Watershed	Description of Change
LL2 & LL3	1992 Orchard was changed to 1/3 Orchard and 2/3 row crops The row crops were assigned 10% imperviousness
PJ7	1992 Orchard was changed to row crops
SL2	1992 Orchard was changed to 1/3 Orchard and 2/3 row crops

There are many published lists of CN values for a variety of land uses. These have been published by the SCS, in a variety of textbooks on hydrology and in local agencies' design handbooks. A set of CN values for use in the Pajaro River watershed is shown in Table 7.4. For each land use there are generally 12 values: there are 4 HSG categories and there are 3 hydrologic conditions possible. Shown on Table 7.4 are the percentages of impervious area that are assumed to belong to each of the land use categories. The column labeled "%" on Table 7.4 is the percentage of the entire 1,300 square mile watershed that is in the noted land use category.

The GIS system can overlay HSG maps with land use maps to determine the percentage of any sub-watershed that is in each of the land use/HSG categories. CN values can then be determined separately for each of the four HSG categories or for the sub-watershed as a whole. The procedure used for the Pajaro River watershed model was that one CN was computed for each of the four HSG categories. Then the A and B CN's were combined. The C and D CN's were similarly combined. Thus each sub-watershed could have up to two different CN values: one for A/B, and another for C/D. This dual CN procedure was used because of the great non-linearity in the CN rainfall-runoff computational system. Averaging CN values over wide ranges can result in distorted estimates of the amount of runoff from a rainstorm. The CN values for each sub-watershed for the A/B categories and the C/D categories are shown in Table 7.5.

The "hydrologic condition" of each of the land uses was generally the "fair" category. There were a number of exceptions, however. For those areas where row crops were in strawberries the condition was specified as "poor" due to the use of plastic and the grading to drain rapidly. All other agricultural uses were placed in the "fair" category. Grassland was also placed in the "fair" category. Shrub land was the only land use placed in the "good" category. These conditions are reflected in the CN values shown in Table 7.5.

Table 7.4

CNN Values

(AMC II)

Land Use	%	A (good / fair / poor)	B (good / fair / poor)	C (good / fair / poor)	D (good / fair / poor)
Open Water	0.11	-	-	-	-
(100% Impervious)		-	-	-	-
		-	-	-	-
Low Density Residential	1.5	35	48	66	70
(25% Impervious)		44	58	71	74
		64	68	78	79
High Density Residential	0.14	35	48	65	70
(50% Impervious)		44	58	71	74
		64	68	78	79
Commercial/Industrial	0.58	35	48	65	70
(80% Impervious)		44	58	71	74
		64	68	78	79
Bare Rock/Sand/Clay	1.5	Varies			
(Imperviousness Varies)					
Quarries/Gravel Pits	0.04	0	0	0	0
(0 % Impervious)		0	0	0	0
		0	0	0	0
Deciduous Forest	3.6	27	30	41	48
(0% Impervious)		35	48	57	63
		48	66	74	79
Evergreen Forest	13	37	43	62	70
(0% Impervious)		45	57	69	80
		58	71	85	90
Mixed Forest	7.7	32	36	51	59
		40	52	63	72
		53	68	80	85
Shrub Land	16.4	27	43	60	68
(0% Impervious)		35	51	65	72
		48	62	72	78
Orchards	3.9	39	52	66	71
(1% Impervious)		43	65	76	82
		57	73	82	86
Vineyards	-	64	70	77	80
(1% Impervious)		67	75	82	85
		71	80	87	90
Grassland	40.4	38	50	69	76
(0% Impervious)		48	60	74	80
		58	70	80	84
Pasture/Hay	7.4	34	50	69	76
(0% Impervious)		44	60	74	80
		64	70	80	84
Row Crops	3.4	64	70	77	80
(1% Impervious)		67	75	82	85
		71	80	87	90
Small Grains	0.05	48	58	70	74
(0% Impervious)		49	59	71	75
		50	60	71	75
Fallow	0.13	64	68	78	79
(1% Impervious)		70	77	84	86
		77	86	91	94
Urban Recreational	0.19	34	48	66	70
(10% Impervious)		44	58	71	74
		64	64	78	79

HSG and Hydrologic Condition: rows within each land use are good / fair / poor.

Table 7.5

Pajaro River Watershed

Percent Impervious & Curve Numbers

Sub-Basin	% Impervious		Curve Number		% of Watershed	
	AB	CD	AB	CD	AB	CD
CL-1	n/a	1.0	n/a	69	0	100
SB-1	n/a	4.7	n/a	70	0	100
SB-2	0.6	0.0	55	71	3	97
SB-3	0.6	3.0	60	75	5	95
TP-3	0.1	0.1	53	76	16	84
TP-4	2.1	0.8	59	79	19	81
SB-4	14.6	5.3	60	76	5	95
SB-5	1.8	5.7	61	72	14	87
SA-1	0.0	0.8	46	77	5	95
SA-2	12.8	2.1	64	80	7	93
ADP-1	0.1	0.7	50	76	29	72
PC-1	n/a	0.0	n/a	69	0	100
PC-2	0.0	0.1	50	72	11	89
PC-3	2.0	0.3	56	69	11	89
TQ-1	2.0	0.5	63	81	30	70
PJ-1	0.9	0.2	56	76	26	74
PJ-2	1.1	0.7	63	77	27	73
LL-1	n/a	0.5	n/a	69	0	100
LL-2	11.5	5.8	62	72	59	41
LL-3	10.7	1.7	62	75	42	58
UV-1	0.1	0.6	42	67	3	97
UV-2	3.2	1.0	48	68	43	57
UV-3	4.7	0.9	59	71	20	80
PJ-3	n/a	1.2	n/a	82	0	100
PJ-4	1.4	2.2	57	79	27	73
PJ-5	0.2	0.2	45	69	48	52
PJ-6	2.3	8.3	58	77	88	12
CO-1	1.3	0.2	45	64	74	26
SL-1	0.7	0.6	46	72	33	67
SL-2	11.0	3.8	64	72	73	27
WS-1	6.2	11.9	44	74	68	32
PJ-7	18.8	4.8	61	78	44	56

Hydrograph Routing

A sub-watershed map with "catch points" is shown in Figure 7.3. The catch points are locations where hydrographs are combined and results are usually presented. Each catch point has a drainage area associated with it.

Not all catch points used in the PRO-FLO model are shown in Figure 7.3 due to bunching of points where many watercourses join at a single location. The points shown in Figure 7.3 are sufficient to provide a good overview of the logic in the routing and combining of hydrographs in the Pajaro River watershed.

For the four engineered water supply reservoirs in the watershed – Hernandez, Uvas, Chesbro and Pacheco – the storage-discharge relationships were based on data supplied by the Santa Clara Valley Water District and the San Benito County Water Agency.

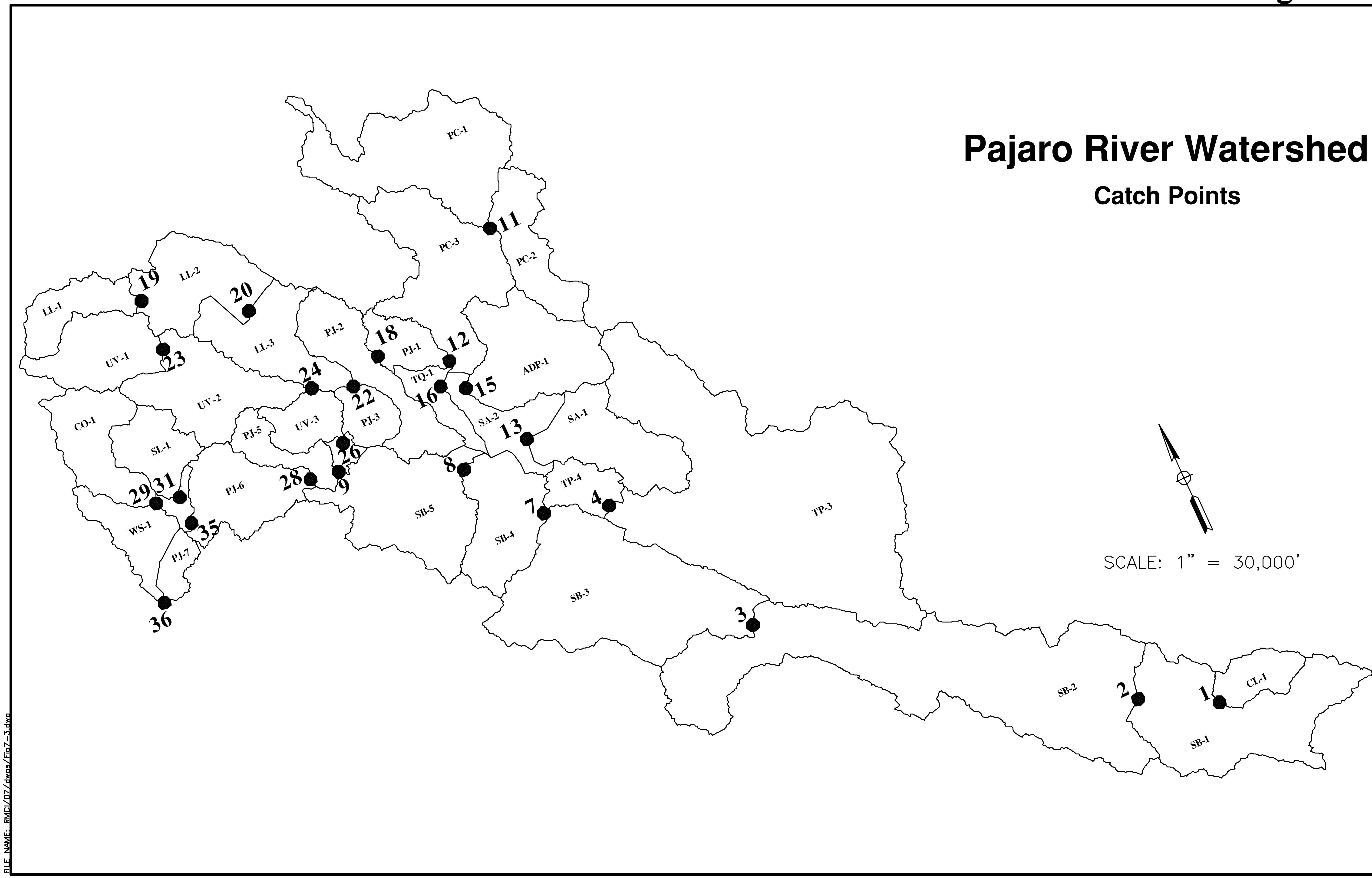
There are two natural reservoirs upstream of Chittenden as described earlier. These lakes have various names. As shown on the USGS San Felipe quadrangle the lake where Pacheco Creek, Santa Ana Creek, Arroyo dos Picachos and Tecesquita Slough all come together is called San Felipe. Many local residents, however, refer to it as "Soap Lake." The lake that forms at the confluence of Uvas Creek the Pajaro River and extends almost upstream to San Felipe Lake during major floods has been called "Soap Lake" on previous Corps of Engineers documents. To avoid naming confusion the remainder of this TM will refer to the two lakes as: "Upper Soap Lake" for San Felipe Lake, and "Lower Soap Lake" for the intermittent lake near the confluence of the Pajaro River and Uvas Creek.

The storage-elevation relationships for Upper Soap Lake and for Lower Soap Lake were obtained from 5-foot contour maps. The discharge elevation relationship for Upper Soap Lake was obtained using the cross section along Millers Canal along with an assumed energy slope during high flows.

The discharge elevation relationship for the Lower Soap Lake was obtained from the HEC-RAS model described in TM 1.2.5 and expanded upon later in this TM.

All other channel routings upstream of Chittenden were done using the Muskingum hydrologic routing or the Muskingum-Cunge method. The Muskingum method was the most often used. Parameters were taken from previous SCVWD models and from previous Corps of Engineers models. The Muskingum-Cunge was used along the Pacheco Creek upstream of Upper Soap Lake, for routings in the upper reaches of Bolsa Lake and for Salsipuedes Creek.

Figure 7.3



Schaaf & Wheeler

Reconstitution of Annual Maximum Flood Events

The maximum annual peak discharge at the Chittenden stream gage was determined each water year from 1994 to 1999 inclusive. These maximum instantaneous peak discharges defined the storms that were considered. These storms were described in TM 1.2.2. A reconstitution was undertaken of the three-day stream gage responses at a number of stream gages in the watershed. The CN values determined for each sub-watershed were used as a starting point. The rainfall over each sub-watershed was taken from the isohyetal maps shown in TM 1.2.2. The pattern of rainfall was obtained by averaging the hourly patterns at the two nearest working rain gages during the three days considered.

Two calibration parameters were used in the reconstitutions: Antecedent Moisture Condition (AMC) and lag time through the sub-watershed roughness parameter. AMC was discussed briefly in an earlier section on CN. The SCS has defined the change in CN as a function of AMC. Three AMC's are defined: I, II and III. AMC I is dry, AMC III is wet, and AMC II is average. The SCS has some guidance on selection of AMC but that guidance is very limited and may not be geographically robust.

For purposes of reconstitution the AMC was varied by increments of 0.5 to attempt to achieve a better fit of the model to the actual data. Therefore, the allowable AMC's were selected from: I, I.5, II, II.5, and III. Using increments of 0.25 rather than 0.5 would not produce any additional confidence in the response of the model.

The model hydrographs are compared to recorded hydrographs. These hydrographs themselves are not without error. Three of the USGS gages are rated as "fair." These are Corralitos Creek, Clear Creek and Pajaro River at Chittenden. The Chittenden gage was rated as "poor" on February 3 1998. The rest of the gages are rated as "poor." In USGS terminology a rating of "fair" means that 95 percent of the daily discharges are within 15 percent of their true value and "poor" means that 95 percent of the daily discharges are more than 15 percent from their true value. In more basic statistical terms this means that gages that are rated as "fair" have a 7.5 percent relative error (or standard deviation) on the daily discharge value published. Stations rated as "poor" have a greater standard deviation that for purposes of this TM can be considered as at least 10 percent. Peak discharge values have an even greater degree of error. The modeling effort is being compared to data that is not error free but represents the best estimate of discharge at any particular gages at any particular time.

Model outputs can be found at the end of this TM. Discussion about the results can be found below.

Clear Creek

The results are shown in Figures CL 94 to CL99. The 1994 reconstitution shows a peak discharge that is much too high and almost a day later than the actual peak. The rainfall pattern most likely has the most to do with the timing discrepancy. The watershed is small (14 square miles) and subject to high flows from intense, localized rainfall. There are no rain gages in the watershed. The AMC used for this reconstitution was I.5.

The 1995 reconstitution was not too bad. An AMC of II was used. The underestimate of the early peaks on 3/9/95 and the overestimate of the peak on 3/12/95 are characteristic of the SCS procedure. Early rainfall goes into loss until soil storage is satisfied. Once a large amount of rain falls the procedure predicts a higher percentage of runoff from incremental rainfall until for very large rain events the later portions of the storm have almost all rainfall being converted into runoff. It would improve the SCS procedure to have a minimum loss rate attached but such is not the procedure as programmed into the HEC-1 computer program. All in all, however, the 1995 event is fairly well replicated by the model.

The 1996 reconstitution produces two peaks that are both slightly high but the timing of the peaks looks fairly good. The AMC was II.5.

The 1997 reconstitution gives one peak that is slightly greater than the actual peak. The actual gage record shows a fairly constant discharge over the two peak days but the reconstitution shows very low flow followed by a large hydrograph. The AMC was I.

The 1998 reconstitution produces a peak that is high. The original peak was even higher but the rainfall depth over three days was reduced by 20 percent from the estimate obtained by using the averages of the nearest rain gages because the closest rain gages were not working during the storm. The AMC was I for the reconstitution. The timing of the modeled peak is approximately the same as the gaged peak.

The 1999 reconstitution at Clear Creek has a peak discharge too low and about a day earlier than the actual peak. The lack of definition of the rainfall pattern is probably the biggest source of error here.

The conclusion for Clear Creek is that the model fairly well reproduces the range of hydrographs during the six years.

Corralitos Creek

The reconstitutions are shown in Figures CO 94 to CO 99. The 1994 reconstitution looks fairly good. The AMC was I.5.

The 1995 reconstitution was also fairly good. The AMC was II. The later peak on 3/11/95 was greater than the gage results probably due to the way the SCS method calculates runoff in the later portions of the storm.

The 1996 reconstitution is not good. The AMC used was II.5. The later peaks are much exaggerated due in part to the SCS runoff computational procedure. It looks like the modeled hydrograph has peaks that are nine or so hours early. The third set of peaks shows occurs at a time that the gage record shows no signs of peaking. This is not a good reconstitution.

The 1997 reconstitution is not too bad. The AMC was III. The timing is good and the peaks are not too bad. This is a reasonably good reconstitution.

The 1998 reconstitution is not too bad. The AMC was I.5. The first peak is missed entirely because all of the rainfall is going into filling the available storage in the SCS method. The second and third peaks are fairly represented.

The 1999 reconstitution looks good. The AMC was I.5. This is a fairly good reproduction of the hydrograph.

The conclusion for Corralitos Creek is that the model, using the Corps of Engineers unit hydrographs, fairly well reproduces the range of hydrographs during the six years.

Pacheco Reservoir Outflow

The reconstitutions are shown in Figures PR 95 to PR 99. There was no data from the SCVWD on the 1994 reservoir levels. The outflow from Pacheco Reservoir was computed by using the spillway width and configuration and the SCVWD data showing elevation in the reservoir as a function of time.

The 1995 reconstitution looks fairly good. The AMC was II. The tail end of the hydrograph could be improved by using a recession function built into the HEC-1 computer program.

The 1996 reconstitution was done using AMC II. The first peak is too low and the second and third are too large. As explained previously the fact that the later peaks are too large is an artifice of the way the SCS method works. The timing of the peaks, however, looks good.

The 1997 reconstitution used an AMC of I.5. The first peak was understated while the second was overstated.

The 1998 reconstitution was poor even though an AMC of I was used. The data showed that there was <u>no</u> inflow to the reservoir until past 2/5/98. These certainly appear to be bad data.

The 1999 reconstitution did not show any outflow from the dam but neither did the actual data although the data did show that the reservoir was filling during the period.

The conclusion for the Pacheco Reservoir location is that the model fairly represented what was actually occurring at the spillway.

Pacheco Creek at Dunneville

The two reconstitutions are shown in Figures PC 94 and PC 95. The 1994 reconstitution was done with AMC I.5 but the model produced too little peak discharge and set it too late in time.

The 1995 reconstitution, however, was somewhat better. The data only consisted on maximum time and discharge and minimum discharge and time. The dashed line just connected these two points each day with a straight line. However, the fit is not too bad.

During larger events the model appears to provide a reasonable estimate of the gage record.

Tres Pinos Creek

The three reconstitutions are shown in Figures TP 97 through TP 99. The 1997 reconstitution was done using AMC III. The peak discharge and the timing are fairly good although the peak is somewhat low.

The 1998 reconstitution hits the gaged peak almost exactly. AMC I.5 was used in the model. The USGS data only lists a peak discharge without a time associated with it so the timing fit cannot be judged.

The 1999 reconstitution used AMC II but no outflow could be generated to produce the flow flows reported by the USGS. Perhaps the rainfall depth in the model was not representative of the actual rainfall over the watershed.

The model predicts Tres Pinos hydrographs fairly well.

San Benito River Near Willow Creek School

The reconstitutions are shown in Figures SBW 94 to SBW 99. The 1994 reconstitution shows a peak flow from the model that is greater than the gaged peak. The model used AMC I.5.

The 1995 reconstitution is fairly good. The peak discharge is slightly too large and is a little late. The AMC was I.5. Included in this model was overflow from Hernandez Reservoir. The reservoir flow creates the peak discharge just after midnight on 3/11/95 according to the model. The peak on the 12^{th} in the early morning is once again an artifice of the SCS computational procedure.

The 1996 reconstitution used AMC II.5. The peak discharge is slightly high.

The 1997 reconstitution used AMC I.5. The model meets the second of the two peaks but does not mimic the first peak. There is no evidence from the rainfall pattern that two peaks should have occurred. While there is no data on the water levels in Hernandez

Reservoir for the 1997 event, the model assumed that there was no overflow during the flood.

The 1998 reconstitution used AMC I. The model predicted a hydrograph with a peak slightly less than that published by the USGS. No timing was available to match model timing with that at the gage. Data was available for Hernandez Reservoir for the 1998 event. The reservoir did not spill during the four days modeled. If the AMC was increased to I.5 the peak discharge would have been 11,000 cfs, a value much greater than that gaged. Obviously something in between was the actual AMC. However, for purposes of downstream routing and combining, the hydrograph with AMC I was considered a better representation of the upper watershed than the hydrograph using AMC I.5. In other words it was felt that it was better to be 1,800 cfs low at this gage than 3,000 cfs high.

The 1999 model used AMC II and produced a peak discharge that was somewhat early and somewhat higher than the gage showed.

Overall the model reconstitutes the gage hydrographs at the San Benito River near Willow Creek Scholl fairly well. A better fit could have been achieved had the CN parameters been taken to the nearest 0.25 AMC rather then the nearest 0.5.

San Benito River at Highway 156

At this catch point (number 8) the model must include the routing and combining of hydrographs from seven upstream sub-watersheds. The AMC's used to calibrate the Tres Pinos and San Benito River near Willow Creek School were used in the model at the 156 gage.

The reconstitutions are shown in Figures SBH 94 to SBH 99.

With the notable exception of 1995, the reconstitutions are fairly good. The 1995 hydrograph occurs later than the actual peak and is approximately 25 percent larger. Possibly the rainfall was somewhat different than what was used in the PRO-FLO model. Again with the exception of 1995 the peak timing is fairly good especially when looking at 1998 and 1997.

Pajaro River at Chittenden

The reconstitutions are shown in Figures PRC 94 to PRC 99. All six plots show the results using only the hydrologic routing procedures in HEC-1. Figures PRC 95.1, PRC 95.2, PRC 95.3, and PRC 98.1 and PRC 98.2 show results using HEC-RAS and will be discussed at the end of this current section.

The 1994 reconstituted flow is only slightly above that recorded at the gage. The 1995 hydrograph, however, shows only one peak rather than two and this one peak is far greater than the recorded peaks. Looking back at the 1995 reconstituted hydrograph at

Highway 156 (Figure SBH95), the simulated peak was later than the actual peak discharge as read at the stream gage. This later simulated peak has combined with the outflow from the Lower Soap Lake to create a peak at Chittenden that is much greater than that actually recorded.

The 1996 hydrograph from the model has a peak discharge about 2,000 cfs greater than that recorded at the gage. The shape of the modeled hydrograph, however, is quite similar to the shape of the gaged hydrograph.

The 1997 reconstituted is close to the observed with the exception of the recession limb of the hydrograph. The model's peak is just about the same as the gaged as is the timing.

The 1998 reconstitution produces a peak discharge 17,000 cfs greater than that measured at the gage. Again, the recession limb of the model drops off faster than the measured hydrograph.

The 1999 reconstitution produces a peak that is about one half of that measured at the gage. There is less total flow in the model's hydrograph than there is in the measured hydrograph.

The 1995 and the 1998 hydrographs were re-routed using the HEC-RAS computer model for one-dimensional, unsteady state hydraulics. The reconstituted hydrographs are shown in Figures PRC 95.1 and PRC 98.1. The HEC-RAS model accounts for the change in outlet hydraulics from Lower Soap Lake due to the passage of flow from the San Benito River into the Pajaro. The resulting backwater on this relatively flat section of channel creates a barrier to flow from Lower Soap Lake and allows the San Benito to drain first while totally or partially holding back the outflow from Lower Soap Lake.

Figure PRC 95.2 shows the discharge at Chittenden using the HEC-RAS hydraulic model but using the actual hydrograph as measured at Highway 156 on the San Benito River. Instead of having a peak discharge of 34,000 cfs as shown in Figure PRC 95.1, there is now a peak of only 27,000 cfs. In addition, the simulated and measured hydrographs look much more similar. This test showed that the model near the confluence was much better than first appeared in Figures PRC 95 or 95.1.

Figures PRC 95.3 and PRC 98.2 show more detail of the hydraulic and hydrologic interactions at the confluence of the San Benito River and the Pajaro River. Figure 95.3 shows the inflow hydrograph to Lower Soap Lake, the gaged San Benito River hydrograph at Highway 156, and the outflow hydrograph from Lower Soap Lake. As the San Benito River starts to peak, the flow from Lower Soap Lake goes down slightly in response to the increased backwater effect in the Pajaro River from the confluence with the San Benito River upstream to the outlet of Lower Soap Lake. The backwater allows more storage to be built up in Lower Soap Lake resulting in more area inundated.

This effect is much more dramatic in Figure PRC 98.2. Here, the very large discharge on the San Benito River actually shuts down the outflow from Lower Soap Lake. It is important to note that the simulated outflow from Lower Soap Lake is actually greater than the maximum peak inflow due to the fact that the backwater effect stopped the outflow and increased the water level in the lake. The San Benito hydrograph recessed very rapidly. This dropping of the water surface allowed Lower Soap Lake to drain again but this time with a much greater head – resulting in higher discharges than would normally be expected under reservoir routing conditions.

Conclusions

The PRO-FLO model did a moderately successful job of reproducing gaged hydrographs from 1994 to 1999. The lack of specificity regarding the rainfall depths over the watersheds was believed to be the most important reason for the less than perfect reconstitutions. However, the reconstitutions did show that the timing of the unit hydrographs was fairly good at all the gages. The HEC-RAS routings showed that the interaction between the outflow from Lower Soap Lake and the flow at the mouth of the San Benito River is important and complex. It is important because high discharges on the San Benito would tend to naturally limit the contribution from Lower Soap Lake. The interaction is complex because the flow can actually reverse on the Pajaro River if the water level at the San Benito River mouth is sufficiently higher than that in Lower Soap Lake. Only an unsteady flow model such as HEC-RAS can capture this complex, but important interaction.

Calibration to Frequency Curves

Five stream gages were selected for the calibration: Pajaro River at Chittenden; San Benito River at Highway 156; Pajaro River near Gilroy; Pacheco Creek at Dunneville; and Uvas Creek near Morgan Hill. Statistical analyses were performed for the peak discharges and the 3-day average discharges for these gages as shown in Figures 3.17, 3.16, 3.11, 3.10 and 3.12 in TM 1.2.3.

The PRO-FLO model was run with design precipitation patterns for the 2-, 10-, 25-, 50-, 100-, and 200-year 72-hour storms. The patterns were modified to account for the reduction of the 1-hour depth based on the area reduction factor as shown in Figure 2.17 of TM 1.2.2. Appropriate area reduction factors based on Figure 2.17 in TM 1.2.2 were also used to modify 72-hour rainfall depths.

Calibration of the PRO-FLO model to the five stations at each of the six frequencies was done with only two parameters: Antecedent Moisture Condition and base flow.

The AMC could range from I to III. It was allowed to do so in steps of 0.25. Thus allowable AMC's could be I, I.25, I.5, I.75 etc. The SCS has a relationship for changing CN for AMC conditions from II to I or from II to III. The PRO-FLO model interpolated between those published SCS values in four equal increments from II to I or from II to III

For the 200-year flood the AMC was I.75. For all five other return period floods the AMC was I.5.

The second calibration parameter was base flow. Base flow was added on a "per square mile of drainage area" basis. The base flow varied from sub-watershed to sub-watershed with sub-basins draining to Lower Soap Lake having higher base flow components as opposed to those draining to the San Benito River. Base flow also varied with flood frequency and generally the more frequent events had lower base flows.

Along the San Benito River just upstream of the Highway 156 gage, a channel loss was permitted for the 2-, 10- and 25-year floods. The San Benito River is very sandy and channel losses are expected for many of the smaller flood events. At the 2-year flood the loss was 1,700 cfs. At the 10-year the loss was 2,500 cfs and at the 25-year flood the loss was 1,500 cfs. For greater floods there was no channel loss but base flow was added to the computed hydrographs.

At the 2-year flood there was a channel loss of 1,000 cfs downstream of Upper Soap Lake to account for the infiltration into the porous streambed and Millers Canal. For larger flood events there was no channel loss.

The San Benito River sub-watersheds had no base flow added for the 2-, 10-, and 25-year floods. There was 2-cfs/square mile base flow added for the 50-year flood; 3-cfs/square mile for the 100-year flood; and, 5-cfs/square mile for the 200-year flood.

Other sub-watersheds had no base flow for the 2-year flood; 5-cfs/square mile for the 10-year flood; 10-cfs/square mile for the 25-year flood; and, 15-cfs/square mile for the 50-year flood, the 100-year flood, and the 200-year flood. There were variations in these values in some of the sub-watersheds. The largest variation was in the Uvas Creek sub-watershed above Uvas Reservoir where more based flow was used for all return periods.

Results

The calibration results are shown graphically for five stations in Figures 7.4 through 7.8. In all cases PRO-FLO produces results close to the actual frequency curves.

A more analytical approach to the results is shown in Table 7.6. On that table are shown the percentage error for the peak and for the 3-day average discharge for each of the six storm events at each of the five stream gage stations.

For each of the five gages the standard error is shown for the peak discharge estimates and the 3-day average discharge estimates. These estimates are shown on the right side of each line. There is a standard error for all six return periods and for five of the return periods minus the 2-year flood.

Figure 7.4

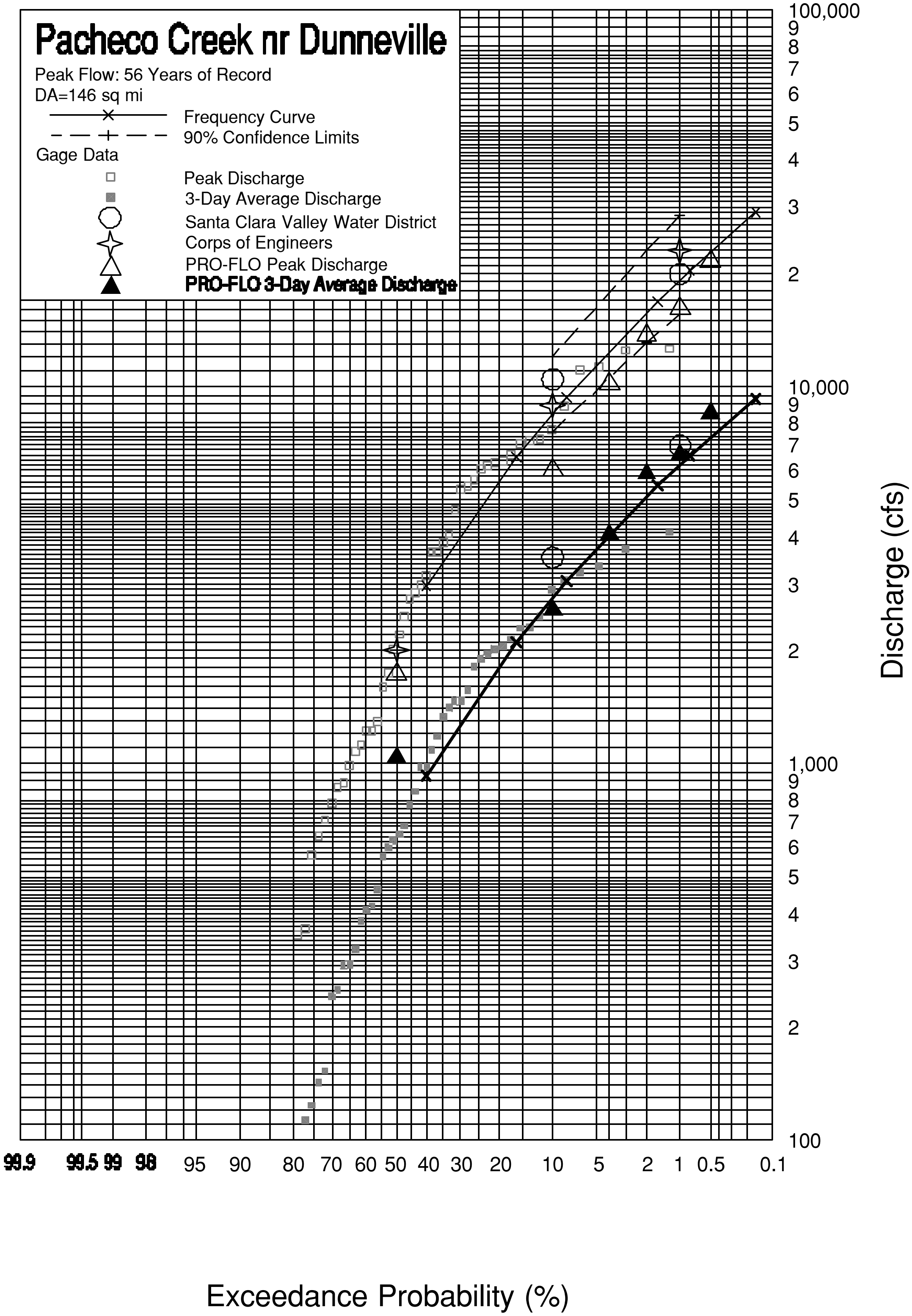


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Figure 7.5

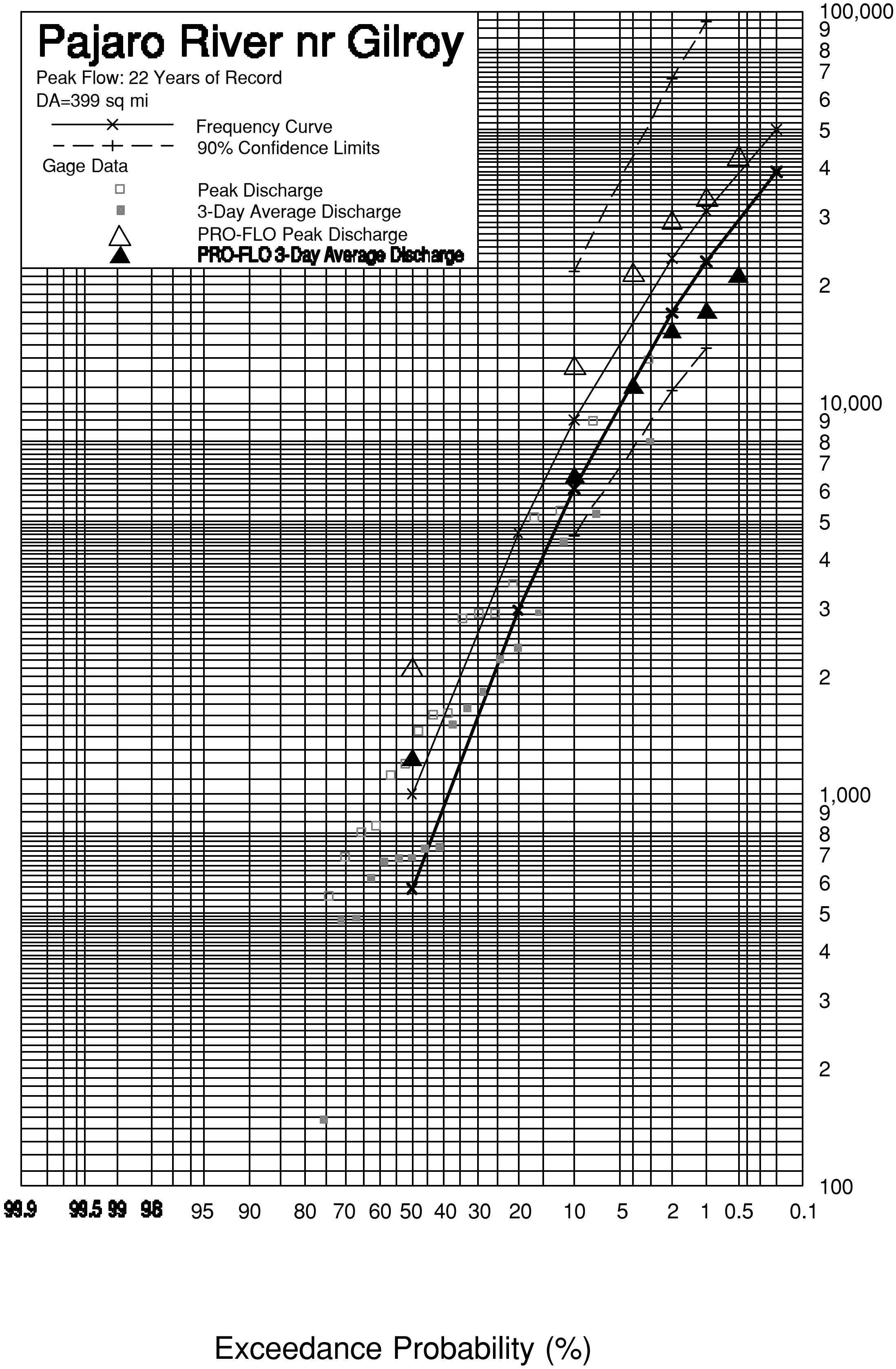

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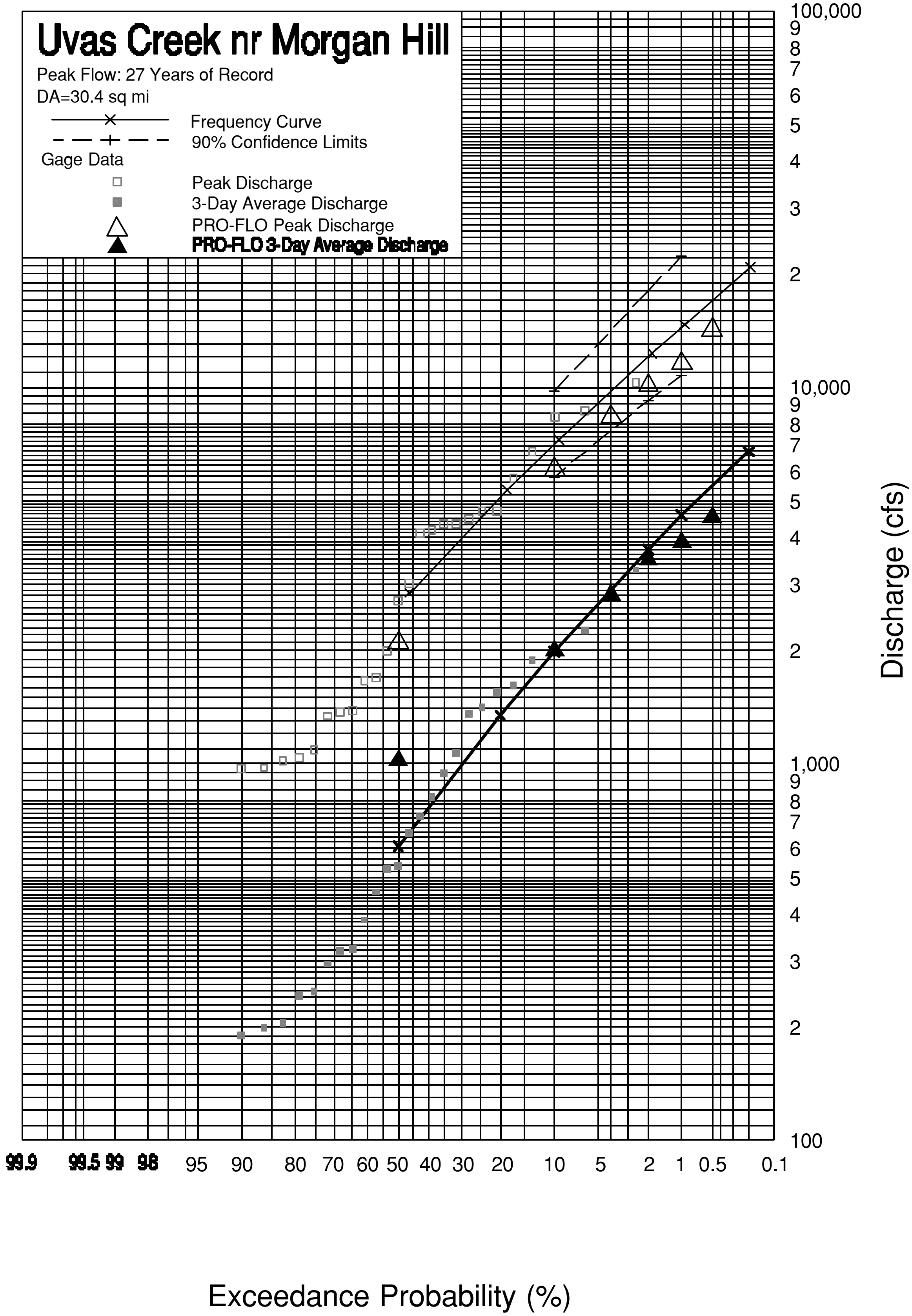
Figure 7.6



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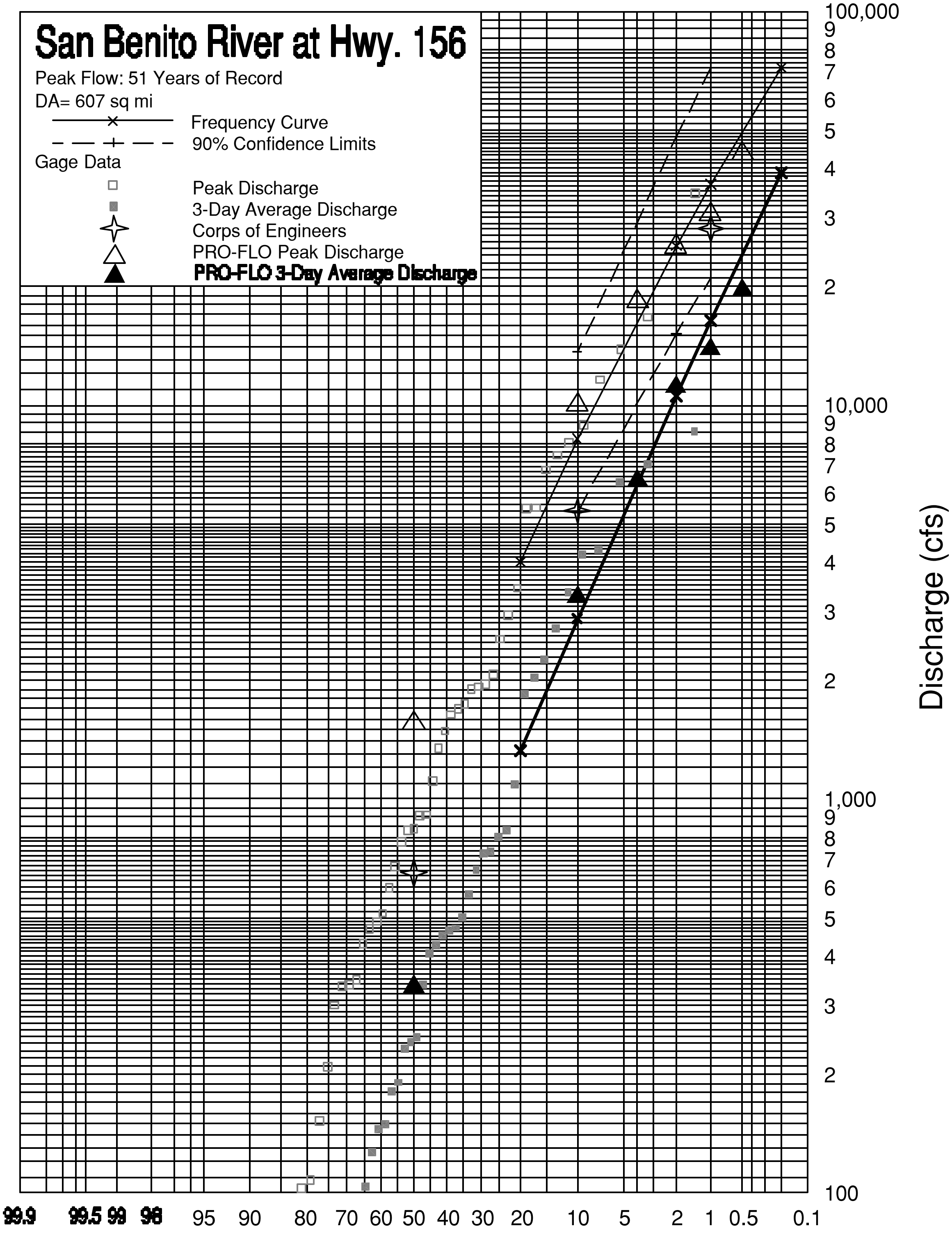

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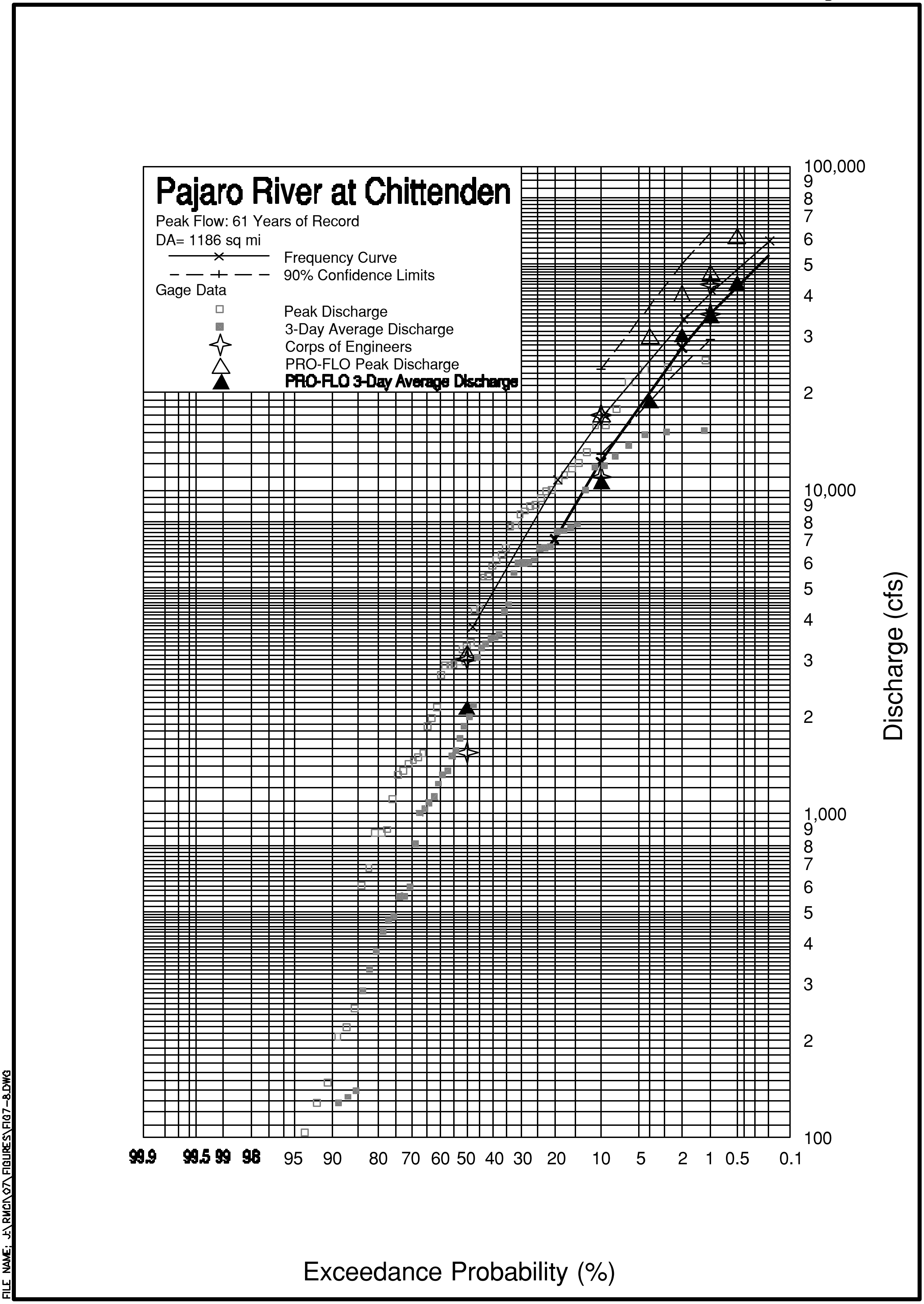

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Table 7.6

Standard Errors for PRO-FLO Fit

GAGE	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr	No 2-yr SE	All Yrs SE
PRC	1186								
Pk Q		-235	373	4,125	6,758	5,432	10,890		
Pk %		-7.1%	2.3%	16.4%	20.5%	13.4%	22.7%	18.6%	17.0%
3-Day Q		191	-1,759	-1,416	2146	-461	88		
3-Day %		10.1%	-14.4%	-7.1%	7.8%	-1.3%	0.2%	8.9%	9.2%
SBH	607								
Pk Q		170	1,899	1,731	-225	-6,099	-6,150		
Pk %		20.0%	23.4%	10.5%	-0.9%	-16.7%	-12.4%	16.5%	17.3%
3-Day Q		95	372	119	647	-2611	-4,347		
3-Day %		39.6%	12.8%	1.9%	6.2%	-15.8%	-18.1%	14.0%	21.7%
PRG	400								
Pk Q		677	3,212	5,151	5,231	2,003	3,515		
Pk %		48.4%	35.7%	32.2%	22.3%	6.5%	9.1%	27.1%	32.5%
3-Day Q		521	465	-305	-1,856	-6,037	-7,939		
3-Day %		74.4%	7.8%	-2.7%	-10.9%	-26.2%	-27.4%	20.2%	37.8%
PCD	146								
Pk Q		-473	-2,505	-2,023	-2,045	-3,085	-1,285		
Pk %		-21.5%	-29.5%	-16.6%	-12.9%	-16.1%	-5.6%	20.0%	20.3%
3-Day Q		256	-193	66	778	423	1,234		
3-Day %		40.0%	-7.0%	1.6%	15.3%	6.8%	16.9%	12.4%	21.1%
UCM	30.4								
Pk Q		-553	-1,056	-1,398	-1,908	-2,944	-2,846		
Pk %		-20.9%	-14.9%	-14.4%	-15.9%	-20.3%	-16.7%	18.5%	19.0%
3-Day Q		159	7	-85	-204	-683	-890		
3-Day %		26.5%	0.4%	-2.9%	-5.5%	-15.0%	-16.5%	11.6%	15.7%
PEAK									
Average Error		3.8%	3.4%	5.6%	2.6%	-6.6%	-0.6%		
Standard Error		30.4%	27.0%	21.8%	18.3%	17.1%	16.3%		
3-Day Discharge									
Average Error		38.1%	-0.1%	-1.8%	2.6%	-10.3%	-9.0%		
Standard Error		48.8%	11.0%	4.3%	11.0%	17.4%	20.2%		

Standard Errors	**All Gages**		`
Peak Discharge	18.7%	Without 2-year	
3-Day Average	12.7%	Without 2-year	
Peak Discharge	20.4%	With 2-Year	
3-Day Average	21.5%	With 2-Year	

LEGEND:
PRC = Pajaro River at Chittenden
SBH = San Benito River at Hollister
UCM = Uvas Creek near Morgan Hill
PRG = Pajaro River near Gilroy
PCD = Pacheco Creek at Dunneville

The standard error (SE) was computed by first squaring each percent error, then summing those squares, then dividing that sum by the number of observations less one, and finally by taking the square root of the result. As can be seen in Table 7.6, the SE for the Chittenden gage (PRC) is 17 percent for the peak discharges for all six return periods and 9.2 percent for the 3-day average discharge. The PRO-FLO model does a good job at the Chittenden gage.

The SE at the San Benito River at Hollister gage is not as good for the 3-day discharges as for the peak discharges. The PRO-FLO model is not as good at that gage as for the Chittenden gage. The worst fit was at the Pajaro River near Gilroy gage (PRG). Here the 2-year discharge errors were very large. The large percentage errors for these low flows drove up the overall SE for the PRO-FLO fit at that gage.

The overall SE for all frequencies, for all gages is shown at the bottom of Table 7.6. The 20.4 percent error for peak discharges and a 21.5 percent for 3-day average discharge look large. However, looking at Figure 7.8 for the Pajaro River at Chittenden, the 95 percent and 5 percent confidence limit lines are shown for the peak discharge statistics. The percent of the 100-year discharge can be found to be approximately plus or minus 40 percent. From standard normal distribution probability tables it can be seen that the 95 percent confidence is 1.28 standard deviations beyond the mean. Thus the standard deviation (the SE) is 31 percent. This value is greater than the overall SE of the PRO-FLO model. Thus the model produces a SE better than that using 60 years of data to predict the 100-year flood discharge.

Conclusion

The PRO-FLO hydrologic model produces a good representation of the frequency curves for both peak discharge and for 3-day average discharge at the Chittenden stream gage. The overall Standard Error of the model is plus or minus approximately 20 percent of the predicted peak and the predicted 3-day average discharge.

<u>Storm Centerings</u>

The PRO-FLO results reported thus far have all been developed on the premise that the area reduction factor shown in Figure 2.17 in TM 1.2.2, applies uniformly to the entire watershed upstream of the catch point in question. When PRO-FLO is applied to the drainage area above the Chittenden gage the area reduction factor is based on the 1,186 square miles of drainage area at the Chittenden gage.

As shown in TM 1.2.2 "Rainfall," rainstorms can be centered over different portions of the watershed above the Chittenden gage. The best examples of this centering were the 1998 storm which was centered over the Tres Pinos Creek portions of the San Benito River watershed, and the 1955 storm which was centered over the Gilroy and Hollister areas.

To assess the impact of different storm centerings on the PRO-FLO results, three alternate centerings were put into the model. The first was a centering over the San Benito River watershed. This centering provided for an area reduction that corresponded to the 661 square miles of watershed along this river. The remainder of the watershed had a much lower reduction factor. This lower factor was selected so that the sum of the two drainage areas multiplied by their respective reduction factors would equal to the 1,186 square miles at Chittenden multiplied by its reduction factor.

The 50-year and 100-year floods were used to determine whether alternate centerings were worth performing for all PRO-FLO investigations into various land use or upstream control strategies.

For the San Benito River watershed storm centering the peak discharges were approximately 2 percent less than PRO-FLO results obtained from the uniformly applied area reduction factor. The 3-day average discharges were approximately 12 percent less.

For the centering over Lower Soap Lake, the PRO-FLO model produced peak discharges that were approximately 3 percent lower than those from the uniformly reduced model. The 3-day average discharges were approximately 6 percent less.

For a centering that was half Lower Soap Lake watershed and half San Benito River watershed PRO-FLO produced peak discharges approximately 1 percent less than those using the uniform upstream reduction. The 3-day average discharges were approximately 8 percent less.

The conclusion from this assessment is that the uniformly applied area reduction factor is the most appropriate way to apply the reduction factor. Other centerings of the rainstorm would not produce greater peaks or 3-day average discharges.

Figure CL 94

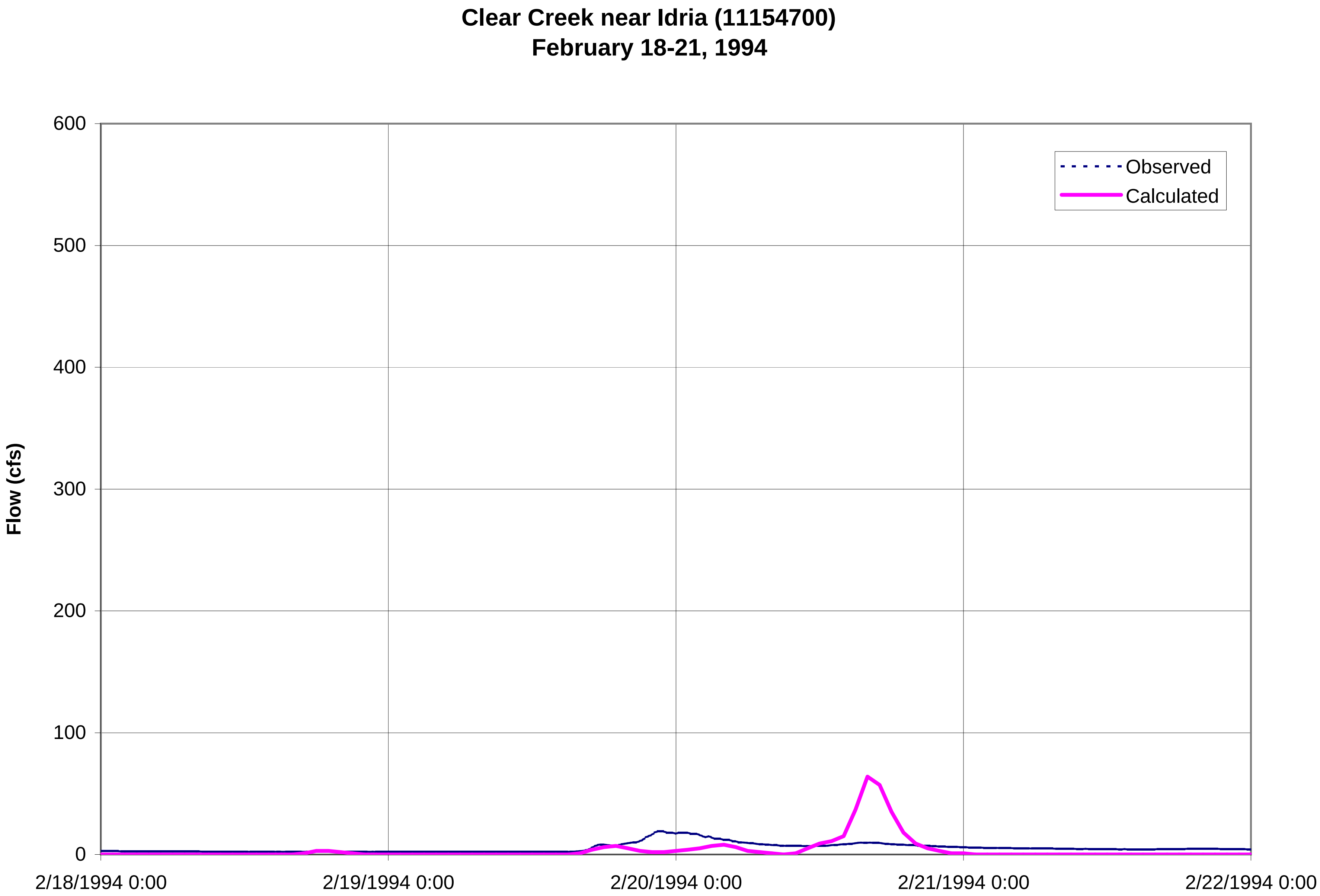

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Figure CL 95

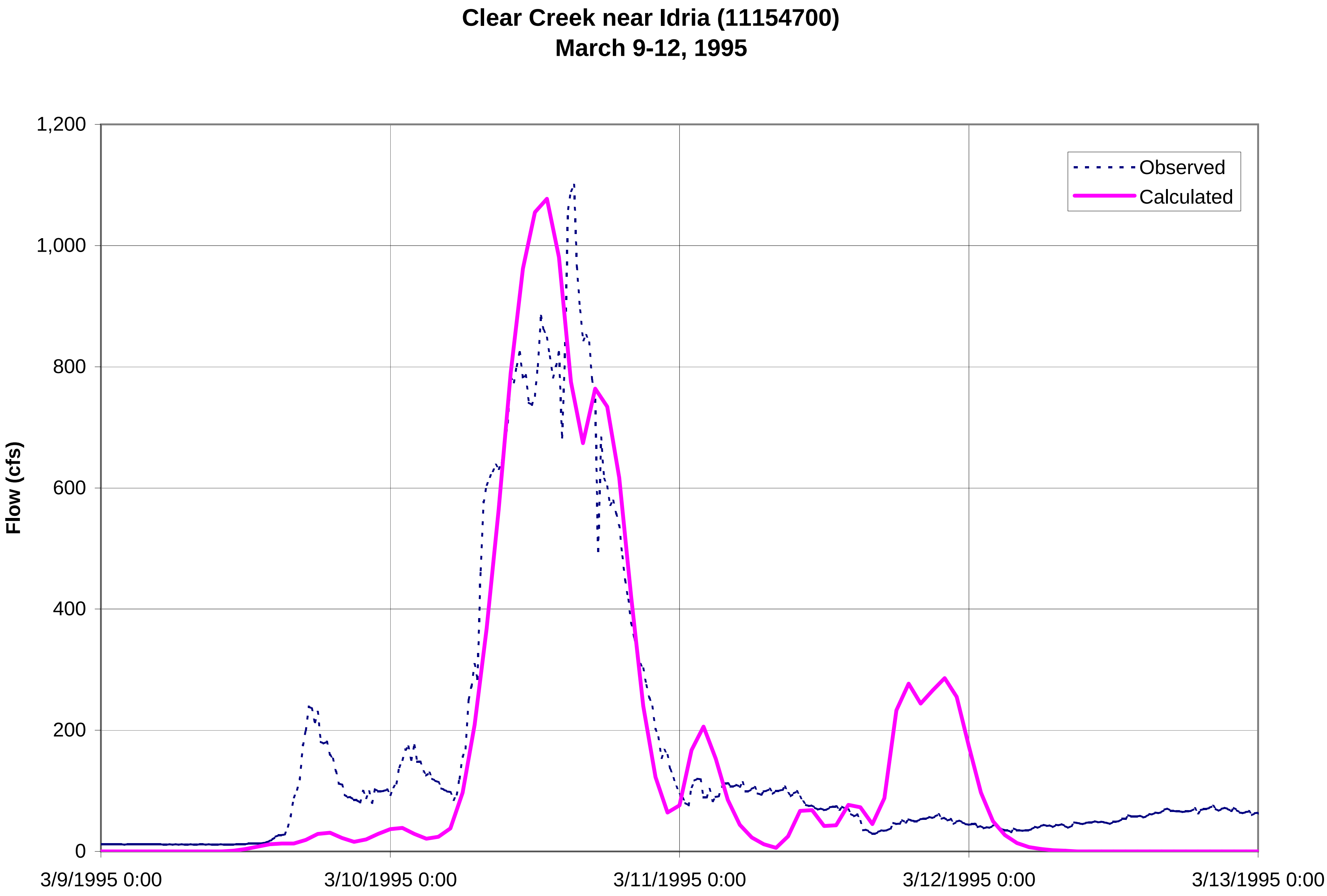

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Figure CL 96

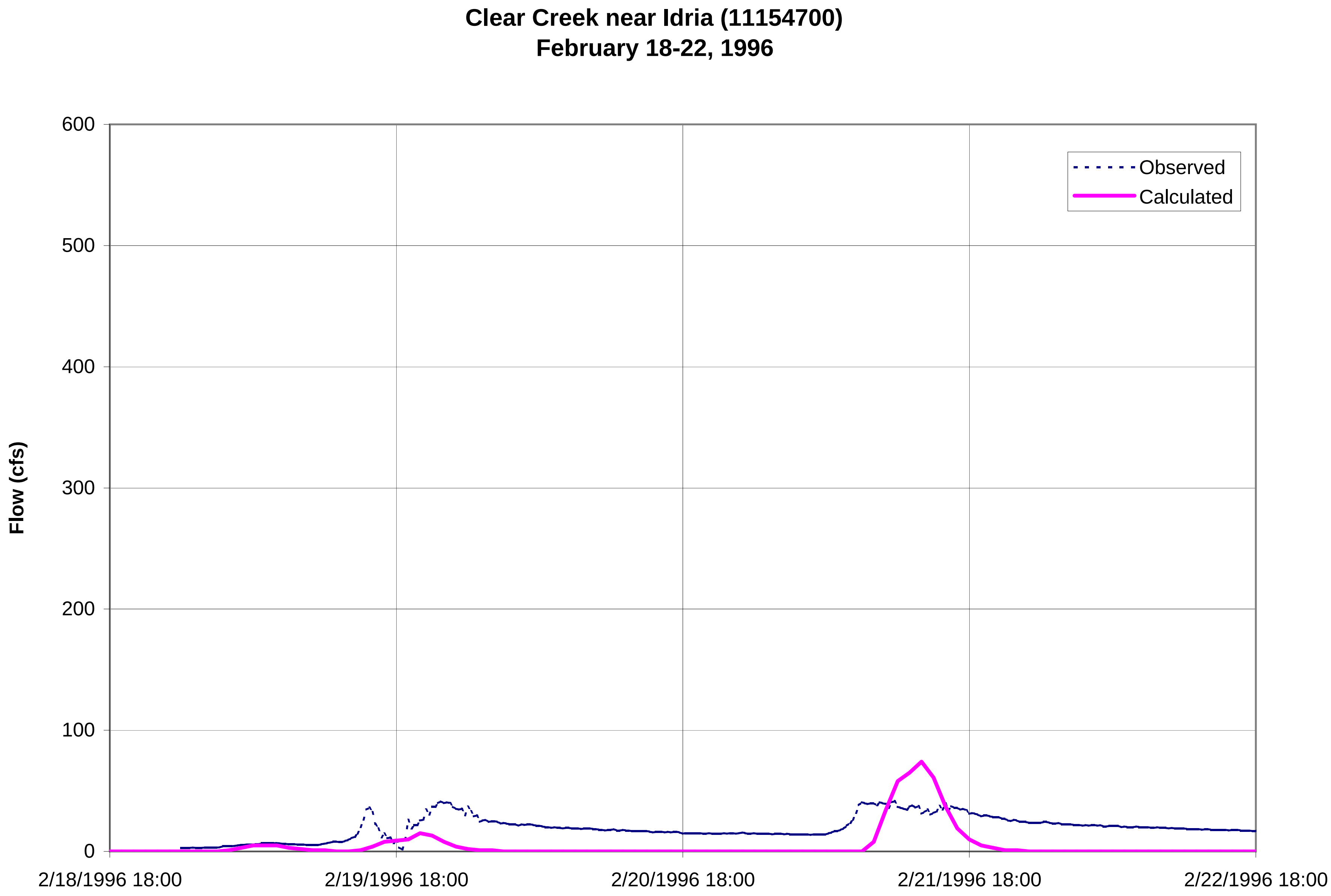

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Figure CL 97

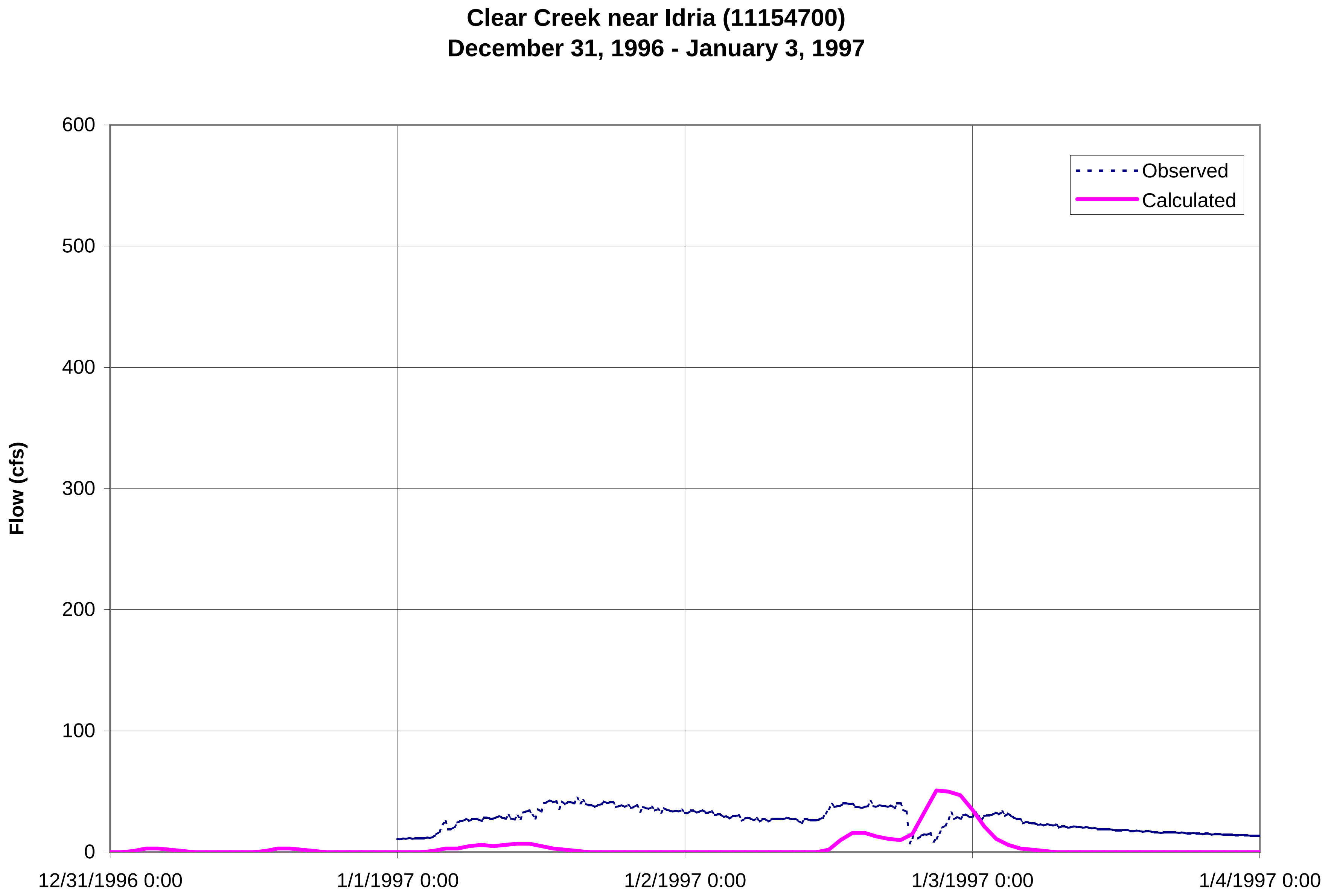

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Figure CL 98

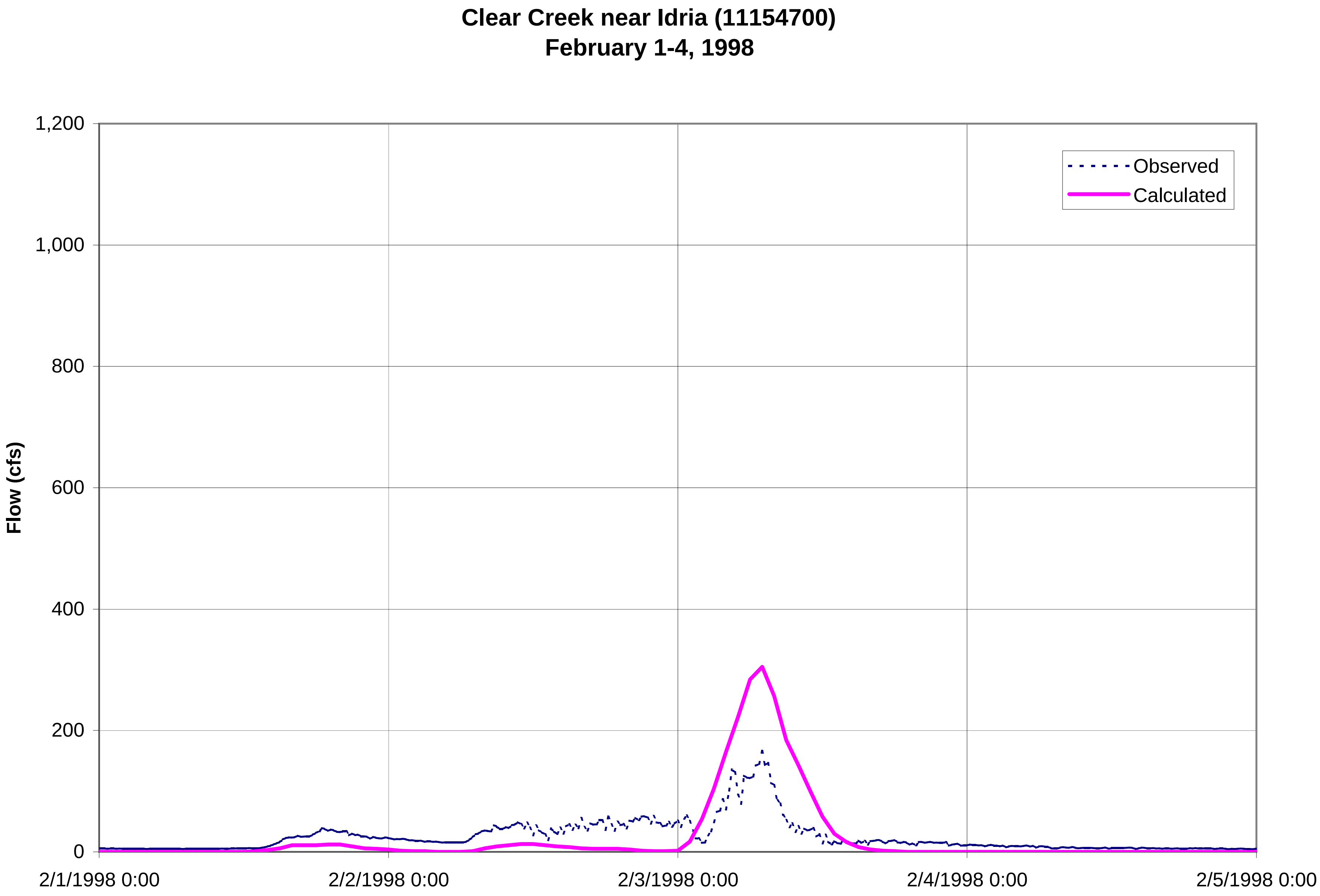

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Figure CL 99

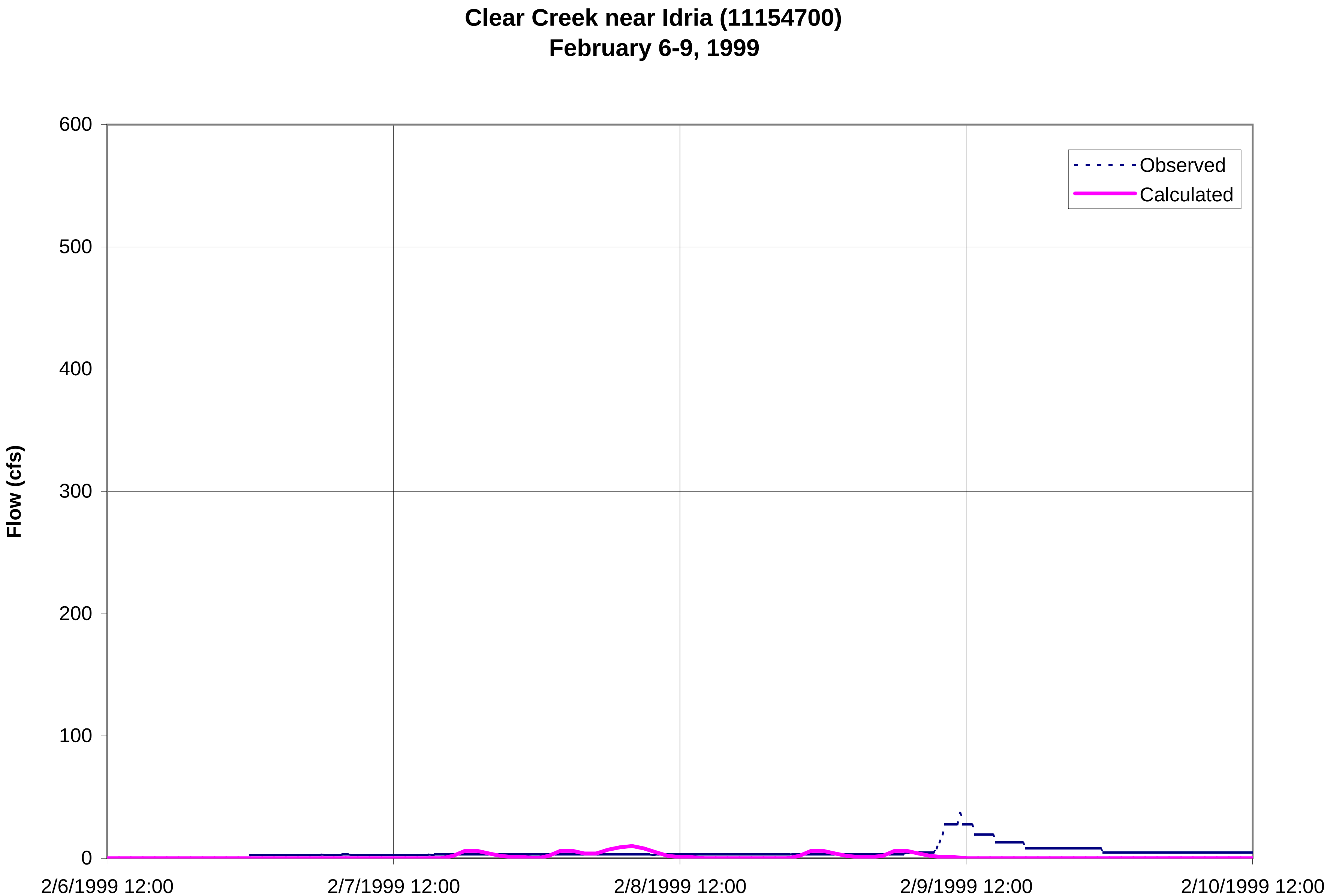

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Figure CO 94

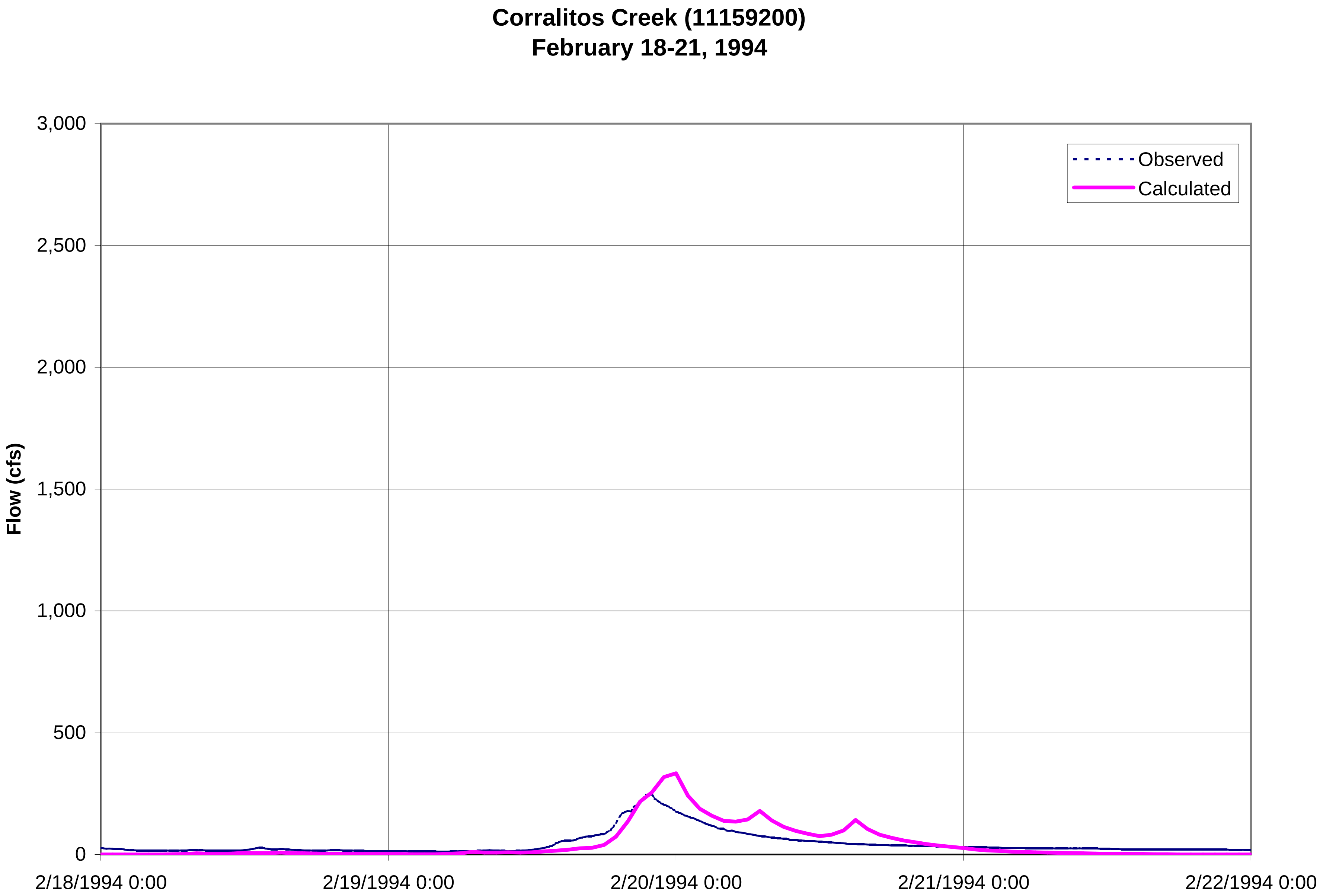

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Figure CO 95

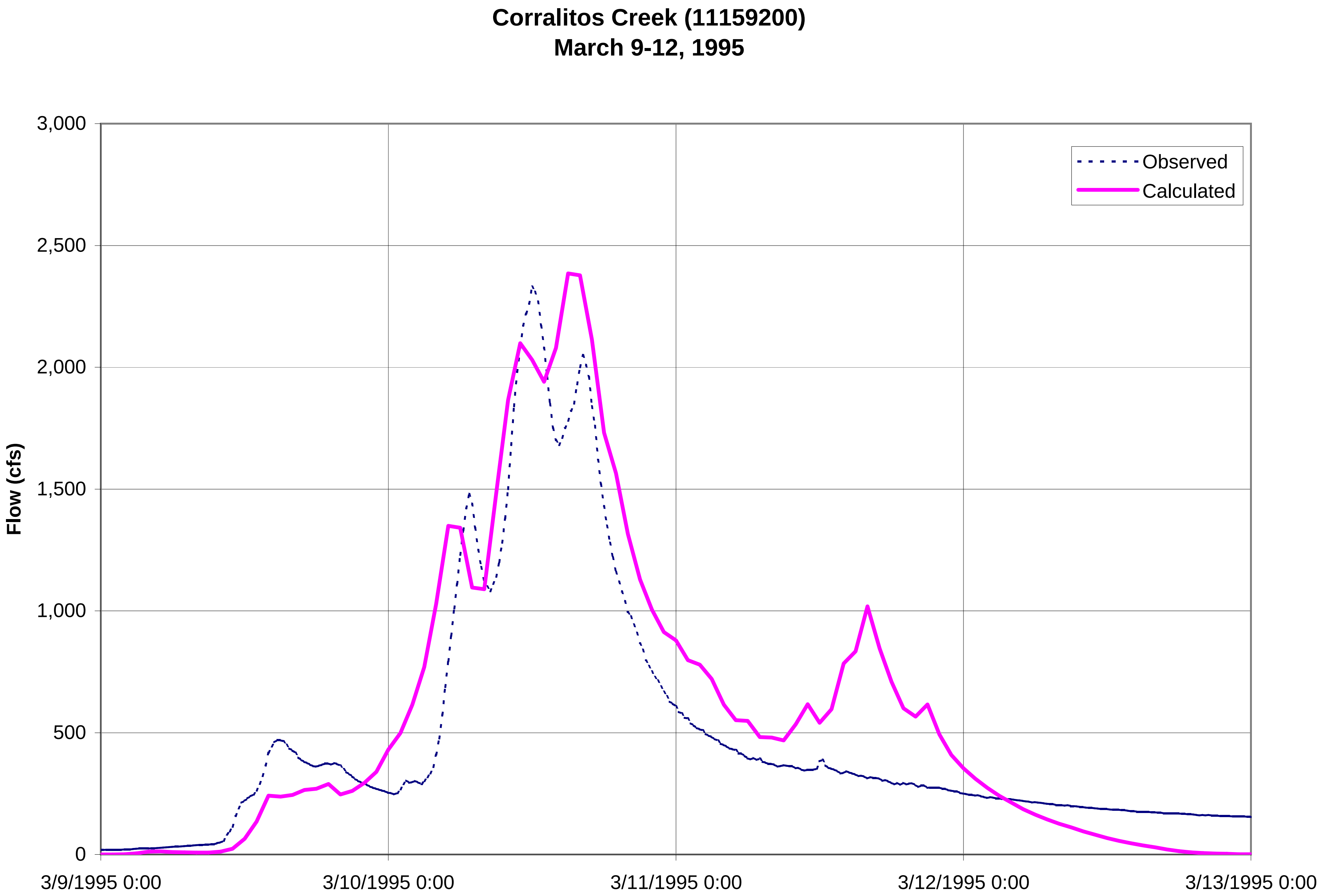

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Figure CO 96

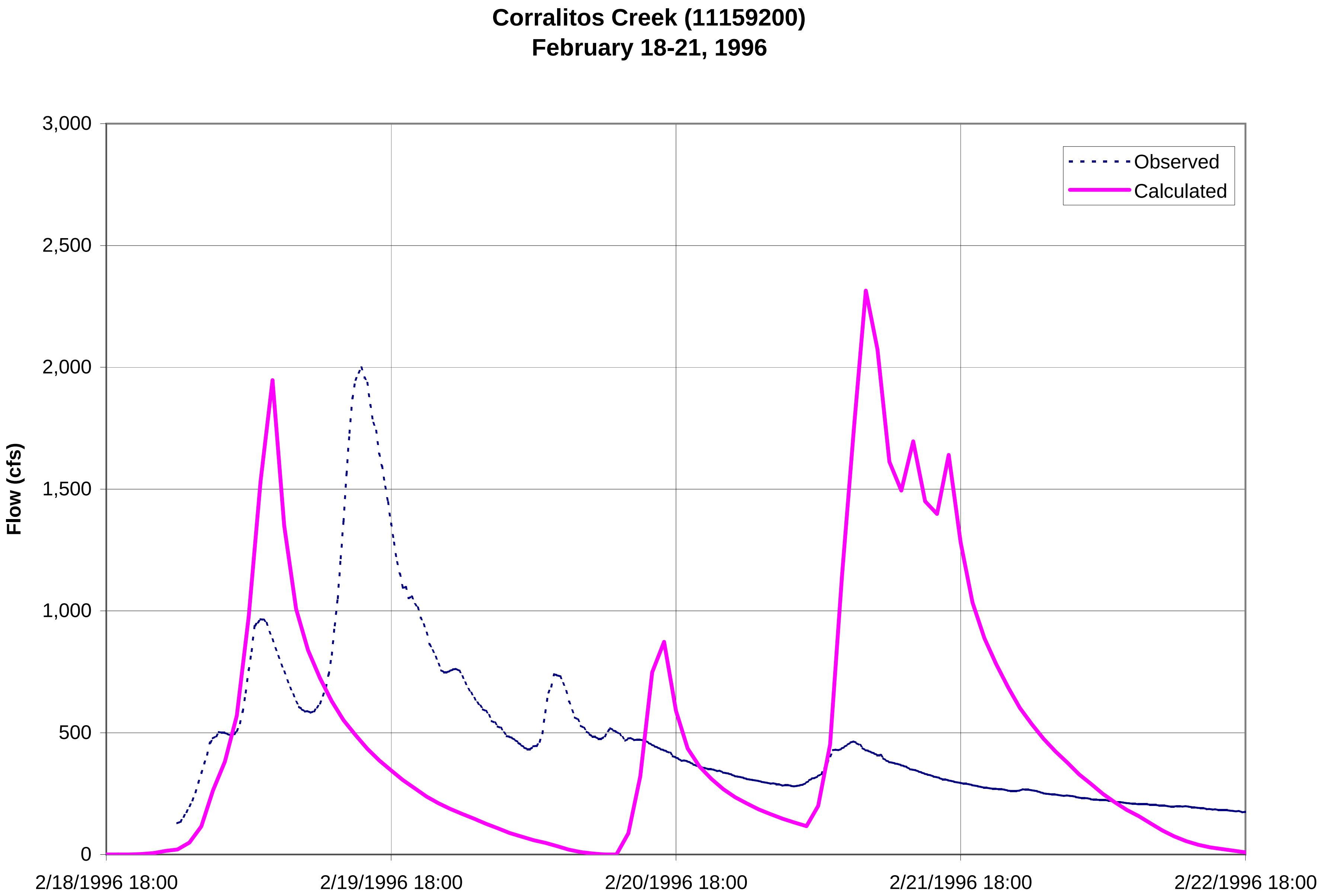

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Figure CO 97

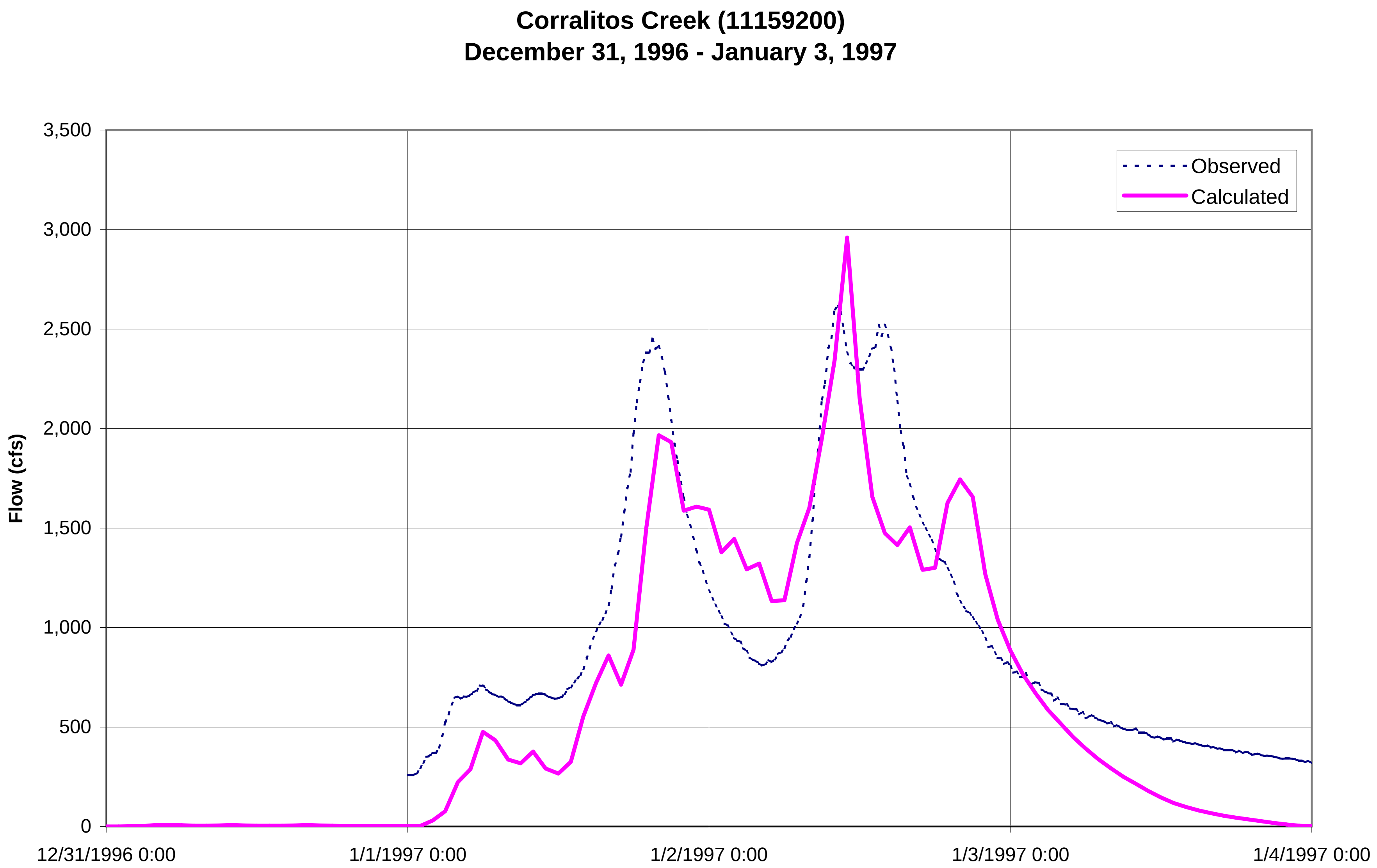

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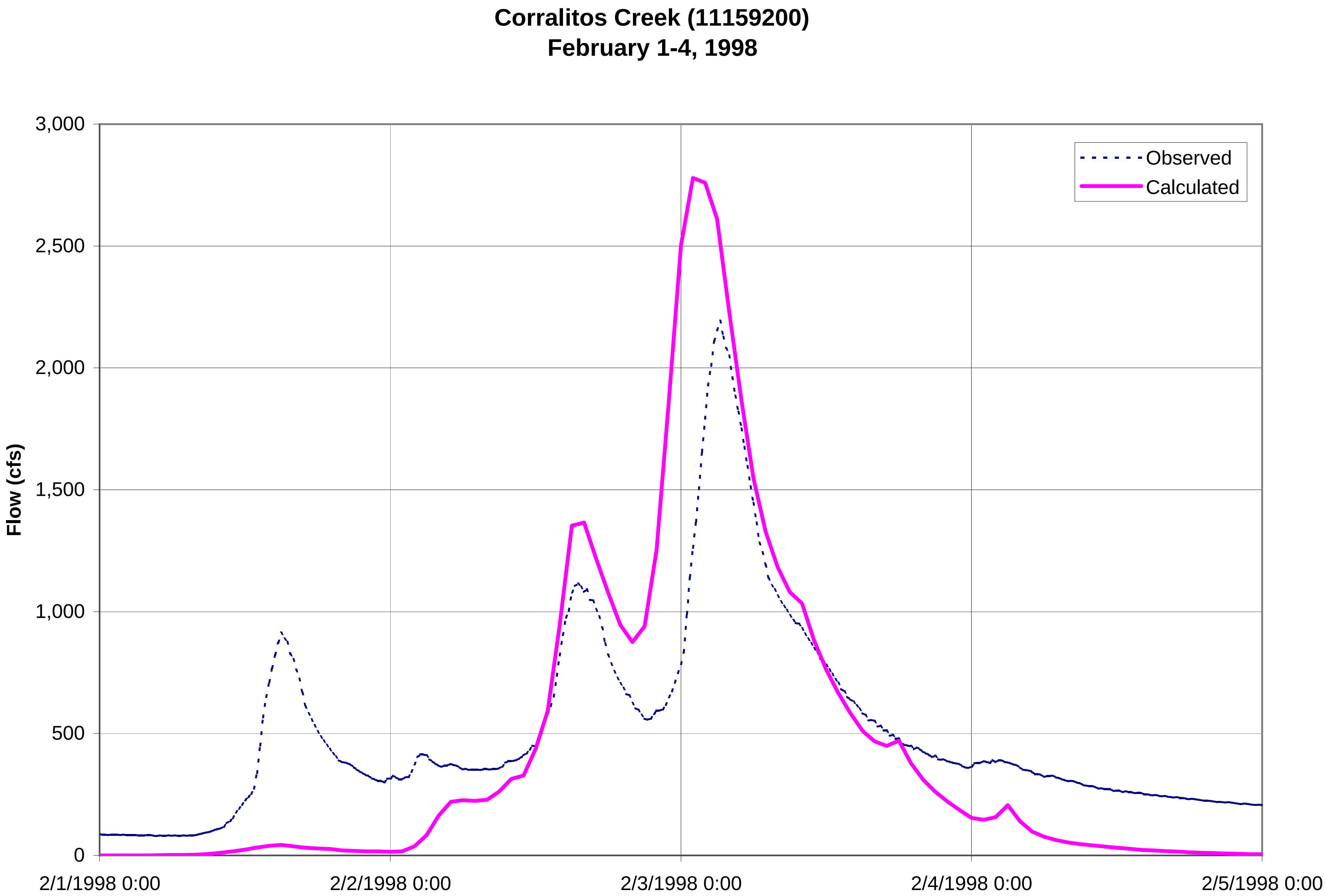
Figure CO 98



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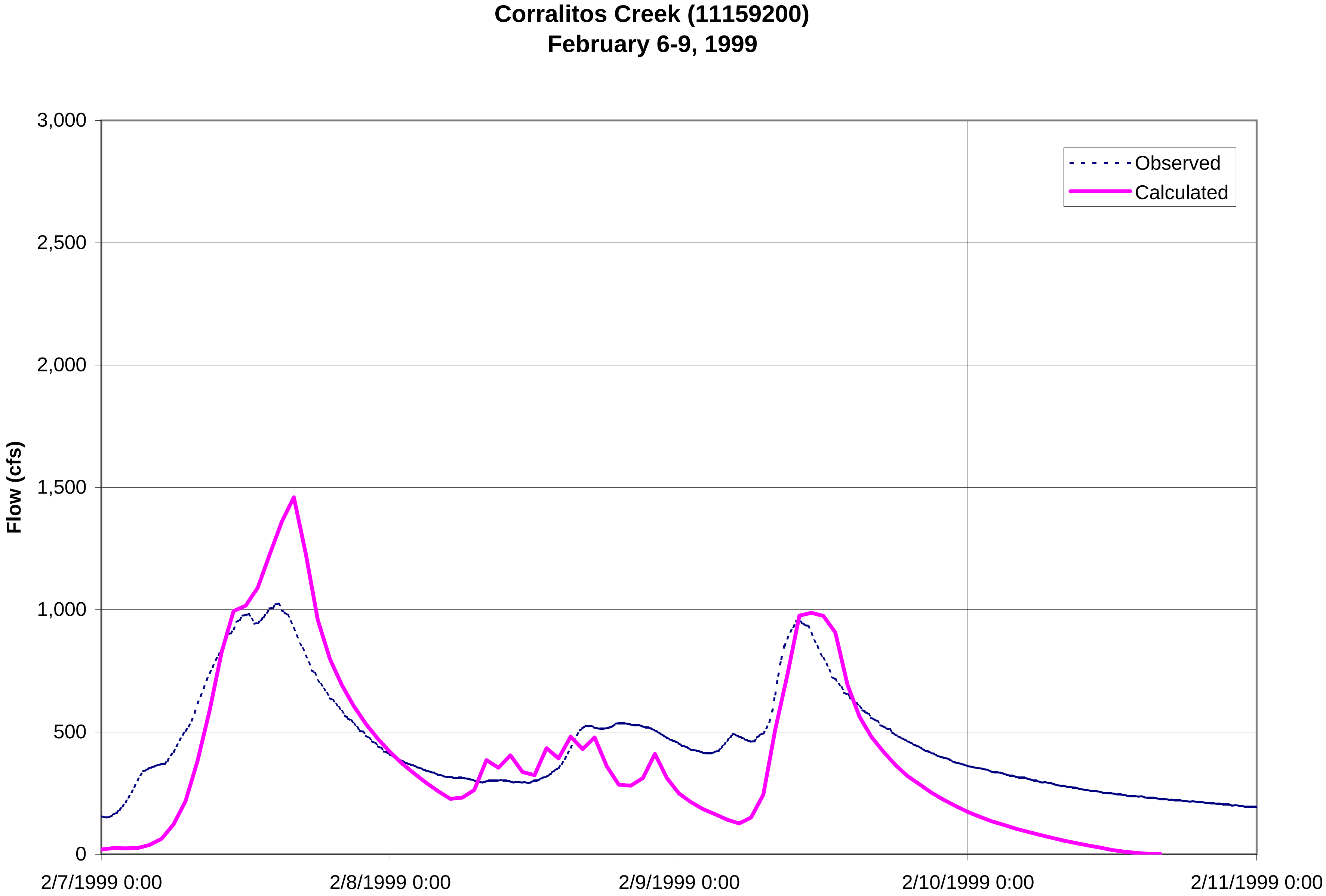

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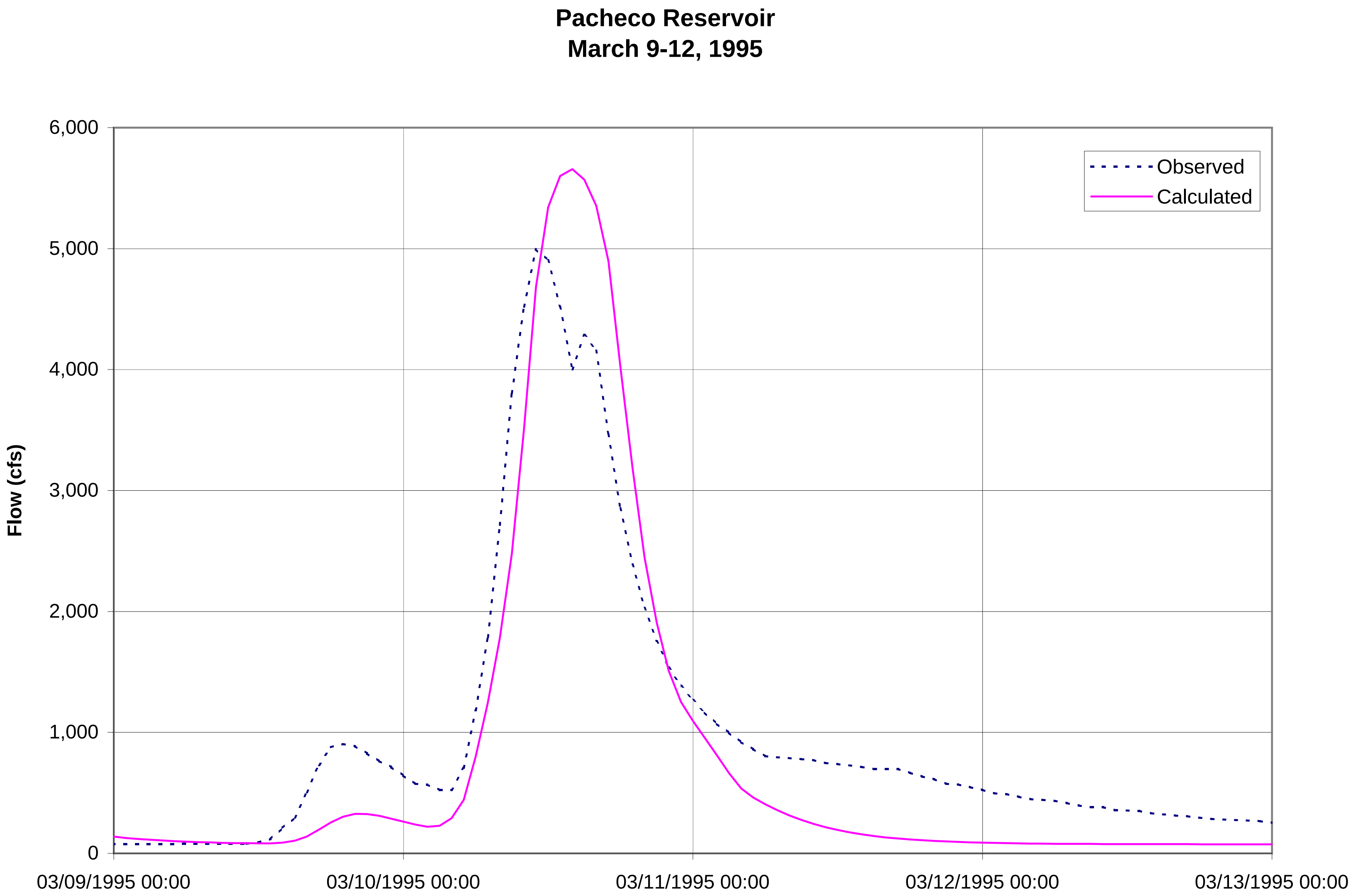

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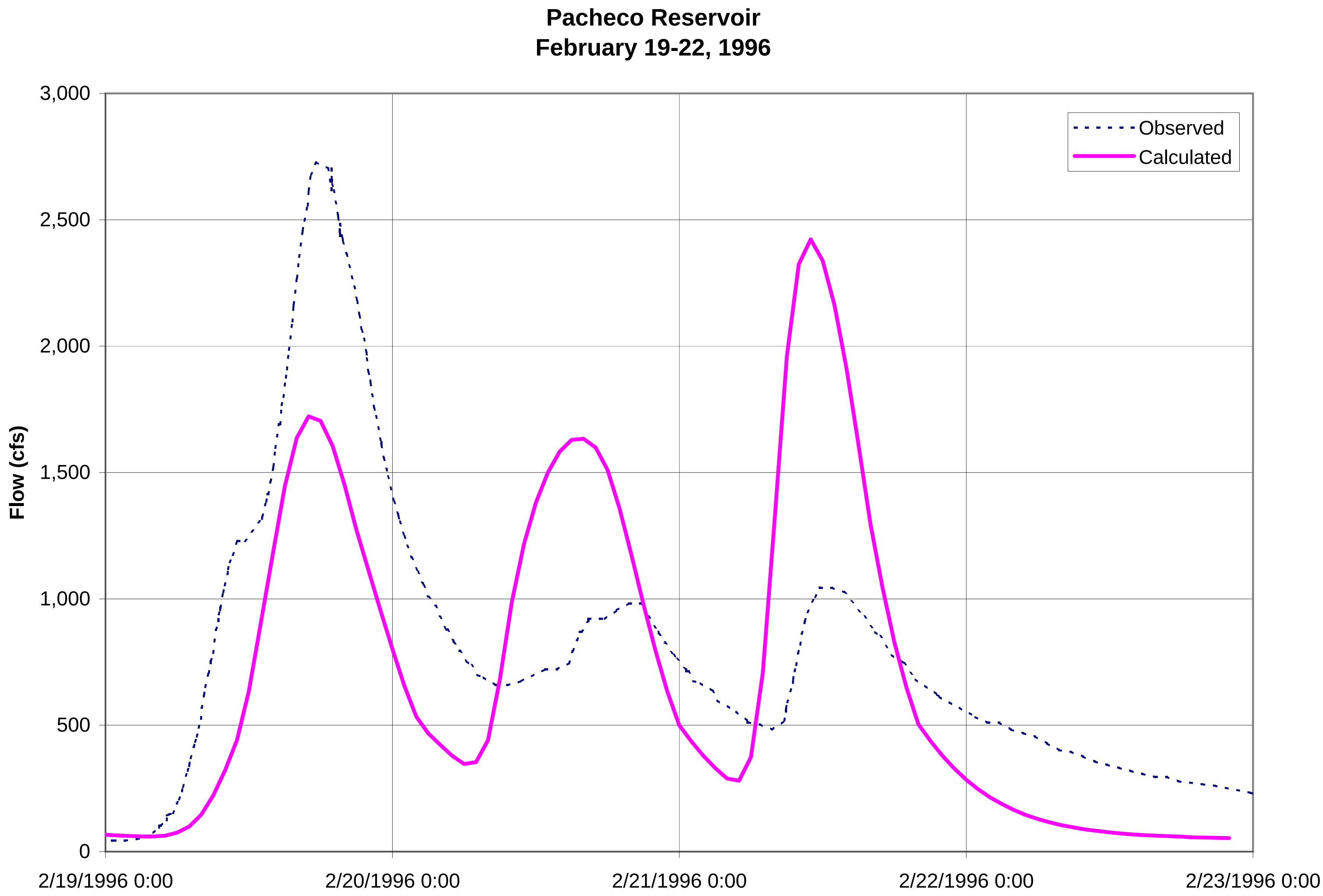

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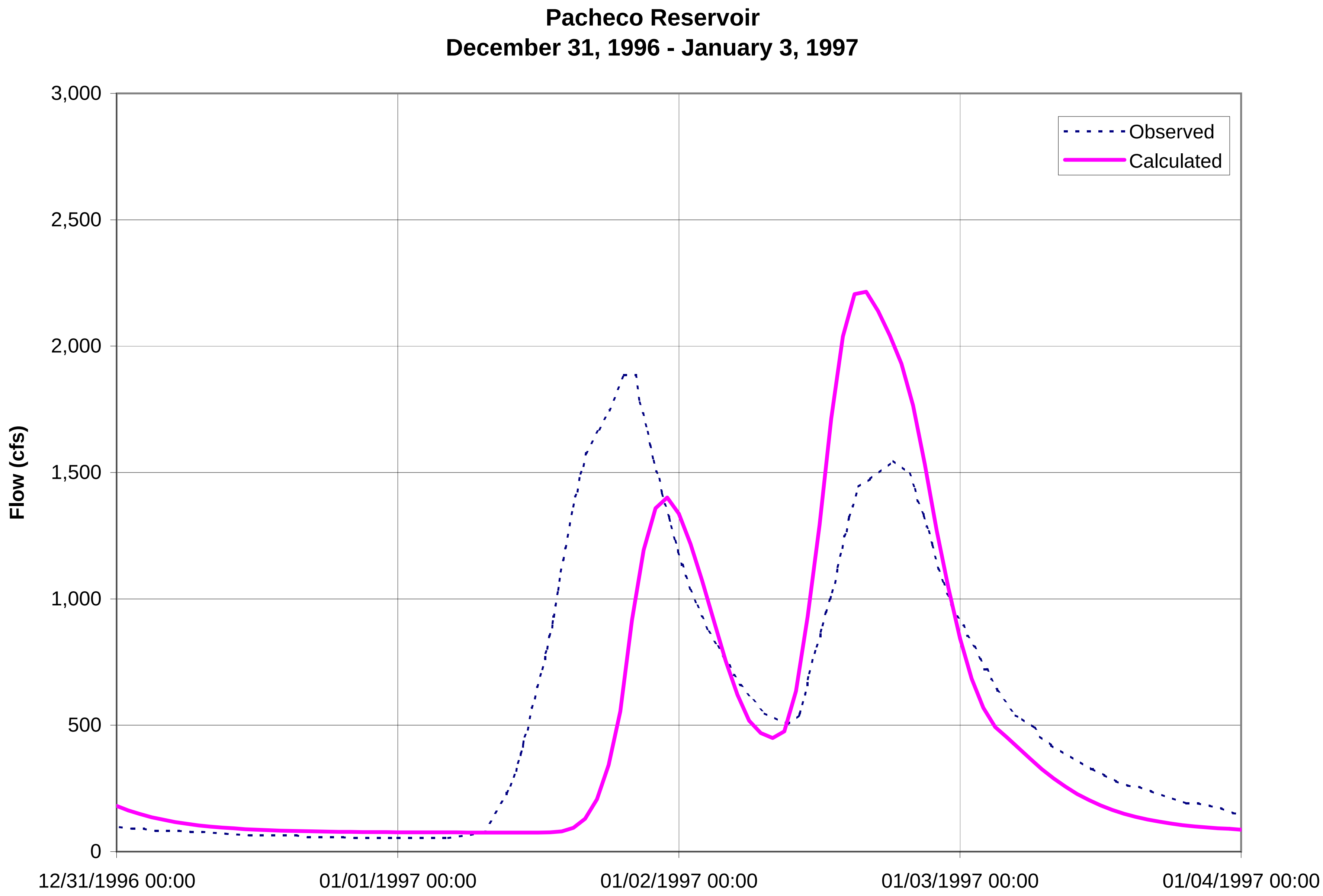

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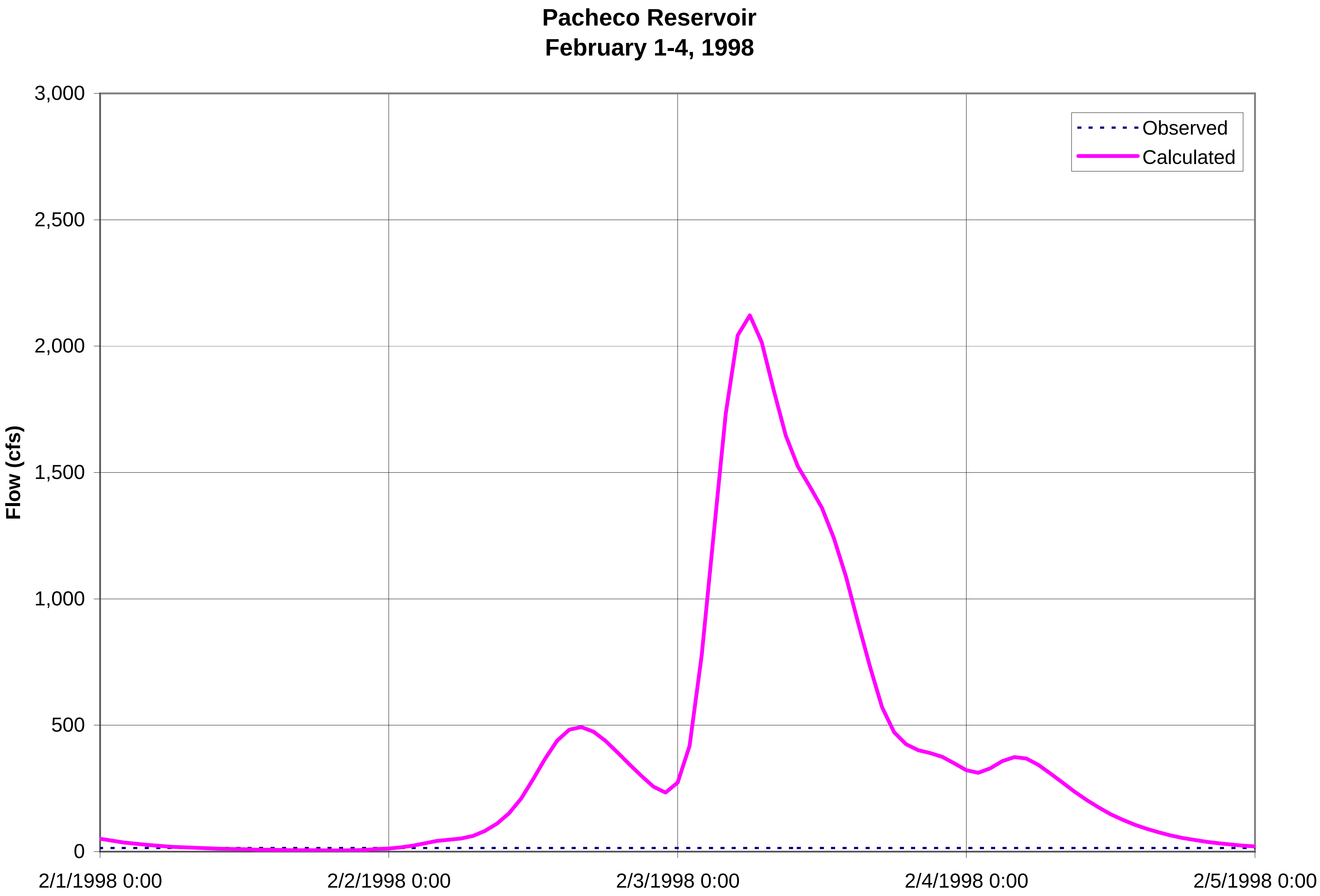

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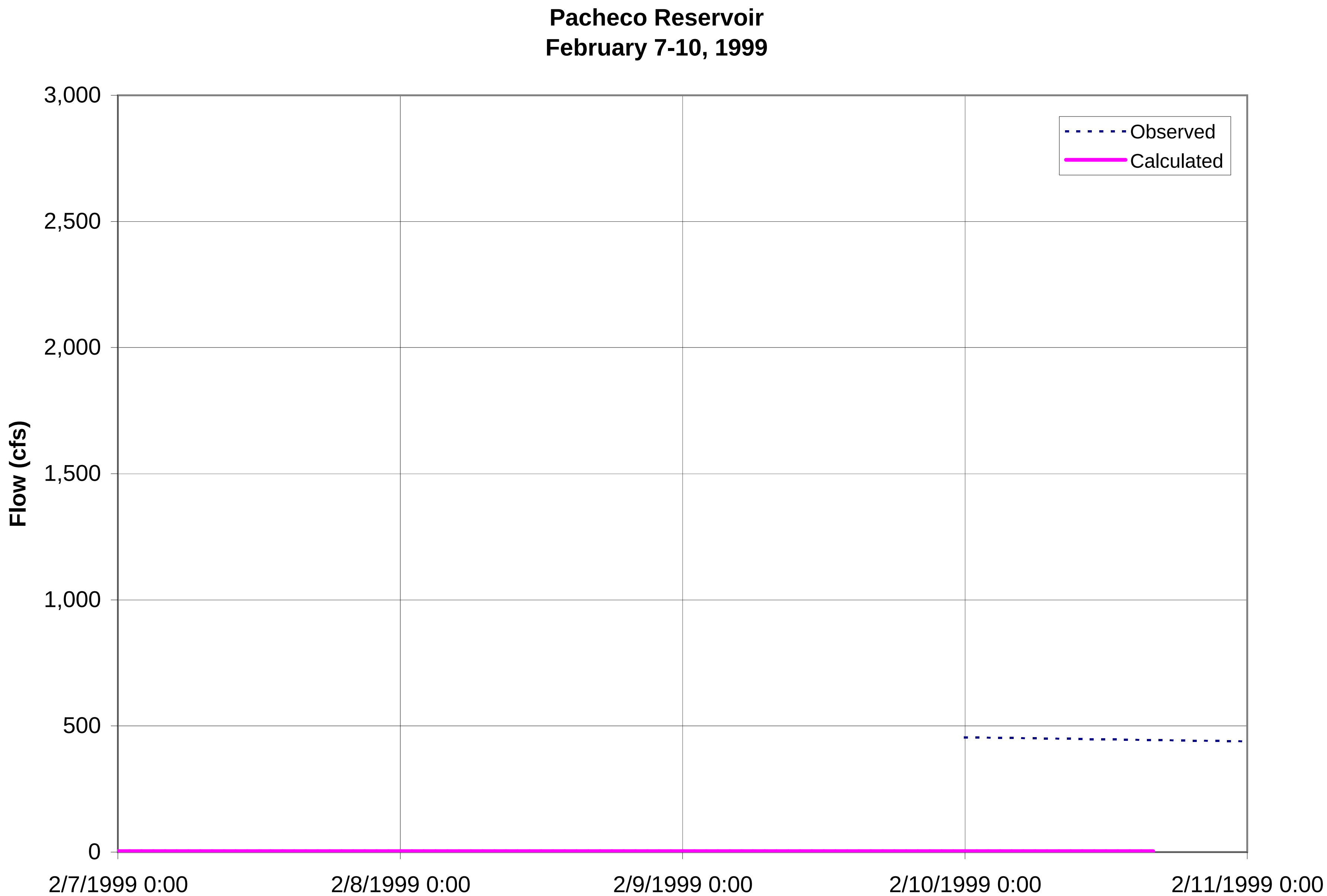

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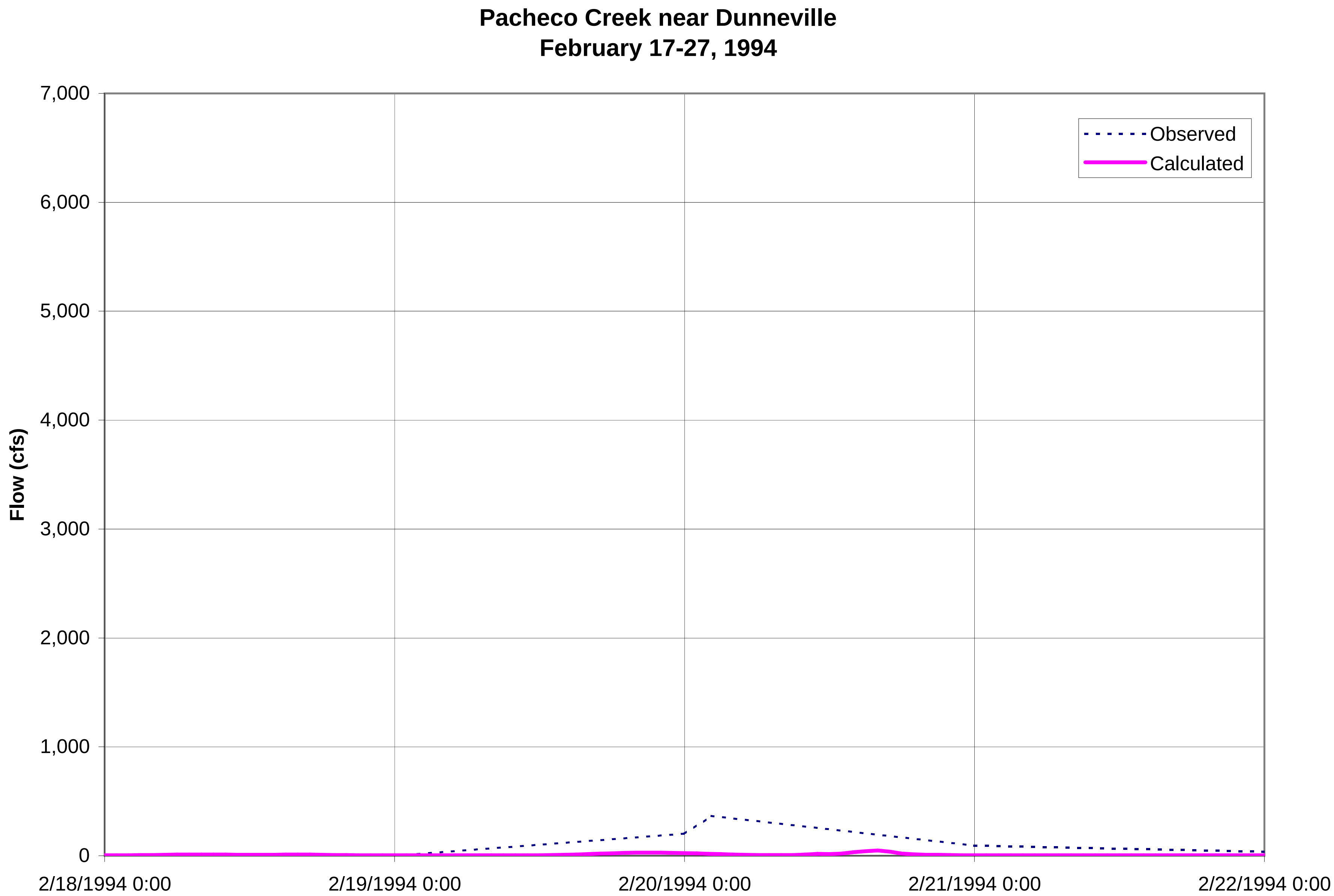

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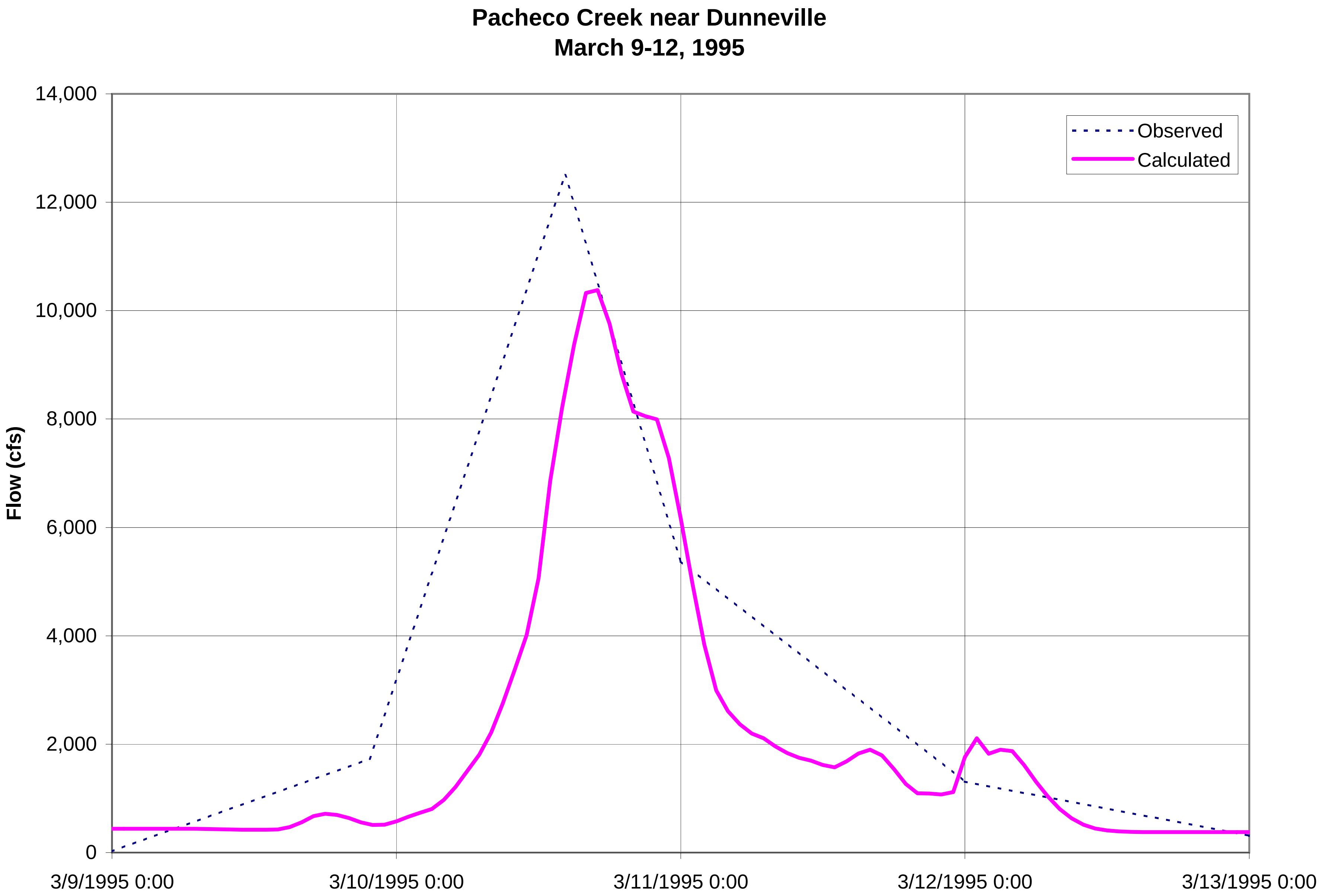

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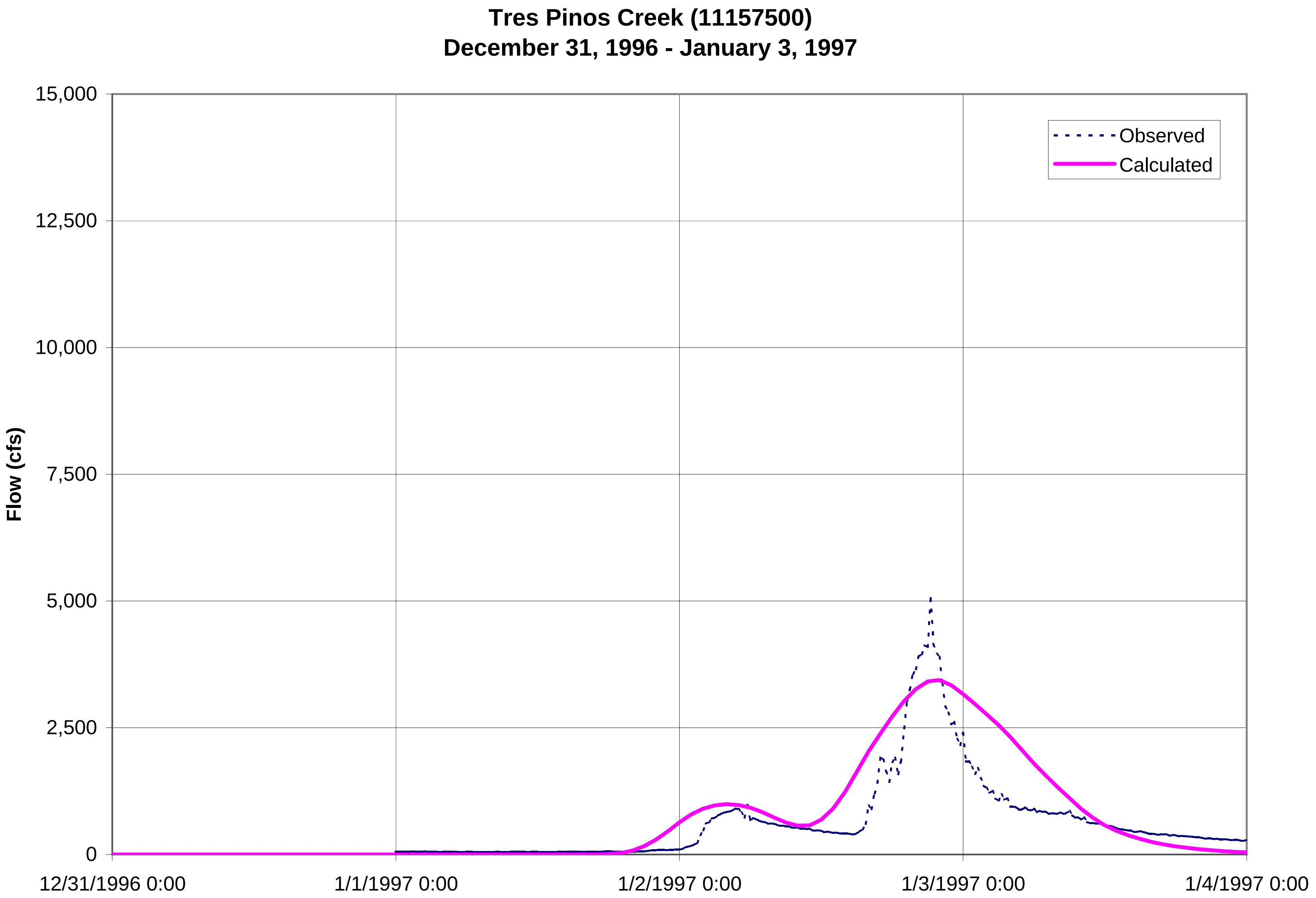

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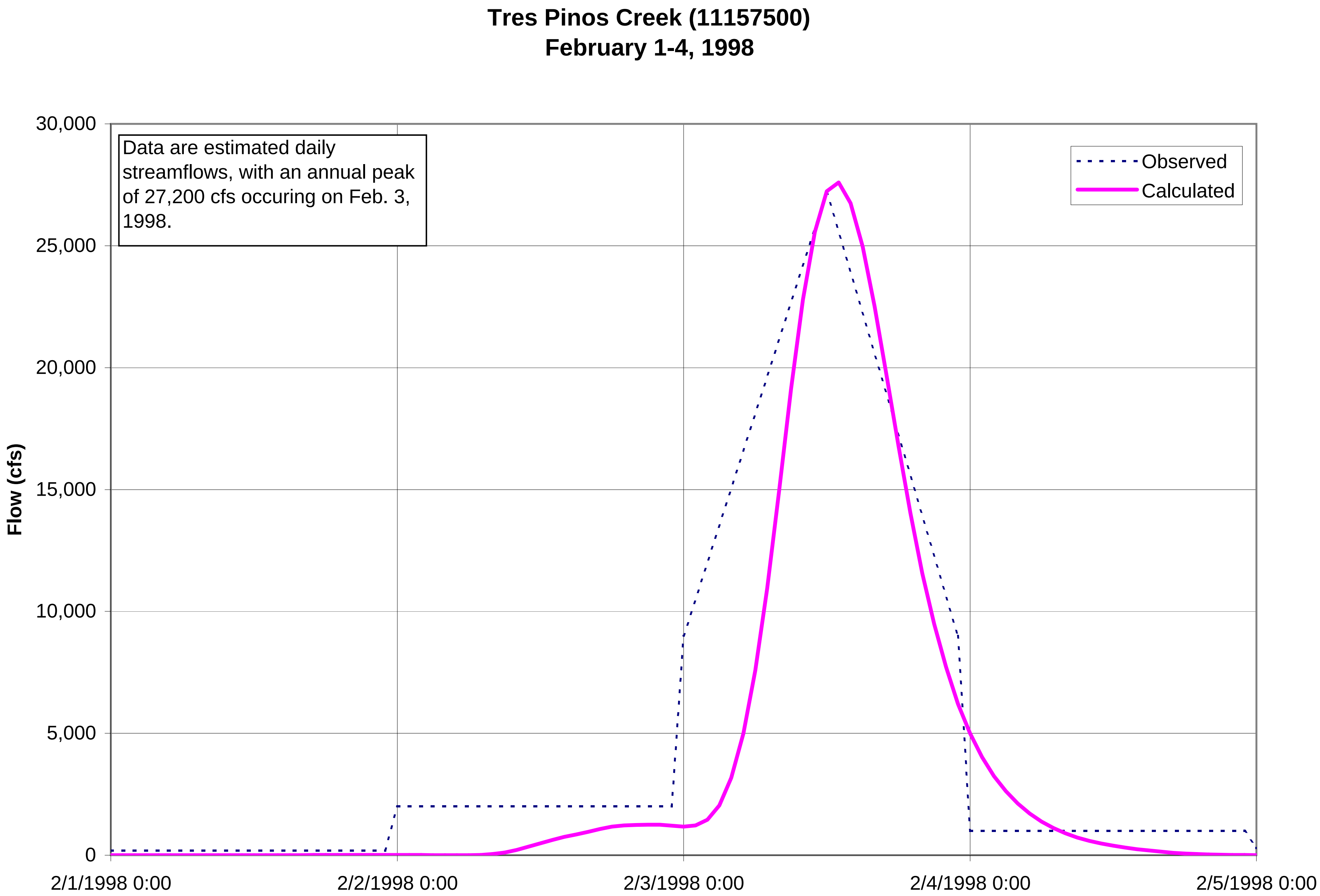

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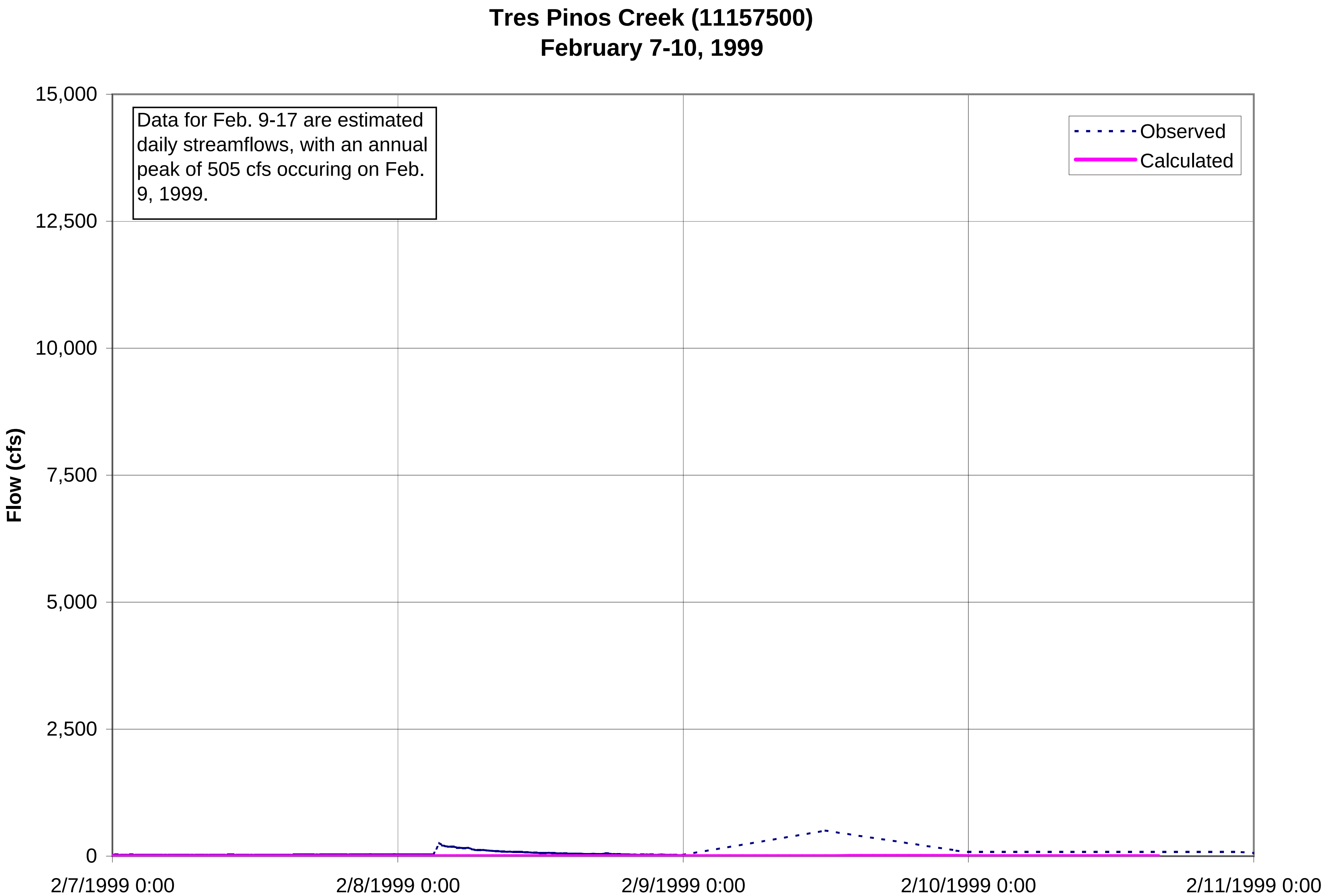

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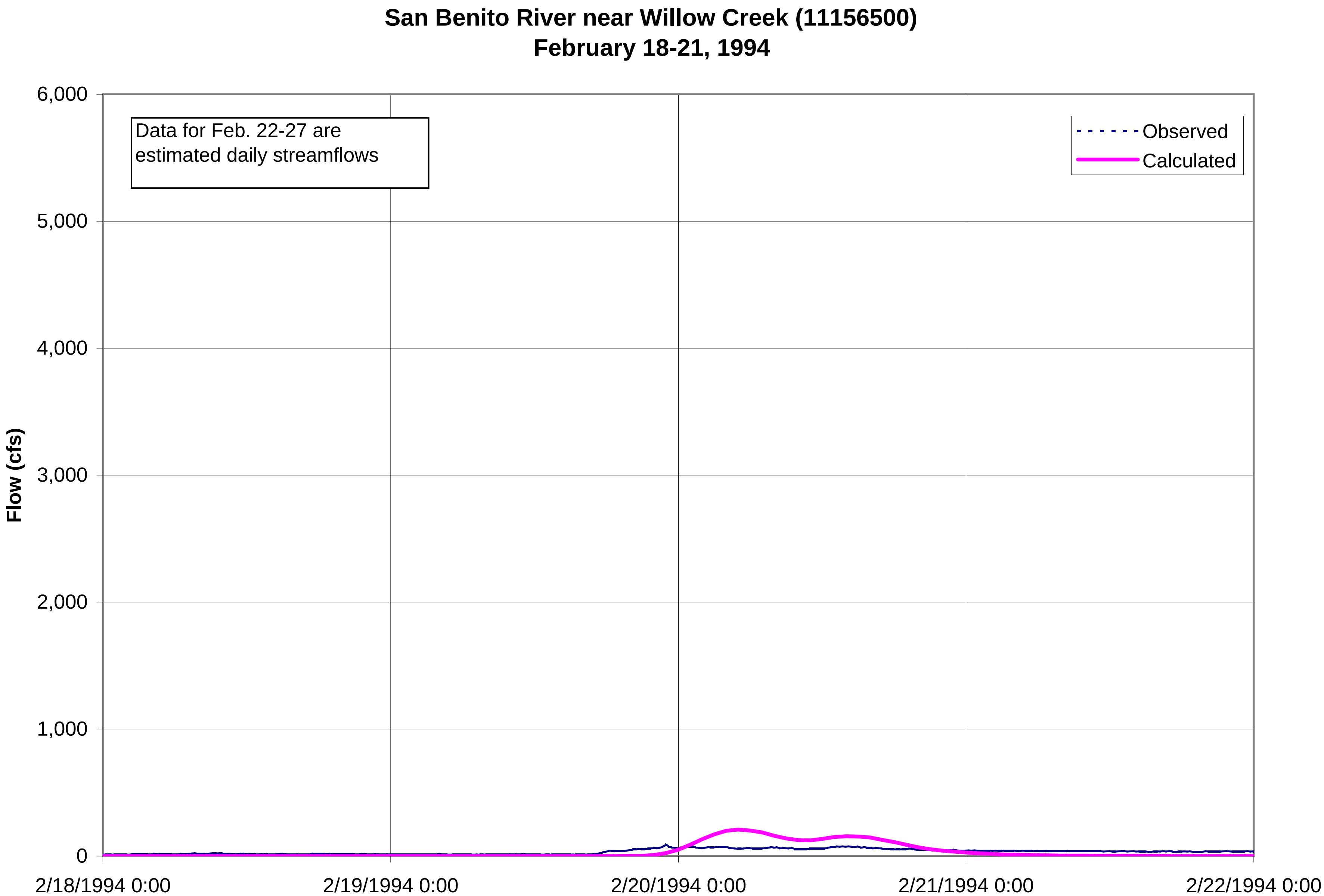

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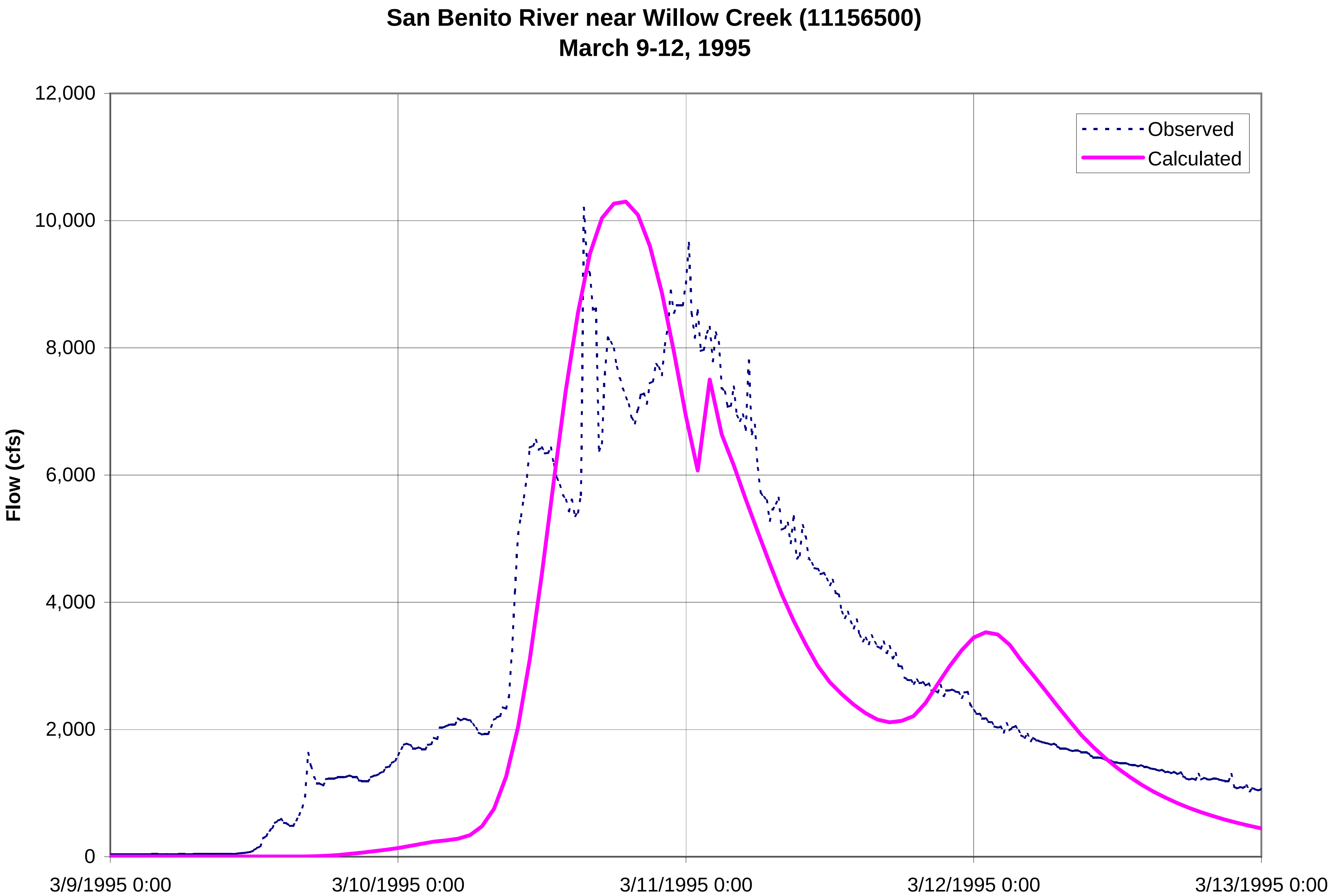

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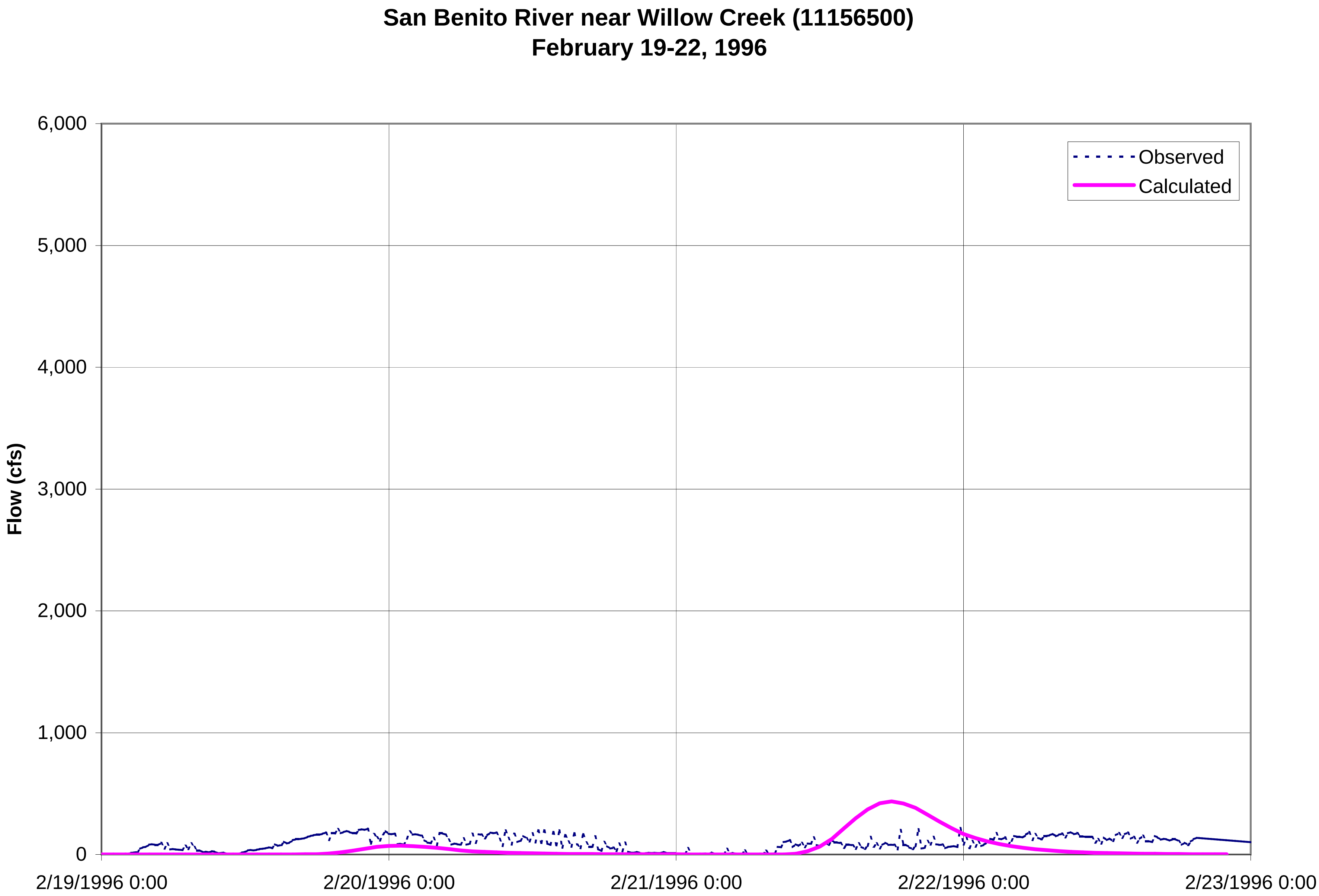

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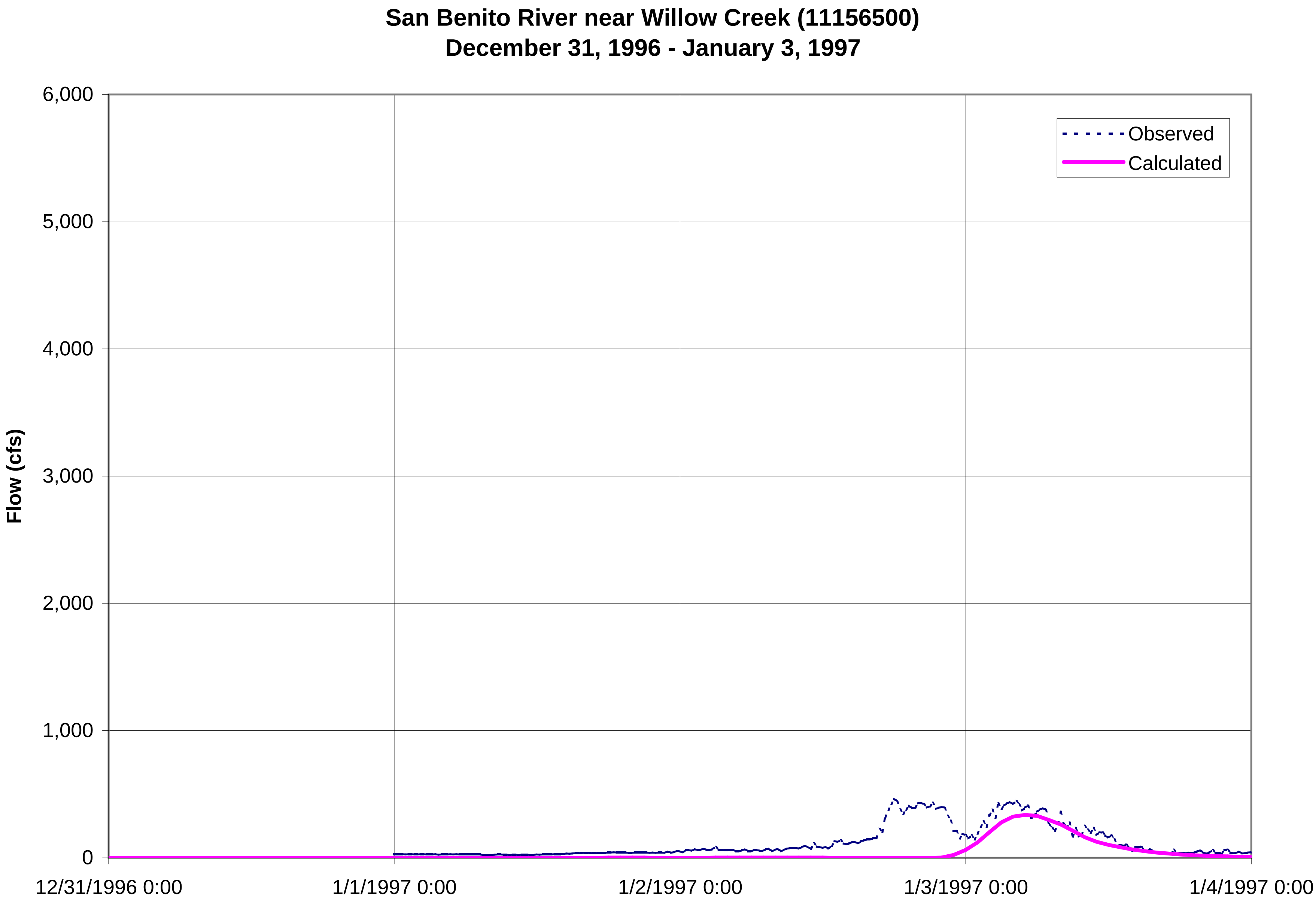

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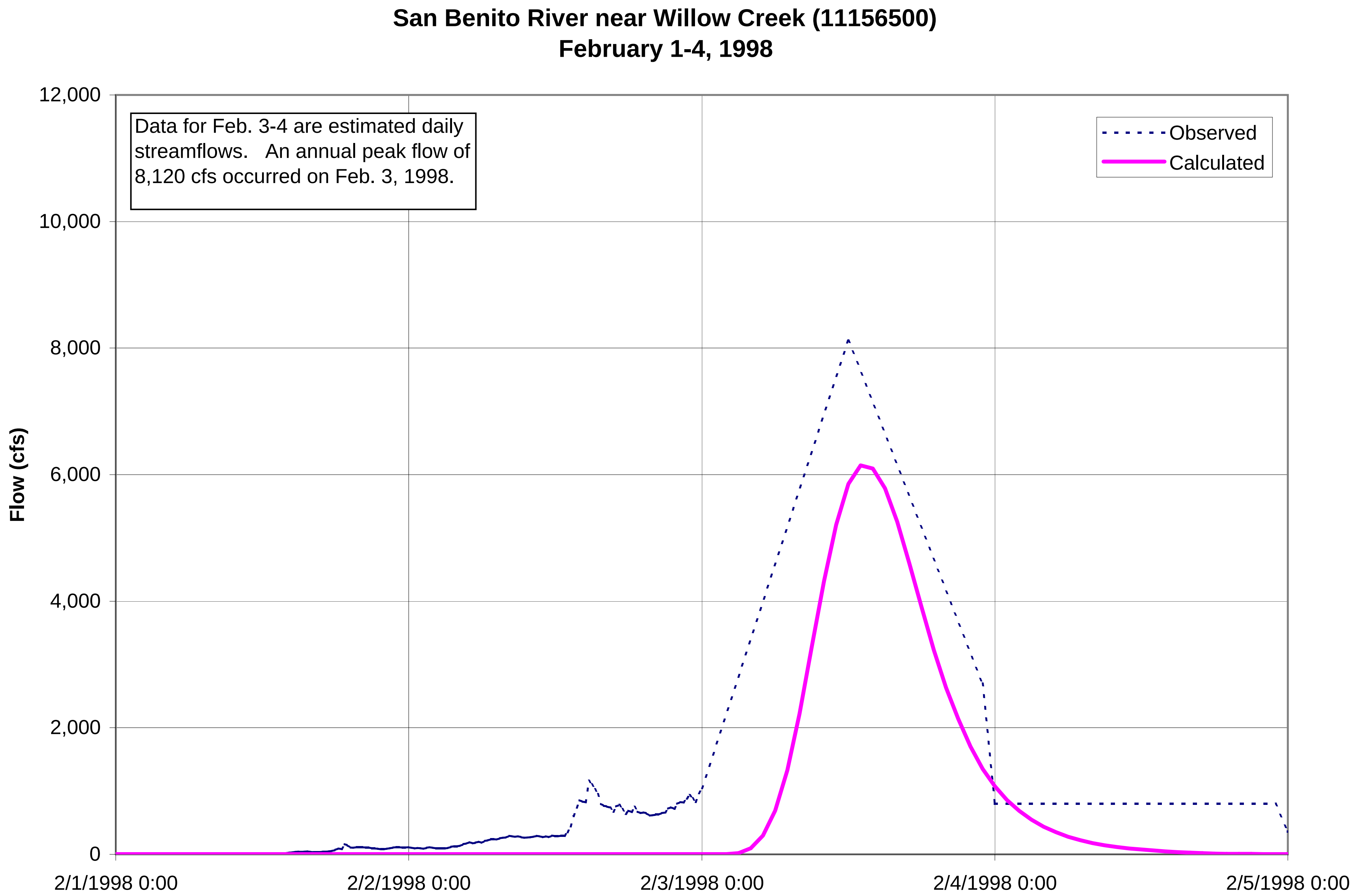

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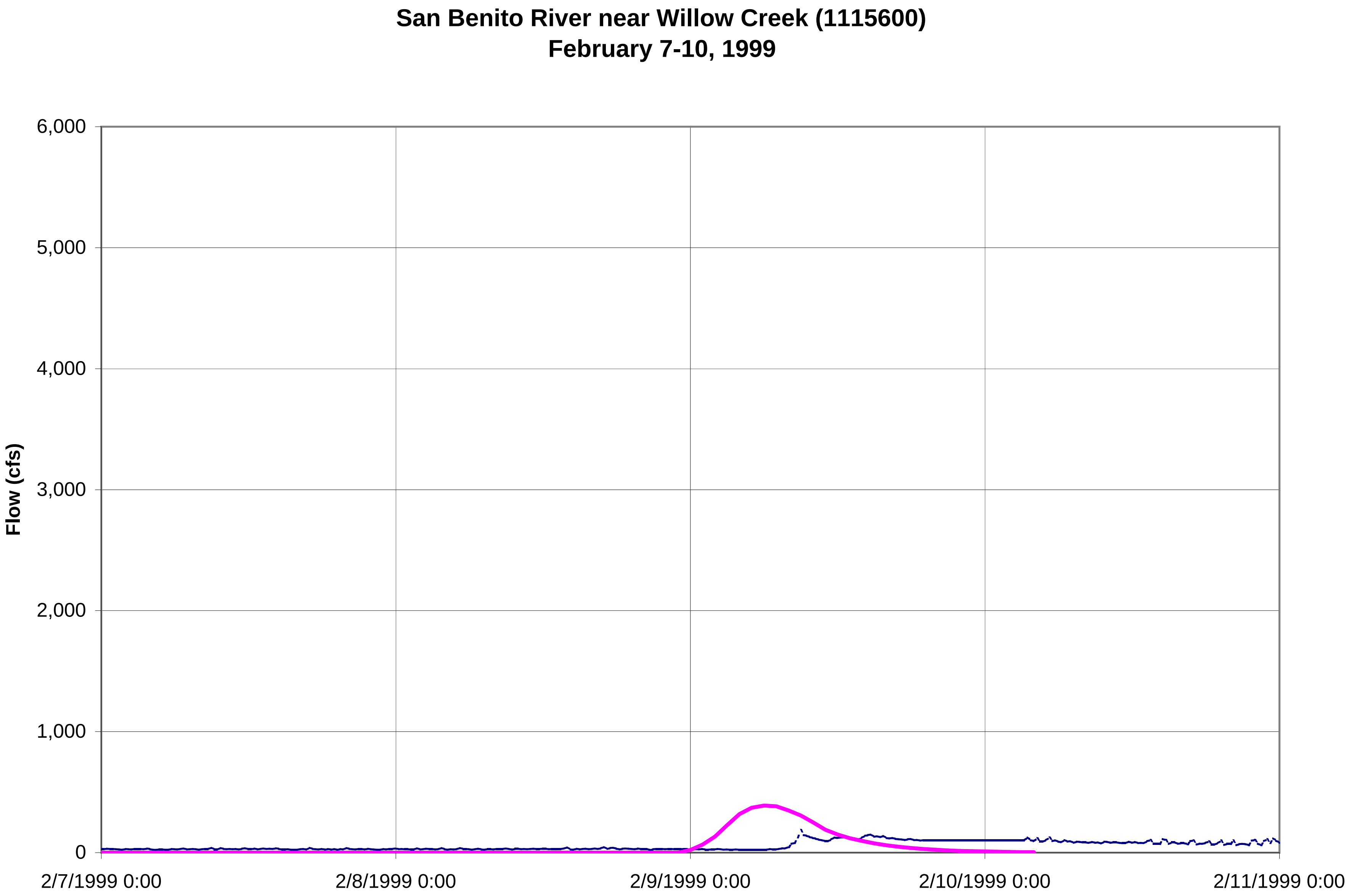

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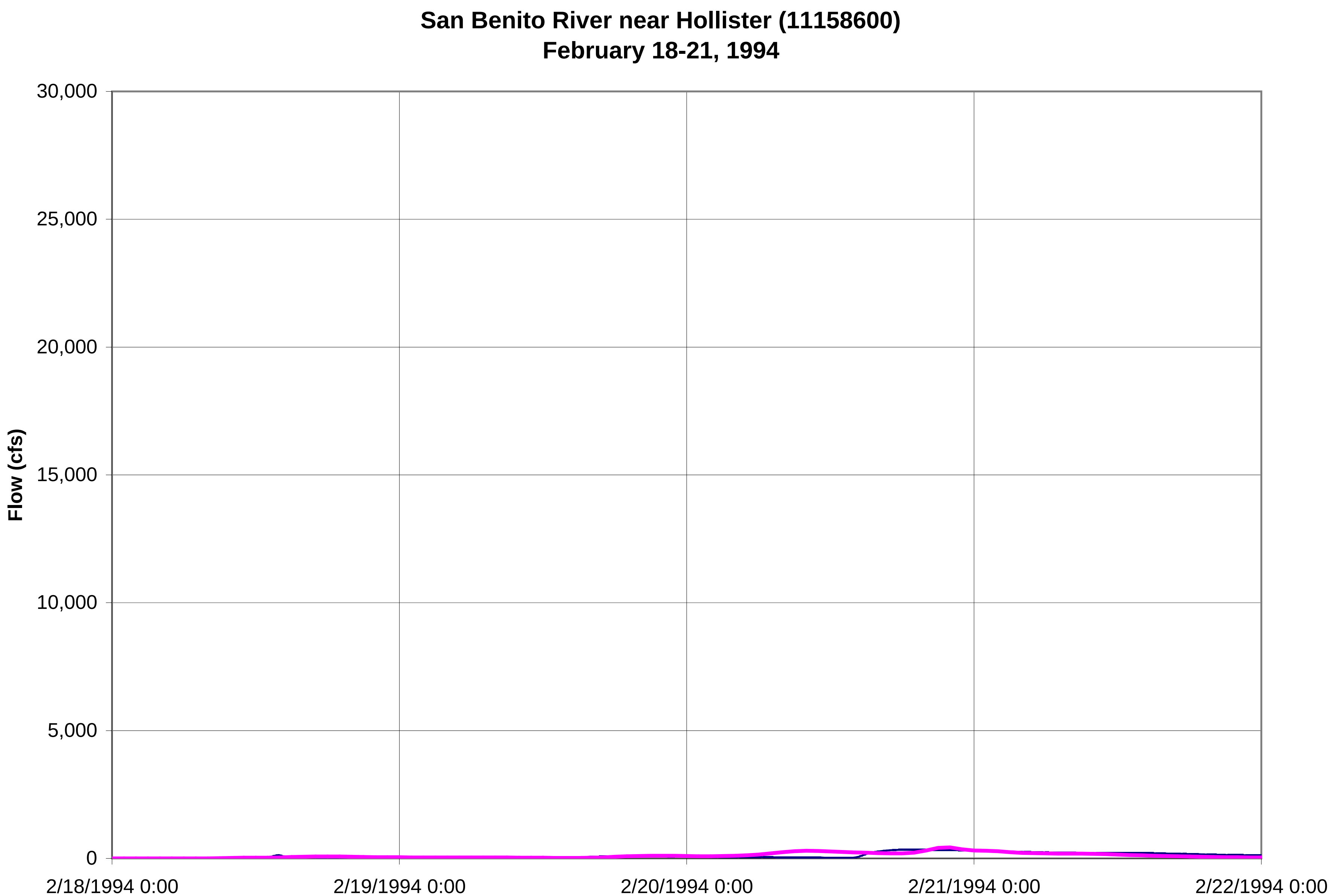

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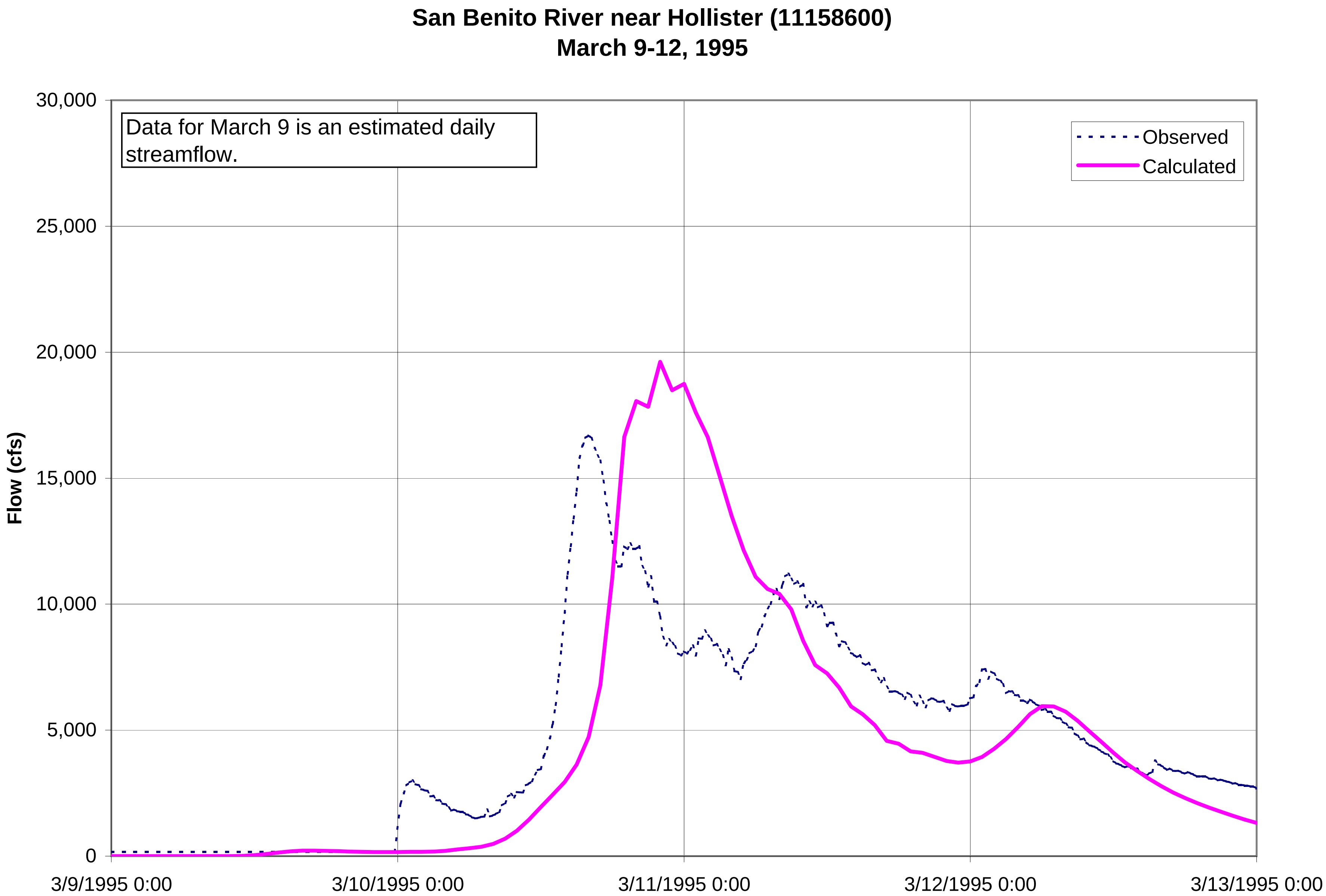

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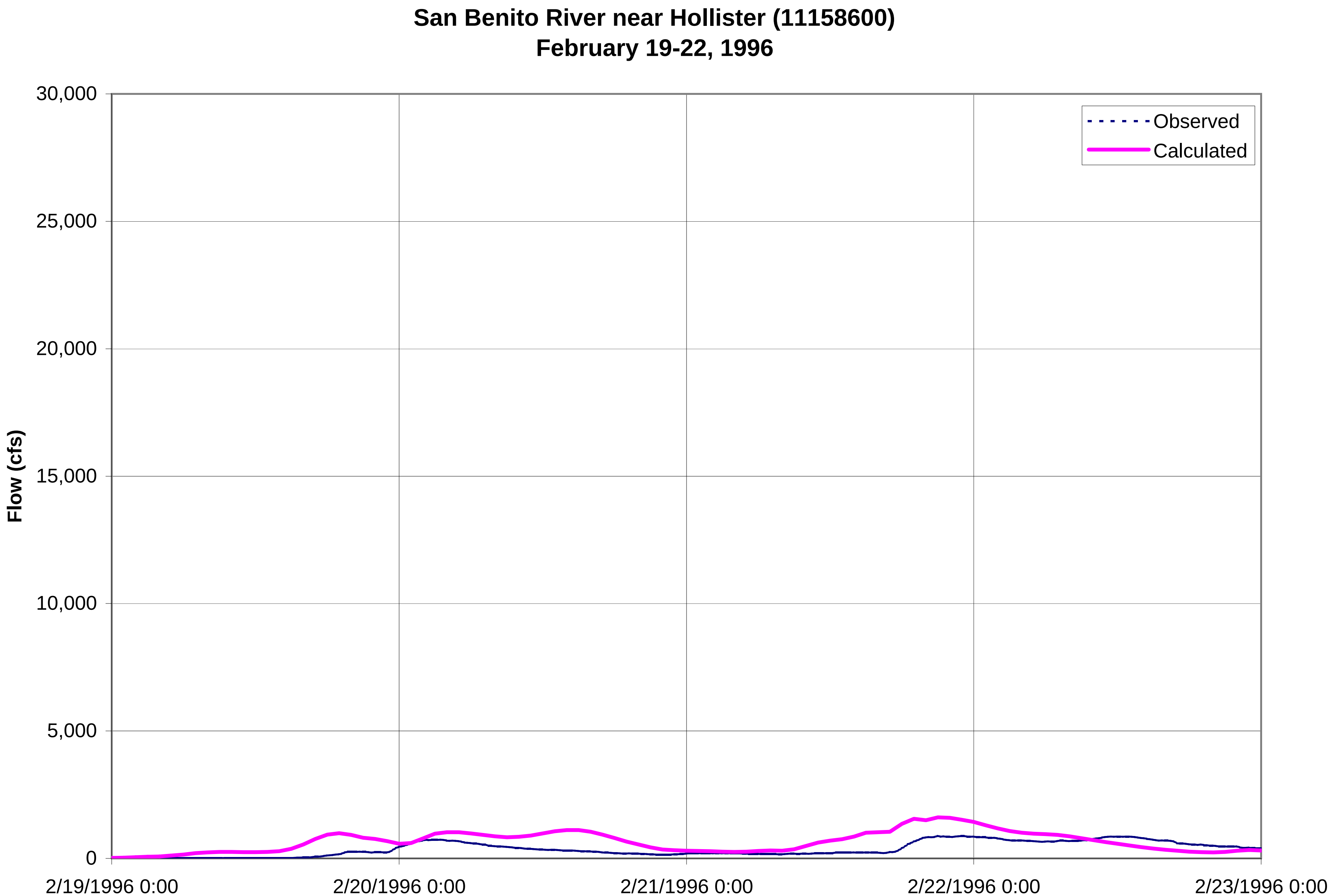

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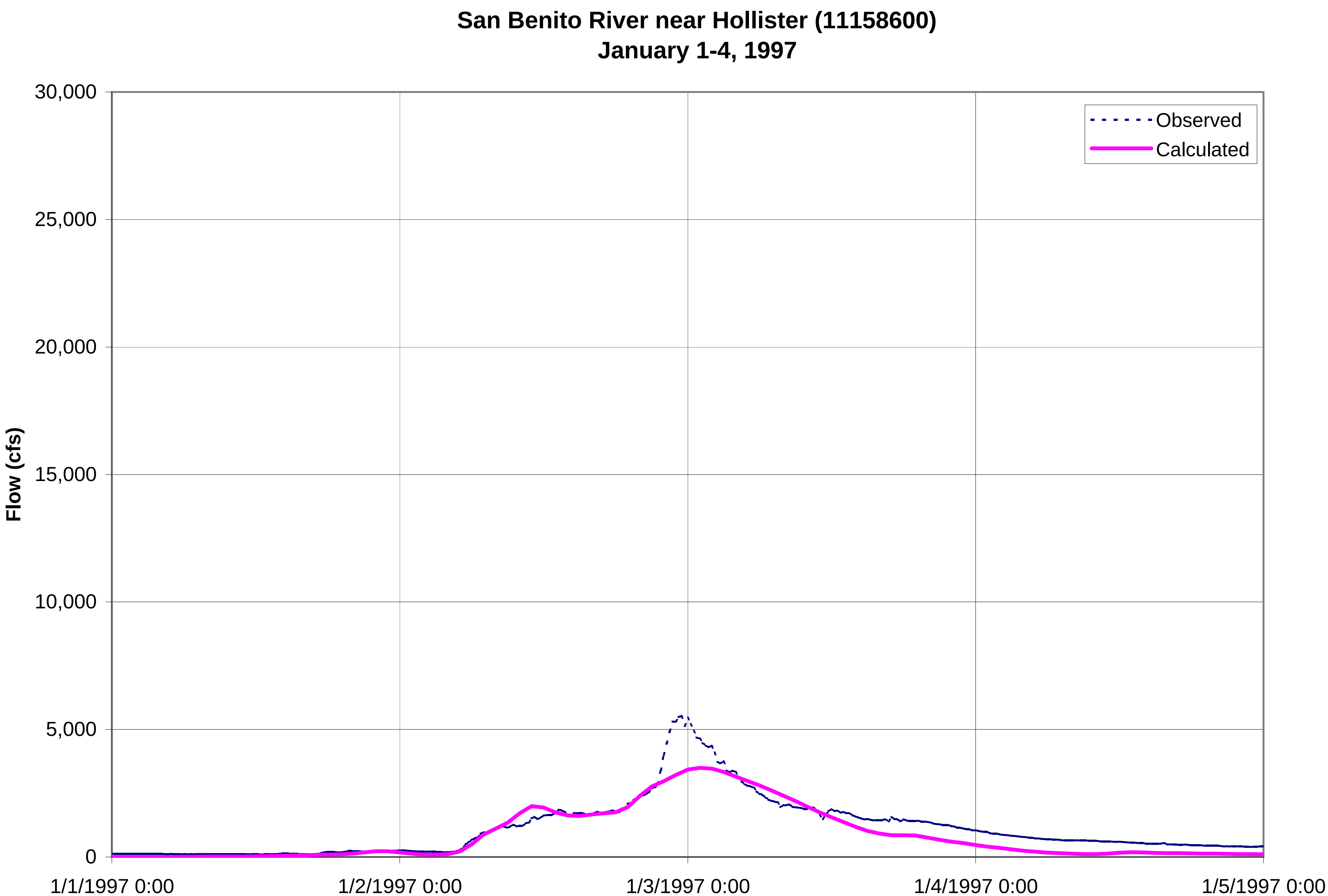

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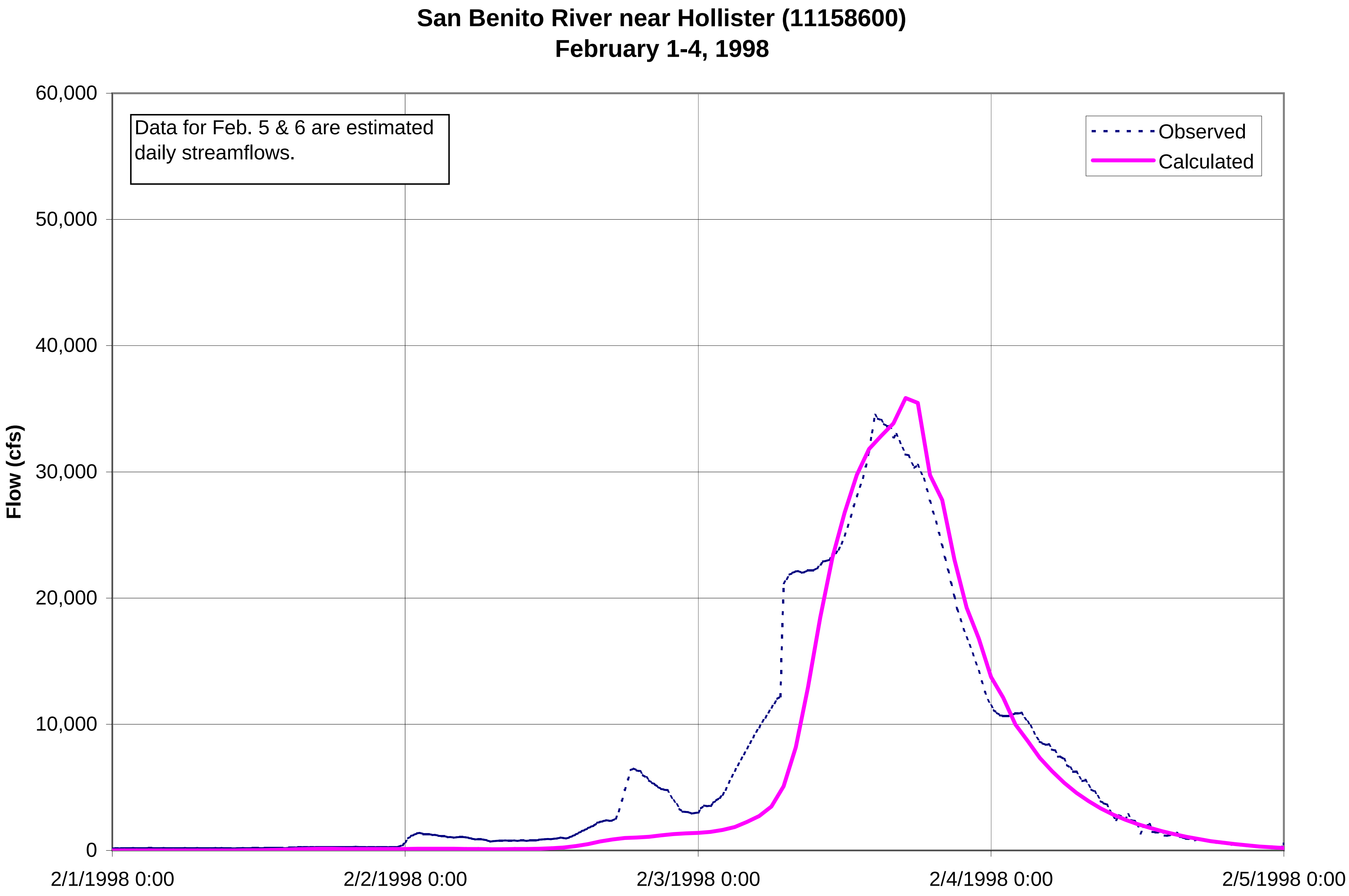

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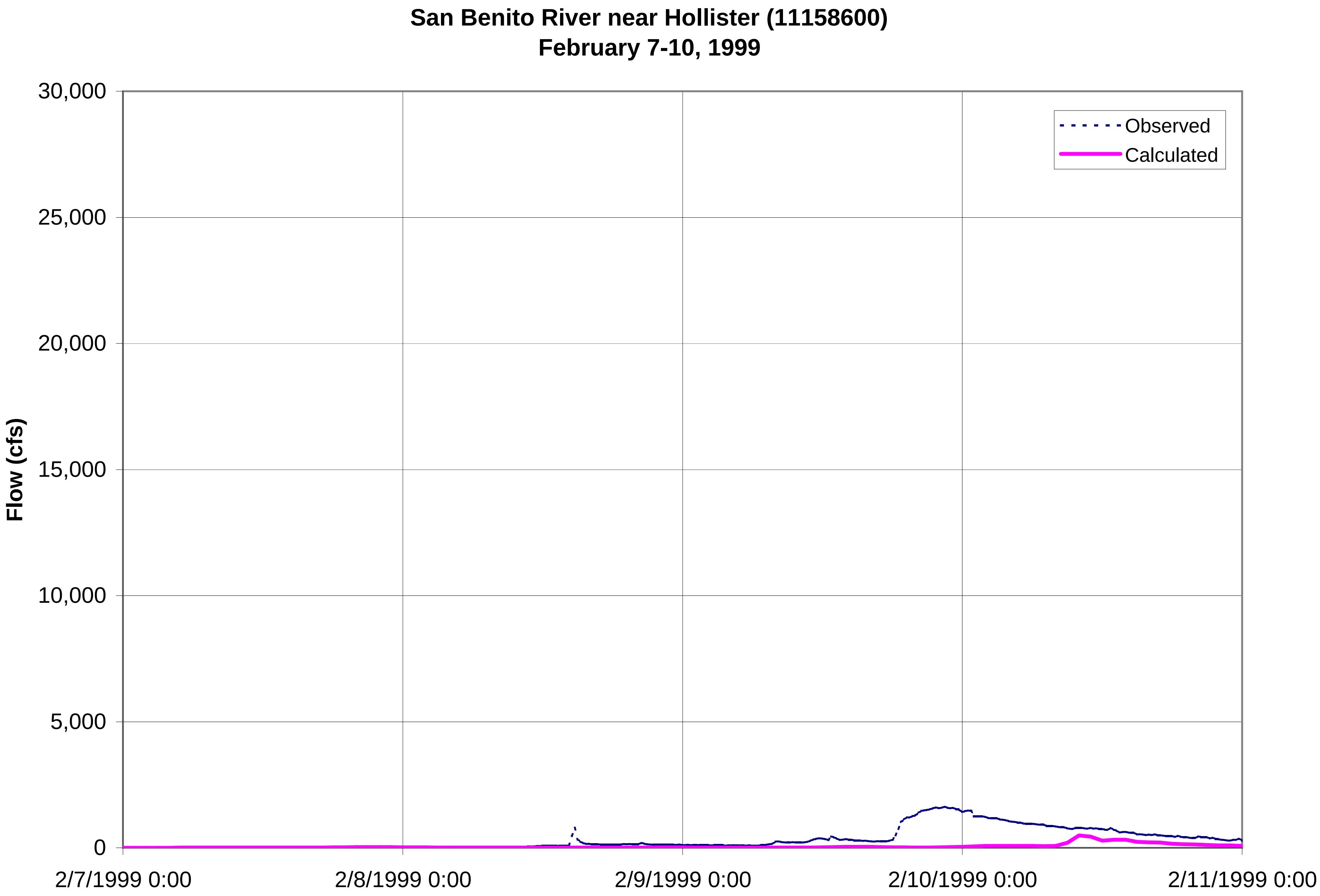

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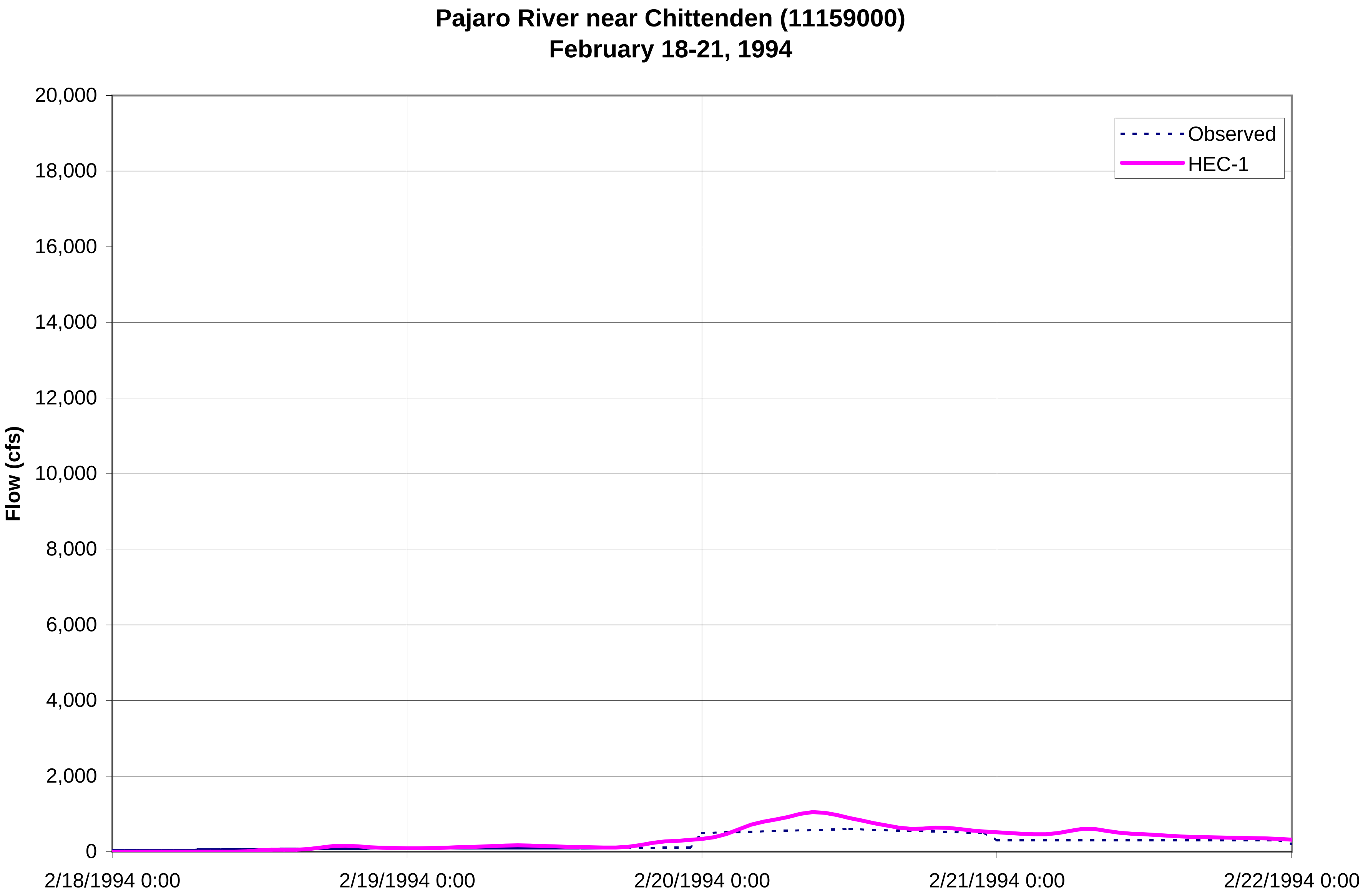

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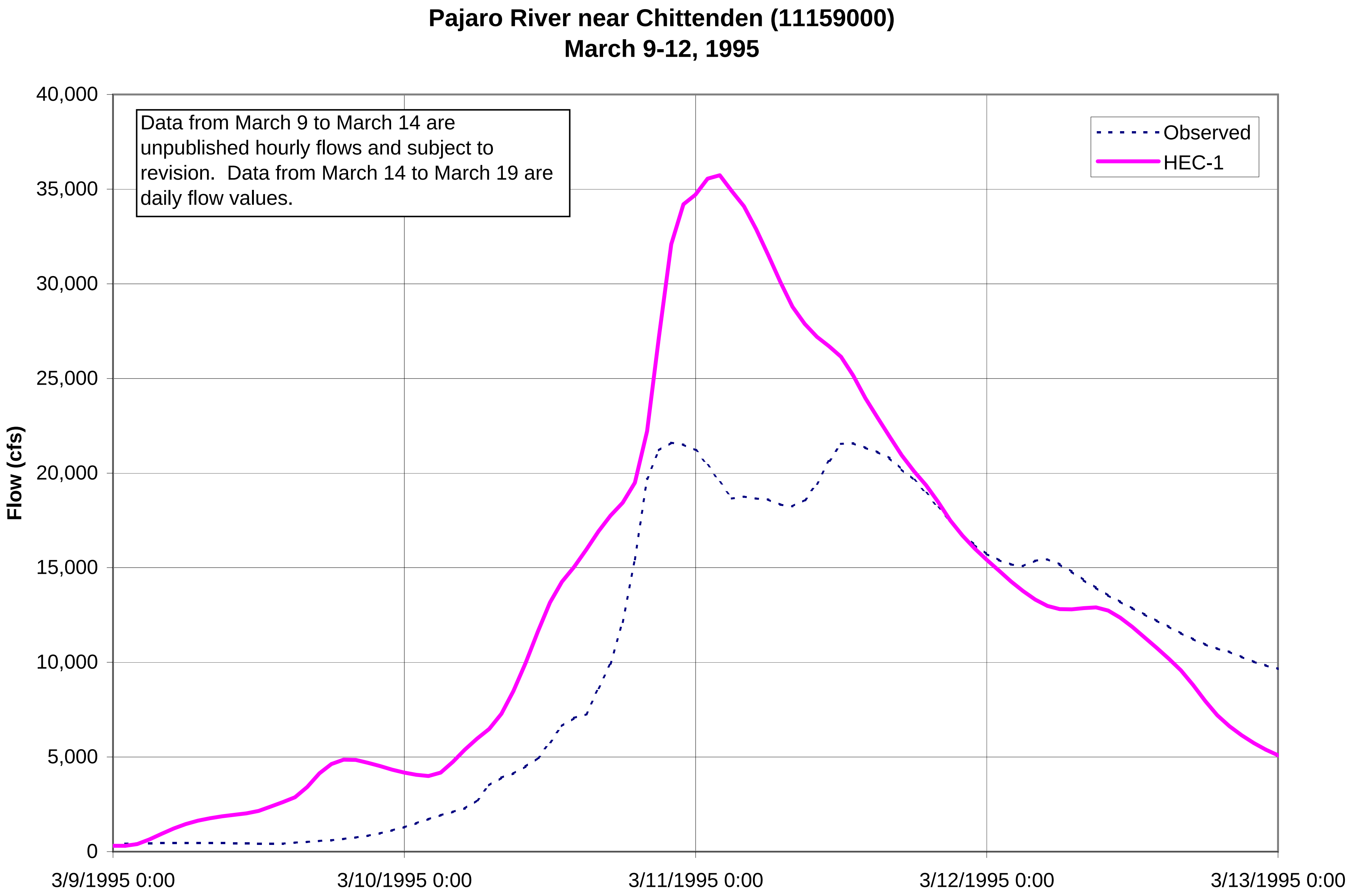

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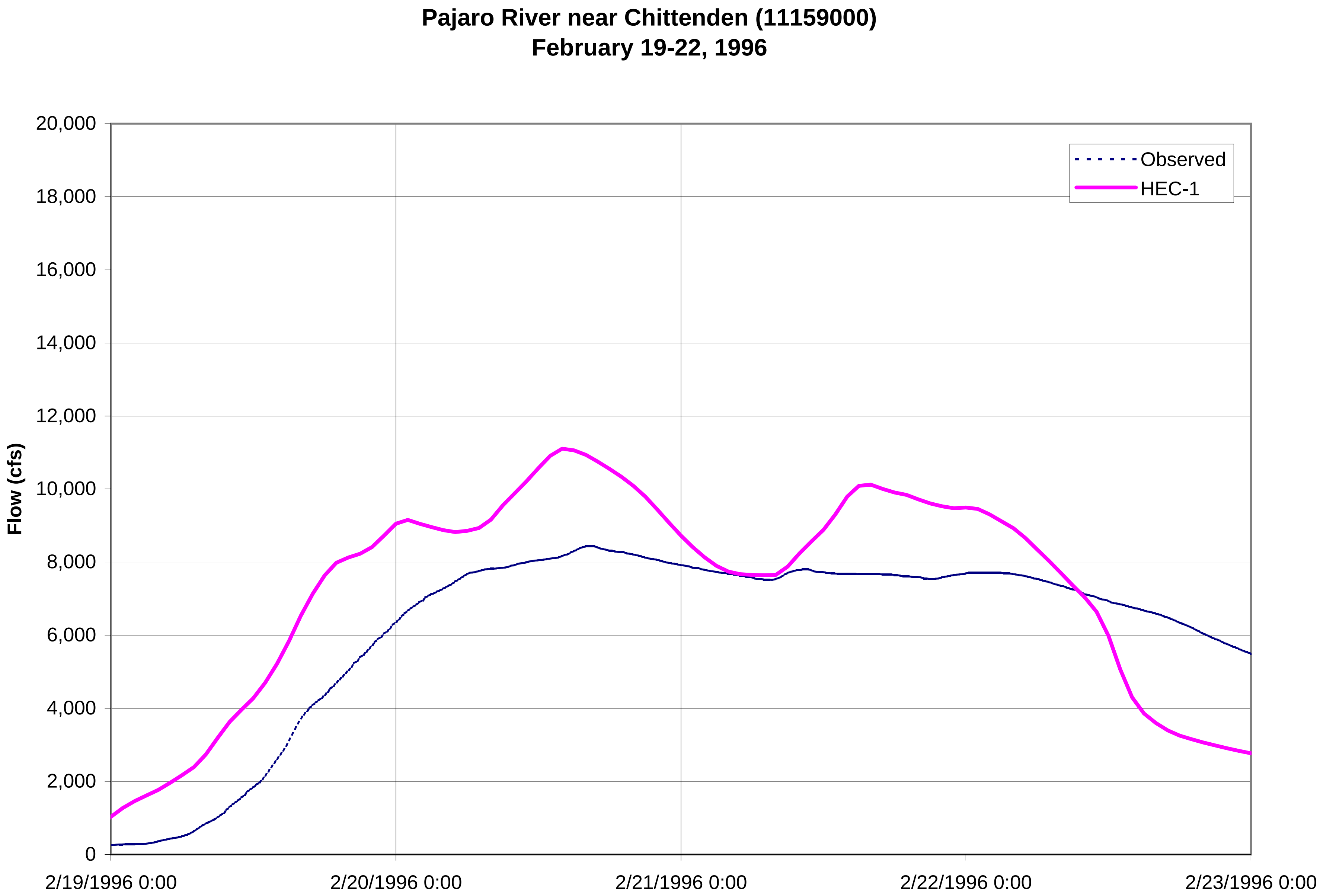

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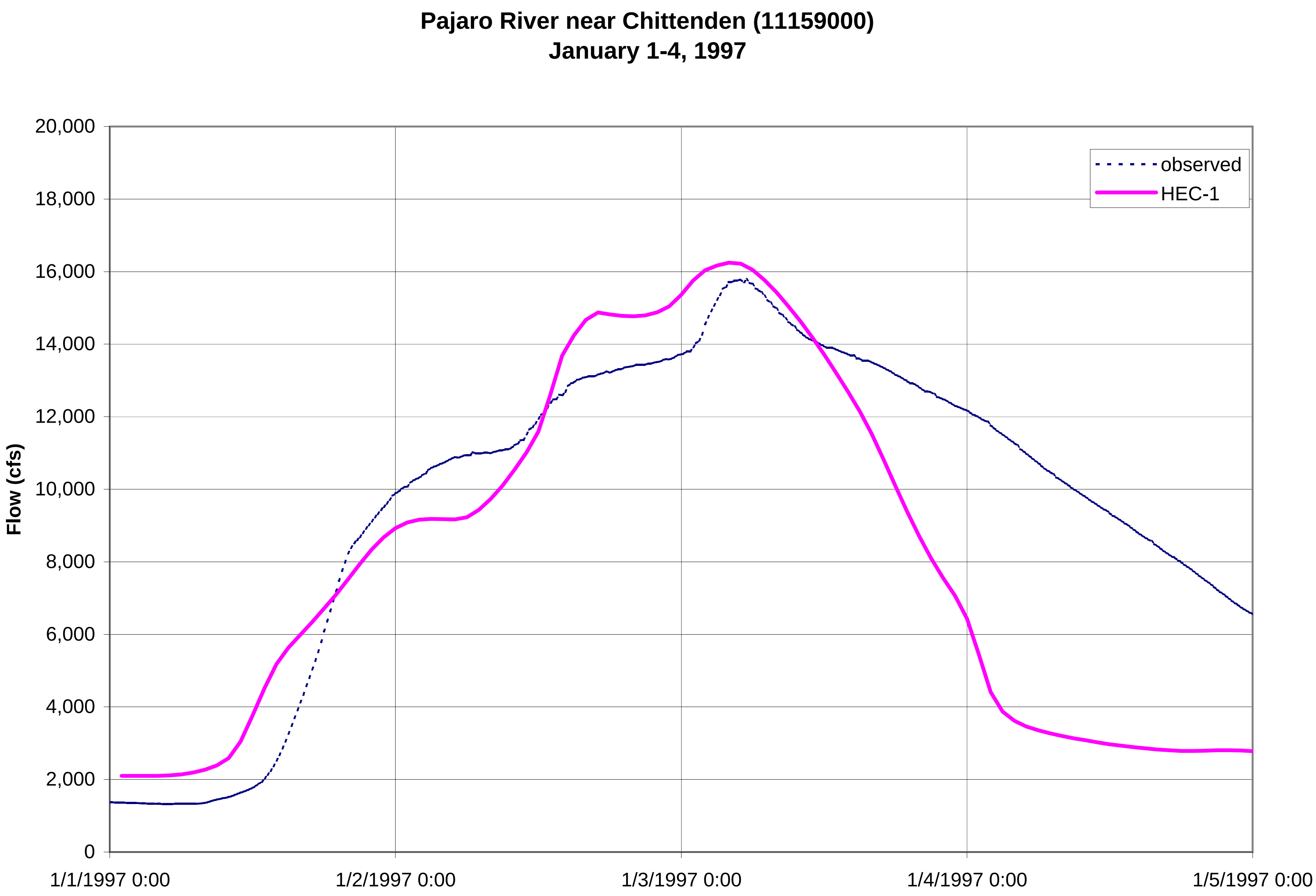

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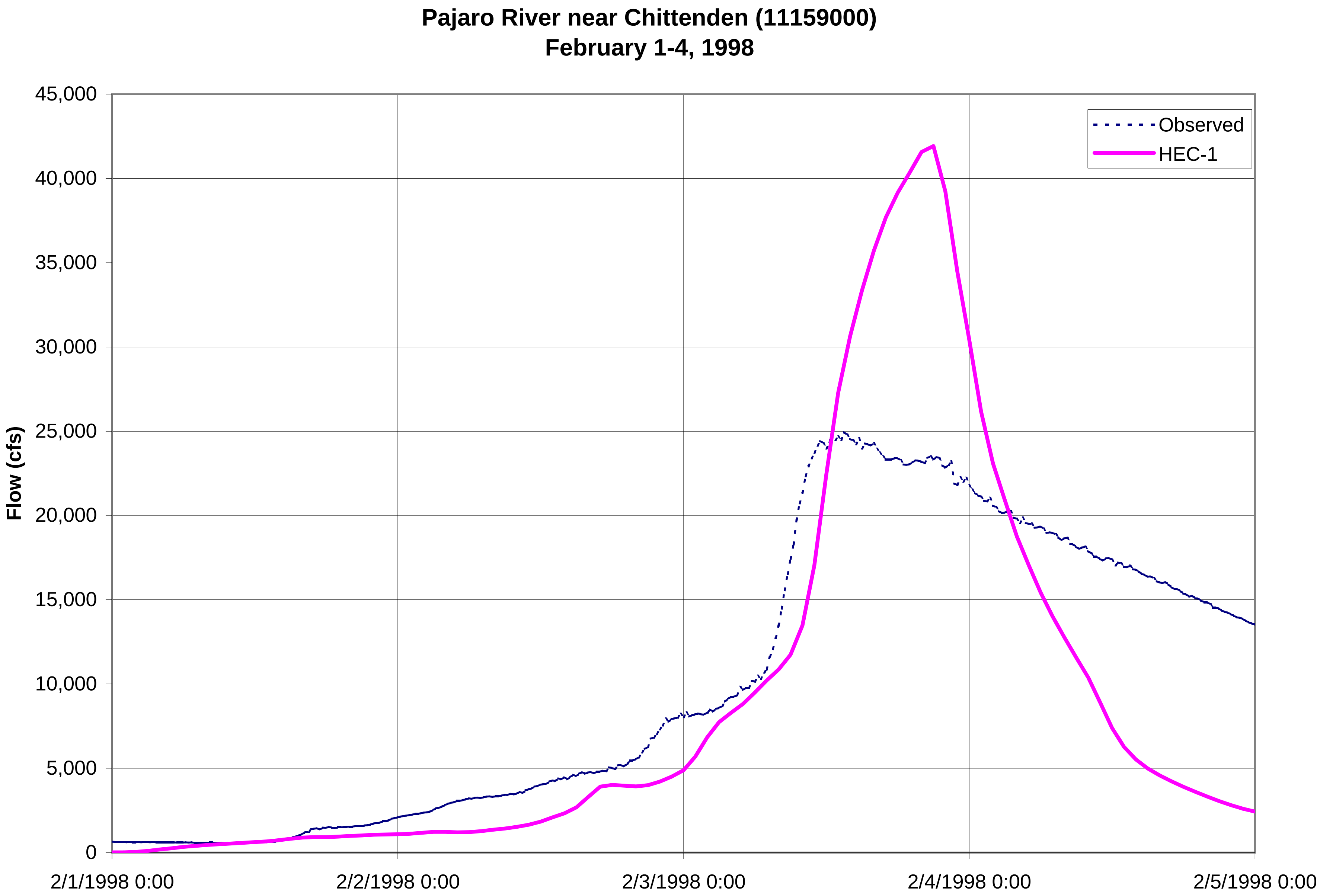

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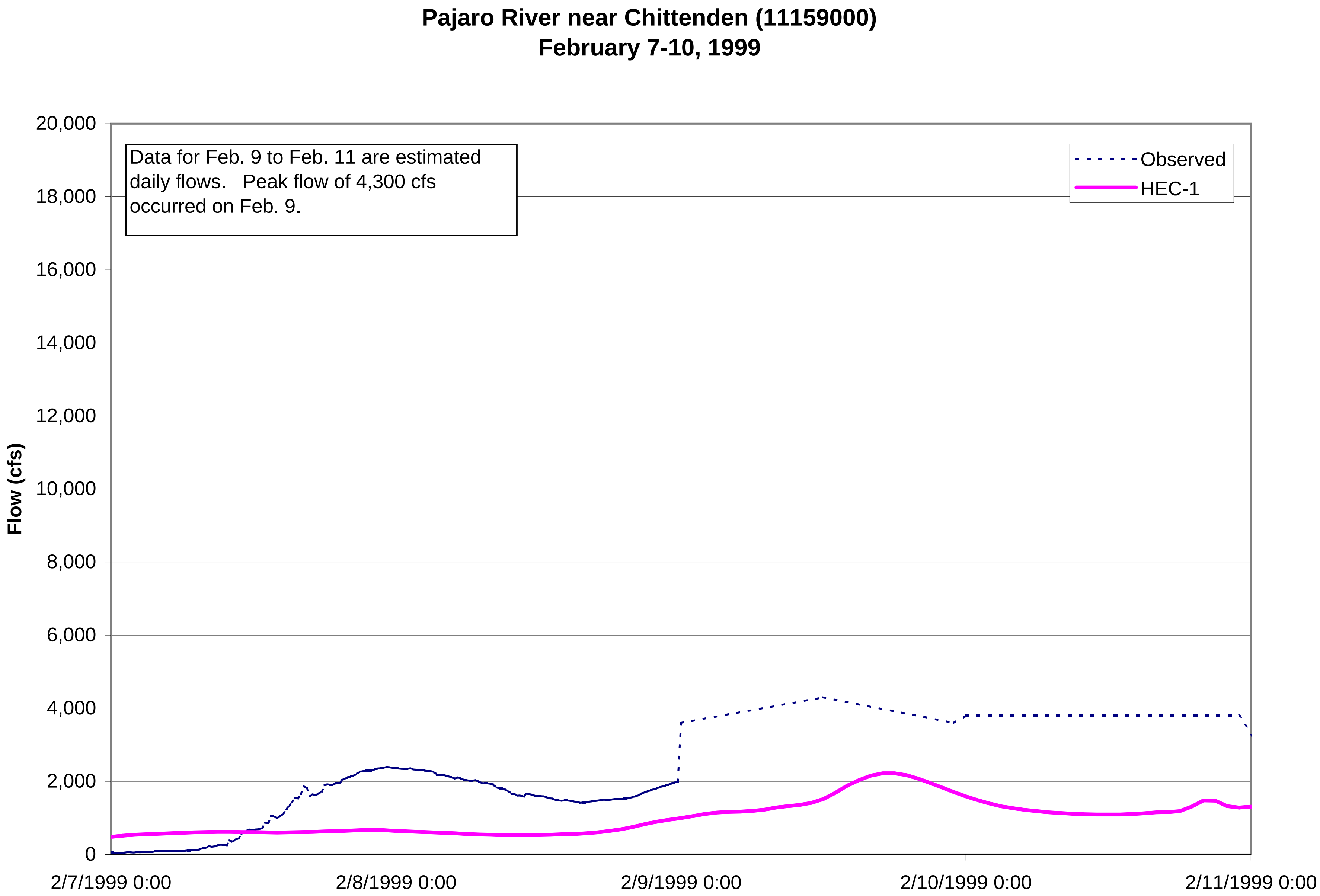

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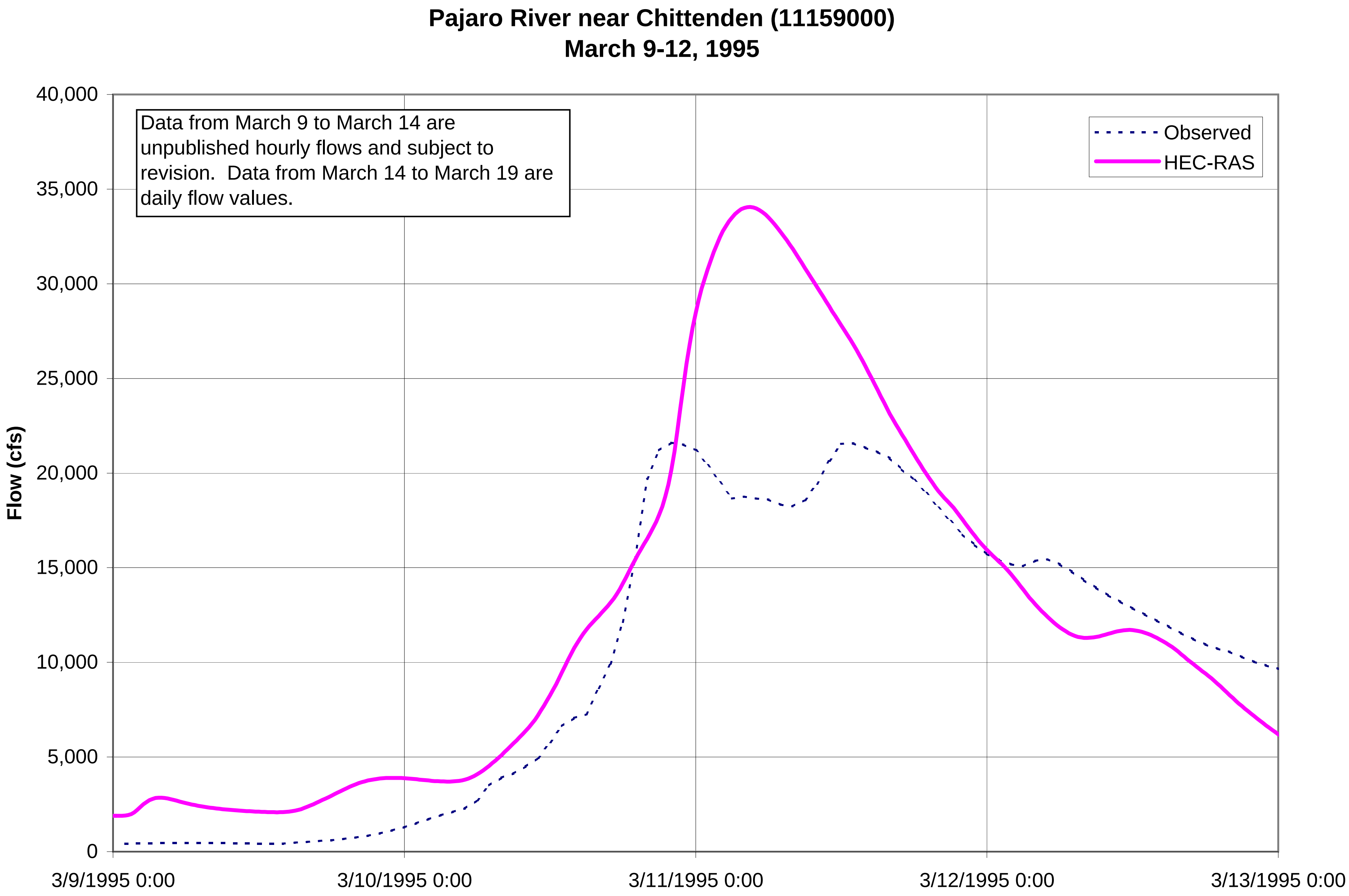

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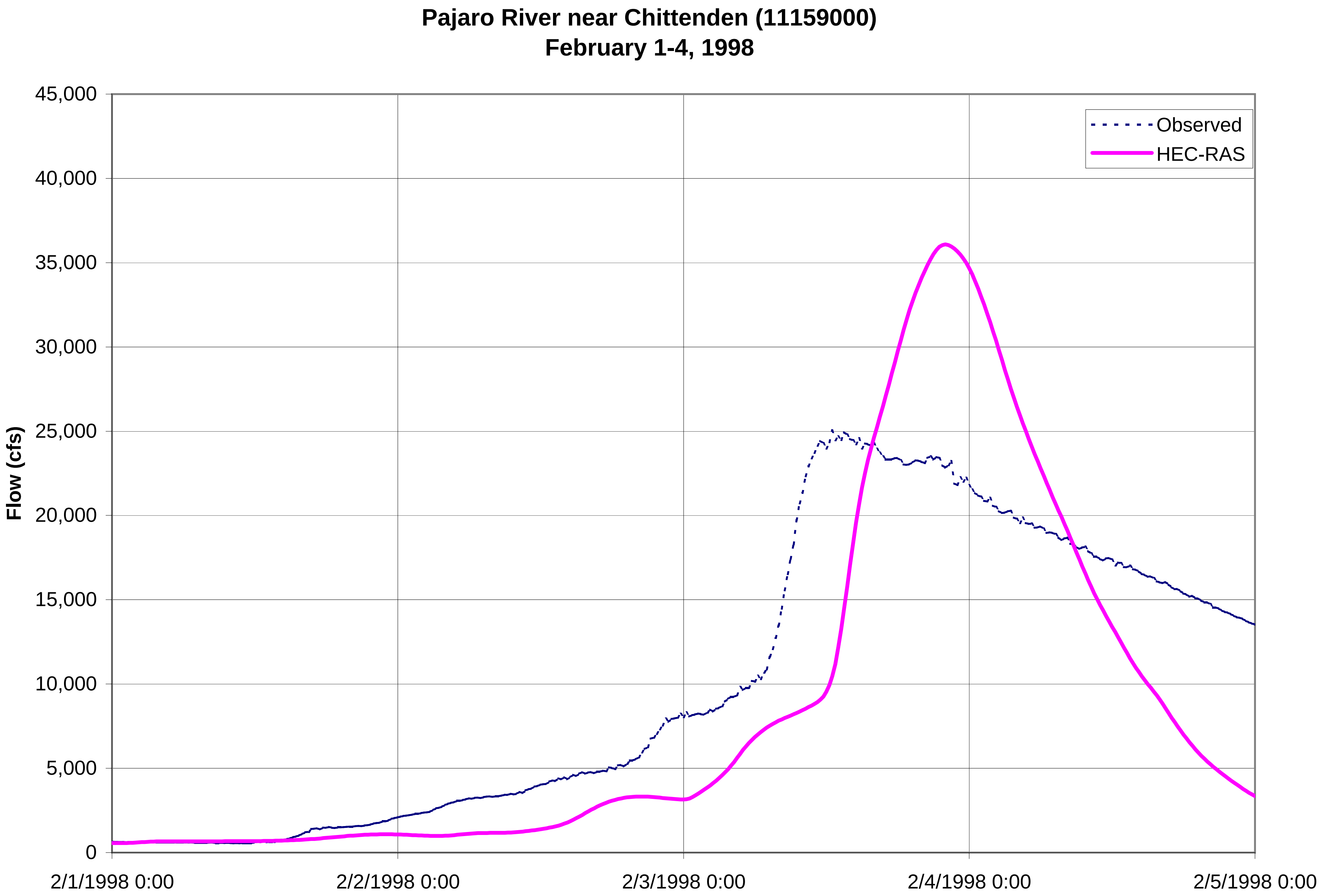

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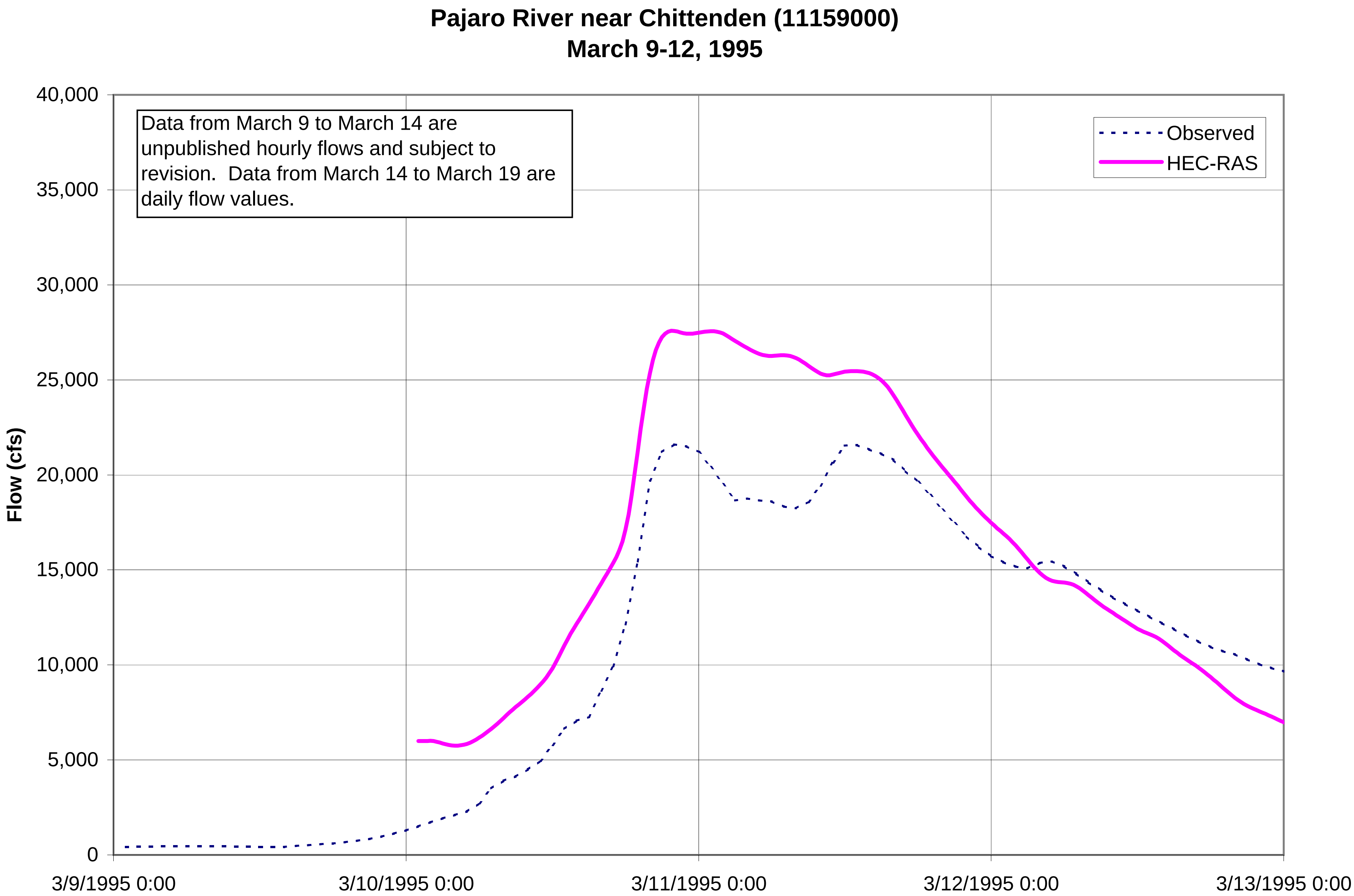

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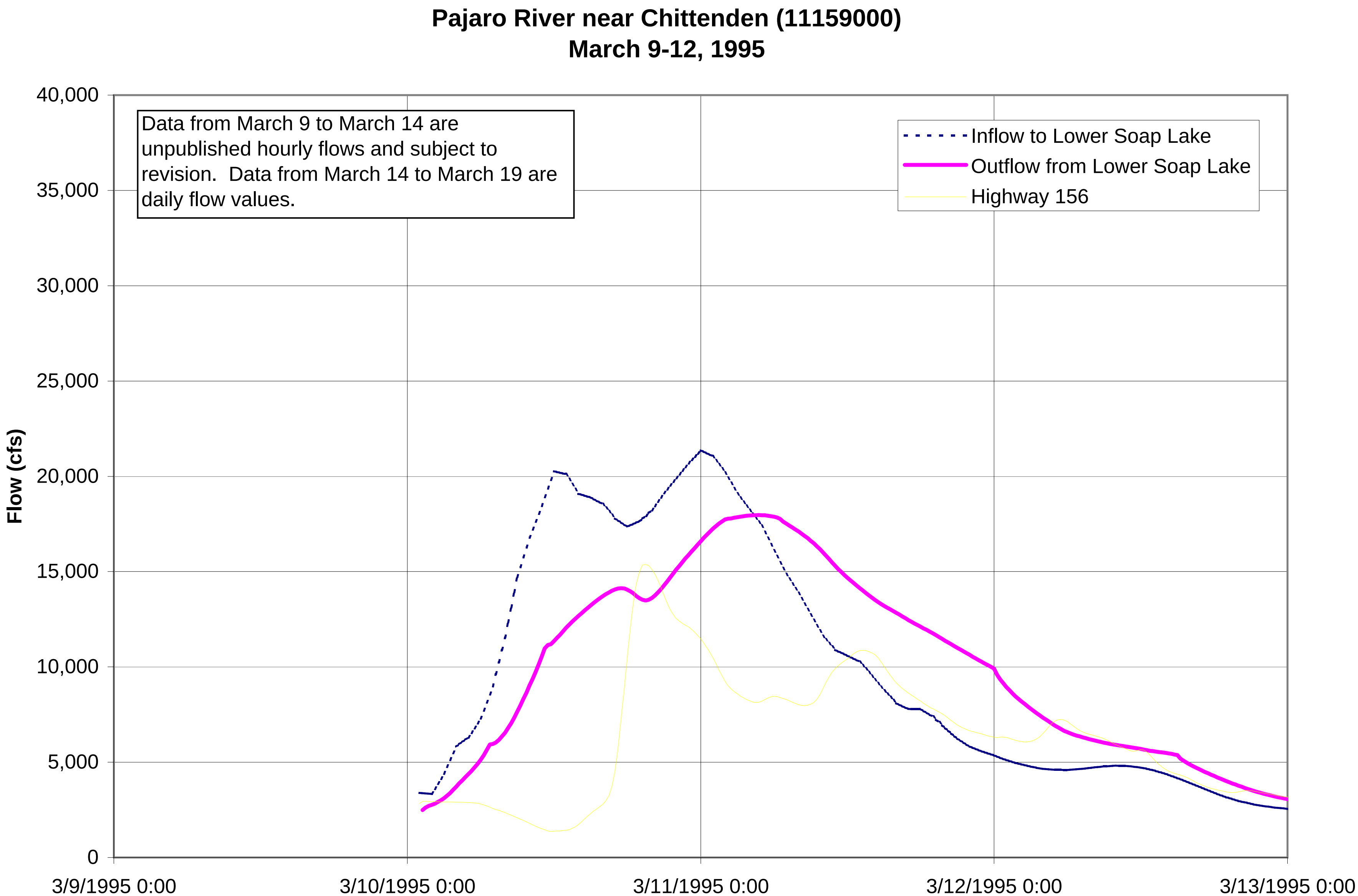

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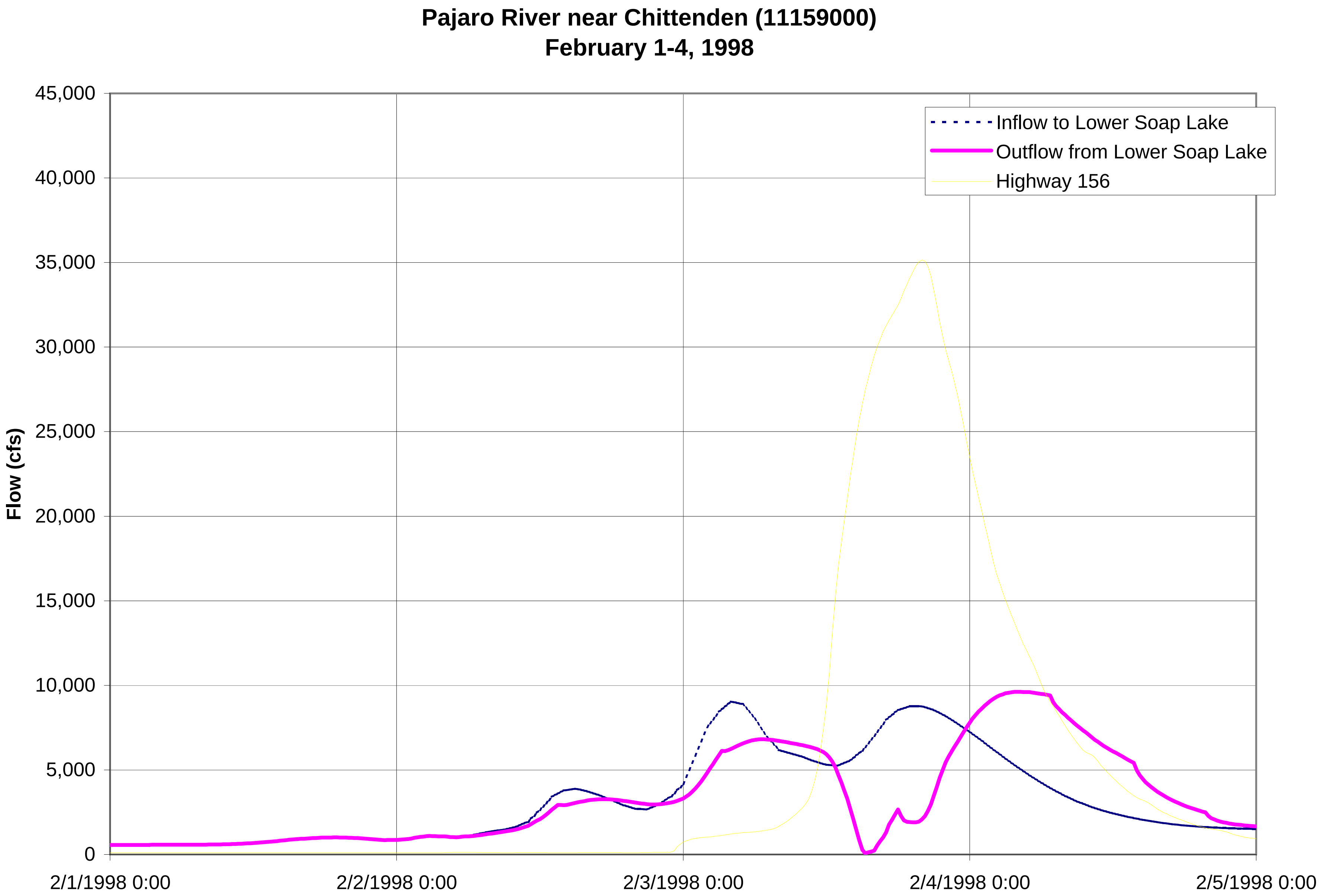

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Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers
in association with
Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.8

Task: Qualitative Sediment Analysis

To: PRWFPA Staff Working Group

Prepared by: Tamara L. Butler

Reviewed by: George W. Annandale, T. Harrison

Date: February 13, 2002

Introduction

This Technical Memorandum (TM) summarizes various data sources and field studies conducted by Engineering & Hydrosystems Inc. (E&H). The qualitative (geomorphological) analysis creates an understanding of river behavior necessary for quantitative sediment modeling, which will be addressed in a future TM.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority commissioned a study to determine the causes of flooding on the Pajaro River (Figure 1). Flooding of the Pajaro River main channel historically occurred every two to five years until the 1930's settlers began building levees in the Watsonville area. In 1949 the current levees on the lower Pajaro River were completed (CH2M HILL 1996). The levees only protect the Pajaro Valley from approximately the 25-year event (Stakeholder Meeting #1 2001).

E&H as part of the study team has developed TM 1.2.4 Sediment Data Analysis, which summarizes available data and field notes pertaining to sediment characteristics, sediment sources and sediment yield from the watershed. Other team members have completed TMs for hydrology of the watershed and hydraulics of the Pajaro and San Benito Rivers.

Objectives of this TM

TM 1.2.8 outlines the fluvial geomorphology of the rivers that will be used in addition to the sediment transport modeling results to determine the effect of sediment on flooding in the Pajaro River Valley. The description of the fluvial geomorphology is based on the work conducted by E&H during the course of this project, previous work by various others on the Pajaro River and a previous study on the San Benito River (Golder 1997). Data was also collected from historical aerial photos, USGS quadrangle sheets, historic topographic maps and available satellite imagery to develop the qualitative model. Issues that are addressed include lateral stability of the rivers, long term aggradation and degradation, changes in levee configurations, and identification of changes in riparian vegetation that may have impacted river behavior. Appendix A includes a list of collected data and corresponding sources.

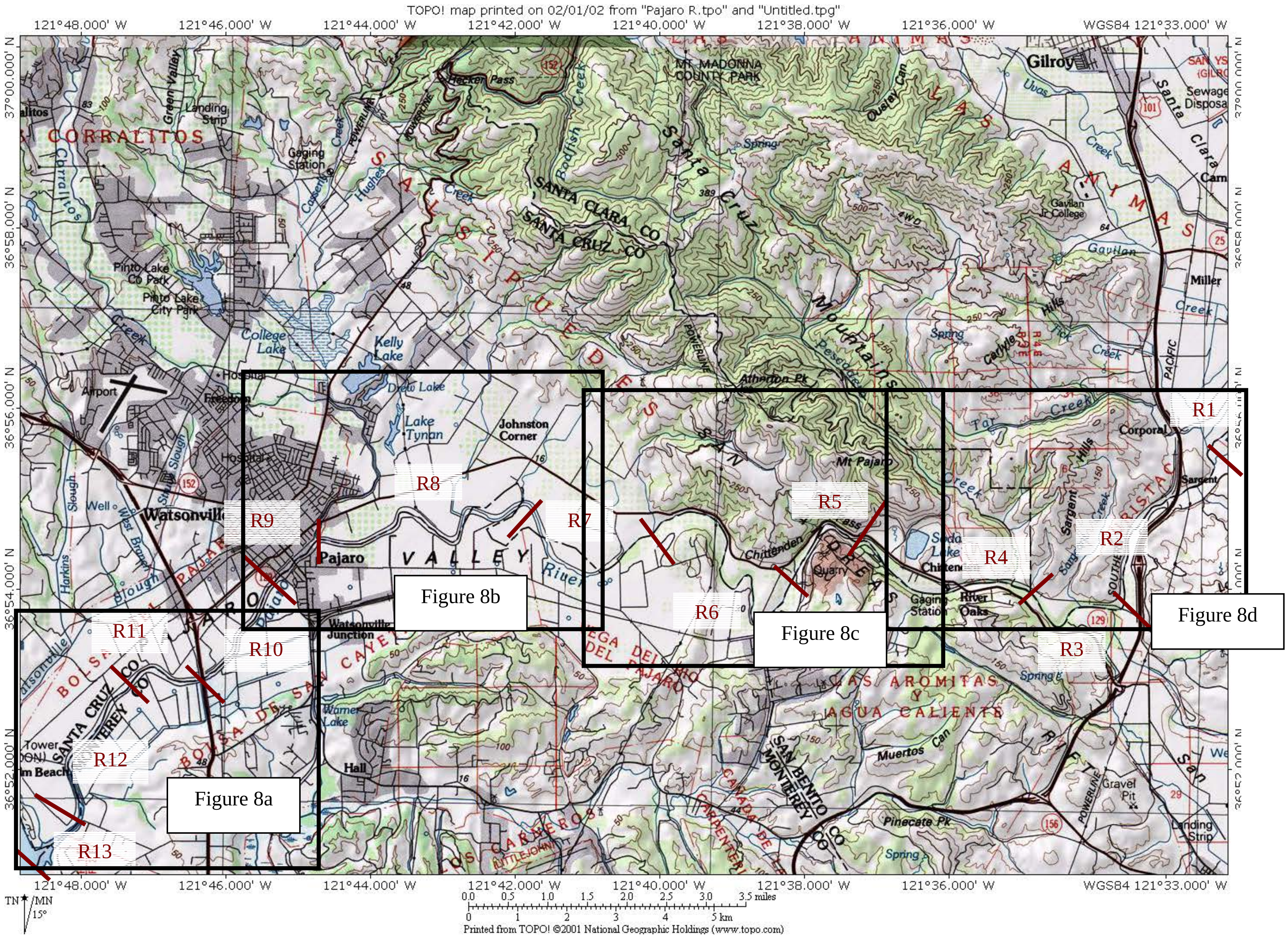

Figure 1. Pajaro River Study Area.

Approach

The purpose of this baseline is to understand the current state of the river using geomorphic principles (Summerfield (1991), Ritter et. al. (1995)). The approach is to determine if the controlling variables (water and sediment) are in equilibrium with the channel morphology (dimension, pattern and profile). If they are not in equilibrium, channel aggradation, degradation or lateral migration will occur. If they are in equilibrium, the channel could have local erosion but the river will remain in a state of quasi-equilibrium. Knowing whether or not a river is in quasi-equilibrium is useful when developing river and flood management strategies.

To fully describe the river and determine its state of equilibrium, existing and historical data is collected and analyzed. The data that is collected include hydrology, sediment properties of the riverbed and banks, river planform, river profile, channel width, channel depth, floodplain width, topography, geology, land use, and channel forming discharge. Changes in hydrology, e.g. periods of increased flow could result in degradation of river channels, whereas regular changes in the river planform implies potential lateral instability of a river. Changes in the width / depth ratios and slope of channels indicate how water and sediment discharge carrying capacity can change. Narrowing or elimination of the floodplain width of a channel (e.g. by building levees) can lead to degradation of the river due to increases in flow velocity and depth, whereas confirmation of the same can be found by comparing the magnitude of channel forming discharge to the discharge capacity of the active channel.

Geology and topography can impact a river's equilibrium through geologic controls and base levels. These elements play an important role in defining the fluvial geomorphology of the Pajaro River. A base level is a theoretical plane denoting an elevation below which a river will not erode and the maximum depth to which a river could grade. An example of a base level is the Monterey Bay at the Pajaro River mouth. Its average elevation is considered not to change with time.

A geologic control can also control a river's slope and constrict flow, but it is considered "active" in terms of erosion over geologic time. An example of a geologic control is a narrow rock valley like Chittenden Pass. Lowering of a geologic control increases the river slope, thereby increasing sediment erosion rates. However, if the geologic control at the downstream end remains virtually stable over the short term (measured in geologic time), then the upstream reaches will degrade relative to the downstream control.

The data that was collected and its analysis is first presented, followed by an interpretation of the overall behavior of the Pajaro River and its major tributary, the San Benito River.

River and Watershed Analysis

General Geology of the Watershed

The Pajaro River basin, which is located in the Coast Range province of California, is shaped by numerous active fault zones including San Andreas, Calaveras, San Gregorio, Zayante, and Corralitos. The lower Pajaro Valley is separated from the upper basin by the narrow canyon at Pajaro Gap where the San Andreas Fault crosses the Pajaro River. The Pajaro River's major tributary, the San Benito upstream of the Pajaro Gap, runs roughly along the San Andreas Fault. The upper Pajaro Watershed includes Llagas Creek along the Calaveras fault to the north. The San Andreas Fault has primarily horizontal movement of the western block to the north in relation to the eastern side of the fault (CH2M HILL 1996). This movement is of concern to the long term stability of this reach, as a drastic move could cause a shift in planform pattern and channel slope.

The upper basin geology consists of Fransiscan Complex Mesozoic sedimentary and metasedimentary rocks on the east side of the Pajaro and San Benito valleys, while plutonic rocks are located along the west sides of the San Benito and Santa Clara valleys. Lower elevations in the upper basin and the Pajaro Gap are characterized by Cenozoic marine and non-marine sedimentary rocks. The lower Pajaro basin was once submerged by the sea so the valley floor is alluvium with extensive deposits of sand (CH2M HILL 1996).

The soil in the Pajaro watershed valley varies from gravelly loam, sandy and fine sandy loam, to clay adobe (CH2M HILL 1996). RMC provided GIS mapping of the watershed in terms of soil classification and texture and are included herein as Figures 2 and 3.

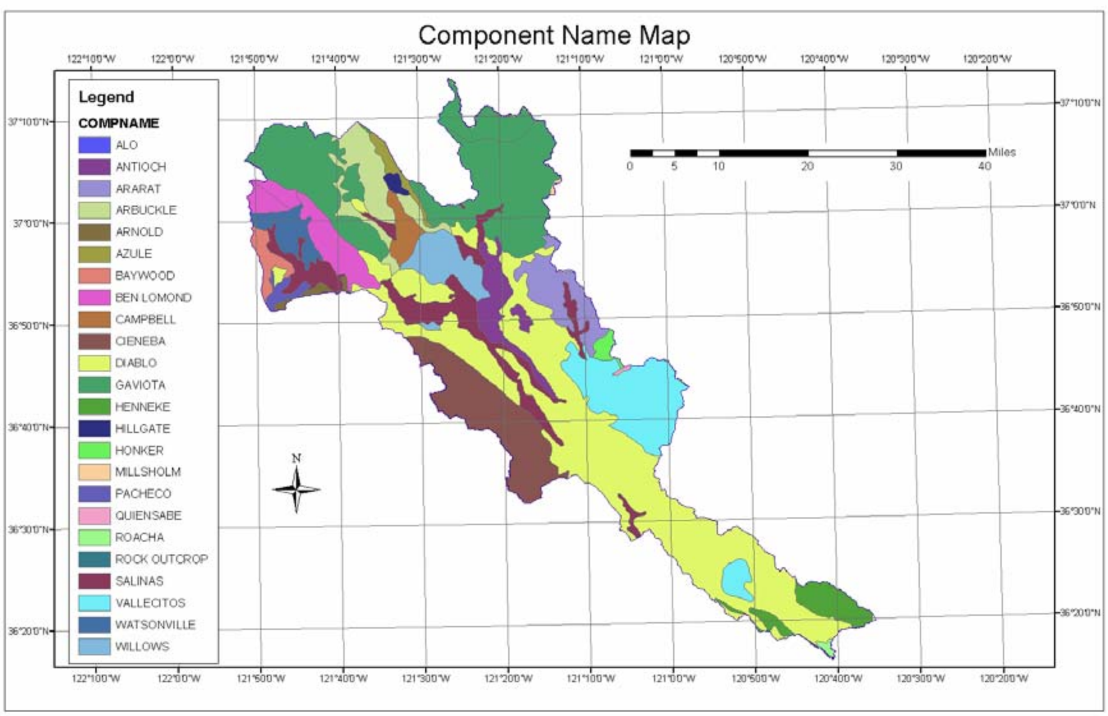

Figure 2. USDA Soil Classification for Pajaro River Watershed (RMC 2001).

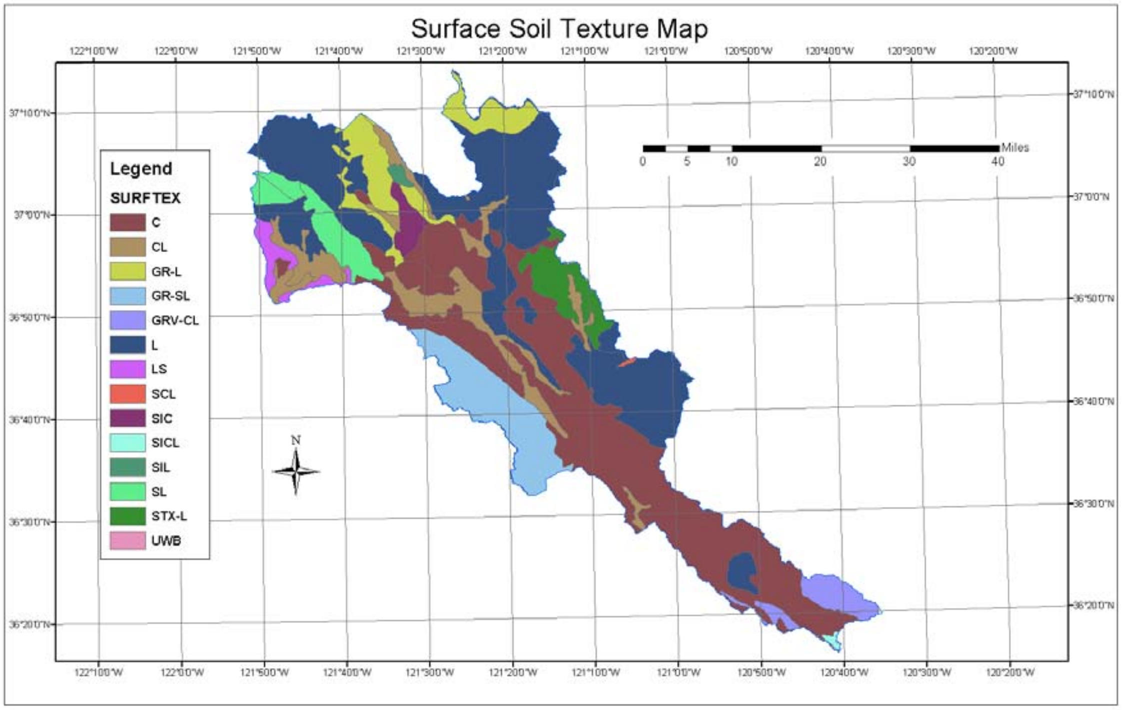

Figure 3. Surface Texture for Pajaro River Watershed (RMC 2001).

Pajaro River Tributaries and Proximity

The head of the Pajaro River is fed by runoff from the Diablo Range. During its approximately 31-mile course to the Pacific Ocean from the Upper Soap Lake area, six major tributaries contribute water and sediment. Three tributaries are in the upper portion of the Pajaro River, and three are in the lower Pajaro Valley.

The upper portion of the Pajaro River watershed is northeast of Chittenden Pass and has three major tributary creeks. Pacheco Creek drains part of the Diablo Range west of San Luis Reservoir and joins the headwaters of the Pajaro River on the east side of the Santa Clara Valley near Gilroy at Upper Soap Lake (San Felipe); the Pacheco drainage area is 154 mi^2 and the confluence is 31 miles upstream of the Pajaro River mouth. Pacheco Lake is located on the north fork of Pacheco Creek about five miles west of Pacheco Pass. Llagas Creek drains 102 mi^2 of relatively wet, densely vegetated area on the east side of the Santa Cruz Mountains. The creek joins the Pajaro River near Gilroy about 27 miles upstream of the Pajaro River mouth after passing through Chesbro Reservoir on the eastern slope of the Santa Cruz Mountains and flowing in multiple alluvial channels in the Santa Clara Valley. Uvas Creek, where Uvas Reservoir is located, drains the Santa Cruz Mountains south of the Llagas Creek. Uvas Creek turns into Carnadero Creek, and together they drain 90 mi^2. The Carnadero Creek junction is 24 miles upstream of the Pajaro mouth just upstream of the Lower Soap Lake outlet (CH2M HILL 1996 & COE 1964). Site observations and discussions with the study team's hydrologic and hydraulic modelers have lead to the assumption that most sediment flowing in the Pajaro River at this point is deposited in Lower Soap Lake.

The largest tributary to the Pajaro River is the San Benito River (661 mi^2), which has its confluence just upstream of the Pajaro Gap, 21 miles upstream of the Pajaro River mouth. The headwaters of the San Benito River are approximately 65 miles southeast of the confluence in the Diablo Range; the river drains runoff from the Gabilan Range to the west and Diablo Range on the east and southeast. The Hernandez Reservoir on the San Benito empties to a meandering alluvial stream. The San Benito Valley is relatively narrow, with steep valley sideslopes, poor vegetative cover, and erodible soils (CH2M HILL 1996). As seen in Figure 4 mass wasting on riverbanks is abundant.

Figure 4. San Benito River.

The Pajaro River morphology is influenced by the geologic structure in the Pajaro Gap near Aromas, which separates the upper portions of the watershed from the Pajaro Valley. Downstream of the gap, the river flows through the wide alluvial plain referred to as the Pajaro Valley for 16 miles; however, flood control levees separate the river from the wide plains for the final 12 miles to the ocean.

Coward Creek joins the Pajaro River 8.8 miles from the bay. Coward Creek does not have any riparian vegetation, has a very low sinuosity, and is frequently cleaned to remove sediment (Figure 5). It appears to be the largest source of sediment in the Lower Pajaro River.

Figure 5. Coward Creek 0.5 miles from confluence with Pajaro River after channel cleaning observed in August, 2001.

Salsipuedes Creek joins the Pajaro River six miles upstream of the ocean. Salsipuedes Creek and its major tributary, Corralitos Creek, drain the eastern side of the Santa Cruz Mountains (CH2M HILL 1997). Salsipuedes Creek is shown on Figure 6.

Figure 6. Salsipuedes Creek 2.6mi from confluence with Pajaro at Hwy 152.

Below Salsipuedes, no other major tributaries enter the Pajaro River until Watsonville Slough, which is at the river mouth.

Summary of Hydrologic Data

Precipitation

About 93 percent of the basin precipitation occurs between November and April. Based on data for precipitation occurring before 1956, the average annual precipitation for the entire Pajaro River basin is about 19 inches and about 32 inches for the Pajaro Valley. The Corps of Engineers divided the Pajaro watershed into three parts concerning flood characteristics in 1964 using rainfall and flow data up to 1956 (COE 1964). First, the San Benito River basin has a relatively low average annual rainfall of 17 inches. Second, the upper Pajaro basin, including Uvas-Carnadero, Llagas, and Pacheco Creeks, and the Hollister-Gilroy valley area's average rainfall, varies from 44 inches to 13 inches in various parts. Third, the lower Pajaro River basin consisting of Salsipuedes Creek and hillside basins between Chittenden and Watsonville has 32 inches average annual rainfall (COE 1964).

Runoff

Two US Geological Survey (USGS) gages are of interest for the Pajaro River study: the Pajaro River at Chittenden (11159000) and Corralitos Creek at Freedom (11159200). The Chittenden gage records streamflow from a 1,186 mi^2 (over 90 percent of the Pajaro watershed). The average annual runoff at Chittenden is 173 cfs (cubic feet per second), which is 124,900 acre-feet or 1.97 inches of runoff using data from 1940-1999. This average is higher than that given in 1996 of 108,800 acre feet or 1.72 inches of runoff (CH2MHill 1996). The higher average was caused by a period of high flow years between 1995 through 1998.

In 1997, the Corps of Engineers developed peak discharge versus frequency curves for the Pajaro River below Salsipuedes Creek, the Pajaro River at Chittenden, Salsipuedes Creek at the Pajaro River confluence, and Corralitos Creek at Freedom (COE 1997). The curves are included in Appendix B along with average 1-day flow and average 3-day flow versus frequency curves for the Pajaro River at Chittenden (COE 1997). Appendix B also contains hydrographs for the Pajaro River below Salsipuedes Creek, the Pajaro River at Chittenden, and Corralitos Creek at Freedom (COE 1997).

Figure 7 shows cumulative mean flow for the period of record for the Pajaro River at Chittenden Gage. From Figure 7, trends in historical hydrology can be summarized. Relatively dry periods occurred from 1946 to 1950, 1960 to 1961, 1976 to 1977, and 1987 to 1992. Conversely, 1983 and 1998 were relatively wet years, with the period from 1995 to 1998 having higher average precipitation than the historical average. More recent data (after flood of 1998 to present) show that rainfall seems to be returning to more of a historical average. The peak daily discharge recorded at the Chittenden gage was 21,700 cfs on December 24, 1955 (USGS 2001).

The peak instantaneous discharge measured for Pajaro River at the Chittenden gage is 28,250 cfs, which occurred on February 3, 1998 at 2pm (NHC 1998). Northwest Hydraulic Consultants (NHC) notes that flows between 1995 to 1998 were relatively high compared to discharges over period of record but that an increased channel capacity due to vegetation clearing within the channel prevented levees from overtopping in the area upstream of Highway 1 during the February 1998. However, the March, 1995 flood did overtop and breach the levees on both the Monterey County and Santa Cruz County sides. Other historical floods caused flooding on Corralitos and Salsipuedes Creeks, but did not overtop the Pajaro River levees (COE 1997).

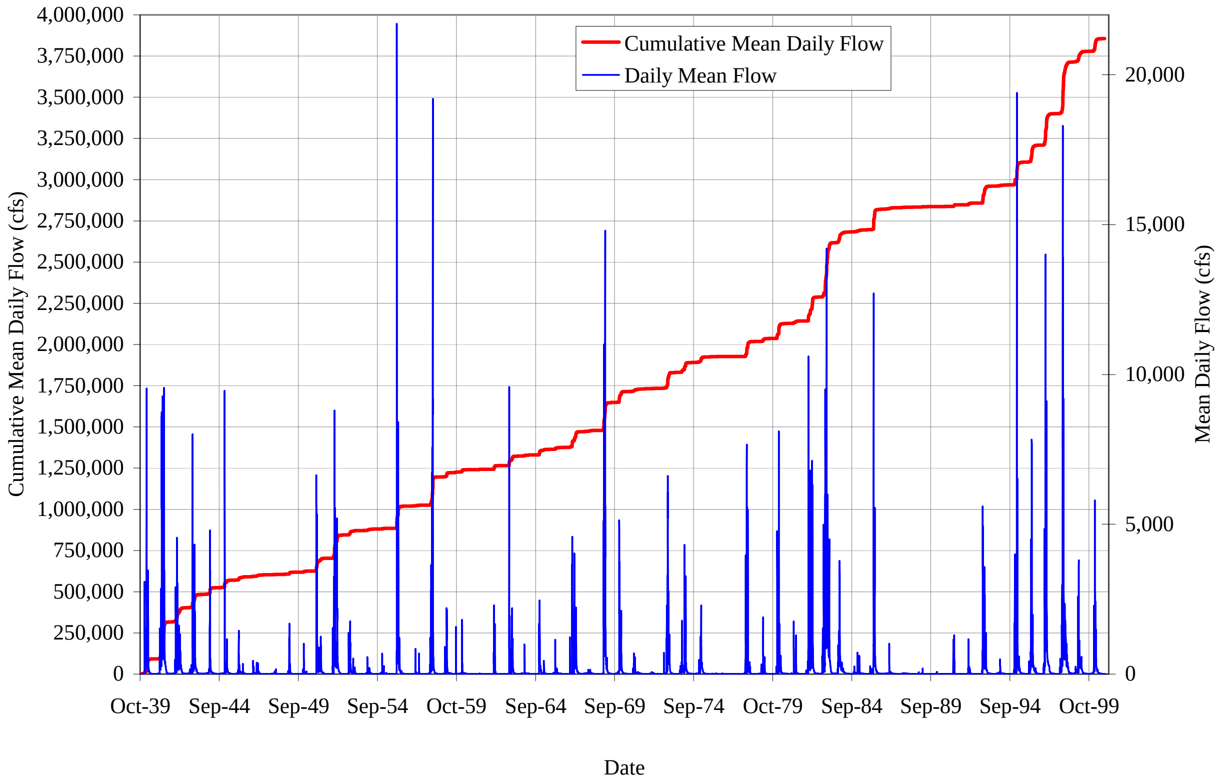

Figure 7. Mean Daily and Cumulative Mean Daily Flows at Chittenden Gage.

Summary of Previous Qualitative Study of San Benito River and its Watershed

Golder Associates (1997), found that the San Benito River was actively degrading. The reason for degradation was identified as sediment starvation caused primarily by mining operations. The report found that degradation rates varied depending on location in the San Benito River, but that the Pajaro River at Chittenden Pass provided a local base level control for the downstream end of the San Benito River. The study identified localized channel armoring that slows degradation for short periods of time but is easily breached to release fine sediments resulting in continued degradation.

Pajaro River Study Reach

The Pajaro River project reach is from the mouth at the bay to Upper Soap Lake. Figure 1 shows the river and surrounding terrain with Figures 8a to 8d showing quadrangle maps of sub-areas of the river. This study describes the Pajaro River in terms of 13 reaches that were defined using planform features and patterns obtained from field inspection and aerial photography. The reaches are indicated on Figure 1 by maroon tick marks across the river channel and on Figures 8a to 8d by yellow dots on the river. River miles are indicated on Figures 8a – 8d by red flags. Blue points with numbers next to them are global positioning waypoints that correlate with the field visit notes. Figures that include site photographs list the waypoint location of the photograph and the date on which it was taken in parentheses. Information pertaining to the San Benito River was obtained from Golder (1997).

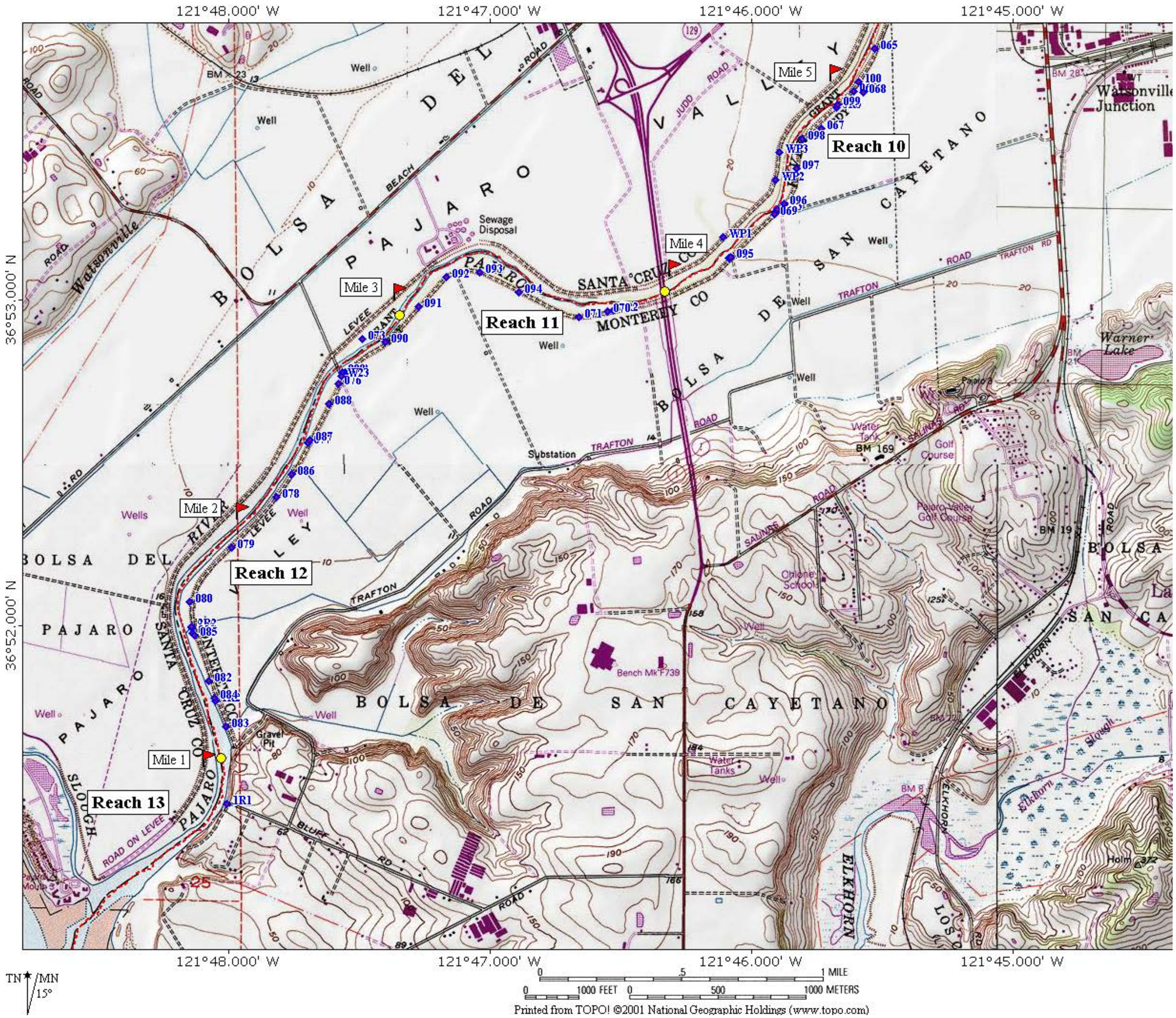

Figure 8a. Pajaro River Mouth at Bay to Mile 5.

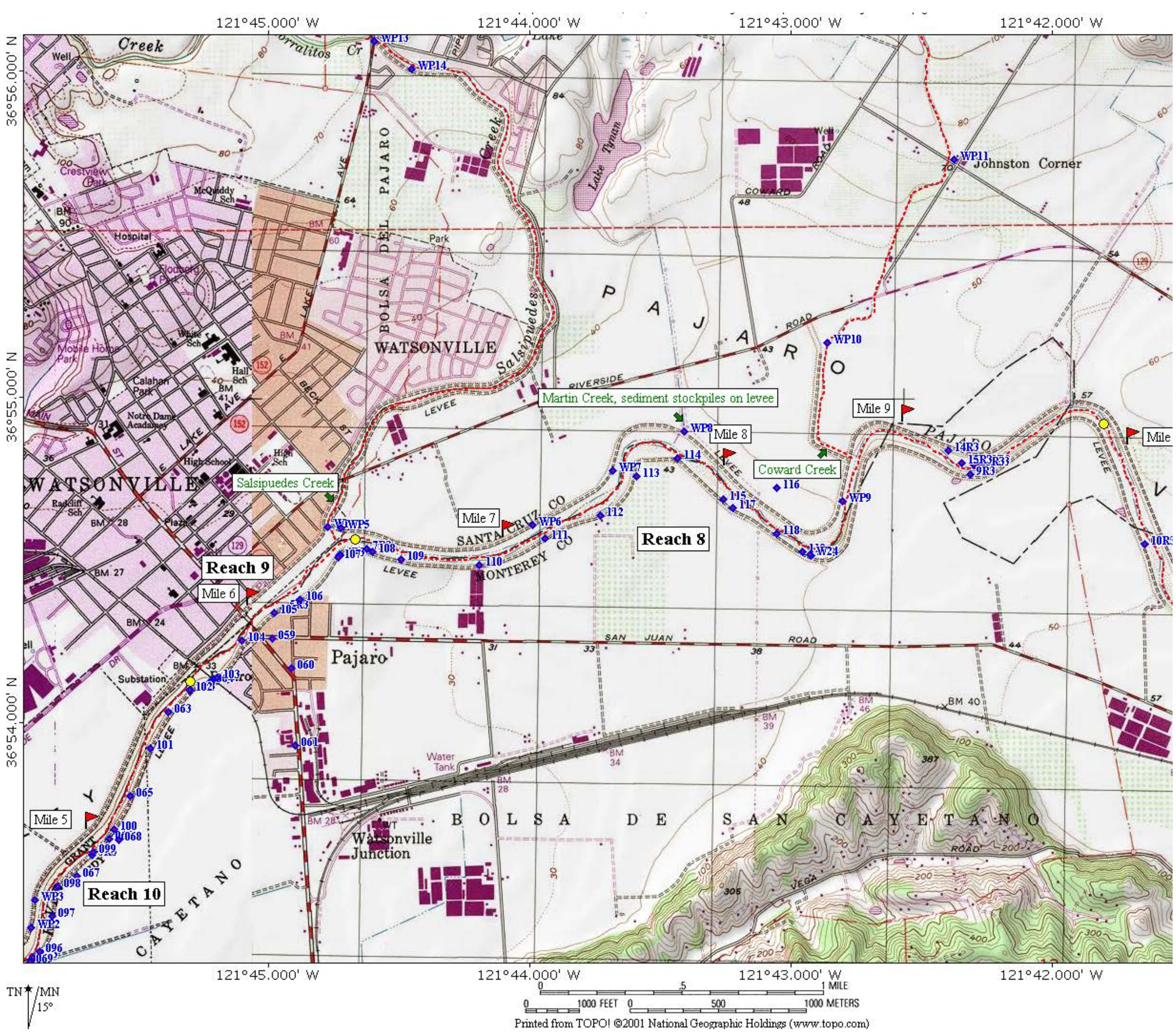

Figure 8b. Pajaro River Mile 5 to Mile 10.5.

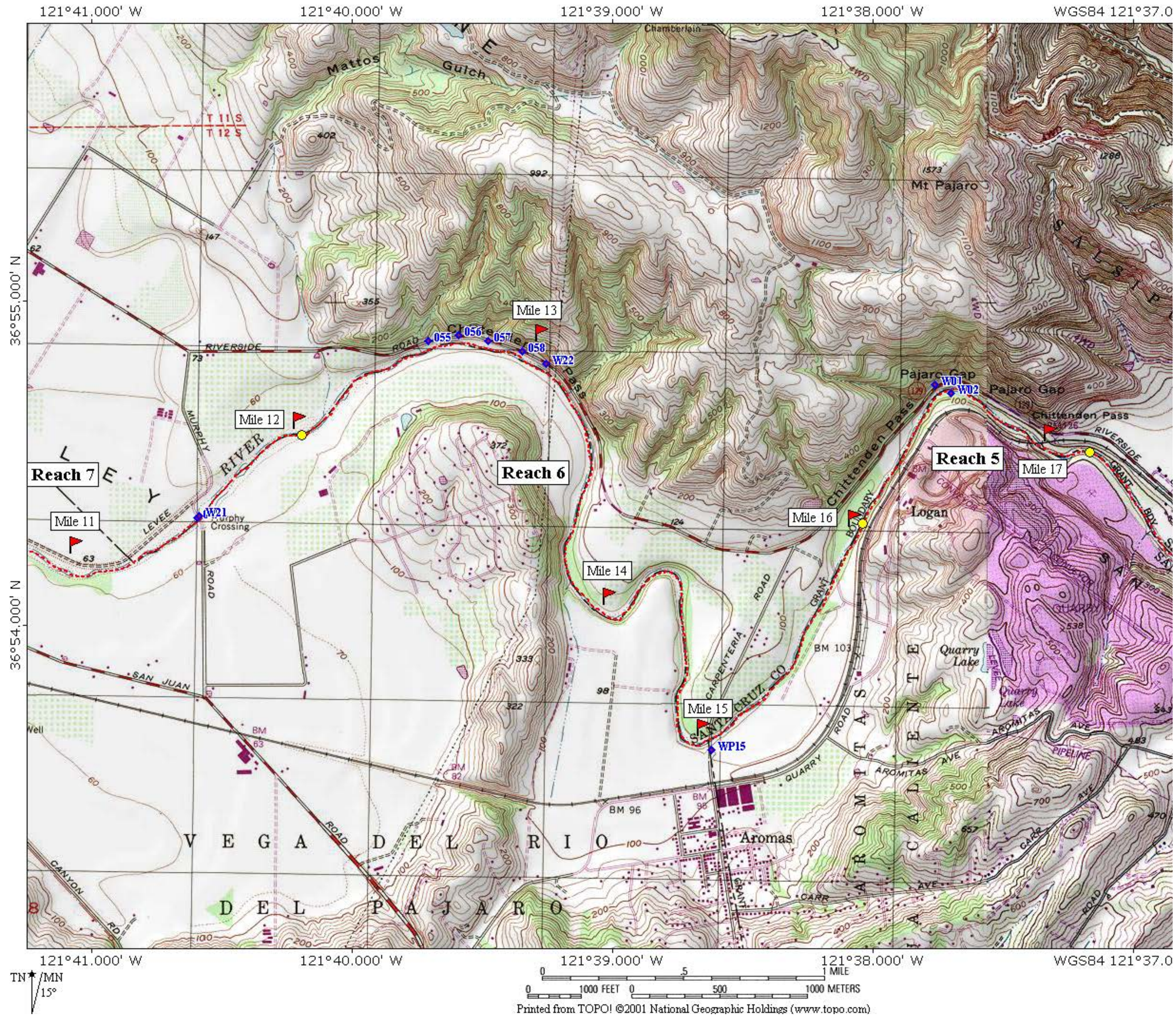

Figure 8c. Pajaro River Mile 10.5 to Mile 17.5.

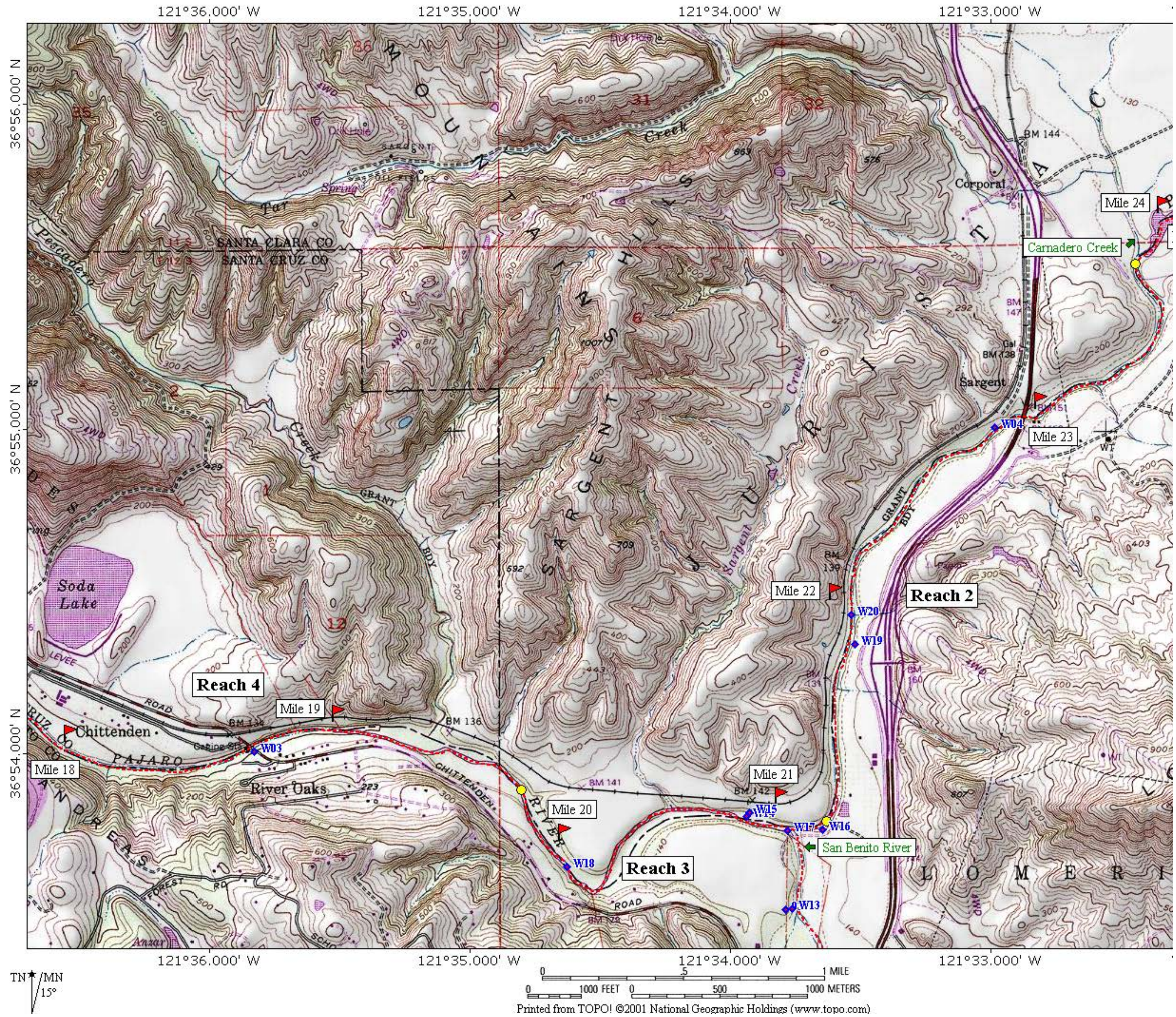

Figure 8d. Pajaro River Mile 17.5 to Mile 24.5.

Historical Changes to Planform Features, Cross Sectional Features and Profile Patterns

CH2MHill and NHC developed a topographic map of the lower Pajaro River from USGS maps and historical data sources. The map includes channel alignments from 1858, 1912, 1931, and 1995 shown in Appendix C (CH2M HILL 1996). Between miles 9 and 11 a major change in planform occurred between the 1858 and 1912 channel records. The sinuosity decreased from 1.9 in 1858 to 1.3 in 1912. The meander belt width between mile 7.5 and 8 increased by approximately 900 ft between 1858 and 1912, but decreased between 1912 and 1995 by approximately 300 ft. The sinuosity increased from 1.2 in 1858 to 1.3 in 1912. Also over the years, the confluence of the Salsipuedes Creek and Pajaro River apparently shifted further downstream on the Pajaro River, by approximately 600 feet. The river changed alignment in the Watsonville area between 1858 and 1912.

When levees were constructed in 1948-49, the Pajaro River channel was straightened upstream of the present Highway 1 location (mile 4 to 5), increasing the gradient of the river in this area. The sinuosity was decreased from 1.4 to 1.0 in this reach by the levee construction. The meander cutoff is visible today, as seen in Figure 9.

Figure 9. 4.3mi from bay—meander bend cutoff caused by levee construction (WP1: 8/2001).

Bankfull width, in its truest sense, is defined as the width of the water surface in the river channel when flow just fills the active portion of the channel. Bankfull width is determined by investigating cross sectional surveys and field conditions. PWA compared cross section and bankfull widths in 1945 and 1995 and found that the bankfull channel has been narrowing since 1945 (PWA 1997).

The Pajaro River profile is shown on Figure 10. Included are partial and complete profiles of the river from various sources. The FEMA survey that was executed in the 1970’s is judged to possibly reflect the low water surface profile instead of a thalweg profile. The general trend of the graph shows degradation of the river, particularly in the Pajaro valley reaches where the river is constricted by levees.

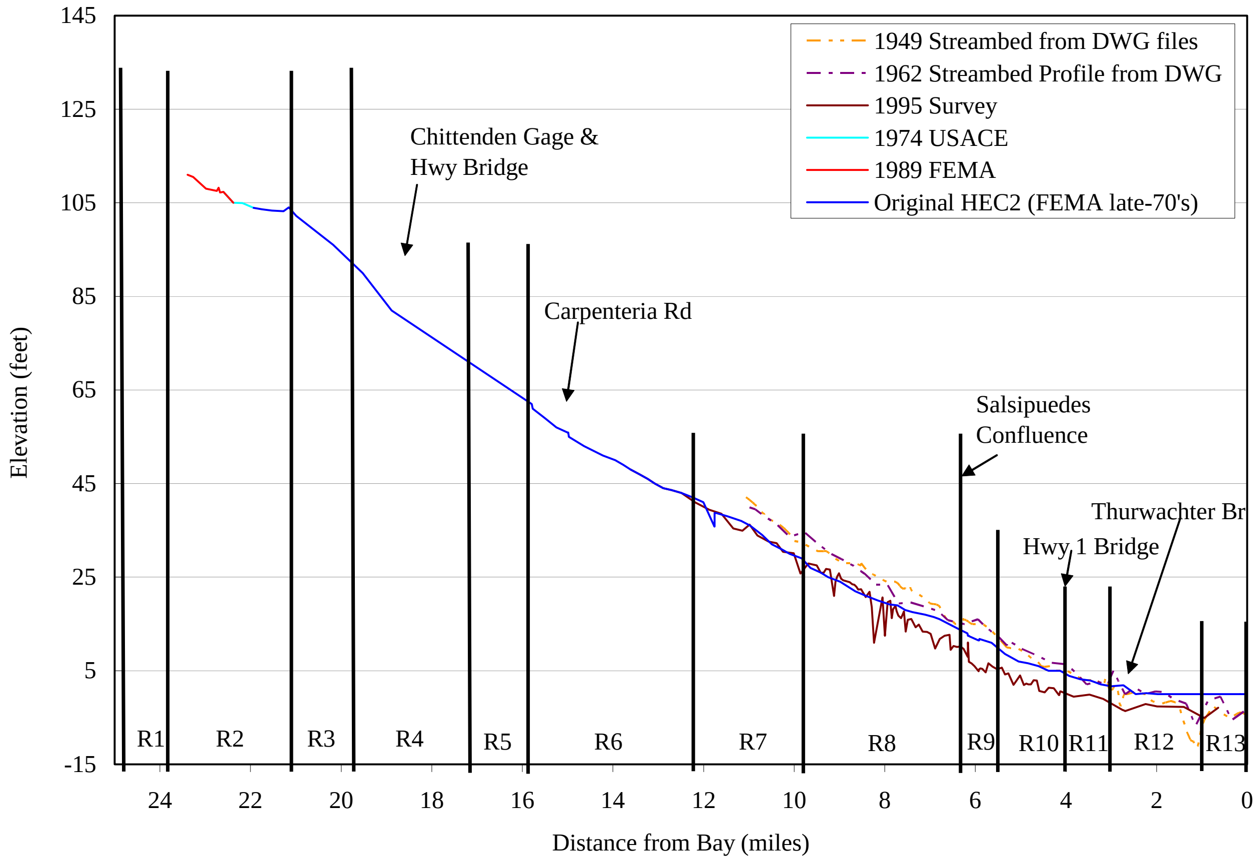

Figure 10. Existing and historic profiles of Pajaro River.

Existing Pajaro River Reach Conditions

Field study, aerial photography, and available surveys were combined to generate an analysis of 13 Pajaro River reaches, with Reach 1 being the upstream end of the study area to Reach 13 located at the downstream end of the river. Reaches are designated on Figures 1 and 8a – 8d. Stream reconnaissance record sheets from site visits are included in Appendix D.

Pajaro River Reach 1 is in the Soap Lake area. Soap Lake consists of an upper and lower lake formed by low-lying areas in the Santa Clara Valley. The Santa Clara Valley is agricultural with grazing and row crops. During high flow events, the upper and lower Soap Lakes flow together in the valley. This reach is characterized by lake deposits and large mature densely vegetated islands. Dense stands of mature trees and willows grow on the banks of the lake. Velocity in this reach is very low, at times almost stagnant, as shown on Figure 11.

Figure 11. Between Upper and Lower Soap Lakes.

The reach downstream of Soap Lake to just upstream of the San Benito River confluence is identified as Reach 2. This reach contains pool & riffle sequences in upper portions as seen on Figure 12, with deep tranquil flow at the lower end of the reach. The left floodplain has a densely vegetated riparian zone and cultivated floodplains in some areas. The more narrow right floodplain is constricted by the mountains. Erosion and geotechnical bank failures were visible at 22.9 miles from the bay.

Figure 12. 22.9mi from bay looking upstream at a pool from a riffle (W04-11/2001).

Reach 3 extends from just upstream of the San Benito River confluence to the point where Chittenden Pass narrows. The Pajaro River meanders between the bluffs in this reach. Large sand bars are present at the San Benito River confluence as seen on Figures 13 and 14.

There are many mid-channel bars in this reach and the river has a very mild slope as seen on Figure 15. Dense vegetation grows in the riparian zone, with some leaning and felled trees on the river banks.

Figure 13. 20.1mi from bay—looking downstream on San Benito River to confluence with Pajaro River (W17-11/2001).

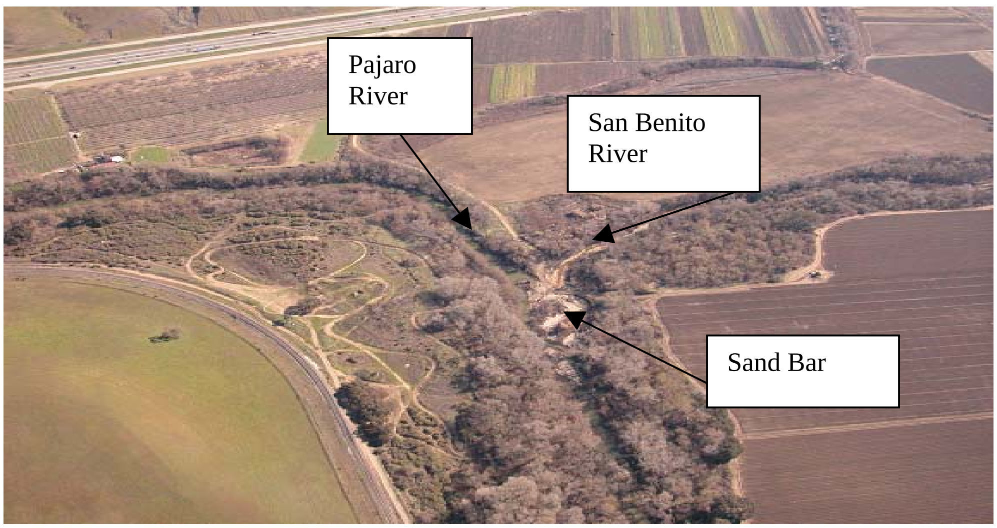

Figure 14. Aerial view of San Benito and Pajaro Rivers Confluence.

Figure 15. 20.9mi from bay downstream of the San Benito Confluence looking upstream.

Reach 4 is shown on Figure 16; the Chittenden area comprises Soda Lake and Chittenden Gage at the Highway 129 Bridge. Steep valley slopes have frequent failures in this area, sometimes forming gullies that flow into the Pajaro River, as seen on Figure 16. Trees lean into the main branch of the river with many felled into the channel and some exposed roots indicating bank instability. Mid-channel vegetated bars are frequent, as seen on Figure 17.

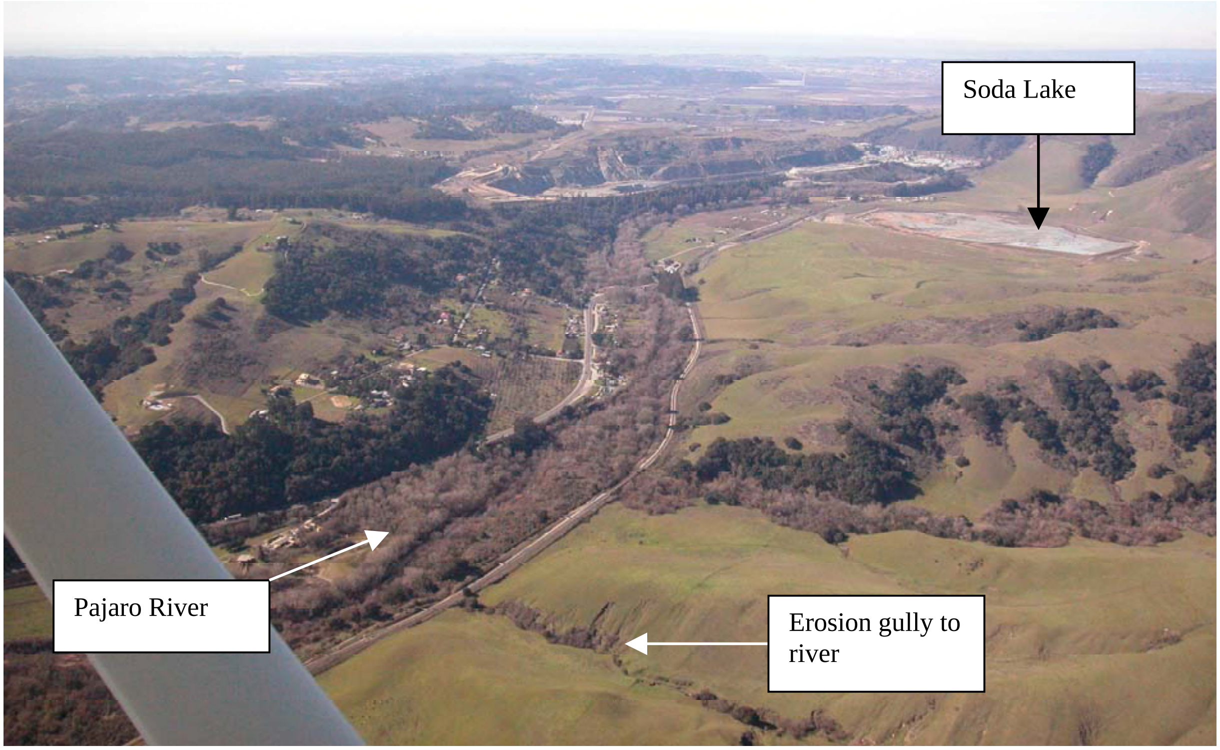

Figure 16. Looking down Pajaro River towards Bay.

Figure 17. 18.7mi from bay looking downstream of bridge (W03-11/2001).

Reach 5 is located in the Pajaro Gap, which also contains a large quarry area on the southern hillside. This is a narrow, geologically controlled reach where the San Andreas Fault crosses the river. Dense vegetation grows on the right side of the channel up to the highway, while on the left side dense vegetation covers the valley up to a quarry area. Some trees lean into the river and there is minor bank erosion on both banks as seen on Figure 18. This reach is characterized by alternate bars. The bed is armored in some reaches.

Figure 18. 16.6mi from bay looking downstream in Pajaro Gap (W02-11/2001).

Figure 19. 16.6mi from bay right bank erosion or geotechnical failure with exposed roots (W02-11/2001).

The reach between Muphy's Crossing to just downstream of the Pajaro Gap is known as the Carpenteria Road (Rogge Lake) area, designated as Reach 6. In the upstream end the river meanders through bluffs where row crop is grown. Further downstream, the mountains control meander amplitude. Dense riparian vegetation exists with trees leaning into the river indicating localized bank instability. Numerous mid-channel bars were noted. Figure 20 shows a typical cross sectional view of the river in this reach.

Figure 20. 13.0mi from bay looking downstream (W22-11/2001).

Reach 7 commences 9.8 miles from the bay and ends just upstream of Murphy's Crossing. It is confined by levees from the downstream end to Murphy's crossing and is characterized by a two-phase system of braiding at low flows and meandering at higher flow. Massive point bars have formed at meander bends. Dense riparian vegetation covers mid-channel bars. Vegetation clearing is conducted on benches in this reach to increase channel capacity. Figure 21 shows a typical view of this reach.

Figure 21. 11.6mi from bay looking DS of Murphy's Crossing Bridge (W21-8/2001).

Reach 8 commences at the Salsipuedes Creek confluence with Pajaro and ends 9.8 miles from the bay. The reach is braided with frequent smaller bars than in Reach 7 at low flow. At higher flow the river follows more of a meandering pattern dictated by the levees. Some areas have little to no flow in the summer with massive vegetated and unvegetated sandbars as seen in Figure 22. Santa Cruz and Monterey Counties clear vegetation on benches up to Murphy's Crossing. Riprap protection was noted on the left bank at 6.5 miles, 6.9 miles, 8.4 miles from the bay. An example of toe erosion is shown on Figure 23. Lateral erosion sites that are now riprapped were noted at 7.1 miles and 7.5miles from the bay. Downstream of the Coward Creek confluence around mile 8.6, left bank erosion and resulting sandbar formation is caused by impinging flow. Vegetation clearing is conducted on benches in this reach.

Figure 22. Looking downstream along Pajaro River in Reach 8. Notice the prevalence of bars.

Figure 23. 8.4mi from bay (W24) concave left bank with 2-3' high erosion caused by impinging flow (11/2001).

Reach 9 is located adjacent to the town of Watsonville. The river is very narrow, entrenched and sinuous, with numerous alternate bars, as shown on Figure 24. The vegetation on the benches have been cleared.

Figure 24. Looking downstream along Pajaro River at Watsonville.

Reach 10 is from Highway1 Bridge to downstream of the railroad bridge. On the end the river is narrow, sinuous and entrenched. Numerous alternate bars were observed. Previous levee failures have occurred during floods due to impinging flow. Figure 25 shows a typical section of the reach, with riprap protection at a previous levee scour location. Vegetation clearing is conducted on benches between the levees.

Figure 25. 4.5mi from bay looking upstream at river and riprap protection on left levee (2R3-8/2001).

Reach 11 is located between Mile 3 upstream of Thurwachter Bridge and the Highway 1 Bridge. The river in this reach narrows and becomes more sinuous as it moves upstream. Numerous points of lateral erosion were noted, such as the 50-ft lateral erosion scar on the right bank that was formed during a flood at mile 4.6 over a longitudinal distance of 600-ft. The floodplain is confined by levees. No vegetation clearing occurs in this reach. Figure 26 shows the shape of the river in this reach.

Figure 26. Looking upstream toward Highway 1 Bridge.

Reach 12 commences at mile 1 (near the downstream end of the left levee) up to mile 3 on the upstream side of Thurwachter Bridge. The reach is similar to the reach downstream of it, but narrows slightly in the upstream direction. It is judged that this section is not as impacted by changes in tidal elevation as the downstream reach. No vegetation clearing occurs in this reach; thus, riparian vegetation is dense, even though the corridor is relatively narrow compared to upstream and downstream reaches (less than five river widths). Flooding is not reported to be a problem. The USGS observed flood events in the Pajaro River at Thurwachter Bridge and notes that discharges of varying magnitude do not result in significant changes in the water surface elevation at this location (personal communication, Peter Blodgett, NHC). This is most probably due to riverbed material mobilization in this reach that creates a larger flow area within the channel. A typical view of the river in this reach is shown on Figure 27.

Figure 27. 2.6mi from Bay looking downstream of Thurwachter Bridge (11/2001).

Reach 13 extents from the bay to mile 1. Levees begin on the right bank at the Watsonville Slough and Pajaro confluence and on the left at around mile 1. Downstream of the levees, a 25-ft high bluff exists on the left bank. The river is wide with tranquil, tide-controlled flow. Flooding is not reported to be a problem in this reach. To accommodate higher flows, the riverbed is believed to mobilize to create more flow area within the channel. No vegetation clearing occurs in this reach; but very little bank vegetation has been observed here. Figure 28 shows the mouth of the river where sandbars form during lower flows.

Figure 28. Looking up mouth of Pajaro River.

Summary of Scour Locations

E&H noted sites of previous and continuing scour during field reconnaissance trips. While some locations of scour may not have been noted, the ones documented are in Table 1.

Table 1. Scour Locations Noted by E&H During Field Reconnaissance.

River Mile	E&H Location Name	Description
0 - 1	0R1-1R1	Frequent past bank failures
~3.8	downstream of HY1	Levee erosion and break
4	HY1 Bridge SC side	Isolated scour areas
4.25	1R3	Failure
4.6 - 4.7	WP2 - WP3	50-foot floodplain recession on Santa Cruz County side
4.9	3R3	Previous levee break during flood
5.6	4R3	Downstream of railroad bridge levee failure
6.1	5R3	Monterey County side levee breakout at no floodplain point
6.35	6R3	Monterey County side major erosion
6.4	WP4	Salsipuedes River rotational failure upstream of confluence with Pajaro
6.4	WP5	Localized erosion with 20 feet of bank loss
6.5	close to 7R3	Erosion in channel; banks stable
6.9	110	Riprap protection of levee (previous scour point)
7.1	WP6	15-foot floodplain erosion for 460 yards
7.5	WP7	15-foot wide 170-yard reach floodplain erosion
8.4	8R3, W24	Previous and continuing erosion on bank
8.6	WP9	Erosion of floodplain on Coward Creek to downstream
11.6	W21	Upper bank erosion at Murphy's Crossing
16.6	W02	Erosion on lower banks, lower valley side geotechncial failures
22.9	W04	Left bank toe erosion and upper bank geotechnical failures

Geomorphic Parameters and Hydraulic Geometry for Pajaro River Reaches

Qualitative, geomorphic analysis of rivers is based on the theory that rivers try to achieve equilibrium. Generally speaking, a river tries to reach equilibrium while responding to controlling variables. These controlling variables are defined by changes in sediment and/or hydrology. The river reacts to a change in the controlling variable by aggrading or degrading until a "balance" is obtained between the controlling variables. These changes may be naturally-occurring processes such as landslides or droughts, or may be induced by human activity, such as mining or urbanization (Golder 1997).

Stable conditions (no net aggradation or degradation) can occur when the amount of sediment entering a system is equal to the amount of sediment exiting a system. When there is a decrease in the amount of sediment entering a system, the river is capable of carrying larger sediment loads so it obtains the extra sediment by eroding the bed and banks. Similar conditions can occur when gravel mining removes the sediment after it enters a system; in an effort to maintain the same amount of sediment exiting the system, a river will degrade by eroding its bed and banks. A base level is a theoretical plane denoting an elevation below which a river will not erode and the depth to which a river will grade. Lowering a base level increases the slope in a system which thereby increases sediment erosion rates; conversely, increasing the elevation of a baselevel decreases erosion rate (Golder 1997). Geology can control river slope and capacity, thus affecting sediment transport in a river system, but geology is active, even if only changing on a geologic time scale. Slope is a controlling factor by of a river's energy to move sediment downstream.

The qualitative geomorphic analysis concentrates on: 1) identifying controlling variables acting upon the river; 2) studying the river morphometry; i.e., channel pattern, slope, and cross section geometry; and 3) relating which controlling variables are affecting the river's effort to reach an equilibrium (Golder 1997).

Streams have various patterns in planimetric view which are described as straight, meandering, or braided forms, which exhibit specific geometric relationships that are quantified by measurements of sinuosity, meander wavelength, and meander belt width. Sinuosity is a measure of the channel length divided by the valley length of the river. Meander wavelength is the distance from trough to trough measured along the river valley. Meander belt width is the distance from trough to peak measured across the river.

Using USGS quadrangle maps, average reach sinuosity, wavelength and meander width for the Pajaro River were estimated. Average reach slope was estimated from profiles (Schaaf & Wheeler 2001). Table 2 summarized geomorphic parameters for each reach.

Cross sections provided in Schaaf & Wheeler's HEC-RAS model (2002) were used to determine the hydraulic geometry of the primary channel. Width/Depth ratio is the channel top width divided by the maximum flow depth at bankfull flow. The average width/depth ratio and cross sectional area for each reach is shown in Table 2. Width-depth ratios and cross sectional areas for bankfull flow at each HEC-RAS section are shown on Figures 29 and 30, respectively.

The purpose of E&H's geomorphic parameter calculations is to aid in determining whether degradation or aggradation has occurred in the Pajaro River. Prior to levee construction, the floodplains outside of the existing levees were connected to the Lower Pajaro River and the river frequently overflowed its channel onto the plains (COE 1997). For this reason, E&H defined the original active channel of the river at the elevation of the original floodplains, which is often significantly higher than the current low flow channel banks.

Table 2. Geomorphic and Hydraulic Parameters for Pajaro River Reaches.

Reach #	River Mile		Sinuosity	Average Meander Wavelength (ft)	Average Meander Width (ft)	Average Reach Slope (%)	Average Flow Area	Average Width/Depth
	US end	DS end						
13	0	1	1.2	6600	1800	-0.13	2700	54
12	1	3	1.2			-0.01	1900	23
11	3	4	1.2	6800	1400	0.04	2000	14
10	4	5.5	1.0	6800	1400	0.09	2400	15
9	5.5	6.4	1.0	5600	1200	0.10	2300	17
8	6.4	9.8	1.3	5500	1825	0.10	2000	18
7	9.8	12.3	1.3	8200	2300	0.12	2100	15
6	12.3	15.9	1.5	4800	1950	0.11	2500	12
5	15.9	17.2	1.0	4900	1150	0.19	1400	9
4	17.2	19.7	1.0	7200	1700	0.24	1400	15
3	19.7	21.1	1.2	6000	2050	0.16	1000	11
2	21.1	23.8	1.1	3800	1700	0.06	1300	13
1	23.8	24.8	N/A	N/A	N/A	-0.11	N/A	N/A

The river is highly to moderately sinuous and has high meander widths in the reaches from Carpenteria Road to Salsipuedes Confluence with the Pajaro (reaches 6, 7, and 8). The reaches upstream of the San Benito confluence with the Pajaro (Reaches 11, 12, and 13) are moderately sinuous.

The slope of Reaches 12 and 13 is negative according to Table 2; this is caused by the presence of a baseline control at the ocean and bed scour upstream of that. The slope in Reach 1, Lower Soap Lake, is also negative which may be an artifact of survey points, but nevertheless, the area is very flat with negligible flow velocity. The steepest portions of the river are in the Chittenden Pass (Reaches 3 through 5), with the Pajaro Gap (Reach 4) being the steepest of all. In terms of flooding, the slopes predict that reaches in Chittenden Pass would not have problems with flooding, whereas the gentle slopes in Reaches 7 through 11 would indicate a chance of flooding based on other parameters. Note that locations of high sinuosity and meander width occur in milder sloped areas. Sinuosity and meander width are based on the balance between sediment load and sediment size versus stream slope and discharge. Thus, the river is trying to dissipate any excess energy in these milder sloped areas.

In Table 2 (Figure 30), main channel cross sectional flow area generally increases moving downstream. Figure 31 and Table 2 demonstrate that width-depth ratio is generally increasing from upstream to downstream in the river. This trend is expected for a river coming out of mountains passes and opening to the ocean. As width/depth ratios increase in the lower Pajaro River, it potentially points to increased stability in the downstream direction.

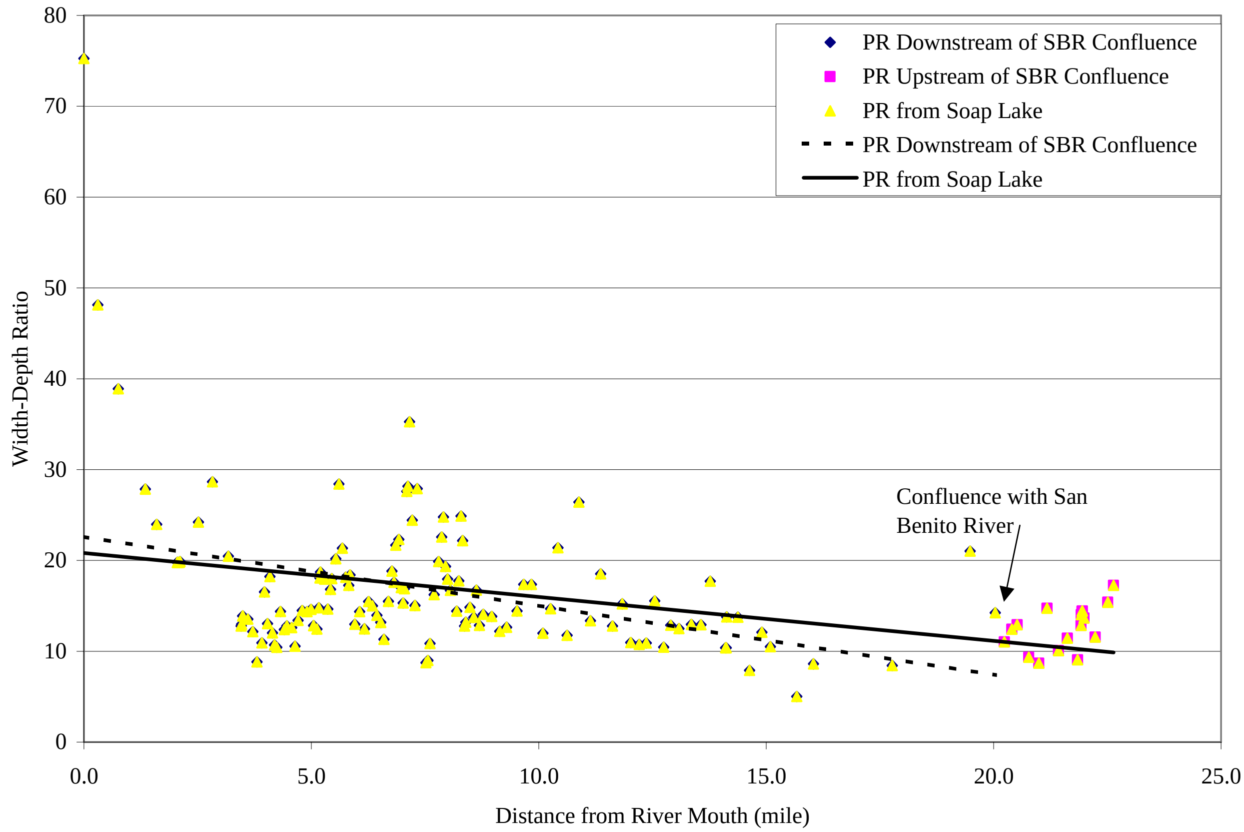

Figure 29. Width/Depth Ratio for Pajaro River from Downstream of Soap Lake to Outlet.

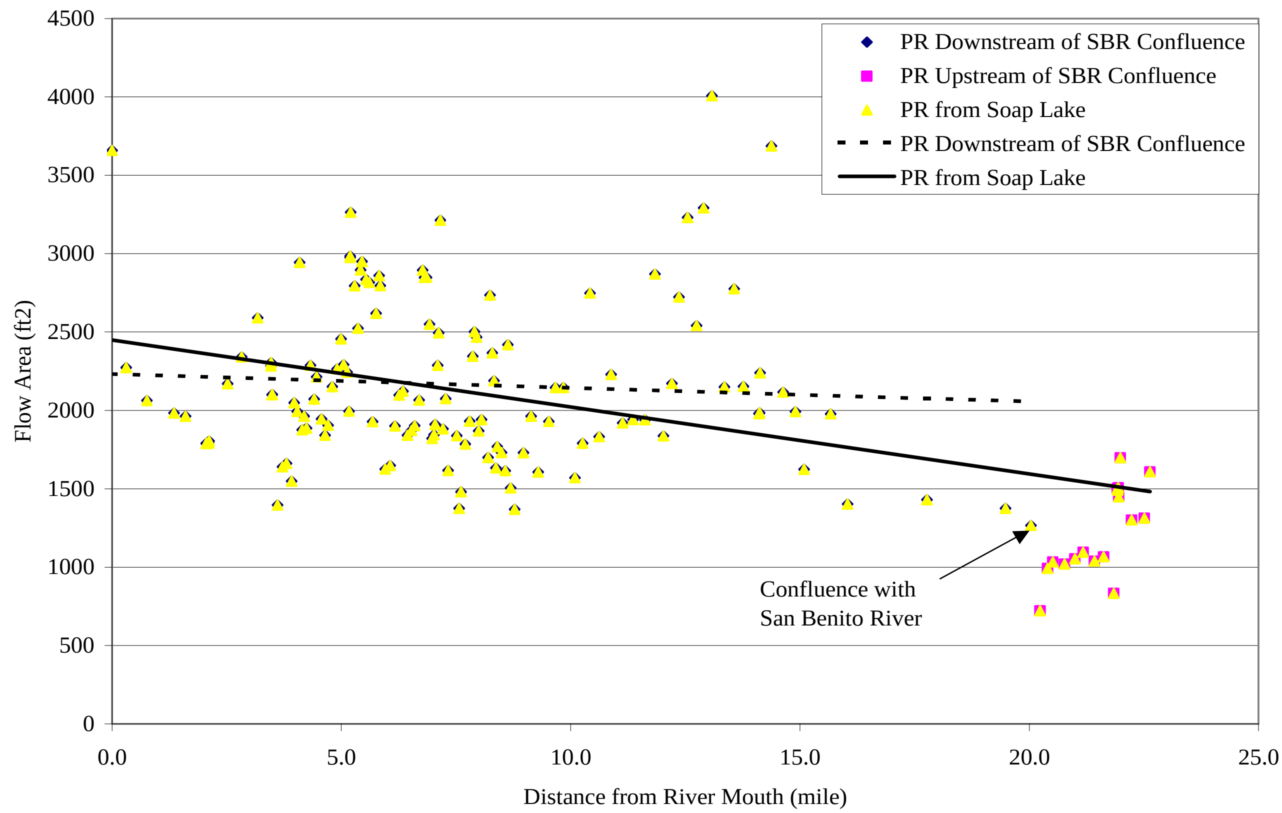

Figure 30. Bankfull Flow Area for Pajaro River Cross Sections.

Riverbed and Bank Material Properties

CH2MHill and NHC sampled and analyzed riverbed and bar sediment samples from Chittenden Gage to the Highway 1 crossing area of the Pajaro River and reported median grain sizes in (CH2M HILL 1997).

E&H sampled bed and bank materials on the Pajaro River from upstream of Soap Lake to the downstream reaches of the Lower Pajaro River. Grain size analyses are included in Appendix E. Figure 31 shows median particle sizes for the Pajaro River from Soap Lake to the bay, while Figure 32 shows E&H median sizes compared to CH2MHill samples (CH2M HILL 1997) for the lower Pajaro River .

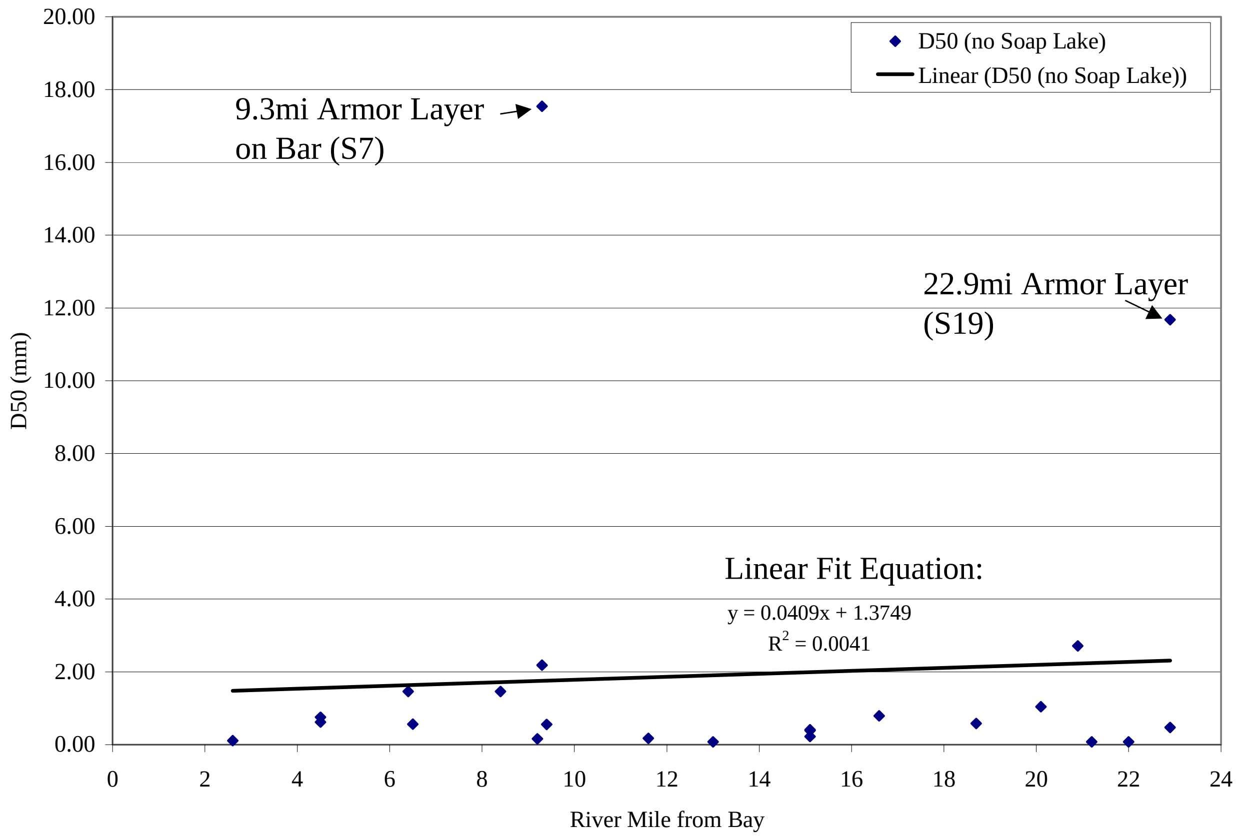

Figure 31. Pajaro River median grain sizes from downstream of Soap Lake to the bay.

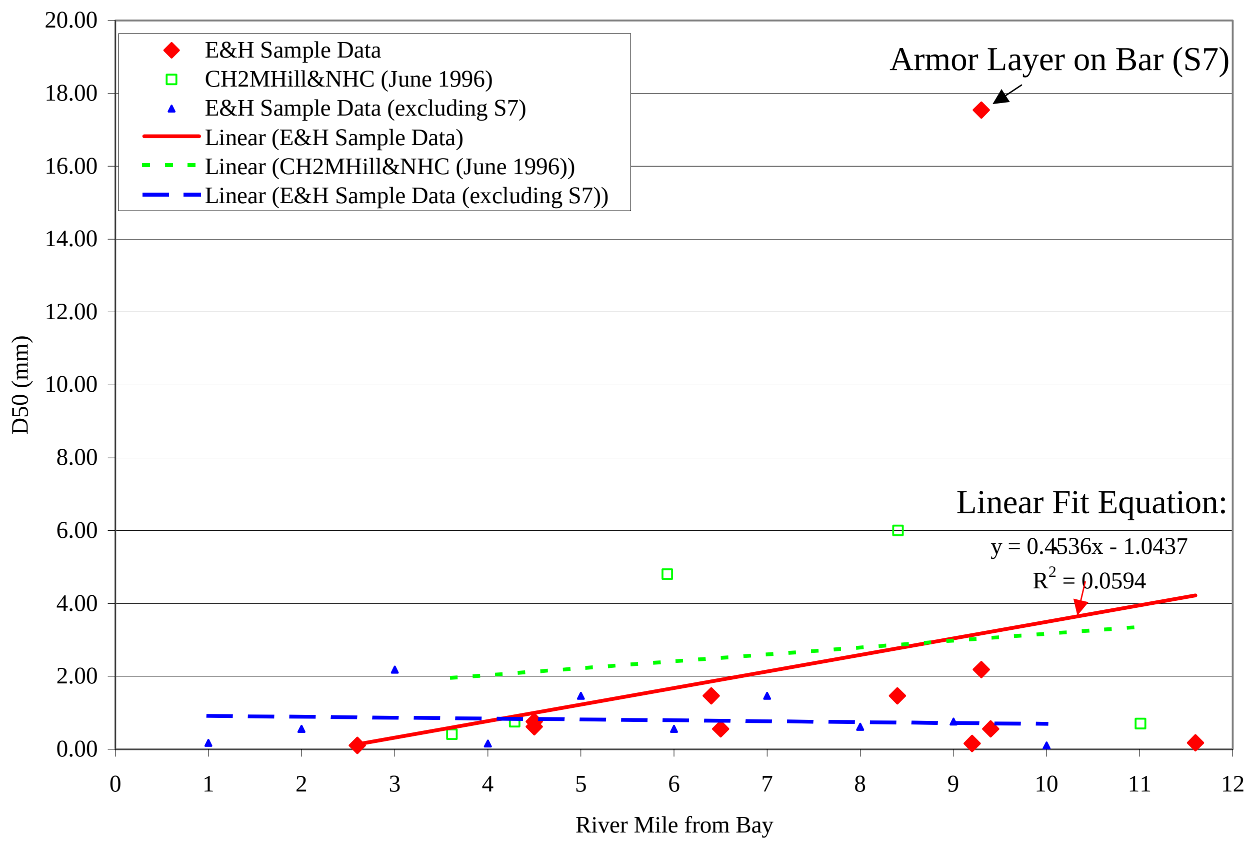

Figure 32. Comparison of E&H and CH2MHill (CH2M HILL 1997) median grain sizes for the lower Pajaro River.

The median grain size figures show significant scatter among data points which is understandable considering that bed, bank, and bar samples are all included in the figures, as well as substrate and armor layers. The general trend of decreasing median grain size moving downstream is expected. In general, bank material is silt to sandy silt, while bed material is poorly graded sand.

Dominant Discharge and Range of Effective Flows

The dominant discharge or channel forming flow is theorized to be approximately the 2-year flow in most rivers (Leopold et al. 1995) and typically ranges from about the 1.3- to the 2.5-year event (Rosgen 1996). The 2-year flow for the Pajaro River just downstream of Soap Lake is approximately 2,450 cfs and is 3,200 cfs downstream of the USGS gage at Chittenden, and 3,500 cfs downstream of Salsipuedes (Schaaf 2002).

As discussed in the geomorphic parameters section, the purpose of E&H's calculations is to quantify whether degradation or aggradation has occurred in the Pajaro River. When the actual discharge necessary to fill the active channel of a river is significantly greater than the 2-year flow, it is an indication that the river is potentially degrading (Leopold et al. 1995). Because the floodplains outside of the existing levees of the Lower Pajaro were previously connected to the river's existing floodplains and the river frequently flowed onto these floodplains prior to levee construction, E&H defined the original upper bank limit of the active channel of the river at the elevation of the original floodplains, which is often significantly higher than the current low flow channel.

The flows required to fill the Pajaro River active flow channel as defined by E&H are significantly larger than the 2-year discharge downstream of river mile 15.7. Channel forming discharge increases in the downstream direction to attain its highest value in the Watsonville Reach 9 (approximately 12,000cfs) according to rough hydraulic model estimates conducted by E&H. Analysis of aerial photography from 1995 confirmed a narrow incised channel in this reach. From Watsonville, degradation decreases towards the ocean, yielding to the influence of the base level provided by the ocean. Comparison between the estimated 2-year discharge and the bankfull discharge as defined herein by E&H for the Pajaro River confirms that the river is degrading.

As a note of clarification, PWA calculated geomorphic parameters by defining the active channel as the low flow channel in 1997 (the choice typically used by geomorphologists). PWA's results differ from those calculated by E&H herein because of E&H's choice of active channel elevation at the original flood plain elevation. E& H used the original flood plain elevation to assess whether degradation has occurred since construction of the levees.

Conclusions

The investigation indicates that the Pajaro River watershed can be divided into three principal elements, viz. the Pajaro and San Benito Rivers upstream of Chittenden Pass, and the Pajaro River downstream of the pass. The fluvial geomorphology of the river reaches upstream of the pass are determined by the geologic control at Chittenden Pass, as is sediment discharge.

Overall Fluvial Geomorphology

The overall fluvial geomorphology of the Pajaro River and its tributaries is determined by the geologic control at Chittenden Pass and the base level control at the Monterey Bay. A base level is a feature that defines the depth below which erosion would be unable to occur in river system. For example, a water body such as the ocean at the mouth of a river acts as a base level for the river. A geologic control can control a river's slope and constrict flow, but it is considered "active" in terms of erosion over geologic time. An example of a geologic control is a narrow rock valley.

The geologic control of the Pajaro River at Chittenden Pass is formed by the rock below the mobile bed that is present in the river as it flows through the pass. The geologic control of Chittenden Pass affects flows from the Upper Pajaro River. The Soap Lake area upstream of Chittenden Pass has likely formed over millennia as the upper watershed eroded and deposited sediment upstream of the geologic control. With most of the sediment from the Upper Pajaro River depositing in the Soap Lake area, the geologic control at the Pass plays an important role in maintaining the outlet elevation of Soap Lake, and thus controlling sediment discharge to the Lower Pajaro River. The hydrologic and hydraulic studies performed for this project by Schaaf & Wheeler indicate that Chittenden Pass constricts flow during extreme flow events, thus increasing the sediment trap efficiency of Soap Lake.

An earlier study on the San Benito River (Golder 1997) showed that the degradation that is taking place in the San Benito River pivots around the same geologic control of the Pajaro River at Chittenden Pass. The pass forms a local base level water surface for the San Benito River mouth. The elevation of the riverbed of the San Benito River at the confluence with the Pajaro River, at the upstream end of Chittenden Pass, remains in the same location, while the upstream reaches of the San Benito River are degrading.

The geologic control at Chittenden Pass therefore plays an important role in shaping the fluvial goemorphology of the rivers upstream of it, and in determining the *magnitude of sediment loads* that pass through to the Lower Pajaro River.

The base level at the mouth of the Pajaro River, the Monterey Bay, determines the lowest elevation to which the Pajaro River may degrade. It has been observed that the degradation at the lower end of the Pajaro River is not as pronounced, almost absent in the lower reaches of the Lower Pajaro River close to the ocean. The river adjusts at the downstream end for the impact of this base level by widening of the channel (Figures 29 and 30). Widening of the channel allows more water to flow through to the ocean without causing significant flooding in these lower reaches. The channel widening is also influenced by backwater from the ocean.

The base level provided by the Monterey Bay and the geologic control at Chittenden Pass play important roles in defining the behavior of the Pajaro River watershed, as does the presence of the levees in the downstream reach of the Lower Pajaro River. The geologic control at Chittenden Pass forces most of the sediment from the Upper Pajaro Catchment to deposit in the Soap Lake area. This implies that the sediment load measured at Chittenden Pass is mostly representative of loads discharging from the San Benito River. The total amount of water flowing past Chittenden Pass can therefore carry more sediment than what is available from the San Benito River only. The deposition of large volumes of sediment in the Soap Lake area leads to "sediment hungry" water discharging through Chittenden Pass into the lower reaches of the Pajaro River, downstream of the pass.

Stream Degradation

One of the most important conclusions of the qualitative fluvial geomorphologic assessment is that the lower portion of the Pajaro River is degrading and not aggrading. This means that the riverbed of the Lower Pajaro River is not experiencing sedimentation, but scour. Stream degradation in the lower portion of the Pajaro River results from narrowing of the river channel and floodplain resulting from the construction of levees, excess sediment carrying capacity of water flowing in the river, and historical straightening of the river (both natural and manmade) by elimination of some meander bends.

The combined sediment load that is discharged through Chittenden Pass from the Upper Pajaro and San Benito Rivers is judged to be much lower than the sediment transport carrying capacity of the Lower Pajaro River (a phenomenon that is sometimes known as "sediment hungry" water). This means that the Lower Pajaro River can carry more sediment than what is supplied from upstream through Chittenden Pass. The additional sediment carrying capacity of the Lower Pajaro River results in it eroding sediment from its river bed and carrying it downstream towards the ocean.

The presence of the levees in the Lower Pajaro River further exacerbates the degradation that is expected to occur from the excess sediment carrying capacity in the river, as explained above. The levees narrow the river down by forcing the floodwaters that would have been located on the floodplain during high flow conditions to flow between the levees and in the river channel. This leads to increased flow velocities and increased flow depths during flood conditions. Such increases result in increased erosive power of the water at the bed of the river, causing it to scour even more. As sediment is removed from the riverbed and transported downstream, it continues to degrade.

In addition, it was found that the meander pattern of the Lower Pajaro River, immediately downstream of Chittenden Pass changed quite substantially since 1858. It resulted in a shortening of the river path, which increases local slopes and the erosive power of water in the river. The increased erosive power that resulted from this shortening of the river path is maintained and exacerbated by the construction of levees that were subsequently built in 1949.

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Appendices

Appendix A: Data Resources

Appendix B: Army Corps of Engineers Hydrology Figures

Appendix C: Historical Planform Changes

Appendix D: Field Record Sheets

Appendix E: Grain Size Analysis

Data Resources

Geometry

1. Cross-sectional changes to build levees (mat'l removed from section to build levees) (1)
2. Pajaro River historical flood plain delineation (1), (5 in color)
3. Channel divided into flow channel, main channel, and overbank benches. Benches are strips of original flood plain w/in levee confines; width varies 0-100' and is generally wider on Santa Cruz side than Monterrey side (3).
4. Cross section schematic interpretation of channel changes over time (5).
5. Can relate plan changes to river to failures of levees.
6. Get historic topographic maps from USGS Microfiche in Lakewood.
7. Bank profile sketches from site visit.
8. HEC-RAS model by Schaaf & Wheeler (2002).

Drainage/Land Use/Geography

1. Historical description of local drainage—delineation of watershed and description of land use (1)
2. Historical perspective (5)
3. Some aerial photography of San Benito, Uvas and Chesbro Reservoirs, Pajaro R assumed ~1996 (5)
4. 1931 Aerial photo of Pajaro R near Murphy's Crossing (5)
5. June 2000 Aerial photo of Pajaro R from Bay to past Murphy's Crossing, showing much of watershed for this reach (13)
6. Basin location and geography description (7).
7. Reservoir capacity studies (7).
8. Flood hydrographs and determination of peak flow for basin, including hydraulic characteristics (such as routing parameters) (7).
9. Locations and drainage area, topography and cover (16).
10. Geology, etc., land use, DWR 1989 Land Use Survey (10).
11. Land use and historical changes.

Hydrology/Hydraulics

1. Peak flow for Pajaro River at the Chittenden gage is 28,250 cfs on Feb. 3, 98 @2pm, which exceeded previous peak of 24,000 cfs in 1956 (2). Includes hydrology and hydraulics discussions.
2. Historical flood hydrographs from gage data and mean daily flow for 10/1/1939 – 9/30/3000 (3&18).
3. Peak discharges for return periods 1.3 yrs – 15 yrs; 50-yr and 100-yr flows assumed = to 15-yr because COE established 15-yr would be contained w/in levee system during the larger floods.
4. Tidal data for Monterey Bay Harbor, NOAA Datum Section. 17 miles southwest of Pajaro River mouth at seaward end of Municipal Wharf Number 2 in Monterey (Longitude 121deg 53.3'W, Latitude 36deg 36.3'N)—on internet; methods of converting to proper location and datum in (12).

5. Pajaro River water surface elevations Feb 5 & 20, 97; profiles for Jan 2&3, 97. Salsipuedes Creek Feb 20, 97 (12).
6. Stage-Discharge graph for Main Street Bridge from 1997 (12).
7. Flood frequency curve for Pajaro R @ Chittenden and Corralitos Cr @ Freedom from COE 1994 (5) .
8. Mean Annual precip isohyets and locations of rain gages in watershed (5)
9. Existing Pajaro R capacity as of August 1997 (6).
10. Temperature, rainfall, stream gage records, flood characteristics (3 distinct parts along river), and floods of record as of 1964 (7).
11. Measured and computed hydraulic properties in 1984, including hydraulic roughness for 1993 storm crest for Pajaro R below Watsonville (11 pages 21, 25).
12. Major tributaries; climate and precipitation (16).
13. Peak discharge versus frequency curves and storm hydrographs for 10, 25, 50, and 100-yr events (16).
14. Discussion of hydraulic roughness (9, pages 5, 6).
15. In-basin reservoir storage (10).
16. Hydrology (8).
17. Flow duration curve—cumulative flow versus time curve, where change in slope indicates change in flow such as drought—create from daily flow data.

Sediment Data

1. Suspended sediment gradation curves for various dates 10/1801978 – 9/8/1992 at Chittenden gage; very sparse data (3).
2. Bed sediment gradations for 11/17/81 – 2/21/90 at Chittenden gage (3).
3. Suspended sediment discharge (tons/day) 2/1/78 – 9/10/90 and suspended sediment concentration (mg/L) 3/23/83 – 9/8/92 (more data points for latter) (3).
4. Mean flow statistics for period of record (3).
5. Sediment Yield Estimates (4).
6. Daily flow and sediment data for Corralitos Creek at Freedom gage 11159200 (18).
7. Suspended sediment rating curves for Pajaro River @ Chittenden and Corralitos Creek at Freedom (4).
8. Bed Material gradations for Pajaro River @ Main St., Salsipuedes Creek @ Riverside Ave., Pajaro River @ Thurwachter Rd. (12)
9. Bedload discharge at Salsipuedes Creek @ Riverside Ave (12).
10. Sediment concentration sampling at Pajaro R @ Main St, Murphy’s Crossing, Thurwachter Bridge, Chittenden; and Salsipuedes Cr @Riverside Ave (12).
11. Pajaro R @Main St, @Murphy’s Crossing, @Chittenden, and @Thurwachter stage data for Feb 19,96 – Jan 3, 97 (12)
12. Geomorphology including bed material samples along Pajaro and Corralitos (D50 reported) (5)

Geology/Geomorphology

1. Erosion sites after February 98 flood in Table C-1 of (2).

2. Summary of field observations after Feb 98 including history of erosion, sedimentation process, possible bed degradation, and affect of recent bank protection measures (2).
3. Geologic setting (5)
4. Geomorphology including basin and study area characteristics (5)
5. Nice graphic representation of sustainable channel design/management (5)
6. Nice figure showing idealized watershed classification of alluvial channel and major physiographic provinces (5)
7. Idealized compound flood control channel for Pajaro as suggested by (5)
8. Erosion noted in 6 SC Co. sites and M Co. 12 sites after flood & veg removal of 95 and heavy rains 97 (5).
9. Channel stability problems and recommendations for improvement (9).
10. Plan sandbar sketches include volume and dimensions of sandbars, profile of river thalweg, location of drainages into river, description of reinforcement and vegetation/management (14).
11. Sketches of areas and volumes of Pajaro R channel sediment that was to be removed ~1994 (14). Note that sketches show “stockpile area” on the river banks within the levees; if this was permanent, could have been reintroduced to channel in floods of 95 and 97.
12. Hydrologic soil groups description and figure for Watsonville Slough System (17).

Miscellaneous

1. List of stakeholders (13).
2. Chronology of past 64 years of Pajaro Flood Control Project (13)
3. Flood control alternatives report by COE, November 2000 (13).

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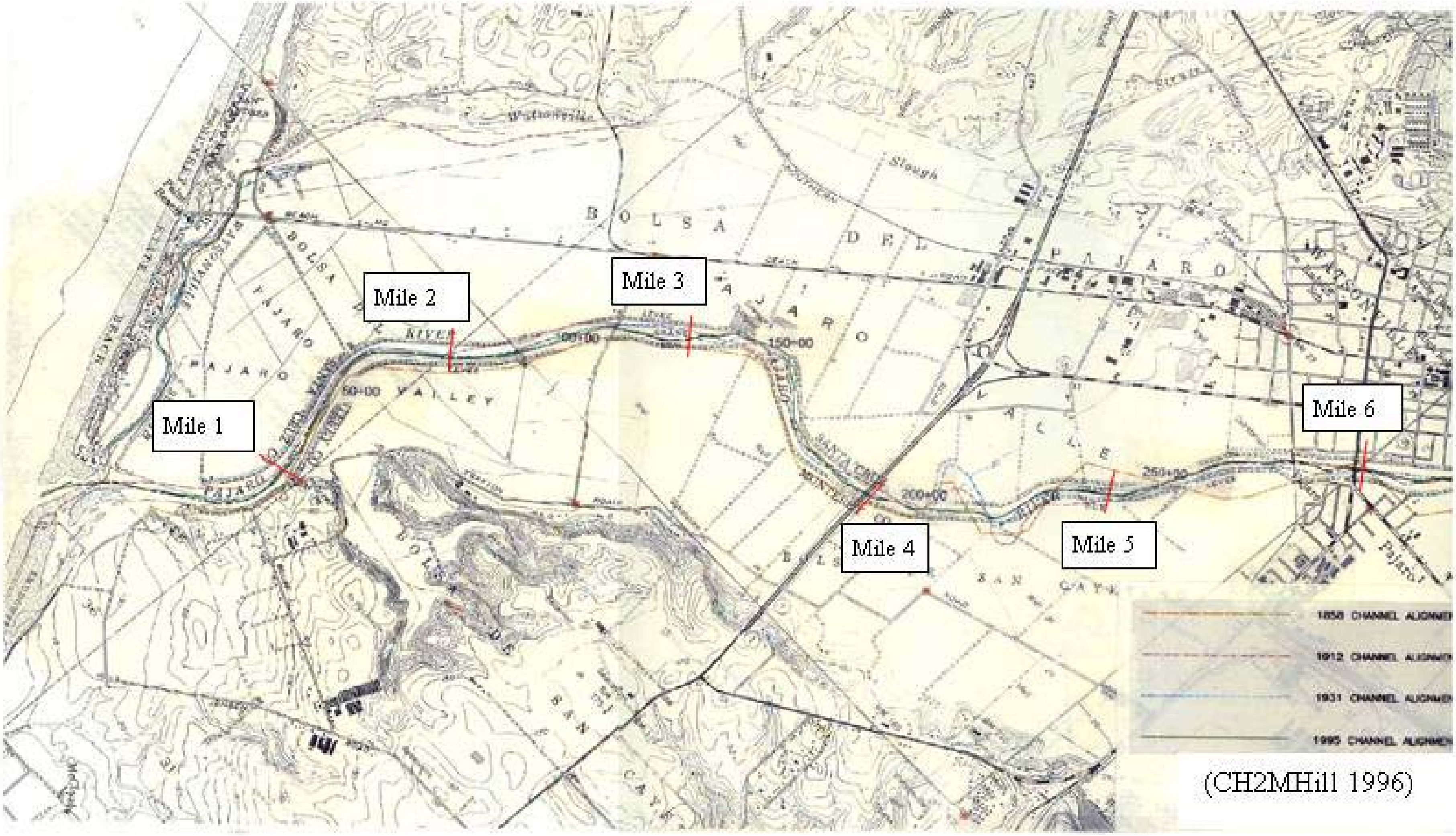
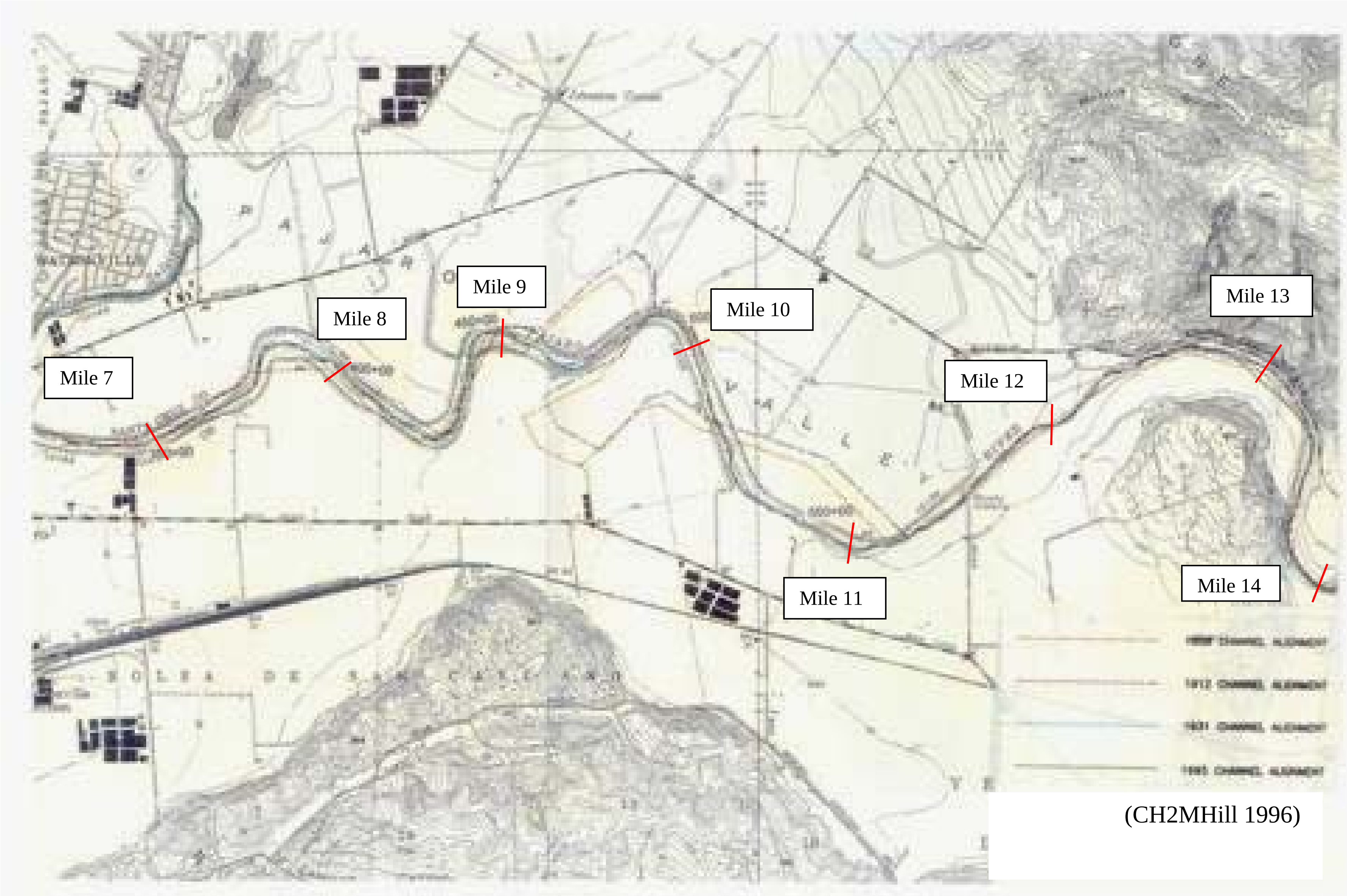
Army Corps of Engineers Hydrology Data Figures

Available in paper copy upon request.

Historical Pajaro Planform Changes





(CH2MHill 1996)

Stream Reconnaissance Record Sheets

Available in paper copy upon request.

Pajaro River

HO-07719-01

December, 2001

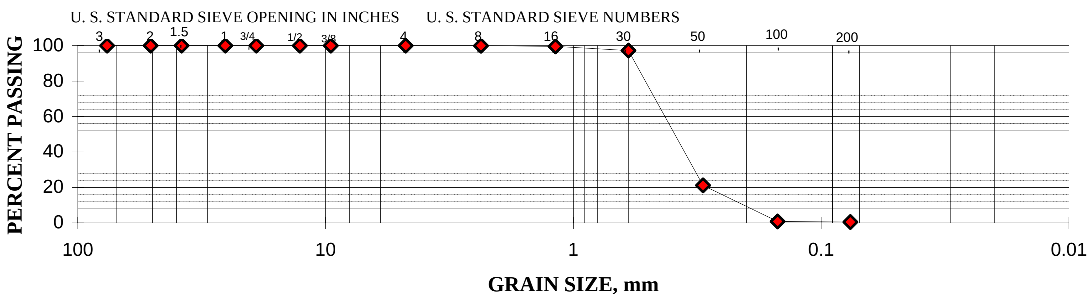
PARTICLE SIZE ANALYSIS

ASTM D 422-90; D 1140-92

S13 @ WP15-U.S. of Bridge Bedrock Sediment

poorly graded SAND (SP)

Sieve size	% Retained	% Passing
3"	0	100
2"	0	100
1.5"	0	100
1"	0	100
3/4"	0	100
1/2"	0	100
3/8"	0	100
#4	0	100
#8	0	100
#16	0	100
#30	3	97
#50	79	21
#100	99	1
#200	99	1



Pajaro River Watershed Study

in association with

Technical Memorandum No. 1.2.9 – Sediment Model

Task: Development of Sediment Model

To: PRWFPA Staff Working Group

Prepared by: Gregory Morris and Elsie Parrilla

Reviewed by: George W. Annandale

Date: Draft Dated March 12, 2002

Study Objectives

The overall project objectives are to address the following issues:

- What are the causes of flooding along the Pajaro River below Chittenden?
- Has stream flow increased downstream with increasing development upstream?
- Has stream channelization and maintenance affected flooding downstream of Chittenden?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?

This Technical Memorandum describes the sediment transport model that will be used to simulate the four watershed conditions that have been formulated by the Staff Working Group for assessment of the performance of the Pajaro River under flood conditions.

Objectives of TM

The objectives of this TM are to:

- Develop a sediment transport model for the analysis of coarse sediment along Pajaro River below Chittenden. The model will simulate transport of coarse sediment only, since this is the size that could be deposited in the channel. Coarse sediment is defined as sand size and larger (>0.062 mm diameter). Fine sediment, smaller than 0.062 mm is likely to be conveyed through to the ocean without significant deposition.
- The sediment transport model should have the ability to simulate both long- and short-term hydrographs.

- Calibrate the model by making use of historical stream flow data and comparing it with the water surface elevations of the HEC-RAS model that was developed in TM 1.2.7.

Field Observations

The modeling team visited the Pajaro River on January 30-31, 2002. The Pajaro River was observed on the ground at several sites from the area of Gilroy to the ocean, and the San Benito was observed in the vicinity of Hollister. This same area was also flown in a small aircraft, including the San Benito upstream to the area of the Pinnacles.

- Sand-size sediment predominates in the bed materials throughout the system. Gravels are present in localized areas due to tributary inputs, particularly the Salsipuedes Creek at Watsonville. Materials finer than sand (<0.062 mm diameter) are not found in significant quantities in the movable bed, and thus are not important from the standpoint of modeling within this system.

- The coastal floodplain below Chittenden consists of river flows through alluvial materials, which are generally fine-grained.

- There is a large sandbar at the river mouth. The grain size of the sand at the mouth is very similar to the grain size in the river.

- Sand was observed in the riverbed downstream of San Benito/Pajaro River confluence. It is apparent that the San Benito River is the principal source of coarse sediment input into the Pajaro River system. There is no evidence that significant quantities of coarse sediment are transported along the Pajaro River above its confluence with San Benito. This conclusion was supported by the characteristics of the San Benito riverbed (braided, coarse bed), and the evidence of sources of coarse sediment from slope failure and stream bank erosion.

Photographs illustrating the current condition of the river are presented as Figures 1, 2 and 3.

Sediment Model Inputs

Model Inputs and Data Availability

It is necessary to establish the amount of sediment entering the sediment transport. Because the grain size of interest in the Pajaro River is coarse sediment, primarily sand, the inflowing load of coarse sediment must be determined. The following data are available to determine inflowing sediment load at the Chittenden gage (11159000) operated by the USGS.

- Stream flow data are available for 61 years, from 10/1/39 to 9/30/00.

- The USGS has reported suspended sediment load on 46 different days at the Chittenden gage on Pajaro River, between 1978 and 1990. While this is a rather small dataset, it is important to note that several large flows were included in the dataset.

- Of the available suspended sediment load data, on 37 days the percentage of the total sediment load which consisted of sand (>0.062 mm diameter) was reported.

These data were used to construct a relationship between water discharge and sediment discharge, and this relationship was then applied to the entire stream flow record to estimate the inflowing load over time.

As a limitation, this procedure incorporates the assumption that the relationship between discharge and sediment load measured during the 1978-1990 period is applicable over the entire 61-year period of stream flow record. This would not necessarily be true if upstream land use or channel conditions (including in-stream gravel mining) changed significantly during this period.

Computation of Inflowing Sediment Load

To establish the relationship between discharge and sediment load, the daily suspended sediment load was plotted as a function of daily discharge on log-log coordinates from which a rating curve for total suspended sediment was developed. Because a regression on logged data will not undercount load, the equation was then adjusted so that the measured and predicted total sediment load matched within 2 percent (Morris & Fan 1997).

Because suspended sediment samplers do not reach the bottom of the stream, there is an unsampled zone adjacent to the bed, and the rating equations were adjusted to include this 5% adjustment in load.

The 37 suspended sediment load measurements with grain size distribution data were then plotted separately and a new rating curve was developed for the coarse sediment only. The coefficient for this curve was then adjusted to account for the 5% unsampled load. Because this is a sand-bed system, the unsampled zone will be transporting bed material, and therefore the entire 5% was attributed to coarse sediment. The resulting load vs. discharge rating curve for the coarse sediment inflow is:

$$\text{Load} = 0.007 * \text{Qcfs}^{1.56}$$

Where, Load is the coarse sediment load in tons/day and Qcfs is the mean daily discharge in cfs. The rating relationship for both total and coarse loads is presented in Figure 4.

Temporal Variation in Sediment Load

The rating equation for coarse sediment load was applied to the 61-year discharge dataset for Pajaro River at Chittenden, to compute the daily coarse sediment discharge. The total water and sediment discharge were totaled for each water year, which is a year ending on September 30. The annual total water discharge and the coarse sediment discharge computed in each year are summarized in Figure 5. This graph illustrates that there is a large year-to-year variation in both the sediment and water discharge.

Variation of Sediment Load with Discharge

Daily stream flow discharge and coarse sediment loads were grouped by discharge classes with intervals of 1000 cfs. The total water discharge and coarse sediment load was computed within each discharge class, and plotted as a histogram in Figure 6. About 96% of the time flow in Pajaro River at Chittenden is less than 1000 cfs, and these flows account for less than 10% of the sediment discharge; the remaining 90% of the sediment is discharged on the 4% of the days with discharges exceeding 1000 cfs.

Modeling Concepts and Approach

Model Concepts

The sediment transport model consists of two basic elements, a hydraulic model and a sediment transport module. A purely hydraulic model, such as HEC-RAS, performs hydraulic computations along channels assuming a fixed bed geometry. In contrast, the bed in a sediment transport model can be altered over time by scour or deposition, thereby producing changes in river geometry, which will influence hydraulic behavior over time.

The hydraulic behavior of the sediment transport model in fixed-bed mode was calibrated against the HEC-RAS model using identical cross-section data, which minimizes the differences between the two models for a fixed geometry. However, because the riverbed in the sediment transport model will be deformed over time by deposition and scour, hydraulic results from the sediment transport model running in movable-bed mode will be different from the fixed-bed condition used for initial calibration.

Model Description

Sediment transport modeling was undertaken using the MIKE11 software developed by the Danish Hydraulic Institute (DHI). The MIKE11 software consists of a one-dimensional unsteady-flow hydraulic engine coupled to a mixed-bed sediment transport model. The software has been widely used internationally on a wide variety of river systems, and it is used in California. The software has been approved by FEMA. It also incorporates a state-of-the-art Graphical User Interface that greatly helps visualization of the system.

Model Geometry and Boundary Conditions

The sediment transport model represents the river system from the upstream end of Chittenden Pass to just upstream of the Pacific Ocean. The upstream boundary of the model is located at the upstream end of Chittenden Pass. Water inflow in the form of a hydrograph is introduced at the upstream end of the model, and sediment discharge is calculated at this same location by the model using the rating curve previously presented in this TM. The water and sediment discharge form the upstream boundary conditions.

The downstream boundary of the model is not located at the ocean. Therefore, the downstream boundary condition can be represented by the normal water surface elevation at the downstream end of the reach. It is not necessary to use tidal conditions because the end of the model is far enough from the ocean to escape the impact of variation in water surface elevations due to tides.

The plan of the model is shown in Figure 7.

Model Calibration

The MIKE11 model has been calibrated by comparing the simulated hydrographs between the HEC-RAS and the MIKE11 models. The comparison is shown in Figure 8. The figure indicates that the simulated hydrographs of the two models compare very well. It is therefore considered reasonable to use the MIKE11 model to simulate sediment transport in the Pajaro River.

Figure 1: Photograph of Pajaro River immediately below the Roggie Lane Bridge in the Chittenden area, looking downstream. Notice the sand deposits in the channel.

Figure 2: Photograph looking upstream along Pajaro River at Watsonville, with Salsipuedes creek entering on the left.

Figure 3: Aerial photograph of confluence of Pajaro River and Salsipuedes Creek illustrating the levees, main channel with sand bars, and the very small floodplain between the top of the channel bank and the levees. View looking upstream. A residential area of Watsonville is in the bottom of the photo.

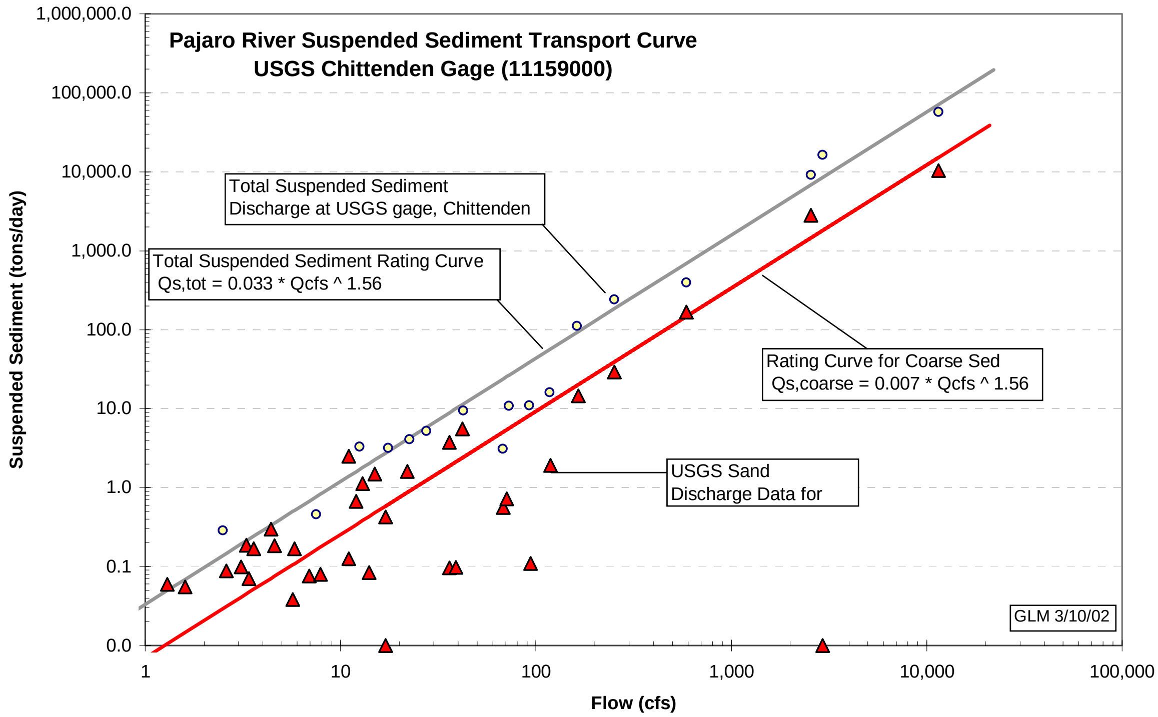


Figure 4: Sediment discharge data at Chittenden and resulting sediment rating relationships. The circles are data points for total suspended sediment load, and the triangles are data points for the coarse sediment fraction (dia.>0.062 mm) of the total load based on reported grain size distribution of the sample. A grain size distribution was not available for all sediment data. The rating curves have been fitted to the data and adjusted to include an estimated 5% unsampled bed load. The entire unsampled load has been applied to the coarse sediment load.

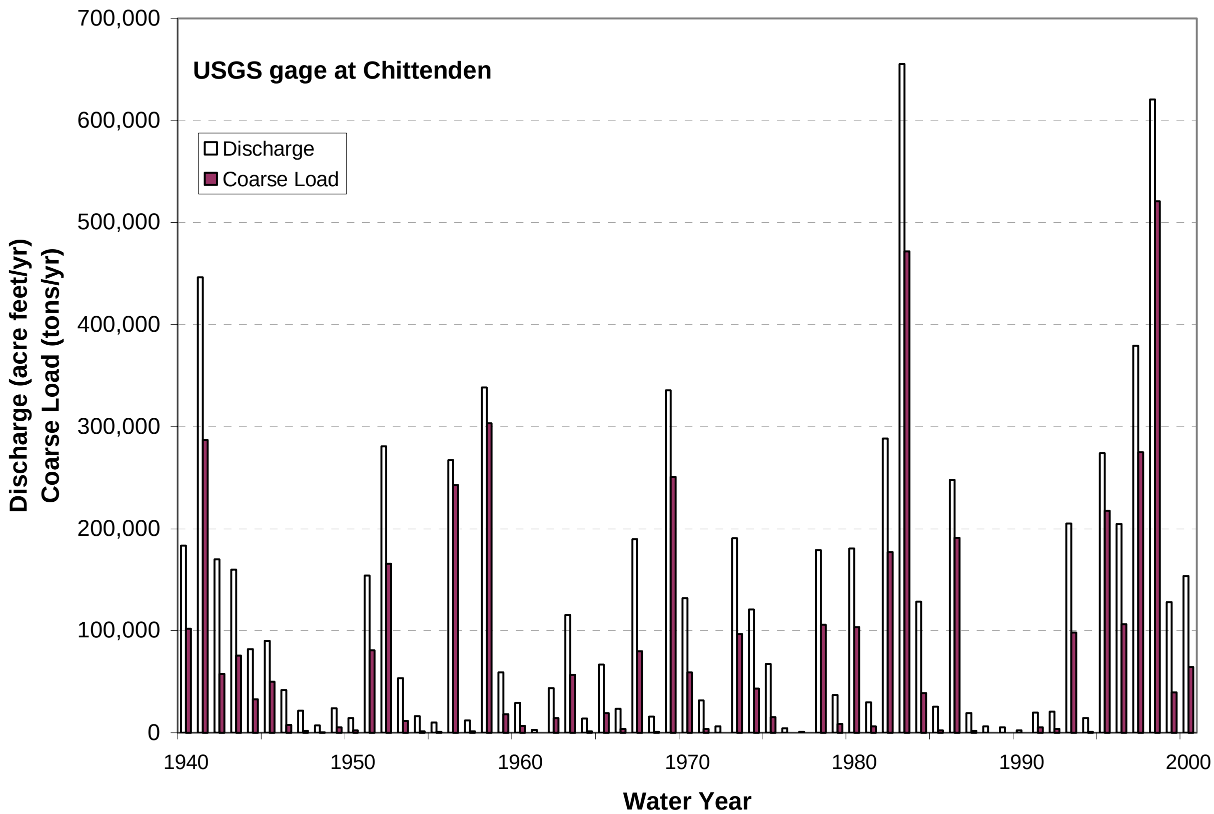


Figure 5: Discharge of water and coarse sediment load at Chittenden, by water year.

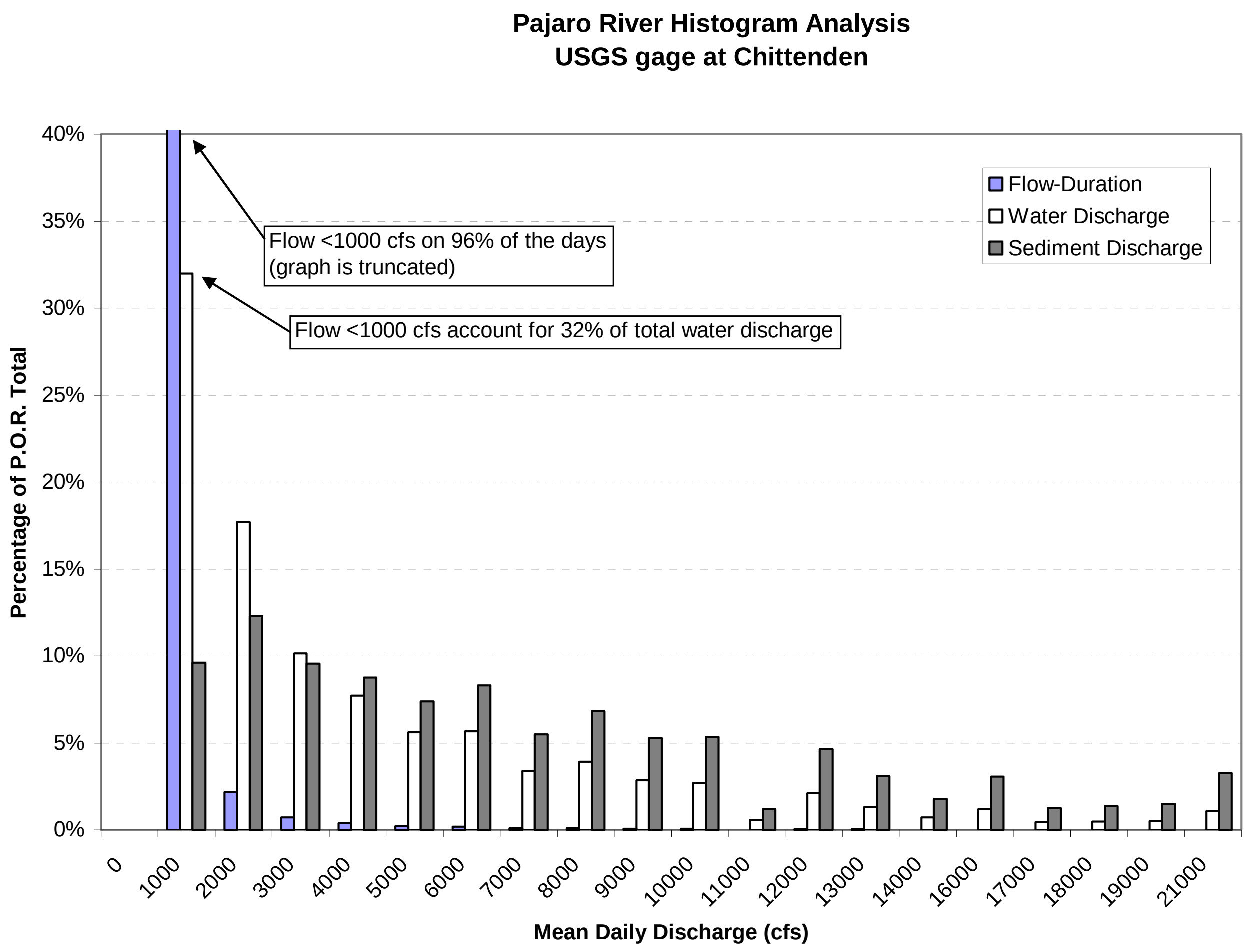


Figure 6: Histogram showing the percentage of total sediment and water discharged by discharge class (1000 cfs per class interval).

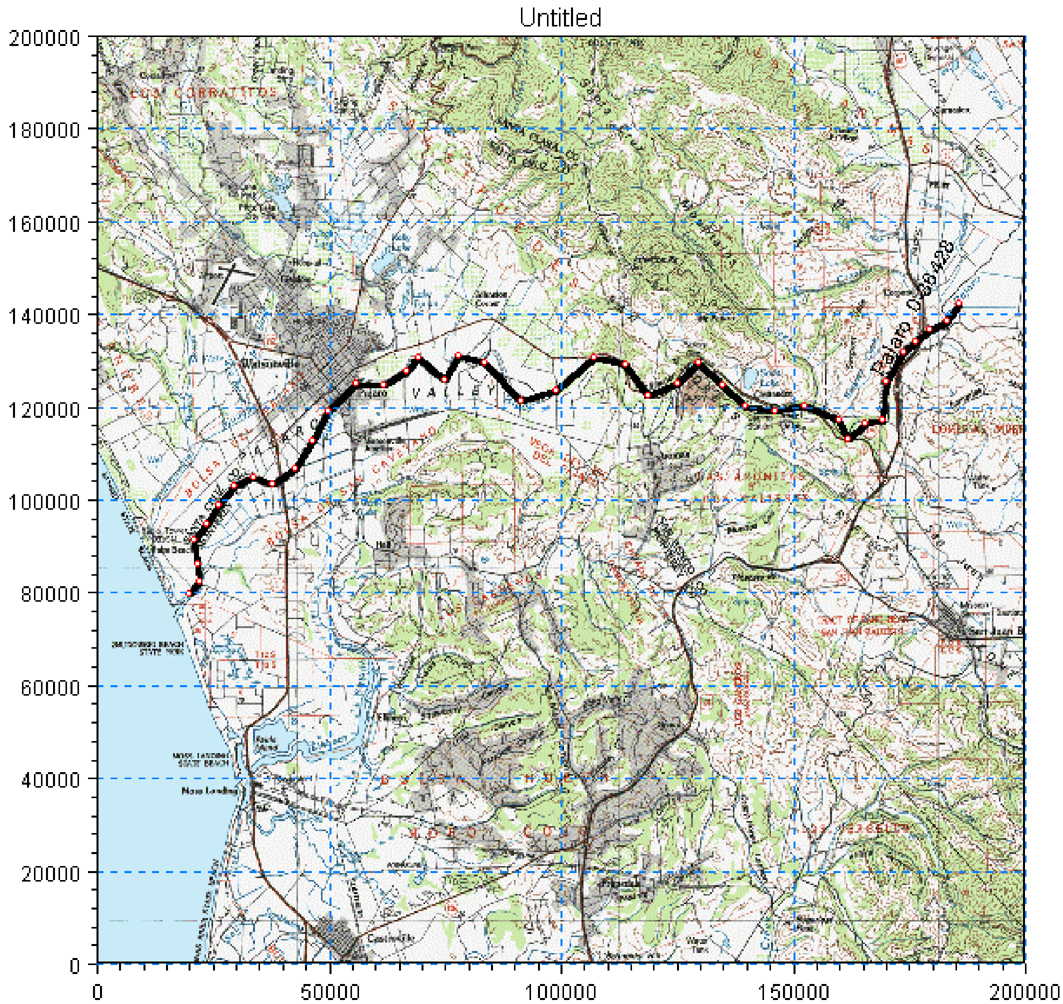


Figure 7. Plan of the sediment transport model, with mileage shown form downstream to upstream.

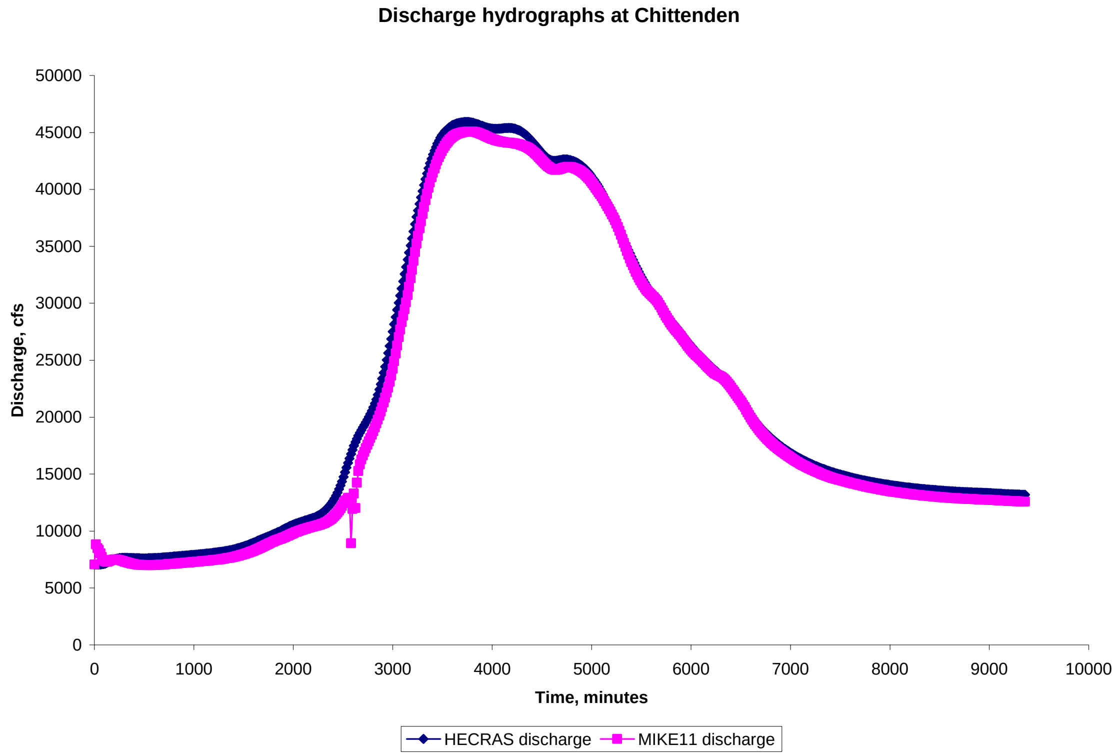


Figure 8. Comparison between HEC-RAS and MIKE11 simulated hydrographs at Chittenden

References

Morris, G.L. & Fan, J. (1997), Reservoir Sedimentation Handbook, McGraw-Hill, New York.

Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers

in association with Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.10 – Watershed Scenarios

Task: Use Model to Show Impacts of Four Land Use Scenarios

To: PRWFPA Staff Working Group

Prepared by: J. Schaaf

Reviewed by: R. Raines

Date: April 10, 2002

Introduction

This Technical Memorandum (TM) describes the impacts that past and potential future land use changes have on peak discharges and 3-day average discharges at the four locations in the watershed used as a basis of comparison. (See TM 1.2.1 for a description of the basis of comparison.) Four land use scenarios were agreed-upon by the Staff Working Group and accepted by the Board of the Pajaro River Watershed Flood Prevention Authority. These four scenarios look at past land use, future planned land use, an extension to planned land use, and at changes to existing agricultural uses.

Project Scope and Background

The Pajaro River Watershed Flood Prevention Authority was formed to develop flood protection strategies in the Pajaro River Watershed. The first phase in developing the strategies is to construct a stream flow model. The model shall address a number of key issues, including the following:

- What are the causes of flooding on the Pajaro River?
- Has rainfall runoff increased downstream with increasing development upstream?
- Has the improvement and/or maintenance of streams affected flooding?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?
- How will future conditions change the degree of flooding?

Answering these and other related questions regarding Pajaro River flooding requires the development of hydrologic and sediment models for the Pajaro River and its tributaries.

Setting

The Pajaro River drains an area of approximately 1,300 square miles of the coastal plains and mountains of Central California. A tributary of Monterey Bay, the watershed drains portions of Santa Cruz, Monterey, Santa Clara and San Benito Counties. As shown in Figure 1 (previously submitted with TM1.2.1) the watershed is somewhat elongated toward the southeast.

The lower portions of the Pajaro River from Murphy's Crossing to the Pacific Ocean are protected by a Corps of Engineers levee project constructed between 1949 and 1952. Four miles above this federal project is the USGS stream gage – Pajaro River at Chittenden, CA. This gage has been in continuous operation since the 1939 water year. The drainage area at this gage is 1,186 square miles.

Two miles above the Chittenden gage site, the San Benito River is confluent to the Pajaro. At this point the San Benito River drains 661 square miles - slightly more than half the drainage area at the Chittenden gage. The Pajaro River at US Highway 101 is just downstream of the outlet of "Lower Soap Lake" – a low-lying area of Santa Clara and San Benito Counties. This outlet has drainage area of approximately 500 square miles and includes such tributary watercourses as: Uvas Creek, Llagas Creek, Pacheco Creek and Santa Ana Creek.

The Four Scenarios

PRO-FLO, the hydrologic model for the Pajaro River watershed, was described in TM 1.2.7. The model uses Curve Numbers and percentage of imperviousness along with a unit hydrograph to convert design rainfall into a runoff hydrograph. Runoff hydrographs yield two discharge parameters that are used as comparators: instantaneous peak discharge, and 3-day average discharge. The PRO-FLO model was calibrated to frequency curves at stream gages in the watershed under existing land use conditions.

This TM focuses on the potential changes in instantaneous peak and 3-day average discharges that might have occurred over time, and that might occur should urban development continue in the watershed or should some major changes in agricultural uses occur throughout the watershed.

Four land use scenarios were conceptualized and agreed-upon by the Staff Working Group and by the Board of Directors of the Authority. These four land use scenarios are: General Plan Build-out; 1947 Conditions; Ultimate-ultimate Urbanization; and Worst Case Agricultural Conditions.

General Plan Build-out

This land use scenario simply reflected the total build-out as called for in current land use plans of record for: Monterey, San Benito, Santa Cruz and Santa Clara Counties; as well as the cities of Gilroy, Hollister, Morgan Hill, San Juan Bautista and Watsonville. Many of the jurisdictions are undergoing land use plan changes. However, for this hydrologic analysis, the existing land use plans of record were used.

While there is no specific date associated with the general plan build-out scenario, it is believed that the year 2020 would be a reasonable date to use if one were needed. Most of the jurisdictions have land use plan dates earlier than 2020. However, it was believed that 2020 would be the date that represented an optimistic time when the plans might be expected to be at build-out conditions.

Table 10.1 shows the changes in Curve Number (CN) and percent impervious from existing conditions. The CN's in the table are for Antecedent Moisture Condition II.

Large changes in imperviousness in sub-watersheds SB-4, SA-2 and TQ-1 reflect general plan urbanization in and around the city of Hollister. Changes in SB-5 reflect general plan urbanization in and around the city of San Juan Bautista. Changes in LL-2 reflect the planned urbanization in the city of Morgan Hill. Changes in LL-3 and UV-2 reflect planned changes in and around the City of Gilroy. Changes in CO-1, SL-2 and WQS-1 reflect planned changes in and around the city of Watsonville.

Viewed from an overall watershed perspective, the amount of the 1,300 square mile watershed that is in urban uses (defined as Low Intensity Residential, High Intensity Residential, Commercial/Industrial/Transportation, and Urban/Recreational Grasses as shown in Appendices A and B in TM 1.2.6) changed from 2.4 percent under existing conditions to 6.2 percent under General Plan build-out conditions. This change in land use accounts for a change in impervious surfaces in the watershed of only 1.3 percent. Under existing conditions approximately 1.7 percent of the 1,300 square miles of drainage area is impervious, while under general plan build-out conditions the percent of the watershed that is impervious would be approximately 3 percent.

1947 Conditions

This land use scenario was selected because it was believed that it best reflects watershed conditions as they existed when the Corps of Engineers planned the existing Pajaro River Flood Protection Project. Modeling flooding for the year 1947 also represents conditions as they were in the year 1955.

The land uses in 1947 were estimated using USGS quadrangle maps from the years 1945 to 1953. Urban areas were fairly easily identified in the old quadrangles. Cropping patterns were more difficult to determine. The quadrangle maps showed a large portion of the valleys in orchard. Estimates based on the quadrangle maps and various historic photos were used to develop the changes in CN shown in Table 10.2. The decreases in percent impervious reflect the reduction in urbanization based on existing conditions. CN's generally decrease slightly from existing levels.

In addition to changing percent imperviousness and CN, the 1947 hydrologic model also changed four important routing parameters in the model. Three dams had not yet been constructed and thus were removed from the existing conditions model. These were: Uvas Dam, Chesbro Dam and Hernandez Dam. The only dam in place in 1947 was Pacheco Dam. Llagas Creek in 1947 did not have the existing engineered, partially leveed channel in its lower reaches. To account for this pre-channel condition, the routing in this reach was changed to reflect more attenuation that would be expected with a smaller channel and a larger floodplain. .

The urbanization of the watershed in 1947 is estimated as 1 percent as compared to 2.4 percent under existing conditions. The percent imperviousness of the watershed was approximately 1.1 percent as compared to 1.7 percent under existing conditions.

Ultimate Build-out Conditions

This land use scenario was simply an extension of the existing general plans of the nine jurisdictions in the watershed. It took the "2020" plan and extended it to "2050." Thus the scenario is alternately called the "2050" scenario or the "ultimate-ultimate" scenario. The planning put into this scenario was simply that of extending currently planned urbanization by using a mathematical formula. There was no planning work done to see if the areas could accommodate the projected growth from any standpoint, whether water supply, sewer capacity, transportation, environmental, water or air quality or any other of the myriad considerations that go into developing a proper land use plan. While there are other independent growth projection studies for communities, this method was chosen to ensure consistency throughout the watershed. Individual communities use various methods and therefore should be used in conjunction with one another. This "2050" plan is only for use in determining whether a flood protection project, constructed on the Pajaro River today, could be in jeopardy of having its level of protection significantly altered by future urban growth in the watershed during the life of that project.

The percent of the watershed that was in urban uses increased to 9.6 percent from the existing level of 2.4 percent and the general plan build-out level of 6.2 percent. The percent imperviousness in the watershed would be expected to rise to 4.1 percent from an existing level of 1.7 percent and a general plan build-out level of 3 percent.

The change in percent impervious and CN from General Plan Build-out level is shown in Table 10.3. The pattern of urbanization can be seen to mirror the existing trend as shown in the existing general plans – urban areas were projected to grow in and near Morgan Hill, Gilroy, Hollister, San Juan Bautista and Watsonville.

Maximum Agriculture

This land use scenario was included so as to assess the hydrologic impact of agriculture in the watershed. Under existing conditions while urban uses account for 2.4 percent of the watershed, agricultural uses account for 7.5 percent (excluding the pasture/hay category.) If, it was wondered, all of this 7.5 percent was converted to row crops and all of it was farmed under poor hydrologic conditions, what would the impact be on downstream peak discharge and 3-day average discharge? The runoff from agriculture under this worst-case condition could then be expected to be at a maximum. This gave rise to the scenario's title – Maximum Agriculture.

Similar to the "2050" scenario, there was no consideration given to the availability of water to convert the land to row crops nor thought to the soil conditions or any other consideration a farmer might make before changing orchard or vineyard or fallow land to row crops. The assumption of "poor hydrologic conditions" implies that the row crops uses do not have any features to control runoff by contour plowing or any other conservation practice recommended by the Department of Agriculture.

For this scenario the changes in CN from existing condition are shown in Table 10.4. There were no changes to percent impervious as this scenario assumes that only agricultural uses change – there were no changes to urban uses.

Results

The PRO-FLO hydrologic model was run with each scenario and compared to existing conditions model results. Table 10.5 shows the changes for peak discharge for the six return periods at the four decision locations. Table 10.6 shows the changes in 3-day average discharge for the same return periods at the same four locations.

Focusing on the Maximum Agriculture Scenario on Tables 10.5 and 10.6, it is evident that even if all currently agricultural uses in the watershed were converted to row crops under poor hydrologic conditions the changes in peak discharge and 3-day average discharge for the 25-year to 200-year return periods is well under a 2 percent increase from existing conditions in the watershed at the four decision points. Agricultural practices can have an impact on both peak discharge and 3-day average discharge but that impact is small.

At the 2-year and 10-year return periods the changes in agricultural practices have a much larger impact. The major impact comes from the Lower Soap Lake watershed that includes agricultural uses in the South Santa Clara Valley and the Hollister Valley as well as in the Bolsa. Changes in the San Benito River watershed were very small as only a small percent of that watershed is currently in agricultural uses.

Focusing on the General Plan Build-out Scenario and the Ultimate Build-out Scenario on Tables 10.5 and 10.6, it can be seen that, similar to the Maximum Agriculture scenario, the changes to the design discharges at the larger return periods are rather small, ranging from a high of 7.9 percent for peak discharge at Chittenden under Ultimate-ultimate conditions for the 25-year flood, to 0.2 percent for the 3-day volume for the 200-year flood for the San Benito River watershed.

The changes to peak discharge and volume are greater on a percentage basis downstream of Salispuedes Creek than they are at the Chittenden stream gage. Urbanization downstream of the Chittenden stream gage has an impact on the design discharges on the lower Pajaro River.

The changes to 2-year peak discharges and 3-day average discharges are significantly increased under either General Plan Build-out or Ultimate-ultimate. The impervious surfaces added as part of the urbanization conditions generate more runoff. Even if held temporarily to reduce peak discharges, the volume of runoff is increased. The more common the event, the more the percent change in runoff volume.

At Chittenden, for example, the existing 2-year, 3-day average discharge is approximately 2,000 cfs and the 10-year is 12,000 cfs. Using the percent change from Table 10.6, under the Ultimate-ultimate scenario the 2-year discharge would increase to 2,400 cfs and the 10-year discharge to 12,800 cfs. The 100-year, 3-day average discharge would change from 34,000 cfs to 34,900 cfs under this same scenario. Urban land uses have only a small effect on the design levels of peak discharge or 3-day average discharge. However, urban land uses could create (percentage-wise) significantly more discharge during the more frequent events.

The modeling of the hydrologic changes due to urbanization in either the General Plan Build-out scenario or the Ultimate-ultimate scenario did not consider any control mechanisms that could mitigate the increases in peak discharge from the smaller flood events. It is currently common practice to require some type of detention basin (and in some cases retention basins) to mitigate the immediate downstream effects of urbanization on peak discharge. While inclusion of such mitigation measures might change the model results somewhat, it is clear that without retention facilities, the 3-day volumes will increase as shown in Table 10.6 even with small detention basins. Those basins usually store large flood waves for only a short time and release them at a rate lower than the maximum inflow rate. These detention basins do, however, release all the runoff volume into the downstream system in a relatively short time. Therefore, it is not expected that mitigation measures that consist of only detention basins will have any impact on the potential increases in the 3-day average discharge due to urbanization.

The use of retention basins where runoff in percolated into the ground can be effective means of reducing the volumes of runoff from urbanized areas. Unfortunately, the infiltration capacities of many of the soils in the watershed are too low to allow this type of stormwater control. Percolation basins are in use, however, in Morgan Hill and in Hollister on a limited basis.

While it is generally considered appropriate to use detention basins to control the changes in instantaneous peak discharge due to urbanization for the more frequency events, it is not clear that widespread use of these control devices will produce a commensurate reduction in instantaneous peak discharge over large watersheds. The operation of systems of unregulated (unoperated) reservoirs could conceivably result in different degrees of attenuation of instantaneous peak discharges as the watershed becomes larger and larger and more and more of the watershed is controlled by detention basins. Therefore, it is not clear just what the degree of downstream peak attenuation can be accomplished using the standard stormwater detention facility.

The scenarios that involve increasing urbanization above the existing level produce increases in the volume of runoff as reflected in the 3-day average discharges as shown in Table 10.6. Instantaneous peak discharges as shown in Table 10.5 may be somewhat amenable to mitigation through use of upstream detention basins attached to new urban developments. It should be noted however that the downstream Corps project will be completed by the year 2050 and would be able to accommodate the increase predicted in the Ultimate Build-out Scenario.

The 1947 Conditions Scenario provided some surprising results as shown in Tables 10.5 and 10.6. This PRO-FLO model for this scenario did not include the storage and attenuation effects of the three large reservoirs – Uvas, Chesbro and Hernandez. This "removal" of these control devices led to some very interesting and perhaps unanticipated results.

In Table 10.5 under Location, San Benito River, the instantaneous peak discharges increased significantly for all return periods. It was discovered that removal of Hernandez Reservoir had a significant impact on downstream peak discharges because the reservoir held back and significantly attenuated the runoff hydrograph from the 85 square miles tributary to that reservoir. Removal of the reservoir not only increased the peak discharge, but equally importantly, moved that peak discharge up in time so that as it traveled down the San Benito River valley it added almost directly to the peaks of other sub-watershed hydrographs. With Hernandez Reservoir in place the peak discharge from the upper 85 square mile watershed was lagged approximately 8 hours behind the time when the peak inflow reached the reservoir. This timing effect resulted in the large increases at the San Benito River location as well as at the Chittenden location and the D/S Salsipuedes location.

For the Lake Outlet location the discharges were impacted by the removal of Uvas and Chsesbro Reservoirs. Similar to the San Benito River the peaks were increased significantly on Llagas and Uvas Creeks. However, when Llagas Creek joined the Pajaro River, the Pajaro River peak dominated. This peak was slightly larger and was lagged in time due to the attenuation effects of Pacheco Reservoir and Upper Soap Lake (San Felipe Lake.) However, once Uvas Creek joined the Pajaro the peak shifted back to a combination of Llagas and Uvas Creek being the dominant peak and the outflow from Upper Soap Lake being somewhat smaller. This complex interaction due to the timing of runoff hydrographs resulted in a slight increase at the larger return periods and much greater increases at smaller frequencies. The two reservoirs do indeed provide significant peak reduction for the more frequent events.

In 1955, stream gages indicate that runoff from the storm, which was about a 22-year event, jumped from their normal peak discharge and 3-day average discharge of 5,755cfs and 2,130cfs to 24,000cfs and 15,100cfs. Stream gage data regressions indicate the peak discharge should be 24,500cfs and the 3-day average to be 19,000cfs. PRO-FLO, which is calibrated to those regressions, models a 25-year event in 1955 to have a peak discharge of 31,255cfs and a 3-day average discharge of 19,048cfs. Since the model relatively accurately reproduced stream gage data, assumptions made about land use and the impact of reservoirs are further confirmed.

Looking at Table 10.6 under the Lake Outlet location it will be noted that the 1947 volumes are increased slightly. These increases are due to the amount of runoff currently trapped by the reservoirs during flood events and held for later release for groundwater recharge. Those stored volumes are much more significant at the more frequent events than they are at the less frequent events.

Conclusions

Urbanization increases peak discharges and 3-day average discharges. From a percentage increase standpoint, the effects are more significant at the flow return periods than at the higher return periods. However, from a watershed-wide perspective the potential increase in peak discharge from a build-out of all current general land use plans is relatively small – less than four percent increase for the 25-year flood and approximately 2 percent for the 100-year flood.

Increases in 3-day average discharge are slightly smaller than the increases in peak discharges.

The small changes in design discharges can be found to be slightly more significant when looked at in terms of a change in level of protection to the existing Corps of Engineers flood control project on the Pajaro River downstream of Murphy's Crossing. The current project has a design capacity of 18,000 cfs from Murphy's Crossing to just upstream of the confluence with Salsipuedes Creek and can hold approximately 25,000 cfs based on the project's performance during the February 1998 flood event.

Changing the peak discharge at the Chittenden gage for "Ultimate-ultimate" conditions as shown in Table 10.5 would result in the return period of the 18,000 cfs design capacity being reduced from its current 12-year capacity to an 11-year capacity – approximately a 10 percent reduction in level of protection. Looking at the 25,000 cfs carrying capacity as experienced in 1998, this level of protection would be reduced from its current value of 25 years to approximately 23 years – again, approximately a 10 percent reduction in level of protection.

While it is true that upstream detention of urbanizing areas may have detention basins constructed as mitigation measures to reduced localized increases in peak discharge, it is not as evident that these mitigation measures will be just as effective in mitigating those increases in peak discharge at the Chittenden stream gage.

Therefore, while urbanization does not significantly add to the design discharges downstream of Chittenden, this urbanization may create a lowering of the level of protection of the existing flood control project.

The three large reservoirs in the watershed – Hernandez, Uvas and Chesbro – have been very effective in reducing the peak discharges of the more frequent events and, in the case of Hernandez Reservoir, have been effective in reducing peak discharges across the frequency spectrum.

Table 10.1
Pajaro River Watershed
Changes to Percent Impervious & Curve Numbers
(From Existing to General Plan Buildout Scenario)

Sub-Watershed	% Impervious		Curve Number		% of Sub-Watershed	
	AB	CD	AB	CD	AB	CD
SB-1	n/a	0.0	n/a	0	0	100
SB-2	0.0	0.0	3	0	3	97
SB-3	0.3	0.0	1	0	5	95
TP-3	0.1	0.0	1	0	16	84
TP-4	0.0	0.6	3	0	19	81
SB-4	7.5	1.2	-1	-1	5	95
SB-5	5.2	0.0	2	0	14	87
SA-1	0.0	0.2	4	1	5	95
SA-2	17.5	11.3	-5	-2	7	93
ADP-1	0.0	0.0	0	0	29	72
PC-1	n/a	0.0	n/a	0	0	100
PC-2	0.0	0.1	0	0	11	89
PC-3	1.2	0.0	4	1	11	89
TQ-1	21.2	12.8	-1	-1	30	70
PJ-1	0.3	0.4	7	1	26	74
PJ-2	0.8	0.0	2	1	27	73
LL-1	n/a	0.5	n/a	0	0	100
LL-2	9.1	0.0	-1	-1	59	41
LL-3	21.9	15.1	-4	0	42	58
UV-1	0.0	0.3	1	0	3	97
UV-2	1.9	2.2	2	-2	43	57
UV-3	0.0	0.0	0	2	20	80
PJ-3	n/a	0.0	n/a	0	0	100
PJ-4	2.7	0.0	0	0	27	73
PJ-5	0.6	0.0	0	1	48	52
PJ-6	1.7	0.0	3	2	88	12
CO-1	1.6	2.8	0	3	74	26
SL-1	0.0	1.4	3	2	33	67
SL-2	16.9	15.2	-4	0	73	27
WS-1	13.3	4.8	3	4	68	32
PJ-7	0.0	2.8	0	0	44	56

Table 10.2
Pajaro River Watershed
Changes to Percent Impervious & Curve Numbers
(From Existing to Historical 1947 Scenario)

Sub-Waters	% Impervious		Curve Number		% of Sub-Watershed	
	AB	CD	AB	CD	AB	CD
SB-1	n/a	-0.7	n/a	-1	0	100
SB-2	-0.3	0.0	0	0	3	97
SB-3	0.0	-0.1	-1	-1	5	95
TP-3	0.0	0.0	0	0	16	84
TP-4	-0.7	-0.3	3	0	19	81
SB-4	-8.3	-1.5	1	-1	5	95
SB-5	0.0	-0.7	0	-2	14	87
SA-1	0.0	0.0	0	0	5	95
SA-2	-5.2	0.0	-2	0	7	93
ADP-1	0.0	-0.4	-1	-1	29	72
PC-1	n/a	0.0	n/a	0	0	100
PC-2	0.0	0.0	0	0	11	89
PC-3	0.0	-0.1	0	0	11	89
TQ-1	0.0	0.0	-1	-1	30	70
PJ-1	0.0	0.0	0	0	26	74
PJ-2	0.0	-0.3	-1	0	27	73
LL-1	n/a	-0.3	n/a	0	0	100
LL-2	-10.5	-5.7	1	1	59	41
LL-3	-7.0	-1.0	1	1	42	58
UV-1	-0.1	-0.5	1	0	3	97
UV-2	-2.2	-0.9	1	-3	43	57
UV-3	-4.0	-0.7	-2	2	20	80
PJ-3	n/a	-0.6	n/a	-3	0	100
PJ-4	-1.1	-2.1	1	-2	27	73
PJ-5	0.0	0.0	0	0	48	52
PJ-6	-0.9	-4.0	-1	0	88	12
CO-1	-0.9	0.0	0	0	74	26
SL-1	-0.4	-0.3	3	3	33	67
SL-2	0.0	0.0	-2	0	73	27
WS-1	-1.4	-8.2	-1	2	68	32
PJ-7	-16.6	0.0	-5	-4	44	56

Table 10.3
Pajaro River Watershed
Changes to Percent Impervious & Curve Numbers
(From General Plan Buildout to Ultimate Urbanization Scenario)

Sub-Watershed	% Impervious		Curve Number		% of Sub-Watershed	
	AB	CD	AB	CD	AB	CD
SB-1	n/a	0.0	0	0	0	100
SB-2	0.0	0.0	0	0	3	97
SB-3	0.0	0.0	0	0	5	95
TP-3	0.0	0.0	0	0	16	84
TP-4	0.0	0.0	0	0	19	81
SB-4	16.7	5.1	-6	-2	5	95
SB-5	4.3	0.0	-8	3	14	87
SA-1	0.0	0.0	0	0	5	95
SA-2	23.6	10.4	1	-2	7	93
ADP-1	0.0	0.0	0	0	29	72
PC-1	n/a	0.0	n/a	0	0	100
PC-2	0.0	0.0	0	0	11	89
PC-3	0.0	0.0	0	0	11	89
TQ-1	17.8	10.2	1	0	30	70
PJ-1	0.0	0.0	0	0	26	74
PJ-2	0.2	0.1	-2	3	27	73
LL-1	n/a	0.0	n/a	0	0	100
LL-2	7.1	2.2	-2	6	59	41
LL-3	7.2	3.6	4	3	42	58
UV-1	0.0	0.0	0	0	3	97
UV-2	1.1	0.8	-3	2	43	57
UV-3	0.0	0.0	0	0	20	80
PJ-3	n/a	0.0	n/a	0	0	100
PJ-4	0.0	0.0	0	0	27	73
PJ-5	0.0	0.0	0	0	48	52
PJ-6	1.8	3.7	0	-2	88	12
CO-1	2.2	6.0	4	6	74	26
SL-1	0.9	2.5	3	0	33	67
SL-2	11.7	-11.0	-2	2	73	27
WS-1	16.8	14.4	11	-2	68	32
PJ-7	0.0	0.0	5	-1	44	56

Table 10.4
Pajaro River Watershed
Changes to Percent Impervious & Curve Numbers
(From Existing to Worst Case Agricultural Scenario)

Sub-Watershed	% Impervious		Curve Number		% of Sub-Watershed	
	AB	CD	AB	CD	AB	CD
SB-1	n/a	0.0	n/a	0	0	100
SB-2	0.0	0.0	0	0	3	97
SB-3	0.0	0.0	1	0	5	95
TP-3	0.0	0.0	0	0	16	84
TP-4	0.0	0.0	1	0	19	81
SB-4	0.0	0.0	1	0	5	95
SB-5	0.0	0.0	0	0	14	87
SA-1	0.0	0.0	0	0	5	95
SA-2	0.0	0.0	3	2	7	93
ADP-1	0.0	0.0	0	0	29	72
PC-1	n/a	0.0	n/a	0	0	100
PC-2	0.0	0.0	0	0	11	89
PC-3	0.0	0.0	2	0	11	89
TQ-1	0.0	0.0	4	1	30	70
PJ-1	0.0	0.0	1	0	26	74
PJ-2	0.0	0.0	5	2	27	73
LL-1	n/a	0.0	n/a	0	0	100
LL-2	0.0	0.0	3	1	59	41
LL-3	0.0	0.0	6	2	42	58
UV-1	0.0	0.0	0	0	3	97
UV-2	0.0	0.0	0	0	43	57
UV-3	0.0	0.0	2	2	20	80
PJ-3	n/a	0.0	n/a	3	0	100
PJ-4	0.0	0.0	0	0	27	73
PJ-5	0.0	0.0	0	0	48	52
PJ-6	0.0	0.0	1	1	88	12
CO-1	0.0	0.0	1	0	74	26
SL-1	0.0	0.0	1	0	33	67
SL-2	0.0	0.0	1	0	73	27
WS-1	0.0	0.0	1	0	68	32
PJ-7	0.0	0.0	1	2	44	56

TABLE 10.5

PRO-FLO RESULTS
FOUR LAND USE SCENARIOS
Percent Change in Peak Discharge
from Existing Conditions

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
Chittenden	1,186						
Build-Out		17.8%	3.1%	2.9%	1.3%	1.3%	1.0%
1947		21.3%	19.2%	12.0%	10.2%	12.5%	14.8%
Ultimate		39.3%	6.0%	5.7%	2.4%	2.3%	1.8%
Ag. Changes		6.7%	1.5%	1.8%	0.7%	0.7%	0.7%
San Benito R.	664						
Build Out		1.0%	0.5%	0.4%	0.3%	0.3%	0.3%
1947		48.1%	24.4%	14.7%	16.9%	18.4%	17.2%
Ultimate		5.0%	1.3%	0.7%	0.5%	0.5%	0.4%
Ag. Changes		0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
Lake Outlet	505						
Build Out		18.7%	3.4%	2.0%	1.0%	1.1%	1.0%
1947		32.0%	4.9%	2.7%	1.0%	1.1%	1.1%
Ultimate		38.6%	4.2%	3.5%	1.7%	1.9%	1.7%
Ag. Changes		9.4%	2.2%	1.4%	0.7%	0.9%	0.9%
D/S Salsipuedes	1,274						
Build Out		14.6%	4.1%	3.9%	2.2%	2.2%	1.8%
1947		13.9%	12.6%	9.6%	6.4%	8.4%	11.0%
Ultimate		39.9%	8.1%	7.9%	5.0%	4.8%	3.7%
Ag. Changes		4.8%	1.5%	1.8%	0.9%	1.0%	0.9%

TABLE 10.5b

PRO-FLO RESULTS
FOUR LAND USE SCENARIOS
Peak Modeled Flow

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
Chittenden	1,186						
Existing		3,065	16,394	27,910	38,147	44,627	59,892
Build-Out		3,610	16,901	28,714	38,649	45,210	60,517
1947		3,719	19,540	31,255	42,045	50,200	68,764
Ultimate		4,269	17,373	29,489	39,053	45,659	60,975
Ag. Changes		3,270	16,635	28,405	38,409	44,956	60,306
San Benito R.	664						
Existing		1,269	10,708	18,734	26,113	31,458	44,557
Build Out		1,282	10,765	18,805	26,196	31,558	44,696
1947		1,880	13,322	21,485	30,537	37,255	52,214
Ultimate		1,333	10,844	18,866	26,253	31,622	44,727
Ag. Changes		1,270	10,715	18,745	26,126	31,473	44,576
Lake Outlet	505						
Existing		3,388	14,441	19,784	24,541	26,094	29,625
Build Out		4,023	14,930	20,185	24,780	26,384	29,919
1947		4,473	15,151	20,318	24,775	26,379	29,954
Ultimate		4,695	15,041	20,485	24,967	26,599	30,134
Ag. Changes		3,707	14,753	20,069	24,721	26,322	29,883
D/S Salsipuedes	1,274						
Existing		3,787	19,058	30,834	42,330	49,399	66,232
Build Out		4,340	19,845	32,049	43,274	50,478	67,427
1947		4,313	21,460	33,789	45,054	53,526	73,545
Ultimate		5,299	20,610	33,285	44,447	51,746	68,660
Ag. Changes		3,967	19,353	31,385	42,726	49,877	66,802

TABLE 10.6

PRO-FLO RESULTS
FOUR LAND USE SCENARIOS
Percent Change in 3-Day Avg. Q
from Existing Conditions

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
Chittenden	1,186						
Build-Out		10.2%	3.6%	2.3%	1.6%	1.4%	0.9%
1947		2.6%	8.3%	7.4%	4.5%	3.9%	3.0%
Ultimate		20.7%	7.1%	4.5%	2.9%	2.6%	1.6%
Ag. Changes		4.0%	2.1%	1.4%	1.0%	0.9%	0.7%
San Benito R.	664						
Build Out		2.9%	0.9%	0.5%	0.3%	0.3%	0.2%
1947		32.6%	23.2%	15.0%	7.5%	5.9%	4.4%
Ultimate		16.3%	3.2%	1.6%	0.9%	0.8%	0.5%
Ag. Changes		0.0%	0.1%	0.1%	0.0%	0.0%	0.0%
Lake Outlet	505						
Build Out		10.7%	4.0%	2.7%	2.0%	1.6%	1.2%
1947		12.7%	5.1%	2.5%	1.4%	1.2%	0.9%
Ultimate		20.1%	5.3%	4.8%	3.4%	2.9%	2.0%
Ag. Changes		5.4%	2.6%	1.9%	1.5%	1.3%	1.0%
D/S Salsipuedes	1,274						
Build Out		11.8%	4.8%	3.4%	2.4%	2.1%	1.6%
1947		1.4%	6.9%	7.0%	4.5%	3.9%	3.1%
Ultimate		26.3%	10.2%	7.0%	4.9%	4.4%	3.2%
Ag. Changes		3.2%	2.0%	1.5%	1.1%	1.0%	0.8%

TABLE 10.6b

PRO-FLO RESULTS
FOUR LAND USE SCENARIOS
3-Day Average Modeled Flow

Location	Area	2-yr	10-yr	25-yr	50-yr	100-yr	200-yr
Chittenden	1,186						
Existing		2,091	10,441	17,729	26,624	30,927	40,109
Build-Out		2,304	10,821	18,145	27,040	31,361	40,470
1947		2,146	11,311	19,048	27,809	32,138	41,309
Ultimate		2,523	11,186	18,528	27,409	31,732	40,767
Ag. Changes		2,175	10,658	17,983	26,894	31,218	40,375
San Benito R.	664						
Existing		454	3,687	6,963	11,864	14,825	21,027
Build Out		467	3,719	6,998	11,904	14,874	21,079
1947		602	4,542	8,010	12,750	15,703	21,942
Ultimate		528	3,804	7,075	11,973	14,943	21,140
Ag. Changes		454	3,690	6,967	11,869	14,830	21,034
Lake Outlet	505						
Existing		2,071	9,723	15,178	19,858	21,856	25,617
Build Out		2,293	10,115	15,588	20,246	22,214	25,914
1947		2,335	10,217	15,555	20,145	22,109	25,854
Ultimate		2,487	10,236	15,910	20,538	22,481	26,135
Ag. Changes		2,183	9,980	15,466	20,147	22,133	25,875
D/S Salsipuedes	1,274						
Existing		2,677	12,414	20,046	29,210	33,866	43,947
Build Out		2,993	13,016	20,720	29,898	34,575	44,635
1947		2,714	13,274	21,448	30,513	35,180	45,326
Ultimate		3,380	13,678	21,445	30,636	35,366	45,369
Ag. Changes		2,764	12,661	20,349	29,535	34,220	44,308

RMC
Raines, Melton & Carella, Inc.
Consulting Engineers/Project Managers

in association with

Schaaf & Wheeler
CONSULTING CIVIL ENGINEERS

Technical Memorandum No. 1.2.10

Task: Evaluation of Four Watershed Conditions - Sediment

To: PRWFPA Staff Working Group

Prepared by: Gregory Morris and Elsie Parrilla

Reviewed by: George W. Annandale

Date: April 29, 2002

INTRODUCTION

Study Objectives

The overall project objectives are to address the following issues:

- What are the causes of flooding along the Pajaro River below Chittenden?
- Has streamflow increased downstream with increasing development upstream?
- Has stream channelization and maintenance affected flooding downstream of Chittenden?
- Has erosion or sedimentation in the streams affected flooding?
- Have upstream retention basins reduced or mitigated the degree of flooding?

Objectives of This Technical Memorandum

This Technical Memorandum (TM) summarizes use of the sediment transport model to analyze the impact of different upstream watershed conditions on sedimentation conditions within the channel of the Pajaro River, along the reach from the San Benito confluence to the ocean. Simulations were made for the 100-year event which is critical from the standpoint of flood control.

The PRO-SED sediment transport model was described in TM 1.2.9 along with boundary conditions, field conditions, calibration and other aspects of modeling. That description is not repeated here.

MODEL DESCRIPTION

The calibrated sediment transport model was used to simulate the impact of different upstream watershed conditions for the 100-year flood event. Discharge hydrographs for an Existing Condition and four different scenarios were developed using PRO-FLO. These models simulate the response of the watershed (hydrologic system) and the stream channels and storage areas (the hydraulic system) to different land use conditions. The four different conditions modeled by the HEC-RAS portion of PRO-FLO are summarized in Table 1.

Table 1: Summary of Scenarios Developed by HEC-RAS Modeling and Used as Input for Sediment Transport Modeling.

Scenario	Chittenden Peak Discharge (cfs)	Description
Existing	42,501	**Existing Condition:** Current condition in watershed and channel; baseline against which all other simulations will be compared.
1	43,151	**General Plan Build-out**: This scenario allows the model to predict the watershed flood potential using the urbanization and land use for each city based on the efforts of the individual planning departments.
2	47,103	**Back in Time to 1947**: The year 1947 is significant because it is just before the Army Corps of Engineers' levees were built in 1949 and has similar conditions to when the 1955 flood occurred. In addition, three of the four existing reservoirs and some additional levees were not yet in place.
3	43,675	**Ultimate Build-out in 2050**: This scenario represents a worst-case scenario, in terms of flooding, for urbanization. The model predicts how the watershed responds to unchecked growth in the cities beyond what the general plans currently allow. The year 2050 is the approximate end of the economic life of a project started at the time of this report.
4	42,921	**Changes in Agriculture**: Agriculture can play a large role in the amount of runoff and therefore flooding in an area. This scenario parallels the urbanization scenario and acts as a worst-case agricultural condition.

As can be seen from Table 1, there are very small differences in peak discharges between the different scenarios for the 100-year flood event. The largest difference occurs between the Existing Condition and Scenario #2 (1947 condition). Peak discharge is lower for the Existing Condition due to reservoir construction. The remaining three scenarios are virtually identical to the Existing Condition in terms of peak discharge as well as the hydrograph shape. For this reason, the sediment transport analysis was run comparing only the Existing Condition against the 1947 Condition hydrograph (Scenario #2), and for determining its sensitivity to changes in hydraulic roughness and incoming sediment load.

INPUT DATA

Hydrograph Scenarios

The HEC-RAS modeling generated hydrographs for the 100-year storm with a duration of 6½ days. Discharge values were computed by HEC-RAS at 15-minute intervals, and these data were input into the PRO-SED sediment transport model. Scenarios #1, #3 and #4 were not run as their discharge hydrographs were very similar to the Existing Condition. The Existing Condition model was compared to the 1947 Condition, because this represented the greatest difference between the scenario hydrographs (an 11% difference in peak discharge).

Channel Vegetation Scenario

An additional scenario was constructed by altering the Existing Condition model to examine the possible impact of additional shrubby vegetation growth in the channel. This was simulated by increasing the value for hydraulic roughness (Manning's n-value) in the model. For this scenario channel hydraulic roughness values were increased by 50% over the Existing Condition model; floodplain hydraulic roughness was unchanged.

Changes in roughness values reflect only the impacts of vegetation on average flow velocities and water depths in the channel. However, vegetation will also mechanically trap coarse sediment and reduce flow velocities at the sediment-water interface on the channel bed. These mechanisms will increase sediment deposition in the channel and are not accounted for by increased hydraulic roughness values. Thus, hydraulic roughness provides only an approximate idea of the potential effect of increased vegetation coverage, and actual sediment deposition in the channel could be greater than simulated by roughness changes alone.

Changes in Inflowing Sediment Load

Changes in the inflowing sediment load can result from changes in upstream land use, instream gravel mining, incision and erosion of upstream channels, and reservoir construction. The state-of-the-art of sediment yield estimation does not allow exact estimation of the impact of watershed changes on sediment delivery to the river. It was therefore decided to determine the sensitivity of the model to changes in inflowing sediment load. A 20% change in incoming sediment load in rivers that are as large as the Pajaro River is considered significant, especially under the conditions that prevail in this watershed. Therefore, should the model indicate little sensitivity to a change of 20% in incoming sediment load, it would be an indication that the changes in sediment delivery from the upper river sub-watershed would probably have an insignificant effect on riverbed response during extreme flood events.

Sediment was input into the model using the sediment rating curve (sediment discharge as a function of water discharge) for total sediment load, previously presented as Figure 4 of TM 1.2.9 (and reproduced below as Equation #1). The equations used to represent changes in total sediment load, 20% higher and lower, are presented in Equations #2 and #3 respectively:

Existing condition (from Figure 4 of TM 1.2.9):

$$\text{Load} = 0.033 * \text{Qcfs}^{1.56} \quad (1)$$

20% increase in total sediment load:

$$\text{Load} = 0.040 * \text{Qcfs}^{1.56} \quad (2)$$

20% decrease in total sediment load:

$$\text{Load} = 0.026 * \text{Qcfs}^{1.56} \quad (3)$$

Application of these equations incorporates the assumption that the increase in load is evenly distributed over all discharges, and there is no change in the inflowing grain size distribution.

Summary of Simulations

The conditions simulated by the PRO-SED sediment transport model are summarized in Table 2.

Table 2: Summary of Conditions Modeled.

Simulation Number	Hydrograph Scenario	Peak Discharge (cfs)	Hydraulic Roughness	Sediment Input Rating Curve
1	Existing Condition	**42,501**	Existing	Existing
2	1947 Condition	**47,103**	Existing	Existing
3	Existing Condition	42,501	**50% higher**	Existing
4	Existing Condition	42,501	Existing	**20% Increase**
5	Existing Condition	42,501	Existing	**20% Decrease**

SEDIMENT TRANSPORT MODELING RESULTS

Graphical Simulation Results

Sediment transport modeling results are summarized graphically by showing the changes in bed elevation along the length of the river, which reflects either net scour or deposition of coarse bed material sediment.

- Simulation #1: Results of the Existing Condition simulation are shown using the **Bed Profile Graph** presented in Figure 1. This graph compares the pre-flood bed profile against the post-flood profile along the length of the river, indicating the net scour or deposition of sediment along the streambed.

- Simulations #2-#5: Results for each simulation are illustrated in Figures 2 - 5 as the change in bed profile at the end of the flood event, as compared to the Existing Condition simulation. The **Change in Bed Profile Graph** shows the difference in the bed profile at the end of the flood for the simulation event, as compared to the Existing Condition bed profile. Zero values in this graph represent "no difference" between the Existing Condition and Simulated bed levels at the end of the flood event.

The Existing Condition initial condition riverbed composition and profile is used for all simulations.

Discussion of Modeling Results

Existing Condition Model: The bed profile for the Existing Condition model is presented in Figure 1, comparing the pre-flood and post-flood bed profile. Very little net change occurs in the bed profile over the duration of the flood event. Scour and refilling of scour holes may occur during the event, but is not shown here.

Changes of Hydrology: The greatest difference in hydrology occurs between the Existing Condition and the 1947 Condition, the latter having a greater peak discharge than the former. This is not a particularly large difference, and the hydrograph shapes are very similar.

The end-of-flood bed levels for the Existing Condition and the 1947 Condition are compared in Figure 2. The increase in peak discharge results in an increase in sediment input at the peak of the flood. This results in about 0.12 m (5 inches) of additional bed material deposition in the vicinity of the confluence of Pajaro and San Benito Rivers, but along the remainder of the river the changes in bed profile are essentially insignificant and no net change is evident.

These results indicate that the change in discharge between the 1947 Condition and the Existing Condition does not significantly impact sedimentation conditions along Pajaro River, as long as the sediment yield relationship remains unchanged.

Vegetation and Increase in Hydraulic Roughness: As shown in Figure 3, a 50% increase in hydraulic roughness (simulating increased in-channel vegetation) increases deposition in the upstream portions of the river; reduced velocities allowed more of the coarser material to deposit. Maximum increase in deposition depth is 0.15 m (about 6 inches). Scour to a depth of 0.25 m (about 10 inches) occurs at one cross section. For the most part, the model predicts deposition in the upstream area of the model, with virtually no change in bed material further downstream in the vicinity of Watsonville.

Part of the deposition pattern is attributed to the single-event nature of this simulation. Inflowing sediment experiences greater trapping in the upstream portion of the model due to increased roughness. Over a period of multiple events the area of deposition could advance further downstream.

The simulation indicates that sediment deposition would be increased by the growth of shrubby in-channel vegetation which significantly increases channel hydraulic roughness.

Change in Inflowing Sediment Load: The simulated response to a 20% increase in the inflowing sediment load is presented in Figure 4. Sediment deposition occurs at the upstream end of the model, with bed elevation increasing about 0.43 m (about 17 inches) over the duration of the event. Over time (multiple events) this bed material could be expected to be transported further downstream along the river.

The river's response to a 20% decrease in the inflowing sediment load is presented in Figure 5, showing scour of about 0.43 m (17 inches) at the upstream end of the model, in the vicinity of the confluence of San Benito and Pajaro Rivers. Scour in the area of Chittenden would be limited by geologic controls.

It should be noted that the deposition at the upstream end of the model could be the result of boundary conditions. As the change in bed elevation at this location is relatively minor (compared to the total increase in sediment load), the absence of change in riverbed elevation over the rest of the model indicates that the sediment transport capacity in the downstream river may be adequate to convey relatively large changes in sediment input to the model. Further long-term simulations are needed to better define this issue.

Summary

Sediment transport modeling indicates that changes in peak discharge alone, over the range predicted for the 100-year flood by HEC-RAS modeling, should not significantly alter sedimentation conditions within the Pajaro River channel.

If significant shrubby vegetation grows within the channel, this should be expected to cause an increase in sediment deposition.

A significant (e.g. 20%) change in coarse sediment load appears to have a relatively minor impact on sedimentation in the Pajaro River during extreme flood events such as the 100-year flood, except potentially at the confluence with the San Benito River. The simulated increase in deposition at the confluence could potentially result from boundary conditions within the computer model. Should this be the case, the model results indicate that the sediment transport capacity of the lower Pajaro River during 100-year flood conditions could be adequate to convey relatively large changes in sediment load without significant changes in deposition pattern. Long-term simulations are required to better define potential change in bed elevation subject to changes in sediment load.

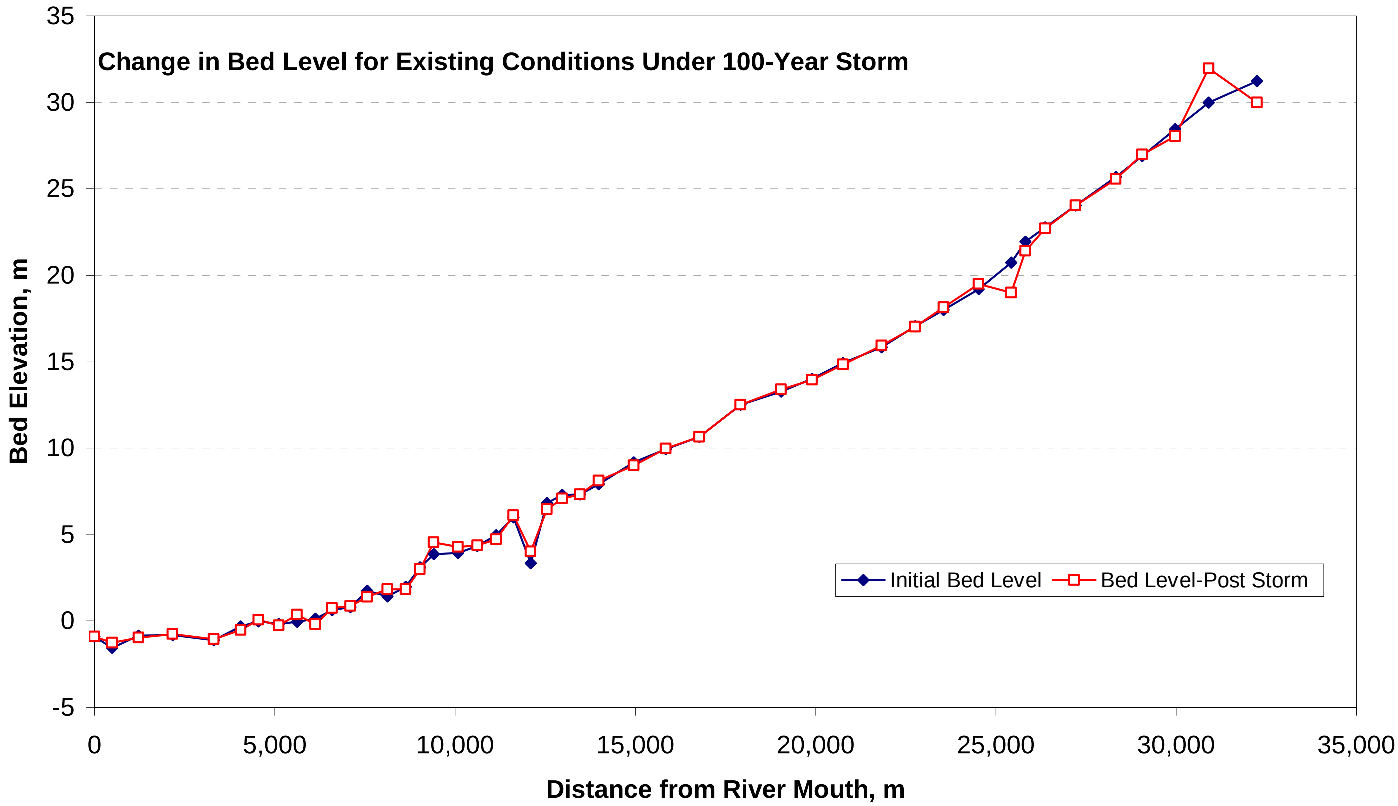


Figure 1: Results of Simulation #1. Comparison of initial and final riverbed profiles at the start and the end of the 100-year flood, Existing Condition model.

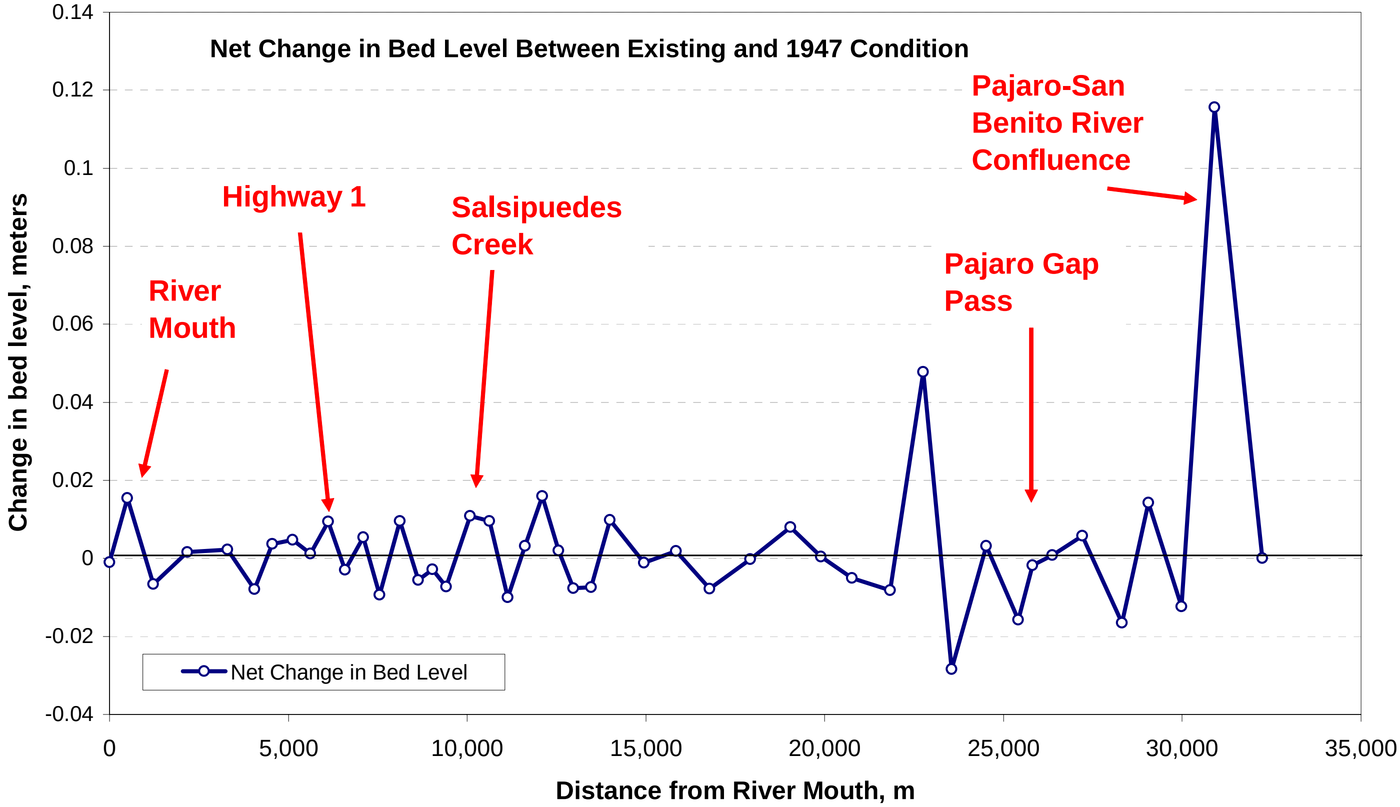


Figure 2: Results of Simulation #2. Difference in the end-of-flood bed profile along Pajaro River for the 1947 discharge hydrograph, as compared to the end-of-flood bed level for the Existing Condition model.

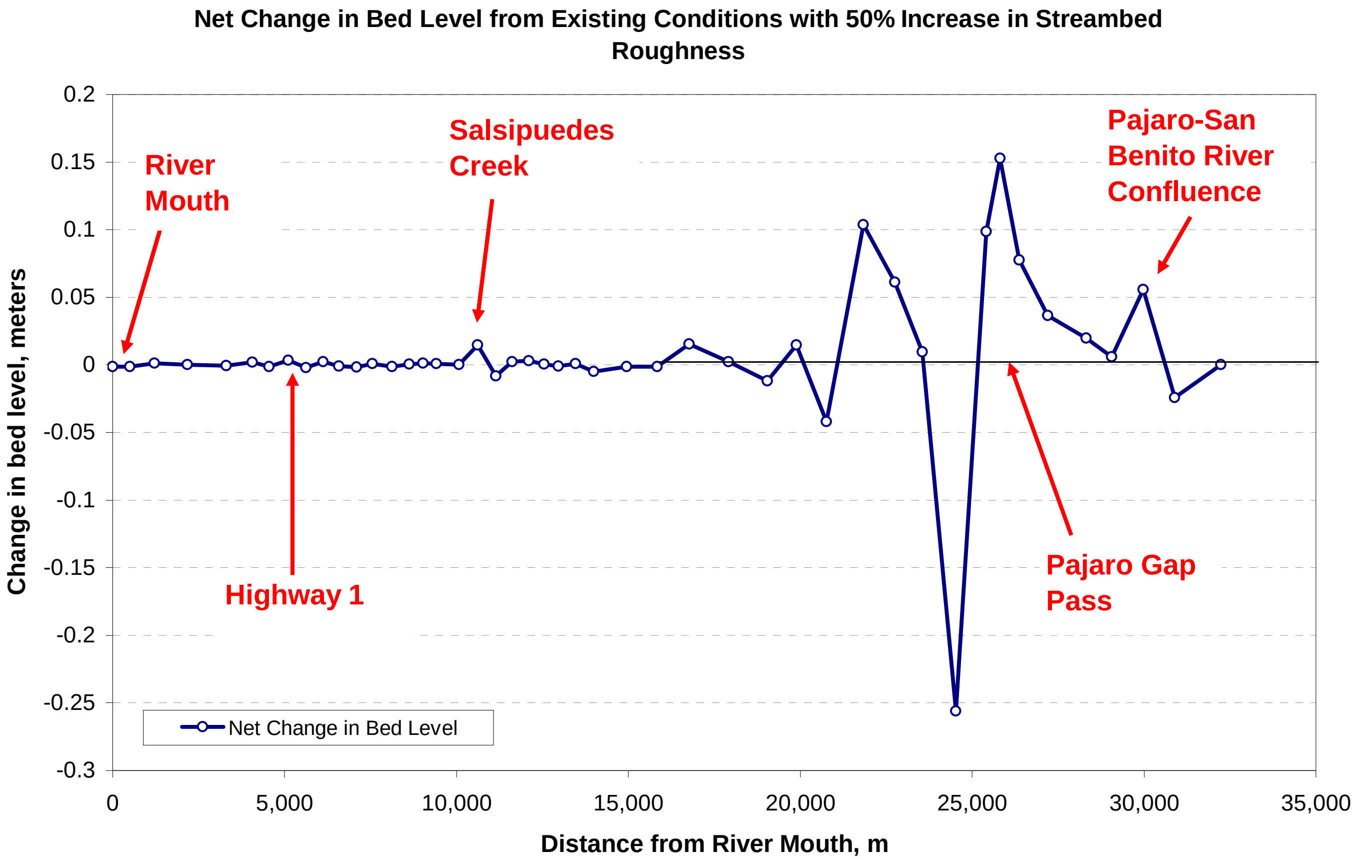


Figure 3: Results of Simulation #3. Difference in the end-of-flood bed profile along Pajaro River for a 50% increase in channel hydraulic roughness, as compared to the end-of-flood bed level for the Existing Condition model.

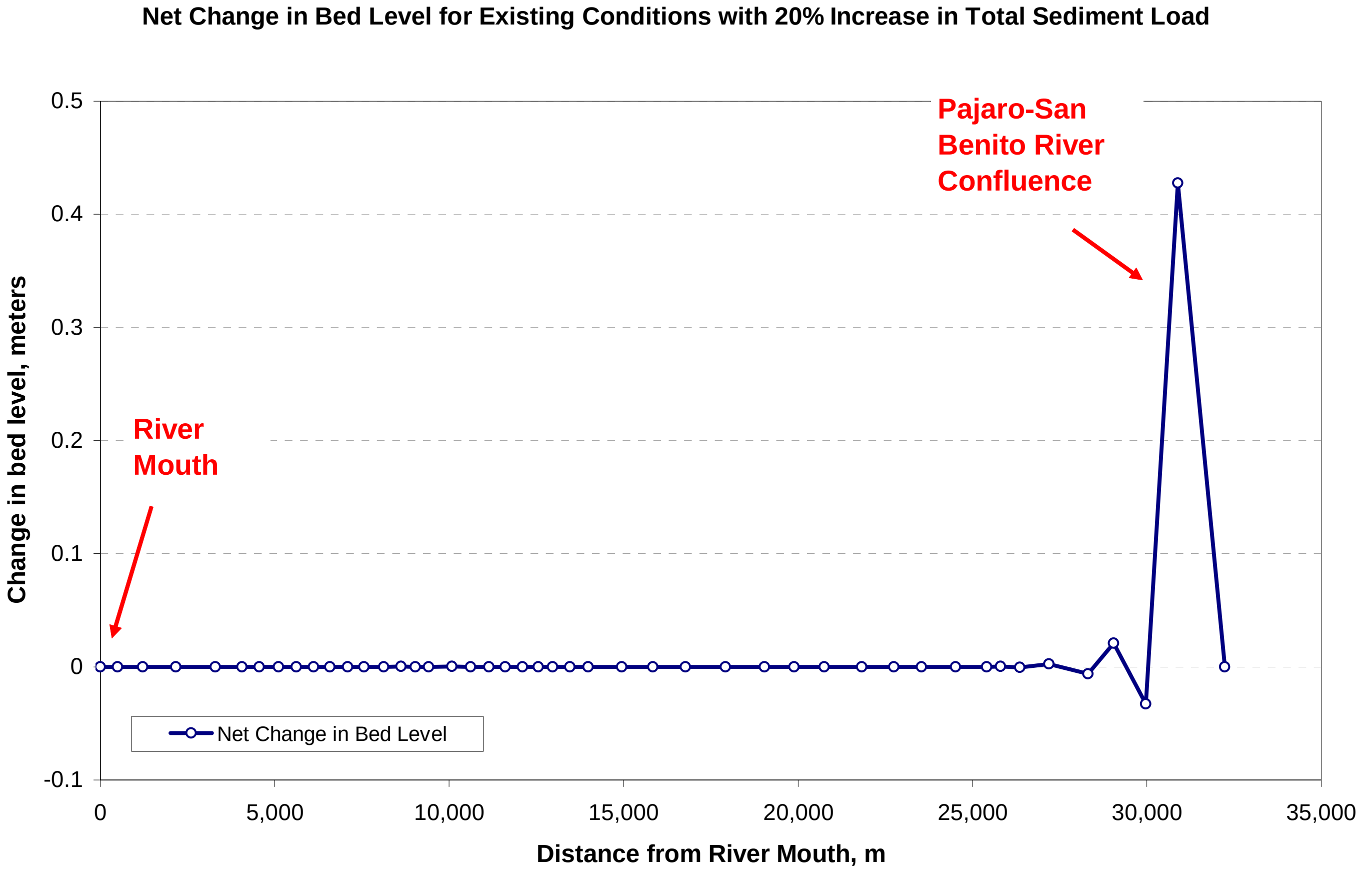


Figure 4: Results of Simulation #4. Difference in the end-of-flood bed profile along Pajaro River for a 20% increase in total sediment load, as compared to end-of-flood bed level for the Existing Condition model.

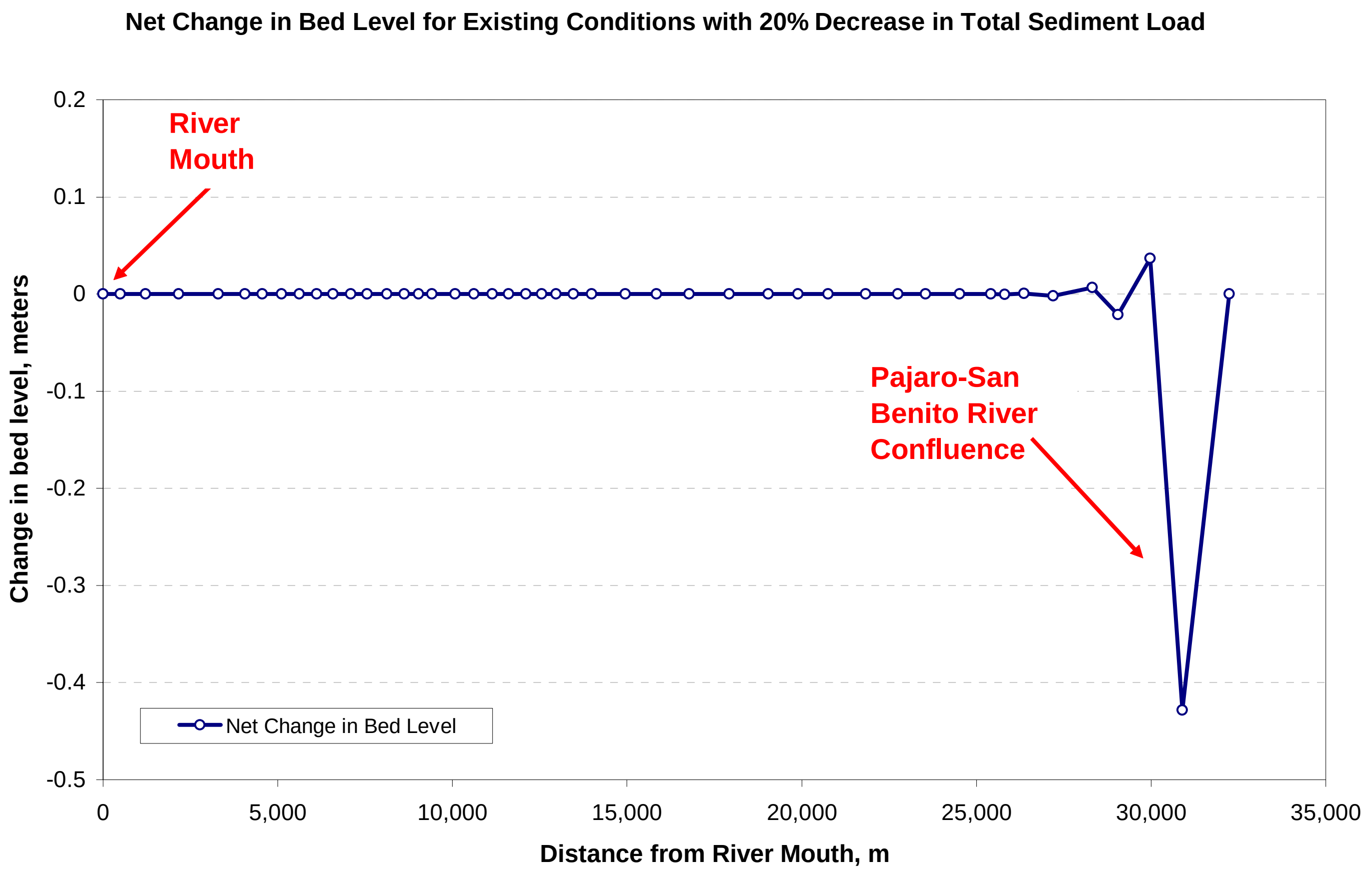


Figure 5: Results of Simulation #5. Difference in the end-of-flood bed profile along Pajaro River for a 20% decrease in total sediment load, as compared to end-of-flood bed level for the Existing Condition model.