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memorandum

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from Justin Gragg and Andy Collison, PhD

subject **Pajaro and San Benito Rivers Sediment Study and Transport Model Update**

1.0 Introduction

This report describes the results of flow and sediment monitoring during water year (WY) 2013, topographic data collection and field verification, and an updated sediment transport model for the San Benito River (including a segment of the lower Pajaro River).

The Pajaro River is the largest coastal stream between the San Francisco Bay and the Salinas River Watershed. The watershed is approximately 1,300 square miles and covers portions of Santa Cruz, Santa Clara, San Benito, and Monterey Counties. The upper Pajaro River drains the large Soap Lake basin, which includes Uvas and Llagas Creeks as tributaries. For approximately 4.2 river miles (RM) downstream of the confluence of the upper Pajaro and San Benito Rivers, the lower Pajaro River traverses through the Chittenden Pass, a narrow valley controlled by a natural constriction at its downstream (western) end. Downstream of this point the Pajaro River flows through the wider, lower-gradient Pajaro Valley, eventually draining to Monterey Bay. The lower Pajaro River was subject to major flooding in 1995 and again in 1998, causing damages and one fatality in the towns of Watsonville and Pajaro. One factor in the flooding was an increase in vegetation that had grown in the channel, reducing flood capacity below the original level of the 1940s flood control project. Associated with vegetation growth, there is believed to have been sediment deposition in both the channel and on the floodplain within the levees, though the exact balance between sediment deposition and removal is not clear.

The San Benito River is the main tributary to the Pajaro River, with a watershed area of 607-square miles upstream of Hollister, California, which is at the upstream end of the current study (**Figure 1**). The San Benito River watershed has relatively high relief, and lies parallel with, and slightly north of, the San Andreas Rift Zone for a length of approximately 60 miles. Land use within the watershed is largely rural, dominated by agriculture and ranching. Whether the San Benito or the upper Pajaro River is the main source of sediment to the lower Pajaro River is uncertain; the San Benito River watershed is larger (659 square miles compared with 513 square miles for the upper Pajaro River at the confluence of the two channels), has steeper overall relief and has fewer depositional areas that would trap sediment from the upper watershed. By contrast the upper Pajaro River watershed is slightly smaller but generates more runoff due to higher annual rainfall. Uncertainty about the relative sediment contribution of the two tributaries and the rate at which sediment is transported to the downstream flood management reaches was a factor in the development of the present study.

The Pajaro River Watershed Flood Prevention Authority (Authority) has initiated and participated in a number of comprehensive studies, including the Pajaro River Watershed Study and the Lower Pajaro River Levee Reconstruction Project, led by the U.S. Army Corps of Engineers (USACE). The Authority completed several studies that evaluated effective and sustainable flood management solutions throughout the watershed and opportunities to influence downstream outcomes through upstream modifications. As part of the Pajaro River Watershed Study, a three-part sediment assessment (Phase 4b Study) was commissioned to complement the USACE Project by partially addressing some of the channel maintenance concerns and further the Authority's understanding of how various processes operate and interact within the entire watershed, but primarily focusing on the San Benito River. Our work presented here updates a prior sediment transport analysis for the San Benito River completed as part of the Phase 4b Study (PWA, 2005) and improves our understanding of the relative sediment loads of the San Benito and Pajaro Rivers.

The previous study provided insights into how sediment is eroded, transported and deposited in the Pajaro River watershed. However, it also highlighted data gaps that must be filled to reach consensus on the Levee Project and meet the objectives of the Integrated Regional Water Management Plan (IRWMP). The data gap was identified in the current sediment transport model between the confluence with the Pajaro River and River Mile 0.7 on the San Benito River. This gap, due to the limit of high resolution spatial data, meant that it was unknown how much sedimentation or erosion occurs just prior to the two rivers joining.

The goals of this assessment, aimed in part at addressing existing data gaps as well as extending the understanding of the system through field observation and measurements, were as follows:

- Establish a monitoring program to collect sediment concentration and flow data on both the Pajaro River and the San Benito River above their confluence, so that an accurate sediment budget for the two river systems can be developed;
- Update, extend, and calibrate the existing San Benito River sediment transport model;
- Compare historic profiles and select cross sections to 2010 data;
- Provide refined estimates of the relative sediment contributions from the San Benito River and Upper Pajaro River to the Lower Pajaro River.

2.0 Flow and Sediment Monitoring

The purpose of the monitoring effort was to measure flow and suspended sediment in the Pajaro and San Benito Rivers during water year (WY) 2013 and to generate a flow and suspended sediment rating curve for each site. These data would also support hydraulic and sediment transport modeling. The monitoring approach and procedures followed those described in the sampling and analysis plan (PWA, 2012).

Two monitoring sites were established in the fall of 2012, one each on the San Benito and Pajaro Rivers just upstream of their confluence (Figure 1). Each monitoring site was equipped with an ISCO Portable Sampler (model no. 6712) for measuring suspended sediment and an area/velocity meter for measuring stream velocity and depth. Staff plates were installed and surveyed at each site for manual readings of water surface elevations. The sampling equipment at each site is housed in a rugged, weatherproof portable shelter (photos of the sampling sites and equipment are included in **Appendix A**). In some cases, manual grab samples of suspended sediment were taken to supplement automatic water samples. Manual velocity measurements were also made throughout the field season in order to calibrate the flow rating curve at each site. All collected samples were analyzed in a laboratory for suspended sediment concentration.

Monitoring Results

WY 2013 was a dry year, and as a result there were fewer opportunities than anticipated for collecting flow and sediment data at each site. The peak events recorded at the U.S. Geological Survey (USGS) gages on the Pajaro River at Chittenden (USGS 11159000) and the San Benito River at (old) Highway 156 (USGS 11158600) were relatively small, particularly on the San Benito River (**Figure 2**).

A summary of the flow and sediment monitoring results for the upper Pajaro River site are presented in **Figure 3** and **Figure 4** (the flow rating curves, surveyed cross sections, and tables summarizing the field data collected are presented in **Appendix B**). Two peak events were sampled for suspended sediment, that of December 2-3, 2102, and December 24-25, 2012. Only the Pajaro River exhibited any notable discharge during these peak events, the San Benito River watershed generated little-to-no runoff at the monitoring site. A reasonable range of discharges were sampled at the upper Pajaro River site, spanning from approximately 50 to just over 5,000 cubic feet per second (cfs), with which to establish a suspended sediment rating curve. The range of sampled discharges for the San Benito site were too small to establish a reasonable suspended sediment rating curve (all discharges sampled were less than 10 cfs). This tendency for the San Benito River to lag behind the upper Pajaro River in runoff timing and production has been previously documented and is explained partly by differences in watershed geology, size and shape. Flood peaks in the lower San Benito River are reduced considerably by channel storage in the river and percolation into the stream bed (USACE, 1944). Further, the San Benito River watershed is elongated (i.e., “stretched” along the northwest trending San Andreas fault zone) resulting in relatively long travel times for runoff generated in the upper watershed areas. Based on the data collected from the monitoring sites, approximately 98 percent of the flow volume and essentially 100 percent of the sediment volume delivered to the lower Pajaro River was attributable to the upper Pajaro River during WY 2013.

3.0 Topographic Data/Field Verification

The purpose of collecting and acquiring additional topographic and sediment data was to update and extend the previous sediment transport model. To update the existing sediment transport model geometry, ESA PWA acquired high-resolution Light Detection and Ranging (LiDAR) data (AMBAG, 2010) and conducted a limited field survey of the lower San Benito River to supplement the LiDAR data. Though the initial focus of the model update was the lower 1.4 miles of the San Benito River, given the availability of LiDAR data, the geometry update was extended to include the entirety of the San Benito River study area as well as the lower Pajaro River from the San Benito River confluence through the Chittenden Pass. A secondary purpose of acquiring LiDAR data was to compare the bed profiles and select cross-sections of the San Benito and upper Pajaro River over time.

Field Surveys (June 2012)

On June 18, 2012 and June 25, 2012, ESA PWA staff inspected and surveyed the San Benito River from the monitoring site (approximately RM 0.96) downstream to the confluence with the Pajaro River. The purpose of these visits was to collect channel geometry data and to make general observations on the condition of the channel. Channel width measurements, a surveyed cross section, and surveyed bed profile points, were used as input to the sediment transport model and to verify the accuracy of the LiDAR data within this lower reach (discussed below). Survey data were collected using a combination of a total station and a Real Time Kinematic (RTK) – GPS unit (select photos from the field survey are included in Appendix A).

The channel in this lower reach is straight, narrow, and confined by levees. Generally, there is an extensive amount of riparian vegetation within the floodplain (i.e., for areas not subject to existing industrial or agricultural uses), on the banks, at the channel margin, and, in some cases, within the channel. Overall channel morphology was relatively uniform. Riffle and pool bed undulations were apparent, but there was little concurrent variation in channel width associated with these features. Pools were typically long and deep, especially in the reach upstream of Highway 101. The active channel width (as measured between the bank toes) generally varied between 20 and 30 feet, with an average of 24 feet. The channel bed was comprised of mostly gravel at the riffles, and gravel, sand, and fines (silt and clay) within the pools. A layer of very fine material ("muck") and/or sand (approximately six inches thick), overlying gravel, was present throughout the channel. Underneath the vegetation, the banks and floodplain were mostly comprised of fine, non-cohesive sediment. Coarser gravels were observed in the bank profiles in the lower part of the reach (i.e., the lower 1,200 feet of the San Benito River).

At its mouth, the San Benito River widens and flow becomes shallow, draining into a wide, gravel-filled pool of the Pajaro River. At the time of the survey, the bed and water surface of the San Benito River was hanging approximately 4 to 5 feet above the Pajaro River at the confluence. The bed substrate here, which includes gravels, sands, and finer material, is highly cemented, likely due to the chemistry of the Pajaro River (e.g., the presence of calcium and/or carbonates).

To supplement the bed sediment data collected previously (PWA, 2005), additional bed surface samples were collected at 5 riffle locations within the surveyed reach (Figure 1). Samples were analyzed in a laboratory for grain size distribution (**Figure 5**). The bed sediments within the surveyed portion of the lower San Benito River are generally much coarser (overall D50 = 9.13 millimeters [mm]) than those summarized previously for the upper reaches (PWA, 2005) (overall D50 = 0.84 mm). This lowermost reach of the San Benito River is more confined, straightened, and steeper than the upstream reaches, and this may explain, in part, the contrast in overall bed sediment size.

2010 LiDAR Data

Geometry data for the updated sediment transport model was derived from the *LiDAR dataset for the Central Coast of California, 2010,* compiled by Digital Mapping Inc. for the Association of Monterey Bay Area Governments (AMBAG) (2010), using the Arc 10.1 HEC-GeoRAS and 3D analyst extensions. The original dataset extended beyond the study area and was recompiled to maximize processing within HEC-GeoRAS.

The source triangular irregular network (TIN) tiles overlapping the study area were processed in the following steps to preserve digital terrain model (DTM) characteristics between the source-supplied LiDAR tiles and recompiled TINs used for model input:

- Tin nodes were extracted from the LiDAR TINs and grouped into an ArcGIS geodatabase for terrain processing;
- A Terrain Model (TM) was constructed with the TIN nodes set as mass points and clipped against a polygon representing the project reach. The resulting TM excluded areas outside the study reach to maximize computing efficiency, display, and surface sampling within GeoRAS;

- The TM was converted to TINs at full resolution and sampled at user defined cross sections along the Pajaro and San Benito Rivers;
- Channel centerlines, reach lengths, cross sections, and other required HEC-RAS geometry data was extracted from the GeoRAS database and imported to HEC-RAS model software. Cross section spacing varied from approximately 200 to 1,000 feet.

The LiDAR-derived cross-sections and resulting profile for the lower San Benito River were compared to 1) field observations and survey data collected in June, 2012 (described above), and 2) the modeled geometry in a previous HEC-RAS model developed by RMC and acquired from AMBAG. The LiDAR data correlated well with the collected survey data though poorly with the previous HEC-RAS model geometry through the lowermost extent of the San Benito (**Figure 6**). The gradient of the lower San Benito River in the RMC HEC-RAS model (0.0063 ft/ft) was much steeper than that derived from both the LiDAR and survey data (0.0035 to 0.0036 ft/ft), and the elevation of the San Benito river mouth in the previous HEC-RAS model was much lower than what was measured in the field and derived from the LiDAR data. The LiDAR data for the lower Pajaro River were not field verified.

Historic Profile and Cross Section Comparison

The LiDAR data were used, together with information previously published as well as data acquired from the Federal Emergency Management Agency (FEMA), to assess and verify rates of channel elevation change in the San Benito River and the upper Pajaro River (upstream of the San Benito River confluence). With respect to previously published data, the 2000 channel geometry data are from the previous version of the sediment transport model (PWA, 2005), which were originally derived from a digital elevation model (DEM) of the San Benito River created by the Granite Rock mining company in 2000. The 1985 and 1991 (below) channel geometry data are from the existing FEMA HEC-RAS models for the San Benito and upper Pajaro Rivers (FEMA, 1989; 1991), respectively, and the 1955 and 1974 data are from the Golder Associates (1997) report.

San Benito River

The San Benito River has undergone dramatic changes in channel morphology over the last 50 years, many related to gravel mining activities (PWA, 2005). Previous studies have documented substantial periods of incision since 1955 and 1974, primarily in the upper reaches of the study area (Golder Associates, 1997; PWA, 2005).

A comparison of long profiles indicates overall degradation of the San Benito River over the long-term, with the highest rates evident in the upstream reaches (**Figure 7**). Recent profile comparisons (2000 and 2010) indicate that erosion still persists in the upper reaches, though downstream the San Benito River now appears stable to depositional. Upstream of new Highway 156, the San Benito River has generally shown consistent incision between 1955 and 2010, though at varying rates. Between new Highway 156 (RM 8.37) and Nash Rd (RM 10.7), the San Benito River has incised by an average of approximately 2.5 feet since 2000 (or 0.25 feet/year). Upstream of Nash Road, the degree of incision since 2000 ranges from approximately 3.5 to 6.25 feet (or 0.35 to 0.63 feet/year). Presently this reach exhibits the highest rate of incision. Cross section comparisons at the old Highway 156 (RM 9.5) and at Union Road (12.1) also indicate notable incision and channel widening, particularly when compared to the 1985 FEMA data (**Figure 8**). The cross-section at Union Road shows approximately 8 feet of channel incision since 1985 (or 0.32 feet/year). Based on the 2010 bed profile, the San Benito River has incised at an average rate of 0.25 to 0.63 feet per year upstream of new Highway 156. These rates are consistent with previous estimates of 0.4 to 0.7 feet per year upstream of RM 6.0 (Golder Associates, 1997).

Knickzone migration appears to play a role in some of the observed bed incision on the San Benito River. The 2000 profile indicates a possible knickzone at approximately RM 5.5, which appears to have migrated headward to RM 6.6 based on the 2010 profile, resulting in approximately 2.6 to 5.1 feet of incision over this short reach (or 0.26 to 0.51 feet/year). Previous analysis (Golder Associates, 1997) suggested that, from 1955 to 1974, a different knickzone on the San Benito River had migrated headward from RM 6.5 to a point between RM 7.5 and 9.0. It is likely that multiple knickzones are migrating headward within the San Benito River system. However, the apparent stability in the lower profile over the last 40 years implies that a large-scale change in base-level control is an unlikely explanation for the knickzone initiation, suggesting that the causes may be more localized.

Downstream of RM 5.5, the profile of the San Benito River has remained relatively consistent to depositional since 2000. A distinct break in slope occurs at approximately RM 3.9 as the gradient flattens downstream of this point, and this is generally concurrent with a change in channel pattern from wide and braided to a more meandering channel. Further, though the lowermost reach of the San Benito steepens significantly, it is interesting to note that compared to 1974 the mouth of the river has aggraded by approximately 3.1 feet. Thus, between the mouth and RM 5.5, the San Benito River appears to be storing a portion of the channel sediments being eroded through incision upstream.

Upper Pajaro River

In contrast to the San Benito River, the upper Pajaro River (from the San Benito River confluence upstream to Highway 101) has shown substantial aggradation since 1992 (**Figure 9**). Based on the bed profiles from 1991 (FEMA) and 2010, the upper Pajaro River has experienced aggradation along its length of between 1.9 to 5.1 feet (or 0.11 to 0.28 feet/year), with the maximum amount occurring near Highway 101 (**Figure 10**). Comparison of the cross sections at Highway 101 also indicates notable filling and narrowing of the channel, resulting in reduced capacity. Just upstream of the San Benito River, the bed elevation of the upper Pajaro River has increased by 3.3 feet over the last 20 years, which is consistent with the observation above that the mouth of the San Benito River has aggraded by approximately 3.1 feet (based on the 1974 and 2010 profiles). Flood discharges from the San Benito River can create an extensive backwater on the upper Pajaro River (between the San Benito River confluence and Soap Lake) (RMC, 2001; 2004), possibly promoting substantial sediment deposition during floods. The observed aggradation on the upper Pajaro River, as well as at the San Benito River mouth, was perhaps in part a result of the large flood events in 1995 and 1998. It does not appear that systemic incision on the upper Pajaro River, between the San Benito confluence and Highway 101, is a potential, notable source of sediment to the lower Pajaro River.

4.0 Sediment Transport Model Update

ESA PWA utilized the sediment transport module within HEC-RAS (RAS Sediment), developed by the U.S. Army Corps of Engineers (USACE, 2010), to build an updated version of the previous model and simulate sediment transport in the San Benito and lower Pajaro Rivers.[1] RAS Sediment is a one-dimensional, open channel flow and mobile-bed sediment transport model that simulates erosion and deposition of river channels based on varying flow events and routes sediment downstream. In general, a sediment model requires channel geometry, hydrology (quasi-unsteady flow hydrograph), and bed sediment gradation inputs. RAS Sediment takes the geometry and hydrology inputs and calculates a water surface profile providing energy slope, depth, velocity, and other necessary parameters at each cross-section. RAS sediment also allows definition of mobile bed and erosion

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1 HEC-RAS version: *HEC-RAS 4.2.0 July 2013 Beta (Alpha 2D Flow Areas)*

limits that define where each cross-section can change volumetrically over the duration of the modeled flows. Sediment transport rates are computed using a variety of sediment transport functions, and each cross-section is then adjusted during the simulation, accounting for bed and bank change.

Selection of an appropriate sediment transport functions is critical to this study, and must be appropriate for the observed bed grain size distributions. Multiple functions are available within RAS Sediment. Yang and Huang (2001) compared 13 sediment transport formulae under different flow and sediment conditions to develop a comparative index of applicability of each method for use in modeling different size ranges. Based on their results, and the results of the previous modeling effort (PWA, 2005), ESA PWA selected the Ackers and White (1973) sediment transport function. This function is particularly suited for the sediment size ranges present within the San Benito and lower Pajaro Rivers.

Model Setup – Hydrology and Geometry

The study area comprises approximately 12.4 miles along the San Benito River from near the town of Hollister to the confluence with the Pajaro River (river miles on the San Benito River are from the confluence with the Pajaro River), and approximately 4.1 miles of the lower Pajaro River from the Chittenden Pass (RM 16.01) upstream to the San Benito River (RM 20.15) (river miles on the Pajaro River are from the ocean) (**Figure 11**). The upstream boundary is at RM 12.40 on the San Benito River, approximately 0.3 miles upstream of Union Road, and the downstream boundary is located at RM 16.01 on the lower Pajaro.[2] Cross section geometry was extracted from the LiDAR data (as described above) and input to the model. No structures (bridges, culverts, etc.) were included in the model.

Flow hydrographs were routed from the upstream boundary on the San Benito River through the downstream boundary of the lower Pajaro River at the Chittenden Pass (essentially treating the San Benito and lower Pajaro River as one large reach). The previously developed sediment transport model simulated several flow conditions, including a 100-cfs flow that approximates the 1.5-year recurrence interval on the San Benito River, as well as the 10-, 25-, 50-, and 100-year floods. We utilized these same flow hydrographs as our upstream inflow boundary condition (**Figure 12**). For calibration and longer-term simulation, we also used the instantaneous flow record for the USGS Gage at (old) Highway 156 on the San Benito River (USGS 11158600), over the period of WY 1988 through 2010. The 15-minute flow records were converted to hourly averages and, for purposes of modeling, the flow-record was consolidated to only include average hourly flows at or above 100 cfs (**Figure 13**). Initial model roughness values were taken from the Flood Insurance Study (FIS) (FEMA, 2009).

Model Setup – Sediment Inputs and Boundary Conditions

Two sets of sediment input data are needed for sediment transport modeling: the concentration and distribution of inflowing sediment (sediment rating curve) and the particle size distribution of the bed material. Observed sediment concentrations and size distributions of the inflowing sediment load were not available for the upstream boundary, so these data were synthesized using the transport capacity of the upstream bounding cross section for the San Benito River (i.e., the upstream boundary was set to the *equilibrium load* option in RAS Sediment). Given the persistent incision observed in the upper San Benito River over time this boundary condition likely overestimates the incoming sediment load as incision is indicative, in part, of supply-limited sediment conditions.

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[2] Cross section geometry for the upper Pajaro River, from the San Benito River to just upstream of Highway 101, is included in the model. This was done to facilitate future use of the model for the upper Pajaro River; the upper Pajaro River was not included in the model runs and analyses of this study.

Bed gradation information was taken from the previous report (PWA, 2005) as well as from the recent field survey effort (above). For the upper reaches of San Benito River (RM 1.22 to 12.40) we used the average of the bed gradations collected in 2005 and used in the previous sediment transport model (PWA, 2005) (see Figure 5). For the lowermost section of the San Benito (RM 0.0 to 1.22), we used the average of all bed gradation samples, including those collected within that reach in June, 2012, which represents a coarser distribution (i.e., a higher content of coarse sand and gravel) (see Figure 5); we also used this gradation for the lower Pajaro River. Field observations suggested that the overall bed gradation within this reach of the San Benito River is indeed coarser, and is likely a reflection of a higher overall transport capacity as this lowermost reach is notably steeper and straighter than the upstream reaches. Further, the overall average gradation was consistent with gradations reported previously for the lower Pajaro River (PWA, 1997).

Calibration

Model calibration generally involves adjusting a number of input parameters and subsequently assessing model stability, sensitivity, and performance with respect to known or measured values (e.g., measured sediment loads). However, as described above, due to the lack of any notable flows at our San Benito River monitoring site, a useful sediment rating curve could not be established. Therefore, the model could not be calibrated with measured sediment transport data from the San Benito River, and we subsequently took a more qualitative approach to model calibration and assessment.

Initially, the model was set up and run with the 25-year hydrograph to assess overall model stability and pin-point problematic reaches or cross sections (e.g., areas of unrealistic bed change predictions). This initial effort primarily involved assessing and adjusting the mobile-boundary limits of the cross sections and carefully defining areas of assumed ineffective flow, both of which can have a large impact on model stability and results. After initial model set-up and preliminary runs to assess stability, the primary factors to adjust with respect to calibration were the sediment transport equation parameters and channel roughness values.

In place of measured transport rates on the San Benito River, we assessed the transport equation parameters with respect to the sediment transport data collected at the USGS gage on the Pajaro River at Chittenden (USGS 11159000) (USGS, 2013a). Three parameters in the Ackers and White (1973) sediment transport equation can be adjusted within a limited range: the threshold mobility parameter (A) and two transport function coefficients (C, m). Ackers and White (1973) empirically related all these values to median grain size based on their experiments. In RAS Sediment, the parameter and coefficient values in the Ackers and White equation were adjusted based upon the median sediment size of the upper San Benito River (0.84 mm), as derived from the previously collected bed samples (PWA, 2005).[3] This likely slightly overestimates the sediment load in the lowermost reach of the San Benito River and the lower Pajaro River, as coarser grain size distributions were assumed for these reaches. However, this produced the most realistic, order-of-magnitude results when comparing the predicted sediment transport rates to the sediment transport data collected at the USGS gage (USGS 11159000).

In-lieu of using measured transport rates, and to generally assess model accuracy with respect to observed rates of erosion or deposition, we executed model runs using the 2000 (PWA, 2005) model geometry. The 2000 geometry was largely unmanipulated, save for adjusting the mobile-bed boundaries to be consistent with those assumed for

[3] The following parameter and coefficient values were used in the Ackers and White (1973) equation: $A = 0.193$, $C = 0.032$, and $m = 2.037$

the 2010 geometry. We used the hourly-average flow hydrograph that we developed from the USGS gage at (old) Highway 156 (USGS 11158600) to simulate the 2000-2010 hydrograph. A roughness value on 0.04 for the main channel of the San Benito River, from the model boundary (RM 12.40) downstream to RM 3.97, produced the best results with respect to predicting observed changes in bed profile and cross section. Therefore, a roughness value of 0.04 (vs. 0.05, the value from the FIS) was subsequently used in the model for the main channel of the San Benito River over this reach; all other roughness values were unchanged from those presented in the FIS (FEMA, 2009). In many areas the upper San Benito has a wide bed comprised of fine gravel and sand, with little in-channel vegetation, and it is reasonable to assume that these reaches may have a lower roughness value than those assumed in the FIS.

Though the model was satisfactory in accurately predicting general areas of erosion and deposition, or areas of no real net change, the model generally did not approximate the magnitude of observed bed change over most of the San Benito River (**Figure 14**). For example, the model does a good job at estimating the degree of incision at the old Highway 156 bridge between 2000 and 2010 (Figure 14), though it does not well approximate the degree of incision further downstream. The inability of the model to accurately approximate the observed bed changes could be attributable to a number of factors in this case, and does not negate the model’s ability to accurately predict sediment transport based on the existing 2010 geometry. Gravel mining activities have a significant influence over observed changes in the bed, directly and indirectly, and these cannot be explicitly accounted for in the model. Further, some or most of the observed channel incision and bed lowering is likely attributable to the upstream migration of knickzones and local changes in base-level control, processes which cannot be accurately modeled using the 2000 geometry data. Sediment transport is highly sensitive to cross section geometry variations and the extent of the mobile-bed boundary, and the relatively coarse resolution of the 2000 geometry data, particularly in the wide reaches of the San Benito River (e.g., from RM 4.9 to 8.3), may result in the underestimation of transport rates because the low-flow channels are not adequately defined.

Modeling Results

ESA PWA analyzed two primary outputs from the RAS Sediment model, channel bed volume change at each station throughout the San Benito River, and sediment load throughout the study reach. The first of these outputs provides a spatial framework to evaluate locations of consistent bed erosion or deposition, and the latter is an overall measure of the sediment being delivered to and transported through the lower Pajaro River.

Spatial Patterns of Bed Erosion and Deposition

For almost all flow conditions, the model results suggest that the San Benito River is generally erosional between the Hollister area downstream to approximately RM 4.5, just upstream of where a notable break in slope and change in river plan form occurs (at RM 3.9). Downstream of RM 4.5, the change in bed elevation is generally depositional to neutral. Spatial patterns of bed erosion and deposition are consistent between all flow events (**Figure 15**), though the magnitude of erosion and deposition changes between events. Further, the spatial variations predicted by the model agree well with the existing bed profile as well as changes observed from 2000 and 2010. The pattern of erosion and deposition is discussed from upstream to downstream.

- Upstream of RM 9.5 generally shows the most persistent erosion and this is consistent with the observed changes in the bed profile (Figure 7). From RM 12.4 (upstream model boundary) to 11.5, and from RM 10.8 to 9.0, the channel is erosional, particularly in the lower reach just downstream of Nash Road. A short, depositional reach (RM 11.5 to 11.0) occurs just upstream of Nash Road, which is where the existing bed profile is generally flat (Figure 7). The channel narrows at the Nash Road crossing, and this likely induces deposition and a flattening of the channel gradient upstream.

- Between RM 9.5 and 7.0 there is little incision or deposition and subsequently little net change in the bed elevation, which suggests the channel is relatively stable. The flat area of essentially no change, from RM 7.7 to 7.0, coincides with the widest section of the San Benito River (Figure 1) as well as with the only section of the profile that shows deposition between 1974 and the present (Figure 7). The one consistent area of erosion in this reach, apparent during the 50- and 100-year events, coincides with the new Highway 156 crossing (RM 8.4).
- From RM 7.0 to 4.5 there is no obvious pattern, though it appears slightly erosional overall. The bed profiles from 2000 and 2010 show little change over this reach (Figure 7).
- From RM 4.5 to 3.0 two persistent areas of deposition are obvious. This is consistent with a marked decrease in the overall bed slope near this point (at RM 3.9) and a concurrent change in channel pattern from straight or braided to a more meandering channel with two large bends in the river downstream of this point (at RM 4.5 and 3.3). Once again, the bed profiles from 2000 and 2010 show little change over this reach (Figure 7).
- From RM 3.0 to 2.0 the channel is erosional. The channel narrows over this short section (PWA, 2005) and is relatively straight, thus prompting incision during large flow events. Downstream of this point, the general pattern of deposition from RM 2.0 to 1.7 is again coincident with a relatively large bend in the river.
- Downstream of RM 1.7 the model generally shows alternating areas of substantial erosion and deposition, though overall this lowermost reach exhibits net erosion of the channel bed. Downstream of RM 1.2 the channel steepens considerably, and the large variations between erosion and deposition within this reach, over all flows, could be the result of subtle changes in channel hydraulics leading to large changes in transport potential. This dramatic variation in bed elevation could also indicate that the present slope and/or channel geometry within this reach are not stable. The tendency for this lowermost reach to incise over time, given its steeper slope, is perhaps counteracted by the apparent aggradation within the Pajaro River at the confluence with the San Benito River (discussed above) and/or the backwater effect of the lower Pajaro River. However, in the absence of large flows emanating from the upper Pajaro River, this reach may erode.

Cumulative Sediment Loads (Event-Based)

The cumulative sediment loads for the complete duration of each event are summarized in **Table 1** for three locations: the San Benito River mouth (model RM 0.10), the lower Pajaro River at Chittenden/Highway 129 (model RM 17.86), and the lower Pajaro River at the downstream end of the Chittenden Pass (model RM 16.01, downstream extent of model). The sand and gravel fraction of the total load is also presented here (**Table 2**), this

TABLE 1
CUMULATIVE SEDIMENT LOADS DURING EVENT, TOTAL LOAD

Flow Event	San Benito River mouth (tons)	Lower Pajaro River at Hwy 129 (RM 17.86) (tons)	Lower Pajaro River at Chittenden Pass (RM 16.01) (tons)
BANKFULL	3,710	1,317	1,852
Q10	53,353	37,240	37,823
Q25	111,255	84,463	86,552
Q50	233,508	180,857	184,196
Q100	299,515	237,773	242,221

TABLE 2
CUMULATIVE SEDIMENT LOADS DURING EVENT, SAND AND GRAVEL LOAD

Flow Event	San Benito River mouth (tons)	Lower Pajaro River at Hwy 129 (RM 17.86) (tons)	Lower Pajaro River at Chittenden Pass (RM 16.01) (tons)
BANKFULL	911	29	211
Q10	11,775	1,337	4,644
Q25	24,406	4,266	9,748
Q50	54,466	12,106	21,209
Q100	69,373	19,096	30,023

value comprises the material load greater than 0.063 mm in diameter, which represents the division between silt and sand according to the size classification commonly applied in fluvial geomorphology. For all such values reported herein, the majority of the combined sand and gravel load is comprised of sand (0.063 mm to 2.0 mm). This value is important, as the sand and gravel fraction is most likely to accumulate and be stored within the channel over time, whereas silt-sized and a finer material are more efficiently transported through, even at low flows.

A relatively large volume of material is delivered from the San Benito River to the lower Pajaro River during the modeled events. For example, the 100-year event is estimated to deliver 299,515 tons of sediment to the lower Pajaro River. By comparison, the bankfull event, which represents conditions similar to an average flood event, would deliver 3,710 tons of sediment to the lower Pajaro River. Approximately 22 to 23 percent of the total, event-based cumulative sediment load delivered to the lower Pajaro River is comprised of sand and gravel.

The model results also indicate that a portion of the total sediment load delivered to the lower Pajaro River, approximately 19 to 50 percent depending on the flow, is stored within the reach between the San Benito River and Highway 129, much of which is deposited just downstream of the San Benito River mouth. At lower flows approximately half of the sediment load delivered from the San Benito River is stored within the reach of lower Pajaro River just downstream, yet this fraction decreases with increasing flow. However, the portion of the stored sediment that is comprised of sand and gravel increases with flow. For example, during the 50-year event on the San Benito River approximately 52,651 tons (or 23 percent) of the sediment load delivered to the Pajaro River would be deposited upstream of Highway 129, the majority of which (42,360 tons) would be sand and gravel. Extrapolating from this predicted relationship, we might hypothesize that during medium flows the San Benito River contributes sediment that is stored between the confluence and the Chittenden Pass, but that during high flows some of this excess is transported into the Pajaro Valley as the two systems' sediment transport capacities converge. Remobilization of this stored material could subsequently account for a portion of the sediment load mobilized through this reach of the lower Pajaro River when the Pajaro River is at high flow and the San Benito is not.

Sediment Transport Rates (Event-Based)

To facilitate comparisons to existing sediment rating curves, we also used the model to calculate peak transport rates (**Table 3** and **Table 4**). The sediment transport rates shown were calculated for the peak flow condition during the given event. Similar to the cumulative sediment loads, the modeled sediment transport rates indicate that a relatively large volume of material is delivered from the San Benito River to the lower Pajaro River during flood events, and that a fraction of this incoming load is likely stored within the lower Pajaro River upstream of Highway 129.

TABLE 3
PEAK SEDIMENT TRANSPORT RATES, TOTAL LOAD

Flow Event	San Benito River mouth (tons/day)	Lower Pajaro River at Hwy 129 (RM 17.86) (tons/day)	Lower Pajaro River at Chittenden Pass (RM 16.01) (tons/day)
BANKFULL	555	203	282
Q10	52,049	38,791	38,857
Q25	110,168	95,199	96,749
Q50	161,638	150,899	154,086
Q100	193,280	178,750	180,776

TABLE 4
PEAK SEDIMENT TRANSPORT RATES, SAND AND GRAVEL LOAD

Flow Event	San Benito River mouth (tons/day)	Lower Pajaro River at Hwy 129 (RM 17.86) (tons/day)	Lower Pajaro River at Chittenden Pass (RM 16.01) (tons/day)
BANKFULL	139	4	32
Q10	10,569	1,292	4,597
Q25	15,553	4,812	9,791
Q50	18,866	9,899	15,034
Q100	20,605	14,155	22,198

In **Figure 16**, the modeled peak sediment discharge rates for the San Benito and lower Pajaro Rivers are plotted and compared to the sediment rating curves derived for the USGS gage on the Pajaro River at Chittenden (USGS 11159000) and our upper Pajaro River monitoring site (for WY 2013). While there is potential error associated in comparisons between predicted (sediment transport model) and observed sediment fluxes over non-concurrent time periods, such comparisons do give a general idea of the relative sediment contributions. Our modeling shows a relatively close fit between the predicted sediment transport rates at the San Benito River mouth and in the lower Pajaro River as compared to the observed sediment flux at the USGS Pajaro River gage at Chittenden, and improves upon the previous relationship presented by PWA (2005).

Assuming that for a given event all of the flow is coming from the San Benito River, a comparison of the model results to the USGS sediment rating curve would indicate, similar to the analyses above, that some portion of the sediment delivered from the San Benito River is stored within the reach of lower Pajaro River immediately downstream. For example, at a given flow the sediment load derived from the USGS gage data on the lower Pajaro River is smaller than the incoming sediment loads predicted by the model. It should be noted that the USGS data do not account for the bedload component of the total load, which is accounted for in the model. However, this fraction would likely only represent around a 5 percent increase in the transport rate predicted by the sediment rating curve for the USGS gage. The rating curves are very similar at the largest flows, confirming that during very large events (e.g., 50- and 100-year events) the transport capacities of the two systems converge.

In **Table 5** we compare the modeled San Benito River sediment transport rates to those measured at ESA PWA's upper Pajaro River monitoring site. For a given flow, the San Benito River transport rates are taken from the model and the upper Pajaro River transport rates are calculated from the rating curve equation shown in Figure 16. Assuming the same flow rate is coming from the upper Pajaro River and San Benito River, respectively, the contribution of sediment from the San Benito River to the lower Pajaro River is relatively large (>80 percent) for low the moderate discharges, and this contribution decreases to around 60 percent at large flows. At the highest discharges (e.g., 50- and 100-year events) the transport capacities of the two systems appear to converge. Even if one makes the comparison between the total load of the San Benito *less* the sand and gravel fraction (since the upper Pajaro River monitoring site data reflect only suspended load and exclude the bedload component), the relative contributions remain similar, generally changing by less than five percent.

TABLE 5
COMPARISON OF PEAK SEDIMENT TRANSPORT RATES

	San Benito River mouth[1]			
Flow Event	**Total Load (tons/day)**	**Sand/Gravel Load (tons/day)**	**Upper Pajaro monitoring site, Total Load (tons/day)[2]**	**Percent of Total Load from San Benito River**
BANKFULL	**555**	139	**8**	**98.5%**
Q10	**52,049**	10,569	**14,290**	**78.5%**
Q25	**110,168**	15,553	**61,272**	**64.3%**
Q50	**161,638**	18,866	**138,506**	**53.9%**
Q100	**193,280**	20,605	**191,593**	**50.2%**

NOTES:
1 *From HEC-RAS sediment transport model.*
2 *Calculated using suspended sediment rating curve from ESA PWA's upper Pajaro River monitoring site (see Figure 4).*

Cumulative Sediment Loads (Long-Term)

To assess the magnitude of sediment loads over the long-term, we ran the existing model using the hourly flow hydrograph derived from the USGS gage on the San Benito River at (old) Highway 156 (USGS 11158600) for WY 1989 through 2010. The hourly flow hydrograph was consolidated to include only flow events of 100 cfs or greater (as described above). The results of the long-term simulation are presented in **Table 6**, and are ordered from upstream to downstream (i.e., top to bottom in the table) to show how the cumulative load changes moving downstream.

TABLE 6
LONG-TERM SEDIMENT LOAD ESTIMATES, SAN BENITO RIVER (WY 1989-2010 HYDROGRAPH)

	Cumulative Loads (tons)		Cumulative Loads (cubic yards)	
	Total	**Sand and Gravel**	**Total**	**Sand and Gravel**
RM 8.37 (new Hwy 156)	2,179,396	1,040,354	2,124,610	827,809
RM 4.50	2,069,944	929,407	2,038,030	739,529
RM 1.22	1,711,605	615,374	1,737,713	489,653
RM 0.10 (mouth)	1,686,597	592,823	1,716,971	471,709

Based on the model results, approximately 1,686,597 total tons of sediment (592,823 tons of sand and gravel) would be delivered to the lower Pajaro River from the San Benito River over a period of time reflected by the WY 1989-2010 hydrograph. Volumetrically, this represents approximately 1,716,971 cubic yards of total material and 471,709 cubic yards of sand and gravel. This can be considered a reasonable estimate of the actual, fluvial sediment load delivered over the WY 1989-2010 time period, as well as the potential future load that would be cumulatively delivered over a similar hydrograph. A substantial portion of the cumulative sand and gravel load (approximately 314,033 tons, or 34 percent) is deposited between RM 4.50 and RM 1.22 of the San Benito River according to the model. Recall that downstream of RM 4.50 the San Benito River appeared to be stable to depositional based on the 2000 and 2010 profiles (Figure 7).

For a general comparison, we used the provisional rating curve relationship at our upper Pajaro River monitoring site (Figure 4, Figure 16) to estimate the cumulative sediment load that would be delivered by the upper Pajaro River over the WY 1989-2010 hydrograph. Similar to what was done for the USGS data for the San Benito River gage at (old) Highway 156 (USGS 11158600, we used the flow data from the USGS gage on the Pajaro River at Chittenden (USGS 11159000) to construct an hourly flow hydrograph over the WY 1989-2010 time period (see Figure 13). To construct the flow hydrograph for our upper Pajaro River monitoring site, from the USGS Pajaro River gage data we subtracted out the flow values reported for the USGS San Benito River gage. Using our provisional sediment rating curve from the upper Pajaro River monitoring site (Figure 4), we estimate that approximately 1,318,373 tons of suspended sediment would be delivered from the upper to lower Pajaro River over the WY 1989-2010 hydrograph. Again, this is not necessarily a one-to-one comparison since the San Benito River estimates are derived from the model, and the upper Pajaro River estimates are for suspended sediment only and derived from our provisional sediment rating curve (however, as stated above, including the bedload fraction may add approximately 5 percent to the calculated load). Nonetheless, the comparison provides a reasonable estimate of the relative contributions of the two systems to the lower Pajaro River over an extended period of time. Based on this comparison, approximately 56 percent of the long-term total sediment load delivered to the lower Pajaro River is contributed by the San Benito River.

Further, we used the flow data (Figure 13) and sediment rating curves derived for the USGS gage on the Pajaro River at Chittenden (USGS 11159000) (Figure 16) to estimate the cumulative sediment loads for this location over the WY 1989-2010 hydrograph. The estimated sediment loads are compared to the sediment model estimates for the San Benito River mouth in **Table 7**. Based on this comparison, approximately 48 percent of the long-term, total sediment load delivered to the lower Pajaro River is contributed by the San Benito River. With respect to only the coarse sediment load (sand and gravel) that is the main threat to flood capacity downstream, the estimated long-term contribution of the San Benito River increases to approximately 86 percent. Based on the mean daily flow values for the Pajaro River and San Benito River gages (USGS 2013a, 2013b) over this same time period, only approximately 19 percent of the total flow volume came from the San Benito River, with the remaining majority coming from the upper Pajaro River.

TABLE 7
LONG-TERM SEDIMENT LOAD COMPARISON, PAJARO AND SAN BENITO RIVERS
(WY 1989-2010 HYDROGRAPH)

	San Benito River mouth[1]	Lower Pajaro River at Hwy 129[2]	Percent of Load from San Benito River
Total Load (tons)	1,686,597	3,486,222	48.4%
Sand/Gravel Load (tons)	592,823	686,848	86.3%

NOTES:
1 *From HEC-RAS sediment transport model.*
2 *Calculated using suspended sediment rating curve derived from the USGS gage on the Pajaro River at Chittenden (USGS 11159000) (see Figure 16).*

4.0 Conclusions

Comparing our results with the historic and current long profiles shows that the lower reaches of the San Benito River have generally remained stable to depositional, while the upper half has experienced persistent incision, with the highest observed rates near the upstream extent of the study area. It appears that multiple knickzones have migrated upstream at varying rates, thus propagating incision in a headward direction. Over the past decade, the upper part of the study reach (RM 5.5 to 12.4) has exhibited incision rates on the order of 0.3 to 0.6 feet per year. It is likely that these rates of incision will persist into the near future, generating excess sediment that is stored in the lower reach of the San Benito River and transported downstream into the Pajaro River. The highest rates of future fluvial bed incision are expected to occur upstream of RM 9.5, with the focus being from RM 9.5 to 11.0 (roughly, from the old Highway 156 crossing to approximately one-quarter mile upstream of Nash Road). It is unclear to what degree the observed incision and possible knickzone migration may be attributable to anthropogenic causes as compared to natural processes.

In contrast to the upper San Benito River, the upper Pajaro River (from the San Benito confluence upstream to Highway 101) has shown substantial aggradation since 1992 (between 1.9 and 5.1 feet). It does not appear that systemic incision on this reach of the Pajaro River is a notable source of sediment to the lower Pajaro River. It also appears unlikely that the flood detention function provided by Soap Lake would be threatened by incision along the Pajaro River at this time, as has sometimes been postulated.

The entire sediment transport model has been updated with high-resolution LiDAR data collected in 2010. The model has been extended to include the lowermost reach of the San Benito River as well as the lower Pajaro River from the San Benito River confluence downstream to the Chittenden Pass. The RAS Sediment model is in good agreement with observed areas of net erosion and deposition on the San Benito River, as well as with observed sediment transport rates at the USGS gage on the Pajaro River at Chittenden (USGS 11159000). This study has produced an updated and more accurate sediment transport model of the San Benito River for future flood and sediment studies.

Though the relative contributions between the two systems appears highly variable from year to year, sediment transport model results show that the San Benito River is a significant source of sediment for the lower Pajaro River, contributing a total cumulative load of 299,515 tons during a 100-year event, and 111,256 tons being delivered over the course of a 10-year event. Because the finest sediment largely passes through the lower Pajaro River and is transported to the ocean, in our analysis we have separated out the total load from the sand and gravel load that are more likely to be deposited in the channel and to reduce flood conveyance around Watsonville. Sand and gravel comprise approximately 22 to 23 percent of the cumulative, event-based sediment load from the San Benito River. A fraction of the sediment load delivered from the San Benito River is stored within the lower Pajaro River upstream of the Chittenden Pass and is likely remobilized during subsequent flood events. The remaining material is transported to the lower Pajaro where much is deposited in the flood prone reaches.

Predicted peak sediment transport rates, compared to observed sediment transport rates on the Pajaro River, indicate that the majority of the sediment deposited in the lower Pajaro River is contributed by the San Benito River. Event-based modeling results suggest that during extreme floods (i.e., from the 25-year and 100-year events) 50 to 64 percent of the lower Pajaro River's sediment load comes from the San Benito River, and during smaller, more frequent flood events (i.e., from the 10-year event down) the San Benito River's contribution gets progressively larger, increasing from approximately 80 to 100 percent.

Based on the model results, approximately 1,686,597 total tons of sediment would be delivered to the lower Pajaro River from the San Benito over a period of time reflected by the WY 1989-2010 hydrograph, 592,823 tons (or 35 percent) of which would be sand and gravel (and therefore most likely to be deposited in the area of greatest flood risk). Volumetrically, this represents approximately 1,716,971 cubic yards of total material and 471,709 cubic yards of sand and gravel. By comparison the Bench Excavation Plan has removed approximately 322,000 cubic yards of sand and gravel from the lower Pajaro River, representing about 15 years of cumulative coarse sediment delivery from the San Benito River (assuming all sediment was delivered from the mouth of the San Benito River to the bench excavation project area). Cumulatively, we estimate that the San Benito River accounts for approximately 48 to 56 percent of the total sediment load and up to 86 percent of the sand and gravel load that would be delivered to the lower Pajaro River over an equivalent hydrograph. With respect to the estimated, relative contributions of sediment from the upper Pajaro and San Benito Rivers, we do not quantitatively distinguish natural from anthropogenic sources or mechanisms in the present study.

Recommended Further Study

This study has identified reaches of the San Benito River that are likely to erode in the future, generating sediment that may ultimately reach the lower Pajaro River Flood Plan reaches. We recommend that an opportunities and constraints assessment for erosion reduction be carried out on the San Benito River (between Hollister and the confluence with the Pajaro River). Ideally, this would include an assessment of natural versus anthropogenic causes of erosion and sources of sediment, and should focus on arresting potential knickzones that may migrate upstream and on stabilizing the banks and bed of the San Benito River.

We recommend that flow and sediment monitoring continue on the San Benito and upper Pajaro Rivers, particularly in light of the past dry water year. Additional data on both rivers would allow for further refinement of flow and sediment transport relationships, which could be used to further calibrate the sediment transport model and provide additional estimates of existing and future sediment loads.

With respect to bed changes and model calibration and validation, this should be based upon recent survey data and present conditions. The high degree of anthropogenic disturbance (e.g., sand and gravel mining) on the San Benito River over time introduces substantial uncertainty with respect to the controlling variables in observed channel change, and therefore validation using historic data sets and geometry is complicated and equally uncertain. Select reaches should be targeted for repeated surveys (e.g., between old Highway 156 and Nash Road) and the model could be calibrated/validated with these data sets while minimizing the uncertainty related to external variables.

Additional data regarding channel bed grain size distributions are needed to refine or confirm the assumed size distribution for the lower Pajaro River and, if desired, to adequately describe the upper Pajaro River reach such that it could be added to the sediment transport model.

Future data collection efforts should also focus on the upstream end of the study reach (near Union Road) and assessing and measuring the incoming sediment load. Indirectly, evidence suggests that the San Benito River within the study reach is generally a supply-limited system. However, to what degree this can be attributed to the upstream supply versus the sediment extracted through mining has yet to be examined.

It would be worthwhile for the Authority, or AMBAG, or a similar entity (as appropriate), to explore a potential sponsorship or partnership with the USGS regarding their gages (on the Pajaro River at Chittenden and the San Benito River at (old) Highway 156) and the collection of sediment data. For example, is there a viable and feasible funding mechanism whereby a group of agencies and/or stakeholders could sponsor sediment data collection at these locations? Because of the changes in the channel geometry of the San Benito and upper Pajaro Rivers, it would be very informative to resume collecting sediment data at the USGS gage on the Pajaro River at Chittenden and to re-analyze the sediment rating curve to see how it has shifted over time.

5.0 References

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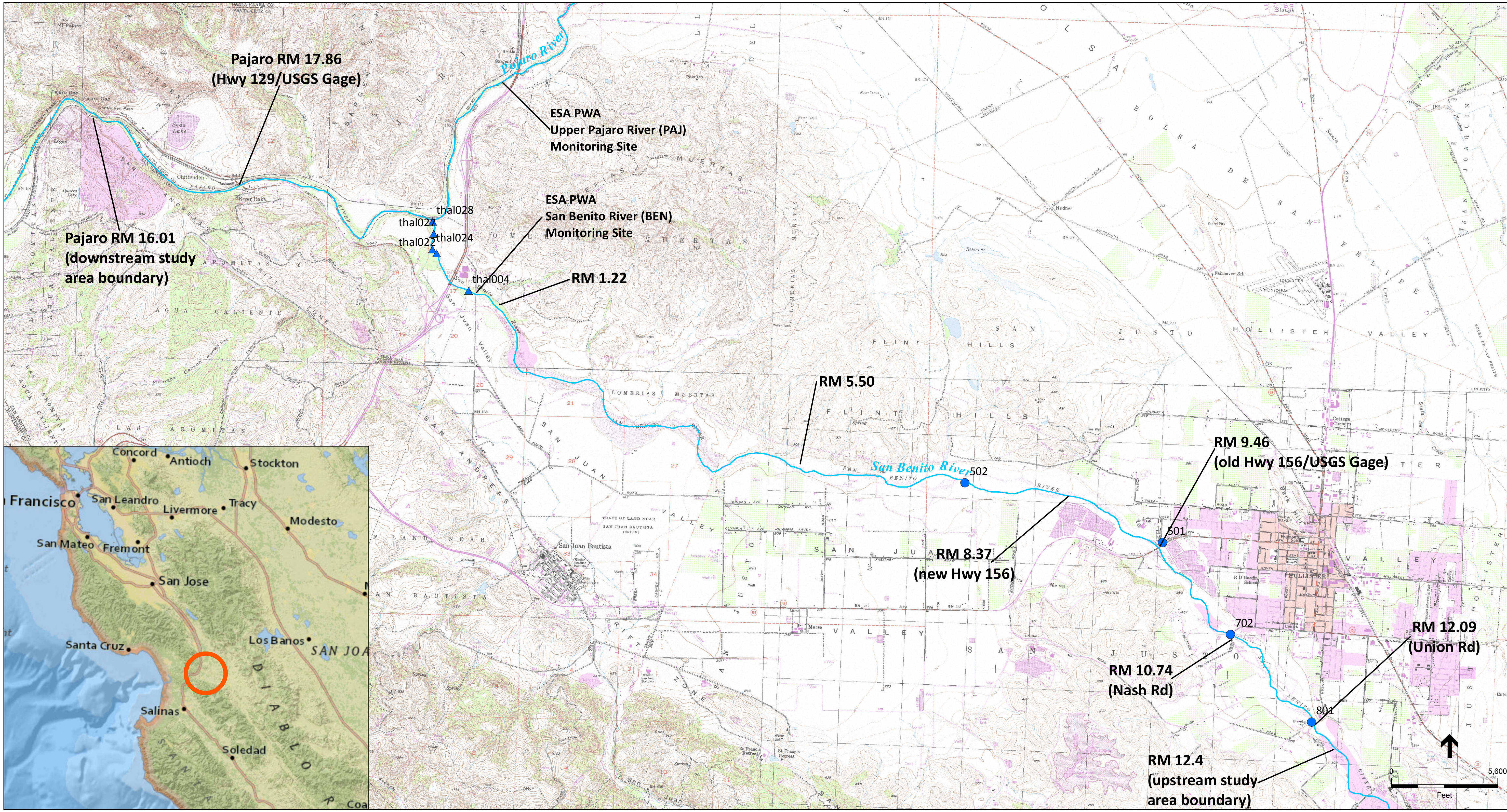
Figures



SOURCE: USGS Quads (basemap)

▲ Sediment Sample Locations (2012)
● Sediment Sample Locations (PWA, 2005)

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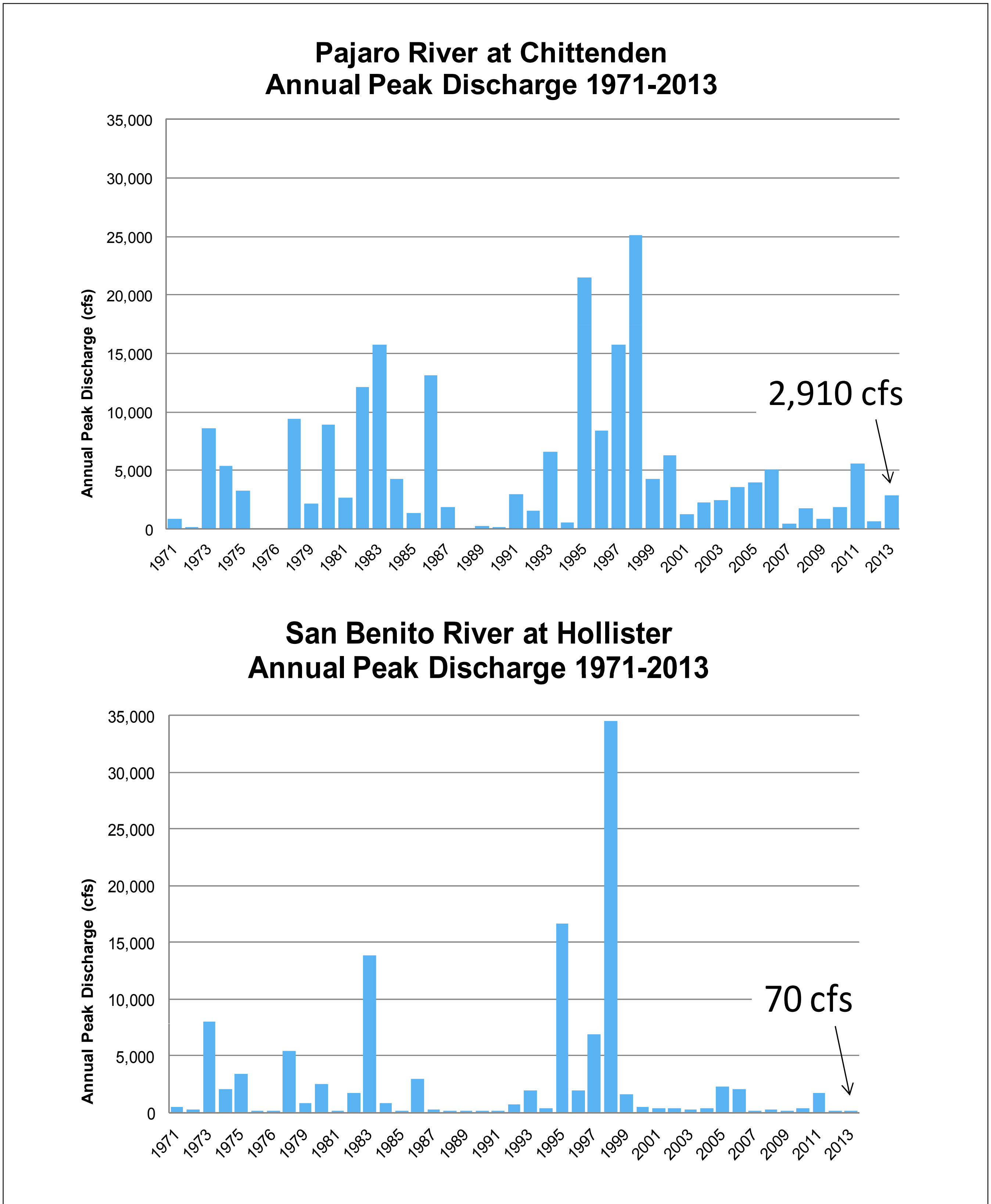
Figure 1
Overview of Study Area



SOURCE: USGS, 2013a, 2013b

Figure 2
Peak Annual Discharges, Pajaro and San Benito Rivers

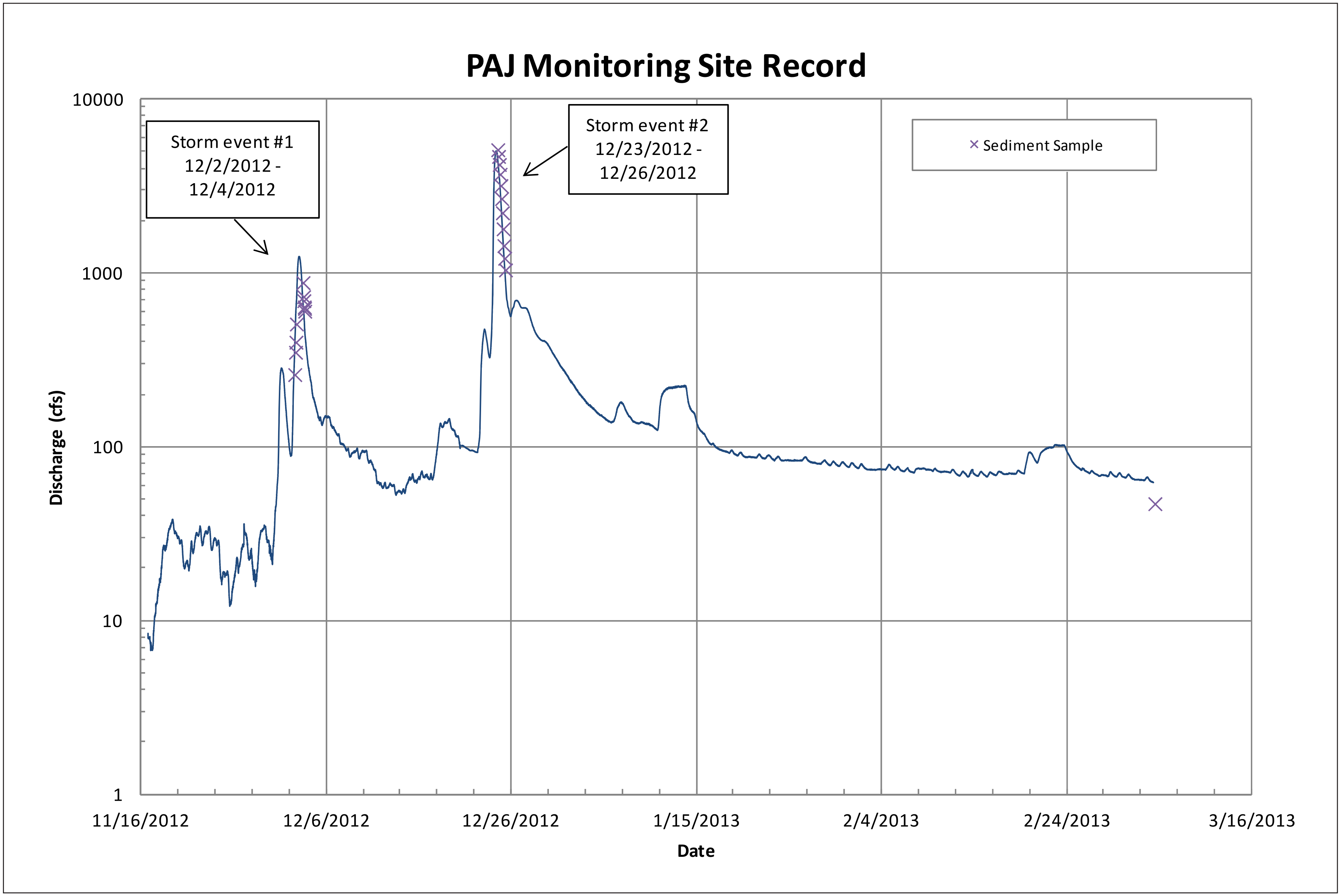


Figure 3
Pajaro River Monitoring Site,
Flow and Sampling Record 11/16/2012-3/5/2013

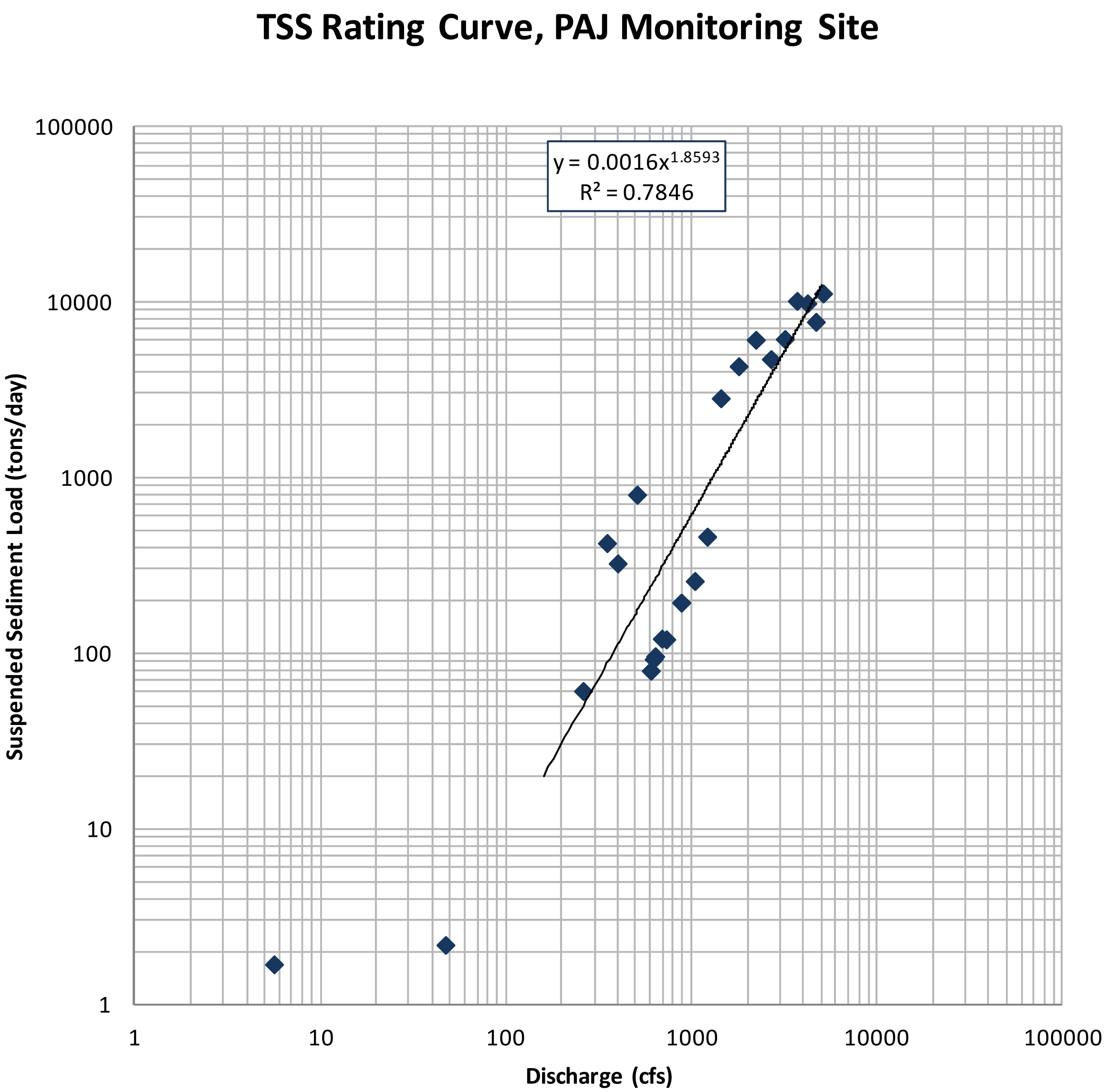


Figure 4

Pajaro River Monitoring Site, Suspended Sediment Rating Curve

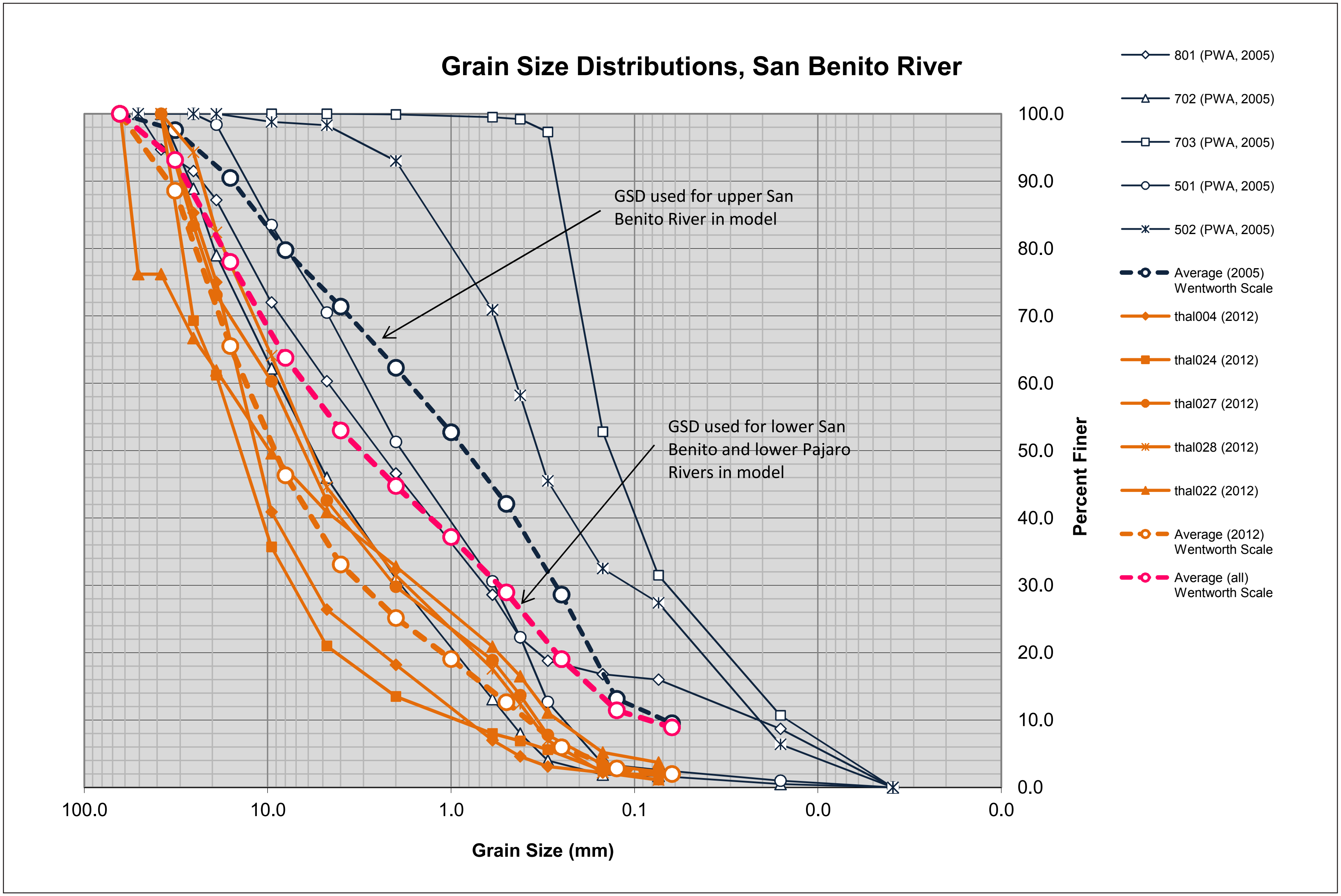


Figure 5

Bed Grain Size Distributions, San Benito River

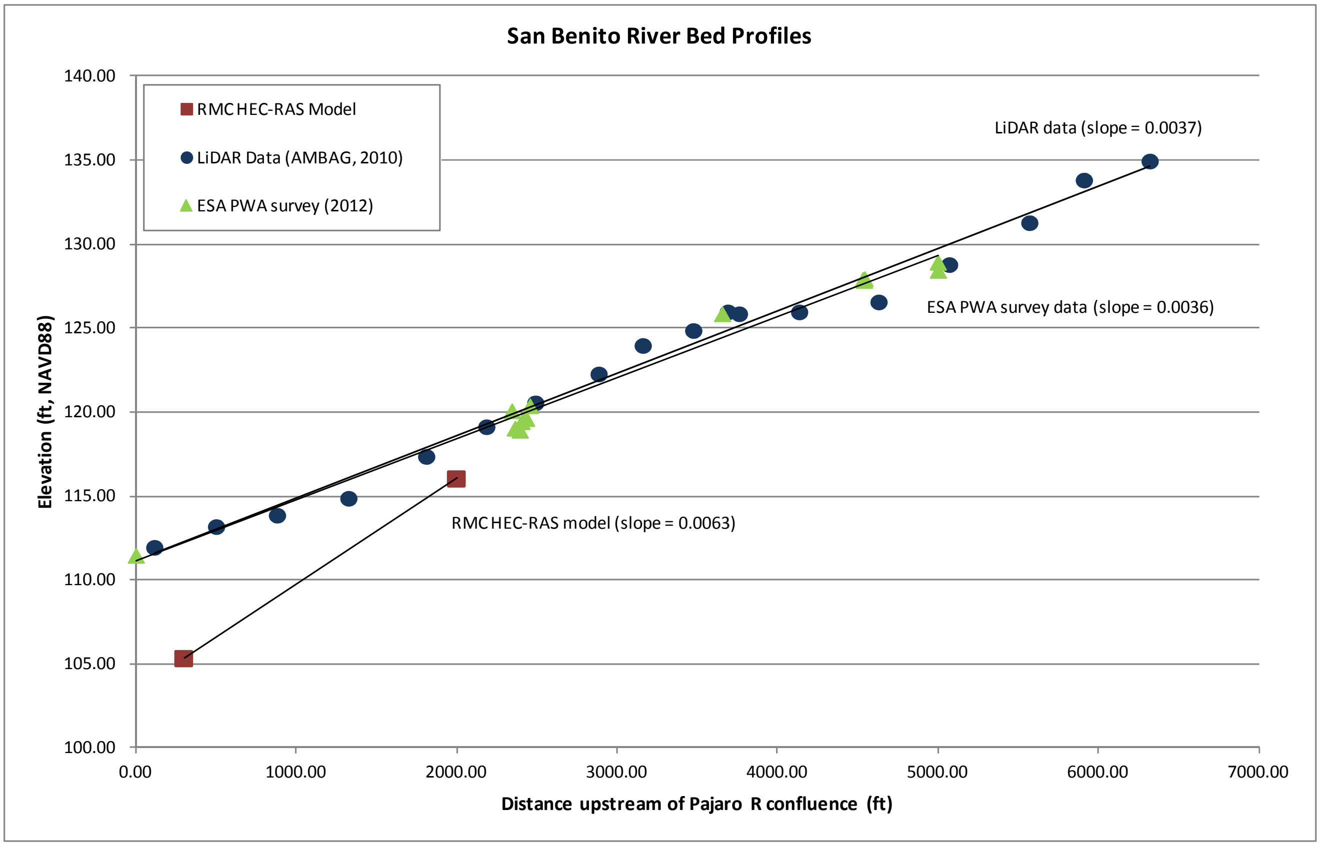


Figure 6
Comparison of Topography/Geometry Data, San Benito River

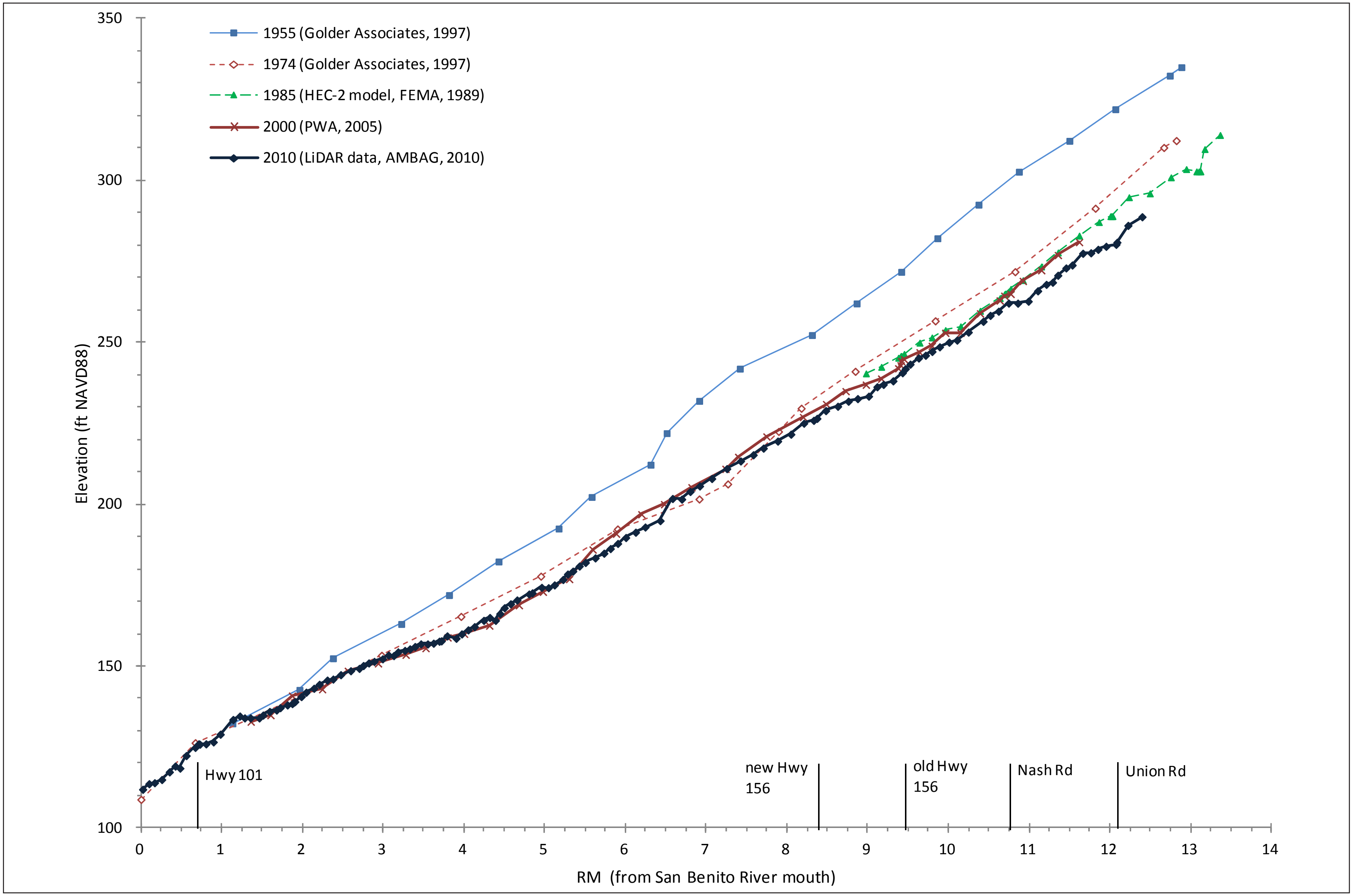
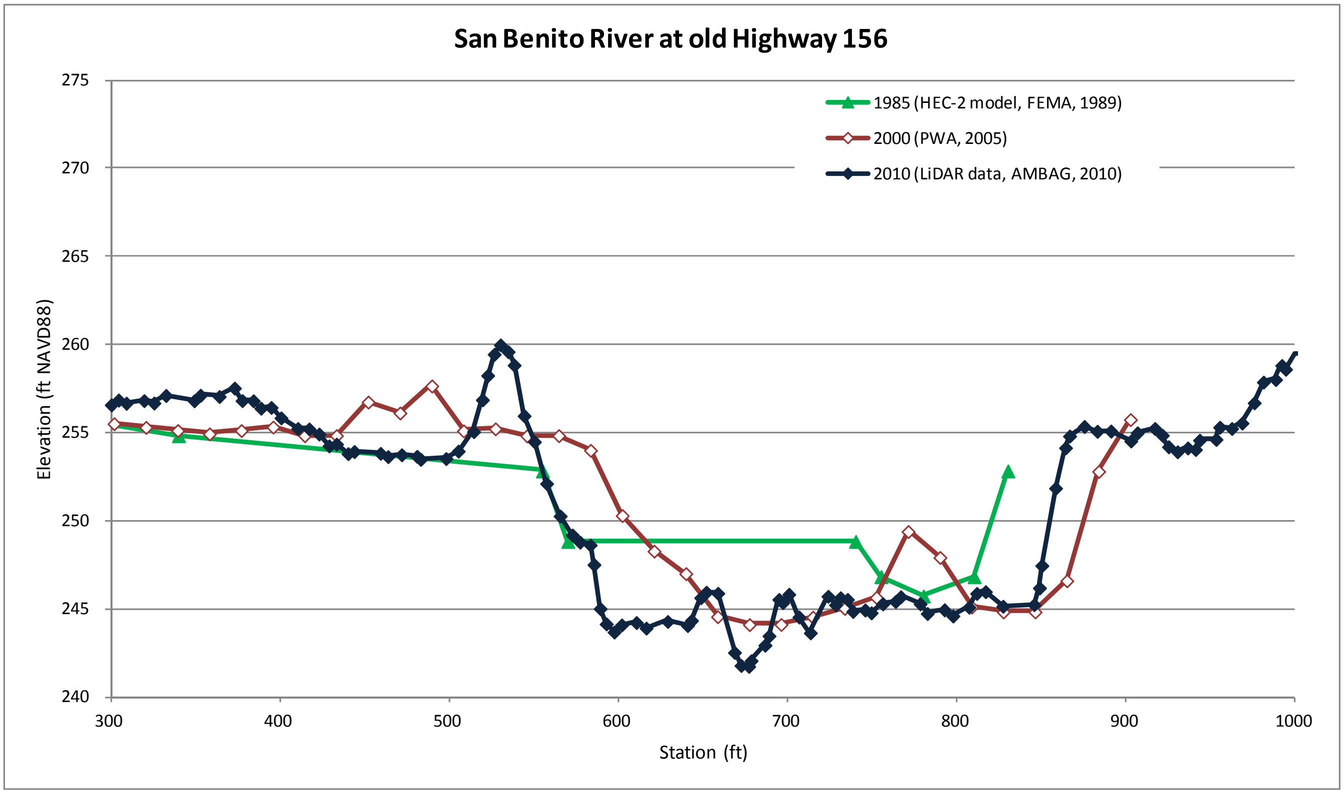


Figure 7
San Benito River Bed Profiles



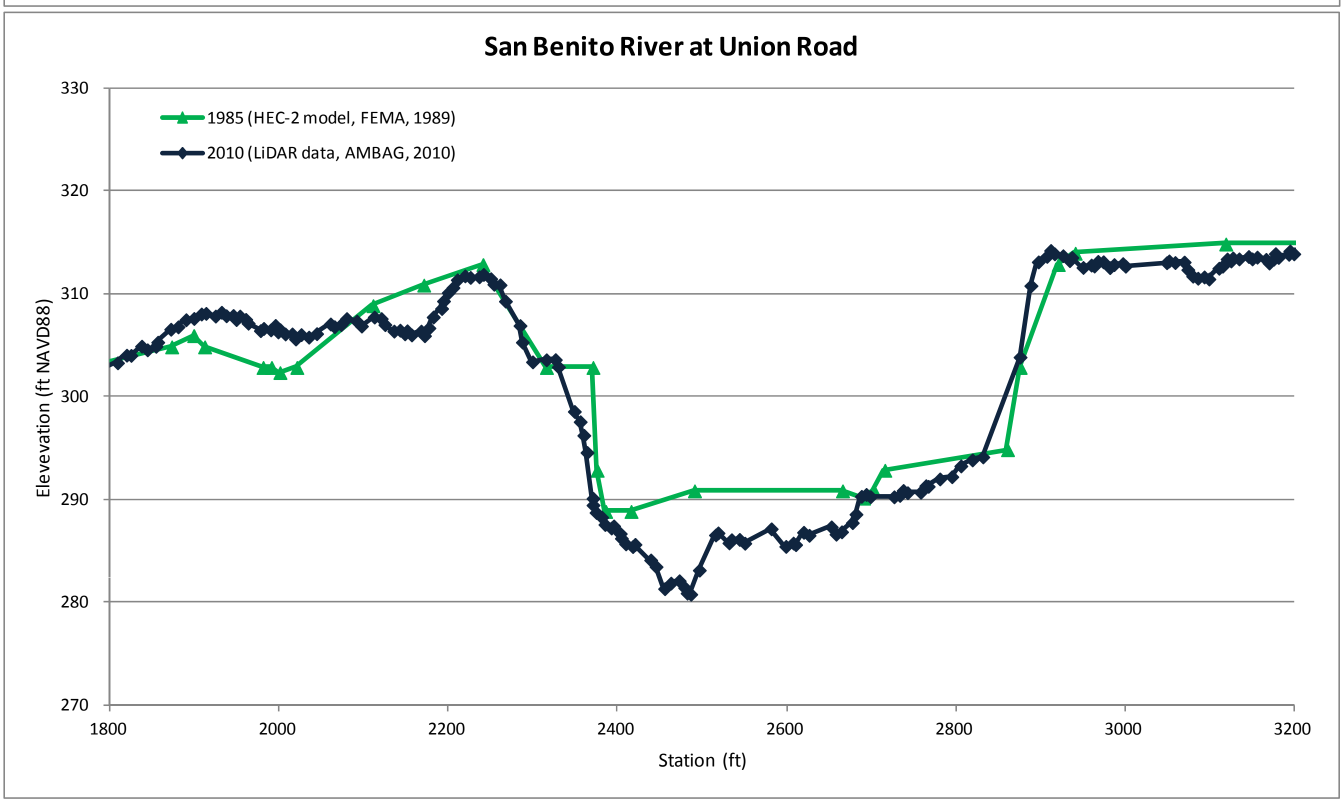


Figure 8
Cross Section Comparison, San Benito River

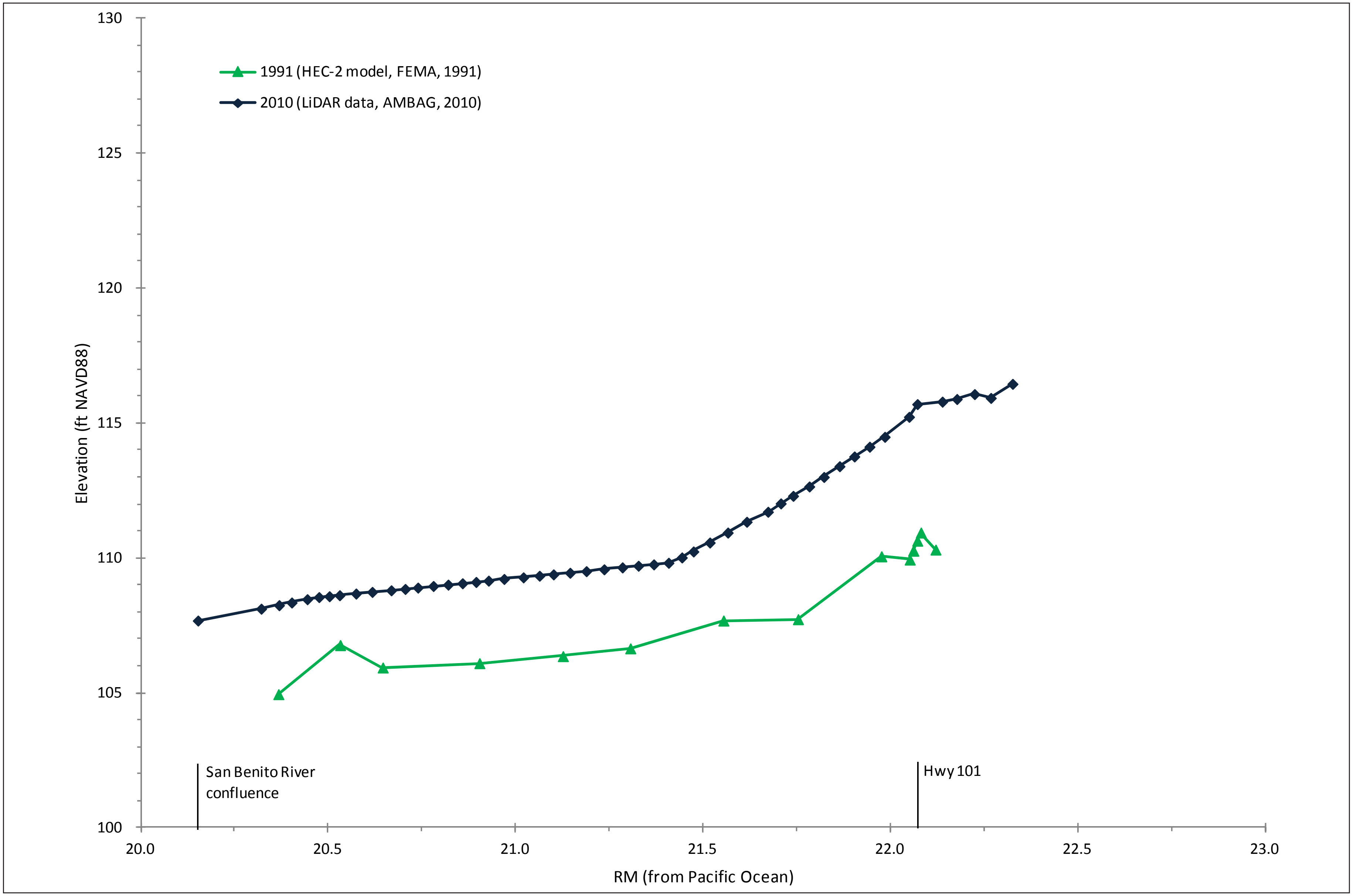


Figure 9
Upper Pajaro River Bed Profiles

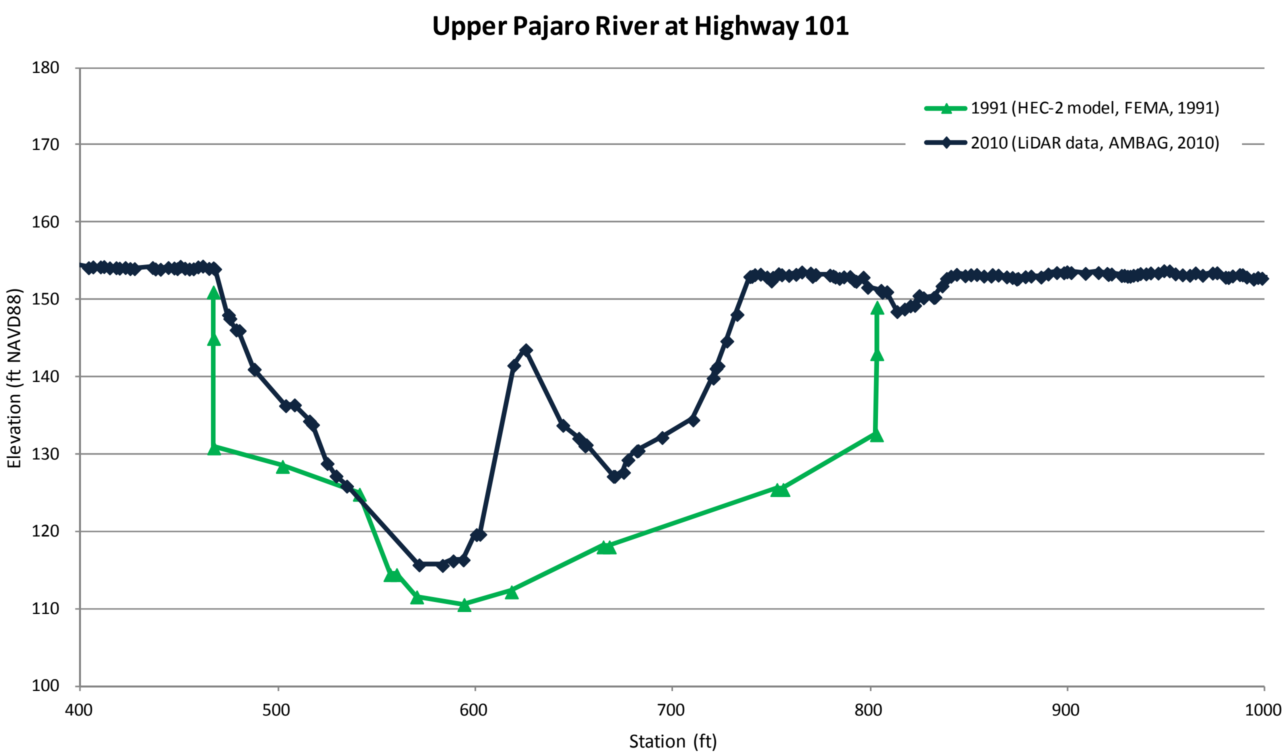


Figure 10

Cross Section Comparison, Upper Pajaro River

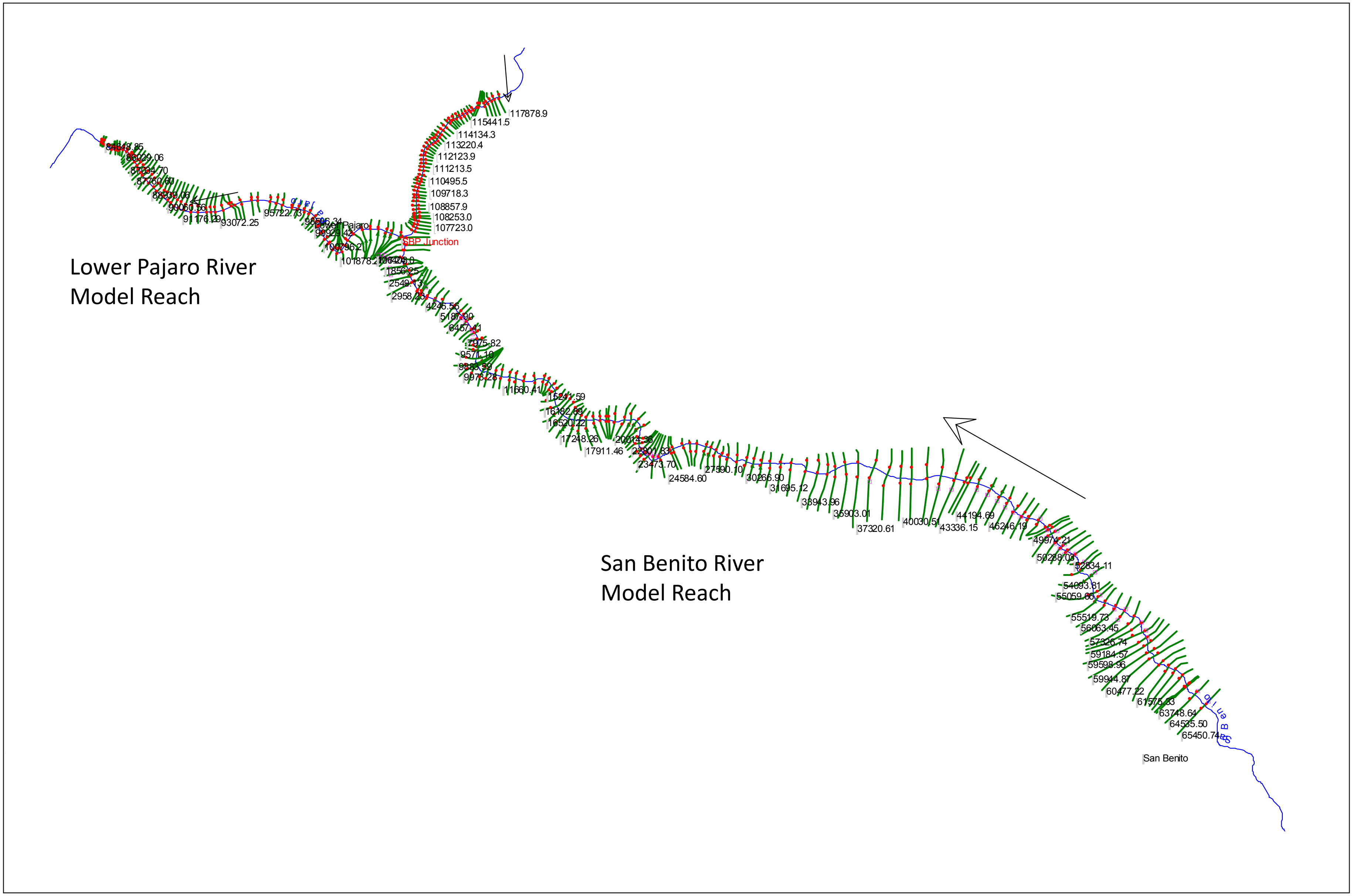


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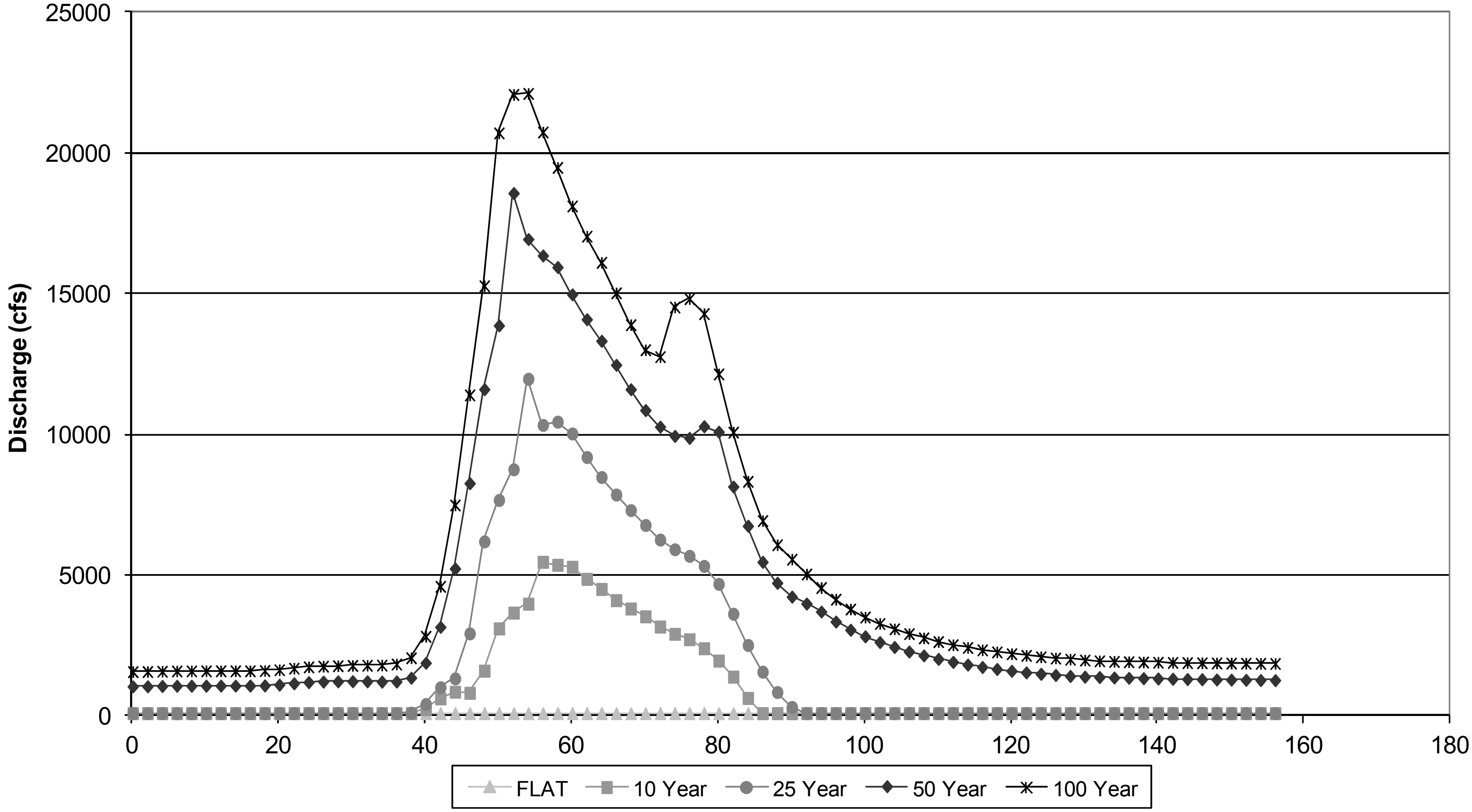
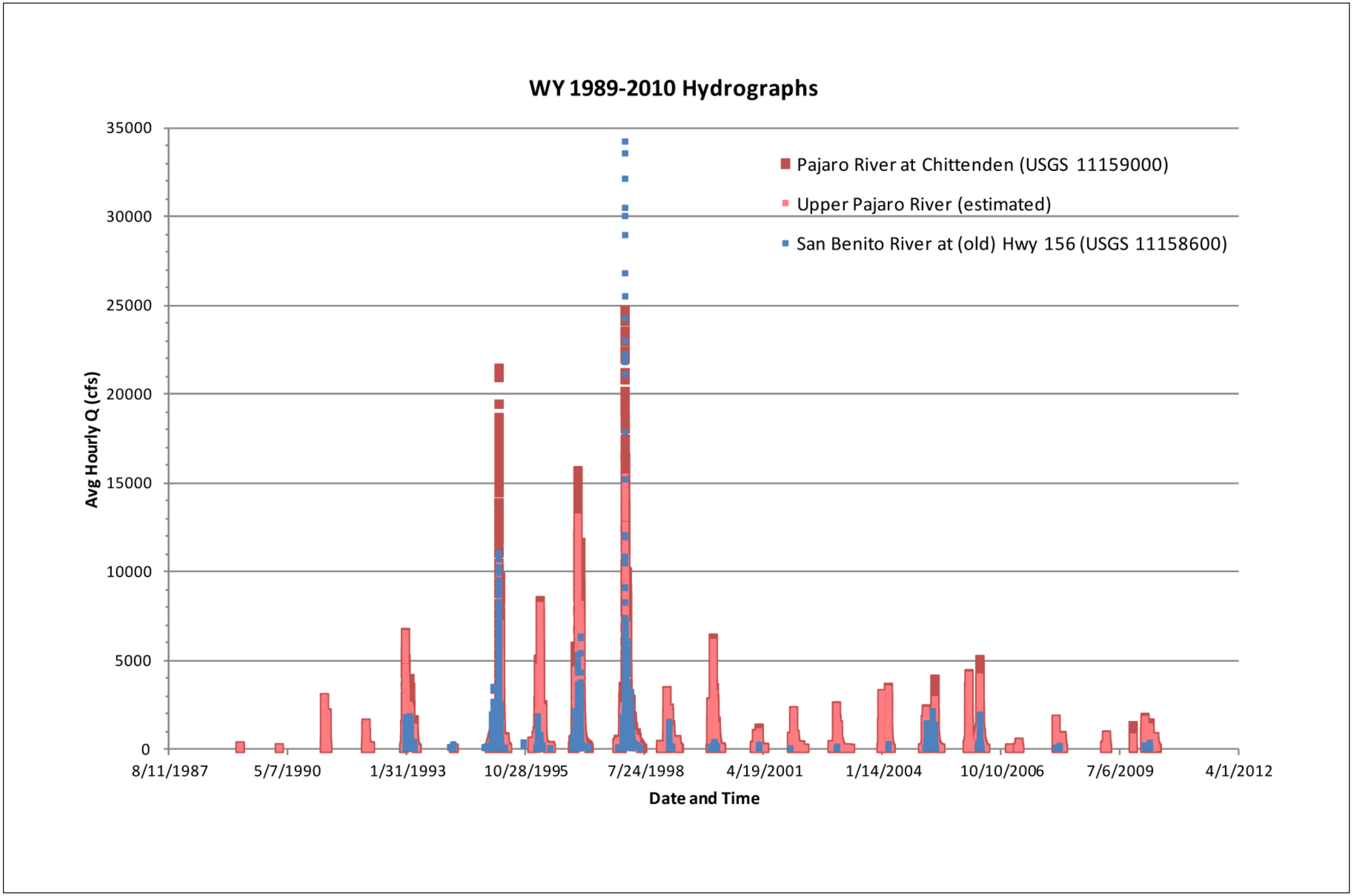
Figure 11

HEC-RAS Model Schematic



SOURCE: PWA (2005); NOTE: the “flat” condition is set at 100 cfs for the duration of the model run

Figure 12
Event Hydrographs for Sediment Transport Model



SOURCE: USGS 11159000 (USGS, 2013a); USGS 11158600 (USGS, 2013b);

NOTES: USGS 11159000 was missing data for the peak between 2/26/1995 and 3/27/1995, these values was interpolated based on the reported peak of 21,500 cfs and adjustments made using mean daily values and the San Benito Gage data; USGS 11158600 was missing data between 2/5/1995 and 3/10/1995, these values were interpolated based on the mean daily values .

Figure 13

WY 1989-2010 Hydrographs (for Q =100 cfs and greater)

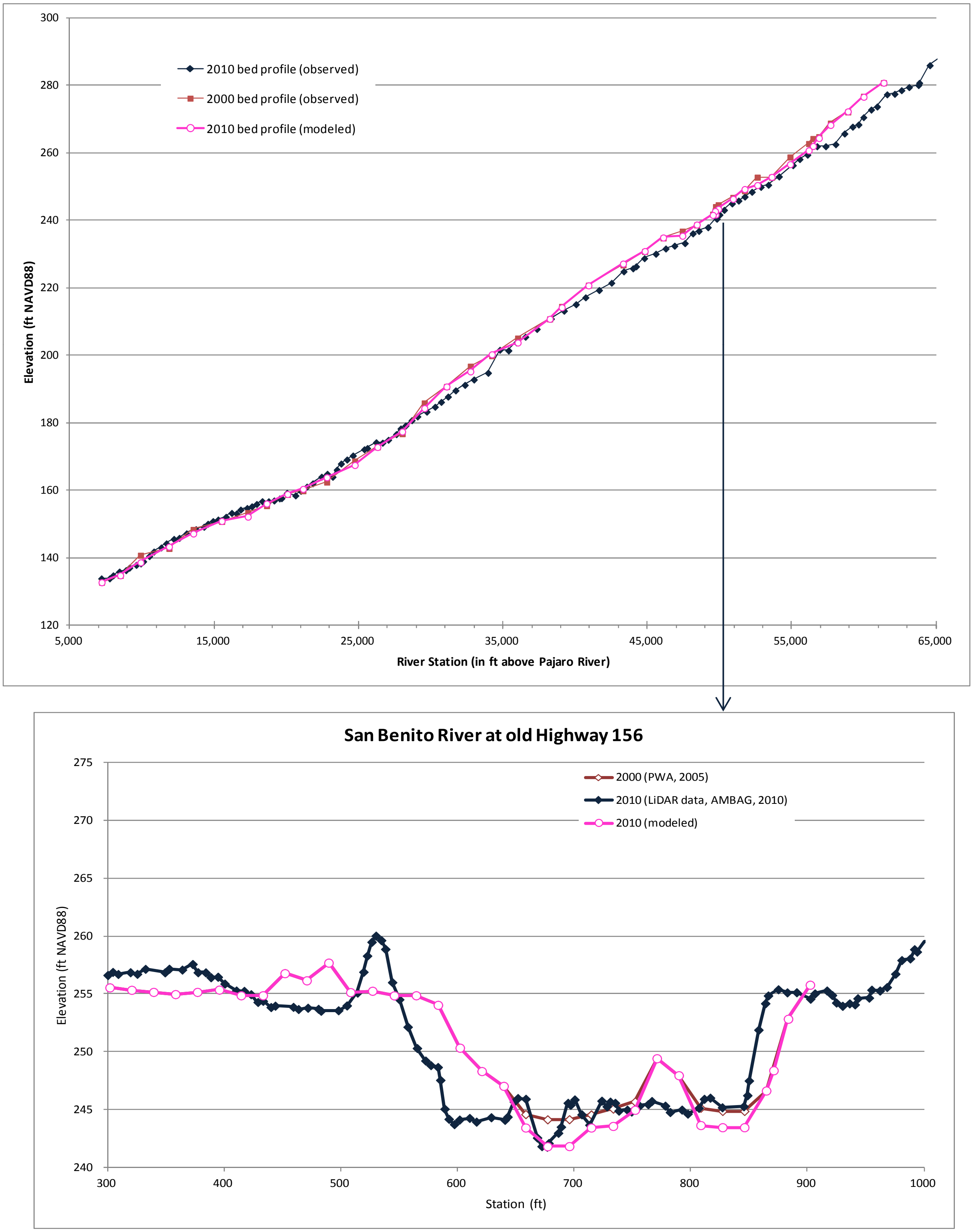


Figure 14

Modeled and Observed Bed Geometry, San Benito River

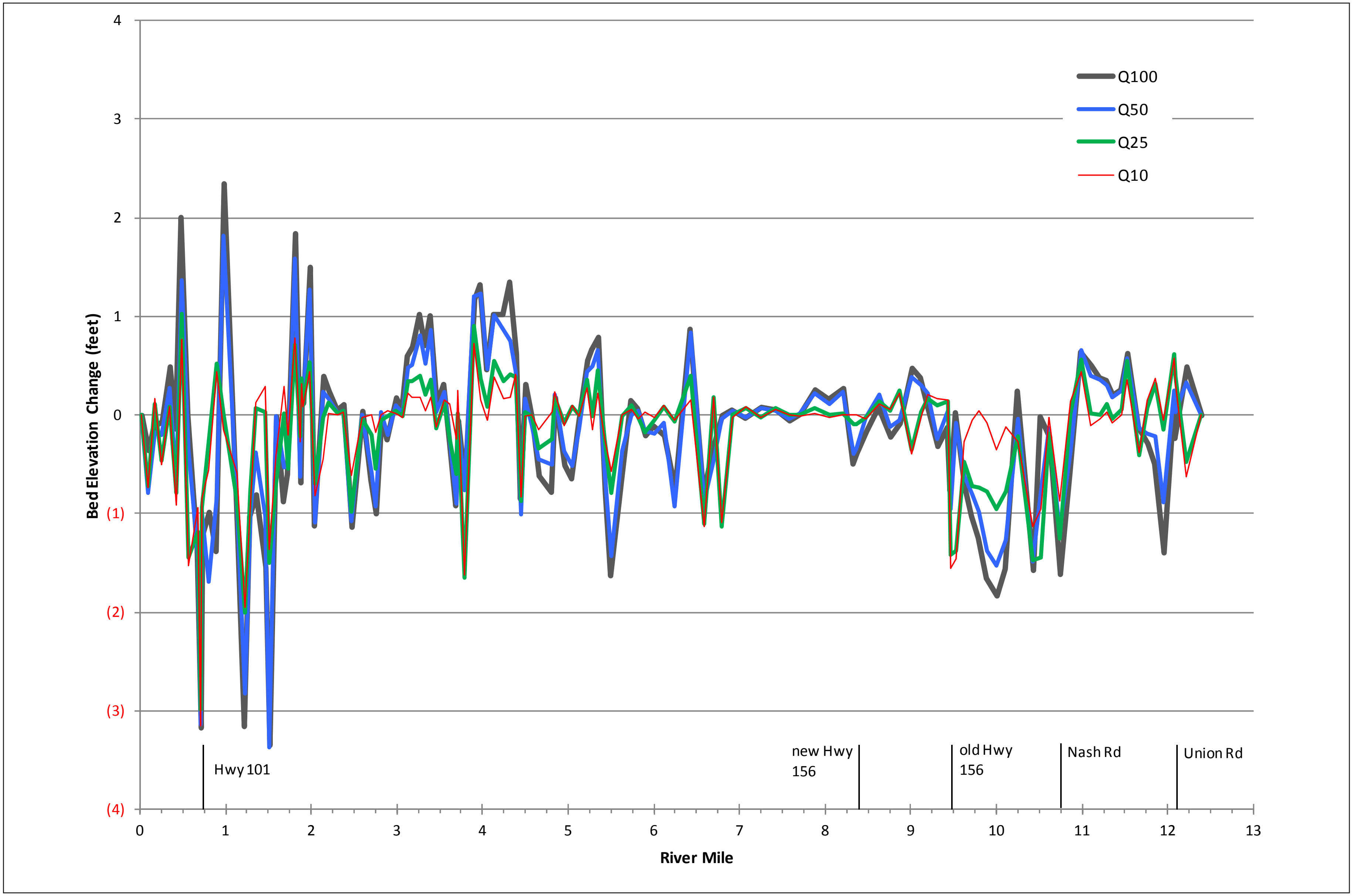
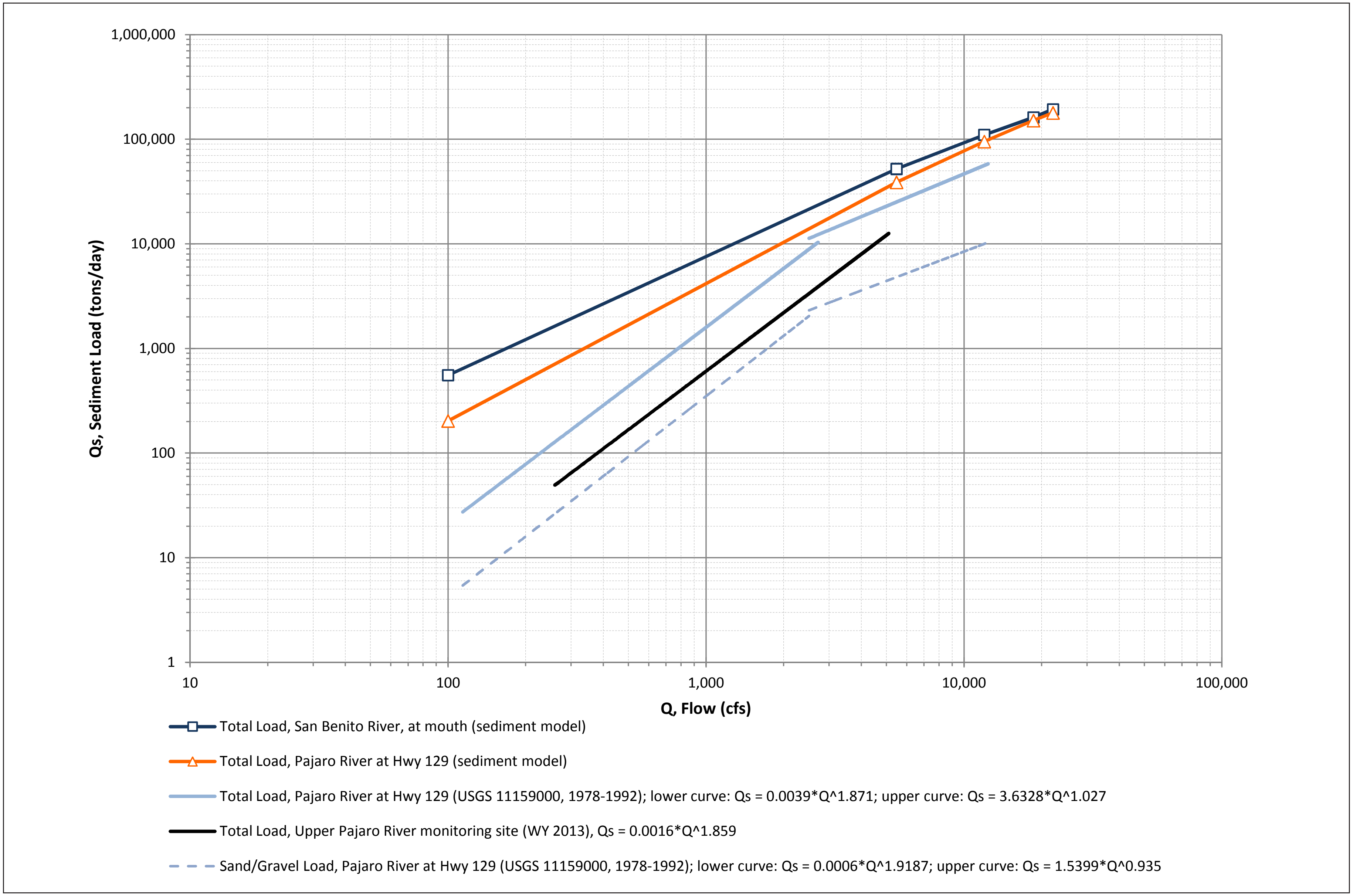


Figure 15

Modeled Bed Elevation Change, San Benito River



SOURCE: USGS 11159000 (USGS, 2013a)

Figure 16

Sediment Rating Curves (for Q =100 cfs and greater)

Appendix A
Field Photos

1. Photograph of the San Benito River from the adjacent floodplain. River is approximately 30 feet below floodplain.

2. Thick vegetation on the San Benito River floodplain

3. Looking downstream on the San Benito River. Channel incision evident from left bank

4. San Benito River showing evidence of channel incision

5. Shear bank on San Benito River showing channel incision. Bank is comprised of cemented gravels.

6. Left bank on San Benito River showing evidence of channel incision

7. Riffle on the San Benito River showing vegetation stabilization.

8. Pool on the San Benito River. Shear bank on left hand side of photograph showing incision.

9. Confluence with the Pajaro River. The water surface elevation in the Pajaro River is approximately 4 feet lower than the San Benito River

10. Looking upstream to the San Benito River from the Pajaro River

San Benito Monitoring Site (1/11/2013): Equipment housing and conduits to protect cables.

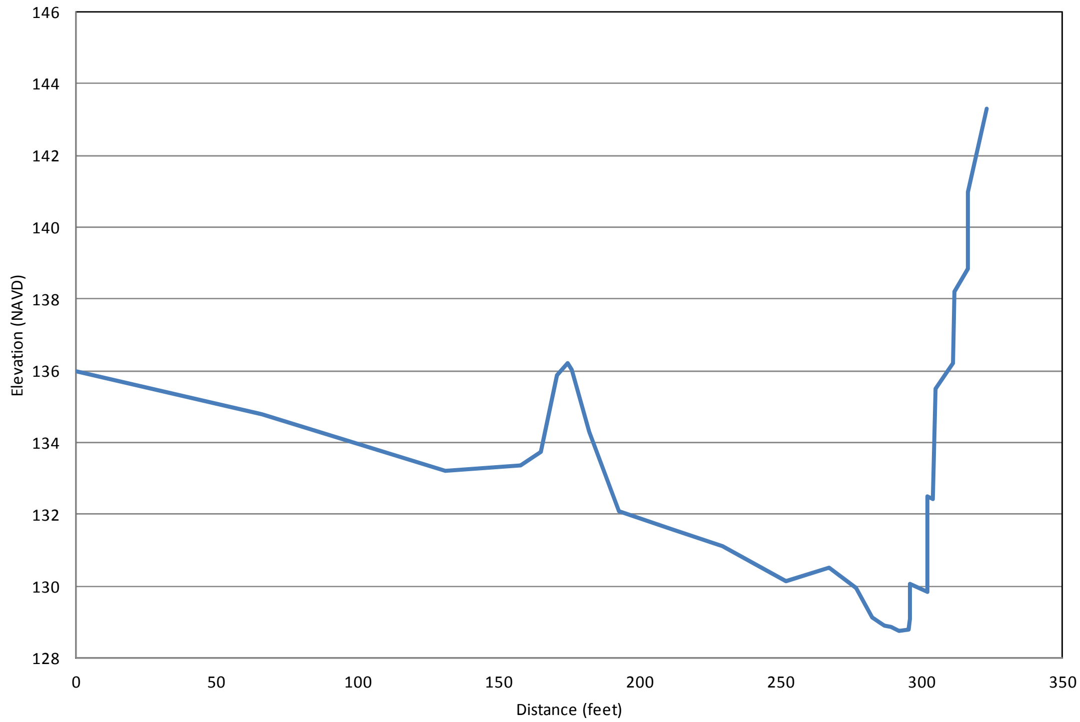
San Benito Monitoring Site (3/5/2013): Looking downstream.

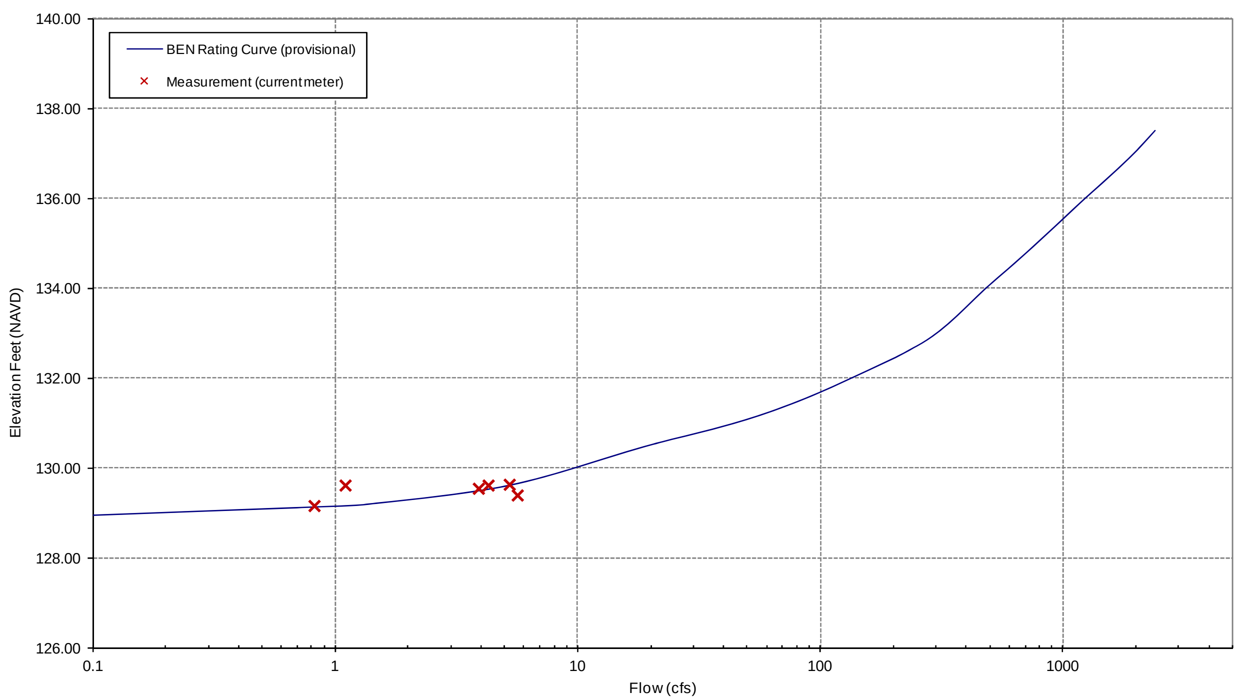
Pajaro Monitoring Site (3/5/2013): Looking downstream at equipment housing on left bank.

Pajaro Monitoring Site (3/5/2013): Looking upstream.

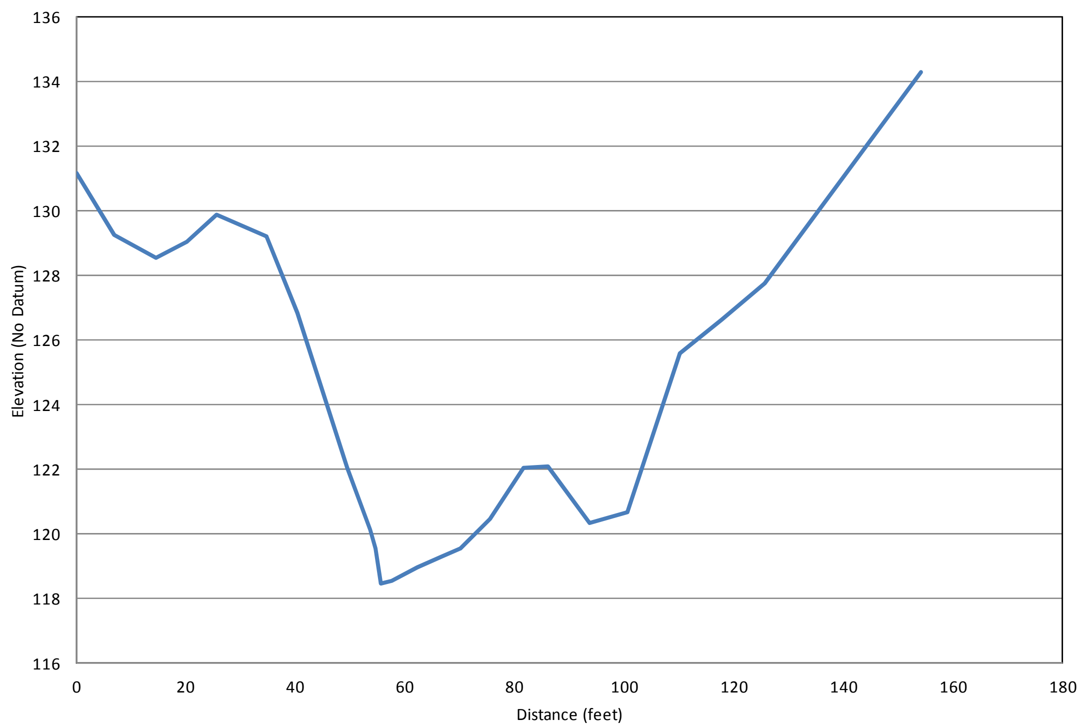
Appendix B
Field Data

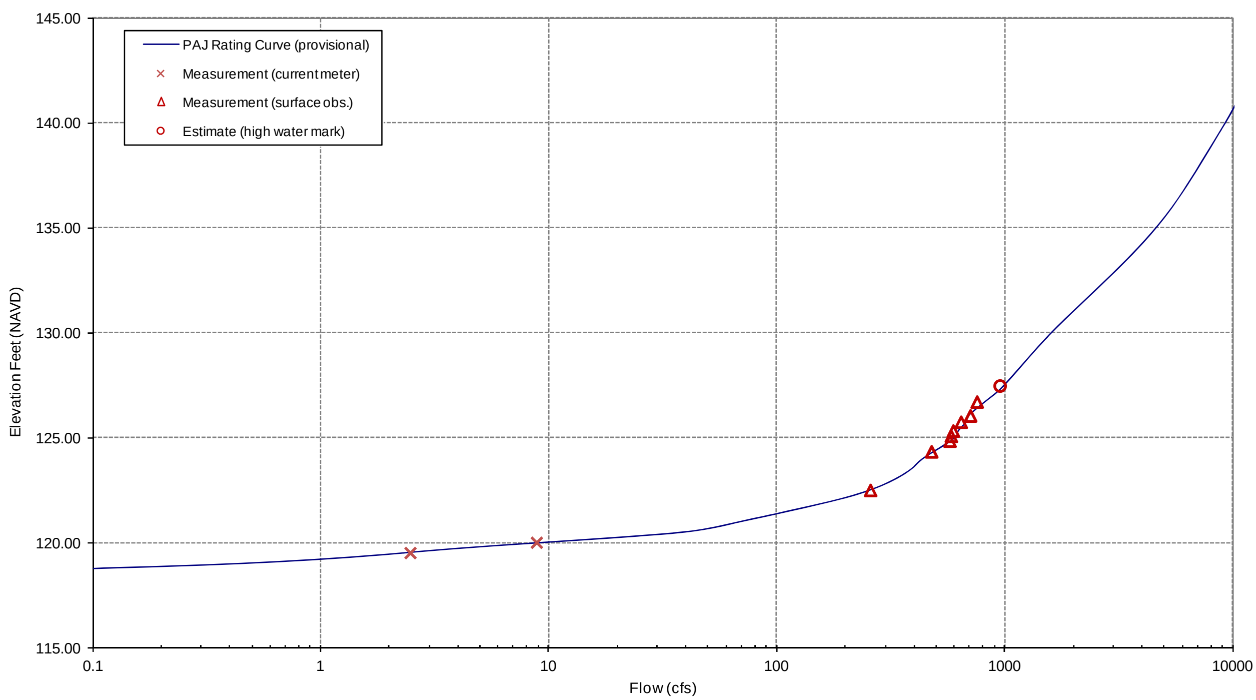
ESA





Appendix B, Figure 1: San Benito River Monitoring Site, WY 2013 (top) channel cross section, (bottom) provisional stage vs. discharge rating curve.





Appendix B, Figure 2: Upper Pajaro River Monitoring Site, WY 2013 (top) channel cross section, (bottom) provisional stage vs. discharge rating curve.

Do not enter data here. Enter data into measurements database and

Date	Time (PST)	Gauge Height (feet)	Hydrograph	TSS (mg/L)	RPD	Observer	Q	Mass mg/s	Mass tons/day		WSE (ft)
12/2/2012	16:58	2.66	Falling	51	1.94	BH, BT	4.26	6153.25	0.59		
12/2/2012	14:05	2.74	Rising	210	2.9	BH, BT	5.09	30256.71	2.88		
12/2/2012	11:37	2.74	Rising	562	1.59	BH, BT	5.09	80972.72	7.71		
2/24/2012	12:31	2.26	Steady	16		CN	0.75	341.27	0.03		
3/17/2012	14:03	2.51	Steady	106		CN	2.94	8817.34	0.84		
12/3/2012	10:45	2.78	Steady	8.800000191	2.25	CN, DJ	5.53	1377.93	0.13		
3/5/2013	13:03	2.38		37	5.26	JG, JNG	1.84	1931.80	0.18		

W.S. Elev	GH	Calculated Q
ft		
128.75	1.87	
128.80	1.92	0.01
129.16	2.28	0.92
129.20	2.32	1.30
129.63	2.75	5.20
130.50	3.62	19.11
131.00	4.12	43.73
131.50	4.62	81.80
132.00	5.12	132.88
132.50	5.62	210.40
133.00	6.12	301.54
133.50	6.62	385.19
134.00	7.12	482.24
134.50	7.62	616.78
135.00	8.12	783.40
135.50	8.62	986.83
136.00	9.12	1242.68
136.50	9.62	1576.93
137.00	10.12	1977.29
137.50	10.62	2409.65

Do not enter data here. Enter data into measurements database and re

Date	Time (PST)	Gauge Height (feet)	Hydrograph	TSS (mg/L)	RPD	Observer	Q	Mass mg/s	Mass tons/day		WSE (ft)
12/3/2012	10:00	5.75	Falling	82	2.47	CN, DJ	877.70	2038224.03	194.12		126.97
12/3/2012	11:43	5.05	Falling	61	1.63	CN, DJ	728.78	1258978.90	119.90		126.27
12/3/2012	12:10	4.72	Falling	65	1.55	CN, DJ	690.25	1270607.91	121.01		125.94
12/3/2012	13:23	4.18	Falling	56	3.51	CN, DJ	635.46	1007786.43	95.98		125.40
12/3/2012	14:30	3.75	Falling	49	2.02	CN, DJ	601.27	834375.93	79.47		124.97
12/3/2012	13:55	3.98	Falling	55	1.83	CN, DJ	623.32	970880.07	92.47		125.20
12/24/2012	11:04	14.38	Falling	812	0	DK	5106.33	117424350.39	11183.46		135.60
12/24/2012	13:04	13.83	Falling	612	2.26	DK	4669.37	80928809.73	7707.64		135.05
12/24/2012	15:04	13.21	Falling	868	0.917	DK	4198.32	103202003.14	9828.93		134.43
12/24/2012	17:04	12.51	Falling	1020	0.917	DK	3688.38	106543931.49	10147.21		133.73
12/24/2012	23:04	10.14	Falling	1020	1.98	DK	2213.48	63939501.12	6089.58		131.36
12/24/2012	21:04	10.96	Falling	656	2.11	DK	2671.35	49628086.73	4726.56		132.18
12/24/2012	19:04	11.76	Falling	718	0.839	DK	3174.40	64547407.27	6147.48		132.98
12/25/2012	5:04	7.29	Falling	141	2.15	DK	1211.65	4838269.35	460.80		128.51
12/25/2012	7:04	6.45	Falling	92	4.44	DK	1038.23	2705047.84	257.63		127.67
12/25/2012	3:04	8.23	Falling	732	0.545	DK	1433.43	29715340.96	2830.08		129.45
12/25/2012	1:04	9.24	Falling	892	2.22	DK	1789.82	45213392.02	4306.11		130.46
3/17/2012	14:50		Rising	112		cn	5.60	17762.30	1.69		121.22
12/2/2012	15:40	2.36	Rising	302	1.97	BH, BT	398.62	3409221.32	324.69		123.58
12/2/2012	14:37	1.94	Rising	450	0.445	BH, BT	349.16	4449659.35	423.78		123.16
12/2/2012	12:35	1.30	Rising	87	1	cn	259.69	639826.42	60.94		122.52
12/2/2012	16:58	3.20	Rising	584	1.97	BH, BT	507.38	8391504.05	799.20		124.42
2/24/2012	12:31		Steady	27		cn		0.00	0.00		121.22
3/5/2013	10:45	(0.58)	Steady	17.20000076	2.35	JG, JNG	47.02	22904.59	2.18		120.64
2/24/2012	12:31			43		cn		0.00	0.00		121.22

measured in the field (i.e., prior to gage and staff plate installation)

W.S. Elev	Calculated Q
ft	
118.50	0
118.75	0.1
119.00	0.4
119.25	1.1
119.50	2.3
119.53	2.4
119.75	4.2
120.00	9.3
120.50	39.0
121.00	69.5
122.00	178.7
122.50	256.7
123.00	328.1
123.50	390.4
124.00	438.7
124.85	582.9
125.09	616.7
125.34	629.8
125.76	680.6
126.06	698.4
126.71	821.4
127.48	995.7
130.00	1609.2
135.00	4630.8
140.00	9310.3
142.00	11577.4