PAJARO RIVER WATERSHED
FLOOD PREVENTION AUTHORITY
Phase 4b: Implementation Plan for Soap Lake Floodplain
Preservation Project and Watershed Flood Protection Actions

Technical Memorandum No. 4.4.3

Task:	**Time of Travel Analysis**
To:	**PRWFPA Staff Working Group**
Prepared by:	**Eric Evans**
Reviewed by:	**Michael Matson, Dr. Jeff Lewandowski**
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Introduction

Floods are one of the few dangerous natural events that can often be predicted several hours in advance. In very large river systems, such as the Mississippi, accurate flood forecasts can sometimes be issued more than one day in advance. A few hours' warning time before high water arrives can be of immeasurable value to people who live in affected areas.

Effective flood forecasting is highly dependent upon the availability of relevant streamflow data and an understanding of how long it takes for high flows from upstream tributaries to arrive at populated areas downstream. A flood forecasting system hindered by insufficient or misinterpreted data can result in false alarms or failure to provide advanced warning.

This technical memorandum (TM) provides data and analysis in support of improved capability to predict potential flooding in populated areas along the lower reaches of the Pajaro River. Graphs of streamflow gage data from several locations in the upper watershed were closely examined for apparent cause-and-effect relationships with data from a downstream gage. Where a probable connection was observed between high upstream flows and their apparent arrival downstream, the time required for the high water to travel the distance between the two gages was estimated.

Analysis of the data was graphical and not based on hydraulic analysis. There were several limiting factors including a lack of data from ungaged tributaries, missing data from gaged tributaries, and unknown storage effects of Soap Lake and San Felipe Lake. Despite these shortcomings, the analysis nevertheless was successful in producing approximate floodwave travel times that can be useful as preliminary estimates to those tasked with issuing flood warnings.

Background

This section describes streamflow routing principles and how to use and interpret hydrographs. These topics are central to the analysis of floodwave travel time.

Streamflow Routing Principles

Figure 2 depicts the behavior of an ideal hypothetical stream system with no tributaries and a streamflow gage at both the upstream and downstream ends. The stream between the gaging stations can be thought of as a long and narrow reservoir. The inflow and outflow hydrographs of this system are recorded from the upstream and downstream gages, respectively. Mathematical techniques of streamflow routing are used to describe the shape of the outflow hydrograph as a function of the inflow hydrograph and the characteristics of the stream system.

When water is conveyed (translated) through the system without the storage effects associated with reservoirs, the outflow hydrograph retains the same shape as the inflow hydrograph. However, the outflow hydrograph is delayed by an amount equal to travel time of the water. When water is stored in the system, the outflow hydrograph is both translated and attenuated. Attenuation results in a reduction of peak flow, an increase in flood wave duration, and a delay in the arrival of the peak flow due to storage effects in addition to the delay caused by translation. In this ideal system, the volumes of water represented by the hydrographs are the same. The time of travel is equal to the delay time between the two peaks, as shown by the arrows in Figure 1.

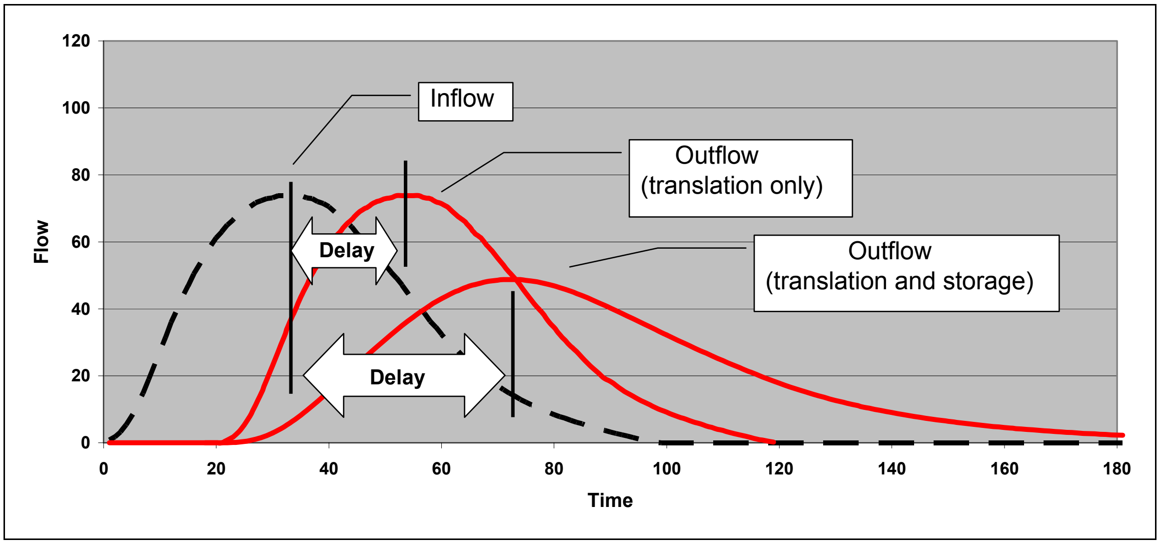

Figure 1: Streamflow routing in an ideal system.

Time of travel analysis of peak streamflows in natural channel networks is inexact. Identifying a single time of travel between two points can be misleading and often times incorrect. The main reason for this is that several immeasurable factors affect the velocity and attenuation of a floodwave in any natural channel. Some of these factors are as follows.

- Flow down a dry channel will be noticeably slower than flow down a channel that has recently experienced moderate to high flows. This is of little concern because nearly all high flows in the Pajaro River occur during wet winters with frequent storms.

- Leafy trees in a channel may slow down the flow more and cause more storage than trees with bare branches, though some observations have shown that leaves can cause branches to be pulled out of the way resulting in faster flow than through bare branches.

- Higher flows tend to travel more quickly than lower flows, though higher flows often result in higher storage as water is allowed to spread out onto adjacent floodplains during its trip downstream. The increased storage can counteract the quicker travel time caused by the higher flow.

Identification of upstream peak flows in downstream hydrographs is not always straightforward. Identical flows of a given tributary will have similar velocities while still in the tributary. However, upon reaching the main stem, the velocity of the commingled waters and therefore the tributary flow's arrival time downstream will vary depending on the volume of flow in the main stem. Also, a peak streamflow seen at a downstream gage does not always correspond to an easily identifiable peak flow of an upstream tributary. Peak flows from upstream tributaries are often blended into, and difficult to distinguish from, the rising and falling limbs of the hydrograph of high downstream flows.

Despite all of these complications, preliminary estimates of times of travel can be determined. With additional data and analysis of different magnitudes of high flow events and rainfall patterns, refined estimates can be developed.

Hydrograph Analysis

In many cases, shortly before or after the arrival of peak flow from one tributary, the peak flow of another tributary will arrive. A simplified description of the result is that the magnitude of contributing simultaneous flows are added to one another to form the downstream hydrograph. The simultaneous or near-simultaneous arrival of peak flows from two or more upstream tributaries often results in a single large peak flow of an amplitude (maximum height or stage) much greater than that of any of its contributors.

Simultaneous arrival of peak flows from 2 or more tributaries is an unlikely occurrence. In most cases, the arrival of different streamflow waves will be sequential with some amount of overlap. The combined downstream flow will have a magnitude equal to some percentage of the sum of all peak incoming flows.

Identification of the arrival of a peak flow from an upstream tributary at a downstream gaging site is easiest and most accurate when both of the following conditions are met:

- The peak upstream flow of interest is large relative to the downstream flow. This is the case when flow contributions from adjacent watersheds are relatively small, and flow at the downstream site is significantly less than what it will soon receive from the upstream tributary.

- Arrival of the upstream flow occurs when the flow rate downstream is not rapidly changing. This is the case when passage of a peak flow from a different tributary hasn't recently occurred at the downstream gage or will not occur for several hours or days.

Methodology

This section describes the watershed area, the data gathered in support of analysis of the Pajaro River watershed, and the analysis method used to determine the travel times of the floodwaves.

Pajaro River Watershed Streamflow Data Sources

The Pajaro River watershed encompasses over 1,300 square miles and includes portions of Santa Cruz, Santa Clara, San Benito, and Monterey Counties. The scope of this study is limited to the portion of the watershed upstream of Chittenden Gap. This 1,186 square mile area includes the majority of San Benito County and a small portion of Santa Clara County (See Figure 2). Significant tributaries to the Pajaro River include Uvas Creek, Llagas Creek, Pacheco Creek, Tequisquita Slough, Tres Pinos Creek, and the San Benito River. Datasets from the five gage sites shown in Figure 2 were obtained from the United States Geological Survey (USGS) and analyzed.

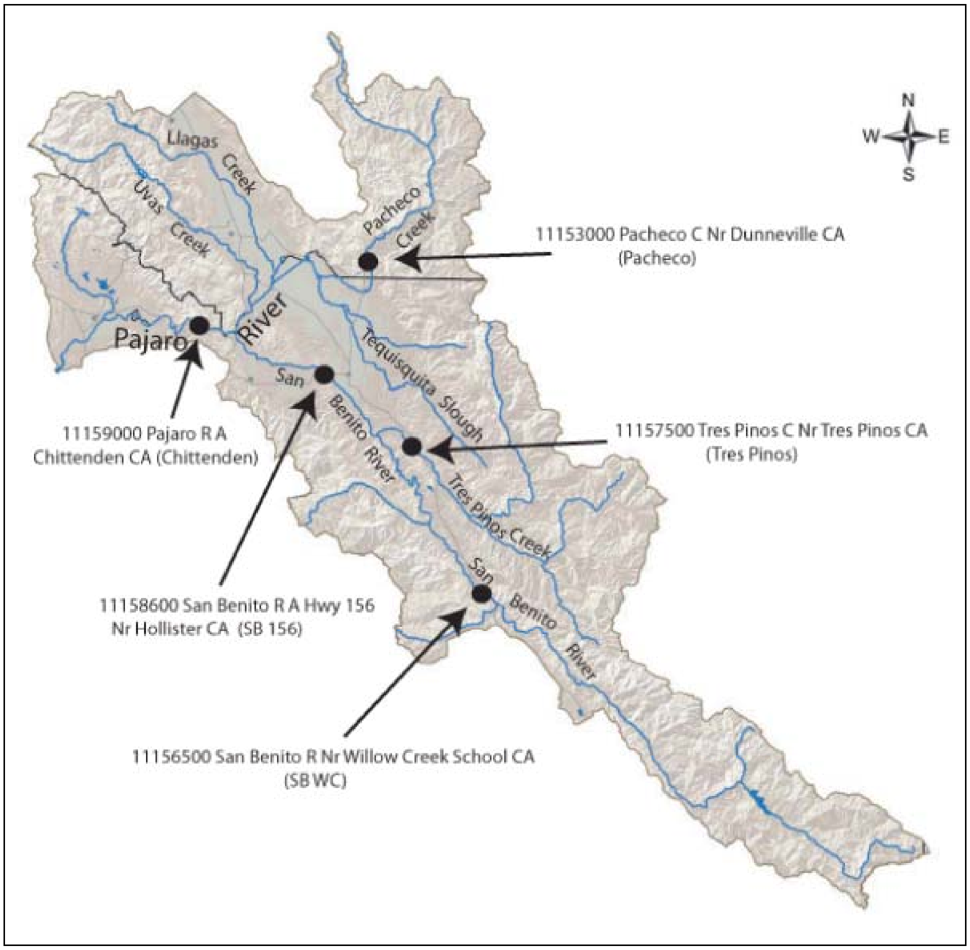

Figure 2: Watershed Map

Streamflow data on 15-minute intervals were gathered from the United States Geological Survey (USGS) and the Santa Clara Valley Water District (SCVWD) in order to evaluate times of travel. Evaluated gaging sites and the periods of record obtained are shown in Table 1. The abbreviated gage names are used later in the report to describe both the gage and its respective channel at that gage site.

Significant periods of data are missing from the records identified in Table 1. Unfortunately, these periods often coincide with high flow events that are of the greatest interest to hydrologists performing flood flow analyses. It is likely that some or all of these data blackouts are at least partially attributed to gage damage caused by the passage of large quantities of water, debris, and sediment. Five events were identified for this TM though that can provide some insight into the time of travel through the Pajaro River watershed.

Table 1: Pajaro River Watershed Streamflow Gages

USGS I.D. No.	Streamflow Gage Site Name	Abbreviated Gage Name	Drainage Area (sq. mi.)	Period of Record
11159000	Pajaro River at Chittenden Gap	Chittenden	1,186	Oct 1988 to Jan 2005
11158600	San Benito River at Highway 156	SB 156	607	Oct 1988 to Jan 2005
11156500	San Benito River near Willow Creek School	SB WC	249	Oct 1988 to Jan 2005
11157500	Tres Pinos Creek near Tres Pinos, CA	Tres Pinos	208	Oct 1996 to Jan 2005
11153650	Llagas Creek near Gilroy	Llagas	84	Nov 2002 to Jan 2005
11154200*	Uvas Creek near Gilroy	Uvas	71.2	Oct 1998 to Sept 2004
11153000**	Pacheco Creek near Dunneville, CA	Pacheco	146	Oct 1982 to Sept 2003

* Site no longer operated by the USGS
** Site no longer operational

Streamflow Event Selection

Peak flow events at Chittenden Gap were considered as a basis of selection of time periods for evaluation in this study. The peak flows for water years 1990 through 2003 are shown in Table 2. A water year is defined as the period of time from October 1st of the previous calendar year to September 30 of the calendar year for which the water year is named. For example, Water Year 2005 begins on October 1, 2004 and ends on September 30, 2005.

The analysis of five of the top seven flow events identified in Table 2 is included in this TM as the basis for time of travel estimates. These events are shown in bold. The remaining nine events are not included due to missing data that could impact the interpretation of the hydrograph or no clear peak patterns could be discerned. These nine events were used though to check assumptions about travel times.

Table 2: Peak flows at the Chittenden Gap, Water Years 1990 to 2003

Water Year	Date	Peak Flow (cfs)
1990	February 17, 1990	148
1991	**March 4, 1991**	**2,960**
1992	February 16, 1992	1,540
1993	**January 14, 1993**	**6,630**
1994	February 20, 1994	600
1995	**March 11, 1995**	**21,500**
1996	February 20, 1996	8,430
1997	**January 3, 1997**	**15,800**
1998	**February 3, 1998**	**25,100**
1999	February 9, 1999	4,300
2000	February 14, 2000	6,320
2001	March 6, 2001	1,280
2002	December 21, 2001	2,240
2003	December 17, 2002	2,510

Analysis Method
Visual examination of hydrographs was deemed appropriate and sufficient to provide preliminary times of travel in the Pajaro River watershed. Traditional mathematical routing techniques such as the Muskingum method were not used. The Muskingum model is applicable for single inflow streamflow routing, such as the evaluation of streams with no tributaries. In real world situations such as the Pajaro watershed, several tributaries join the main channel to form a channel network. The timing and magnitude of each tributary's contribution to the Pajaro River depends on the timing and magnitude of rainfall in each individual catchment.

This channel network could be modeled as a whole using the Muskingum method by substituting the multiple inflows with a single equivalent inflow. However, this would not provide information about the travel times of flows from individual tributaries and would be of limited usefulness to Automated Local Evaluation in Real Time (ALERT) monitoring staff.

Time of Travel Analysis

This section describes how the techniques and data described above were used to develop travel times for the Pajaro River watershed. Hydrographs of several storm events are presented along with discussion of the behavior of each tributary during those events.

Pacheco Creek – Single Peak Example
Although the Pacheco gage has been inoperable since 2003, a great amount of data has been collected from it during previous decades. Water from this creek passes through San Felipe Lake before entering the Pajaro River. During high flows in the Pajaro River, an additional reservoir known as Soap Lake is formed further downstream. Soap Lake occasionally grows to the point of consuming San Felipe Lake upstream. Both of these reservoirs provide significant attenuation of high flows received from Pacheco Creek and other contributing streams. Although helpful in reducing large peak flows, the varying storage provided by these reservoirs complicates the streamflow routing of this tributary and its neighbor, Tequisquita Slough.

Time of travel estimation of an individual tributary is easiest and most accurate when its catchment receives a brief but intense period of rainfall, and all other tributaries to the main stem receive relatively little rainfall. Such conditions were present in early March 1991 when a peak flow of 2,500 cfs passed the Pacheco Creek gage on its way to Chittenden Gap (See Figure 3).

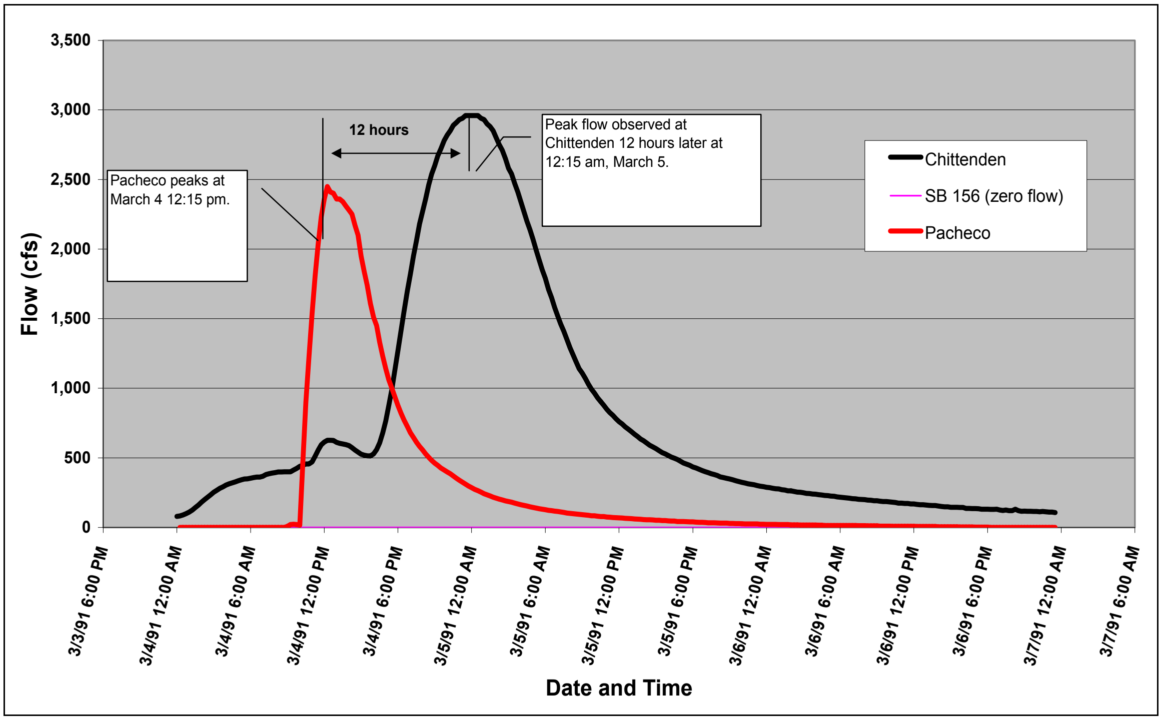

Figure 3: Peak flow event of March 1991. Data from Uvas Creek and Llagas creek were not available. Flow from SB 156 was zero.

12 hours later, a peak flow of 3,000 cfs was observed at Chittenden Gap. The peak flow from Pacheco augmented the relatively small flow contributions from other sources to form a simple and distinct peak in the downstream hydrograph. There do not appear to have been any major contributions from other streams such as the San Benito River. The peak flow at Chittenden may correspond to the attenuated peak flow from Pacheco added to the existing flow at Chittenden.

These hydrographs suggest that a peak flow of 2,500 cfs at the Pacheco Creek gage will take up to approximately 12 hours to reach Chittenden Gap when flows in the Pajaro River are relatively low. Higher flows are likely to travel more quickly, while lesser flows travel more slowly. Knowing this, peak Pacheco Creek flows of greater and lesser magnitudes can be searched for in more complex hydrographs of Chittenden Gap.

Pacheco Creek – Double Peak Example

Figure 4 depicts a double peak hydrograph at the Pacheco Creek gage in January of 1993. As in the previous example, Peak A arrives at Chittenden some time before and after the arrival of other waves. The first peak at Chittenden is most likely the attenuated wave of Peak A.

The Peak A flow of 1,500 cfs is less than the maximum flow of the previous example. However, Peak A appears to have arrived at Chittenden in only 8 hours instead of 12 hours. This is most likely due to the fact that unlike the first example, there was significant flow and greater velocity in the main stem of the Pajaro River. This greater flow was not present in the previous example and is not accounted for at the Pacheco gage site. The shorter travel time could also have been influenced by differing storage effects of Soap Lake and San Felipe Lake along with unknown contributions from Llagas Creek, Uvas Creek, and Tequisquita Slough.

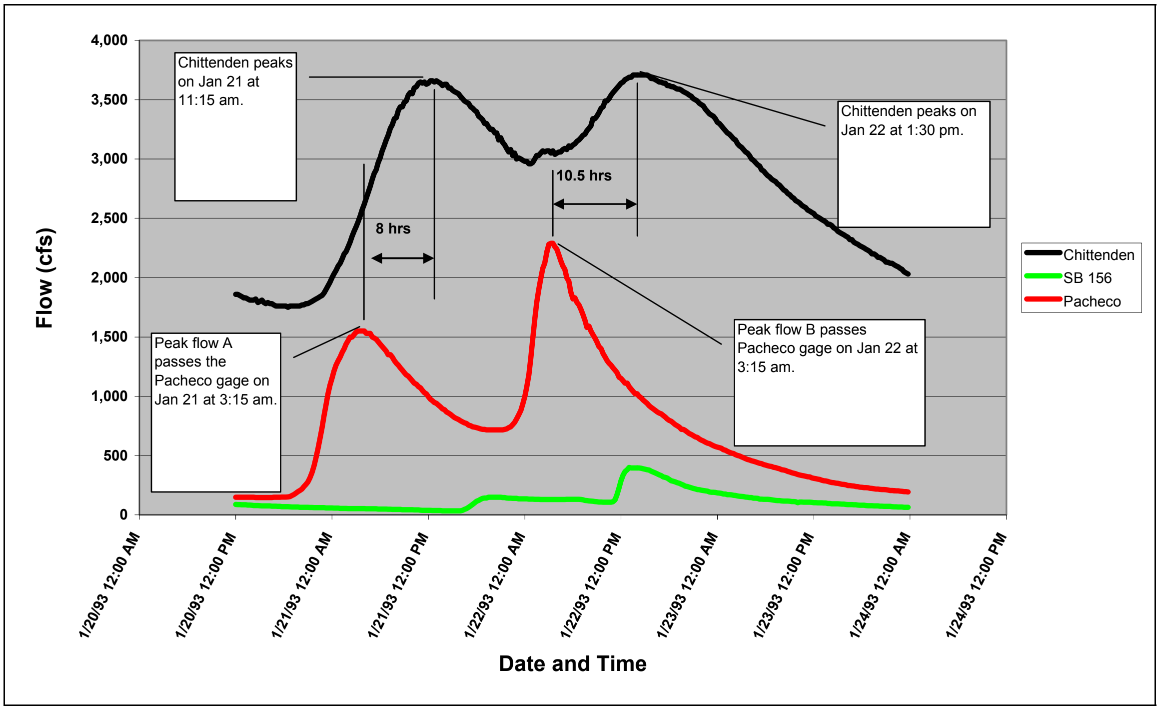

Figure 4: Dual peak event in January 1993.

The second peak at Chittenden also appears to be the same wave as that of Peak B from Pacheco. However, despite high flows in the main stem of Pajaro that would speed up the travel of Peak B, the secondary peak at Chittenden occurs over 10 hours later.

A likely scenario is that Peak B from Pacheco arrived at Chittenden a few hours before the second peak at Chittenden. Very shortly after its arrival, flow from Peak B may have been augmented by flow from Uvas Creek and/or Llagas Creek. This augmentation of flow appears to have pushed the height of water at Chittenden above the peak flow level from Pacheco.

The small but sharp increase in flow seen at SB 156 is probably responsible for Chittenden's gradual decrease down to 3,500 cfs before the more pronounced fall expected in simple hydrographs.

As with all peak flows from Pacheco, one must consider varying and unknown storage effects of Soap Lake and San Felipe Lake, unknown contributions from adjacent tributaries for which data were not available, and differing flows in the Pajaro River when each peak reached the main stem. Nevertheless, observation of the hydrographs presented thus far suggest that flows in the neighborhood of 2,000 cfs from Pacheco Creek tend to arrive at Chittenden approximately 8 to 12 hours later in a variety of flow and storage scenarios.

The relatively strong correlation between high flows from Pacheco and high resultant flows at Chittenden over 8 hours later demonstrates its potential usefulness if equipped with streamflow measuring and transmission equipment.

San Benito River at Highway 156 (SB 156)

A similar streamflow situation occurred for the SB 156 gage on February 19-20, 1998 as did for Pacheco in the first example (see Figure 5). A brief and intense flow past SB 156 occurred when contributions from other tributaries were small. The peak flow of 5,600 cfs appears to have arrived only four hours later at Chittenden. The travel time of approximately 4 hours is much shorter than that of Pacheco because the gage is much closer to Chittenden and because the flow in this case was nearly twice as large. Also, San Felipe Lake and Soap Lake can delay peak flows from Pacheco but do not affect flows from SB 156 because SB 156 meets the Pajaro river downstream of these two storage locations. There are no significant reservoirs downstream of SB 156 to delay and attenuate its travel to Chittenden.

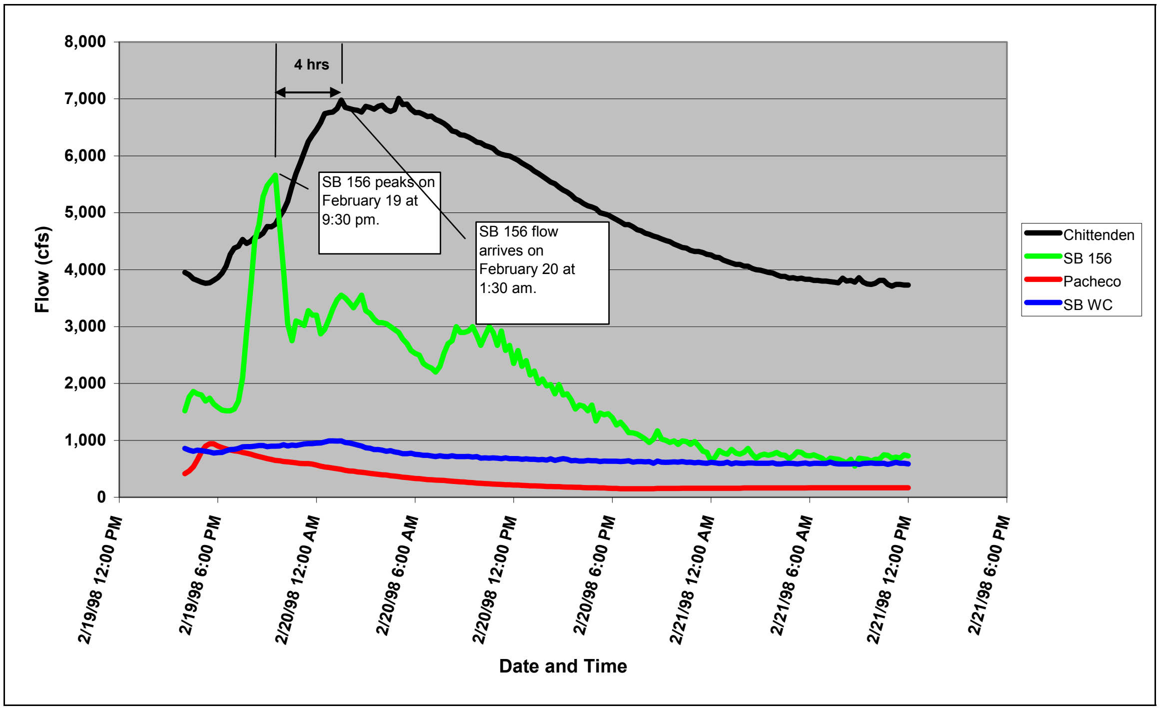

Figure 5: High flow event of February 1998.

This event alone is insufficient to determine the impacts of the travel distance, flow magnitude, and storage effects on the travel time. However, based on the data and distances involved, a flow of 2,500 cfs from SB 156 would arrive at Chittenden more quickly than the 8-12 hours required for a similar flow from Pacheco Creek.

Like Pacheco, a strong correlation exists between flows observed at SB 156 and flow seen a few hours later at Chittenden. However, its closer distance also means that high flows observed via ALERT equipment at this site leave less time to issue a flood warning to communities downstream of Chittenden.

Combined Flow from Pacheco Creek and the San Benito River

On the night of March 10-11, 1995, a very large peak flow of 21,500 cfs was recorded at Chittenden. Extensive flooding damage was sustained further downstream. Although the approximate magnitude of the peak is known, its arrival time and hydrograph at

Chittenden are not known due to damage sustained by the gaging station. Fortunately, useful data were recorded at Pacheco, SB 156, and SB WC (see Figure 6).

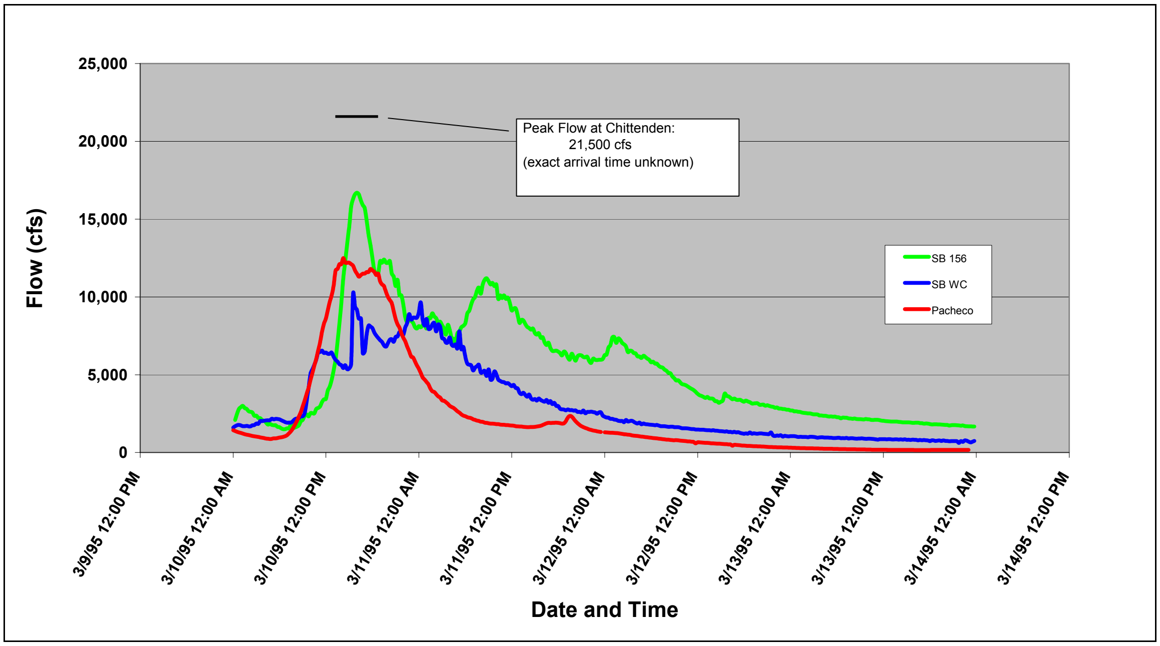

Figure 6: High flow event of March 1995.

A peak flow of approximately 12,000 cfs passed the Pacheco Creek gage at around 2:15 pm on March 10. Roughly two hours later, a peak flow of approximately 16,000 cfs passed by SB 156. Based on the peak flow at Chittenden that is much higher than the flows at either the Pacheco or SB 156 gages, it's likely that both greatly influenced the total flow at Chittenden. While the two tributary peaks did not necessarily arrive at the same time, it's likely that the arrival of the flood waves coincided to some degree. Uvas and Llagas could also have played a role in the total peak. Probable conclusions that can be drawn from this information and analysis are the following.

- A sharp increase in flow at Pacheco followed by a sharp increase in flow at SB 156 roughly 2-3 hours later resulted in a very large combined flow at Chittenden.
- A steep increase of flow at Pacheco and a simultaneous steep increase of flow seen at SB WC (and unseen flows from other creeks) resulted in a very large flow at Chittenden.

Another example of coincident flows is shown in Figure 7. The hydrographs depict high flows from Pacheco followed by high flows at SB 156 several hours later resulting in a very high flow at Chittenden. In this situation during the first week of January 1997, a sharp increase in flow at Chittenden appears to occur simultaneously with a sharp increase in flow at Pacheco.

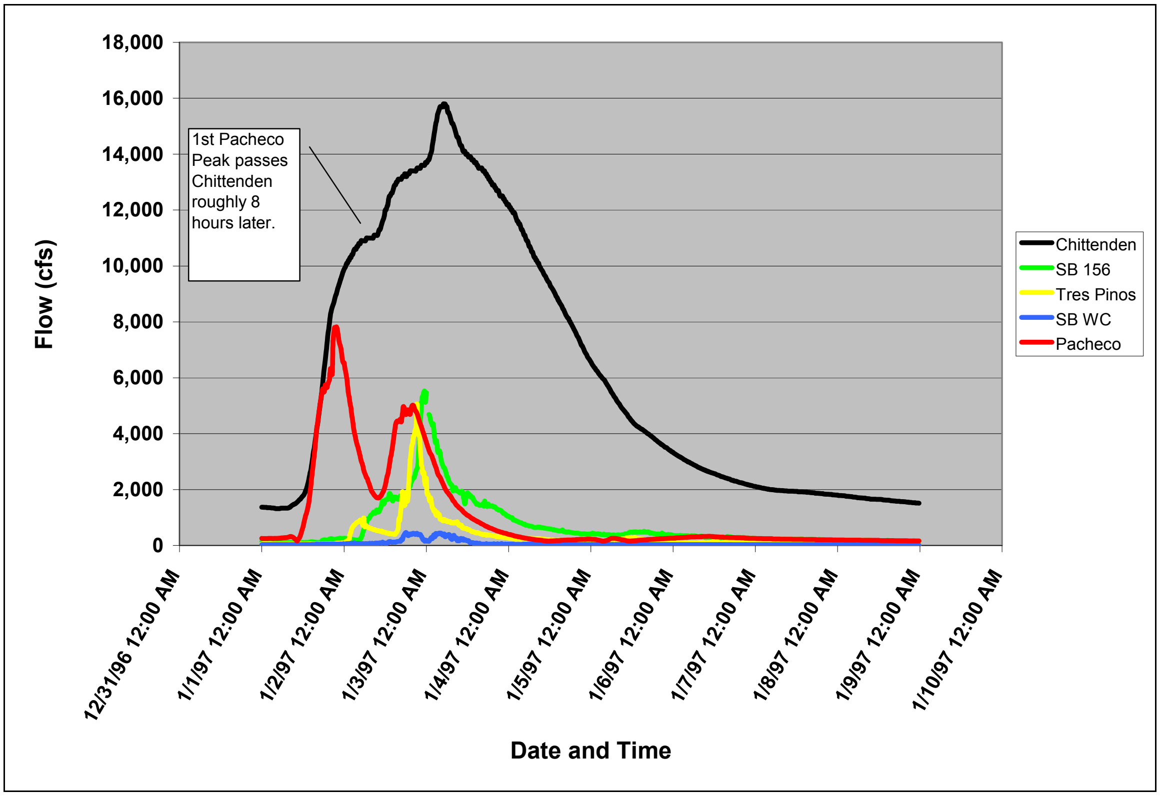

Figure 7: High Flow event of January 1997.

Because the flow at Chittenden continued to rise more than eight hours after the sharp increase in flow at Pacheco, it is likely that the increase of flow at Chittenden to a plateau of 11,000 cfs was caused by the combined effects of Uvas, Llagas, and Pacheco. The rise to the next plateau between 13,000 cfs and 14,000 cfs appears to have been primarily caused by the increase in flow at SB 156 (along with any additional flow from Uvas/Llagas). The second plateau led to a sharp peak of around 16,000 cfs.

This peak of 16,000 cfs at Chittenden is preceded by a secondary peak flow from Pacheco followed by a peak at SB 156 approximately 2-3 hours later. Based on the analyzed data, this lag appears to lead to high flow conditions at Chittenden. Because the secondary peak from Pacheco was not sharp and lasted for a few hours, there was an increased chance for augmentation from SB 156. Although the peak at Chittenden was not dramatically greater than the 12,000 to 14,000 cfs flows that preceded it, this peak flow is probably a great deal higher than what the flow would have been without the combined flows of SB 156 and the secondary Pacheco peak.

Tres Pinos Creek

Tres Pinos Creek is a major tributary to San Benito River upstream of SB 156. There appears to be a strong correlation between high flows at Tres Pinos and high flows shortly thereafter at SB 156. Accordingly, there is also appears to be a strong correlation between flows seen at Tres Pinos and flows seen at Chittenden a few hours later.

Data from Tres Pinos were available for the previously described event during the first week of January 1997 (see Figure 7). The peak flow at SB 156 happens shortly after a similar peak from Tres Pinos Creek. A peak flow of 5,060 cfs passed the Tres Pinos gage at 9:15 pm on January 2nd. Roughly 2-3 hours later, this peak flow appears to have passed SB 156.

A significant conclusion of this is that a sharp increase in flow seen at Pacheco followed by a sharp increase in flow at Tres Pinos roughly 0-2 hours later appears to result in a very large peak flow at Chittenden.

Uvas Creek and Llagas Creek

There were no significant peak flows measured at both the Chittenden gage and either Uvas Creek or Llagas Creek during their available periods of record (2000 to 2005). Furthermore, data from these gages may be inaccurate due to the instability of their channels and infrequent rating curve updates. Consideration was given to potential estimation of travel times from Uvas Creek and Llagas Creek to Chittenden by extrapolation of data from adjacent watersheds and/or estimated velocity based on average channel slope. However, any results produced by these methods would be of little value due to the large degree of uncertainty associated with the lack of direct streamflow data. For these reasons, time of travel from these two creeks to the Chittenden gage were not evaluated in this study.

Conclusions

Despite the many uncertainties of this time of travel analysis, the estimated times of travel presented in this TM appear to be reasonably consistent when applied to a limited number of flow events with data available and presented in this report and others that were studied but not included here. However, further data and evaluation are needed to provide a more accurate estimate of time of travel.

Table 3 shows the estimated times of travel of moderate to large peak flows from their upstream gages to Chittenden. The two sets of ranges are grouped according to the relative amount of flow in the Pajaro River.

Table 3: Estimated flood wave travel times between gages on key Pajaro River tributaries and Chittenden Gap.

Upstream Gage	Approximate distance from Chittenden (mi.)	Travel Time when Pajaro River flows below 2,000 – 3,000 cfs (hours).	Travel Time when Pajaro River flows above 2,000 – 3,000 cfs (hours).
Pacheco	24	10-12	8-10
Tres Pinos	20	8-10	6-8
SB 156	12	4-6	2-4

Combined flows from the Upper Pajaro River subwatershed and the San Benito River subwatershed can lead to large flows at Chittenden. Table 4 quantifies the amount of time after the flows at Pacheco start rising when increasing flows at Tres Pinos and SB 156 are likely to lead to a combined high flow at Chittenden.

Table 4: Conditions likely to lead to a combined high flow at Chittenden.

Upstream Gage	Lag Time After Observed Rising Flow at Pacheco (hours).
Tres Pinos	0-2
SB 156	2-4

Recommendations

With additional streamflow data, further interpretation and analysis is possible for travel times. ALERT gages monitoring the major subwatersheds will allow that analysis to be applied in real time and eventually might help reduce losses due to floods. The following items will help to reach this goal.

- Implementation and maintenance of ALERT gage stations at the following locations:
  - Llagas Creek[1]
  - Pacheco Creek
  - Tequisquita Slough
  - Tres Pinos Creek
  - San Benito River near Willow Creek School
  - Uvas Creek – Currently an ALERT station but requires updated rating curve

- Close evaluation of additional flow events to provide better ranges of travel times.

- Development of a mathematical streamflow routing model, using better data than is currently available, operable in spreadsheet software that can predict the approximate timing and magnitude of an upcoming peak flow at Chittenden based upon real time data received from upstream ALERT gages.

- Separation of known tributary hydrographs from the Pajaro River hydrograph along with development of synthetic hydrographs in order to determine the approximate contributions of non-gaged tributaries.

[1] The Llagas Creek gage previously had ALERT equipment that did not function with the existing USGS instrumentation. This equipment was removed and is not currently scheduled to be reinstalled.