DISSERTATION

An Urban Geomorphic Assessment of the Berryessa and Upper Penitencia Creek Watersheds in San Jose, California

Submitted by:

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY BRETT JORDAN ENTITLED AN URBAN GEOMORPHIC ASSESSMENT OF THE BERRYESSA AND UPPER PENITENCIA CREEK WATERSHEDS IN SAN JOSE, CALIFORNIA BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

AN URBAN GEOMORPHIC ASSESSMENT OF THE BERRYESSA AND UPPER PENITENCIA CREEK WATERSHEDS IN SAN JOSE, CALIFORNIA

A paired watershed study for two adjacent urbanized watersheds in San Jose, California was conducted to investigate vastly different channel morphologic response to urbanization and valley subsidence. The urbanized portion of Berryessa Creek (15.5 km^2) exhibits system-wide channel instability, meanwhile Upper Penitencia Creek (61.3 km^2) has remained stable despite similar urban build out trends. Currently, there is a paucity of field measurements documenting channel response to urbanization and subsidence in the academic literature. Detailed geomorphic field surveys were undertaken to establish 90 permanent cross sections over 9.2 km of urban channel. These surveys were used for sediment transport modeling in this study and will provide a permanent monitoring network. Historic data sources were utilized to establish a baseline context and chronicle change in the watersheds. The historic data sources, field data, and numerical modeling were used to investigate the relative effects of hydrologic alteration, valley subsidence, and river infrastructure on water yield, sediment yield, and channel stability.

Drainage area capture by the urban storm sewer network, a component of urbanization that has not previously been addressed in the scientific literature, and engineered river infrastructure elements are the primary causes of system-wide channel instability in the urbanized valley portion of Berryessa Creek. Hydrologic and sediment transport modeling indicates that drainage area capture and urban land use change has increased water yield 48% and sediment yield up to 61% from 76 to 121 tonnes/yr-km^2. These hydrologic changes have transformed historically depositional reaches into incised reaches leading to system wide instability. An on-line sedimentation basin and a 1.85 m grade-control structure have reduced downstream sediment yield by 15% from 88 to 76 tonnes/yr-km^2 and increased channel incision rates by capturing coarse bed material in transport. Models indicate that measured valley subsidence of 0.23 m results in upstream incision, however sediment yield is not affected and the morphologic response to subsidence is likely obscured by current instability processes dominant in the system.

In the current hydrologic regime of Upper Penitencia Creek, flow diversion and basin reduction by the storm sewer network offset increased runoff produced by the urban landscape and channel stability is not adversely affected by the hydrologic alteration. Water yield is increased by 7%, however sediment yield is reduced by 4% from 41.7 to 39.8 tonnes/yr-km^2 at the outlet. River infrastructure in the form of a system of small grade-control structures aids in the stability of the upstream reaches. Valley subsidence of 1.1 m is predicted to cause incision that would progress 1800 m upstream of the zone of maximum subsidence. Modeling results were verified by reach-scale instability observed upstream of the subsidence zone. The reach scale instability is a result of increase stream power resulting from valley subsidence and channel realignment.

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David Mooney and Blair Greimann developed the sediment transport tools utilized in the study and were very helpful in answering questions and modifying code if necessary.

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This dissertation is dedicated to my mother and father. Their love knows no bounds.

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1.0 RESEARCH NEEDS AND OBJECTIVES

1.1 RESEARCH NEEDS

The deleterious effects of watershed urbanization on stream channel stability and stream corridor health are well documented in the literature (Wolman 1967, Leopold 1968, Hammer 1972, Morisawa and Laflure 1979, Booth 1990, Booth and Jackson 1997, Trimble 1997). However, measured data concerning the effects of urbanization on stream channel form are lacking (Bledsoe and Watson 2001). In a similar fashion, river response to valley subsidence has been studied conceptually from topographic mapping (Schumm *et al.* 2000) and with experimental flume studies (Ouchi 1985), but measured field data of stream channel response to valley subsidence is also lacking.

A unique comparative paired watershed case study of two adjacent stream channels in the Santa Clara Valley region of California provided an opportunity to study the relative effects of multi-faceted watershed urbanization and valley subsidence on channel form, stability and response. Berryessa (15.5 km^2) and Upper Penitencia (61.3 km^2) Creeks have similar innate watershed characteristics (i.e. surficial geology, soils, relief, and vegetation characteristics); however, urbanization processes have imposed distinctly different scenarios for each watershed with respect to drainage network manipulation, hydrologic change and engineering infrastructure. Additionally, historic valley subsidence, as a result of ground-water withdrawal has resulted in differing degrees of base-level lowering for each watershed.

This study couples field measurements and numerical modeling to provide a computational assessment of urbanization and valley subsidence on water and sediment delivery and flux processes. Investigations were conducted to deduce the relative effects of each component driving channel change or stability within the respective watersheds. The three primary methods of investigation utilized in this study were:

1. Time series aerial photo, topographic mapping and longitudinal profile analysis.

2. Field data collection; and

3. Numerical hydrologic and sediment transport modeling.

Numerical computational models were supplied with and validated by detailed field data collected by the investigating author including: stream channel cross-section, planview, and longitudinal profile data; urban infrastructure surveys; streambed and bank material gradation; stream bank stratigraphy and vegetative composition; continuous stream flow gaging; and bed load and suspended load sediment transport measurements. Both the Berryessa Creek and Upper Penitencia Creek watersheds were studied at a high level of detail consistent with the methods outlined by Annable (1996), to properly characterize a stream channel in a state of urbanization. The end result of this study provides insight into the relative effects of multiple concurrent external forcing variables on stream channel response, particularly within an urban context. These results illustrate the fact that computational tools are most valuable if used in conjunction with rigorous field data-collection procedures and protocol.

1.2 RESEARCH OBJECTIVES

The research objectives of this study are as follows:

1. Perform a comparative analysis of the factors leading to channel instability and/or stability in two adjacent watersheds that have encountered vastly different morphologic response to urbanization despite similar upland watershed characteristics. This will be accomplished through historical data analysis, field observations and measurements, and numerical hydrologic and sediment transport modeling.

2. Investigate the relative effects of drainage area manipulation via the storm sewer network, increased imperviousness due to urbanization infill and flow diversion on typical storm hydrographs. The effects of the urban hydrologic changes on water yield, sediment yield, and channel stability will be quantified via numerical modeling for both streams.

3. Investigate the effect of valley subsidence on channel stability and sediment yield for both streams using numerical modeling, historic data sources and field observations.

1.3 SITE INTRODUCTION

A historical perspective of urban watershed land use, natural channel form, and anthropogenic changes to channel planform and profile is essential to understanding the present processes dictating the stability or degradation of an urban stream system. The sedimentation processes currently observed within both Berryessa (15.5 km^2) and Upper

Penitencia (61.3 km^2) Creeks are the result of land-use and channel changes made historically (Trimble 1981). This study combines the historical data available, detailed field data-collection efforts, and a numerical sediment continuity assessment to elucidate the reaches on both creeks that exhibit morphologically stable and unstable conditions.

Upper Penitencia Creek and Berryessa Creek are located in Santa Clara County, California (Figure 1.1). Both watersheds are tributary to the Coyote Creek watershed (826 km^2), which ultimately drains to the San Francisco Bay. Both watersheds have similar basin relief, upland land use, geology, urbanization trends, and precipitation regimes. The basin relief for the upland portion of the watershed is 628 m and 933 m, for Berryessa Creek and Upper Penitencia Creek respectively. The relief ratio, which is the total relief divided by the stream length is 0.076 m/m for Berryessa Creek and 0.072 m/m for Upper Penitencia Creek. Both watersheds were historically alluvial fan systems that have been anthropogenically manipulated along the valley floor to facilitate agricultural and urban development. Berryessa Creek has been subjected to channel realignment, engineering infrastructure, floodplain encroachment, and drainage area expansion via the urban storm sewer network, whereas Upper Penitencia Creek has remained relatively untouched within the bankfull channel and historic meander belt width floodplain since the early 1900s. Upper Penitencia Creek is supplied with a continuous base flow from an upstream reservoir and groundwater sources to support abundant vegetative growth. Peak flows have been extracted from the Upper Penitencia storm hydrographs since the late 1960s to supply groundwater percolation ponds that were built to halt valley subsidence due to agricultural ground water extraction. Primarily as a result of management practices, Upper Penitencia Creek has remained relatively stable, whereas Berryessa

Creek has suffered severe erosion and sedimentation problems. In the summer of 2004, approximately 7,100 m^3 of sediment were dredged from two reaches of Berryessa Creek. Meanwhile, two fish ladders that are used on Upper Penitencia Creek for steelhead migration only needed 30 m^3 of sediment removed from the structure (Santa Clara Valley Water District (SCVWD) 2004). The economic long-term maintenance benefits of geomorphic stable channel design are readily apparent.

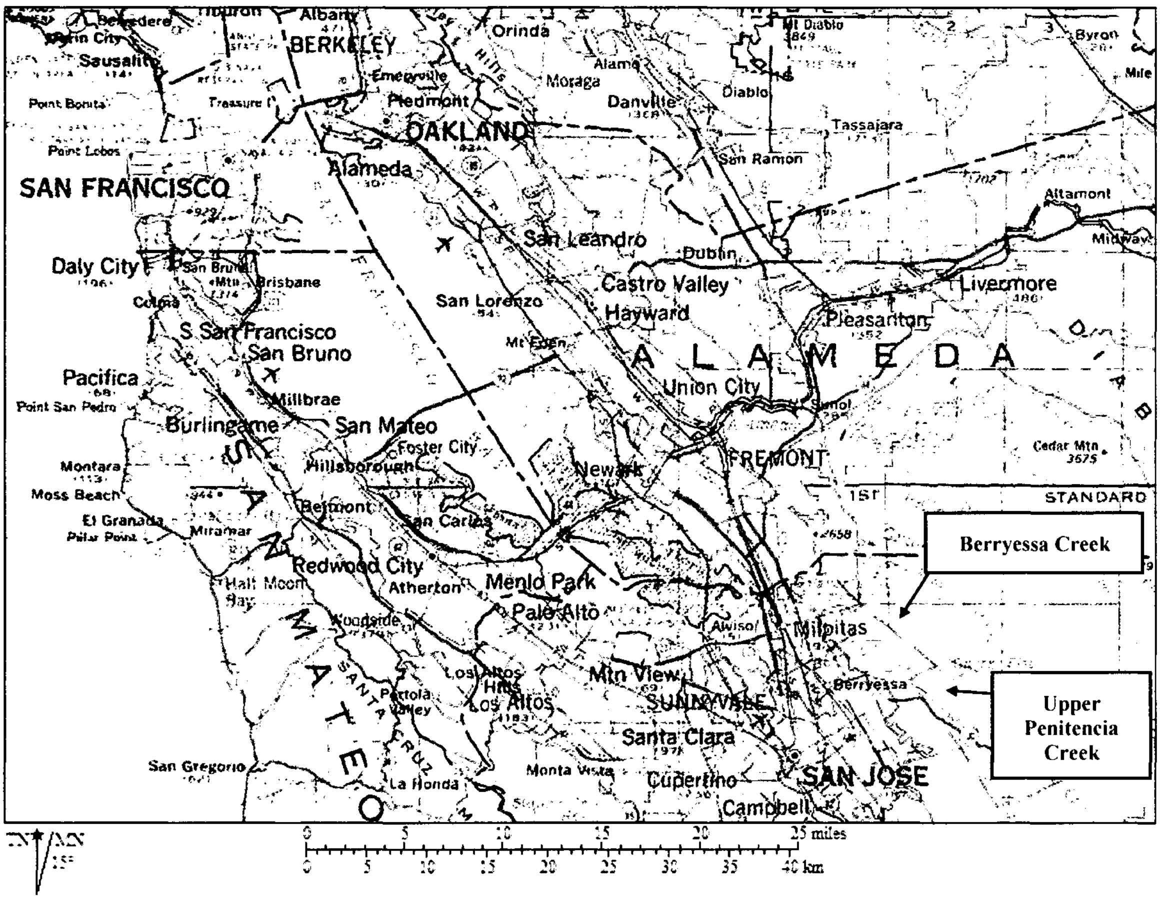


Figure 1.1 **General site map of Upper Penitencia and Berryessa Creeks, San Jose, California.**

1.4 DISSERTATION ORGANIZATION

This document is organized by data collection and analysis methods followed by the subsequent use of the data for hydrologic and sediment transport numerical simulation. Data collection will be broadly classified into desktop data, data that can be collected without stepping foot onto the site being investigated and field data collection. Chapter 2 presents a concise literature review on physical response of streams to urbanization and subsidence. Chapter 3 details the collection and analyses of desktop data sources. These data sources include; Geographic Information System (GIS) and Auto-cad morphometric analyses conducted via time series aerial photographs, local historic precipitation and stream flow gaging records, and engineered structure design data. Strom sewer construction design data were utilized to delineate the timing and extent of drainage area manipulation via the constructed urban storm sewer network. Chapter 4 presents all field data collected, including: preliminary reconnaissance data, longitudinal profiles, repeated monumented cross-section surveys, bed and bank material composition analysis; stream flow and sediment transport data; bank stability, vegetation and stratigraphy surveys; and culvert outfall inventories. Chapter 5 investigates the hydrologic changes to the historic flow regimes due to urbanization and groundwater percolation pond construction. Chapter 6 investigates the morphologic changes in both of the streams due to urbanization and valley subsidence via numerical sediment transport modeling. The dissertation concludes with Chapter 7: a concise summary of the findings related to the research objectives and proposed future research questions to be investigated with these data or other similar datasets.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Stream channels are dynamic and respond to alterations of water and sediment flux from their contributing watersheds with changes in longitudinal, cross-section, and planview form. Two primary alterations have occurred in the Santa Clara Valley region of California where both of the creeks being studied are located: urbanization and land subsidence. Urbanization is considered a land-use change, whereas subsidence is a topographic change in the land surface. Four effects of watershed land-use change (urbanization in this case) on watershed hydrology and stream response are (Leopold 1968):

1. Changes in peak flow characteristics;
2. Changes in total runoff volume;
3. Changes in water quality; and
4. Changes in hydrologic amenities (appearance or impression the river leaves with the observer).

The first two address changes in water and sediment delivery to the channel system. The third point primarily affects chemical and biotic response. The fourth point indirectly addresses channel stability and biotic response.

Another driver of channel change in the streams being studied is valley subsidence. Land subsidence is associated with a lowering of valley base level and a subsequent increase in valley gradient for the streams. This change must be examined in addition to the urbanization processes to gain a complete understanding of channel changes occurring in the study area.

2.2 HYDROLOGIC CHANGES DUE TO URBANIZATION

2.2.1 PHYSICAL CHANGES TO THE WATERSHED LANDSCAPE

Urbanization is a multifaceted and permanent alteration of the watershed landscape. The alterations can be broadly classified as follows:

1. Surface alterations decreasing infiltration, increasing runoff, and increasing susceptibility to erosion

2. Increased routing efficiency of runoff waters to the stream channel

3. Drainage network extension via storm sewers

4. Increased drainage network density via storm sewers

As ground is cleared for construction, landscape vegetation, root structure and protective canopy are lost, making the exposed soil more prone to erosion and increasing sediment supply to the channel system thus leading to a period of channel aggradation (Wolman 1967, Leopold 1973, Graf 1975, Roberts 1989, Clark and Wilcock 2000, Grable and Harden 2006). This cleared ground is then paved for roads, driveways and sidewalks, creating an impermeable surface resulting in vastly increased runoff (Leopold 1968, Hammer 1972, Hollis and Luckett 1976, Neller 1988). The overland flow runoff waters are typically routed in a curb and gutter storm water system ultimately leading to a piped storm sewer system. This system vastly increases runoff efficiency and reduces storm lag time (Hammer 1972, Graf 1975, Doyle *et al.* 2000). The storm sewer network also alters the overall catchment network through network extension (Swezey 1991) and increased catchment drainage density (Whitlow and Gregory 1989). These alterations to the watershed landscape result in significant changes in urban rainfall storm hydrographs and rapid changes in urban stream channel morphology.

2.2.2 STORM SCALE EFFECTS

Two effects of urbanization frequently addressed in the literature are decreased lag time and increased magnitude of the flood hydrograph peak (Leopold 1968, Hollis 1975, Hollis and Luckett 1976, Knighton 1998). These effects can primarily be attributed to two factors: (1) the percentage of impervious area in an urbanized basin; and (2) the improved delivery efficiency due to the storm sewer network. Impervious areas will have essentially no infiltration capacity and the storm sewer and curb and gutter infrastructure provide a routing mechanism with much less resistance to flow than overland processes. The hydrologic effects of urbanization will depend on the basin characteristics, particularly basin length and slope as well as the soil characteristics of the basin. Some observers have found that watersheds with high runoff rates before urbanization will be least affected by the urbanization changes (Dunne and Leopold 1978). Conversely, Roberts (1989) found that channel enlargement was two times greater for "less permeable" watersheds when compared to "more permeable" ones. The flows with more frequent return intervals (bankfull and below) have been found to be the most affected (Hollis 1975, Doyle *et al.* 2000). A recurrence interval of 1.5 to 2 years on the annual maximum series would be expected to be 2 to 3 times as large for a fully urbanized drainage net (Hammer 1972, Hollis 1975, Hollis and Luckett 1976). Leopold (1968) plotted isopleths of the mean annual discharge (2.33 annual return frequency) for varying levels of imperviousness and storm sewer drainage (Figure 2.1) from earlier studies (Carter 1961, Wiitala 1961, Martens 1966, Wilson 1966, Espey *et al.* 1966, Anderson 1968). These indicate that a fully urbanized drainage area (50% impervious (Dunne and Leopold 1978)), with approximately 50% of the area serviced by storm sewers, would expect a two to three fold increase in the mean annual discharge. Larger floods with recurrence intervals in the range of 20 years are less intensified by the urbanized landscape, since overland and subsurface flow from completely saturated soils drowns out drainage efficiency and infiltration differences between urban and rural landscapes (Hollis and Luckett 1976).

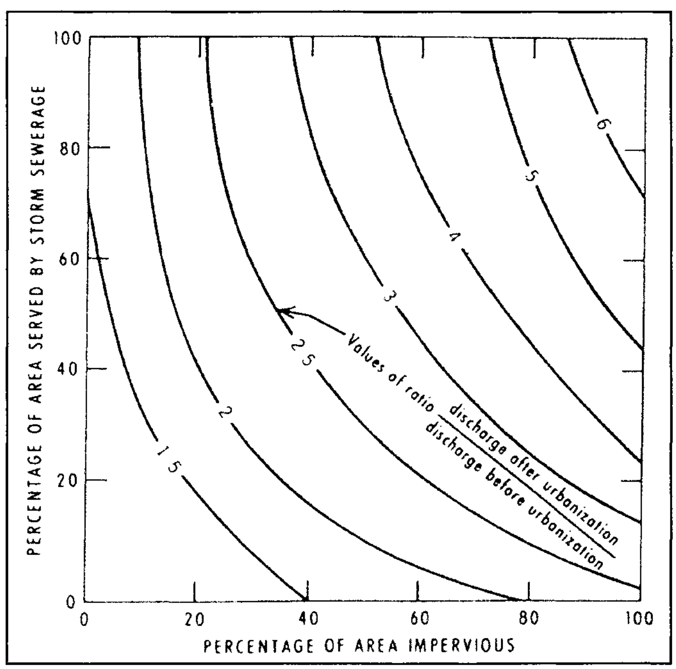


Figure 2.1 **Expected changes in mean annual discharge as a function of watershed imperviousness and storm sewer coverage (from Leopold (1968)).**

A common hydrologic effect of watershed urbanization is a decrease in the storm hydrograph lag time (Anderson 1968, Leopold 1968, Knighton 1998, Byrom and Lahm 2004). The lag time is defined as the time interval between the center of mass of the rainfall hyetograph and the center of mass of the resulting storm hydrograph (Figure 2.2). The lag time is reduced with the increased routing efficiency of watersheds serviced by storm sewers and the decreased resistance to flow offered by impervious surfaces when compared to overland flow routing over natural areas. Decreases in centroid lag time have been found to be a function of drainage basin slope and runoff length (Figure 2.3), as well as the intensity of storm sewer construction in the basin (Anderson 1968). In fully developed and channelized basins, urban lag times could be expected to be 12 to 15% of the natural basin lag times. In partly developed basins, urban lag times were 20 to 25% of their natural counterparts.

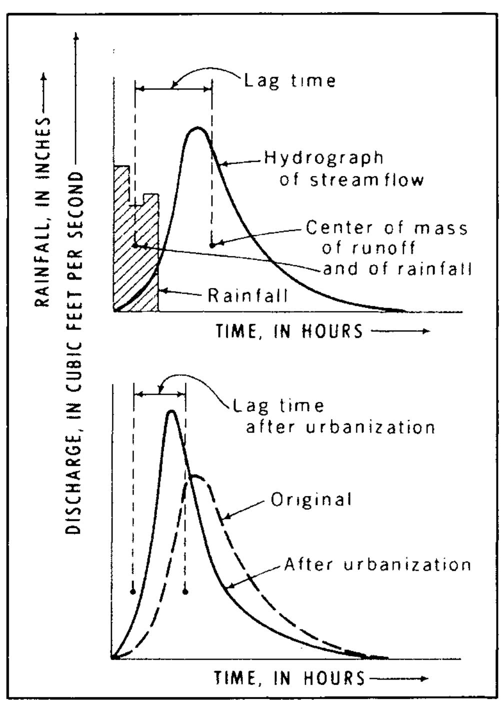


Figure 2.2 Hypothetical unit hydrographs and changes expected from urbanization processes (from Leopold (1968)).

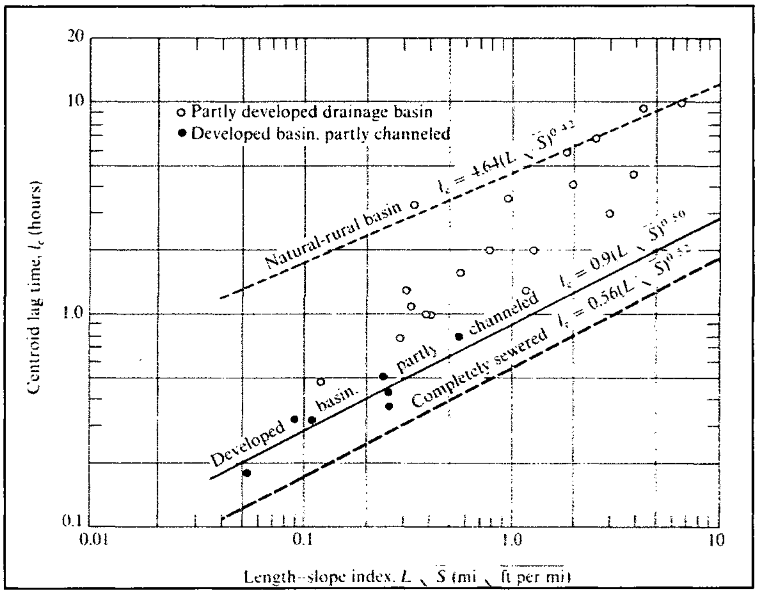


Figure 2.3 Relation of centroid lag time to length slope index for basins with varying degrees of storm sewer infrastructure (from Anderson (1968)).

2.2.3 INTER-ANNUAL TO DECADAL SCALE EFFECTS

The annual flow regime is comprised of a culmination of all the yearly individual storm flows. It is this collection of flows along with the concomitant sediment loads and channel resilience that influence erosion and deposition processes as well as biotic function of a stream channel. Recent work by Konrad and Booth (2005) integrates storm-scale effects into three stream flow metrics:

1. $T_{Q\,Mean}$: the fraction of time that stream flow exceeds the mean stream flow;
2. CV_{AMF}: the coefficient of variation of annual maximum stream flow; and
3. $T_{0.5}$: the fraction of time that stream flow exceeds the 0.5-year flood.

They found that urban streams had low inter-annual variability of annual maximum stream flow and short durations of frequent high flows, when relating all variables to road density as a surrogate for urbanization in the Puget Sound area of Washington. A key point of the study was that the peak flow characteristics were significantly altered but the cumulative stream flow was not. Leopold (1968) had similar findings and attributed the lack of change in the cumulative duration to overbank floodplain storage. Konrad and Booth (2005) suggested that hillslope processes are altered for zero order basins as ground water storage and transmission are substituted for runoff, thereby affecting timing but not cumulative stream flow in the higher-order streams downstream. A caveat to this finding is offered for basins where water is imported to or exported from the basin. This is the case for Berryessa and Upper Penitencia Creeks.

Urbanization can be linked to increased frequency of storm events that mobilize the stream bed material. The benchmark field study for quantifying these hydrologic changes is Leopold's (1973) twenty-year study of Watts Branch near Rockville, Maryland. In this study, monumented cross sections and continuous stream gaging data were in place prior to, during and after significant watershed urbanization. The frequency of bankfull flood events increased from 2 per year prior to urbanization to 12 per year after urbanization. The increased frequency was not limited to the smaller bankfull events, larger storm events up to 4 times bankfull revealed similar trends with regard to frequency of occurrence. Surrogate methods to direct observation have been utilized by other researchers, Doyle *et al.* (2000) utilized incipient motion analysis and stream gaging data to compare the frequency of a critical discharge index (discharge where the median bed material is mobilized) for urban and rural streams. Their findings indicated that stream bed mobilizing events occur twice as frequently; 4 days per year compared to 2 days per year, for urbanized watersheds. Comparative watershed studies on small watersheds in New South Wales, Australia measured a four-fold increase in the frequency of runoff events for urban streams when compared to their rural counterparts (Neller 1988). Hydrologic modeling studies can also be used to quantify land use effects on urban hydrology and incorporated into frequency analysis (Booth 1990, Bledsoe and Watson 2001). The modeling studies revealed similar trends with regard to urban bankfull discharge frequency.

Long term impacts of urbanization on catchment hydrology have been investigated and compared with hydrologic changes induced by climate change. Statistical techniques were used by DeWalle *et al.* (2000) to differentiate the potential impacts of urbanization and climate change on mean annual stream flow in the United States. In their study, urbanization increased mean annual stream flow in proportion to population density increases, with up to a 100% increase for complete urbanization. These changes offset flow declines or augmented flow increases due to climate change alone. Fifty years of hydrologic, land use and climate data on Laurel Creek in Waterloo, Ontario indicated that the long-term runoff ratio computed as the ratio of storm event runoff to event precipitation increased marginally with a thousand-fold increase in urban land use (Morgan *et al.* 2004). However, long-term flood peaks did not substantially increase nor did flood recession time decrease due to increased urban drainage efficiency.

2.2.4 THE ROLE OF CATCHMENT CHARACTERISTICS

Catchment characteristics certainly play an important role in watershed response to urbanization. Watershed permeability was found to influence channel enlargement rates (Roberts 1989), with less permeable watersheds being more susceptible to channel enlargement. The Roberts (1989) study was conducted in the United Kingdom on perennial limestone and chalk (permeable) and sand or clay (impermeable) streams. Less permeable watersheds may be adjusted to floods with shorter return frequencies, which are preferentially affected by the urbanization (Hollis 1975, Knighton 1998). Studies in the Puget Sound area of the Pacific Northwest indicate that more permeable watersheds are adversely affected by urbanization as subsurface drainage is converted to surface drainage resulting in increased runoff peaks (Booth and Henshaw 2000).

Streams that include alluvial fan deposits in arid environments may be expected to respond quite differently than perennial streams in more humid environments (Schick *et al.* 1999, Chin and Gregory 2001). Arid streams typically have a large upstream sediment supply and unstable banks (Leopold and Miller 1956) resulting in relatively high bedload and suspended load sediment concentration. Although extreme events may be relatively infrequent, occurring less than 5% of the time for the total flow regime, they can transport up to 65% of the total sediment load (Garcia 1995). Adjustment processes and recovery times to these extreme events are usually much longer for ephemeral channels than channels in more humid environments (Wolman and Gerson 1978, Chin and Gregory 2001). These aspects make linkages between channel form and process more complex in arid environments than humid environments, where more consistent spatial and temporal adjustments of channel form to hydrologic and sediment supply regimes are the norm (Graf 1983, Rhoads 1988).

Numerous investigations have shown that urbanization has a stronger impact on catchment hydrology for smaller basins than larger basins (Hammer 1972, Hollis and Luckett 1976, Booth 1990, Booth and Henshaw 2000). This is partially due to the dampening effects on runoff processes present in larger drainages and the susceptibility of smaller drainages to relatively subtle changes in runoff, particularly if flow concentration occurs at point outfalls in the stream channel (Gregory et al. 1992, Booth and Henshaw 2000).

2.2.5 BASEFLOW EFFECTS

The effects of urbanization on base flow characteristics are variable. Base flows have been found to decrease due to a reduction in ground water storage resulting from the reduced infiltration on impervious land (Sawyer 1963, Simmons and Reynolds 1982, Rose and Peters 2001, Konrad and Booth 2002). Other researchers have found no effect or increases in base flow due to urbanization (Lerner 1986, Lerner 2002, Meyer 2005, White and Greer 2006). Base flow increases have been attributed to water importation, ground water surcharge from leaky water supply and stormwater systems, and effluent releases (Lerner 2002). Base flows have been found to be unaffected by urbanization in watersheds with high relief and low permeability (Meyer 2005). Baseflow modifications also depend on the seasonality of the precipitation regime. Utilizing road density as a surrogate for urbanization Konrad and Booth (2005) found urbanization to be inversely correlated with unit area base flow for the wet season in the western Washington area, whereas no trend was found during the dry season. The effects of urbanization on base flow characteristics are not straightforward, and depend on infrastructure and basin characteristics, location of the watershed in the regional groundwater flow system, as well as precipitation seasonality.

2.3 GEOMORPHIC IMPLICATIONS OF URBANIZATION

2.3.1 OVERLAND SEDIMENT SUPPLY AND DELIVERY

The commonly accepted temporal sequence for sediment supply and delivery in an urbanizing watershed is that of Wolman (1967) (Figure 2.4). Initially there is a spike in sediment supply during the construction phase, followed by a gradual decline in sediment supply as build out proceeds and areas are rendered impervious. The initial spike of sediment may result in downstream aggradation, which may take years or decades to move through the fluvial system (Wolman 1967, Leopold 1973, Graf 1975, Roberts 1989). Nelson and Booth (2002) found that new construction sediment sources were minimal when compared to landslide activity and channel sources in the Pacific Northwest. After the construction phase of urbanization, sediment sources will decline due to imperviousness and detention. After this stage channel processes, incision and bank failure, will dictate the sediment supply to downstream reaches. In many cases urbanization is preceded by land clearing and denudation for agriculture (Wolman 1967, Clark and Wilcock 2000). In this case the sediment introduced from the agricultural land practices may still be moving through the channel system, making the task of identifying the relative contribution of the urbanization sediment supply speculative at best.

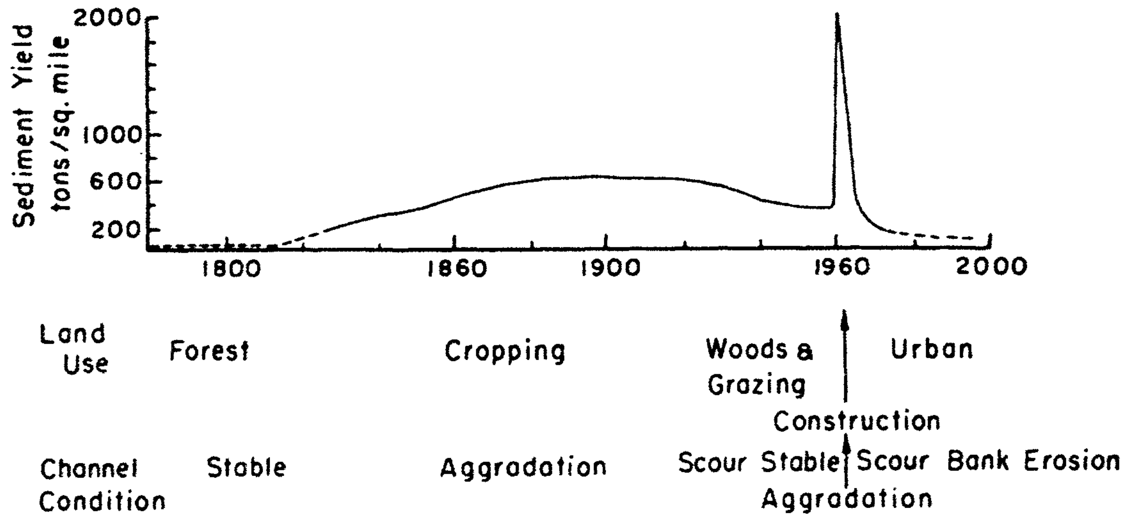


Figure 2.4 **Cycle of land-use changes, sediment yield, and channel behavior (from Wolman (1967)).**

2.3.2 STREAM CHANNEL GEOMORPHIC RESPONSE

Stream channel response to altered urban flow and sediment supply regimen can be quite complex. An initial aggradation phase may be expected due to the spike of sediment from the construction phase, followed by increases in width and depth. Aggradational features, however, may persist for periods up to 20 years (Leopold 1973). A space-for-time channel evolution model (CEM) for incised channels (Schumm *et al.* 1984) suggests that a depth increase would be expected first, followed by channel widening and a final quasi-equilibrium stage once the channel has adjusted to the new water and sediment regime. Channel enlargement of some form is expected, particularly in the upstream urbanized reaches. The magnitude of enlargement will be dictated by the degree of urbanization, storm sewer connectivity, channel and bank materials, pre-urbanization runoff and sediment supply characteristics, watershed and channel slopes, and sediment supplied from the construction phase (Hammer 1972, Leopold 1973, Roberts 1989, Gregory *et al.* 1992, Booth and Henshaw 2000, Pizzuto *et al.* 2000, Chin and Gregory 2001). Typically, space-for-time substitution is used to identify changes between the pre-disturbance rural condition and the urbanized state. Oftentimes, urban channels are compared to rural counterparts that exhibit similar watershed and channel characteristics (Hammer 1972, Pizzuto *et al.* 2000). An enlargement ratio, defined as the ratio of the urbanized cross section to a similar rural cross section, was utilized by Hammer (1972). He found that the enlargement ratio can range from 0.7 to 3.8, with most of the data lying between 1 and 2. Other investigators (Roberts 1989, Pizzuto *et al.* 2000) found that urban channels are generally wider (26%), larger (60%), smoother (10%), and straighter (8%) than similar rural channels. Little is known about the relative contributions of width and depth changes (Knighton 1998). Long-term field measurements of channel change are rare. In a ten-year study of the rapidly urbanizing San Diego Creek in southern California, Trimble (1997) found that about 2/3 of the total sediment yield comes from channel sources. In his twenty-year study of Watts Branch, Maryland, Leopold (1973) found that depth had increased 23%, primarily as a result of overbank sedimentation, and width had decreased 35%, counter to the channel enlargement that would be expected. He attributed the width decrease to the initial sediment pulse from the construction phase and incomplete channel adjustment to this sediment input. Similar trends of decreasing width in the downstream longitudinal direction were found by Clark and Wilcock (2000).

Clearly, the geomorphic implications for channel change are complex and involve multiple interacting variables. Location in the fluvial system plays a key role in the expected channel response. The spatial context of the urban development is a critical component of channel response (Roberts 1989, Gregory *et al.* 1992, Chin and Gregory 2001). Transport and response reaches may see opposite adjustments as sediment from failing stream banks and channel degradation are deposited in downstream reaches, which lack the transport capacity to carry the increased upstream load (Booth and Henshaw 2000). Dredging and channelization in the downstream response reaches of urbanized systems are common, and can create a positive feedback mechanism as the increased stream power in the channelized downstream reach can lead to further upstream degradation and bank failure (Brookes 1988). Stream channel response to urbanization is oftentimes spatially discontinuous (Gregory *et al.* 1992). The spatial discontinuity of urban land use change and in-stream engineering structures can lead to system fragmentation (Chin and Gregory 2001). The spatial location of channel change measurements in the fluvial network and the interconnected watershed processes occurring at these spatial locations are crucial in determining cause and effect relationships of the measured change.

2.4 THRESHOLDS AND BIOTIC RESPONSE TO URBANIZATION

Riverine ecology and biotic health are adversely affected by watershed urbanization. Water quality is degraded with the addition of treated sewage effluent, nutrients, artifacts of civilization, and the transportation of pollutants to the stream (Leopold 1968, Schueler 1994, Paul and Meyer 2001). Many studies underscore the importance of imperviousness and its deleterious effects on stream benthos. Previous researchers have inferred typical threshold values between 10 to 15% imperviousness (Steedman 1988, Schueler and Galli 1992, Booth and Jackson 1997, Wang *et al.* 2000, Wang *et al.* 2001, Morley and Karr 2002, Freeman and Schorr 2004). These imperviousness threshold values should not be taken as a distinct threshold, but rather a range of potential impairment values that will be dependant upon urbanization type, spatial location, connectivity, and watershed resilience. Impairment is often related to increased deposition of fine sediment, introduction of chemical pollutants, and loss of habitat variability and complexity (Morley and Karr 2002, Booth *et al.* 2004, Freeman and Schorr 2004). This indicates that both channel and overland processes degrade biotic health. Channel rehabilitation intervention can be used to improve biotic health, but the degree of impairment and watershed urbanization can dictate the potential strategies used to restore biotic integrity (Figure 2.5) (Booth *et al.* 2004).

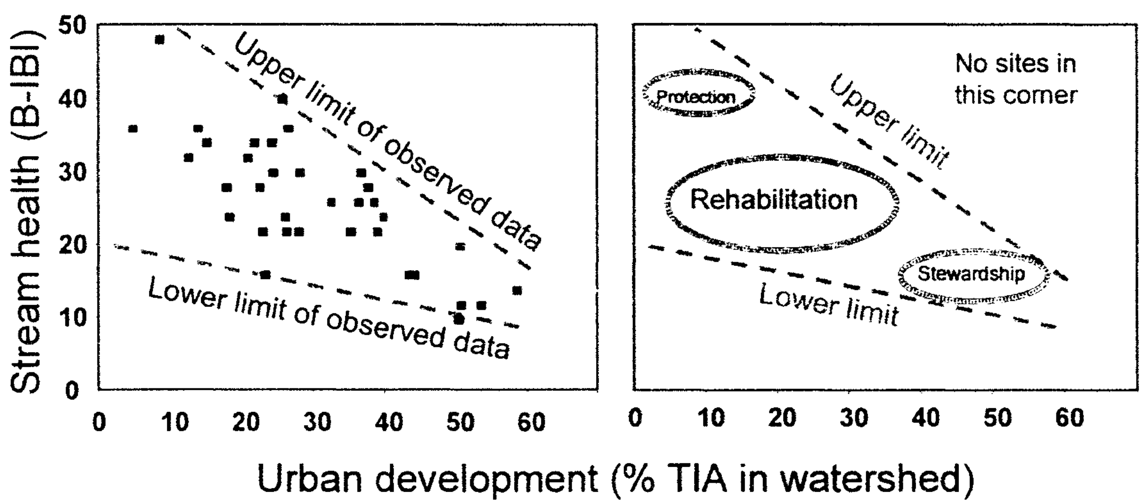


Figure 2.5 **Left: Relationship between stream health (Benthic index of Biological Integrity (B-IBI) and urban development (percent total impervious area (TIA). Right: Recommended management strategy (from Booth *et al.* (2004)).**

2.5 SUBSIDENCE EFFECTS

Land subsidence is associated with change in valley base level. Common causes of land subsidence include aquifer system compaction due to groundwater mining, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost (Galloway *et al.* 1999). Land subsidence of up to 3.5 meters has been measured in the Santa Clara Valley from 1934 to 1967 due to ground water pumping

(Poland 1976, Poland and Ireland 1988). The expected channel response upstream of the subsidence axis is either increased sinuosity or channel degradation depending on channel and valley characteristics. Channels that are free to migrate along the valley floor would be expected to increase sinuosity, whereas channels that are confined laterally would be expected to degrade (Ouchi 1983, Schumm *et al.* 2000). Within the subsidence area, channel response is typically aggradation, leading to in- channel bar development or anastomosing channel forms (Ouchi 1985). Downstream of the subsidence axis, channel degradation can take place due to a decrease in downstream sediment supply resulting from aggradation and sediment capture in the subsidence zone (Ouchi 1985, Schumm *et al.* 2000). Channel pattern response upstream and downstream of the subsidence axis will vary depending on pre-existing channel form, sediment transport regime and channel confinement (Figure 2.6). Channel pattern response to subsidence in flume studies (Begin *et al.* 1981) revealed that channel degradation rates are attenuated exponentially with distance upstream from the disturbance location. Pattern adjustment (increased sinuosity) coupled with channel cross section adjustment (width increase and bar development resulting in increased channel roughness) compensate for slope changes due to base-level lowering from valley subsidence (Jorgensen 1990, Schumm and Galay 1994).

Field measurements of channel response to valley subsidence are lacking. Field studies of channel response have been limited to topographic map analysis (Ouchi 1985, Schumm *et al.* 2000) and one field-based study (Jorgensen 1990). Topographic mapping analysis of Coyote Creek, the stream that both creeks in this study are tributary to, showed a 35% increase in planform sinuosity from 1895 to 1961 in the vicinity where channel gradient was increased due to rapid valley subsidence of 3.5 meters (Schumm *et al.* 2000). Up to

8.5 meters of land subsidence have been recorded in the San Joaquin Valley region of southern California due to groundwater extraction (Tolman and Poland 1940, Galloway *et al.* 1999). Ouchi (1985) found no significant channel pattern response in the San Joaquin River due to this rapid subsidence. This may be due to the highly controlled nature of the San Joaquin River, which has been heavily engineered (Ouchi 1985). Longitudinal increases in sinuosity and fluctuations were noted, and it was postulated that these longitudinal increases in sinuosity may have been the result of slow geologic-scale subsidence patterns in the area (Ouchi 1985). A field-based study of the Humboldt River, NV subject to geologic time scale subsidence documented: a 40% increase in sinuosity coupled with active lateral migration upstream of the subsidence axis (Jorgensen 1990). Downstream of the subsidence he noted channel aggradation, a 120 % increase in bankfull channel area, and a 46 % increase in bankfull channel width. Downstream fining of the channel bed material through the subsidence axis further validated the depositional trend. Land subsidence in the Santa Clara Valley has been halted since 1967, due to water importation, altered ground water pumping practices, and water table recharge (Poland and Ireland 1988). A time sequence of these base level changes is available and will be discussed in Chapter 3. These geometric changes to the channel and valley profile must be examined in conjunction with urbanization effects to ascertain the relative effects of both processes on current channel form.

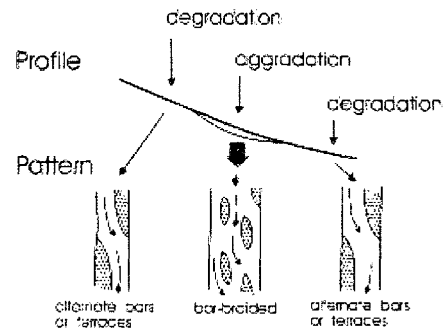
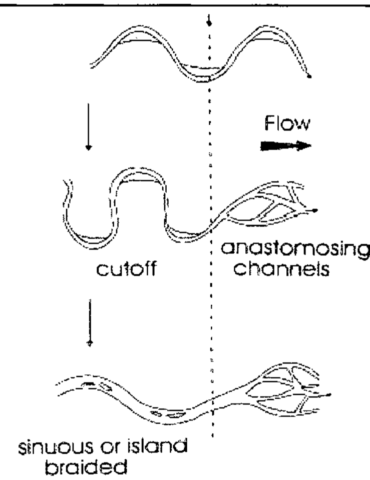
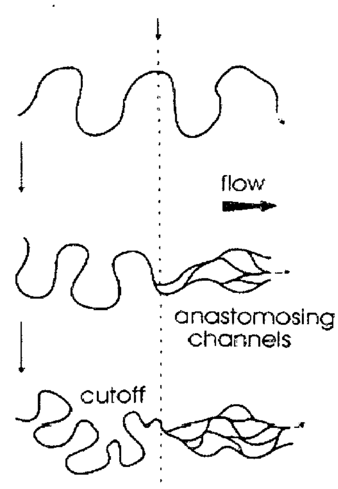
Channel form and transport mechanism	Geomorphic effect of subsidence
Braided/Bedload	
Meandering/Mixed load	
Meandering/Suspended Load	

Figure 2.6 Anticipated geomorphic response of varying channel types to subsidence modified from (Ouchi 1985 and Schumm *et al.* 2000).

2.6 LITERATURE REVIEW SUMMARY

Stream channels are dynamic and respond to alterations of water and sediment flux from their contributing watersheds with changes in longitudinal, cross-section, and planview form. Two primary alterations have occurred in the Santa Clara Valley region of California: urbanization and land subsidence. Urbanization is considered a land-use change, whereas subsidence is a topographic change in the land surface. Urbanization is a multifaceted and permanent alteration of the watershed landscape. The alterations can be broadly classified as follows:

1. Surface alterations decreasing infiltration, increasing runoff, and increasing susceptibility to erosion

2. Increased routing efficiency of runoff waters to the stream channel

3. Drainage network extension via storm sewers

4. Increased drainage network density via storm sewers

An initial pulse of sediment is introduced during the construction phase of the urban development (Wolman 1967, Leopold 1973, Graf 1975). This increase in supply can manifest itself in the form of channel aggradation for many years following the initial construction phase. Increased runoff quantity and runoff efficiency, particularly for frequent rainfall/runoff events capable of transporting bed material load (Hollis 1975), leads to channel erosion and incision being the dominant channel process as time proceeds (Hammer 1972). Space-for-time substitution has been utilized by many investigators to quantify channel enlargement during this phase (Hammer 1972, Hollis and Luckett 1976, Pizzuto *et al.* 2000). The incision process and subsequent channel instability leads to degradation of biotic health, loss of habitat complexity, and overall watershed impairment (Steedman 1988, Schueler and Galli 1992, Booth and Jackson 1997, Wang *et al.* 2001, Morley and Karr 2002, Freeman and Schorr 2004). Watershed urbanization and resulting channel response can be spatially discontinuous throughout the watershed (Roberts 1989, Gregory *et al.* 1992, Chin and Gregory 2001, Booth and Henshaw 2000, Doyle *et al.* 2000). Channel rehabilitation intervention can be used to improve biotic health, but the degree of impairment and watershed urbanization can dictate the potential strategies used to restore biotic integrity (Booth *et al.* 2004).

Land subsidence is associated with change in valley base level. Land subsidence of up to 3.5 meters has been measured in the Santa Clara Valley from 1934 to 1967 due to ground water pumping (Poland and Ireland 1988). The expected channel response upstream of the subsidence axis is either increased sinuosity or channel degradation, depending on channel and valley characteristics. Both of these mechanisms serve to reduce the stream gradient that has been previously increased by the base-level lowering. Channels that are free to migrate along the valley floor would be expected to increase sinuosity, whereas channels that are confined laterally would be expected to degrade (Ouchi 1983, Schumm *et al.* 2000). Within the subsidence area, channel response is typically aggradation, leading to in-channel bar development or anastomosing channel forms (Ouchi 1985). Downstream of the subsidence axis, channel degradation can take place due to a decrease in downstream sediment supply resulting from aggradation and sediment capture in the subsidence zone (Ouchi 1985, Schumm *et al.* 2000). Field measurements of channel response to valley subsidence are lacking, but limited data corroborate flume study results.

3.0 DESKTOP DATA COLLECTION AND MORPHOMETRIC ANALYSIS

3.1 DESKTOP DATA COLLECTED

A variety of data sources have been gathered for both watersheds being studied. Data not collected in the field by the investigating author, will be hereafter termed "desktop data", referring to data that can be collected without stepping foot in the stream being studied. A summary of all desktop data collected is presented in Table 3.1.

The data have been categorized into digital data that were previously available and required no manipulation by the research staff, digital data that have been created or manipulated by the research staff, and previously published reports and maps concerning the creeks being studied.

Desktop data serve a myriad of uses including: planform analysis of stream channel change through time; tracking and quantifying land use changes with time series aerial photographs; flood and precipitation frequency analysis from historic stream gaging records; soils and geologic mapping to understand the underlying basin stratigraphy; and basin delineation and upland catchment characterization with DEM data. Desktop data assist the investigator in understanding the watershed-scale processes that aren't readily apparent with site-specific field investigations. The timing of urbanization build out and in channel infrastructure works can be gleaned from desktop data. Desktop data provide an opportunity to investigate the history that has led to the present channel condition and possibly forecast future changes based on observed historical trends.

Table 3.1 Summary of desktop data.

Data type	Data piece
Original GIS-digital data	Digital Elevation Models (DEM)
	Stream vector coverage
	Digital Raster Graphic (DRG) Maps (1899, 1943, 1953, 1961, current)
	Scanned aerial photographs (1939, 1950, 1960, 1980, 1987)
Computed GIS-digital data performed by CSU	Watershed delineations (1899, 1950, 1960, 1980, 1987, 1999, 2002)
	Ortho-rectified digital aerial photographs (1939,1950,1960,1980,1987)
	Stream traces from aerial photographs (1939, 1950, 1960, 1980, 1987, 1999, 2002)
	Urbanization grid delineated from aerial photographs (1939, 1950, 1960, 1980, 1987, 1999, 2002)
	Expanded storm sewer network drawn from recent mapping efforts by William Lettis and Associates (WLA)
	Flow direction and accumulation grids computed from DEM and storm sewer network connectivity
Computed GIS-digital data performed by other agencies	Ortho-rectified digital aerial photograph (2002) Santa Clara Valley Water District (SCVWD)
	Ortho-rectified digital aerial photograph (1999) State of California
	Storm sewer network (current) (WLA)
	Land use grid
	Soils grid (WLA and United States Department of Agriculture -USDA)
	Bedrock and Quaternary geology grids (United States Geological Survey-USGS)
	Catchments and outfalls (storm sewer)-(WLA)
Print data sources	Historical stream channel and storm sewer network maps (WLA)
	Geologic fault mapping
	Previous stream channel improvement project reports and construction plans (United States Army Corps of Engineers (USACE),United States Department of Agriculture Soil Conservation Service-(USDASCS),and others
Historical field data	USGS and SCVWD stream gaging records
	SCVWD and NCDC precipitation records
	Historic longitudinal profile data constructed from archived engineering construction documents (Santa Clara County Flood Control and Water District (SCCFCWD) 1967, USDASCS 1985, USACE 1993)
	Land subsidence and groundwater Table mapping (Poland and Ireland 1988)

3.2 VALLEY SUBSIDENCE ANALYSIS

Detailed records of resurveyed vertical control benchmarks were available from the National Geodetic Survey (NGS) and other researchers (Poland 1976, Poland and Ireland

1988). Valley subsidence contour maps and vertical time series profiles from 1934 to 1969 were created from these records (Figures 3.1 and 3.2). Resurveyed vertical benchmark data were available for the years 1934, 1936, 1940, 1954, 1960, 1963, 1967, and 1969. Utilizing this data source and GIS mapping of the field survey extents and stationing, valley subsidence profiles from 1934 to 1969 for the reaches surveyed on Berryessa Creek (Figure 3.3) and Upper Penitencia Creek (Figure 3.4) were constructed from these records at known locations along the longitudinal profile by the investigating author. Results show that the maximum base level drop was much larger for Upper Penitencia Creek (1.1 m) compared to Berryessa Creek (0.23 m). This is in part due to the length of channel surveyed within the valley corridor on Upper Penitencia Creek. The base level drop increases substantially from the mountain valley interface to the central portion of the valley. The Upper Penitencia Creek survey extended 5000 m downstream of the mountain front, whereas the Berryessa Creek survey extended 2000 m downstream of the mountain front. The base level subsidence on Upper Penitencia Creek 2000 m downstream from the mountain front was 0.38 m, which is 0.15 m greater than the drop on Berryessa Creek indicating that the stream corridor of Upper Penitencia Creek is in closer proximity to the zone of maximum valley subsidence, located near downtown San Jose. The constructed subsidence profiles reveal that the zone of maximum base-level drawdown is in the vicinity of river stationing zero to 550 meters for Berryessa Creek and river stationing 250 to 2750 meters for Upper Penitencia Creek. Subsidence total fall and yearly rates decrease substantially upstream of these locations. The 1950s and 1960s showed the largest rates of base-level decline at the most downstream leveling location (Table 3.2). The peak base-level lowering rate for Upper Penitencia Creek was 7.4

(cm/yr) from 1960 to 1963. The peak base-level lowering rate for Berryessa Creek was 1.7 (cm/yr) from 1948 to 1954. These data indicate that base-level lowering was nearly an order of magnitude larger for Upper Penitencia Creek during the groundwater drawdown period. The anticipated geomorphic responses within this maximum subsidence region are either increase channel sinuosity or channel degradation depending on the degree of boundary material and urban infrastructure restraint on lateral channel mobility (Schumm *et al.* 2000).

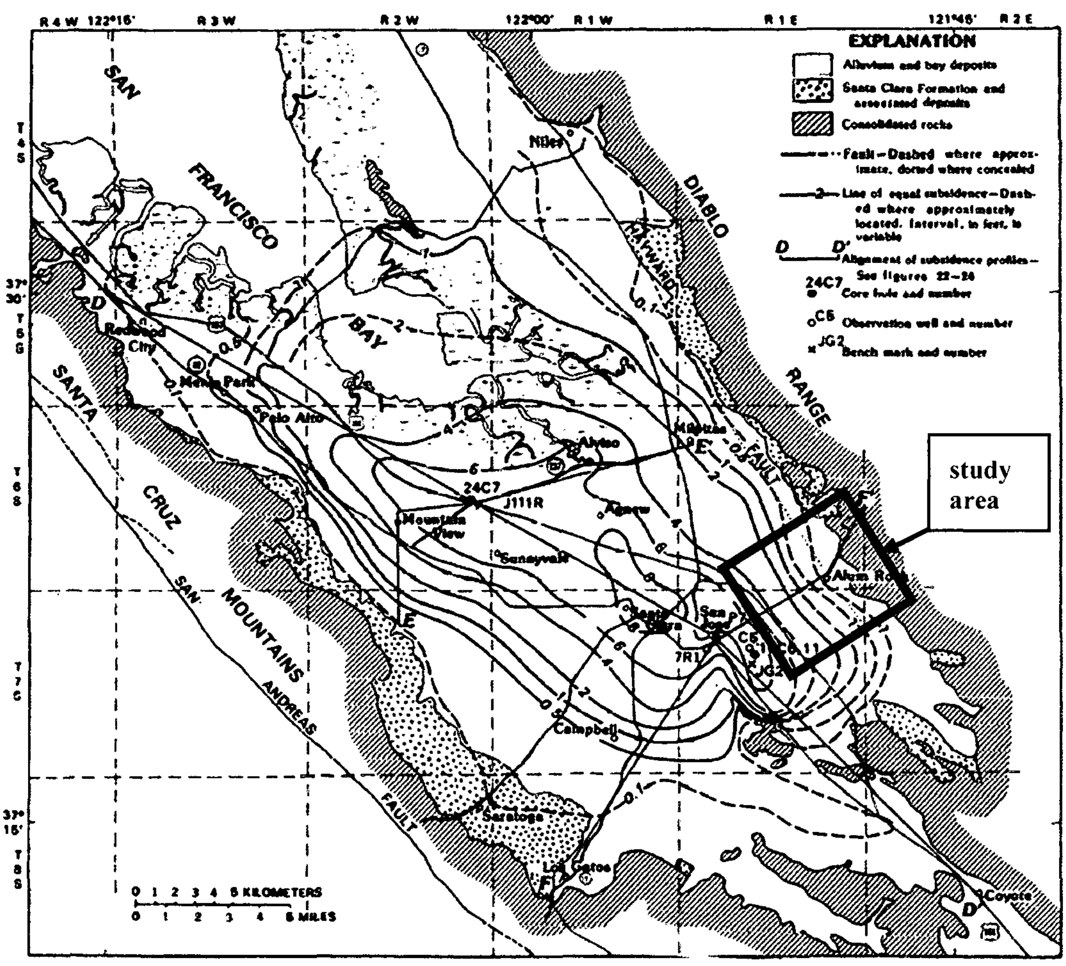


Figure 3.1 **Subsidence from 1934 to 1967 in Santa Clara Valley, California (modified after Poland and Ireland (1988)).**

Table 3.2 **Base-level lowering rates at the downstream extent of the field surveys for Berryessa and Upper Penitencia Creeks.**

	Upper Penitencia		Berryessa	
Year	Total drop (m)	Base-level lowering rate (cm/yr)	Total drop (m)	Base-level lowering rate (cm/yr)
1934	0	---	0	---
1936	0.09	4.3	0.02	0.9
1940	0.15	1.7	0.04	0.5
1948	0.17	0.2	0.04	0.0
1954	0.51	5.7	0.14	1.7
1960	0.68	2.8	0.16	0.5
1963	0.90	7.4	0.20	1.2
1967	1.11	5.1	0.23	0.7
1969	1.11	0.0	0.23	0.0

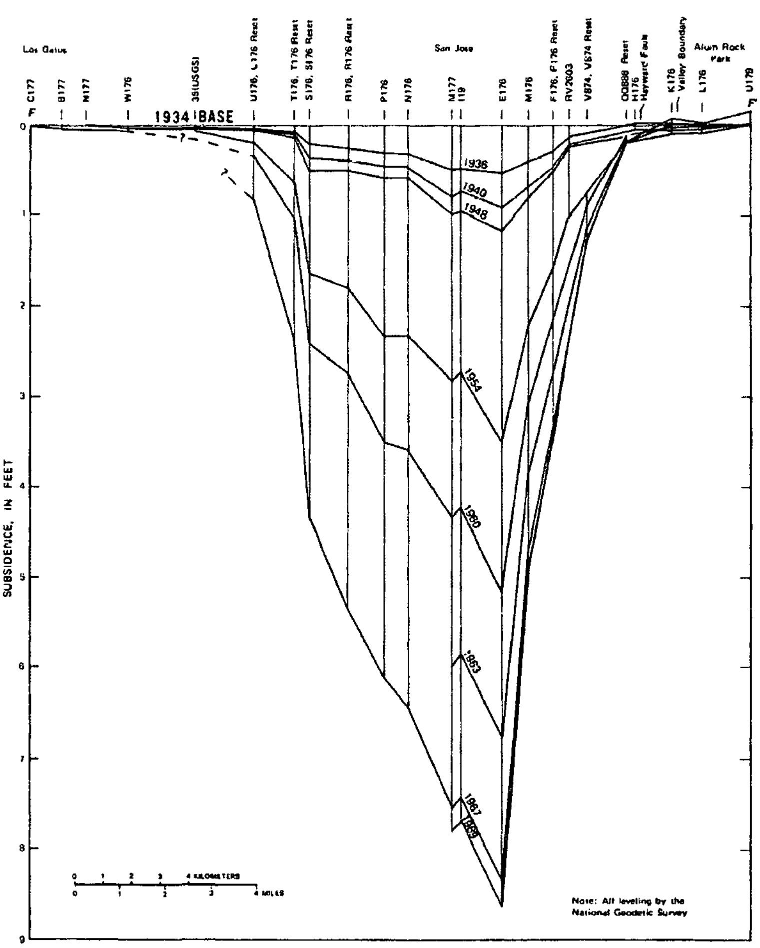


Figure 3.2 **Time sequence of valley subsidence from 1934-1969 for the Santa Clara Valley, California (from Poland and Ireland (1988)).**

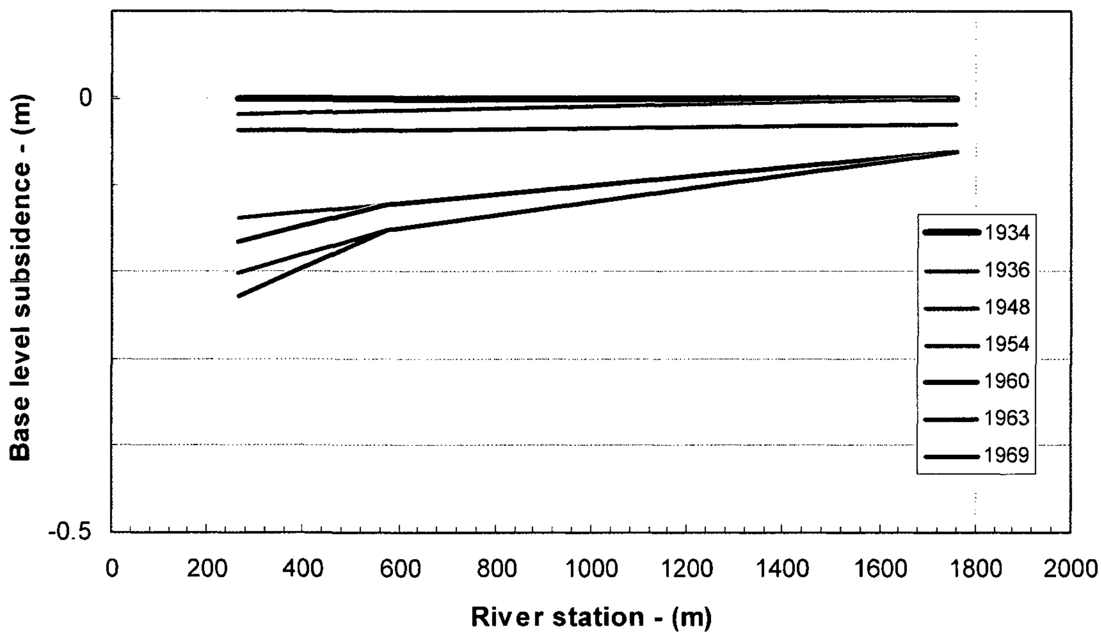


Figure 3.3 Base level subsidence profile for Berryessa Creek.

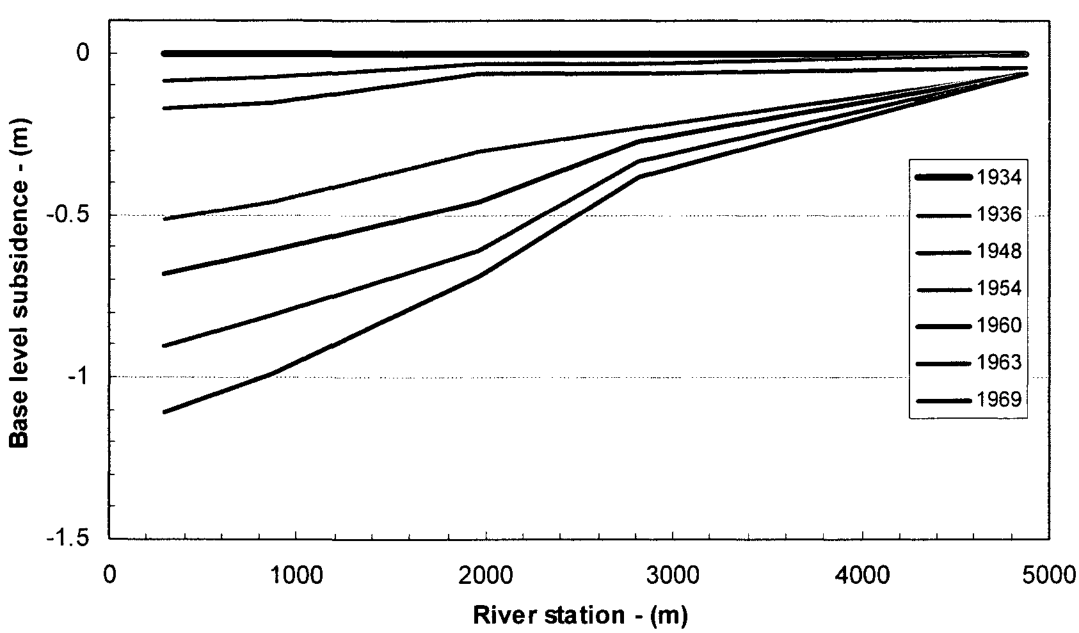


Figure 3.4 Base level subsidence profile for Upper Penitencia Creek.

3.3 HISTORIC LONGITUDINAL PROFILE DATA

Archived construction drawings from the Santa Clara County Flood Control and Water District (SCCFDWDO), the United States Department of Agriculture Soil Conservation Service (USDA-SCS) and the USACE were utilized to construct historic longitudinal profiles for both streams. The location of the cross sections surveyed in 2004 by the investigate author were reconstructed on the archived engineering drawings. The stationing of the cross sections was measured from the channel centerline on the drawing and the resulting elevation at the time of the drawing was measured on the profile data accompanying the drawing. These constructed profiles were then reconciled to the 2004 profiles that we surveyed to compare historic and current longitudinal profiles (circa 2004) (Figures 3.5 and 3.6). Historic longitudinal profiles from 1967 and 1987 were generated for Berryessa Creek (SCCFDWD 1967, USACE 1993). A longitudinal profile from 1985 was constructed for Upper Penitencia Creek (USDA-SCS 1985). This allows comparison of a 39-year trend for Berryessa Creek and a 21-year trend for Upper Penitencia Creek. These profiles were examined for longitudinal aggradation and degradation trends.

Results from these profiles indicate that Berryessa Creek has undergone up to 1.5 m of incision and or dredging in the reach of channel where the steep upland stream transitions to the valley flat. This is an area that would be expected to be depositional. The primary reason for this incision is channelization and floodplain encroachment. Downstream of this reach there is a short (350 m) depositional reach in the vicinity of a constructed sediment detention basin. Bedload capture in this sediment basin and flow regime changes from urbanization have resulted in incision in the downstream reaches. Portions of this reach have incised up to 1.4 m. The general trend along the profile is incision.

The Upper Penitencia profile shows deposition in the upper reaches where the upland stream transitions to the alluvial valley. This is the trend that would be anticipated in this portion of the watershed as the steeper, more confined upland stream transitions to a lower gradient, less confined alluvial fan valley portion of the watershed. This deposition is at a maximum (0.52 m) at the most upstream cross section and decreases along the profile, until the stream becomes incised approximately 1000 m downstream of the upland/valley transition where urban encroachment on the floodplain has occurred. The stream is depositional for a short reach (500 m), then incises again upstream of the zone of subsidence. In the zone of maximum subsidence the stream is generally depositional. These profiles and factors leading to the observed adjustment will be examined in further detail in the sediment transport discussion in chapter 6.

Figure 3.5 Historic longitudinal profiles for Berryessa Creek

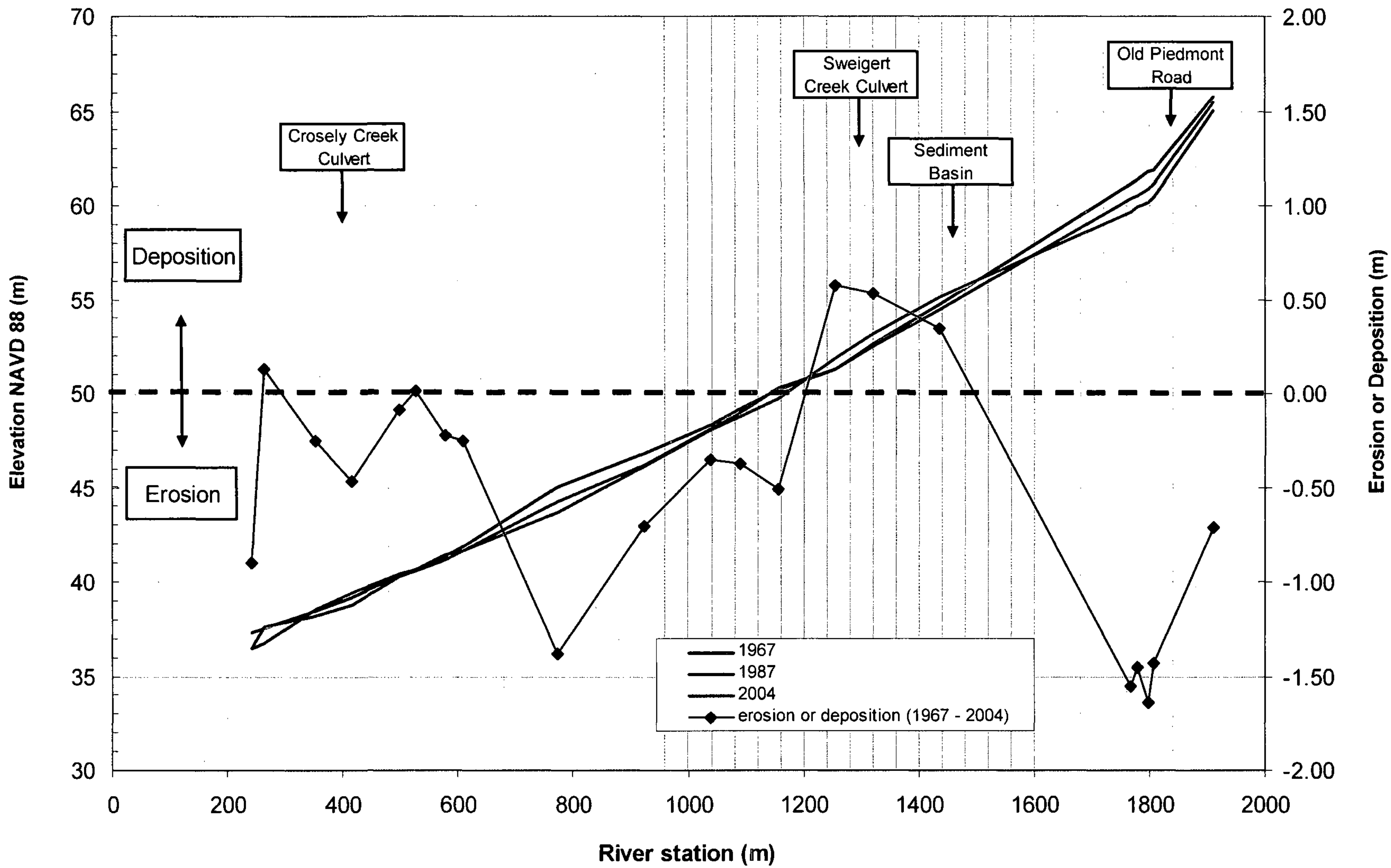
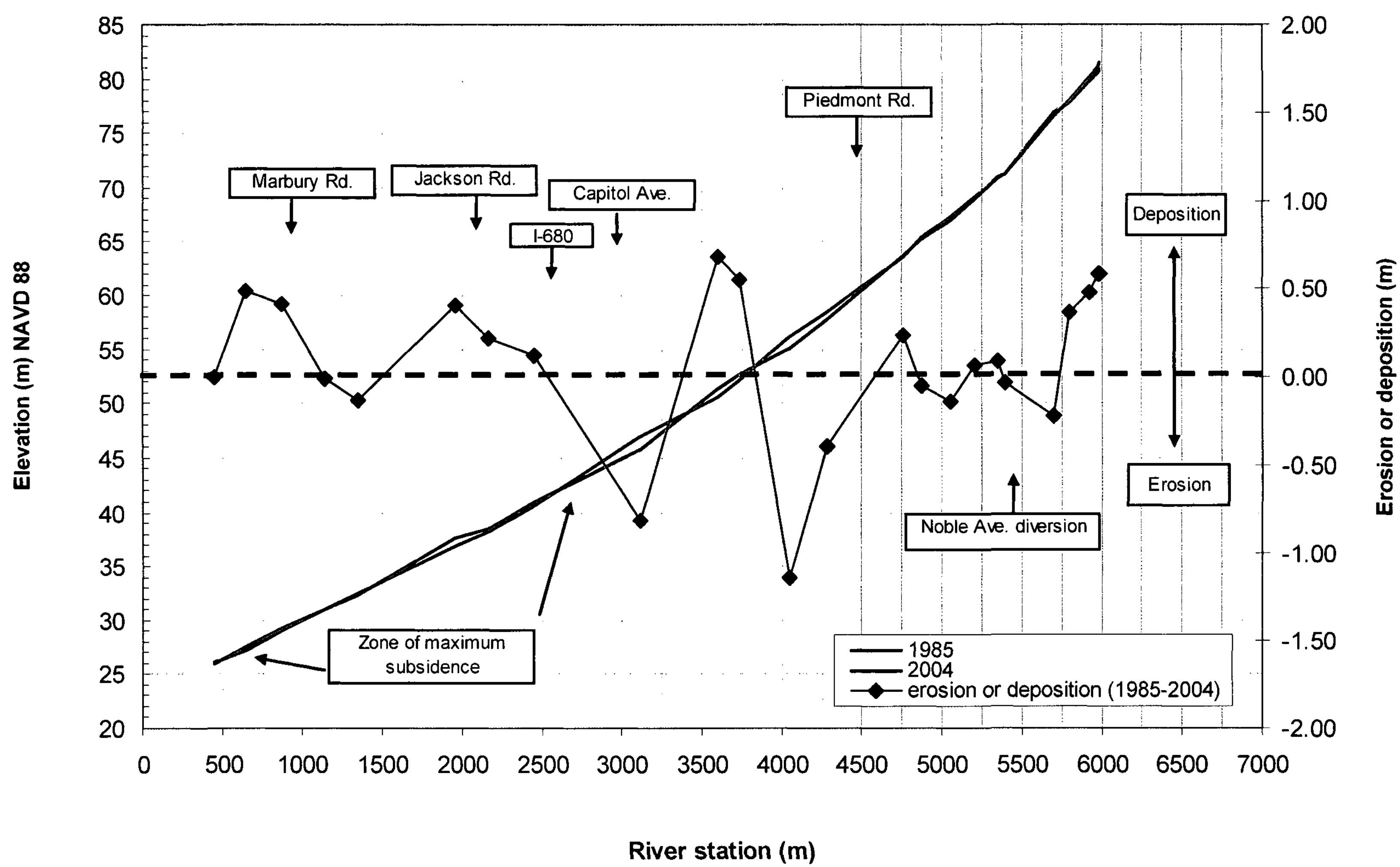


Figure 3.6 Historic and current longitudinal profiles for Upper Penitencia Creek



3.4 AERIAL PHOTOGRAPH AND TOPOGRAPHIC MAP TIME SERIES ANALYSIS

A historical GIS-based morphometric analysis was conducted for both watersheds. The primary goal of the investigation was to provide insight regarding the historical planform characteristics, land-use changes, and channel realignments of both creeks within the rapidly urbanizing valley floor. Historical maps and aerial photographs of both watersheds were gathered from a variety of sources. Data sources included historical maps of the area dating from 1899 to present and a series of aerial photographs (from 1939, 1950, 1960, 1980, 1987, 1999, and 2002). The time-sequenced aerial photographs were digitally reconciled to the 2002 geo-referenced aerial photographs using common geodetic control points. Examining the historical planform changes (Figure 3.7) of both creeks provided valuable insight into the cause of many of the erosion and sedimentation trends observed.

The 1899 topographic maps of the area indicated that a morphologically defined channel was not present for Berryessa Creek below the terminus of the mountain range, because the lower lands to San Francisco Bay are dominated by alluvial fan deposits to the limit of the estuarial low-land deposits. Between 1899 and 1939, a single-threaded creek channel was coalesced and channelized to permit agriculture on the alluvial fan terminus. This channel was made tributary to Lower Penitencia Creek, which is tributary to Coyote Creek. Anthropogenic channel lengthening for development and flood control on Berryessa Creek has resulted in significant decreases in channel slope through time, particularly in the downstream reaches, which are outside of the surveyed reach extents.

The channel slope at the terminus of the alluvial fan in 1899 was 0.02 m/m, the lengthening in the 1930s decreased the average longitudinal slope to 0.01 m/m, and the final lengthening stage in the 1950s decreased the slope to 0.005 m/m. The natural stream response to slope reduction is aggradation. This has been the observed result in the lower reaches of the stream leading to the San Francisco Bay.

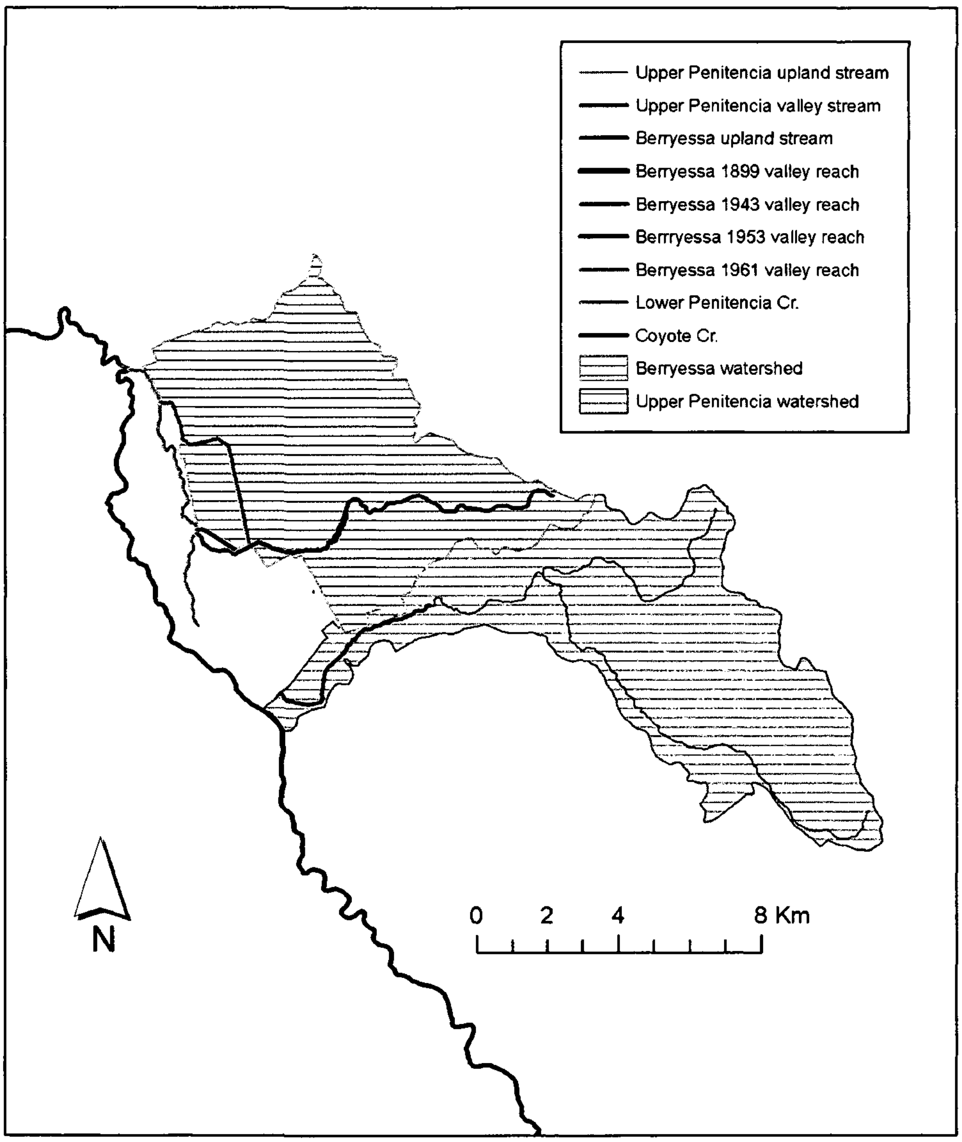


Figure 3.7 Large scale planform changes for Berryessa and Upper Penitencia Creek from 1899 to present

The Upper Penitencia Creek channel outlet to a larger receiving body (Coyote Creek) has remained consistent from 1899 to the present. The only changes made to this creek were the addition of a small upstream reservoir in 1936, the addition of an irrigation diversion canal in the 1940s, the removal of Silver Creek as a tributary close to the channel outlet to Coyote Creek in the 1940s, and channel realignment in the vicinity of the interstate 680 crossing in the early 1970s (Figure 3.8). Planform changes induced by urbanization have been local reach scale changes. Generally, the stream has remained stable in planform for the past 100 years. Localized instability has been introduced due to stream alignment modifications in the vicinity of the I-680 crossing, roadway encroachment on the floodplain in the upper reaches and subsidence effects.

In the vicinity of I-680, the channel has been straightened from the original planform alignment, shortening the stream reach by 155 feet and increasing the channel slope from 0.0075 m/m to 0.0087 m/m a 16 % increase. This interstate was constructed in 1973. Localized channel stability problems have been documented upstream and downstream of the channel realignment.

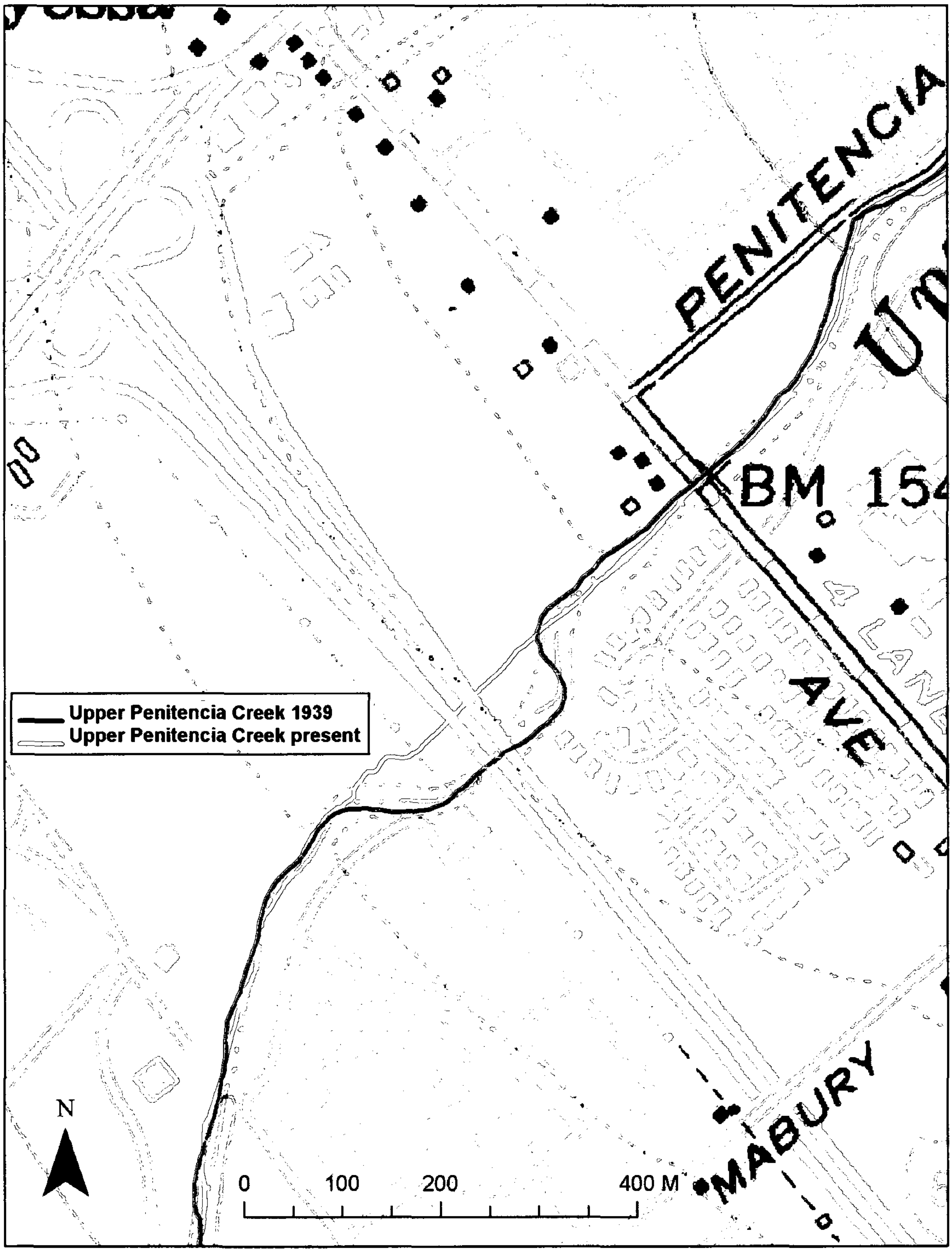
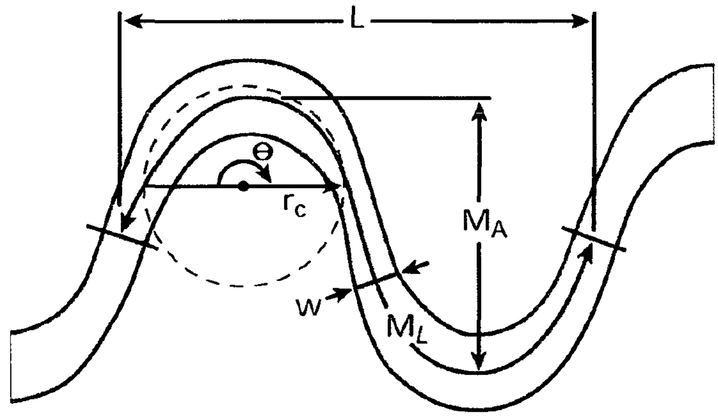


Figure 3.8 Channel realignment on Upper Penitencia Creek in the vicinity of the Interstate I-680 crossing.

3.4.1 PLANFORM MEASUREMENTS OF TIME SERIES AERIAL PHOTOGRAPHS

3.4.1.1 DATABASE DEVELOPMENT

A series of aerial photographs (from 1939, 1950, 1960, 1980, 1987, 1999, and 2002) were collected to examine channel planform functional relationships and changes through time. The time record of the database was expanded by including the field survey of both streams conducted in the summer of 2004. Historical aerial photograph analysis serves to extend the period of record of the field database. Bends surveyed during the 2004 field survey were included in the historical analysis to examine present bend stability as a function of historical evolution. The time-sequenced aerial photographs were digitally reconciled to the 2002 SCVWD geo-referenced GIS aerial photographs using common geodetic control points. The centerline of the stream channel was then digitized in the GIS environment and exported to AutoCAD for measurement. Due to the dense vegetation in the riparian zone and relatively small width of the channel, it was sometimes difficult to know the exact location of the bankfull channel centerline. This fact leads the investigator to have minimal confidence in channel migration rates and bankfull width measurements through time. However, estimates of larger scale planform characteristics can be inferred from this photograph time series. Sinuosity characteristics were calculated for reaches along the general valley trend. Reaches were delineated where there were changes in the course of the valley trend. Planform measurements were also calculated for the time series for ten meander wavelengths along Upper Penitencia Creek and eleven meander wavelengths along Berryessa Creeks that were visibly present in all aerial photographs. The same meanders were measured for each year to maintain a consistent data set. The metrics presented in Figure 3.9 were measured for each meander. In addition to these metrics, the reach characteristics of meander belt width and reach sinuosity were also measured.



L meander wavelength
M_L meander arc length
w average width at bankfull discharge
M_A meander amplitude
r_c radius of curvature
θ arc angle

Figure 3.9 Meander metrics used for aerial photograph measurements (from Federal Interagency Stream Restoration Working Group (FISRWG) (1998)).

To facilitate the comparison of similar river planform features through multiple years of historical aerial photographs, some measurement rules were incorporated in the analysis procedures.

1. The stream must be separated into reaches that have a consistent valley trend (Figure 3.10) for morphometric analysis.

2. The meander amplitude is measured from the crest of the upstream bend along a line parallel to the valley trend, and ending in the trough of the downstream bend along a line perpendicular to the valley trend (Figure 3.11).
3. The meander arc length and meander wavelength beginning and end, are measured at the channel station that would correspond to the tangential point at which the radius curvature circle intersects the stream (Figure 3.12).

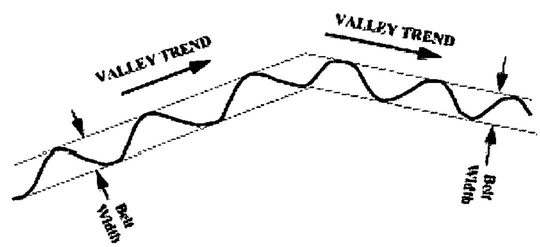


Figure 3.10 Valley trend and meander belt width conceptualization (from Annable (1996)).

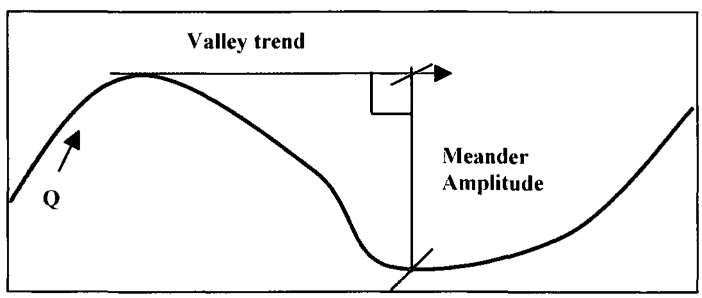


Figure 3.11 Meander amplitude and valley trend schematic.

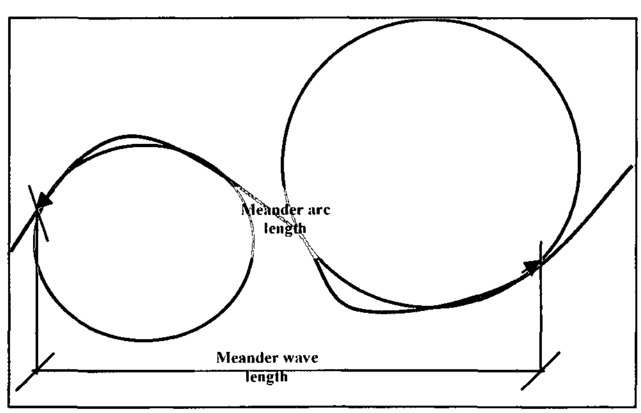


Figure 3.12 Meander arc length and wavelength schematic.

3.4.1.2 DATABASE ANALYSIS

An extensive database has been developed from the planform measurements, which can be used to analyze channel pattern changes through time. Changes in the water and sediment regimes will manifest via changes in channel form. The channel pattern relationships may change as a function of time due to historic perturbations of the system, particularly channel coalescence in the historic alluvial fan in the earlier part of the 19th century, valley subsidence from 1940 to 1970 and the urbanization infill from 1970 to the present. Database analysis of planform response to the external forcing variables of watershed urbanization and valley subsidence was conducted for large scale planform adjustments of channel sinuosity, meander belt width, and bankfull channel radius of curvature relationships. For each stream, the stream channel within the urbanized valley portion of the watershed was discretized into reaches based upon changes in the valley trend. Three reaches of consistent valley trend were defined for Berryessa Creek and four reaches were defined for Upper Penitencia Creek (Table 3.3).

Table 3.3 Valley trend reaches defined for planform analysis.

Stream	Reach	River Stationing (m)	Valley subsidence at downstream extent of reach (m)
Upper Penitencia	1	4030-6100	0.19
	2	2200-4030	0.6
	3	1363-2200	0.85
	4	290-1363	1.11
Berryessa	1	1125-2000	0.11
	2	710-1125	0.14
	3	250-710	0.23

The expected planform adaptation to base-level lowering due to valley subsidence is an increase in channel sinuosity (Schumm *et al.* 2000). The anticipated planform adjustment due to urbanization would be a decrease in sinuosity as lateral migration will be restrained by urban infrastructure, bank protection and stream channelization, prohibiting natural channel migration. Qualitative inspection of Lane's (1955) relationship (Equation 3.1) indicates that if the channel slope is steepened and lateral channel adjustment is restrained, the channel would be expected to degrade, armor, or increase sediment discharge. However, at the same time urbanization would be expected to qualitatively increase discharge and possibly decrease upstream sediment supply over the long-term. The adjustments in sediment supply are spatially and temporally discontinuous (Wolman 1965, Leopold 1973, Graf 1975). The anticipated slope response to urbanization would be slope reduction, which could be in the form of increased sinuosity or channel degradation.

$$QS \approx Q_s d_s \qquad \textbf{Equation 3.1}$$

$Q = water\ discharge$
$S = channel\ slope$
$d_s = bed\ material\ size, and;$
$Q_s = sediment\ discharge$

Planform analysis can detect slope adjustment due to increases in sinuosity, channelization efforts to decrease sinuosity and meander belt width, and urban infrastructure encroachment on the historic meander belt width. These will be examined for each stream.

3.4.1.3 PLANFORM ANALYSIS OF BERRYESSA CREEK

In reach 1, the most upstream reach of Berryessa Creek, time series data from 1939 to the present indicate a long-term decrease in sinuosity. This is primarily due to channelization (Figure 3.13). The channelization occurred between 1960 and 1980. After 1980 the sinuosity has increased marginally, but infrastructure elements have limited lateral migration. The stream is highly incised within this reach from field observations. Reaches 2 and 3 have not been channelized and indicate a trend of increasing sinuosity, likely a response to increased urban water discharges and decreases in sediment supply due to an in channel sedimentation basin. In reach 2, channel incision and moderate channel migration are the dominant channel processes. Reach 3 shows the strongest increases in sinuosity. This reach receives the bulk of the increased storm water discharge and has subsided 0.23 m. Longitudinal profile time series data from 1967 to 2004 indicate historic incision in this reach, but the current dominant channel process is lateral migration.

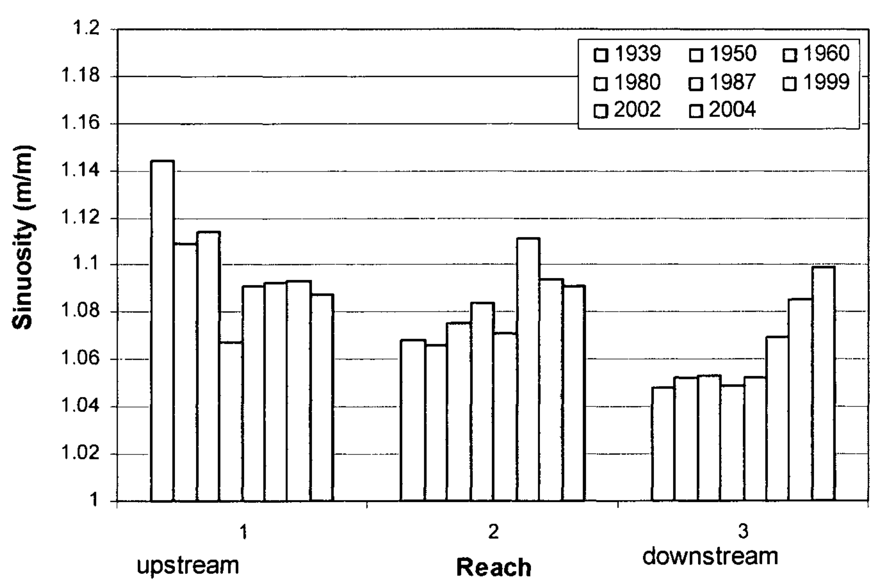


Figure 3.13 Sinuosity changes from 1939 to 2004 for Berryessa Creek.

Examination of the changes in meander belt width for Berryessa Creek reveals similar trends (Figure 3.14). The upstream portion of the channel, reach 1, has been laterally restrained, resulting in a reduction of the meander belt width, whereas reach 2 has maintained the historic meander belt width. Reach 3 has responded with increases in meander belt width, particularly in recent years as it adjusts to the altered urban flow regime and lateral migration is the dominant channel process.

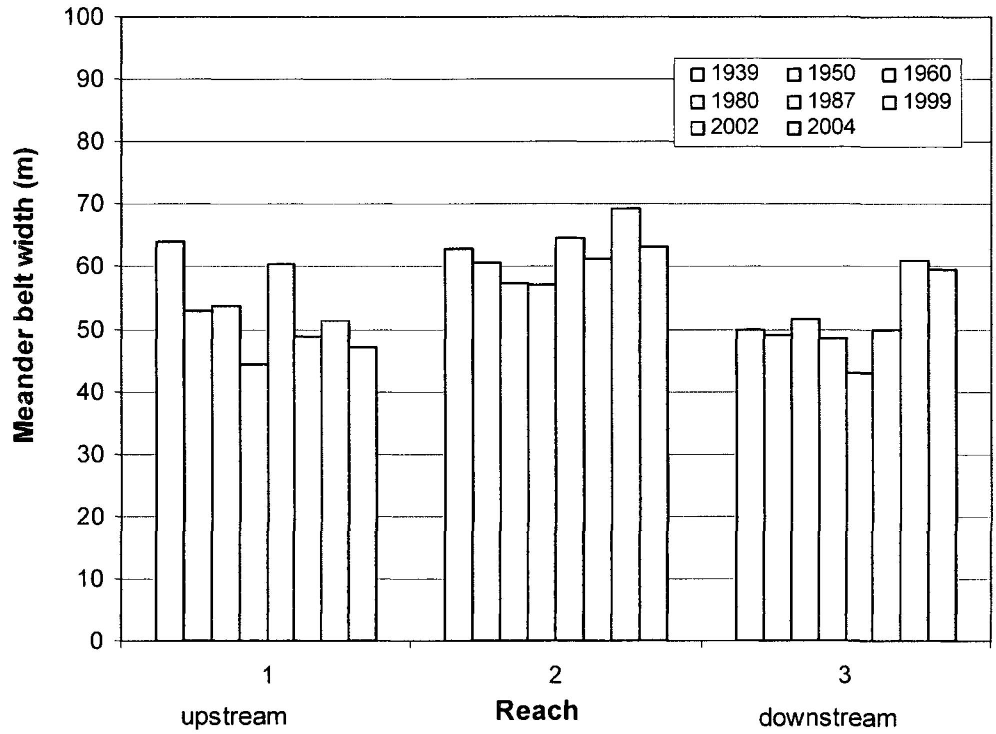


Figure 3.14 Meander belt width changes from 1939 to 2004 for Berryessa Creek.

3.4.1.4 UPPER PENITENCIA CREEK PLANFORM ANALYSIS

The subsidence effect on base-level lowering at the downstream extent of the survey data is stronger for Upper Penitencia Creek (1.11 m) compared to Berryessa Creek (0.23 m). Examination of the sinuosity trends with time (Figure 3.15) reveals that Upper Penitencia creek has shown a trend of increasing sinuosity, particularly in the more downstream reaches (2, 3 and 4) that have been subject to the strongest rates of historic base-level lowering. Reach 1, which has encountered relatively small levels of historic subsidence (0.19 meters), has not significantly increased sinuosity since the end of the subsidence era (~1970). Inspection of these data reveals the channelization in the vicinity of Interstate 680 in the time series. This is indicated by the abrupt decrease in sinuosity in reach 2 from 1960 to 1980. After this abrupt sinuosity change, the stream has shown a trend of increasing sinuosity within this reach. Sinuosity increases are rather small in the response reaches. The sinuosity increases for reaches 2, 3 and 4, respectively, are 5%, 3%, and 1.5% since the end of the subsidence period in 1969. Channelization at the Interstate 680 crossing resulted in a 16% increase in local slope. This indicates that the majority of the slope re-adjustment is taking place via channel incision rather than sinuosity increases. This is corroborated by field observation of local channel incision upstream of the I-680 crossing (Figure 3.16) where lateral migration has been restricted on the left bank due to urban infrastructure.

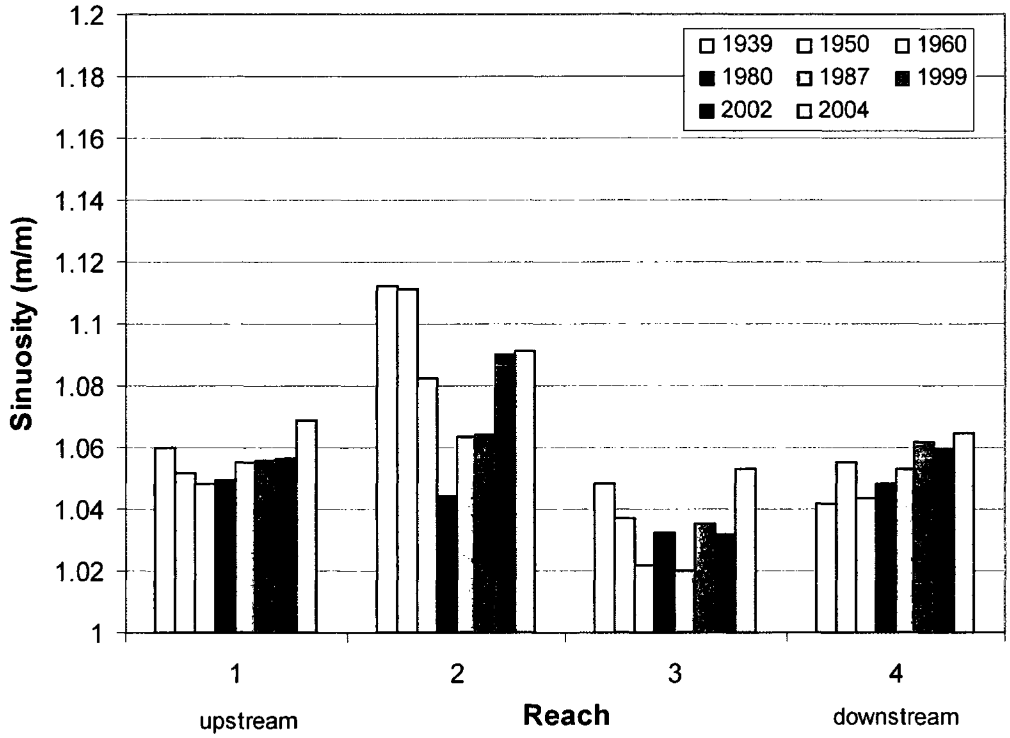


Figure 3.15 Sinuosity changes from 1939 to 2004 for Upper Penitencia Creek.

Figure 3.16 Channel incision in reach 2 of Upper Penitencia Creek upstream of the I-680 crossing

Examination of the Upper Penitencia meander belt width time trends (Figure 3.17) reveals urban encroachment on historic meander belt width within reach 2. This reach has decreased in meander belt width from 127 meters to 83 meters from 1939 to 2004, a 35% decrease. The reach has responded to valley subsidence and channelization through incision. Reach 1 is an exemplary urban stream that exhibits stable channel morphology; this stream has had minimal urban encroachment on the historic meander belt width. Likewise, reach 4 at the downstream portion of the channel has encountered minimal urban encroachment on the historic meander belt width. This illustrates the importance of determining historic meander belt widths for channel stability in the urban planning and zoning process.

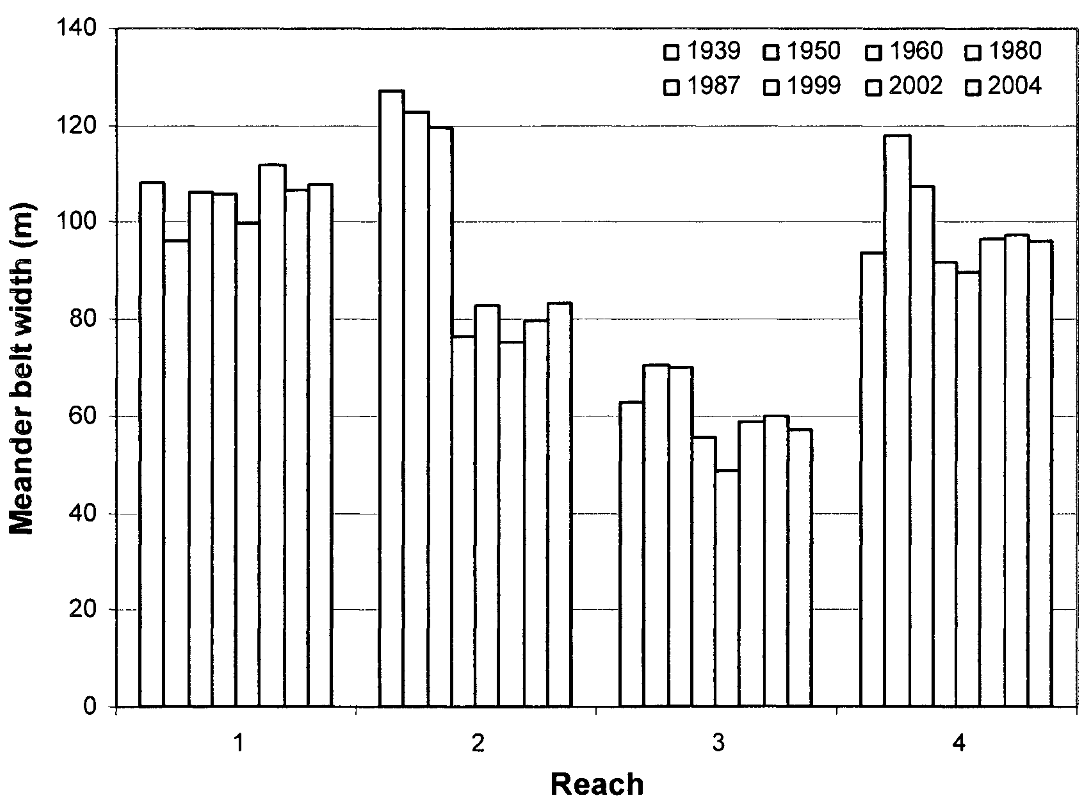


Figure 3.17 Meander belt width changes from 1939 to 2004 for Upper Penitencia Creek.

3.4.1.5 COMPARISON OF MEASURED URBAN MEANDER GEOMETRY TO THEORETICAL VALUES

Meander geometry relationships have been examined by other researchers for low-gradient alluvial streams (Leopold *et al.* 1964, Langbein and Leopold 1966, Williams 1986), but little is known about meander geometry for urbanized streams. Langbein and Leopold (1966) proposed that the most probable shape of a meander curve is that of a sine-generated curve. This shape has the characteristic that the deviation angles from the downstream direction are minimized. Using this theory, the radius of curvature can be predicted from the sinuosity (k) and the meander wavelength (λ) with the following equation:

$$R_c = \frac{\lambda}{13}\frac{k^{3/2}}{\sqrt{k-1}} \qquad \textbf{Equation 3.2}$$

Where: R_c = radius of curvature;

λ = meander wavelength; and

k = sinuosity.

Analysis was conducted to test this theoretical estimate for the planform measurements made on Berryessa and Upper Penitencia Creeks. The sine-generated result tends to underestimate radius of curvature in both streams (Figures 3.18 and 3.19). This may be a result of the coarse consolidated bank material present in these alluvial fan systems as well as urbanized restraint on the meander development process. The deviation is particularly strong for bends with a larger observed radius of curvature; in these cases, historic meander belt width constriction can lead to elongated bends that have been restrained from full meander development.

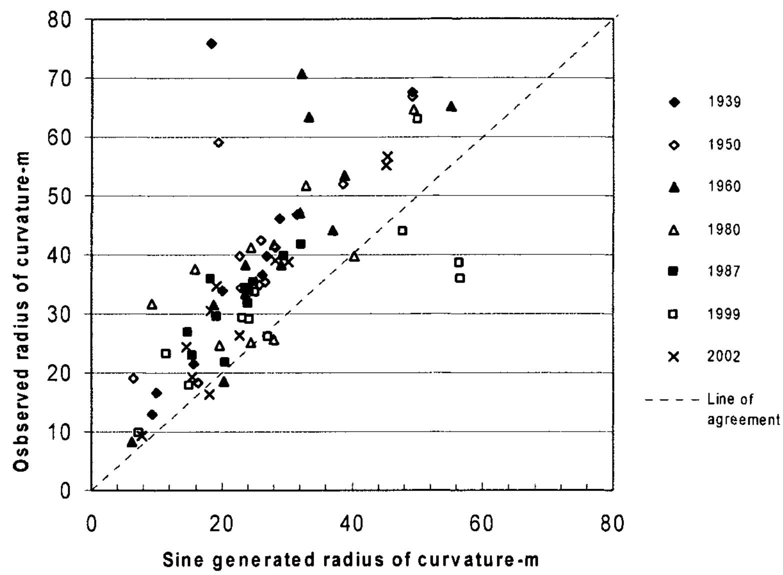


Figure 3.18 Observed vs. sine-generated radius of curvature for Berryessa Creek.

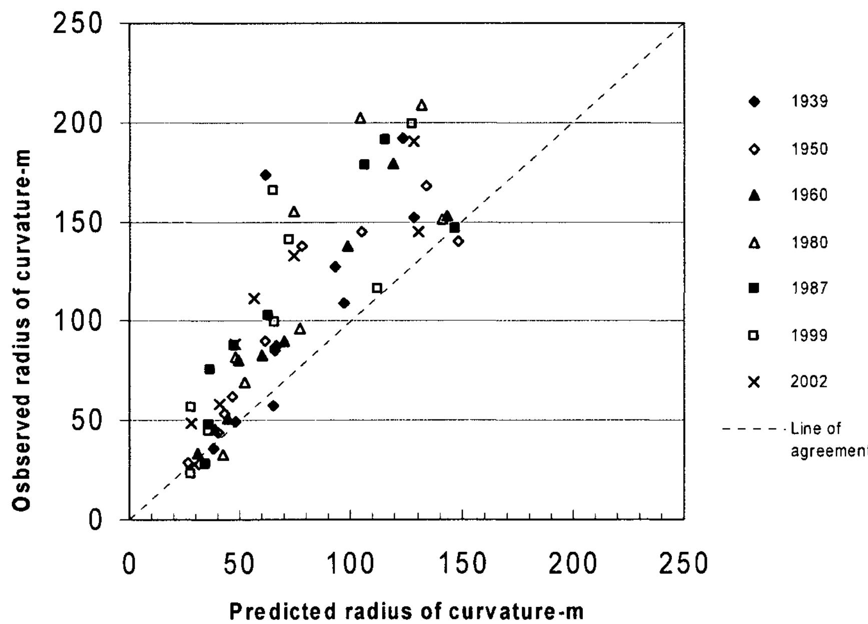


Figure 3.19 Observed vs. sine-generated radius of curvature for Upper Penitencia Creek.

3.4.2 TIME SERIES URBANIZATION ANALYSIS

Urbanized areas in the Berryessa Creek and Upper Penitencia Creek watersheds were mapped using GIS for each of the time sequenced aerial photographs (1939 to 2002). The urbanization polygons were separated into the upland and valley portions of the watershed. The urbanization time series for each watershed are presented in Figure 3.20. The vast majority of the urbanization has taken place in the valley area of the watersheds between 1960 and 1980. Little urbanization has taken place in the upland portion of the watersheds. The urbanization trends are quite similar. The Upper Penitencia Creek watershed was urbanized earlier than the Berryessa Creek watershed, but the final infill has been greater in the Berryessa Creek watershed, indicating that the development in the Upper Penitencia area is older and the stream has had a longer time to adjust to the urban flow and sediment regime. The majority of urbanization within both watersheds occurred from 1960 to 1980, indicating that much of the urbanization has been in place for nearly 30 years on both streams. Upper Penitencia Creek has had a longer period of time to adjust to the alerted urban hydrologic and sediment regime. The present total urbanization percentages of Berryessa Creek (14%) and Upper Penitencia Creek (7%) are in the range of thresholds for ecological impairment proposed by other researchers (Wang *et al.* 2001, Wang and Kanehl 2003, Ourso and Frenzel 2003). Upper Penitencia Creek has a larger upland drainage area to buffer the urbanization effects on the flow regime in the valley portion of the creek. The present valley urbanization percentages for Berryessa Creek (85%) and Upper Penitencia Creek (76%) are well beyond proposed threshold limits for impairment.

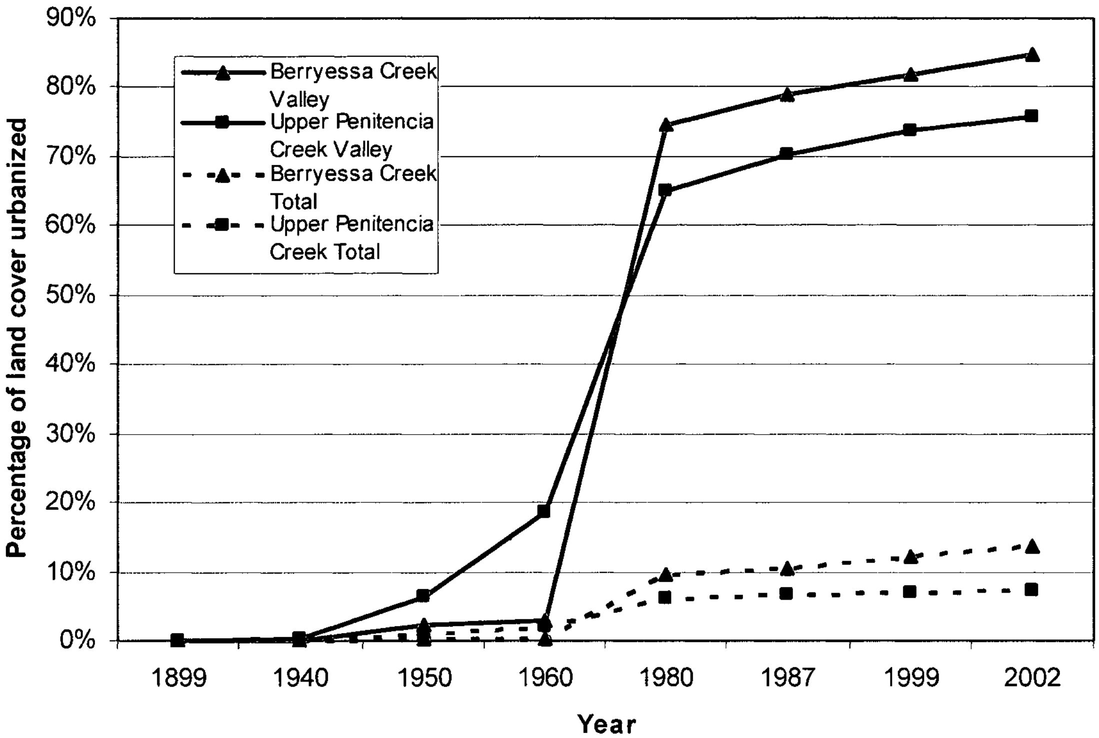


Figure 3.20 Urbanization time series from 1899 to 2002.

3.4.3 TIME SERIES ANALYSIS OF DRAINAGE NETWORK STRUCTURE

Typically, urbanization impacts are quantified through a percent impervious measurement for a fixed catchment area. However, in this study area the storm sewer network build out has also significantly altered the catchment area size for both watersheds. The total drainage area flowing to the creek via the storm sewer network and overland connectivity will hereafter be termed the effective catchment area. The drainage area flowing to the stream via overland connectivity will be termed the topographic catchment area. Berryessa Creek has encountered drainage area expansion from the storm sewer network due to the addition of two adjacent historic alluvial fan streams, Sweigert Creek and Crosley Creek (Figure 3.21). Conversely, drainage area reduction has occurred on Upper Penitencia Creek, particularly in the valley portion of the watershed (Figure 3.22). The catchment area reduction is due to construction of the storm sewer network serving to route flow paths to adjacent watersheds, from areas that historically drained to Upper Penitencia Creek. Catchment area alterations with time are summarized in Table 3.4.

Table 3.4 Changes in effective catchment area from 1899 to 2002 for Berryessa and Upper Penitencia Creek.

Year	Berryessa		Upper Penitencia	
	Effective catchment area on valley floor (km^2)	Total effective catchment area (km^2)	Effective catchment area on valley floor (km^2)	Total effective catchment area (km^2)
1899	0.9	13.0	6.6	63.5
1940	1.1	13.2	6.9	67.1
1950	1.1	13.2	6.6	63.5
1960	1.1	13.2	6.6	63.5
1980	1.9	15.5	4.7	61.6
1987	1.9	15.5	4.7	61.6
1999	1.9	15.5	4.7	61.6
2002	1.9	15.5	4.7	61.6
Percentage increase or decrease (1899-2002)	123%	20%	-29%	-3%

The results of this analysis illustrate the substantial alterations to the effective catchment area that both watersheds have undergone over time. In the case of Berryessa Creek, the effective catchment area within the highly urbanized valley floor portion of the watershed has increased 123% from 1899 to 2002. Within the same time period, the total watershed effective catchment area has increased from 13 km^2 to 15.5 km^2 , which is a 20% increase. These drainage area changes have had detrimental effects on channel stability within the urbanized valley portion of the watershed. Rapid channel widening as well as headcut formation and migration have been observed downstream of the inflowing culvert from the Crosley Creek drainage that was added to Berryessa Creek within the study area (Figures 3.22 and 3.23).

In the same time period the total effective catchment area of Upper Penitencia Creek has decreased 3% and the effective catchment area within the urbanized valley portion of the watershed has decreased 29%. The decreased catchment size has served to mitigate increased flow runoff volumes produced by the impervious urbanized areas.

Quantification of the observed changes in channel form, along with results of the numerical modeling performed to quantify the hydrologic and morphologic changes, will be detailed in chapters 5 and 6.

Figure 3.21 Berryessa Creek watershed with the historic topographic and current effective catchments delineated.

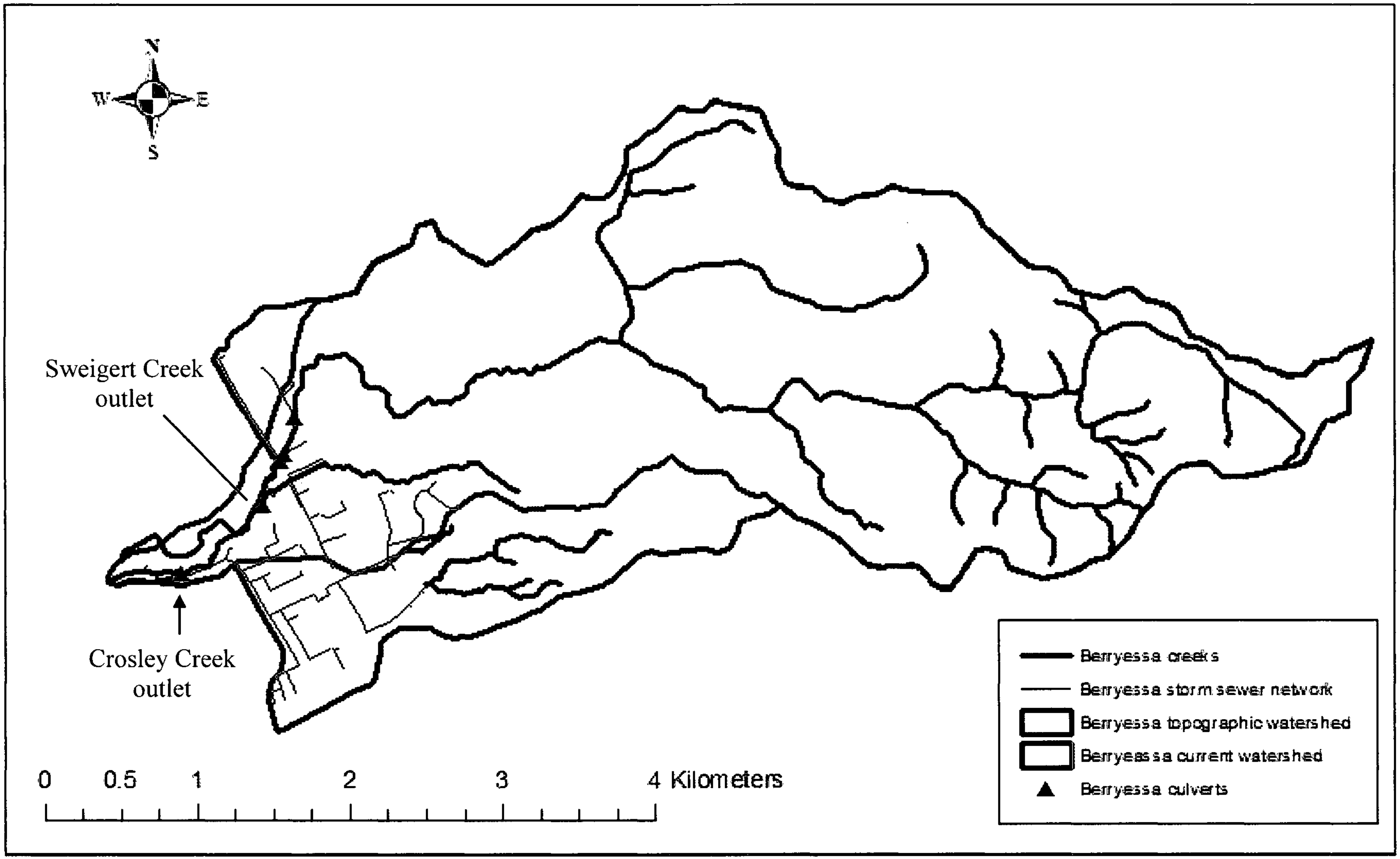


Figure 3.22 Upper Penitencia Creek watershed with the historic topographic and current effective catchments delineated.

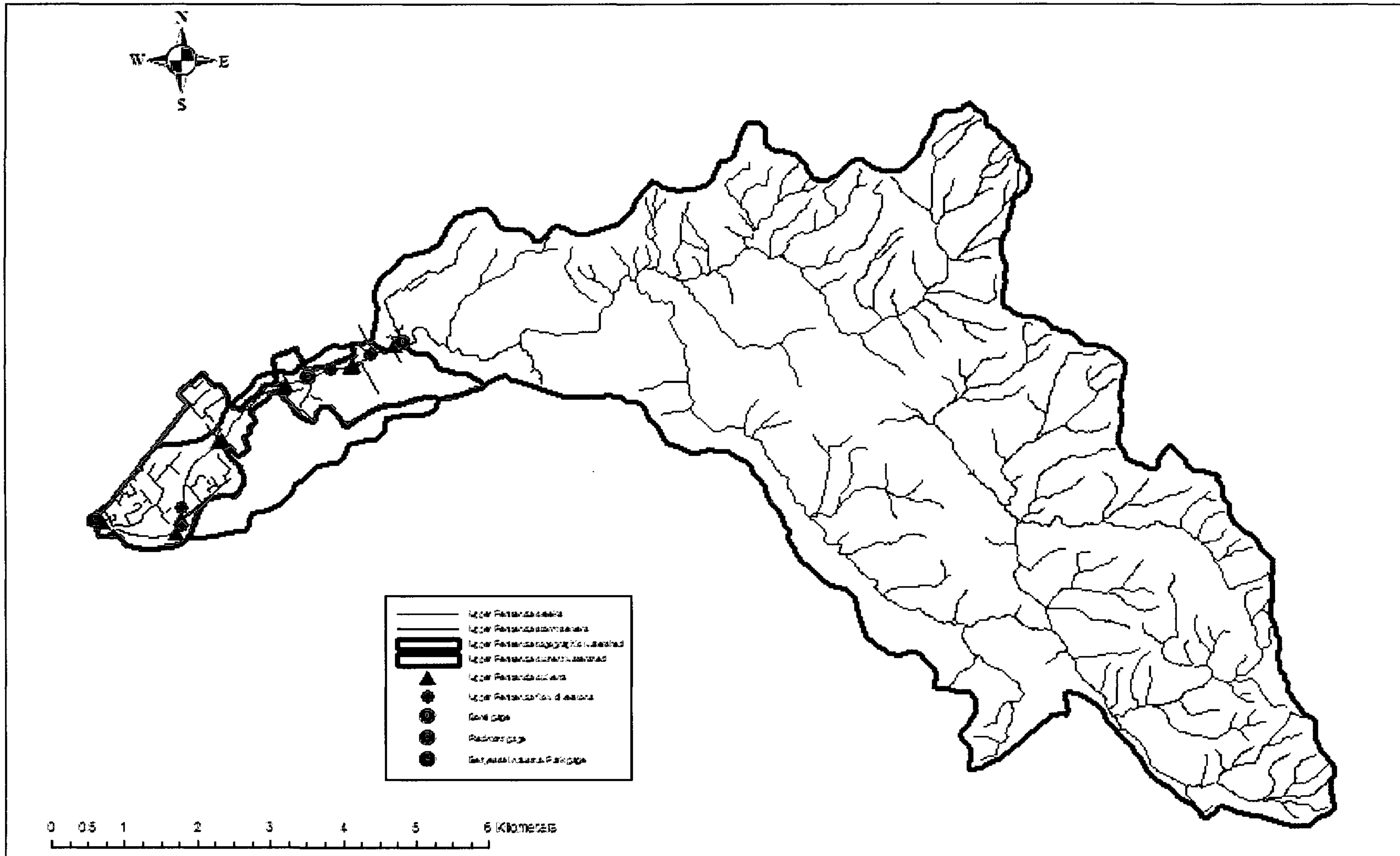


Figure 3.23 Channel widening observed downstream of Crosley Creek culvert on Berryessa Creek.

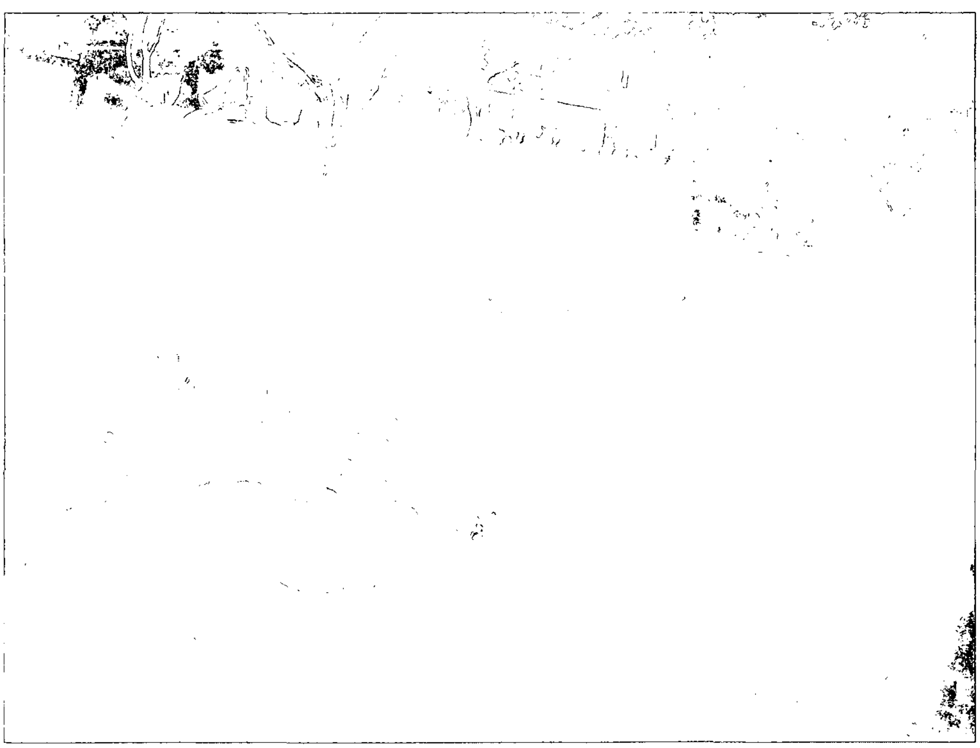


Figure 3.24 Channel headcut observed downstream of Crosley Creek culvert on Berryessa Creek.

3.5 TECTONIC SETTING

Both watersheds are located along the tectonically active Hayward fault (Figure 3.25). The active tectonics result in a relatively large amount of landslide activity introducing significant sediment loads to the streams. Changes in channel gradient from the steeper upland portion of the watershed to the valley transition have created historically depositional environments at these interfaces. An engineered sediment/debris basin was first constructed on Berryessa Creek in 1962 to capture upstream sediment loads (Figure 3.26). The current basin at the site was re-designed and updated in the early 1990's (USCACE 1993). This basin has been effective in inducing sediment deposition in an area that can be excavated conveniently; however, by inducing sediment deposition at this point, sediment continuity to downstream reaches has been disrupted. Sediment dredging records were available from the SCVWD from 1984 to 2004 (Figure 3.27). Records indicate that this sediment basin is dredged on average every other year. The mean annual sediment dredging volume is 620 m^3. This sediment basin is particularly effective in capturing any larger particles (> 16 mm) transported via bedload transport processes. The downstream repercussion of this bedload discontinuity is channel incision. Sediment loads remain high due to landslide activity in the upland portion of the watershed within the fault zone.

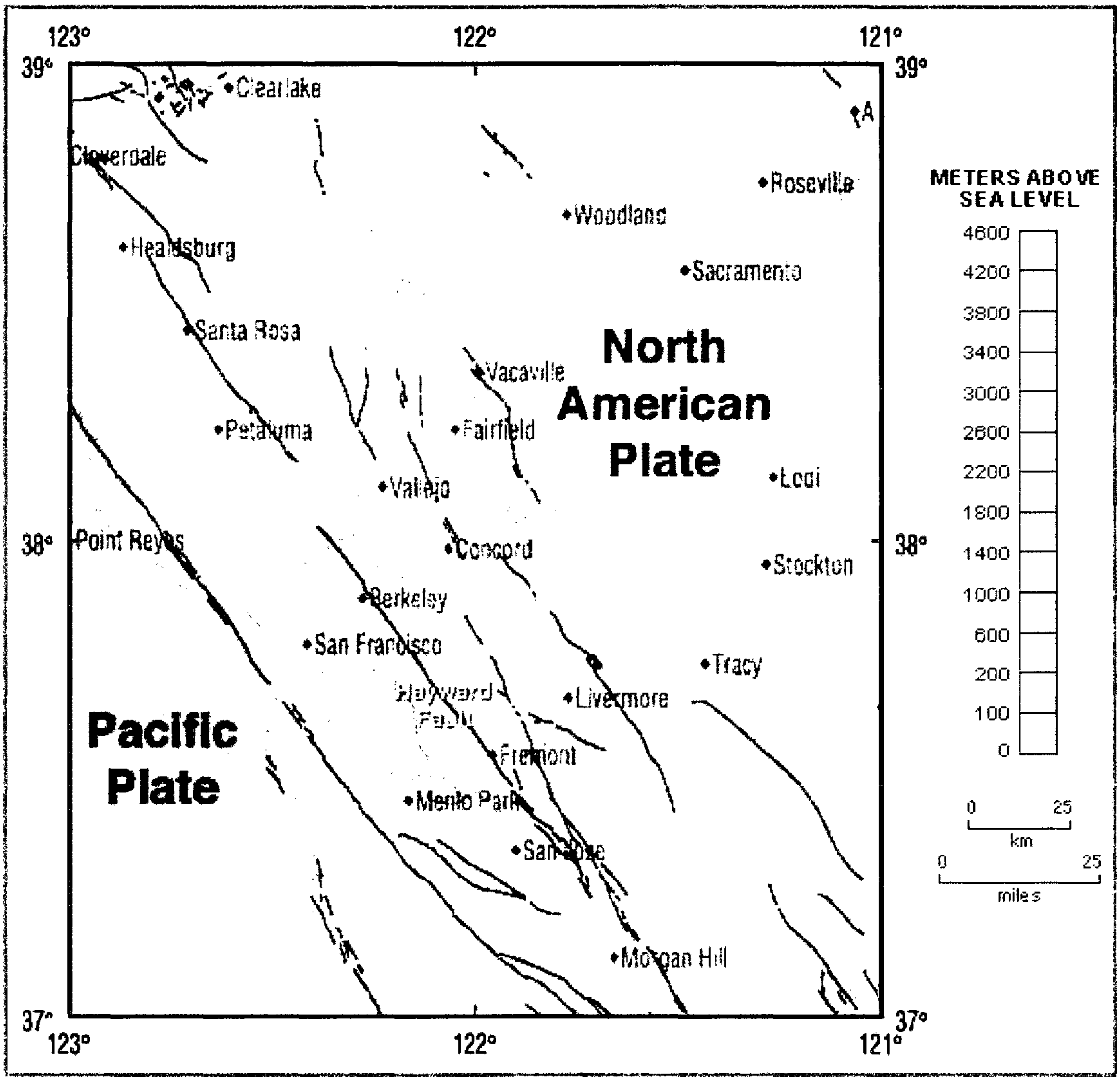


Figure 3.25 **Hayward fault map for the San Francisco Bay region (from USGS Earthquake hazard mapping website).**

Figure 3.26 Sedimentation basin constructed on Berryessa Creek at the upland to valley transition portion of the watershed

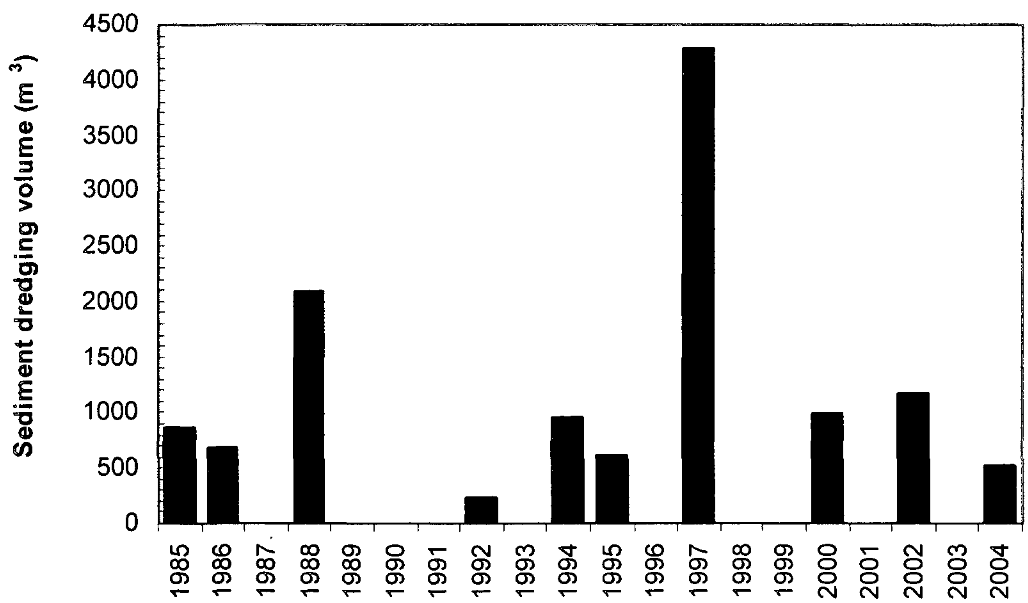


Figure 3.27 Sediment dredging records for the Berryessa Creek sedimentation basin immediately downstream of Piedmont Avenue.

3.6 STREAM GAGE AND RAINFALL DATA COLLECTED BY OTHER AGENCIES

3.6.1 HISTORIC STREAM GAGE DATA

The SCVWD operates two stream gaging stations on Upper Penitencia Creek in the region where the creek leaves the upland area and enters the valley portion of the watershed. Historical record is available from 1946 to present. These gages are located at the Piedmont and Dorel road crossings. The USGS maintained the Dorel road gage from 1961 to 1987. These data, coupled with the field measured data collected during this study, will be used to calibrate the hydrologic models, and implement and calibrate the sediment transport models.

3.6.2 RAINFALL DATA

No rainfall data were collected by the investigating author; however, there are numerous sources of rainfall data dating from 1874 to present (Table 3.5). Data at time intervals of 15 minutes are available from 1963 to present. Hourly data are available from 1948 to present and daily data are available from 1874 to present. These rainfall data will be used as input for the hydrologic models to supply long-term flow duration information where stream flow measurements are lacking.

Table 3.5 **Summary of rain gage data available in the vicinity of the study site.**

Rain gage station	Elevation above sea level (m)	Operating agency	15-minute period of record	1-hour period of record	Daily period of record
Upper Penitencia water treatment plant	143	SCVWD	1967-present	x	x
Curtner ranch	610	SCVWD	1963-present	x	x
Haskins ranch	195	SCVWD	1936-present	x	x
San Jose airport	20	National Weather Service cooperative	1981-present	1948-present	1893-present

x- Indicates record not available

3.7 SUMMARY OF DESKTOP ANALYSIS

Urbanization analysis reveals that both Berryessa and Upper Penitencia Creeks have undergone significant urbanization infill as well as drainage area changes in the past 100 years (Table 3.6). The upland portions of both watersheds have been relatively unaffected by the urbanization process. However, within the valley portion of the watershed both streams are highly urbanized. The land cover for Berryessa Creek is 85 % urban within the valley portion of the watershed, and Upper Penitencia is Creek is 76 % urban. For the entire catchment area, Berryessa Creek is 14% urban and Upper Penitencia Creek is only 7 % urban, indicating there is a substantially larger non urbanized upland portion of the watershed available to Upper Penitencia Creek to buffer the downstream urban effects. The effective drainage area of Berryessa Creek has been expanded 20% for the entire catchment and 123% in the valley corridor. Conversely, the effective drainage area of Upper Penitencia Creek has been decreased 3% for the entire catchment and 29% in the valley corridor. The effective catchment area for both streams has been altered by the constructed urban storm sewer network. In essence, water has been exported from Upper Penitencia Creek and imported to Berryessa Creek from historic drainage conditions.

Table 3.6 Urbanization summary for Berryessa and Upper Penitencia Creeks from 1899 to 2002.

Creek	Catchment urbanization (%)	Valley urbanization (%)	Increase or decrease in full catchment area (%)	Increase or decrease in valley catchment area (%)
Upper Penitencia	7	76	-3	-29
Berryessa	14	85	+20	+122

In addition to the alterations imposed by the storm sewer network on the hydrologic regime, off channel percolation ponds have been constructed on Upper Penitencia Creek. Water diversions to these ponds have been operated to extract a portion of the peak flows from the upland basin to allow slow percolation to the local groundwater table providing more consistent base-flows promoting and sustaining riparian vegetation growth.

The hydrologic modifications magnify hydrograph peaks and duration of flows capable of producing bedload transport in the urban valley portion of the Berryessa Creek watershed. Conversely, peak flows and bedload transport duration have been attenuated by the storm sewer network structure and percolation pond diversions in Upper Penitencia Creek.

Historic longitudinal profiles for both streams were determined from archived construction drawings. By combining our longitudinal survey data with the archived construction drawings profiles from 1967 to 2004 were created for Berryessa Creek and profiles from 1985 to 2004 were created for Upper Penitencia Creek. Analysis of the data indicates an overall degrading trend for Berryessa Creek, with up to 1.5 meters of incision from 1967 to 2004 downstream of the on-line sedimentation basin. Additionally, up to 1.5 meters of incision or channelization has occurred at the mountain/valley interface downstream of Old Piedmont Rd. from 1967 to 2004. The Upper Penitencia Creek data shows up to 0.8 m of deposition at the mountain/valley interface. Approximately 1.1 m of incision has occurred upstream of Capitol Ave. since 1985, this area is located upstream of the zone of maximum valley subsidence. The trend within the zone of maximum subsidence is deposition, which corroborates with the flume studies and mapping analysis available from past studies (Ouchi 1985, Schumm et al.2000).

Valley subsidence magnitude and rate were quantified for each stream from the NGS historic benchmark data. This analysis reveals that the lower reaches of Upper Penitencia Creek have encountered valley subsidence of 1.1 m at the downstream extent of our surveyed reach, whereas the Berryessa Creek valley has only subsided 0.23 m. These data indicate that the degree of base-level lowering has been much stronger for Upper Penitencia Creek.

Time series planform analysis for Berryessa Creek indicates that sinuosity has been decreased from 1.14 to 1.09 in the upstream reach as a result of channelization. Downstream reaches of Berryessa Creek show an increasing trend in channel sinuosity from 1.04 to 1.1 due lateral migration in response to drainage area capture in the lower reaches. The increase in sinuosity indicates that this reach is currently responding to the increased urban discharges by reducing slope via lateral migration rather than incision.

Significant planform change was detected for a reach on Upper Penitencia Creek in the vicinity of the I-680 crossing. During construction of the interstate in the early 1970s the channel was straightened and a historic meander was abandoned. This planform change resulted in a 16% local increase in the channel slope. The meander belt width in this reach has decreased from 120 m to 80 m from 1939 to 2004, indicating that the reach has responded to valley subsidence and channelization by incising. This was corroborated by field investigation.

4.0 URBAN GEOMORPHIC ASSESSMENT FIELD DATA

4.1 INTRODUCTION

The investigating author implemented a rigorous field data-collection program for both Berryessa Creek and Upper Penitencia Creek beginning in the summer of 2004 and continuing until the summer of 2008. Three field seasons were completed. Colorado State University (CSU) and SCVWD staffs have performed all the field work to date, with the exception of the continuous flow monitoring and some of the sediment transport measurements, which have been conducted by a local San Francisco Bay Area consulting company, Balance Hydrologics. CSU staff designed all survey, sampling, and measurement protocols. The field data-collection program consists of:

- preliminary field reconnaissance;
- detailed initial longitudinal and cross sections surveys;
- repeated cross section and headcut migration surveys;
- channel resistance estimates;
- pebble count and bulk sampling bed material gradation analysis;
- bank stratigraphy and vegetation composition surveys;
- measurement of bank material gradation and shear stress characteristics;
- bank rod installation and monitoring on unstable bends;
- supplementary bank height and bank angle survey to assess bend stability characteristics;
- continuous stream flow gaging;

- bedload and suspended load sediment transport measurement; and
- a culvert inventory of all storm sewer outfalls.

This dataset was utilized to assess channel hydraulic and sediment transport characteristics for both streams, and the resulting effects on channel stability in an urban setting.

4.2 PRELIMINARY STREAM RECONNAISSANCE

Subsequent to the morphometric analysis, preliminary field reconnaissance was undertaken. The goals of the field reconnaissance were to; (1) Gain a perspective of the processes forming the channel and creating channel change longitudinally; (2) Map with global positioning system (GPS) technology potential cross-section locations for riffles and bends to implement long-term cross-sectional monitoring stations; (3) Plan logistics for the longitudinal survey (i.e., potential turning points, existing control, and feasible upstream and downstream limits); and (4) Ground-truth potential areas of channel stability noted during the desktop morphometric study, for future stable reference reach data. The GIS field reconnaissance data were mapped to investigate the spatial distribution of riffle and bend cross-section locations. The end goal was to survey a consistent spatial distribution of riffle and bend cross sections of varying hydraulic and sedimentary characteristics for both stable and unstable bend and riffle morphologies along the surveyed reaches of both streams. Maps of the cross-sections surveyed are presented in Figures 4.1 and 4.2.

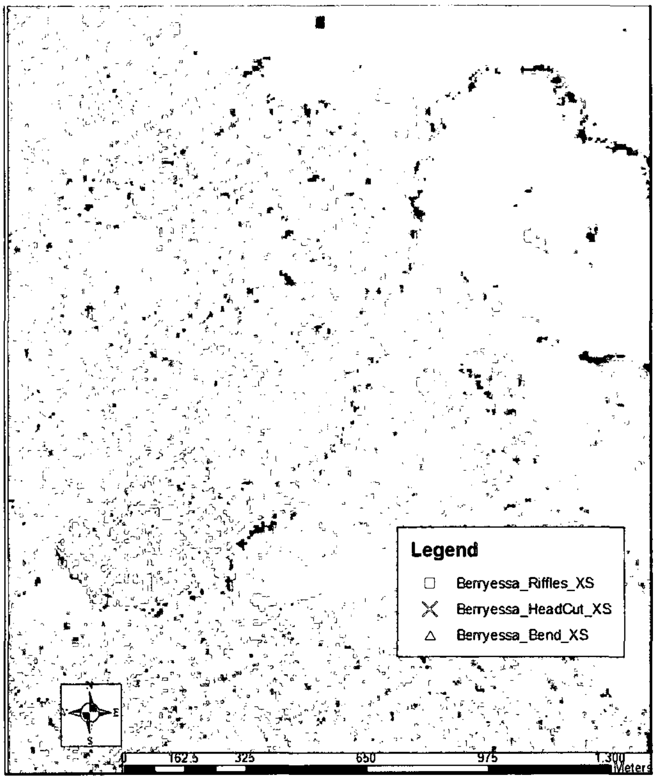


Figure 4.1 Surveyed cross-section location map of Berryessa Creek.

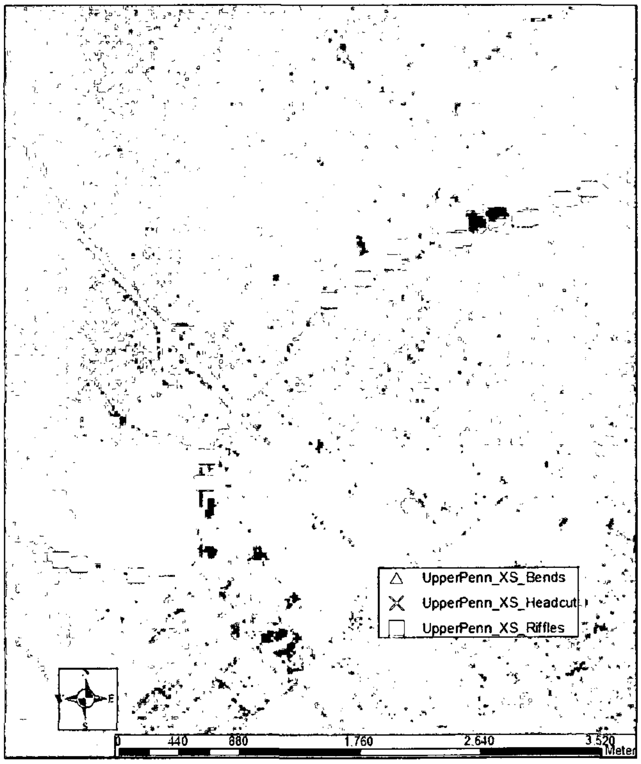


Figure 4.2 Surveyed cross-section location map of Upper Penitencia Creek.

4.3 LONGITUDINAL PROFILE SURVEYS

A detailed longitudinal survey was conducted in the summer of 2004 for approximately 3,000 m of Berryessa Creek and 6,200 m of Upper Penitencia Creek. The geomorphic survey was conducted according to methods outlined by Annable (1996). The high degree of longitudinal slope resolution enables accurate modeling of local hydraulics utilized in sediment transport studies. It is important to survey morphologic features (i.e., bends and riffles) rather than fixed intervals because hydraulic characteristics vary significantly in riffle and bend sections. The morphological features surveyed were: riffle top and bottom, step top and bottom, maximum pool depth, bankfull stage, bank top, bankfull channel centerline for planform characteristics, channel thalweg (1 discrete point was acquired approximately every bankfull channel width longitudinally down the channel, and wherever any breaks in slope were noted), point bar slopes, central bar, and chute cutoffs. Infrastructure features recorded during the survey included bridge openings, grade-control structures, storm water detention out flow structures, storm water culvert inflows, and existing control points. Longitudinal profiles for Berryessa Creek (Figure 4.3) and Upper Penitencia Creek (Figure 4.4) are provided.

Figure 4.3 2004 longitudinal profile survey of Berryessa Creek.

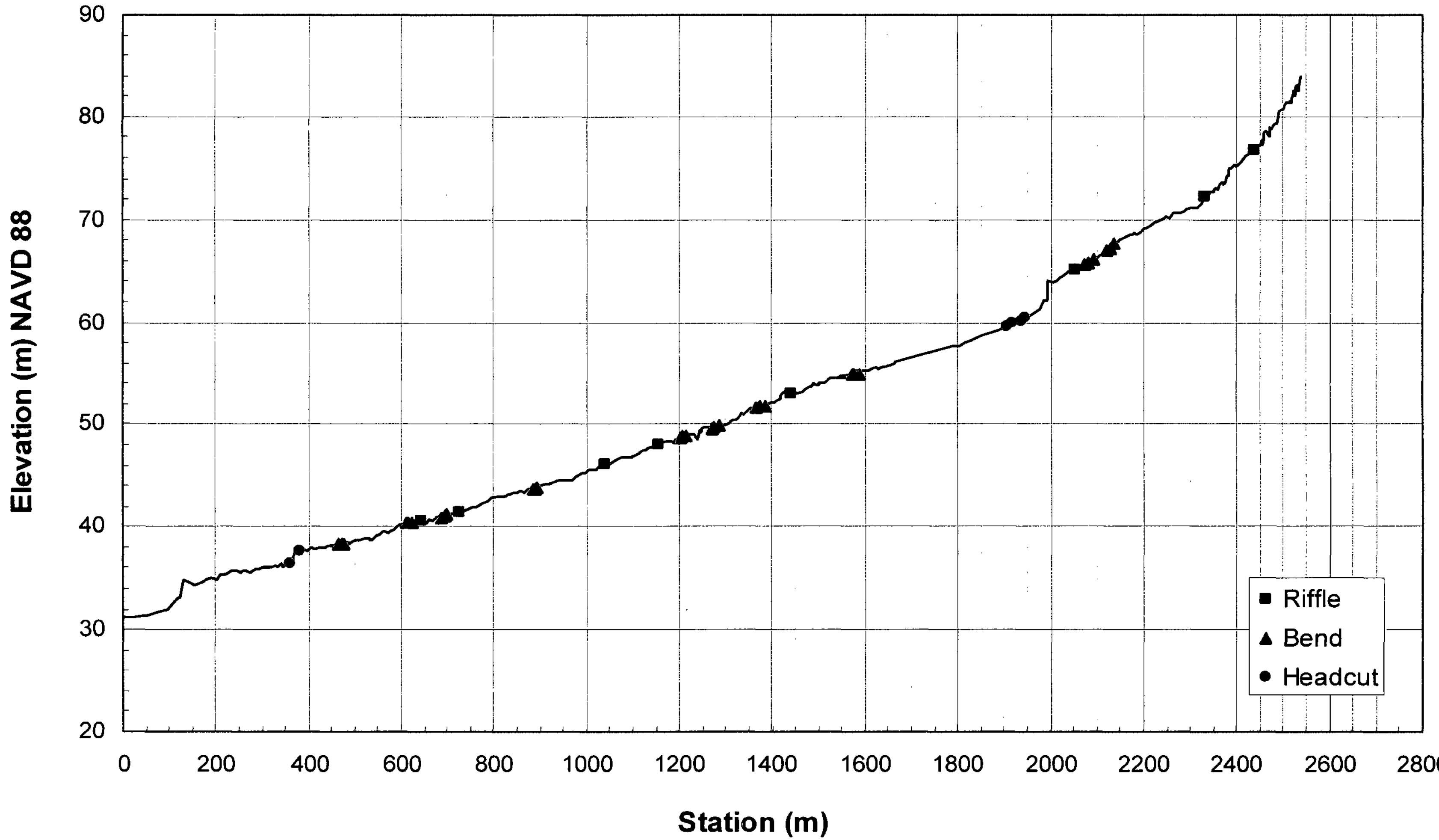
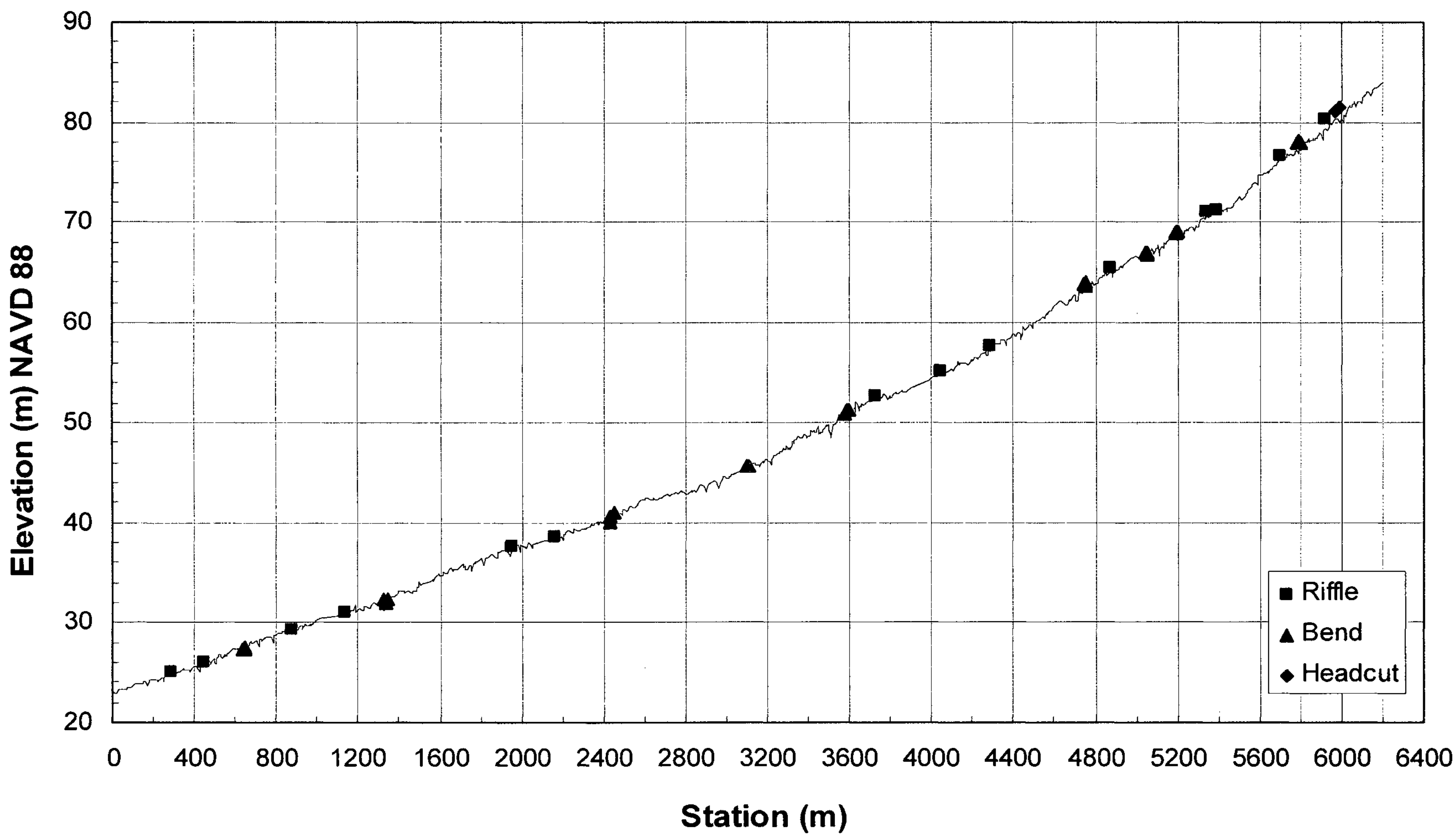


Figure 4.4 2004 longitudinal profile survey of Upper Penitencia Creek.



4.4 CROSS SECTION SURVEYS

4.4.1 SURVEY PROCEDURES

Cross-section surveys were conducted concurrently with the longitudinal survey. Forty-three transects were surveyed on Upper Penitencia Creek and 47 were surveyed on Berryessa Creek. Transects were located on riffles, bends, and at locations upstream and downstream of headcut locations. Endpoints for the cross-section surveys were monumented with 1.2-m. long, 25-mm. diameter iron bars. These endpoints were acquired during the longitudinal survey (using a total station), and then a relative elevation level survey between the endpoints was conducted after the completion of the longitudinal survey using an automatic level, steel tape, and stadia rod. The level method was selected for each cross section for accuracy and repeatability, allowing the investigator to monitor cross section erosion and deposition over time. The cross sections were resurveyed yearly after the high-flow season, which occurs during the winter months in this region.

The cross-section endpoints were located with three goals in mind: (1) Measure a representative natural cross section that is not affected by extensive foot traffic or urban hardscape; (2) Locate the cross-section perpendicular to the dominant direction of flow at bankfull stage; and (3) Locate the survey endpoints in discrete locations that are unlikely to be disturbed by pedestrian or city maintenance traffic. Riffle locations were placed at the top third of the riffle. These sections are used as hydraulic sections in the computer modeling aspect of the project. Three cross sections were established at the top, middle, and lower third of each bend of interest to determine hydraulic and channel geometry for stable bends, and to capture rates of lateral channel migration for unstable bends. Both vegetated and non-vegetated banks were surveyed in order to quantify the differences in erosion rates resulting from vegetation contribution to shear resistance. Lastly, two cross sections were typically established at locations upstream and downstream (±20 m) of significant headcuts to capture migration rates of longitudinal erosion. Typical plan cross-section layouts are shown in Figure 4.5, with the dark arrows indicating the direction of flow.

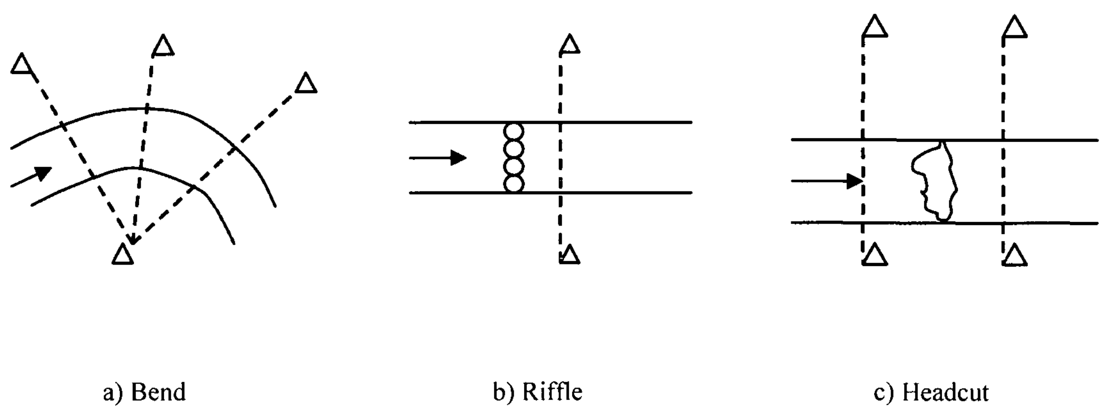


Figure 4.5 Plan view layout of cross-section transects.

Cross-section survey points were collected at the following locations between endpoints: 1-m fixed intervals, breaks in slope, top of bank, bottom of bank, bankfull stage, and channel thalweg. The cross sections were resurveyed yearly in the summers of 2004, 2005, and 2006 to track channel change with time; therefore, a high degree of resolution was recorded to ensure accurate assessment of channel change.

4.4.2 CHANNEL CROSS SECTION CUT AND FILL ANALYSIS.

A cut and fill analysis of channel change was conducted for cross sections surveyed in the summers of 2004, 2005 and 2006. AutoCAD drawings of each cross section were used to calculate cut and fill areas for each cross section. Erosion and deposition for channel processes occurring below the field-identified bankfull stage were calculated. Changes in cross sectional area for each year of survey data were tabulated. The changes in cross sectional area were normalized with channel bankfull width to arrive at aggradation or degradation depths at each cross section.

Channel-forming flows in this area occur during the winter months. The winter for water year 2004 was a typical rainfall year for the area, whereas the winter for water year 2005 was wetter than normal. Both sets of aggradation and degradation data, along with a moving average of the data, were plotted along the longitudinal profile for the period of record to examine trends over a three-year period (Figures 4.6 and 4.7). A simple method of comparing stability is to examine the frequency of cross sectional change crossing an equilibrium threshold for yearly channel adjustment. If the assumption is made that the stream is in quasi-equilibrium if aggradation or degradation rates don't exceed 0.05 m/yr, then Upper Penitencia Creek data only cross this threshold once along the surveyed extents. Berryessa Creek crosses this threshold four times along the surveyed reach. Additionally, the surveyed reach extents are significantly shorter for Berryessa Creek compared to Upper Penitencia Creek. Therefore, the relative rate of crossing this threshold is much stronger for Berryessa Creek, indicating that Berryessa Creek exhibits greater channel instability during the period of record for the cross section surveys. These data will be compared to the long-term longitudinal profile data in the sediment transport and stability discussion in chapter 6.

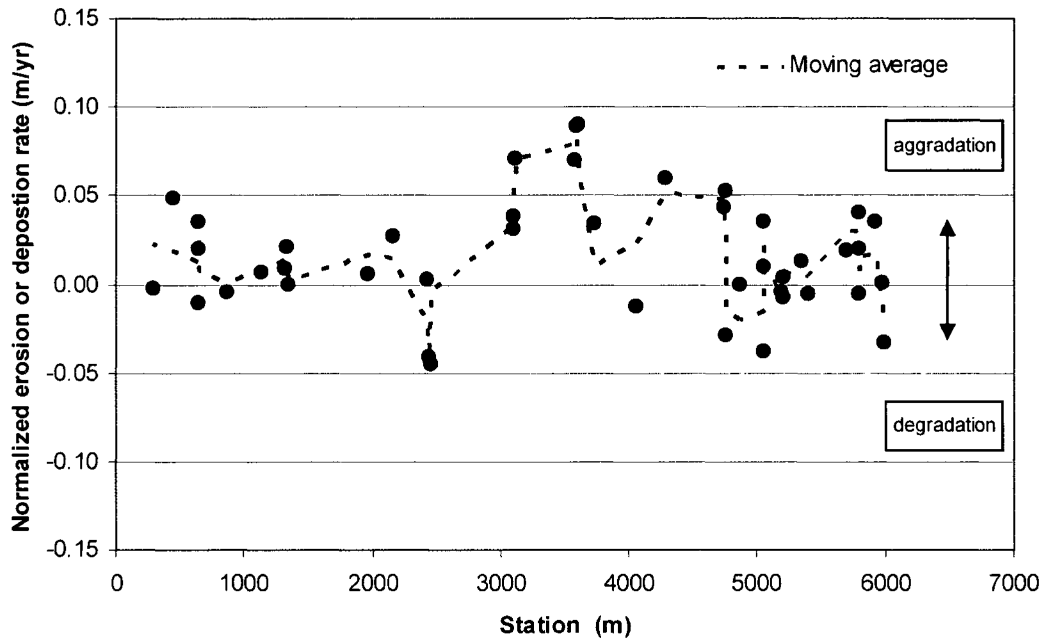


Figure 4.6 Aggradation or degradation rate from 2004 to 2006 as a function of river station for Upper Penitencia Creek.

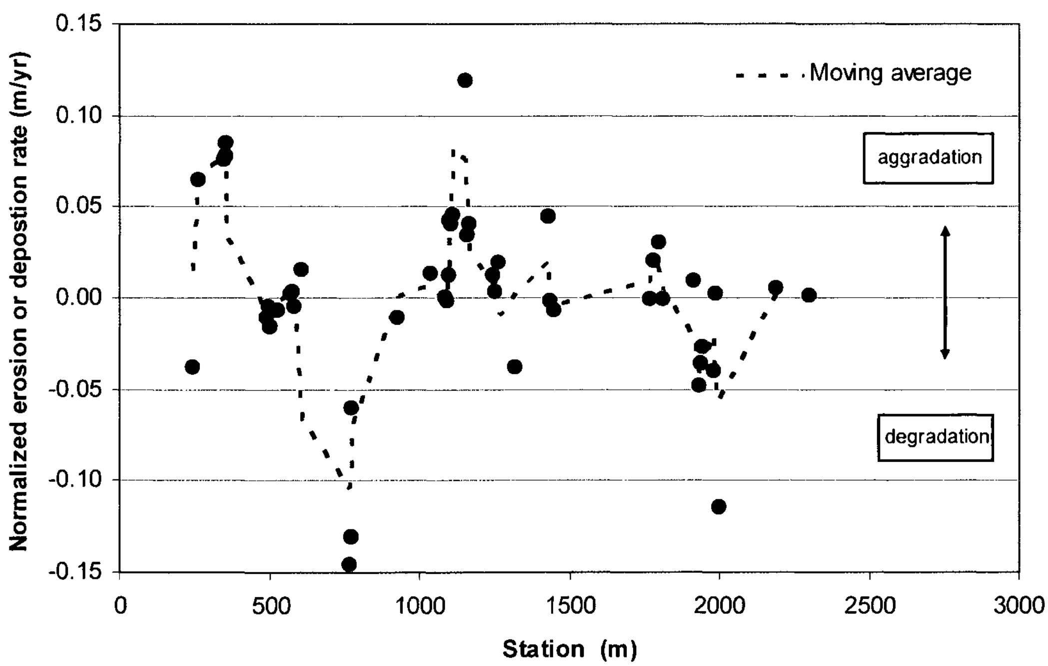


Figure 4.7 Aggradation or degradation rate from 2004 to 2006 as a function of river station for Berryessa Creek.

The data also show oscillation in aggradation and degradation trends along the longitudinal profile. The Upper Penitencia data indicate that the stream is generally depositional within the valley up to river station 3000 m as bedload from the upstream watershed is deposited in the lower gradient valley. Downstream of station 3000 the channel is in quasi equilibrium with the exception of the vicinity near station 2450. This area was observed to be morphologically unstable in the field. Upon initial reconnaissance during the 2004 field season, a channel reconstruction was in place. This project had created a sinuous stream channel downstream of the I-680 crossing. During the next two field seasons the constructed bend was abandoned and the channel formed a chute cut off on the inside of the bend (Figure 4.8).

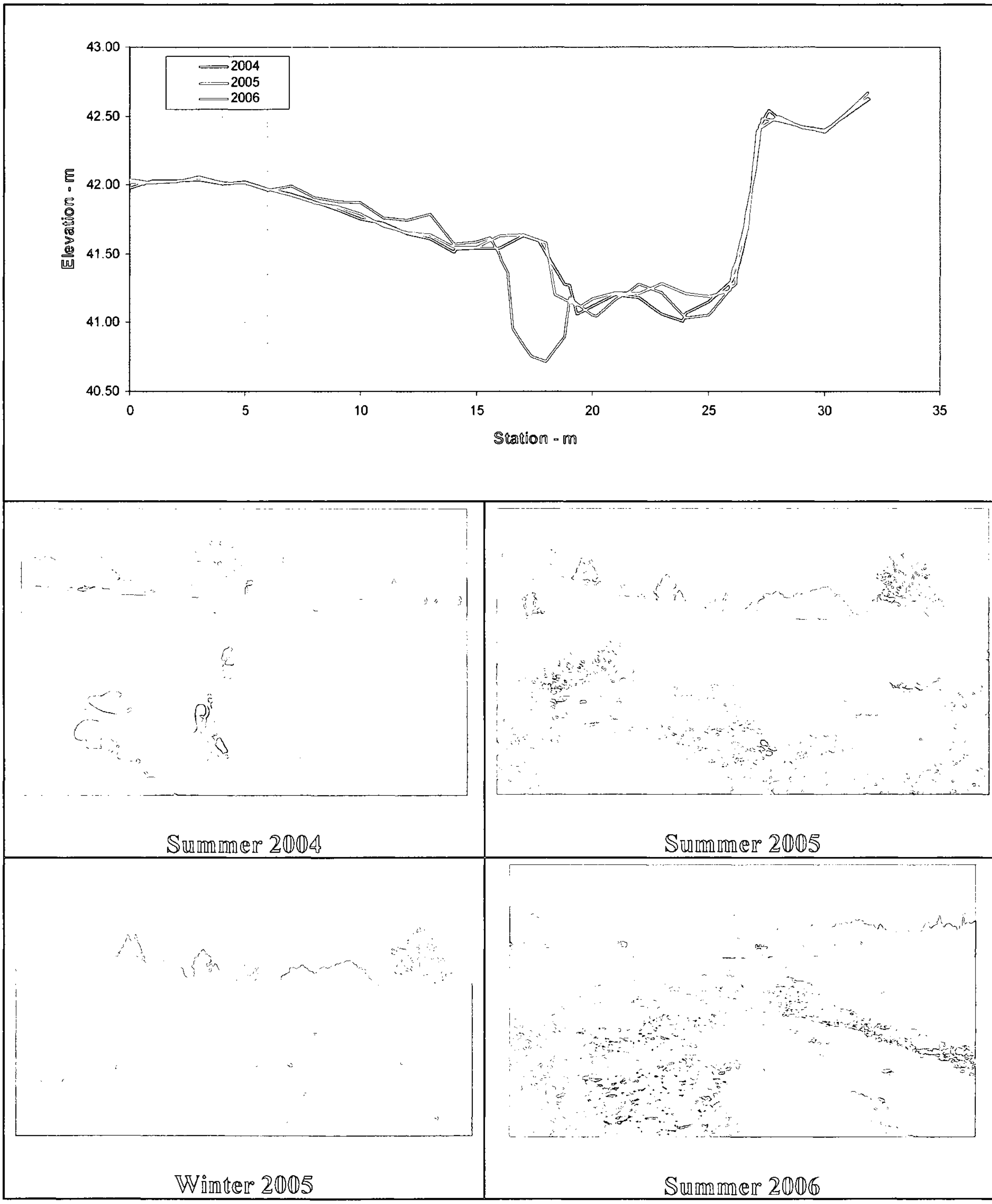


Figure 4.8 Time series photographs and cross section survey data for GCS 18 near river station 2450 m on Upper Penitencia Creek.

The Berryessa Creek longitudinal cross section data show an area of channel degradation immediately upstream of the transition to the valley portion of the watershed in the vicinity of river station 2000 m. The channel then maintains quasi equilibrium until it reaches the sedimentation basin near station 1400 m; at this location coarse bedload is deposited in the sediment basin and the channel is degrading immediately downstream. The stream briefly regains equilibrium until 1200 m, where a depositional trend is observed, likely due to influx of sediment derived from unstable banks in the reach. This reach has been historically degradational, but presently channel widening is the dominant process. The longitudinal trend then becomes briefly degradational near station 750 m, followed by a strong depositional trend at the downstream portion of the reach where failing banks and lateral migration are the dominant channel processes, introducing large volumes of sediment locally.

The channel is currently depositional downstream of the Crosley culvert outlet near station 200 m, despite a substantial increase in water discharge from historic conditions downstream of this culvert. The current Crosley culvert was constructed in 1983, and the downstream channel responded with a period of rapid incision, according to personal communication with local residents and corroborated by the long-term longitudinal profile data. This period of incision has ceased, as inferred from the cross section survey data. Large amounts of sediment are currently being introduced to the reach from failing stream banks due to lateral channel migration at this time. This increase in sediment supply results in channel aggradation downstream of the culvert. A 1.2-m headcut is present downstream of this area, which could cause further incision in the area if the headcut migrates upstream.

Summary statistics for the period of record for cross section resurveys and analysis are presented in Table 4.1. The data indicate that Upper Penitencia Creek has a stronger trend of aggradation than Berryessa Creek by comparison of means (0.016 m/yr versus 0.001 m/yr). The probability distribution (Figure 4.9) is positively skewed, with a value of (0.33) (aggradation) for the Upper Penitencia data, and negatively skewed (degradation), with a value of (-0.74) for the Berryessa data. The Berryessa data show greater dispersion of erosion and deposition amounts, as reflected in the larger range (0.26 m/yr versus 0.14 m/yr) and standard deviation (0.05 m/yr versus 0.03 m/yr). A Kolmogorov-Smirnov statistical test indicates that the erosion and deposition trends of the two streams are not statistically different at the 90% confidence level (D statistic=0.22 p=0.18), implying that both channels may be approaching a quasi-equilibrium state. The altered urban runoff regime has been relatively constant in both watersheds since the early 1980s allowing 20 years of time to adjust channel form. Likewise, the streams have had nearly 40 years to respond to base-level changes from valley subsidence. The data from the current cross section measurements indicate that both channels are approaching re-equilibration to the altered urban flow regimes and base-level changes. This time frame for adjustment is consistent with findings from other researchers (Hammer 1972, Booth and Henshaw 2000).

The urban flow regime has been constant for approximately twenty years, potentially enough time to adjust channel form. However, bedload deposition continues to occur at the constructed sedimentation basin on Berryessa Creek, depriving the downstream reaches of coarse bedload size material necessary for channel stability. This is a process that is ongoing; therefore, the stream continues to adjust to this sediment regime alteration. The cross sections from Berryessa Creek immediately downstream of the sediment basin are currently degrading indicating that the stream continues to incise as a result of this discontinuity in bedload transport. Engineered sedimentation basins do not exist on Upper Penitencia Creek and bedload is routed through the system. Cumulative distribution data (Figure 4.10) indicates that Berryessa Creek currently has a stronger degradation trend in the cross section data. Over 65% of the Berryessa Creek cross sections are currently degrading compared to 45% for the Upper Penitencia Creek sections. This trend is also observed in the long-term profile data. This indicates that Berryessa Creek is still adjusting to the altered hydrologic and sediment regimes caused by urbanization and engineering infrastructure.

Summary tables of the bankfull channel measurements for each stream are provided in Appendix A. Cross section plots for the 2004, 2005 and 2006 survey data along with the identified bankfull stage are provided in Appendix B.

Table 4.1 Aggradation and degradation statistics for Upper Penitencia and Berryessa Creeks from cut and fill analysis for 2004 to 2006 cross section data.

	Upper Penitencia	Berryessa
Mean (m/yr)	0.016	0.001
Standard deviation (m/yr)	0.033	0.050
Range (m/yr)	0.135	0.264
Minimum (m/yr)	-0.045	-0.146
Maximum (m/yr)	0.090	0.118
Skewness	0.331	-0.737
Kurtosis	-0.055	2.072

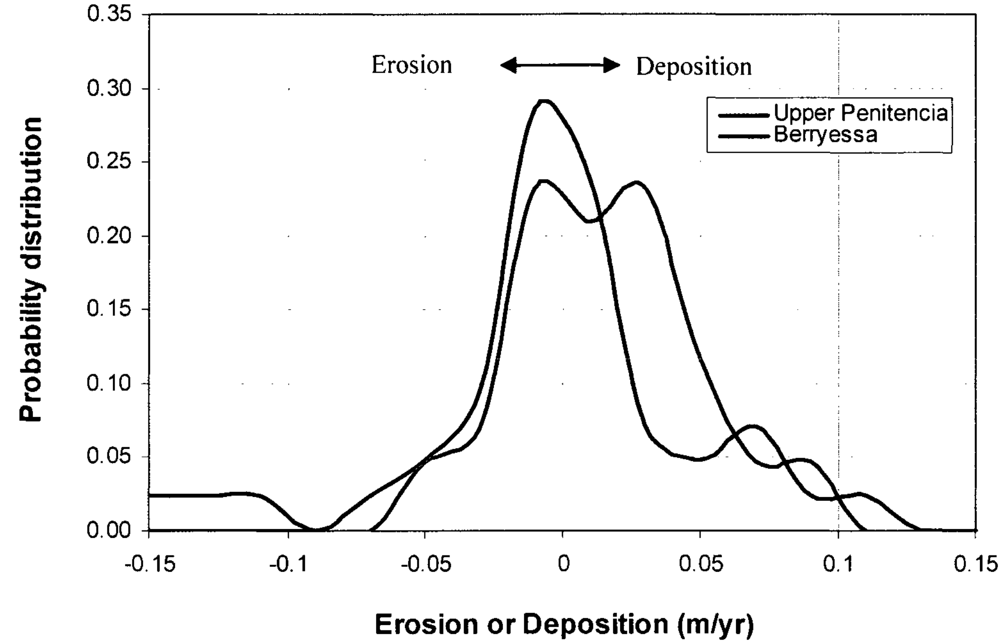


Figure 4.9 Probability distributions for the Berryessa and Upper Penitencia Creek cross section erosion and deposition measurements.

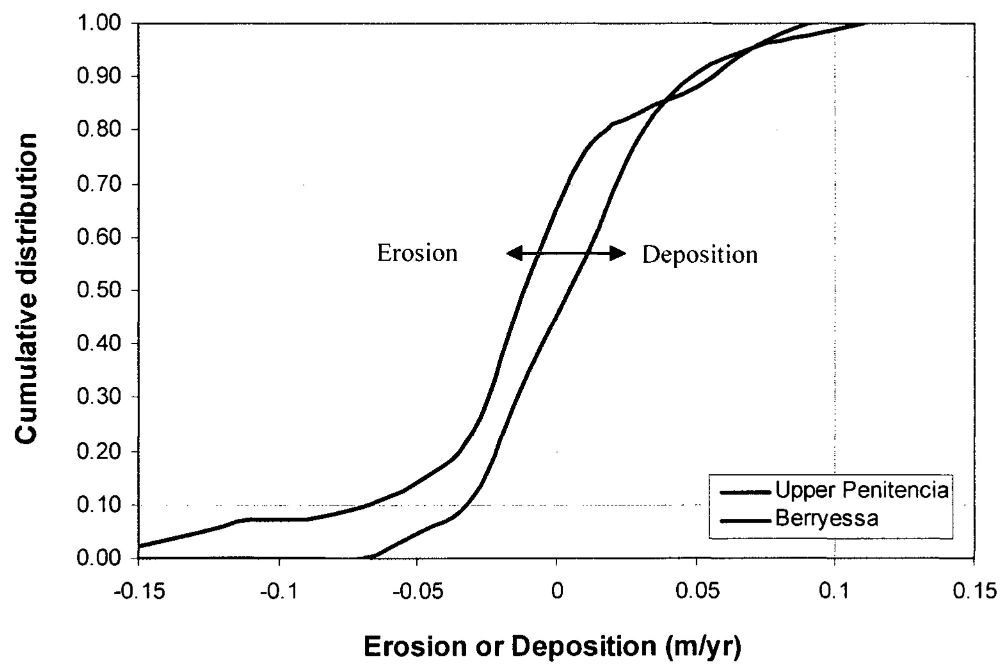


Figure 4.10 Cumulative distributions for the Berryessa and Upper Penitencia Creek cross section erosion and deposition measurements.

4.4.3 BANKFULL CHANNEL CHARACTERISTICS

The bankfull stage was estimated for each year of the cross-section surveys. Field indicators of active floodplain bench development, vegetation change, and point bar crests (Leopold et al. 1964, Williams 1978) were used to identify the bankfull stage for each cross section. There was considerable variability in the estimates from year to year as the investigator became more familiar with the subtle bankfull indicators in this region. The channels are typically entrenched, with only small discontinuous floodplain benches present in the current water and sediment regime. Measurements of bankfull width, maximum and average bankfull depth, width/depth ratio, and bankfull area were calculated for each cross section yearly. Surveyed reach-average bankfull characteristics are provided in Table 4.2. A complete summary of the minimum, maximum, and average values is provided in Appendix A.

Table 4.2 Bankfull characteristics using 3-year average values for Upper Penitencia and Berryessa Creeks.

Stream	Morphology	3-year average of bankfull area (m^2)	3-year average of bankfull width (m)	3-year average of mean bankfull depth (m)	3-year average of maximum bankfull depth (m)	Reach average bankfull slope (m/m)
Upper Penitencia	Riffle	4.38	7.84	0.56	0.83	0.0097
	Bend	4.94	8.66	0.57	0.94	0.0097
	Headcut	4.22	8.39	0.47	0.8	0.0097
Berryessa	Riffle	1.5	3.89	0.37	0.56	0.017
	Bend	1.76	4.31	0.4	0.65	0.017
	Headcut	2.00	4.43	0.45	0.76	0.017

4.5 RESISTANCE ESTIMATES

Channel resistance estimates were conducted for each cross section survey using the Arcement and Schneider (1989) modification of the Cowan (1956) method for channel roughness estimation. Summary results are presented in Table 4.3. These field estimates of channel resistance were be utilized in the numerical models for both creeks. Using this methodology the Manning's roughness coefficient can be systematically estimated using the formulation:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad \textbf{Equation 4.1}$$

Where:

n_b = a base value of n for a straight, uniform, smooth channel in natural materials;

n_1 = a correction factor for the effect of surface irregularities;

n_2 = a value for variations in shape and size of the channel cross section;

n_3 = a value for obstructions;

n_4 = a value for vegetation and flow conditions; and

m = a correction factor for meandering of the channel,

Table 4.3 Channel resistance (Manning's n) summary.

Creek	minimum -n	maximum -n	average -n
Berryessa	0.037	0.064	0.047
Upper Penitencia	0.029	0.053	0.038

4.6 BED MATERIAL GRADATION DATA

Random walk pebble count samples (Wolman 1954) and bulk sediment samples were collected in the summer of 2004 to investigate longitudinal trends in bed material gradation and to provide bed material input data for the sediment transport modeling aspect of the project. Pebble counts were conducted at each monumented cross section for a total of 100 samples. Bulk sediment samples were collected on riffles where changes in bed material grain size distribution were noted from analysis of the pebble count data. There were 9 bulk sediment samples of the pavement and sub-pavement bed material collected for each stream, for a total of 18 samples. Bulk samples were also collected on selected bends on the lower third of the point bar to investigate potential grain size distributions of the size fraction of bedload transport. Ten point bar samples were collected in total.

4.6.1 PEBBLE COUNT SAMPLING

A random walk pebble count was conducted for each cross-section location surveyed. Four transects were evenly spaced longitudinally along the morphological feature. Each transect consisted of approximately 25 random counts, evenly spaced along the entire bankfull channel width, resulting in 100 counts per cross section.

Pebble counts provide a quick method of investigating the size distribution of the surface bed material of the study reach and also provide a tool for screening the number of bulk sediment samples required to accurately assess the gradation of the pavement and sub-pavement of the study reach. Significant grain size change of the larger bed material particles (i.e., D_{84}, D_{75}) as a function of river station or channel slope indicates areas where bulk sediment samples should be collected more intensely. The increased sampling frequency is due to a larger standard deviation among potential sample sites. If the larger particle gradations remain fairly consistent along the longitudinal profile, then less frequency in sampling is sufficient if time or cost factors are limiting.

If the bed material grain size for the D_{84}, D_{50}, and D_{16} are plotted along the longitudinal profile for Berryessa and Upper Penitencia Creeks (Figures 4.11 and 4.12, respectively), one can gain insight into bed material variability along the profile. It is clear from these two graphs that there is greater variability among the Berryessa Creek D_{84} particles along the profile and less variability of these larger clasts for the Upper Penitencia Creek data. These data indicate that bulk bed-material sampling should be conducted more frequently on Berryessa Creek, whereas Upper Penitencia Creek could be sampled less intensely along the longitudinal profile.

The data also show the influence of the engineered sediment basin on Berryessa Creek, as the D_{84} decreases from approximately 90 mm to 20 mm from upstream of this feature to downstream. This indicates that the sediment basin is effectively trapping bedload particles larger than 20 mm. This break in the grain size distribution represents a depositional area along the profile and is confirmed via the long-term profile data shown in Figure 3.5. As urban storm water inputs enter the study reach near river station 1200 m, the bed material coarsens and incision has been observed historically. After this break in the profile, typical downstream fining is observed in the pebble count data.

The Upper Penitencia Creek dataset shows less variability along the longitudinal profile of the D_{84} particles. There is a slight dip downstream of the upland valley transition, indicating deposition near station 5700 m, followed by another dip near station 5000 m, where peak flows are extracted into off-channel groundwater percolation ponds. The gradation coarsens until station 3000 m, a reach that has been incising historically (Figure 3.6). After this reach, the coarse grain size fraction remains consistent with a slight downstream fining trend that would be expected.

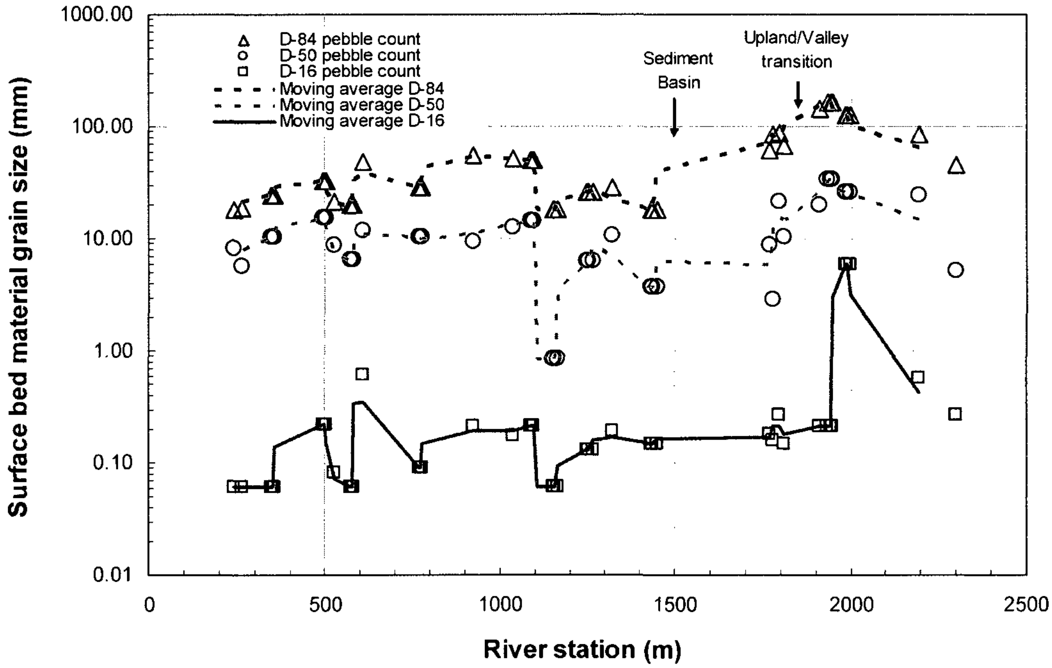


Figure 4.11 Surface bed material as a function of river station for Berryessa Creek bends and riffles.

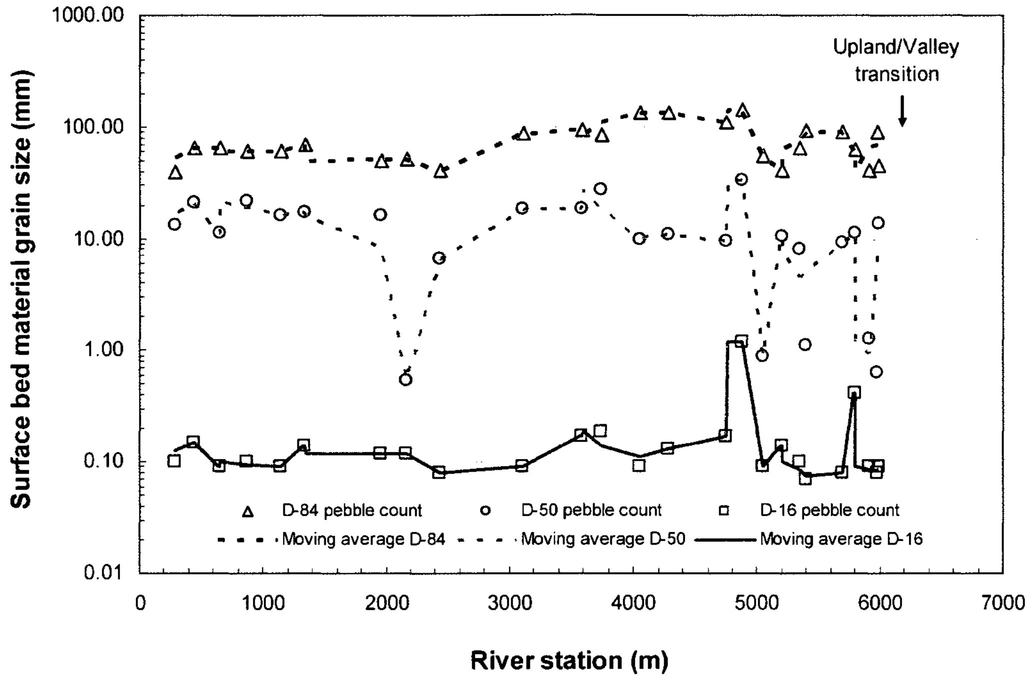


Figure 4.12 Surface bed material as a function of river station for Upper Penitencia Creek bends and riffles.

4.6.2 BULK SEDIMENT SAMPLING

Bulk sampling provides insight into the pavement and sub-pavement stratigraphy of the bed material within the alluvial channel system. It is generally recognized in gravel-bed channels that larger particles are more prevalent on the surface and the subsurface contains a finer gradation of sediments (Leopold 1994). Quantification of the pavement or armor layer is essential to sediment transport and incipient motion studies. A bulk sediment-sampling strategy was employed to quantify this gradation difference. Annable (1996) identified a grain size envelope between sub-pavement and point bar samples, where the typical gradations of sediment transported as bedload are observed. This can be useful for sediment transport model validation if measurements of the grain size distribution of bedload in transport are unavailable. The bulk sediment samples were utilized as bed material inputs for the sediment transport models.

Bulk sediment sampling was conducted according to field methods offered by Annable (1996). At each riffle section, six pavement and six sub-pavement samples were collected. The approximate riffle sampling locations are illustrated in Figure 4.13, with sampling locations denoted with open triangles. On headcut sites, four pavement and four sub-pavement samples were located upstream and downstream of the headcut. Point bar samples were taken at three locations; on the lower third of bends, half-way between the thalweg of the channel, and the bankfull stage located on the inside of the bend.

The protocol for the bulk-sampling diameter dictated that the largest particle should not occupy more than approximately 16% of the total sampling area. This method helps to avoid having a few large particles dominate the sample mass. Sixteen percent was used to ensure that one particle did not occupy more area than two standard deviations of the total sample area. The sample area was excavated to a depth equal to the median (B) axis of the largest particle. Water obstruction and conducting the sampling at low flows reduced the loss of fine material during the sample-collection process. Sample masses were collected in five-gallon containers, sorted, sieved, and weighed on site from the largest particle sizes to the 16-mm size fraction. The remaining size fractions were labeled and placed in thick plastic bags for laboratory sieve analysis down to 0.04 mm. Sub-pavement samples were collected once the pavement sample had been excavated with the same protocol. Point bar samples were collected from the surface of the depositional feature on the lower third of the bend with the same protocol.

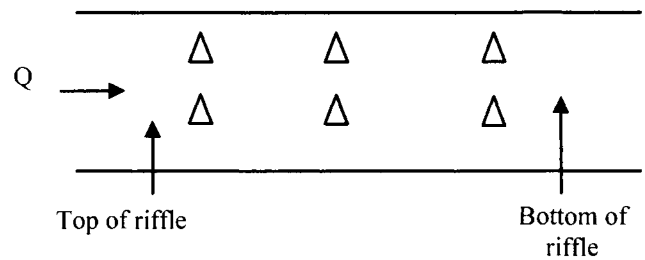


Figure 4.13 Bulk sediment-sampling locations for a typical riffle.

All of the pavement samples for an individual cross section were combined into one cumulative gradation. This is done because using the individual pavement samples for a particular cross section would introduce bias toward the larger clasts, since individual samples were smaller in weight than what is recommended in the literature for streams where the largest particles are on the order of 90 to128 mm (International Organization of Standardization (ISO) 1977, Church *et al.* 1987. Diplas and Fripp 1992). When samples were combined for each riffle or headcut section, the average sample mass for the pavement samples was 75 kg for the Berryessa sites and 225 kg for the Upper Penitencia sites. Sub-pavement samples were also combined at the sampling sites. The average sub-pavement sample mass for Berryessa creek was 21 kg and Upper Penitencia sub-pavement sample masses averaged 75 kg. A frequency analysis conducted on all bed material sampled providing cumulative and frequency distributions of the bed material gradation, an example is shown in Figure 4.14. These gradations were used as input for the sediment transport modeling.

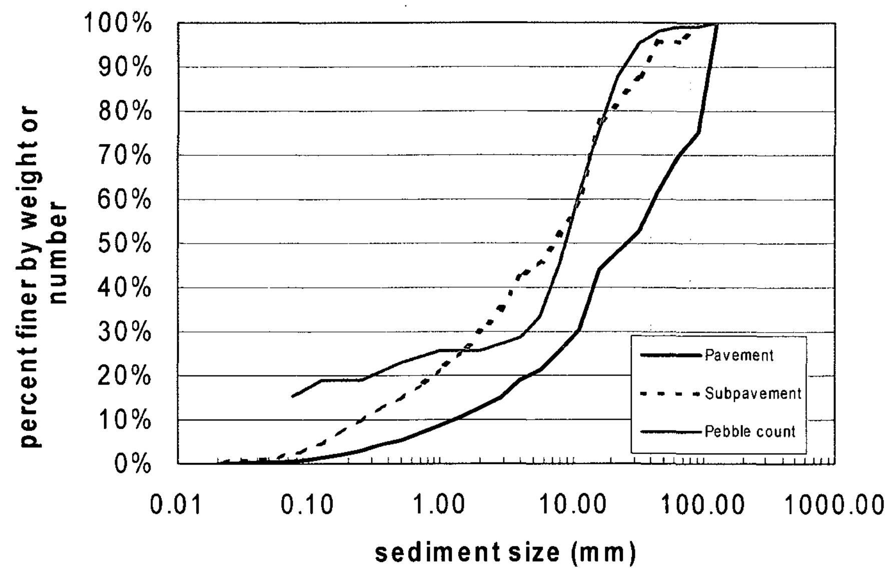


Figure 4.14 Combined pavement, sub-pavement, and pebble count gradations for Berryessa cross-section 25.

The bulk sediment sampling results are plotted as a function of river station for Berryessa Creek in Figure 4.15. The Berryessa data show a general downstream fining trend from the upland reaches into the valley. The strong influence of the constructed sediment basin is evident in these data. Downstream of the sediment basin, the D_{84} particle sizes of the pavement and sub-pavement layers are nearly identical; in fact, the grain size distributions of both layers nearly collapse into one gradation at this point. This is a result of two processes; deposition of coarse bed load size particles in the sediment basin and an overall depositional trend in the reach due to changes in bankfull channel confinement. Downstream of the basin the pavement and sub-pavement distributions diverge and the stream regains a well defined pavement and sub-pavement bed material stratigraphy. Further downstream near station 250 m the influence of channel widening and increased sediment supply from the failing banks is seen. At this site the underlying sub-pavement layer is actually coarser than the pavement layer. This is an indication of deposition in the reach. The sediment supplied from the failing banks generally has a finer grain size distribution than the bed material and the rate of sediment input exceeds the carrying capacity of the channel at this site.

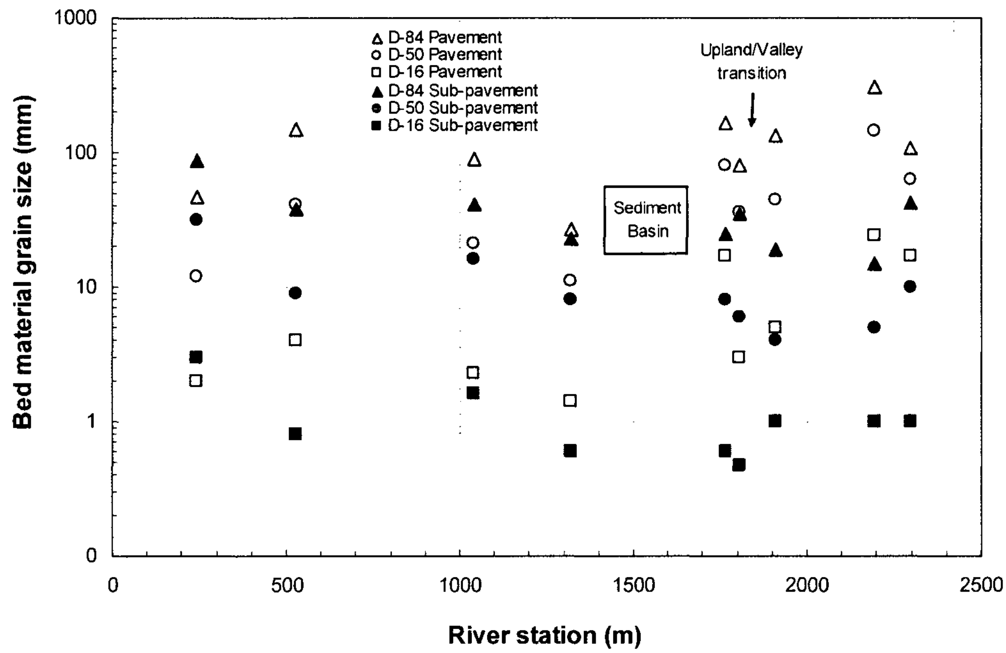


Figure 4.15 Bulk bed material sampling data as a function of river station for Berryessa Creek.

Figure 4.16 shows the bulk sediment sampling results for Upper Penitencia as a function of river station. These data show a well defined downstream fining trend and well developed pavement and sub-pavement stratigraphy. This indicates that sediment sources from failing banks are relatively minor or the sediment supplied from these failing banks is similar in gradation to the existing bed material.

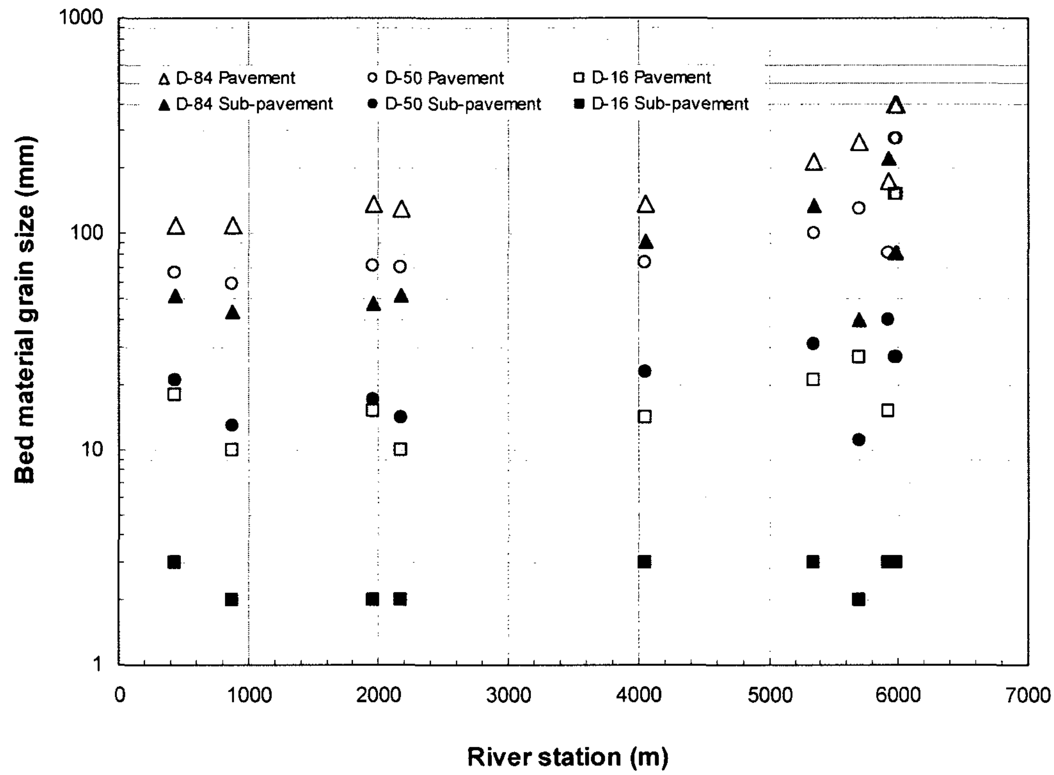


Figure 4.16 Bulk bed material sampling data as a function of river station for Upper Penitencia Creek.

The end result of the sediment sampling efforts is a series of surface bed material, pavement, and sub-pavement bed material gradations for each cross section. These bed-material gradations were utilized in the sediment transport modeling portion of the project. Another benefit of collecting a large amount of bed material data is derived from geomorphic interpretation of longitudinal trends in the bed material data. This provides insight into the erosion and deposition processes taking place at a reach scale without having to perform sediment transport analysis. To some degree, the story of what is happening longitudinally along the stream can be deduced from bed material interpretation. Tables of the bed material sampling results are presented in Appendix C.

4.7 STREAM BANK CHARACTERIZATION

4.7.1 BANK STRATIGRAPHY AND VEGETATION INVENTORY

A qualitative description of bank material composition and stratigraphy, torvane measurements of shear resistance for the bank material and vegetation characteristics were recorded for each riffle, bend, and headcut cross section. Bank sediment and vegetative components were characterized for each cross section by visual inspection of the dominant woody, herbaceous and grass bank vegetation types, overhead and under-story canopy density, rooting depth and density, and bank soil types. Bank soils were inspected by exposing two 0.5-m wide swaths of vegetation (one for each bank) that extended vertically from the bottom of the bank to the top of the bank (Figure 4.17) Soil horizons were classified, demarcated with orange spray paint and photographed, and a stadia rod was used to provide scale for the photographs. The bank sediment information recorded is shown in Table 4.4.

Figure 4.17 Bank stratigraphy survey photograph from Berryessa Creek cross-section 16.

Table 4.4 Sediment properties recorded in bank stratigraphy survey.

Depth of soil layer	Sphericity (rounded, sub-rounded, angular)
Texture and color	Clast/matrix supported sediment structure
Grain size (clay, silt, gravel, cobble)	Sorting

Shear-resistance measurements were collected using a torvane meter for each significant change in soil type along the vertical swaths. The torvane measurements only provide a relative measure of erodibility of the various bank materials and the shear stress is strongly a function of saturation.

Stream banks on Berryessa Creek generally had sparse vegetation consisting of seasonal grasses or were devoid of vegetation. Most banks were buttressed with coarse bed material (cobbles/gravels) at the bank toe. Banks that were devoid of vegetation and lacked buttressing at the bank toe were subject to the highest rates of erosion. Many of the banks actually showed a depositional trend from analysis of the cross section data. Deposition was primarily at the bank toe, indicating active floodplain development. In reaches where lateral migration and active bank erosion were present, erosion rates ranged from 0.01 to 0.11 m/yr. Deposition and erosion rates balance each other, with the average erosion rate equal to 0.004 m/yr. Summary data for Berryessa Creek are provided in Table 4.5.

Table 4.5 **Stream bank summary data for Berryessa Creek.**

GCS	River Station (m)	Left or Right bank	Dominant Vegetation Type	Vegetation density (low, moderate, high)	Grain size at bank toe	Grain size upper bank	Failure rate (m/yr) (positive number indicates erosion)
5	1988	LB	woody	Low	cobble	fine matrix	0.06
6	1940	RB	woody	high	cobble	fine matrix	-0.01
8	1808	LB	bare	low	cobble	fine matrix	-0.01
8	1808	RB	bare	low	cobble	fine matrix	-0.01
9	1798	LB	bare	low	cobble	fine matrix	-0.02
9	1798	RB	bare	low	cobble	fine matrix	-0.01
10	1778	LB	grass	low	gravel	fine matrix	-0.05
10	1778	RB	grass	low	cobble	Silt	0.02
11	1768	LB	grass	Low	cobble	coarse matrix	0.01
11	1768	RB	grass	moderate	cobble	fine matrix	-0.06
12	1436	LB	grass	moderate	silt	silt	-0.06
15	1254	RB	grass	high	cobble	silt	-0.06
16	1157	LB	bare	low	gravel	fine matrix	0.08
16-2	1103	LB	bare	low	silt	fine matrix	0.06
17	1091	RB	woody/grasses	moderate	cobble	silt	-0.01
21	773	RB	grass	low	cobble	silt	-0.02
24	577	RB	woody	moderate	gravel	silt	0.04
26	498	RB	grass	low	cobble	silt	0.02
27	353	LB	none	low	silt	silt	0.11

Generally, the stream banks on Upper Penitencia have more abundant perennial vegetation, but many of the unstable banks are devoid of vegetation, with only the roots from top bank trees providing reinforcement for the exposed alluvial debris flow deposits that compose the majority of the bank soils. The banks on Upper Penitencia Creek have more cobble and gravel material than Berryessa Creek. In many places this material serves to buttress the bank toe if bank erosion occurs. Much like Berryessa Creek, shifting trends of deposition (floodplain development) and erosion are seen along Upper Penitencia Creek. Banks in the downstream reaches (stations 1338 m and 645 m) are typically depositional, with overbank deposition prominent in the most downstream reaches. Erosion rates range from 0.01 m/yr to 0.21 m/yr. Reaches upstream of the historic subsidence axis (from river station 3000 m to 4750 m) exhibit bank instability and bank erosion is prevalent. This reach has erosion rates that average 0.16 m/yr. Upstream of this area the banks are generally stable, well vegetated and show minimal migration. Summary data for Upper Penitencia Creek are provided in Table 4.6.

Table 4.6 Stream bank summary data for Upper Penitencia Creek.

GCS	River Station (m)	Left or Right bank	Dominant Vegetation Type	Vegetation density (low, moderate, high)	Grain size at bank toe	Grain size upper bank	Failure rate (m/yr) (positive number indicates erosion)
4	5792	LB	woody/grasses	moderate	cobble	coarse matrix	0.01
8	5198	RB	woody/grasses	high	cobble	silt	-0.01
9	5054	RB	woody/bare	low	gravel/cobble	silt	0.03
12	4751	RB	bare/grasses	low	cobble	fine matrix	0.1
16	3590	LB	bare	low	cobble	silt	0.18
17	3102	LB	bare	low	cobble/gravel	fine matrix	0.21
18	2437	RB	bare/grasses	low	gravel	gravel matrix	0.1
21	1338	LB	woody/bare	low	gravel/cobble	fine matrix	-0.06
24	645	RB	grasses	moderate	gravel/cobble	silt	-0.02

4.7.2 BANK GEOMETRY AND STABILITY SURVEY

Due to time and expense constraints, it was not feasible to survey all of the bends with monumented cross sections. To supplement this data set, an additional field survey was conducted on both creeks where bank height and bank angles were measured for visually estimated stable and unstable bends. These field measurement were combined with the surveyed cross section data to plot bank angles and heights for bends that were qualitatively classified as stable, moderate, or unstable (Figure 4.18). This survey reveals some useful information concerning bank geometry and stability within this region. Generally, banks under 2.3 m in height and with bank angles less than 45 degrees were found to be stable. A survey such as this can be conducted in one day and can provide useful guidance to the design engineer for engineering bank protection measures.

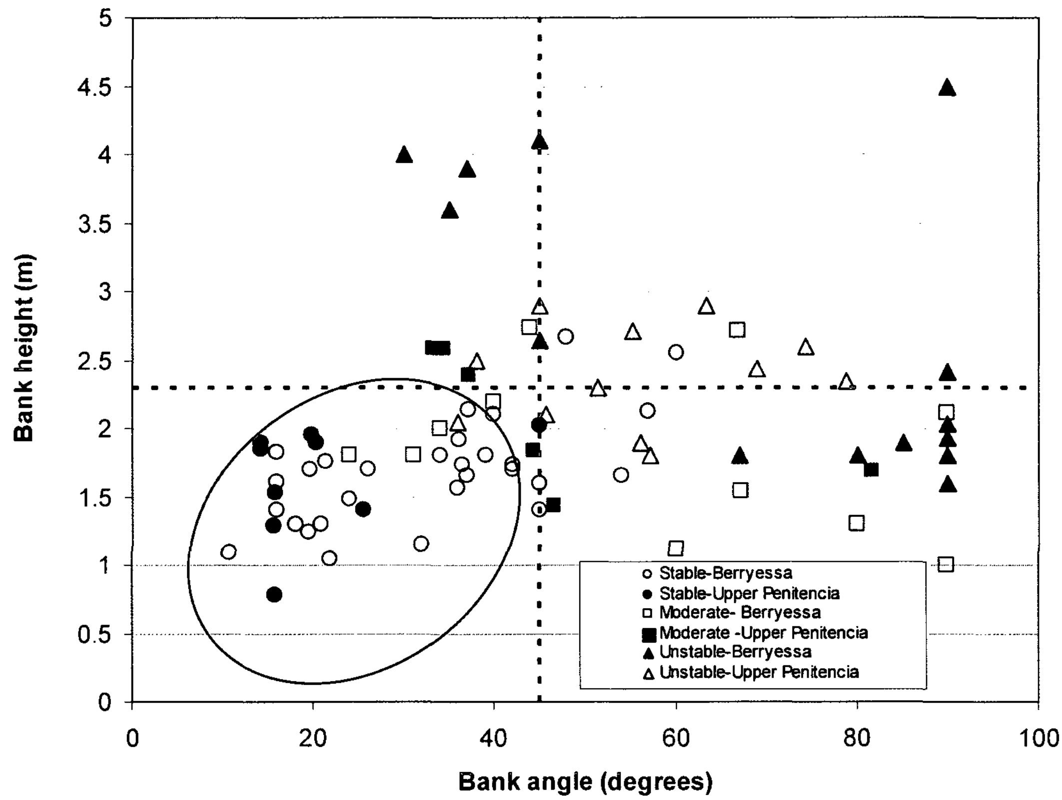


Figure 4.18 Measured bank heights and angles for stable and unstable bends.

The bank height ratio, defined as the lowest bank height divided by the maximum depth (Rosgen 2001), has been proposed as a measure of bank stability. This ratio is a measure of confinement of the bankfull channel in relation to the available floodplain. A ratio of 1 would indicate the occurrence of overbank flow at discharges exceeding the bankfull stage. This ratio is plotted as a function of bank angle (Figure 4.19) for the surveyed bends where the bankfull stage was identified in the cross section data collection efforts. These data indicate that both of these channels are incised within the historic alluvial fan present at the upland/ valley front. Generally, the streams do not have access to significant floodplains at the bankfull stage. The data indicate that bends can be stable within this confined channel as long as the bank angle is less than 45 degrees. At the steeper bank angles (>45 degrees) bends can be unstable regardless of floodplain accessibility to channel forming discharges. Natural lateral migration is present in bends with access to floodplains. Both geotechnical failure and bend migration due to hydraulic forces can take place when banks are steeper than 45 degrees.

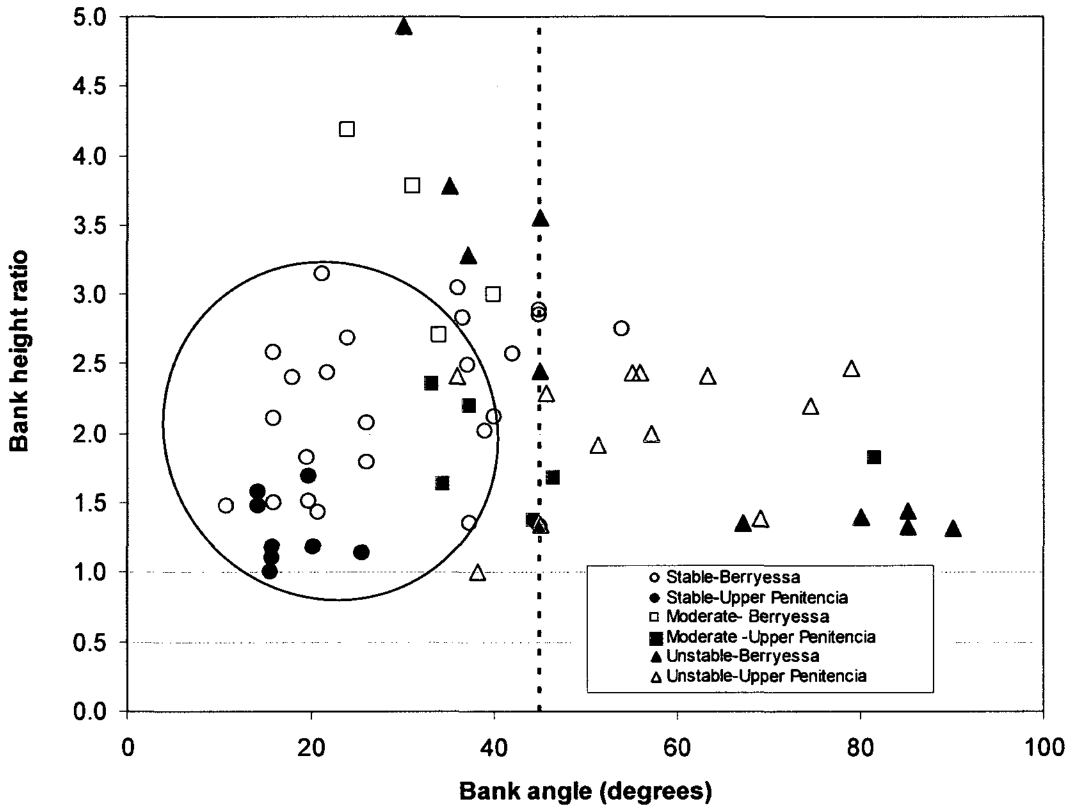


Figure 4.19 Bank height ratio as a function of bank angle for bends and incised stream banks on Berryessa and Upper Penitencia Creeks.

4.7.3 BANK ROD DATABASE

Bank rods (10-13 mm in diameter and 1.2 m in length) were installed in the winter season of 2004 on six bends on Berryessa Creek and 5 bends on Upper Penitencia Creek to measure rates of bank retreat. The bank rods were installed on actively eroding banks. These bank rods have been monitored and re-measured yearly through the summer of

2006. The length of bank rod left exposed was measured yearly and the bank rods were reset if a significant portion of the rod was left exposed after bank retreat. In some instances the exposed rod length was smaller than the previous year, indicating bank settling. Bank retreat rates ranged from 0 to 0.36 m/yr. These data were measured to supplement the bank retreat data from the time sequenced cross section data. The two data sources showed reasonable agreement on sites where both measurement techniques were used (Figures 4.20 and 4.21). The data from the bank rods predicted larger rates of bank retreat than the cross section data. Estimates from the cross section data incorporate an average rate for the entire bank, whereas the bank rod data represent localized measurements on the mid to upper bank region and don't account for the deposition of failed material at the bank toe. These data, in conjunction with the photo grid grain size analysis described in the next section, were utilized in the numerical modeling portion of the project to quantify sediment sources from bank erosion to the streams.

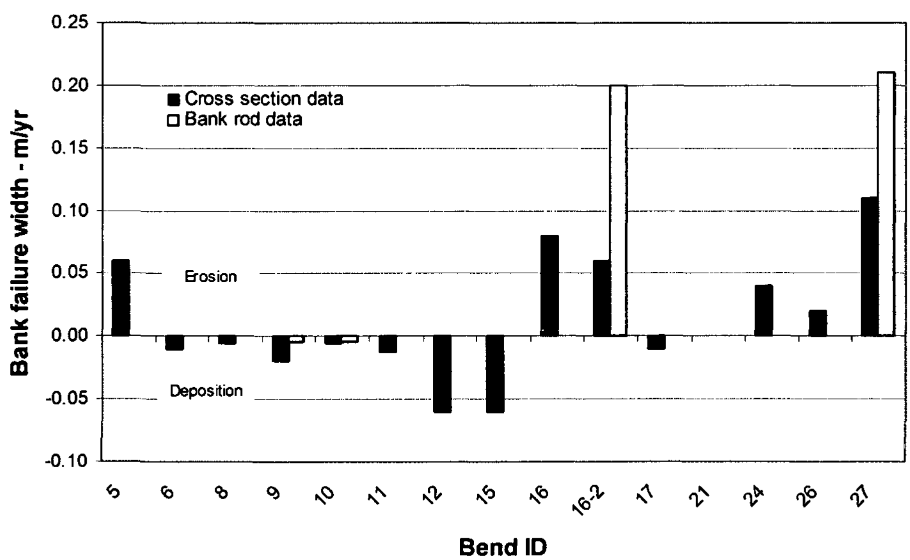


Figure 4.20 Bank rod and cross section measurements of bank retreat and deposition for Berryessa Creek.

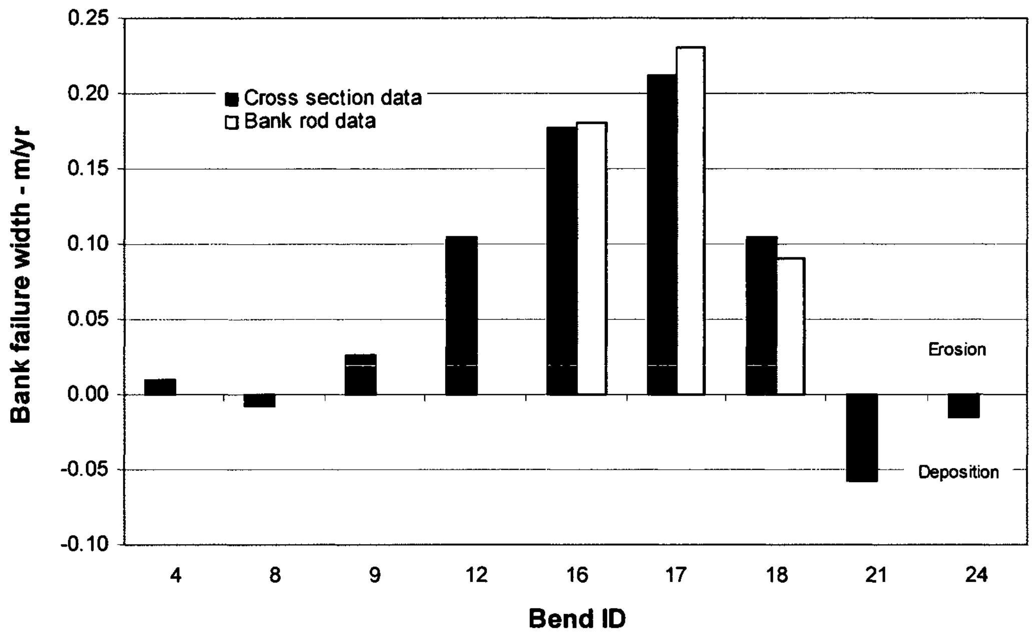


Figure 4.21 Bank rod and cross section measurements of bank retreat and deposition for Upper Penitencia Creek.

4.7.4 BANK-MATERIAL GRADATION

Bank materials in the two streams vary drastically between stratigraphic units. Many of the stream banks are composed of coarse alluvial fan deposits, with composition varying between poorly sorted unconsolidated alluvial debris flow deposits, road-fill base, to depositional alluvial silts (Figure 4.22). At sites where the bank material was fairly uniform and consisted of silts, sands, and small gravels, bulk samples were collected and analyzed for gradation via sieve analysis. At sites where the bank material gradation was too coarse to perform sieve analysis, a visual grid photograph analysis was conducted to estimate the bank material gradation (Figure 4.23). Bank grid photos were imported into AutoCAD and a pebble count analysis was conducted at each grid point. In some instances the bank materials were too small to estimate with this procedure. In these cases a generalized fine grained silt and sand grain size distribution was used for the gradation of the bank material. The resulting data were utilized in the sediment transport models to estimate the grain size distribution of sediment introduced into the system via bank failure. Grain size distributions for bank materials for Upper Penitencia Creek were generally coarser than Berryessa Creek. Deposition of coarse material at the toe of actively failing banks was observed in the field, particularly on Upper Penitencia Creek. This process results in natural bank toe stabilization by the coarse clasts introduced into the stream via bank failure (Figure 4.24). The implications of this process were not quantified but it is possible that this process aids in the stability of stream banks along Upper Penitencia Creek.

Figure 4.22 Stream bank on Berryessa Creek with bank-material gradation varying with stratigraphic unit.

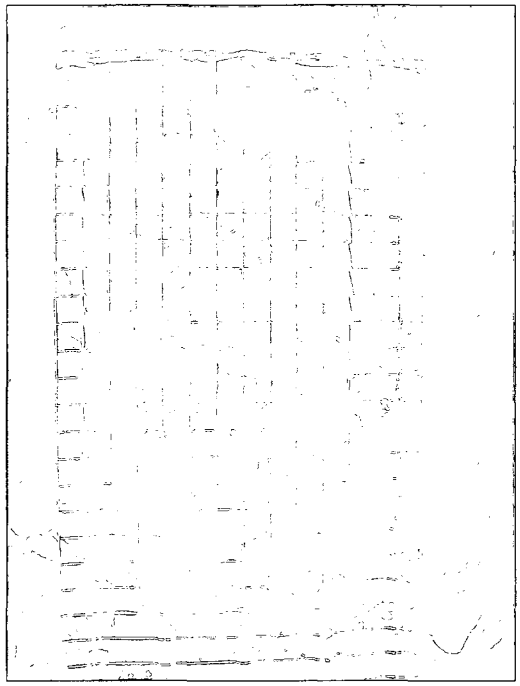


Figure 4.23 Photograph grid utilized to visually determine bank-material gradation.

Figure 4.24 Example of bank toe armoring by failed coarse bank material, Upper Penitencia Creek.

4.8 STREAMFLOW AND SEDIMENT TRANSPORT MEASUREMENT

According to Lane's (1955) relationship (Equation 4.2), the product of the slope and discharge are balanced by the product of the grain size and sediment discharge:

$$QS \propto d_s Q_s \qquad \text{Equation 4.2}$$

The relatively static parameters of slope (S) and bed-material grain size (d_s) are measured during the geomorphic survey. However, to assess channel stability the dynamic parameters, discharge (Q) and sediment discharge (Q_s), must be measured over time for a large range of flow events, from low flows and up to and exceeding bankfull conditions. The discharge and sediment transport rates were measured at several locations within the study reach to examine the effect of the storm sewer network on flow rate and duration, and the subsequent sediment transport from these alterations to the natural drainage network. A continuous stage recorder (15-minute intervals), coupled with a rating curve developed from flow measurements, was utilized to develop continuous flow-records for the wet season in water years 2005 and 2006. Both bedload and suspended load were measured to develop sediment rating curves at the gaging sites. Two gaging sites were monitored on Upper Penitencia Creek and three sites were monitored on Berryessa Creek. The gaging stations for Berryessa Creek were immediately upstream of the Piedmont Road crossing (river station 1750 m), the pedestrian bridge crossing (station 800 m), and the Hillview Avenue crossing, which is far downstream of the study reach. Only the Piedmont Road and pedestrian bridge data will be analyzed in this report. The gaging stations for Upper Penitencia Creek were located at the Piedmont Road crossing (station 4580 m) and the crossing near Berryessa Industrial Park (BIP) (station 10 m).

The suspended load was sampled with a USGS DH-59 depth-integrated suspended sediment sampler. Bedload transport were measured with a handheld 152 mm Helley-Smith sampler when the streams were wadeable, or a cable-suspended 152 mm Helley-Smith sampler for non-wadeable conditions. Bedload gradations were analyzed to gain insight into both the caliber and quantity of bed load transported at the measurement locations. Balance Hydrologics conducted the majority of this sampling effort, with support from CSU and SCVWD staff for select high flow events that were sampled to define the upper end of the rating curve. This was due to the short duration and unpredictable nature of the rainfall events as well as the distant geographic proximity of the investigator to the field sites. CSU staff worked in conjunction with Balance Hydrologics staff to select stream flow and sediment transport measurement locations.

Sediment rating curves were tabulated for all of the gaging locations. The curves were fit as power functions in the form of equation 4.3.

$$Q_s = aQ^b \qquad \text{Equation 4.3}$$

Where:

Q_s = Bedload or suspended load sediment discharge (metric tonnes/day)

Q = Water discharge (m^3/s)

a = regression coefficient

b = regression coefficient (exponent of water discharge)

These rating curves are presented in Figures 4.25, 4.26, 4.27, and 4.28. An additional rating curve was developed by synthesizing all of the measurements on the individual streams (Figure 4.29).

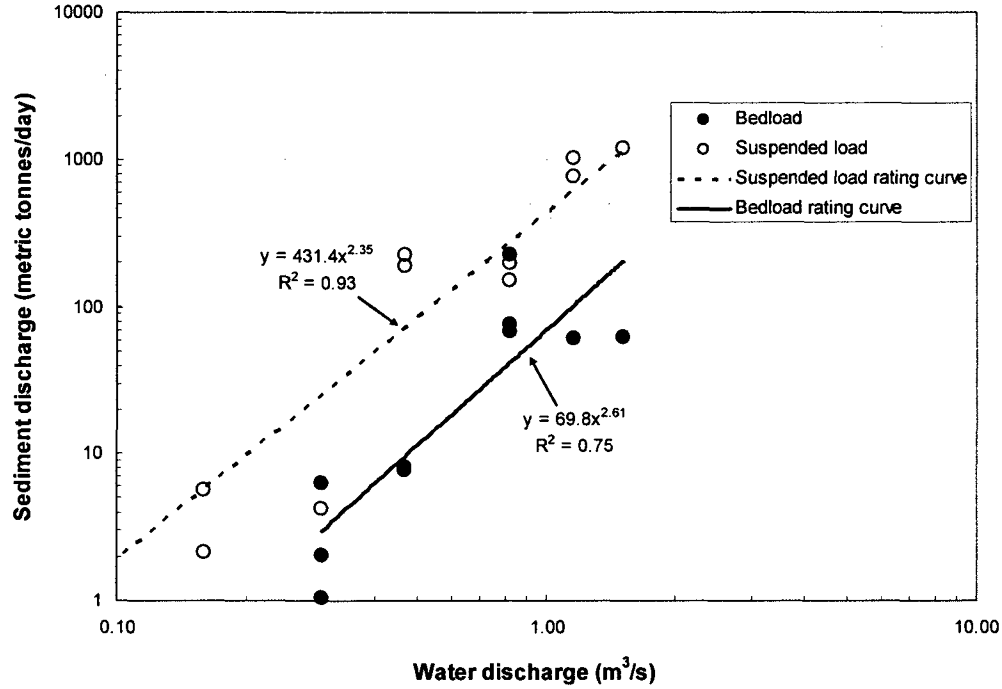


Figure 4.25 Sediment rating curve for Berryessa Creek upstream of the Piedmont Road crossing (river station 1750 m).

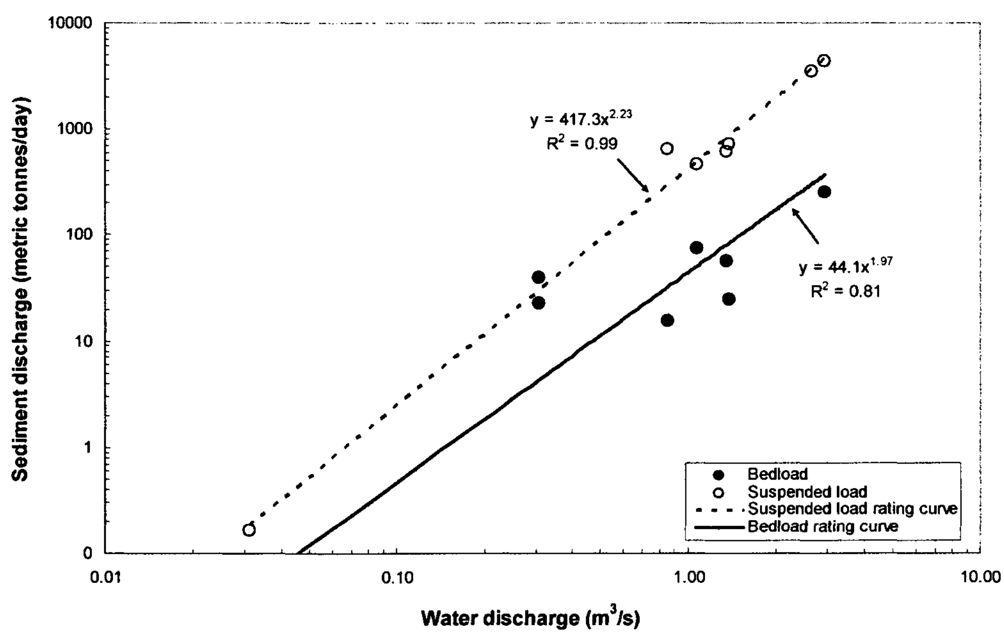


Figure 4.26 Sediment rating curve for Berryessa Creek near the pedestrian bridge crossing (river station 800 m).

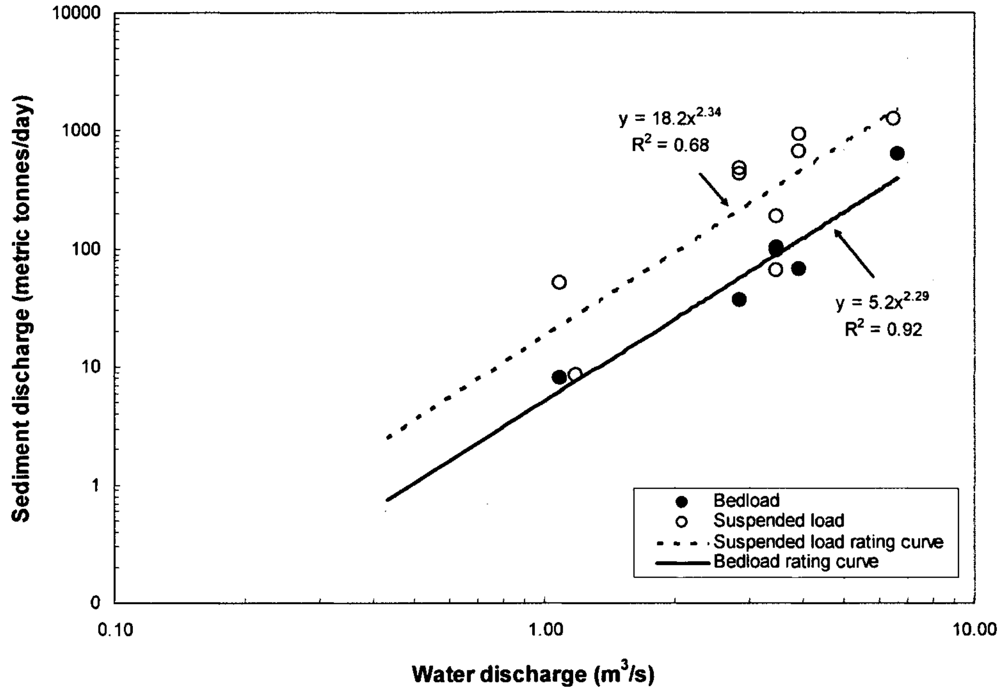


Figure 4.27 Sediment rating curve for Upper Penitencia Creek near the Piedmont Road crossing (river station 4508 m).

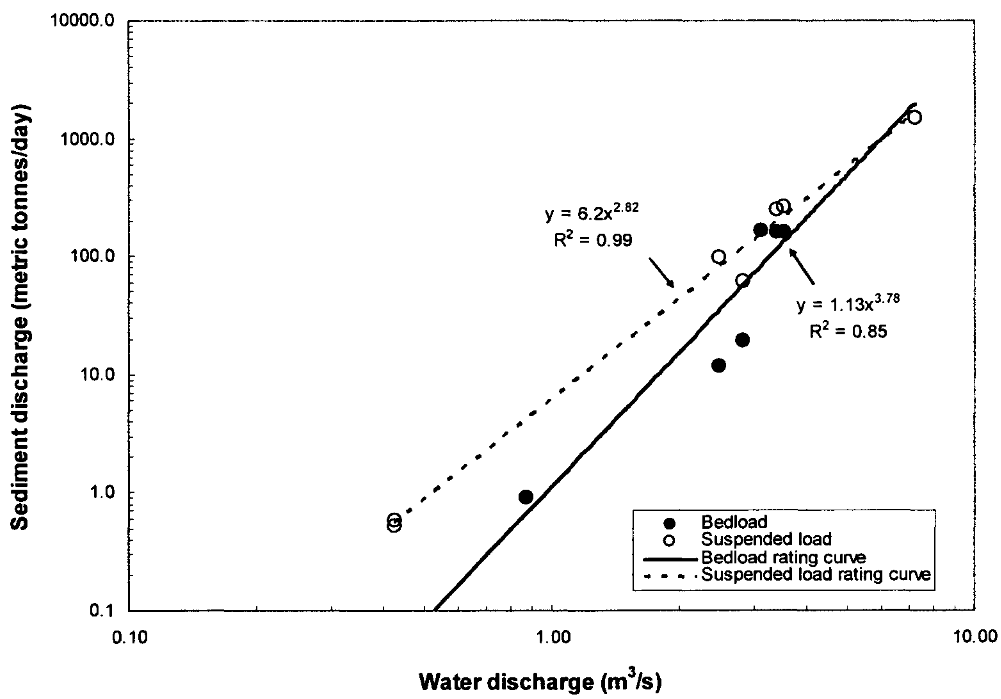


Figure 4.28 Sediment rating curve for Upper Penitencia Creek near the crossing near Berryessa Industrial Park (river station 10 m).

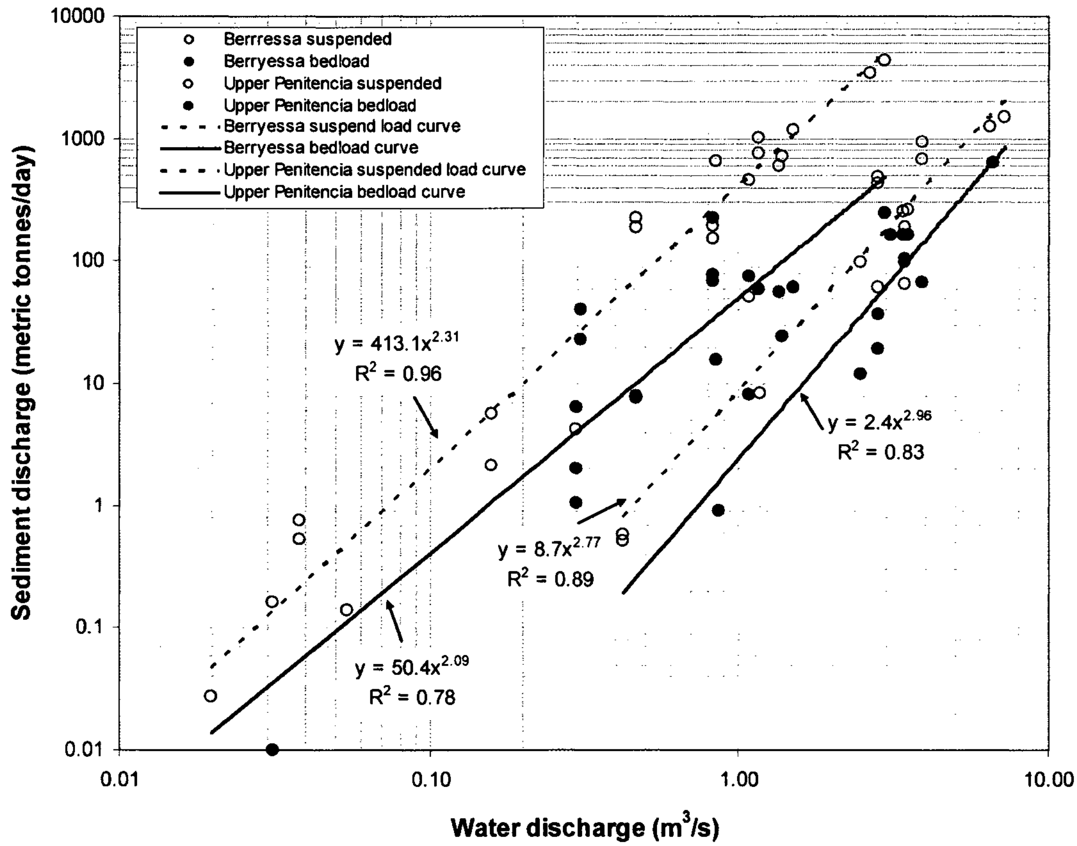


Figure 4.29 Sediment rating curves for all data on Berryessa Creek and Upper Penitencia Creek.

Examination of the regression coefficients provides valuable insight into both the sediment transport and sediment supply characteristics of both streams. A summary of the regression coefficients is presented in Table 4.7.

Table 4.7 Summary of the sediment rating curve regression coefficients for Berryessa Creek and Upper Penitencia Creek.

	Bedload			Suspended load		
Site	a	b	r^2	a	b	r^2
Berryessa at Piedmont	69.8	2.61	0.75	431.4	2.35	0.93
Berryessa at pedestrian bridge	44.1	1.97	0.81	417.3	2.23	0.99
Upper Penitencia at Piedmont	5.2	2.29	0.92	18.2	2.34	0.68
Upper Penitencia at BIP	1.13	3.78	0.85	6.2	2.82	0.99
All Berryessa	50.4	2.09	0.78	413.1	2.31	0.96
All Upper Penitencia	2.4	2.96	0.83	8.7	2.77	0.89

The leading regression coefficient in the rating curve equations (a) can be considered a relative estimate of the amount of sediment supplied to the system. The exponent regression coefficient in the equations is a relative estimate of the capacity of the streams to transport the given supply. Comparison of these coefficients for the streams being studied indicates that Berryessa Creek has a much larger amount of sediment supplied to the system compared to Upper Penitencia Creek. The suspended load coefficient for the Berryessa sites is 47 times larger than the Upper Penitencia sites and the bedload coefficient is 21 times larger. The upland reaches of Berryessa Creek contain many areas of landslide activity and colluvial sediment sources. These features are less prevalent in the upland reaches of Upper Penitencia Creek. The capacity coefficients (b) are greater for Upper Penitencia Creek. The bedload capacity coefficient is 41 % greater and the suspended load coefficient is 20% greater. These capacity coefficients (b) typically fall within the range of 2 to 3 (Leopold et al. 1964, Julien 1994). All of the measured data fit this range with the exception of the gaging site on Upper Penitencia Creek at BIP (3.92). This site is located in a highly incised engineered reach with severe urban encroachment, so the resulting higher exponent is logical due to the limited floodplain and simplified prismatic channel shape in this reach.

It was anticipated that the sediment supply coefficients (a) would decrease in the downstream longitudinal direction in these streams because the majority of the sediment (particularly in the suspended load size fraction) is produced in the upland watersheds. Examining the longitudinal trends in the sediment supply coefficients (a) shows that this trend is present, but the trend is much stronger for Upper Penitencia Creek. The bedload supply coefficient decreases 360% and the suspended load supply coefficient decreases

193% for Upper Penitencia from the upstream gaging station to the downstream gaging station. This indicates that local channel instability within valley is not supplying significant amounts of sediment to the downstream reaches and sediment storage is taking place. On Berryessa Creek the bedload supply coefficient decreases 58% and the suspended load supply coefficient only decreases 3% from the upstream gaging station to the downstream gaging station. This occurs in spite of the presence of a sedimentation basin between the two locations. The sediment basin traps mainly bedload, possibly explaining the larger decrease of this coefficient in comparison to the suspended load coefficient. The lack of a decrease in the supply coefficient indicates that localized channel instability within the valley readily supplies sediment to the downstream reaches, particularly in the finer grained suspended load fraction. This supply likely comes from failing stream banks because overland sources are minimal within the urbanized valley portion of the stream.

In addition to the preceding geomorphic interpretation of the sediment rating curve data, this study utilized the resulting sediment rating curves and gaging data for hydrologic analysis and modeling as well as a calibration tool for the sediment transport modeling.

4.9 STORM SEWER CULVERT INVENTORY

A storm sewer culvert inventory was conducted in the winter of 2005. The investigating author walked the entire study reach of both creeks and all storm sewer outfalls were located with GPS waypoints. Pertinent characteristics such as culvert diameter, culvert type and spatial location were noted in the inventory. This inventory was used to field-verify all culvert characteristics and locations used in the hydrologic modeling analysis.

4.10 SUMMARY OF FIELD DATA COLLECTION EFFORTS

The investigating author implemented a rigorous field data-collection program for both Berryessa Creek and Upper Penitencia Creek beginning in the summer of 2004. Three field seasons were completed. CSU and SCVWD staff have performed all the field work to date, with the exception of the continuous flow monitoring and sediment transport measurement, which was accomplished by teaming with Balance Hydrologics. CSU staff designed all survey, sampling, and measurement protocols. The field data-collection program consisted of:

- Preliminary field reconnaissance;
- Detailed initial longitudinal and cross section surveys;
- Repeated cross section and headcut migration surveys;
- Channel resistance estimates;
- Pebble count and bulk sampling bed material gradation analysis;
- Bank stratigraphy and vegetation composition surveys;
- Measurement of bank material gradation and shear stress characteristics;
- Bank rod installation and monitoring on unstable bends;
- Bank height and bank angle survey to assess bend stability characteristics;
- Continuous stream flow gaging;
- Bedload and suspended load sediment transport measurement; and a
- Culvert inventory of all storm sewer outfalls.

This dataset was used to provide geomorphic interpretation of the presently observed erosion and deposition processes observed through field observation. In addition the dataset provided the foundation for all numerical modeling exercises that will be discussed in the following two chapters. Field data collection is not glamorous or easy and post-processing of the data is an arduous task. Detailed notes, hundreds of spreadsheets and countless hours have brought about the final dataset that was collected in a relatively short time in the field (~7 weeks). The robustness and utility of a dataset of this breadth and scope provides a tremendous source of information in understanding the geomorphic and hydrologic processes occurring in these two streams.

In summary, the major findings of the field dataset are:

- Both streams presently show oscillation between cross section erosion and deposition along the longitudinal profile, with rates generally oscillating between +/- 0.05 m/yr.
- Berryessa Creek crosses the 0.05 m/yr threshold more frequently than Upper Penitencia Creek, indicating greater channel instability.
- Both streams have areas of channel instability, with the Upper Penitencia Creek instability being more localized and Berryessa Creek more system-wide.
- Definitive breaks in bed material gradation were observed along Berryessa Creek due to a sedimentation basin and local channel instability; Upper Penitencia Creek data showed a general downstream fining trend.

- Banks with heights less than 2.3 m and bank angles less than 45 degrees were typically stable, even within confined cross sections with minimal floodplain access.

- Bank rod and consecutive cross section survey data showed reasonable agreement on rates of unstable bank retreat, with the bank rod data generally showing higher rates.

- Inspection of measured sediment rating curves indicates a higher rate of sediment supply to Berryessa Creek, with supply remaining high from bed and bank sources due to channel instability within the urban valley portion of the watershed.

5.0 FLOW REGIME CHANGES DUE TO URBANIZATION FOR THE BERRYESSA AND UPPER PENITENCIA CREEK WATERSHEDS

5.1 INTRODUCTION

There are three processes that have led to flow regime change in the Berryessa and Upper Penitencia Creek watersheds.

1. An increase in impervious area in the valley portion of the watershed due to urban development and construction.
2. Increased connectivity and changes in the effective catchment area manipulation as a result of the constructed urban storm sewer network. This process led to an increase in the effective catchment area for Berryessa Creek and a decrease in the effective catchment area for Upper Penitencia Creek.
3. Flow diversion and retention due to percolation pond and detention basin construction on Upper Penitencia Creek to recharge groundwater tables and mitigate historic valley subsidence problems in the area.

These processes were modeled using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software (HEC 2001) for both basins to produce three hypothetical flow regimes for sediment transport modeling. The HEC-HMS hydrologic model is a lumped parameter, event-based model used to simulate precipitation-runoff processes in dendritic watershed systems (HEC 2001). HEC-HMS models were created for three scenarios for each stream to quantify the relative effects of drainage area modification, increased imperviousness due to urban infill and flow diversion to percolation ponds. The three simulated flow regimes are:

1. The historical flow regime without urbanization infill or storm sewer network manipulation of the effective drainage area.
2. The urbanized flow regime without the modification of drainage area or flow diversion due to the constructed storm water system.
3. An urbanized flow regime that accounts for both the increase in imperviousness of the drainage catchment, the manipulation of the natural or topographic catchment area by the constructed storm sewer network, and flow diversion to the constructed groundwater percolation ponds.

5.2 MODEL DEVELOPMENT

The methods used to simulate runoff processes in the HEC-HMS models are summarized in Table 5.1.

Table 5.1 Methods used HEC-HMS modeling.

Modeling process	Model method
Overland plane losses	Green-Ampt infiltration
Overland plane routing	Kinematic wave
Channel routing	Musingum-Cunge
Base flow estimates	Base flow recession curve

Input parameters for precipitation losses, overland plane routing, channel routing, and baseflow recession were obtained from field data, GIS topographic data, and regional soil survey data.

The upland areas of both streams are characterized by steep hill slopes consisting of clay loam to gravelly loam soils with moderate vegetation, and low infiltration rates (USDA 1974). The valley portion of both creeks is characterized by land surfaces with moderate to low relief sandy to gravelly loam soils with higher infiltration rates (USDA 1974).

Hillslope and upland channel metrics (slope and slope length) were quantified from GIS-based topographic data. Initial estimates for saturated hydraulic conductivity and wetting front suction were based on soil classification and literature values (Rawls et al. 1982) and the values were modified within the ranges specified in the literature as calibration parameters. Soil infiltration rates for upland soils ranged from 2 to 8 mm/hr for Berryessa and 3-10 mm/hr for Upper Penitencia. The Upper Penitencia rates were typically higher reflecting the more permeable soils in this watershed as well as the effects of increased vegetation density in the upland areas. The valley soils are better drained for both watersheds and an infiltration rate of 13 mm/hr was typically used for both watersheds in the valley area. Antecedent moisture conditions to estimate initial losses, soil suction and soil moisture deficit were also modified within reasonable bounds as calibration parameters to fit observed precipitation and resulting discharge measurements.

The changes in imperviousness and effective catchment area were previously discussed and quantified in the aerial photograph and topographic map morphometric time series analysis and are summarized in Table 3.4. The hydrologic models utilized the final urbanized state in the 2002 aerial photograph as the urbanized condition and the historic catchment circa 1940 was used for the historic condition. A GIS database was available to represent storm sewer network pipe sizes, outfall locations, and pipe run lengths. All storm sewer outfall locations were verified by field investigation and mapping. Flow diversions were only present on Upper Penitencia Creek. The location and geometric configuration of these diversions were also mapped during field reconnaissance. The effects of urbanization were modeled with an imperviousness factor determined for each sub-watershed via aerial photograph GIS analysis.

The sub-basin delineation for HEC-HMS was completed by analyzing the significant changes in drainage patterns and topography for the upland areas as well as capturing all of the urban sub-basins delivering water to the stream from storm sewers within the urban areas. A summary of the sub-basin discretization is provided in Table 5.2. Changes in the valley catchment size reflect the alteration in drainage area resulting from the storm sewer network. The alteration in the size of the Berryessa Creek upland catchment results from the capture of adjacent historic alluvial fan upland watersheds by the storm sewer network that were previously not in direct hydraulic connection to the main stem of Berryessa Creek.

Table 5.2 Summary of the sub-basin delineation for the HEC-HMS models.

Stream	Historic sub-basins	Current sub-basins	Valley catchment area (km^2)	Upland catchment area (km^2)
Berryessa	9	16	0.9-1.9	12.1-13.6
Upper Penitencia	21	35	4.7-6.8	56.9

5.3 MODEL CALIBRATION

Both streams can be characterized as having an upland portion in the steep topography of the Diablo Mountains and a valley portion in the presently urbanized alluvial flat. The time series morphometric analysis showed little to no urbanization in the upland areas of both watersheds. Therefore, the assumption was made that the presently observed hydrographs at the upland/valley interface are relatively unaffected by the urbanization process and if they are calibrated to existing storm data, the urbanization effects on the hydrograph along the valley portion can be simulated with HEC-HMS modeling.

Stream gaging data at 15-min intervals were available for both streams for water years 2005 and 2006 at the upland valley interface. Fifteen minute rainfall data were also available for both sites, enabling hydrologic simulation of the upland drainage area of both streams. Six storms were selected for each stream and the HEC-HMS simulated runoff peak and volume from the upland drainage was calibrated to the observed hydrographs (Figures 5.1-5.2). Due to varying rainfall patterns and runoff response, four of the storms that were represented were common to both creeks during the calibration process. Summary statistics of the observed hydrographs and rainfall for these storms are provided in Table 5.3. The storms produced flows ranging from 25% to 310% of bankfull discharge calculated from velocity area method and the field-observed bankfull stage.

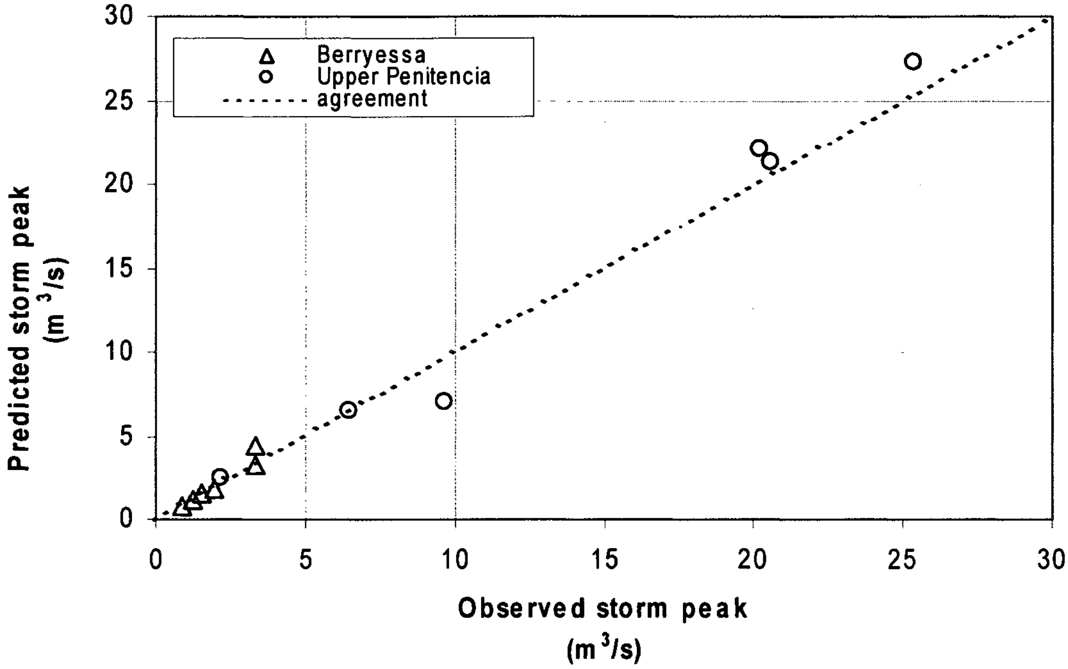


Figure 5.1 Predicted vs. observed storm peak for calibration storms.

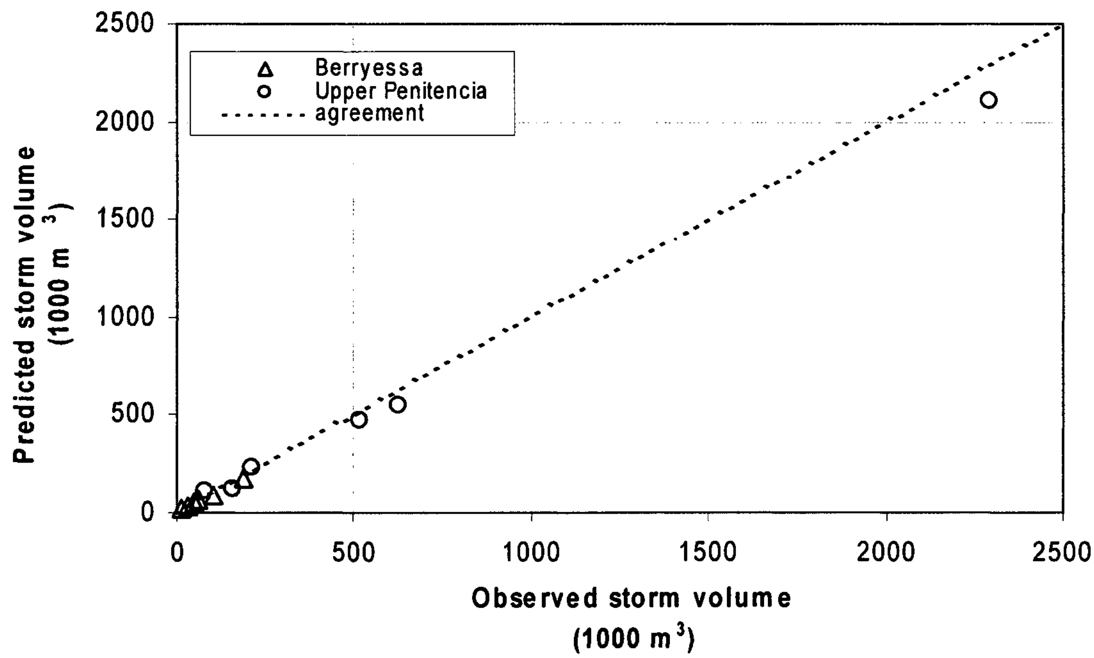


Figure 5.2 Predicted vs. observed storm volume for calibration storms.

Table 5.3 **Summary statistics for calibration storms common to both streams.**

Storm date	Rainfall (mm)	Berryessa Flood peak (m^3/s)	Berryessa Flood volume (1000 m^3)	Upper Penitencia Flood peak (m^3/s)	Upper Penitencia Flood volume (1000 m^3)
14-Feb-05	42	1.6	104	6.5	212
14-Jan-06	23	0.9	14	2.2	156
25-Mar-06	33	3.4	51	20.6	518
4-Apr-06	51	3.3	188	25.4	2293

With the knowledge that the HEC-HMS models were producing storm peaks and volumes similar to those observed in the field, the same storms with the same upland characteristics can be run for the other two scenarios modeled; 1.) The unaltered topographic catchment with the urbanization increase in imperviousness in the valley portion of the catchment, and 2.) The current urban drainage catchment with drainage area modification and flow diversion modification by the constructed storm sewer network and off-channel percolation ponds. These modeling runs will elucidate the changes in the historic flow regime incurred due to the multi-faceted urbanization process in both catchments.

5.4 QUANTIFICATION OF FLOW REGIME CHANGES

5.4.1 BERRYESSA CREEK

The changes in the hydrologic regime in Berryessa Creek (Figure 5.3) can be summarized by two processes: 1.) Urbanization infill and subsequent increases in impervious area and, 2.) Drainage area capture via the storm sewer network of land areas that were not previously hydraulically connected to the trunk stream. The result of the first process is a net increase of 14% in urbanized land use for the entire watershed and a 50% increase in impervious area in the valley portion of the watershed where the urbanized land use has increased to 85%. The result of the second process is a 20% net increase in the effective catchment area through time and a 120% increase in effective catchment area along the urbanized valley floor. These changes in land use and effective drainage area should manifest in higher peak flows and flood volumes. The expected changes in storm runoff characteristics were quantified in the HEC-HMS modeling efforts previously described.

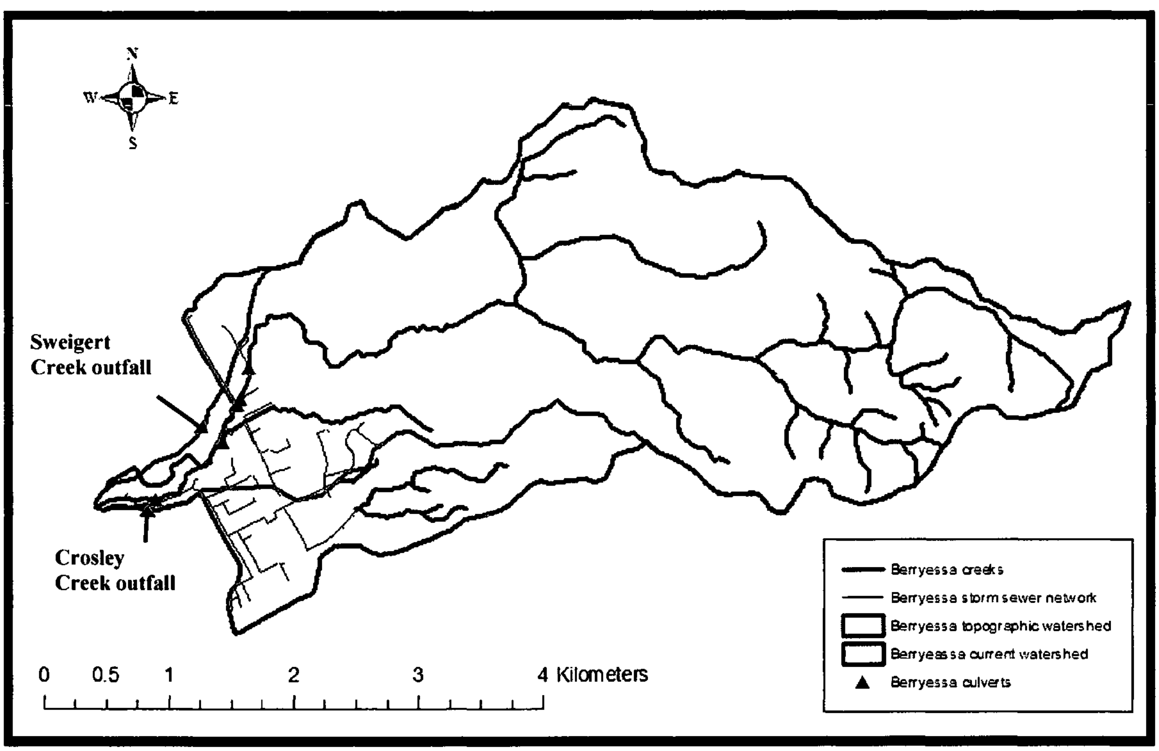


Figure 5.3 Berryessa Creek current (effective) catchment and historic (topographic) catchment.

The changes in the calibration storm peaks and volumes (Table 5.4) are summarized at two locations in the watershed. The first location is downstream of the Sweigert Creek storm sewer outfall, which lies within the historic topographic catchment but lacked direct connectivity historically as the flood waters from Sweigert Creek would spill on to the alluvial fan terminus and typically infiltrate the valley alluvium before reaching Berryessa Creek. Presently this drainage does have direct hydrologic and hydraulic connectivity to Berryessa Creek via the constructed storm sewer network. The second location where the storm runoff hydrograph changes were quantified is downstream of the Crosley Creek culvert outfall. The Crosley Creek drainage does not lie within the historic topographic catchment of Berryessa Creek. However, the present storm sewer network does capture both the upland and valley portions of this drainage and delivers the flow to the lower end of the Berryessa Creek study area. This is termed the outlet in Table 5.4. In this table the non-urbanized historic catchment is termed "historic", the topographic catchment area with urban infill is termed "topographic catchment urbanized" and the present effective catchment that accounts for the basin capture from the storm sewer network as well as the urban impervious land use change is termed "current catchment urbanized".

Table 5.4 Summary of flood peaks and volumes for six calibration storms on Berryessa Creek accounting for increases in impervious area and drainage area capture.

Downstream of Sweigert Creek outfall	Historic		Topographic catchment urbanized				Current (Effective) catchment urbanized			
Storm	Peak (m^3/s)	Volume (1000 m^3)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)
14-Feb-05	1.7	97	1.8	113	11%	17%	1.8	116	10%	20%
27-Feb-05	1.3	37	1.7	44	31%	20%	1.8	44	34%	19%
14-Jan-06	0.8	22	1.0	30	23%	36%	1.1	31	25%	39%
21-Mar-06	1.9	70	2.1	80	11%	14%	2.1	83	13%	18%
25-Mar-06	3.3	55	3.8	63	14%	15%	3.9	66	16%	20%
4-Apr-06	4.5	182	4.7	193	6%	6%	5.1	197	15%	9%

Outlet	Historic		Topographic catchment urbanized				Current (Effective) catchment urbanized			
Storm	Peak (m^3/s)	Volume (1000 m^3)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)
14-Feb-05	1.7	100	1.9	118	12%	19%	2.4	162	43%	62%
27-Feb-05	1.4	39	1.8	47	35%	21%	4.1	69	201%	79%
14-Jan-06	0.8	22	1.1	31	25%	42%	1.5	48	73%	114%
21-Mar-06	1.9	70	2.1	81	13%	16%	2.7	108	45%	54%
25-Mar-06	3.3	55	3.8	64	16%	18%	5.1	87	53%	59%
4-Apr-06	4.5	181	4.8	194	7%	7%	6.5	229	46%	26%

If we compare the two urbanized scenarios, one with the topographic catchment and one with the effective catchment created by the storm sewer network, the magnification effects on flood peaks and volumes due to the current storm sewer network are most pronounced at the downstream outlet below the Crosley Creek storm sewer outfall (Table 5.5). At this location a net increase of 47% for the flood peak and a 37% increase for the flood volume are quantified. These increases account for both drainage area capture and increased connectivity due to the urban infrastructure. The magnification effects are smaller for the reach below the Sweigert Creek outfall because the Sweigert Creek drainage does lie within the historical topographic drainage; therefore, most of the increase is a result of increased hydrologic connectivity and efficiency facilitated by the storm sewer network.

Table 5.5 Summary of flood peak and volume for the urbanized topographic drainage area and current urbanized drainage area on Berryessa Creek.

	Topographic catchment urbanized		Current (Effective) catchment urbanized			
	Average increase in flood peak	Average increase in flood volume	Average increase in flood peak	Average increase in flood volume	Net increase in flood peak due to drainage area capture	Net increase in flood volume due to drainage area capture
Sweigert Creek outfall	16%	18%	19%	21%	3%	2%
Crosley Creek outfall	18%	20%	77%	66%	47%	37%

Flow duration relationships for the three scenarios were calculated for the reaches downstream of the Sweigert Creek and Crosley Creek outfalls (Figures 5.4 and 5.5). The flow duration curves show similar results with regard to the effects of the storm sewer network at Sweigert Creek; at this location most of the flood peak and volume magnification can be attributed to the increase in impervious area rather than the effect of the storm sewer network. The Crosley Creek curve accounts for both processes. The changes in water yield due to urbanization were computed from the flow duration relationships. Results of this analysis are provided in Table 5.6. These calculations show a 48% increase in water yield at the downstream outlet due to drainage area capture and urban land use change, compared to only a 13% increase in water yield due to urban land use change alone.

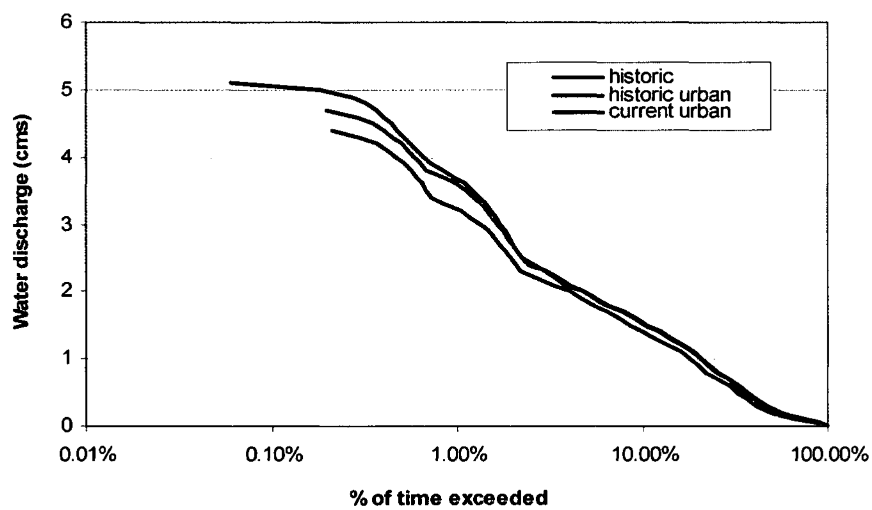


Figure 5.4 Flow duration curve for Berryessa Creek below the Sweigert Creek storm sewer outfall.

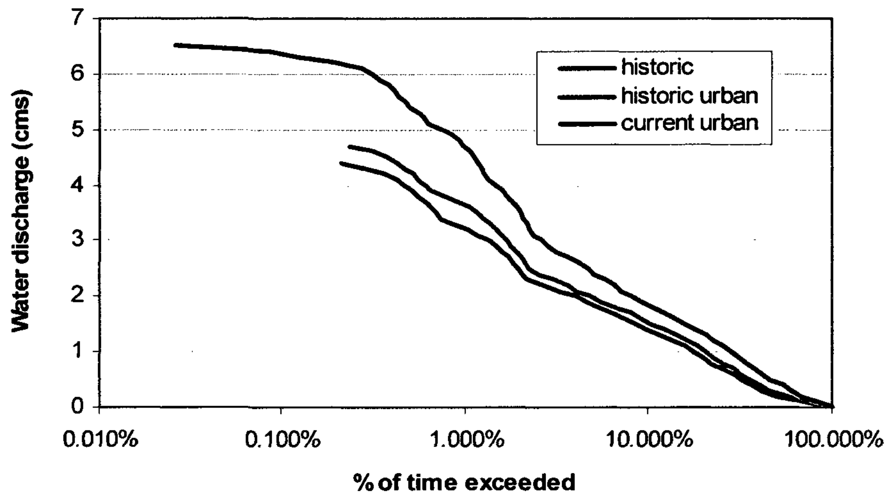


Figure 5.5 Flow duration curve for Berryessa Creek below the Crosley Creek storm sewer outfall.

Table 5.6 Changes in water yield due to urbanization and effective catchment area changes on Berryessa Creek.

	Water Yield from modeled storms (1000 m³)/km²				
Location	Natural historic conditions	Topographic catchment urbanized	Current(effective catchment) urbanized	Increase in water yield due to urban land used change	Increase in water yield due to urban land use change and drainage area capture
Downstream of Sweigert Creek	31.1	34.6	35.5	11%	14%
Outlet downstream of Crosley Creek	31.2	35.3	46.1	13%	48%

The storm hydrographs for the urbanized watershed exhibit flashy peaks that closely follow the rainfall hyetograph due to the impervious surfaces and direct connectivity to the storm sewer network (Figure 5.6) resulting in multiple peaks for a flood event that would historically have one well-defined runoff peak. This is particularly prevalent for storm events with relatively small flood peaks (< bankfull discharge). Multiple peaks are produced primarily as a result of the impervious urban portions of the drainage network that have efficient routing to the main channel as a result of the storm sewer network.

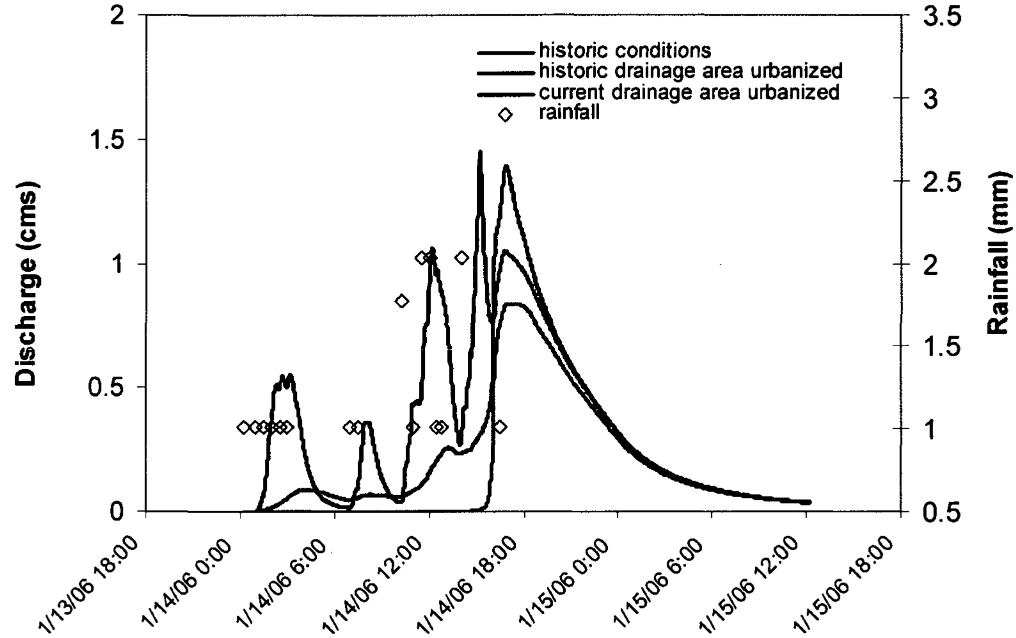


Figure 5.6 Simulated runoff below the Crosley Creek outfall on Berryessa Creek for a storm occurring January 14, 2006.

Inspecting the relationship of flood peak and volume as a function of discharge illustrates this process (Figures 5.7 and 5.8). Flood volumes and peaks are increased at a greater rate for the smaller storms. This finding is in agreement with the findings of previous researchers (Leopold 1973, Hollis 1975). Flood volumes show a stronger trend than flood peak. It would be expected that the sediment transport capacity for the valley reaches under the current urbanized effective catchment scenario would also be increased if the resulting peaks are large enough to mobilize the bed material. This will be investigated in the following chapter.

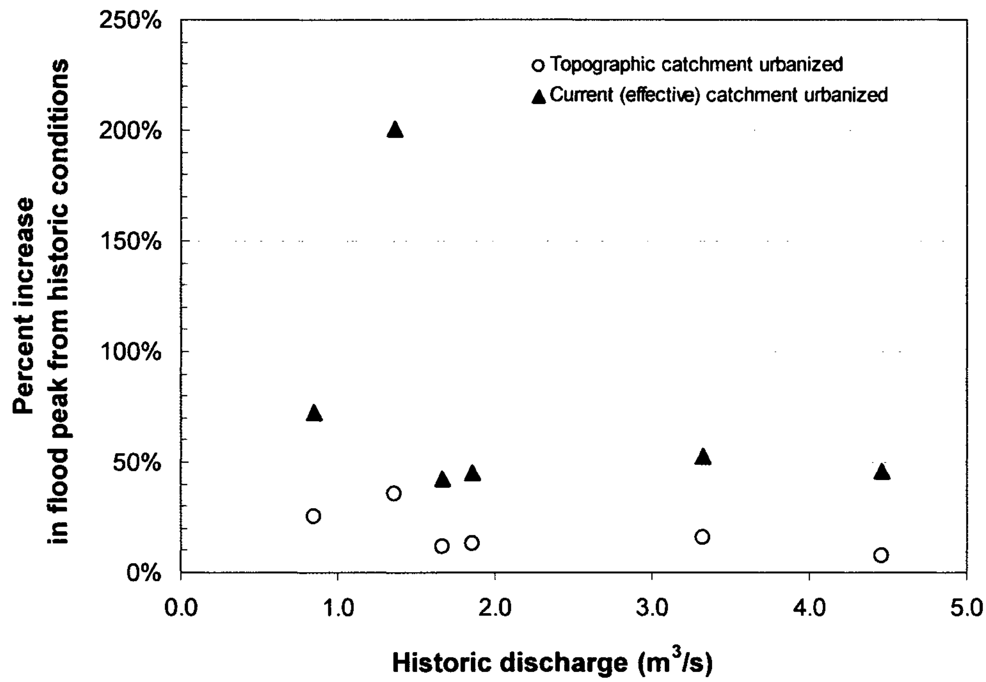


Figure 5.7 Percent increase in flood peak as function of discharge for Berryessa Creek below the Crosley storm sewer outfall.

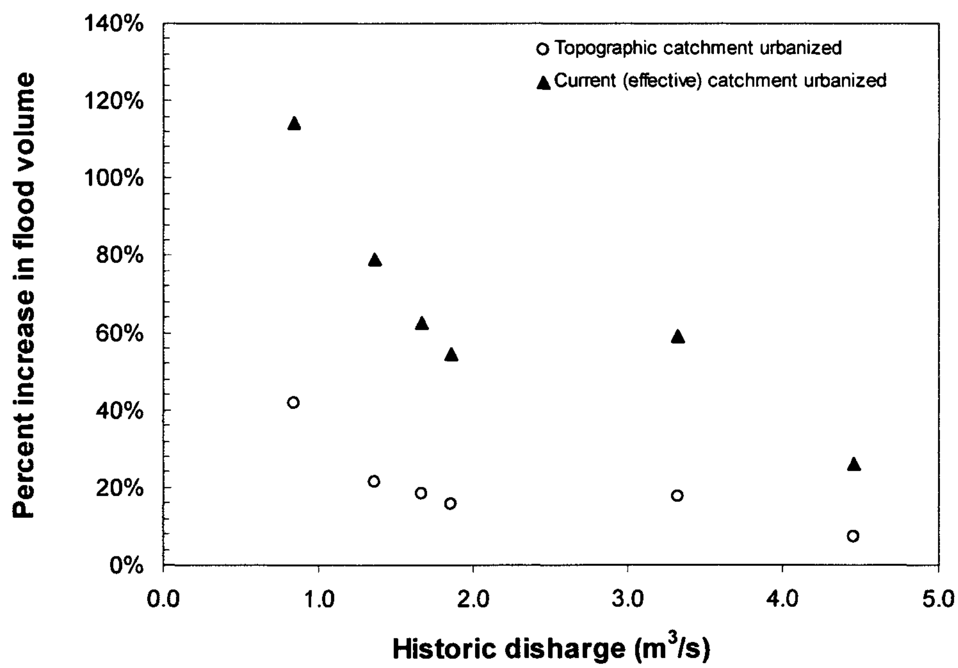


Figure 5.8 Percent increase in flood volume as function of discharge for Berryessa Creek below the Crosley storm sewer outfall.

5.4.2 UPPER PENITENCIA CREEK

Urbanization has affected Upper Penitencia Creek differently from Berryessa Creek. Although both streams have experienced an increase in impervious area, the valley portion of Upper Penitencia Creek is 76% urbanized and the entire catchment is 7% urbanized. The effective catchment area of Upper Penitencia Creek (Figure 5.9) has been reduced due to the storm sewer network. The effective catchment in the valley has been reduced 29% and the total reduction in catchment area due to storm sewer network development is 3%. Additionally, percolation ponds were constructed adjacent to the creek to mitigate groundwater withdrawal and valley subsidence. Water is transferred to these off-channel reservoirs by diversion structures, the result being reduced peak flows and volumes downstream of the diversion. Therefore, there are opposing tendencies altering the flow regime in Upper Penitencia Creek. 1.) Increased imperviousness and hydraulic connectivity from the urbanized valley infill and infrastructure and 2.) Flow diversion and reduction of the topographic drainage catchment. The net result of these processes was quantified in the HEC-HMS analysis. The simulated hydrographs were analyzed at two gaging locations on Upper Penitencia Creek (Figure 5.9).

1. The Piedmont Road gage (river station 4580 m) located downstream from the most prominent flow diversion structure and;
2. The Berryessa Industrial Park gage (river station 10 m) located near the watershed outlet to Coyote Creek.

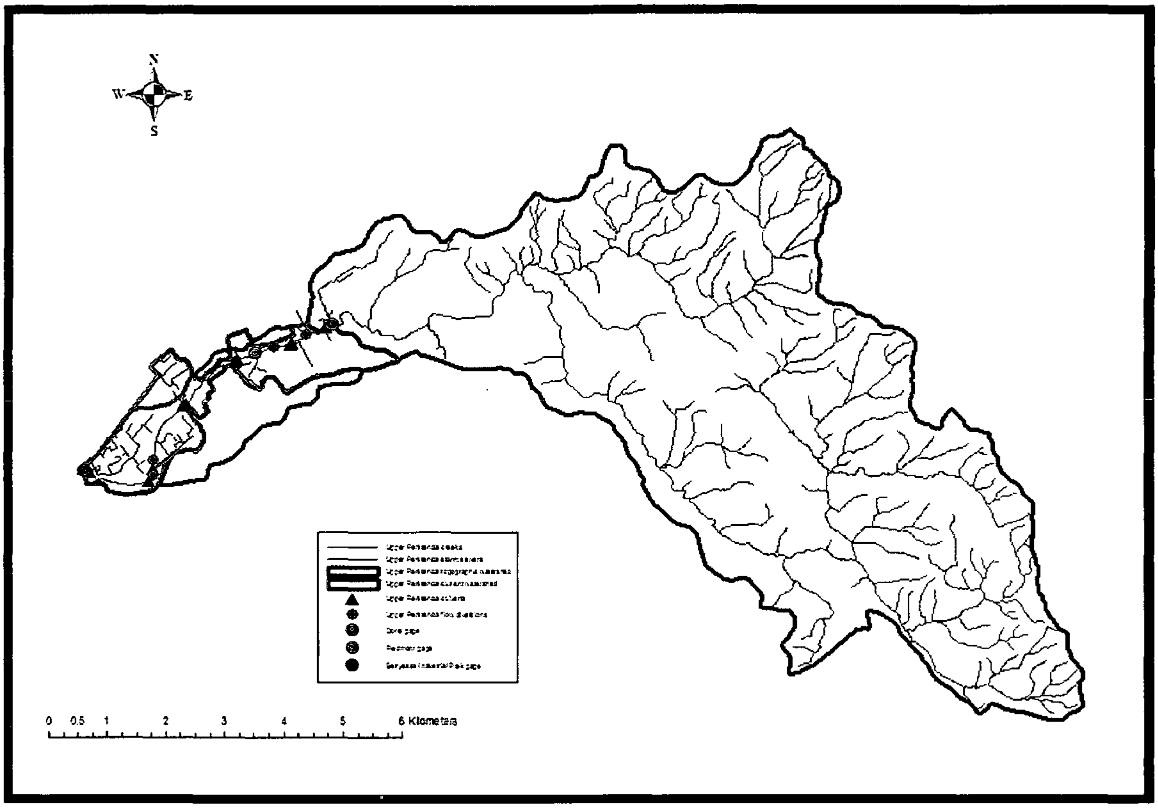


Figure 5.9 Upper Penitencia Creek current (effective) catchment and historic (topographic) catchment.

Measured storm events were analyzed at the Dorel Road and Piedmont Road gaging locations to quantify an average flow percentage that was diverted upstream of the Piedmont gage and a threshold flow when flow diversion could be expected to occur. The Dorel gage is located at the mountain/valley interface, where flow regimes have not significantly changed from historic conditions. Figure 5.10 illustrates an example of measured flow data from a storm on March 25, 2006 where flow diversion took place. The results of this analysis indicated that approximately 25% of the total storm volume over a threshold value of 2 m^3/s could be expected to be diverted into the percolation ponds; this was incorporated into the hydrologic modeling. Diversion structures located near Mabury Avenue, which is approximately 3.5 km downstream, were operated in a different manner. At this location a small portion (~ 0.03 m^3/s) of the wet season base flow was diverted with no effect on the larger storm events.

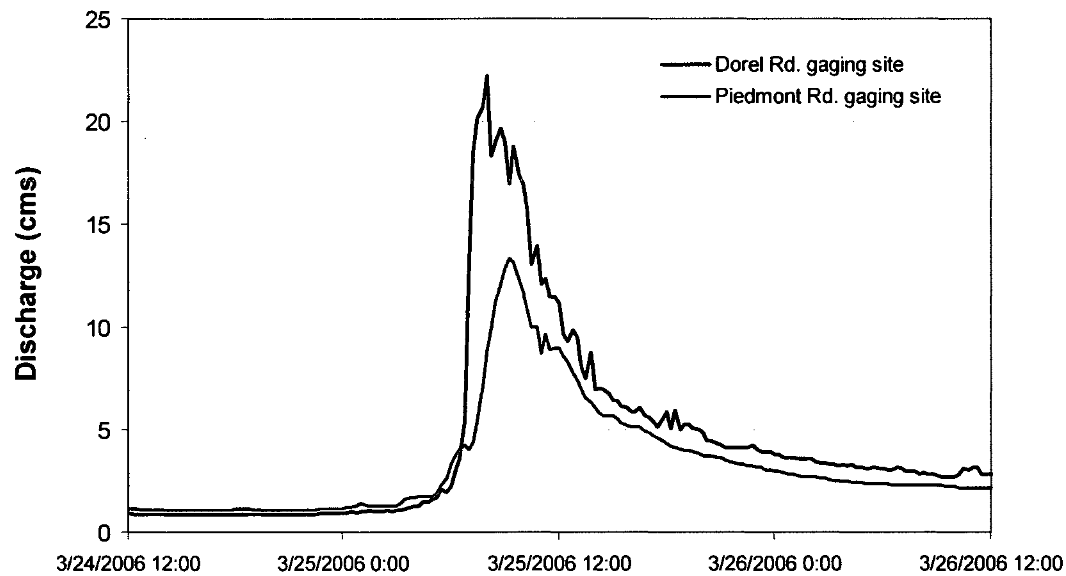


Figure 5.10 Hydrographs for the Dorel and Piedmont gaging locations during a March 25, 2006 storm event.

The reduced peaks and volumes are augmented by runoff generated from the urbanized valley floor. By the time the flood wave arrives at the Berryessa Industrial Park gaging site located 6 km downstream, peak flows are slightly smaller than those measured at the Dorel Road gage upstream (Figure 5.11). This data also indicates that the smaller tertiary peak of the hydrograph was amplified at this location. This magnification can be attributed to a short intense burst of rainfall and the efficiency of the urban landscape and storm sewer network in delivering the runoff from the impervious surface to the gaging location. Therefore the response of the hydrograph attenuation or amplification at the downstream outlet can be expected to vary as a function of storm rainfall duration, intensity and volume.

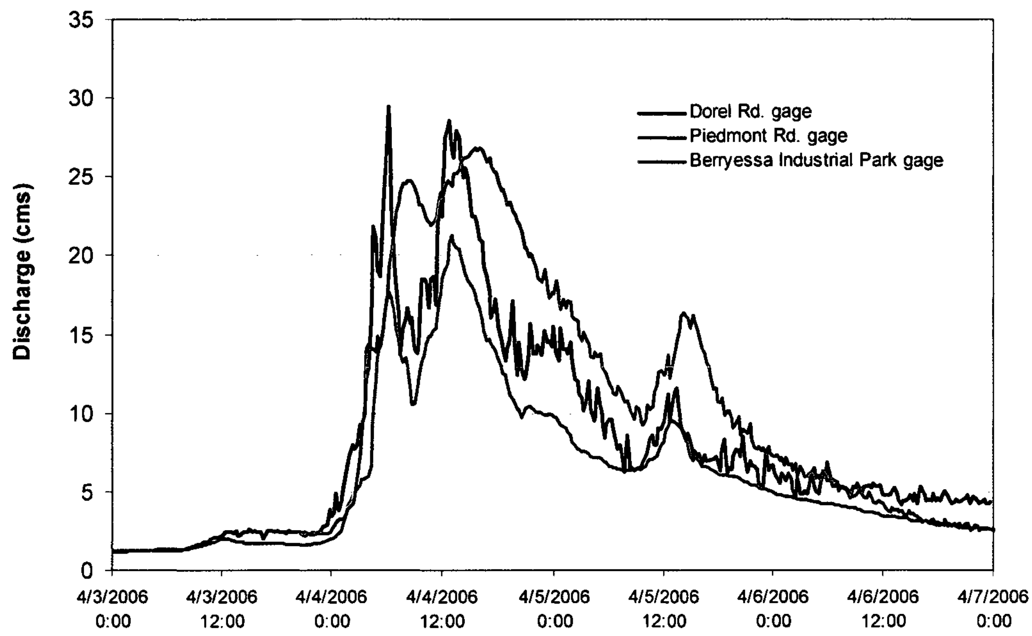


Figure 5.11 Hydrographs for the Dorel, Piedmont, and Berryessa Industrial Park gaging stations for a storm occurring April 4, 2006.

Six storms were simulated using the HEC-HMS modeling procedure described previously. The results of these simulations are summarized in Table 5.7 and 5.8. When analyzing the data in Table 5.7, the small storm on January 14, 2006 was excluded from the summary analysis provided in Table 5.8 because the size of this storm did not reflect the hydrologic regime simulated for the larger channel-forming events. The results from this small outlier would skew the results from the storms that transport the greatest amount of sediment and are responsible for the resulting channel form. The field estimate of bankfull discharge on this stream was approximately 8 m^3/s, the January 14, 2006 storm was approximately 30% of the bankfull discharge.

Model results indicate that given the current urbanized land cover, trans-basin storm-water diversion and flood flow diversion to off-channel groundwater percolation ponds have resulted in a 23% net decrease in the storm peak and a 19% net decrease in storm volume, when compared to the topographic drainage network with no flow diversion. The current drainage network results in a 12% decrease in storm peak and only a 9% increase in storm volume when compared to the non-urbanized historical drainage network. This is in contrast to the scenario on Berryessa Creek, where the constructed storm sewer network has resulted in both flood peak and volume magnification when compared to the urbanized topographic drainage area scenario.

Table 5.7 Summary of flood peaks and volumes for six calibration storms on Upper Penitencia Creek accounting for increases in impervious area, drainage area reduction and flow diversion.

Piedmont gage	Historic		Topographic catchment urbanized				Current (Effective) catchment urbanized			
Storm	Peak (m^3/s)	Volume (1000 m^3)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)
30-Dec-04	7.0	104	7.2	120	3%	16%	5.4	106	-22%	2%
14-Feb-05	6.6	255	6.8	296	3%	16%	5.4	296	-19%	16%
2-Jan-06	24.8	643	25.6	659	3%	3%	19.7	568	-21%	-12%
14-Jan-06	2.3	127	2.6	137	10%	8%	1.9	153	-20%	20%
25-Mar-06	21.5	475	22.4	494	4%	4%	17.1	387	-20%	-19%
4-Apr-06	27.4	2156	27.8	2199	1%	2%	20.8	1719	-24%	-20%

Outlet	Historic		Topographic catchment urbanized				Current (Effective) catchment urbanized			
Storm	Peak (m^3/s)	Volume (1000 m^3)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)	Peak (m^3/s)	Volume (1000 m^3)	Peak change from historic condition (%)	Volume change from historic condition (%)
30-Dec-04	7.4	123	9.0	181	22%	47%	6.0	145	-19%	18%
14-Feb-05	7.0	354	8.7	541	23%	53%	6.6	504	-7%	43%
2-Jan-06	24.8	809	27.2	933	10%	15%	22.8	832	-8%	3%
14-Jan-06	2.4	158	3.1	213	31%	35%	4.1	230	72%	46%
25-Mar-06	22.1	501	25.1	612	14%	22%	20.3	477	-8%	-5%
4-Apr-06	27.7	2288	29.3	2521	6%	10%	22.7	1983	-18%	-13%

Table 5.8 Summary of flood peak and volume for the urbanized topographic drainage area and current urbanized drainage area on Upper Penitencia Creek.

	Topographic catchment urbanized		Current (effective) catchment urbanized			
	Average increase in flood peak	Average increase in flood volume	Average increase in flood peak	Average increase in flood volume	Net change in flood peak due to drainage area reduction and flow diversion	Net change in flood volume due to drainage area reduction and flow diversion
Piedmont Road gage	4%	8%	-21%	-2%	-24%	-9%
Berryessa Industrial Park gage	15%	29%	-12%	9%	-23%	-19%

Flow duration curves for the six storm events were calculated for the three modeled scenarios at the Piedmont Road and Berryessa Industrial Park gaging locations (Figures 5.12 and 5.13). The flow duration relationships indicate a trend of reduced storm peak flow duration at the Piedmont location due to flow diversion. This curve falls below the historic flood flow frequency curve in spite of the valley urbanization. Similar results are found for the Berryessa Industrial Park location. These results show that flood flow frequencies and durations have been reduced by the flow diversions and valley drainage area reduction. The flow duration results calculated for these locations will be used in the SIAM sediment transport analysis to deduce the effects of these flow changes on sediment transport in the stream.

The changes in water yield due to urbanization and flow diversion to the groundwater percolation ponds were computed from the flow duration relationships. Results of this analysis are provided in Table 5.9. These calculations at the outlet show a marginal 7% increase in water yield at the downstream outlet due to urban land use change, drainage area reduction and flow diversion compared to an anticipated 28% increase in water yield if the valley portion of the watershed were urbanized without flow diversion or drainage area reduction.

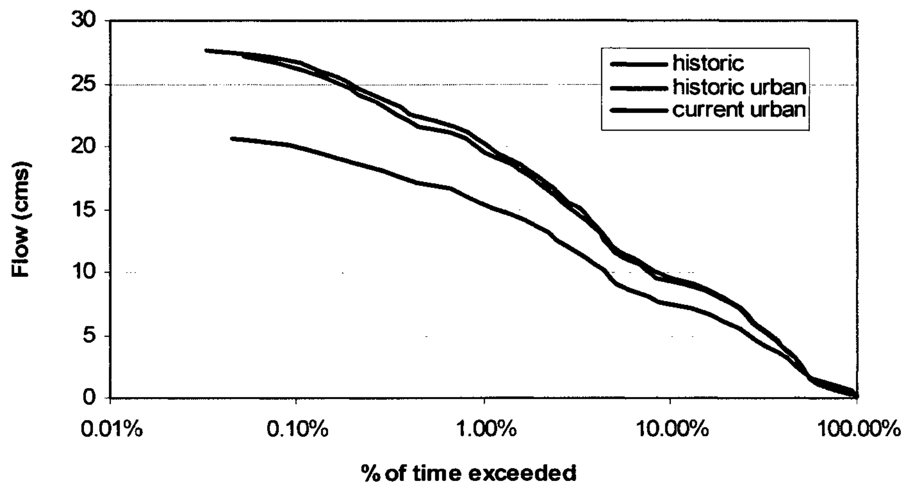


Figure 5.12 Flow duration relationship simulated for the Piedmont Avenue gaging location.

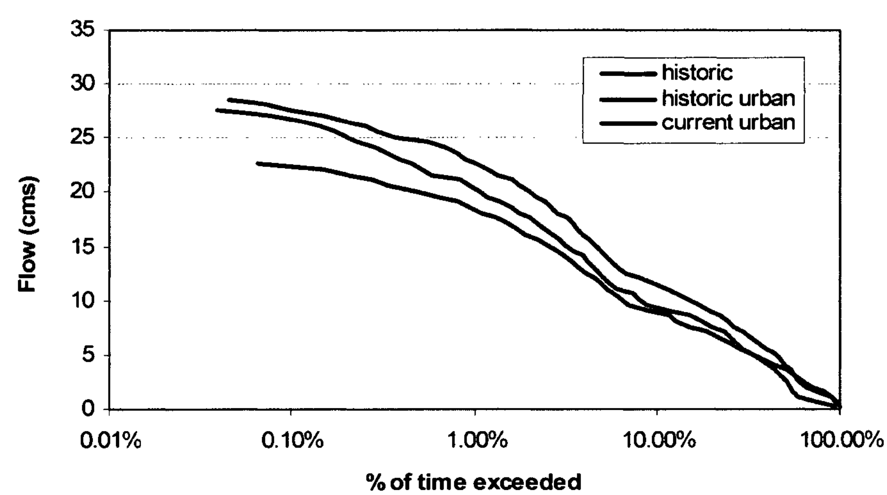


Figure 5.13 Flow duration relationship simulated for the Berryessa Industrial Park gaging location.

Table 5.9 Changes in water yield due to urbanization and effective catchment area changes on Upper Penitencia Creek.

Location	Water Yield from modeled storms (1000 m^3)/km^2 Natural historic conditions	Topographic catchment urbanized	Current(effective catchment) urbanized	Increase in water yield due to urban land used change	Change in water yield due to urban land use change, drainage area reduction and flow diversion
Downstream of Noble Ave.diversion	62.5	65.0	54.4	4%	-13%
Outlet downstream of King St.	64.3	82.2	68.6	28%	7%

The percentage increase of flood peaks and volumes at the Berryessa Industrial Park gage, the most downstream site, decrease as a function of the storm discharge (Figures 5.14 and 5.15) for the scenario where the topographic watershed is urbanized, illustrating that the urbanization has a stronger effect on small storms where the upland runoff contributions are relatively small compared to the runoff generated by the urbanized valley floor. The scenario for the current drainage network shows no trend for flood peak reduction with increasing discharge. The only trend under this scenario is decreased flood peaks when compared to the historic condition. Flood peaks are smaller even though 76% of the valley floor land use is classified as urbanized. The relatively small peak of 2.4 m^3/s, approximately 30% of the bankfull discharge, is magnified in the current drainage structure as a result of drainage efficiency from the storm sewer network. Flow diversion and effective catchment changes attenuate all other peaks. The urbanized topographic catchment scenario demonstrates a pattern similar to Berryessa Creek, where the smaller flows show greater magnification than the larger flow events.

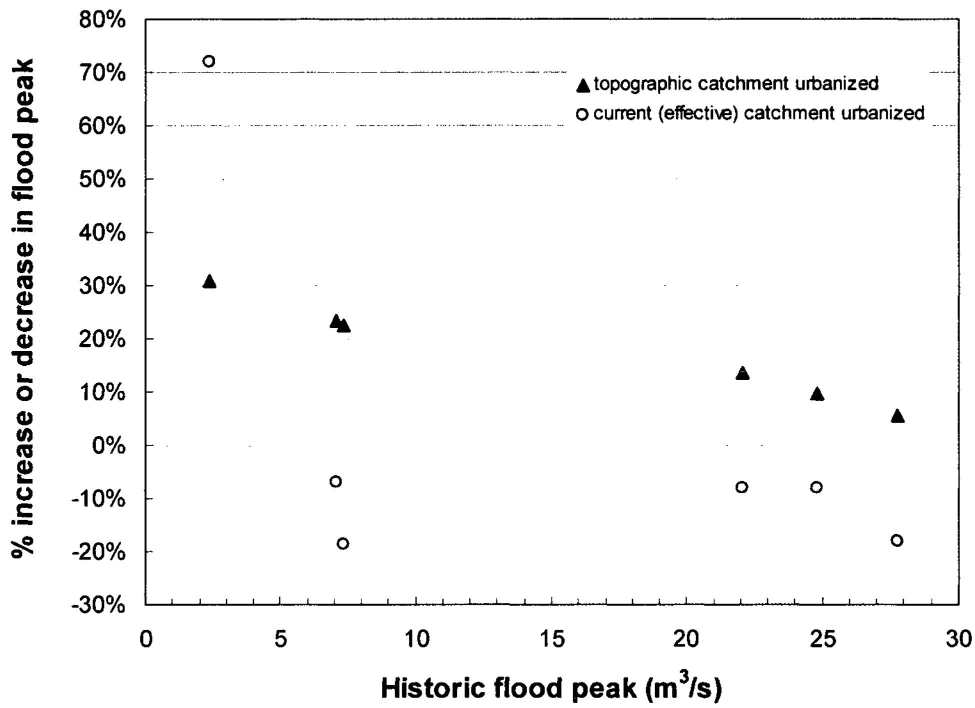


Figure 5.14 Percentage increase or decrease in flood peak as a function of discharge for the Berryessa Industrial Park gaging site at the outlet of Upper Penitencia Creek.

Under the current (effective) catchment scenario flood volumes are increased for flows less than the bankfull discharge of 7.7 m^3/s for the current (effective) drainage network. Flood volumes show slight attenuation for the discharges greater than 7.7 m^3/s for this scenario. The urbanized topographic catchment shows a trend similar to the Berryessa Creek results. In this scenario flood flow volume magnification compared to historic flow volumes decreases with increasing discharges, illustrating the stronger influence of the upland runoff sources during larger storm events.

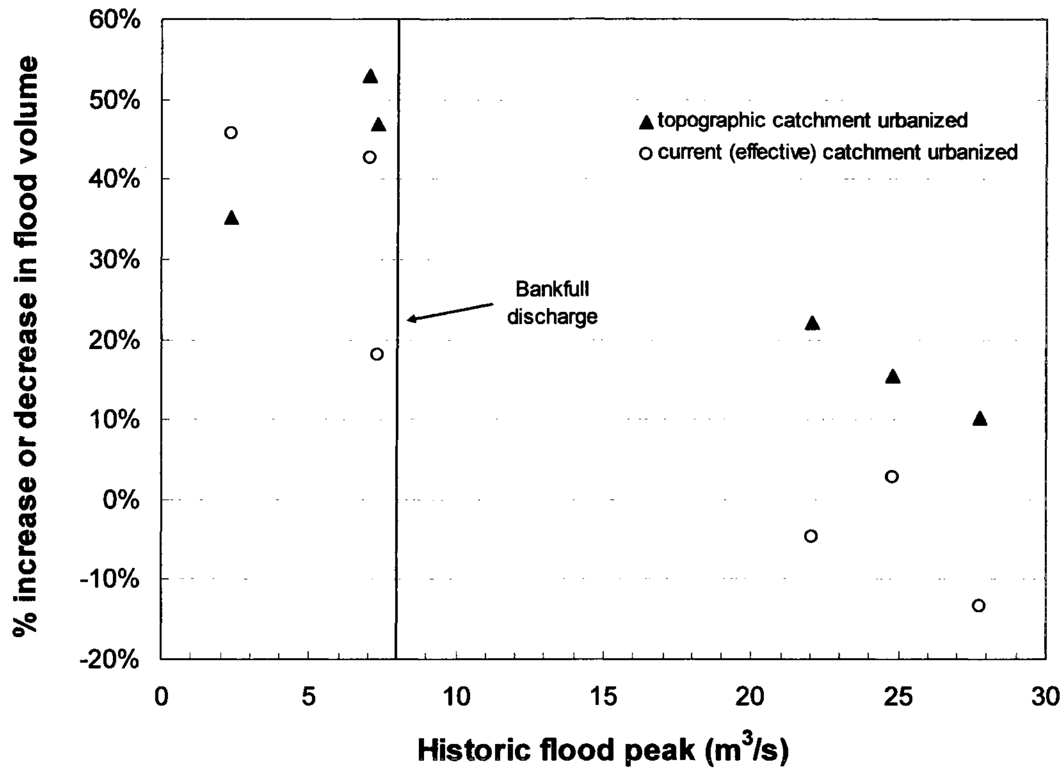


Figure 5.15 Percentage increase or decrease in flood volume as a function of discharge for the Berryessa Industrial Park gaging site at the outlet of Upper Penitencia Creek.

5.5 SUMMARY OF HYDROLOGIC MODELING RESULTS

HEC-HMS modeling was utilized to quantify the changes in the hydrologic regime due to the urban infill, storm sewer network structure and connectivity and flow diversion. Six storm events from water years 2005 and 2006 were simulated for both streams. Upland runoff contributions were calibrated to measured flow data. Subsequently, urban runoff processes and flood routing were modeled with HEC-HMS using the calibrated models.

Results indicate that the hydrologic regimes Upper Penitencia and Berryessa Creek have encountered distinctly different alterations from the construction of the urban storm sewer network and off-channel percolation ponds. Storm peaks and volumes have been magnified on Berryessa Creek due to the alteration of the historic topographic drainage area by the constructed storm sewer network. Model results indicate a net increase at the drainage outlet of 47% for the flood peak and 37% for the flood volume for Berryessa Creek due to drainage area capture and increased hydraulic connectivity provided by the storm sewer network when compared to the historic topographic catchment, if the current urbanized land use is modeled for both scenarios. In the current hydrologic regime flood peaks (77%) and volumes (66%) have been increased from historic non-urbanized conditions at the outlet location of the study site. At the downstream outlet the specific water yield for the typical yearly storm events increases from 31.2 to 46.1 ($1000m^3/km^2$), a 48% increase, due to drainage area capture and urban land use change. If drainage area capture were not considered the net increase in water yield due to urban land use change would only be 13%. These modeling data clearly indicate the strong influence of drainage area capture on the downstream urban flow regime in Berryessa Creek.

At another location on Berryessa Creek, the Sweigert Creek outlet, there was only a 3% net increase in flood peak and a 2% net increase in flood volume, due to the storm sewer network, when the current urban land cover is modeled for the topographic and effective catchment scenarios. This gaging location is located within the historic topographic catchment. Modeling results at this location show a 19% increase in flood peak and a 21% increase in flood volume when comparing the urbanized effective catchment scenario to the historic condition. Specific water yield at this gaging location has only increased from 31.1 to 35.5 ($1000m^3/km^2$), a 14% increase from historic conditions.

Conversely, model results for Upper Penitencia Creek at the downstream outlet location (Berryessa Industrial Park) show a 23% net decrease in flood peak and a 19% net decrease in flood volume due to flow diversion and topographic drainage area reduction, if the topographic and effective catchment scenarios are compared using the current urban land use cover. Modeling results indicate that in the current hydrologic regime the flood peak has decreased 12% and flood volume has increased 9% at the basin outlet compared to historic conditions. If the watershed had not been altered by the storm sewer network and off-channel storage model results predict that peak flows would have increased 15% and flood volumes would have increased 29% due increased watershed imperviousness. Specific water yield analysis shows that the existing urban flow regime produces 7% more water than historic conditions at the gaging outlet, an increase from 64.3 to 68.6 ($1000m^3/km^2$). However if drainage area reduction and flow diversion were not present in this system, modeling results indicate that there would be a 28% increase in water yield at the outlet from historic conditions (64.3 to 82.2 $1000m^3/km^2$). This indicates that the water diversion and drainage area reduction effectively off-set the effects of urban land use change on the flow regime in Upper Penitencia Creek.

Smaller storms showed greater magnification of flood peak and volume for Berryessa Creek. Multiple flood peaks were also observed for hydrographs that historically would have had one well-defined peak. The Upper Penitencia Creek modeling results indicate peak attenuation for all flows with the exception of events much smaller than the bankfull discharge. Results for flood volumes indicate volume magnification for smaller storms and volume attenuation for large flood events. The break between volume amplification and attenuation was approximately 2 times the bankfull discharge.

The results of the hydrologic modeling analysis will be used as input data for the transport modeling. A variety of scenarios will be modeled in sediment budget and continuous simulation context to deduce the implications on sediment transport and channel stability in the two watersheds.

6.0 SEDIMENT TRANSPORT MODELING

6.1 INTRODUCTION

Alterations to the pre-urban hydrologic regime, channel cross section and longitudinal geometry, and valley base level would be expected to have concomitant effects on channel stability within the two watersheds studied. Two sediment transport models were used to evaluate these urbanization and valley subsidence impacts on channel stability in Berryessa and Upper Penitencia Creek. These models are the Sediment Impact Analysis Methods (SIAM) model (Mooney 2007) and the Generalized Sediment Transport for Alluvial River Simulation- One dimension (GSTARS-1D) (Huang and Greimann 2007). The SIAM model assesses reach sediment continuity for fixed boundary cross sections at a snapshot in time (yearly scale) using HEC-RAS hydraulics and a user-specified transport equation, whereas GSTARS-1D is a continuous simulation model that can be used to predict long-term changes in an alluvial channel profile and cross section geometry. A series of sediment transport models was constructed to elucidate the effect of three major influences on channel stability;

1. Hydrologic alteration to the historic flow regime due to increased impervious land cover, drainage area manipulation and water diversion;
2. Urbanization infrastructure elements including grade-control structures, sedimentation basins, and in-stream culverts and;
3. Historic valley subsidence from the period of time between 1939 and 1969.

Six GSTARS-1D and SIAM models were created for each stream, resulting in 24 sediment transport models to elucidate the effects of each factor.

The modeling test matrix is presented in Table 6.1

Table 6.1 Sediment transport modeling scenarios

Scenario	Valley	Cross section	Urban Infrastructure	Hydrology	Simulation length
1	1934	simulated historic	No	Pre-urban	30 years
2	1934	simulated historic	No	Urban	30 years
3	2004	simulated historic	No	Pre-urban	30 years
4	2004	Surveyed	Yes	Urban	3 years
5	2004	Surveyed	No	Urban	3 years
6	2004	Surveyed	Yes	Pre-urban	3 years

These six scenarios allow the comparison of the relative effects of each process on channel stability. The process relationships for the scenario comparisons are summarized in Table 6.2.

Table 6.2 Sediment transport scenario comparison summary

Scenario comparison	Process
1 and 2	Hydrology changes
1 and 3	Subsidence
4 and 5	Urban infrastructure
4 and 6	Hydrology changes with current geometry

Scenario 4 represents the existing condition scenario for both creeks and will be compared to measured data collected from the time period from 2004 to 2006. Other modeling scenarios will simply be compared amongst each other to elucidate the relative effect of each process on modeled channel response.

6.2 MODELING TOOLS

6.2.1 HYDRAULIC MODELING (HEC-RAS)

The HEC-RAS modeling software provides one-dimensional water surface profile computations for both steady and unsteady flow simulations (HEC 2002). The one-dimensional channel hydraulic calculations are utilized to calculate reach sediment transport capacity in the SIAM model. The HEC-RAS model can be utilized to calculate both channel and overbank hydraulics and concomitant sediment transport. Hydraulic structures such as culverts, bridge openings, and drop structures can be modeled in the HEC-RAS program. These infrastructure elements are crucial to hydraulic and sediment transport processes in urban watersheds. HEC-RAS models have been created from the 2004 field survey data for both Berryessa and Upper Penitencia Creek. These models will be utilized in conjunction with the SIAM sediment accounting tool to create reach-scale sediment budgets for the watersheds.

6.2.2 SIAM

The SIAM model, developed at CSU (Mooney 2006), consists of a series of interconnected dendritic sediment reaches. The individual sediment reaches should be homogenous with respect to annual hydrologic flow-duration curves, sediment supply, hydraulic characteristics, sediment transport capacity, and bed-material composition.

SIAM defines a stable reach as one in which the sediment-transport capacity of the reach is balanced equally by the bed material load supplied to the reach from the upstream reach and the bed material size sediment contributed from local sources within the reach. This concept of equilibrium is similar to one proposed by Mackin (1948) in which a stable or graded channel is defined as one that has "just the velocity required for the transportation of the load supplied from the drainage basin." SIAM defines these measures of sediment continuity and equilibrium as local balance. The local sediment supply within a reach is estimated from field data or other sources and is specified by the model user. The sediment supply from upstream reaches is calculated by a sediment accounting algorithm which compares the sediment supply and sediment transport capacity by size fraction for each flow specified in the reach flow-duration analysis. Reach sediment transport capacity is calculated utilizing reach-average channel hydraulics from a steady state, step-backwater model such as HEC-RAS and a user-specified sediment transport function. The SIAM model then calculates reach sediment continuity throughout a channel network.

SIAM is a powerful assessment tool that represents the watershed as a multi-component system. Hydrology, hydraulics, sediment transport capacity, sediment supply, and bed-material characteristics can be isolated and altered within the SIAM model and the effect of each component on sediment continuity, system equilibrium and sediment yield can be evaluated. Other researchers have indicated the importance of estimating sediment supply and sediment continuity in watershed modeling and stream restoration design (Shields *et al.* 2003, Knighton 1998).

SIAM is a robust model that is strongly dependent on an accurate assessment of watershed conditions. The input data include:

- flow-duration curves for all sediment reaches;
- annual sediment loading estimates for overland, gully, and bank erosion;
- channel hydraulics for all sediment reaches;
- sediment transport capacity by size fraction for all sediment reaches;
- upstream boundary sediment influx;
- downstream boundary conditions for the hydraulic model;
- bed material and wash-load characteristics throughout the watershed; and
- when applicable, cohesive sediment scour from the channel bed.

Because this model is in the initial stages, no standard procedures have been developed for creating the input data needed to run the model. This open functionality is beneficial because the user can employ a wide variety of techniques to develop the database for their particular watershed, based on current data availability, project budget, and the level of detail needed to meet the project goals.

6.2.3 CONTINUOUS HYDRAULIC AND SEDIMENT TRANSPORT MODELING GSTARS-1D

The SIAM modeling framework provides a snapshot in time of the stability characteristics of an alluvial stream, but a long-term analysis is necessary to investigate time dependent stability characteristics. The mobile boundary sediment transport model selected for this task was the GSTARS-1D model developed by the United States Bureau of Reclamation (USBR). The continuous simulation transport models utilized a steady flow solution and Exner equation sediment routing (Exner 1920, 1925). The model is capable of simulating lateral inflows from culverts or tributaries. Multiple bed layers were also utilized to simulated varying bed material pavement and sub-pavement gradations. Further information on the specific capabilities of this model can be found in the documented user manual (Huang and Greimann 2007).

6.3 SEDIMENT TRANSPORT MODEL GEOMETRY

Three geometric configurations were created for each stream;

1. Historic (circa 1939)
2. Current (As surveyed in 2004) with urban infrastructure and;
3. Current (As surveyed in 2004) without urban infrastructure.

Scenarios 1-3 utilized a simulated historic model of channel conditions in 1939. These models incorporate the cross section geometry of a stable surveyed cross section in the upper portion of both streams that was outside of the influence of urbanization and subsidence impacts. The channel profile slope was calculated from the historic valley slope and sinuosity measured from the historic aerial photography (circa 1939) for each reach. The historic Berryessa Creek model profile consisted of three specific reaches (Figure 6.1). The modeled conceptual reaches are the upland reaches above the mountain/valley interface (slope = 0.024 m/m), a transition reach located at the mountain/valley interface of the historic alluvial fan (slope = 0.019 m/m), and the more gently sloping valley reach (slope = 0.015 m/m).

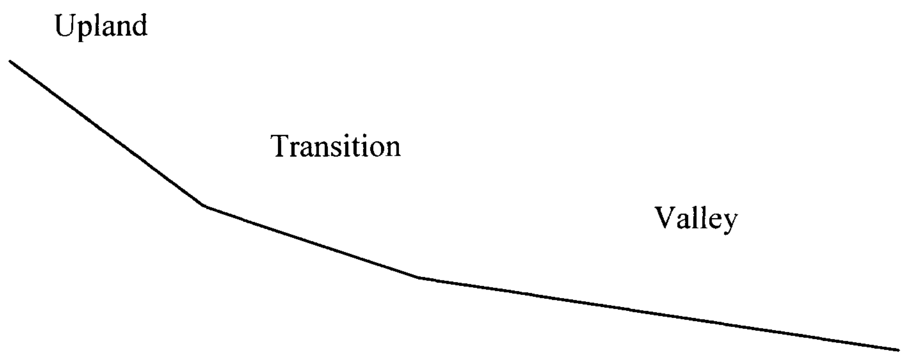


Figure 6.1 Conceptual longitudinal profile for the historic Berryessa Creek sediment transport models.

The historic model for Upper Penitencia Creek consisted of five discrete reaches (Table 6.3) where there were breaks in the longitudinal slope, planform characteristics or bed material. The sediment transport models for Upper Penitencia Creek did not extend into the upland areas due to lack of survey data available in those reaches. The models began at the mountain/valley interface and extended to the downstream extent of the longitudinal profiles survey in 2004.

Table 6.3 Historic longitudinal profile reaches for the Upper Penitencia Creek sediment transport models.

Reach	Stationing	Valley slope	Sinuosity	Channel Slope
	(m)	(m/m)		(m/m)
1	4541-5977	0.0143	1.06	0.0135
2	2953-4541	0.0112	1.1	0.0102
3	1895-2953	0.0087	1.16	0.0075
4	1294-1895	0.0078	1.09	0.0071
5	289-1294	0.0071	1.04	0.0068

Scenarios 4 and 6 utilized approximately 50 surveyed cross sections from each stream from the initial 2004 baseline survey, as well as all urban infrastructure elements surveyed including:

- Culverts
- Grade control structures
- Diversion structures
- Sedimentation basins
- Bridge openings

Scenario 5 utilized the 2004 surveyed cross sections but did not include any of the urban infrastructure elements. Additional cross sections were interpolated to reduce the maximum cross section spacing to 100 meters in all of the modeling scenarios.

A planview example of the current geometric configuration for Berryessa Creek (Figure 6.2) includes the construction of a box culvert and sedimentation basin at the interface of the mountain front and valley portion of the watershed, stream channelization, and the construction of a 1.85 m grade control structure.

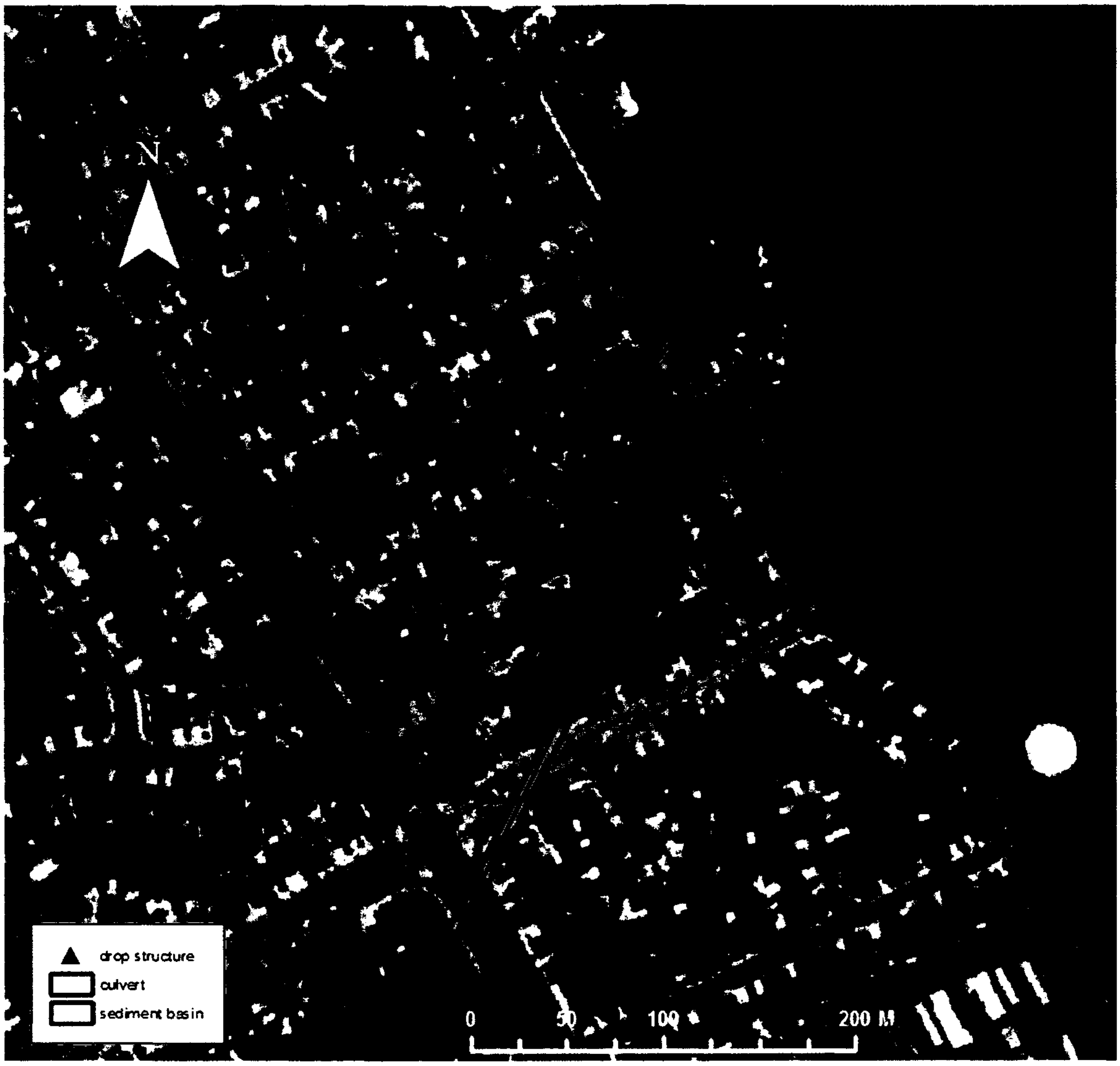


Figure 6.2 Planview of the geometric infrastructure of Berryessa Creek at the upland/valley interface.

The primary infrastructure elements present on Upper Penitencia Creek (Figure 6.3) are a series of drop structures in the upper reaches that range in drop height from 0.3 to 1.25 meters (Table 6.4). These structures may contribute to increased channel stability in the upstream reaches of Upper Penitencia Creek by stabilizing the bed at fixed points along the longitudinal profile. The slope of the invert elevations of these structures (0.0128 m/m) was very similar to the measured bankfull stage slope in this reach (0.0138 m/m) as shown in Figure 6.4. A similar plot for Berryessa Creek (Figure 6.5) shows the location of the grade control structure on this stream. There is only one gradient control present on Berryessa Creek and it has a drop height of 1.85 m. All of these structures were input into the current conditions geometry of Upper Penitencia Creek and the invert elevations were assumed to not degrade in the GSTARS-1D modeling.

Figure 6.3 Drop structure location map of Upper Penitencia Creek

Table 6.4 Upper Penitencia drop structure summary.

River station-m	Drop height-m	Invert Elevation-m	Type
1495	0.6	34.06	Diversion
4096	0.3	56.03	Low drop check dam
4418	0.8	59.7	Low drop check dam
4541	0.3	61.12	V weir for flow measurement
4680	1.25	63.5	Low drop check dam
5371	0.3	71.4	Low drop check dam
5543	1.1	74.95	Diversion/Fish ladder

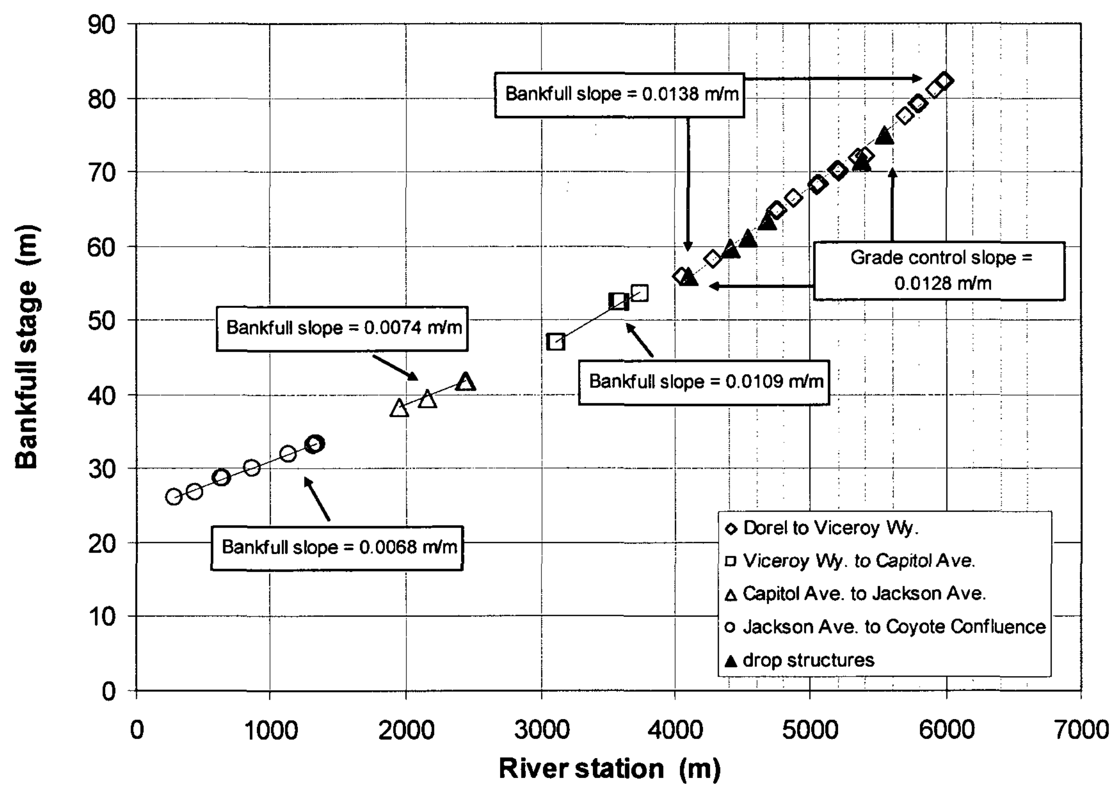


Figure 6.4 Slope of the measured bankfull stage and drop structure inverts located on Upper Penitencia Creek.

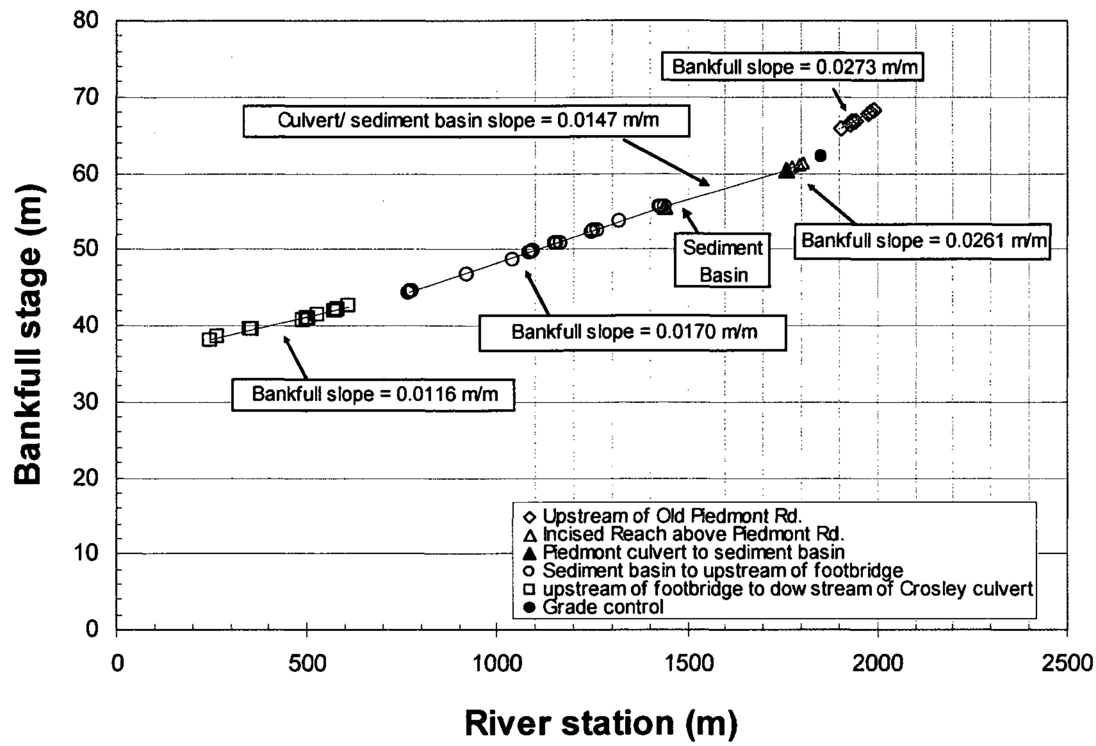


Figure 6.5 Slope of the measured bankfull stage and drop structure invert on Berryessa Creek.

6.4 SEDIMENT TRANSPORT REACHES

The SIAM model requires that the user specify sediment reaches along the channel profile that are homogenous with respect to sediment transport capacity, bed material size, sediment supply, and hydrologic regime. Some judgment is required in assessing appropriate sediment reaches along the stream profile. Breaks in channel slope, bed material size, hydrologic regime, and cross-section geometry are assessed and new sediment reaches are created at these breaks. This procedure was performed for both streams being studied. Tables 6.5 and 6.6 provide a summary of river stationing, bankfull hydraulics and bed material grain size characteristics for each sediment reach in the current geometry models for Berryessa and Upper Penitencia Creeks, respectively. Figures 6.6 and 6.7 show the spatial location of the sediment reaches for Berryessa and

Upper Penitencia creeks, respectively. The values of bankfull discharge were estimated from reach average cross section, slope and resistance properties for the field-identified bankfull stage from three years of data collection. The estimated bankfull discharge values were 2.5 m^3/s for Berryessa Creek and 7.7 m^3/s for Upper Penitencia Creek. These estimates showed good agreement with regional curve data provided by Dunne and Leopold (1978) (Figures 6.8 and 6.9), as well as the 1.5 year recurrence interval for the annual maximum series flood frequency analysis plotted in Figure 6.10. The data plot well below the regional curve for the San Francisco Bay area, with 30 inches (762 mm) of annual precipitation. However, the eastern side of the Santa Clara valley receives only 370 mm of annual precipitation on average from 93 years of rainfall record at the San Jose airport. Thus, it would be expected that the streams draining the dry eastern Diablo Range would have smaller bankfull cross section dimensions and discharge that are better simulated by the regional curve data for the Upper Green River and Salmon River watersheds. All further sediment transport modeling data analysis will be conducted at the reach scale with these aforementioned transport reaches as the analysis unit.

Table 6.5 Sediment reach summary characteristics for Berryessa Creek.

			Bankfull hydraulic characteristics				Pavement			Sub-Pavement		
Sediment Reach	Reach stationing (m)	Reach length (m)	Bankfull width (m)	Bankfull hydraulic depth (m)	Bankfull velocity (m/s)	Bankfull slope (m/m)	D-16 (mm)	D-50 (mm)	D-84 (mm)	D-16 (mm)	D-50 (mm)	D-84 (mm)
GCS 2	2298-2213	85	3.92	0.35	1.85	0.036	18	91	242	0.7	6	25
GCS 4	2213-2020	193	4.74	0.36	1.5	0.023	18	91	242	0.7	6	25
Upstream of Old Piedmont	2020-1854	166	4.48	0.34	1.68	0.025	18	91	242	0.7	6	25
Old Piedmont to Cropley	1854-1521	333	4.48	0.36	1.59	0.019	12	71	153	0.6	8	26
Sediment basin	1521-1447	74	12.92	0.27	0.9	0.011	12	71	153	0.6	8	26
Sediment basin to Sweigert Creek outfall	1447-1247	200	5.43	0.34	1.38	0.017	1	12	27	0.7	8	23
Sweigert to footbridge	1247-768	479	3.6	0.45	1.6	0.015	2	21	89	1.7	16	41
Footbridge to Crosley Creek outfall	768-491	277	4.53	0.39	1.47	0.013	5	41	145	0.9	10	38
Crosley to headcut	491-250	241	6.07	0.45	0.92	0.008	1	11	25	0.9	10	38
Downstream of headcut	250-0	250	3.69	0.51	1.41	0.015	2	12	47	2.9	32	88

Table 6.6 Sediment reach summary characteristics for Upper Penitencia Creek.

			Bankfull hydraulic characteristics				*Pavement*			*Sub-Pavement*		
Sediment Reach	Reach stationing	Reach length	Bankfull width	Bankfull hydraulic depth	Bankfull velocity	Bankfull slope	D-16	D-50	D-84	D-16	D-50	D-84
	(m)	(m)	(m)	(m)	(m/s)	(m/m)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
GCS 1-5	5988-5530	458	6.47	0.60	2.07	0.0137	30	143	295	3	26	201
GCS 6-12	5530-4745	785	7.95	0.57	1.77	0.0092	19	89	183	3	27	110
GCS 12-16	4745-3484	1261	6.38	0.66	1.87	0.0093	14	74	136	3	23	92
GCS 16-I680	3484-2523	961	6.89	0.66	1.78	0.0084	14	74	136	2	19	73
GCS 18-19	2523-2096	427	7.88	0.61	1.60	0.0074	10	70	130	2	14	52
GCS 20-22	2096-1051	1045	8.60	0.61	1.54	0.0067	15	71	136	2	17	48
GCS 23-24	1051-542	509	7.62	0.62	1.59	0.0075	10	59	109	2	13	44
GCS 25-26	542-289	253	6.13	0.77	1.63	0.0062	18	66	109	3	21	52

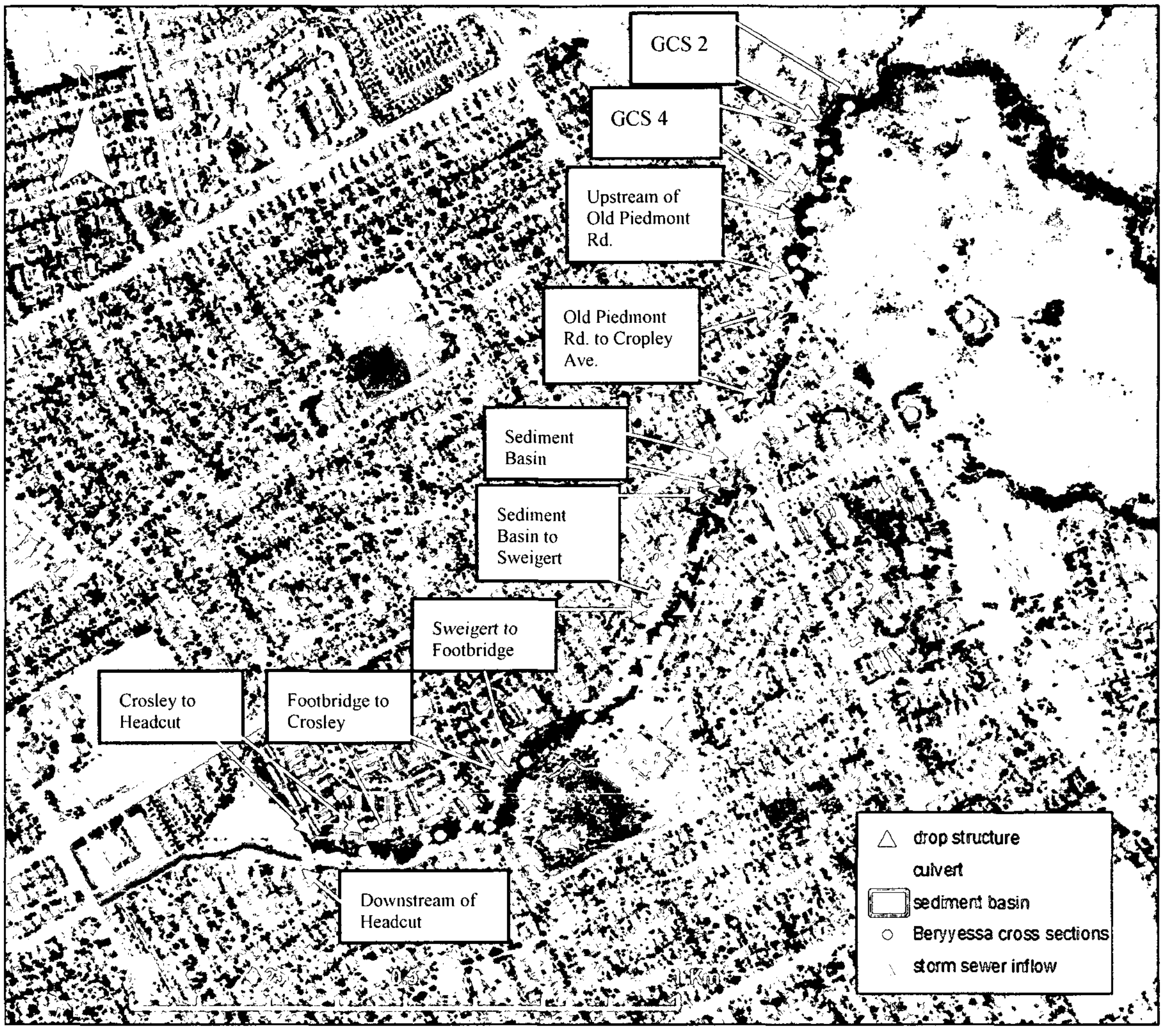


Figure 6.6 Sediment transport reaches for Berryessa Creek.

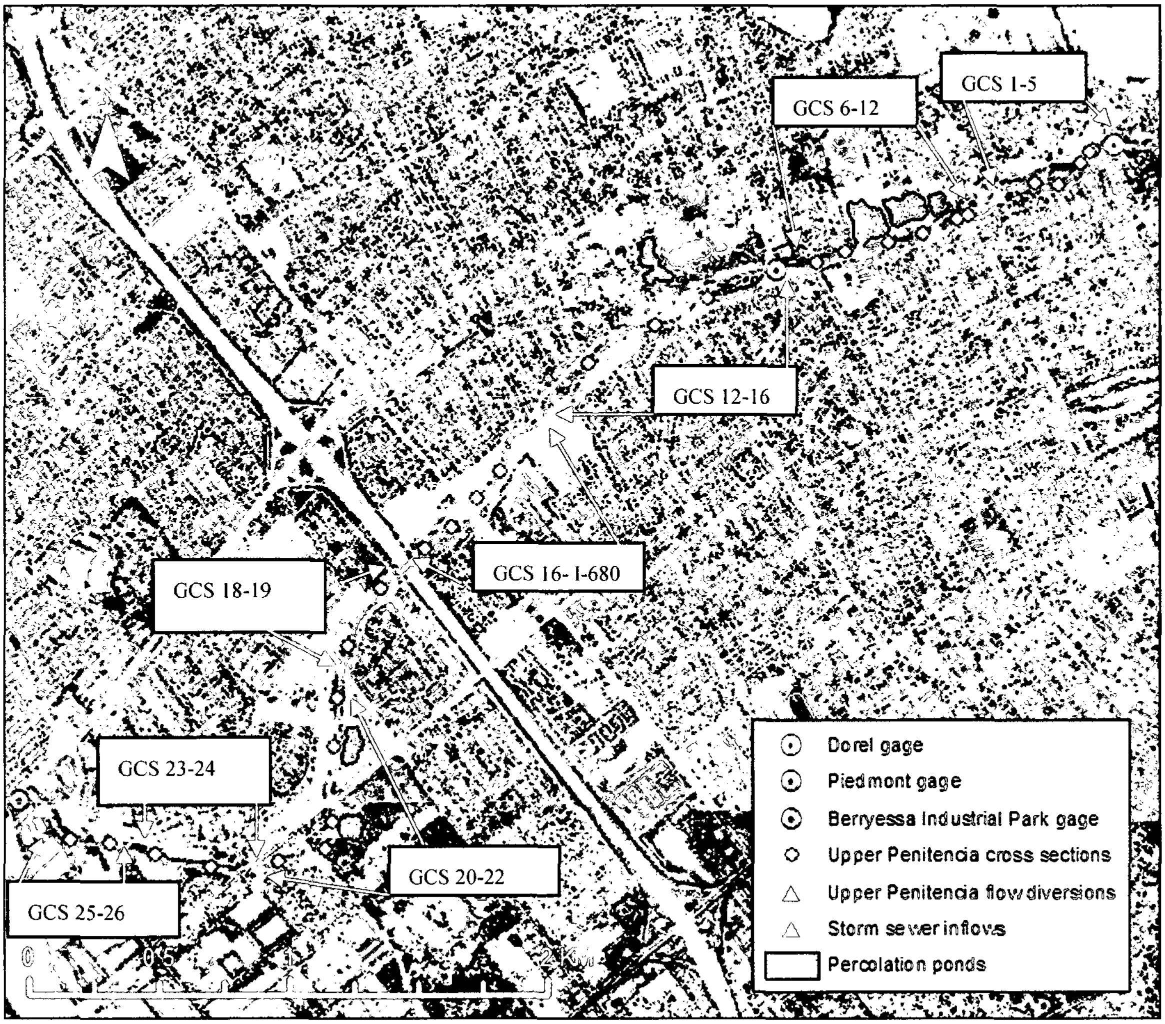


Figure 6.7 Sediment transport reaches for Upper Penitencia Creek

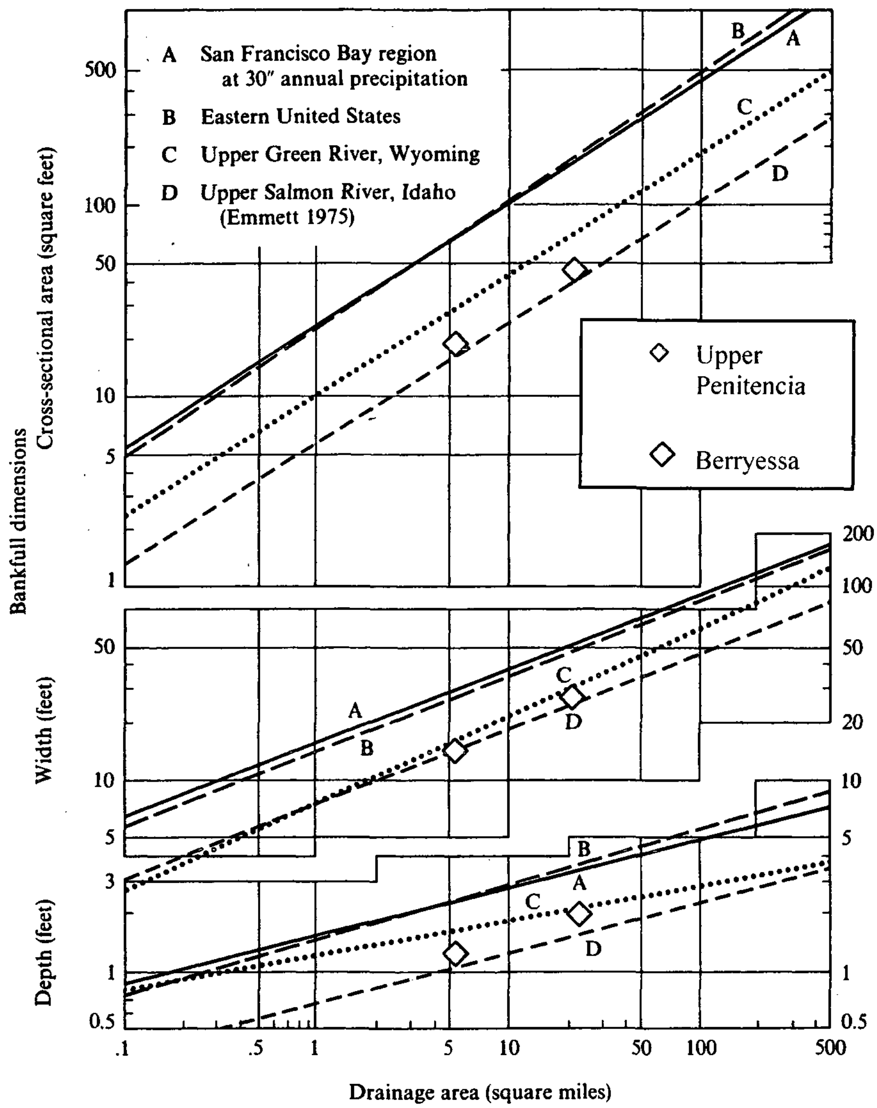


Figure 6.8 Berryessa Creek and Upper Penitencia Creek field estimated bankfull cross section dimensions figure adapted from (Dunne and Leopold 1978).

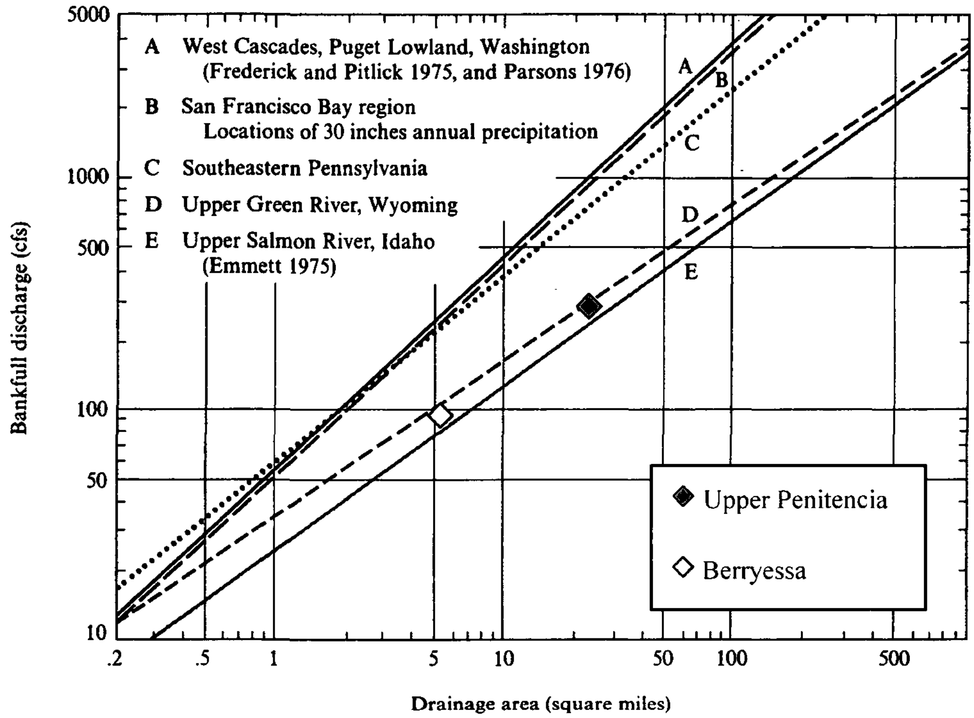


Figure 6.9 **Berryessa and Upper Penitencia Creek field estimates of bankfull discharge Figure adapted from (Dunne and Leopold 1978).**

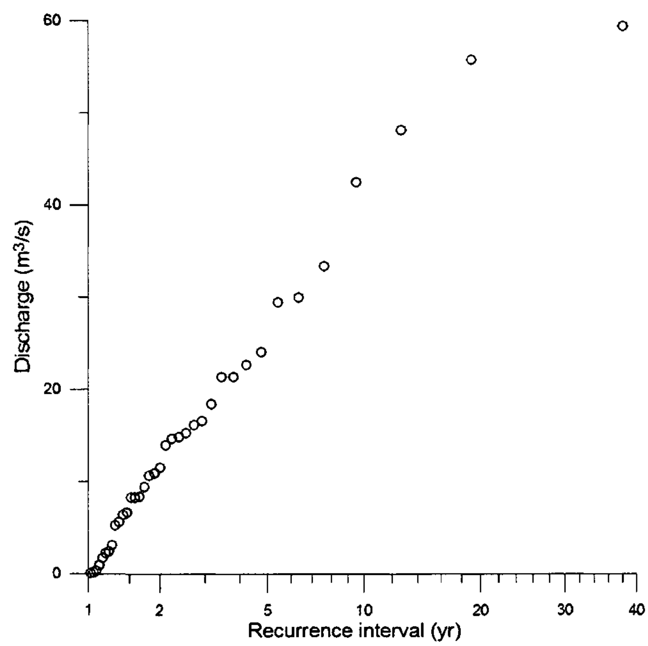


Figure 6.10 **Annual maximum flood frequency analysis for Upper Penitencia Creek.**

6.5 STREAM BED MATERIAL PARAMETERIZATION

Field data collected by the investigating author was utilized to estimate the bed material characteristics for each sediment reach. The sediment transport modeling bed gradations were based on bulk sediment sampling carried out in September 2004. The protocols used for data collection are detailed in chapter 4. The requisite input data for the sediment transport models are a decimal fraction of each grain size present in the channel bed for all sediment sizes modeled. Due to the relatively coarse nature of both stream bed and the uncertainty associated with modeling the transport capacity of supply- limited washload components of the sediment load, only sediment sizes greater than silt (0.062mm) were modeled. In the pavement samples, size fractions less than 0.062 mm represented at most 0.6 % of the bed material in Berryessa Creek and 0.1 % in Upper Penitencia Creek. In the sub-pavement samples, size fractions represented at most 1.4 % of the bed material in Berryessa Creek and 0.2 % in Upper Penitencia Creek. The sediment size gradations were represented in 1 phi class sizes up to 32 mm and ½ phi size classes from 32 mm and larger. The sediment size gradations modeled and the representative grain size (geometric mean) of those gradation intervals are presented in Table 6.7. Where bulk sediment samples were not available, pebble count data were used to estimate the bed material size gradation. This only occurred in the sediment reach below Crosley Creek in the Berryessa Creek models.

Table 6.7 Sediment size gradations modeled in the GSTARS-1D and SIAM sediment transport models

Grain size interval	Representative diameter (mm)
Very fine sand (0.0625 - 0.125mm)	0.09
Fine sand (0.125 - 0.25mm)	0.18
Medium sand (0.25 - 0.5mm)	0.35
Coarse sand (0.5 - 1mm)	0.71
Very coarse sand (1 - 2mm)	1.4
Very fine gravel (2 - 4mm)	2.8
Fine gravel (4 - 8mm)	5.7
Medium gravel (8 - 16mm)	11.3
Coarse gravel (16 - 32mm)	22.6
Very coarse gravel (32 - 45mm)	37.9
Very coarse gravel (45 - 64mm)	53.7
Small cobble (64-90mm)	75.9
Small cobble (90-128 mm)	107.3
Large cobble (128-181 mm)	152.2
Large cobble (181-256 mm)	215.3
Small boulder (256-362 mm)	304.4
Small boulder (362-512 mm)	430.5

A sediment basin was initially constructed in 1962 and re-engineered in 1983 on Berryessa Creek. The re-engineered structure is the one that is currently in place. Deposition of coarse bed load resulted in bed material fining in the reach immediately downstream of the sediment basin, this illustrated in Figure 6.11. Due to this man-made impact, the historic bed gradation for Berryessa Creek had to be estimated utilizing field data outside of the immediate influence of the structure.

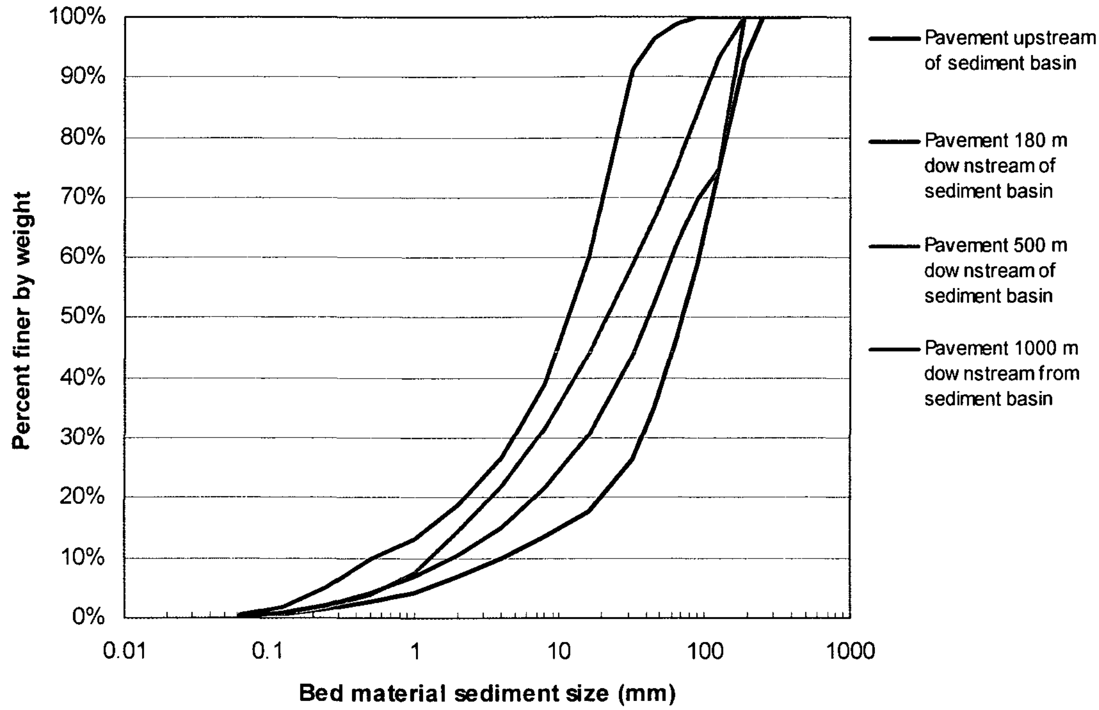


Figure 6.11 Berryessa Creek bed material pavement gradations upstream and downstream of the constructed sediment basin.

All other historic bed gradations were assumed to have not changed with time and are based on spatial averages of field samples collected within the modeled sediment reaches.

6.6 HYDROLOGIC MODEL INPUT DATA

6.6.1 CONTINUOUS SIMULATION HYDROGRAPHS

Two hydrologic regimes were utilized for flow inputs in the sediment transport models; a historical flow regime consisting of flood hydrographs for six storms without urban influence and an urban flow regime which consisted of the same six storms with simulated effects of urbanization described in Chapter 5. A detailed description of the effects of urbanization on the flood runoff for both watersheds is provided in chapter 5. The most pronounced change on the flood hydrograph from urbanization is an increase in the magnitude of runoff peak and volume from relatively small rainfall events. This has been documented by other researchers (Leopold 1968, Hollis 1975). Six measured storms with rainfall depths from 23 to 51 mm were used for HEC-HMS model calibration of upland rainfall runoff response, and rainfall runoff response alteration due to urbanization was modeled within the HEC-HMS modeling framework. Long-term rainfall data were available at the San Jose airport for 72 years of record from 1933 to 2006. Frequency analysis of rainfall data from this time period indicates that on average 6 rainfall events of 20 mm or greater occur each year (Figure 6.12).

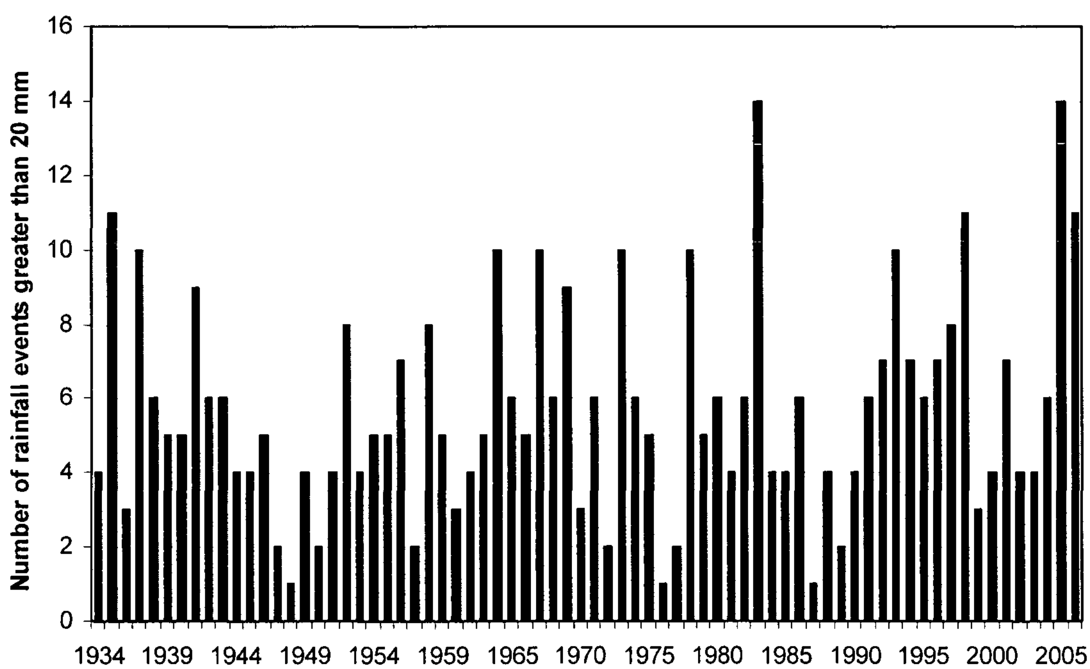


Figure 6.12 Frequency analysis of storm events at the San Jose airport rainfall gage from water years 1934 to 2006.

Storm hydrographs in this region are flashy and rainfall driven, therefore a yearly hydrograph was assumed to consist of six storm hydrographs with base flow recession. For the GSTARS-1D continuous simulation models, three of these simulated yearly hydrographs were used as the flow input for the three year simulations (scenarios 4-6) and thirty of the yearly hydrographs were used for the thirty year simulations (scenarios 1-3). The SIAM models utilize a yearly flow duration relationship developed from the hydrologic modeling analysis in Chapter 5.

6.6.2 CONTINUOUS SIMULATION LATERAL INFLOWS AND OUTFLOWS

Storm sewer culvert inflows and percolation pond diversions were simulated in the GSTARS-1D models via lateral inflow or outflow records. These records are simply a lateral inflow or outflow and a time of the inflow or outflow. These records were mined from the HEC-HMS modeling results and input into the GSTARS-1D models. For the modeling simulations it was assumed that the culvert inflows were clear-water discharge with no sediment transport. Certainly some sediment transport does take place in the closed conduit storm culvert, but the long travel distance from the upland sediment sources through the storm sewer culvert and the relatively flat slope of the storm sewer culvert will minimize bed material transport within the culvert and most of the sediment transported through the culvert will be in suspension, with grain size distributions favoring particle sizes less than 0.062 mm which were not modeled in the simulations. Figure 6.13 shows an example of clear-water discharge from the Sweigert Creek culvert on Berryessa Creek. Because clear water discharge is modeled in the continuous simulation models, the results will represent a worst case scenario of the effects of urbanization and storm sewer discharge on downstream scour.

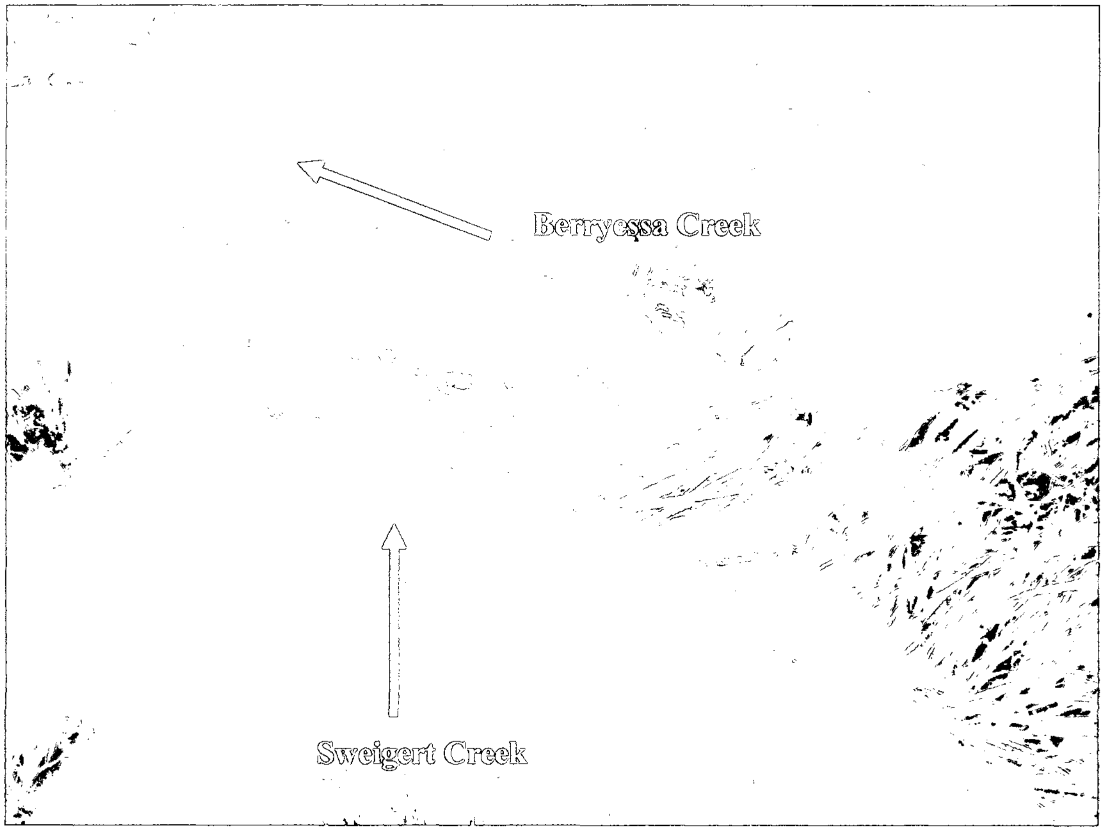


Figure 6.13 Example of clear water discharge from the Sweigert Creek culvert into Berryessa Creek.

6.6.3 ANNUAL FLOW DURATION RELATIONSHIPS

The SIAM sediment transport model utilizes a yearly flow duration relationship in calculating sediment budgets between user-specified sediment reaches. These flow duration relationships were constructed using frequency analysis from HEC-HMS modeling results for both watersheds. The six modeled storms were assumed to represent the yearly storm flows capable of transporting significant amounts of sediment through the catchment network, thus representing a yearly hydrologic cycle. Flow duration relationships for the historic and urbanized hydrology of Berryessa and Upper Penitencia Creeks are presented in Tables 6.8 and 6.9. These flow duration relationships account for storm sewer culvert inflows and flow diversions in the urbanized condition. The Upper Penitencia Creek historic hydrologic models indicated that changes in flow duration relationship were very small along the valley portion of the watershed due to high rates of infiltration and relatively small additions of drainage area along the profile. Therefore, the historic hydrologic regime can be estimated by the flow duration relationship for the most upstream reach indicated by the GCS 1-5 designation in Table 6.9.

Table 6.8 **Flow duration relationship for Berryessa Creek.**

	Upland watershed	Non urbanized watershed below Sweigert Creek culvert	Non urbanized watershed below Crosley Creek culvert	Urbanized watershed below Sweigert Creek culvert	Urbanized watershed below Crosley Creek culvert
Q	Time	Time	Time	Time	Time
(m^3/s)	(days)	(days)	(days)	(days)	(days)
0.175	3.927	4.769	4.779	4.794	3.608
0.450	1.142	1.201	1.199	1.378	1.966
0.750	0.927	1.015	1.026	1.132	1.047
1.050	0.607	0.631	0.634	0.649	0.848
1.350	0.499	0.563	0.560	0.651	0.737
1.650	0.305	0.332	0.336	0.425	0.566
1.950	0.228	0.230	0.230	0.289	0.373
2.250	0.114	0.132	0.133	0.122	0.219
2.550	0.037	0.038	0.038	0.063	0.169
2.850	0.039	0.040	0.040	0.031	0.103
3.150	0.053	0.053	0.052	0.031	0.044
3.450	0.013	0.020	0.020	0.033	0.026
3.750	0.014	0.014	0.014	0.042	0.035
4.050	0.016	0.016	0.016	0.016	0.033
4.350	0.033	0.038	0.038	0.012	0.018
4.650	X	x	x	0.013	0.020
4.950	X	x	x	0.027	0.031
5.250	X	x	x	0.006	0.013
5.550	X	x	x	x	0.009
5.850	X	x	x	x	0.010
6.150	X	x	x	x	0.020
6.450	X	x	x	x	0.013

x indicates given flow rates were not present

Table 6.9 Flow duration relationship for Upper Penitencia Creek.

Q (m^3/s)	GCS 1-5 Time (days)	GCS 6-12 Time (days)	GCS 12-16 Time (days)	GCS 16-I 680 Time (days)	GCS 18-19 Time (days)	GCS 20-22 Time (days)	GCS 23-24 Time (days)	GCS 25-26 Time (days)
0.1	0.094	0.106	0.09	0.122	0.122	0.14	0.14	0.14
0.3	1.354	0.599	0.46	0.483	0.483	0.24	0.24	0.24
0.75	1.924	2.213	1.75	1.006	1.006	0.90	0.90	0.90
1.5	1.669	2.433	2.64	3.011	3.011	2.91	2.91	2.91
3	1.372	1.899	2.05	2.261	2.261	2.42	2.42	2.42
5	1.262	1.381	1.46	1.474	1.474	1.63	1.63	1.63
7	0.975	1.323	1.42	1.47	1.47	1.36	1.36	1.36
9	1.231	0.335	0.37	0.39	0.39	0.57	0.57	0.57
12	0.463	0.299	0.30	0.30	0.30	0.33	0.33	0.33
16	0.217	0.122	0.16	0.17	0.17	0.18	0.18	0.18
20	0.117	0.024	0.03	0.04	0.04	0.06	0.06	0.06
24	0.041	x	x	x	x	x	X	X
27.5	0.015	x	x	x	x	x	X	X

x indicates given flow rates were not present

6.7 SEDIMENT SUPPLY

6.7.1 UPSTREAM WATERSHED SEDIMENT SUPPLY

The most upstream cross sections on both streams surveyed by the investigators were determined to be stable cross sections from field observation, historic morphometric analysis, and yearly cross section re-surveys. Mass conservation would then dictate that at these cross section locations the sediment transport capacity of the cross section and the upstream sediment supply would also be in equilibrium, thus the assumption was made that the upstream sediment supply to the modeled reaches was equal to the sediment transport capacity of the most upstream cross section. This is a simplifying assumption; however, it is a reasonable estimate of sediment supplied to the downstream valley reaches, given the uncertainty in predicting sediment supplied from the upland watersheds. There is limited data availability on the quantity and caliber of upstream sediment sources and little is known about the timing of the release of these sources and expected transport time to the upstream boundary of the transport models. The model results will be useful and valid with this assumption, given the breadth and complexity of all of the other processes being modeled in the study,

6.7.2 INTER-REACH SEDIMENT SUPPLY

Inter-reach sediment supply consists of sediment supplied to the catchment network within the vicinity of the modeled sediment reaches. The sediment reaches are located within the urban valley corridor of both watersheds and the sediment supplied to these reaches consists of channel bank failures (Figure 6.14) and a small amount of overland sediment supplied from gravel service roads adjacent to the urban channels (Figure 6.15).

Inter-reach sediment supply is a required input for the SIAM sediment models. A loading mass by sediment size fraction is the required input. The sediment supplied to the system from bank failure was computed using a combination of time series cross section data for all bends and headcut sections and bank rod data collected by the investigators. Failure widths were computed from the cross section and bank rod data. Bank failure height and longitudinal length were measured in the field. Bank material gradations were calculated using a photo grid pebble count procedure outlined in chapter 4 section 4.7.4 for banks with a large amount of cobble and gravel size material. Sieve analysis from field-collected bank material samples was used to compute the grain size distribution for banks with finer grained material. Service road gully locations dimensions were all measured in the field. Gully sediment size distribution was determined from sieve analysis.

Figure 6.14 Bank failure on Berryessa Creek cross section 16-2 (Bank rod location marked with orange).

Figure 6.15 Overland sediment supply to Berryessa Creek for service road rill and gully formation.

6.8 VALLEY SUBSIDENCE RATES

Detailed records of resurveyed vertical control benchmarks were available from other researchers (Poland 1976, Poland and Ireland 1988). Valley subsidence contour maps from 1934 to 1969 were created from these records. Valley subsidence profiles from 1934 to 1969 for the reaches surveyed on Berryessa Creek (Figure 6.16) and Upper Penitencia Creek (Figure 6.17) were constructed from these records by the investigating author. Results show that the maximum base level drop was much larger for Upper Penitencia Creek (1.1 m) compared to Berryessa Creek (0.23 m). This is in part due to the length of channel surveyed within the valley corridor on Upper Penitencia Creek. The base level drop increases substantially from the mountain valley interface to the central portion of the valley. The Upper Penitencia survey extended 5000 m downstream of the mountain front, whereas the Berryessa survey extended 2000 m downstream of the mountain front. The base level subsidence on Upper Penitencia Creek 2000 m downstream from the mountain front was 0.38 m, which is 0.15 m greater than the drop on Berryessa Creek. This indicates that Upper Penitencia Creek was closer to the zone of maximum subsidence. The maximum valley subsidence for Upper Penitencia Creek was 1.1 m, compared to a maximum subsidence of 0.23 m for Berryessa Creek. This indicates that valley subsidence was a stronger driver of geomorphic change for Upper Penitencia Creek within the surveyed reaches.

Base level lowering rates were calculated for each cross section surveyed and modeled in the GSTARS-1D and SIAM models by amortizing the total base level drop over the 35-year observation period. Subsidence rates for Berryessa Creek ranged from 0.0004 to 0.006 m/yr and rates from Upper Penitencia Creek ranged from 0.0001 to 0.032 m/yr.

The GSTARS-1D model code was modified by the USBR to assimilate this base level drop in the continuous simulation models. The SIAM model does not utilize a time step in the sediment budgeting. Therefore, only two geometric configurations were used in this model; one historic profile with no base level lowering and another profile with the complete base level lowering.

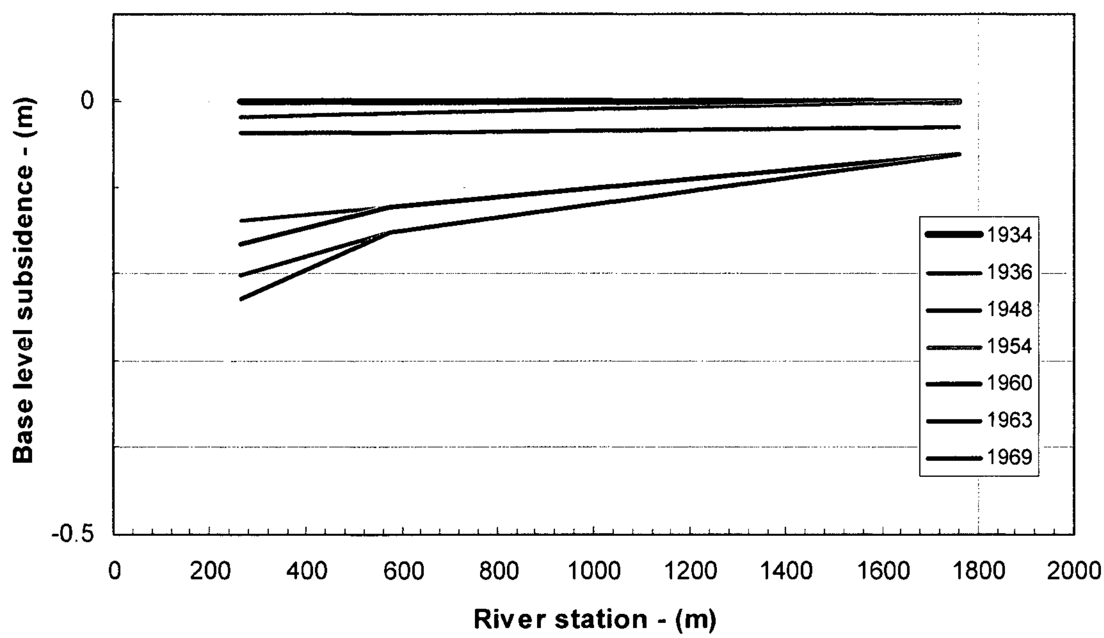


Figure 6.16 Base level subsidence profile for Berryessa Creek.

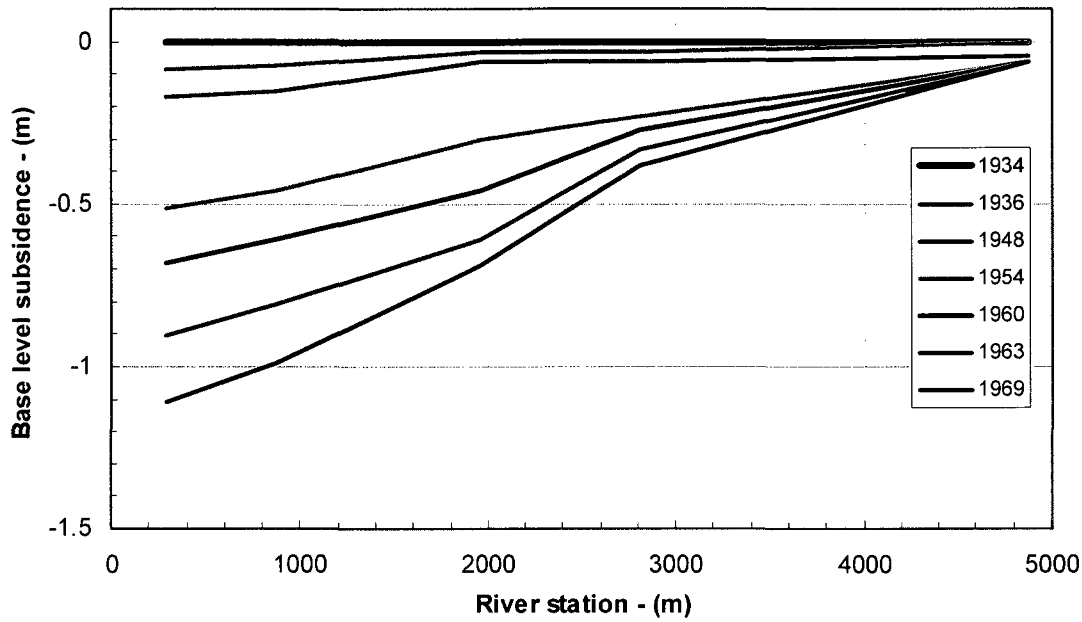


Figure 6.17 Base level subsidence profile for Upper Penitencia Creek.

6.9 SEDIMENT TRANSPORT EQUATION SELECTION

Determining an appropriate equation to model sediment transport can be a difficult task. Various equations were developed for differing ranges of grain size and varied flow conditions. Additionally, some transport equations were developed for bed load transport only, whereas others are used to calculate total bed material load transport capacity. The GSTARS-1D model allows the user to select from 12 different sediment transport equations; 10 transport relationships were chosen to test their applicability for use in this project. Some equations were eliminated because they were strictly limited to modeling sand size bed material or were direct derivations of the selected equations. A total bed material load equation was the preferred alternative but bedload equations were considered due to the high rate of bedload transport in these streams.

Two methods were used to select the transport relationship.

1. Comparison with bedload and suspended load measurements collected during storm events at the gaging sites.

2. Comparison with the measured morphologic change collected from the cross section data.

In the first analysis, GSTARS-1D model results were mined for the transport rates predicted for steady flow simulations at the same discharge at which the bedload and suspended load measurements were collected. This was used as an initial screening tool. The total root mean square error (RMSE) was calculated for each relationship for all the measurements collected on both streams; summary of this analysis is presented in Table 6.10.

Table 6.10 Comparison of sediment transport relationship to collected sediment transport data.

		Berryessa	Upper Penitencia	Total
Equation	Rank	RMSE (metric tonnes/day)	RMSE (metric tonnes/day)	RMSE (metric tonnes/day)
Engelund and Hansen (1972)	1	1014	46	1060
Yang (1973 +1984)	2	810	956	1766
Wilcock and Crowe (2003)	3	1029	890	1919
Laursen-Madden (1993)	4	423	1974	2397
Parker (1990)	5	1854	988	2842
Wu et al. (2000)	6	1431	1923	3354
Ackers and White Modification (HR Wallingford 1990)	7	2582	2691	5273
Meyer-Peter and Muller (1948)	8	5180	3236	8416
Laursen (1958)	9	21084	1075	22159
Ackers and White (1973)	10	14286	75019	89305

After this initial screening, the existing conditions GSTARS-1D models were run for both streams for a simulated three-year time period and the resulting simulated longitudinal profile data were compared to field-observed data collected from the multiple years of cross section re-surveys. A more detailed analysis was conducted for the Engelund and Hansen (EH) (1972) and the combination of the Yang (1973) and Yang (1984) relationships. Both of these relationships utilize a form of the stream power concept to predict sediment transport. It has been shown that stream-power-based relationships provide the best predictions, particularly in streams with high rates of bedload transport (Gomez and Church 1989). A summary of the comparison with the cross survey data is provided in Table 6.11. The comparison was done on a reach basis, using the sediment reaches described earlier. The most upstream cross section was not used for comparison because this cross section is used as a measure of supply to the downstream reaches and remains unchanged through the simulations. The RMSE for the simulated and measured aggradation and degradation rates was used for the analysis. A negative number indicates degradation in this table. The analysis indicates that the combination of the Yang (1973) and Yang (1984) equation provides the best prediction of the observed morphology, with a total RMSE of 1.53 for the Berryessa data and 0.92 for the Upper Penitencia data. The RMSE values for the Engelund and Hansen relationship were 2.2 for Berryessa and 2.37 for Upper Penitencia.

Furthermore, the Yang relationship provided the most realistic prediction of the observed longitudinal erosion and deposition trends. On Berryessa Creek the Engelund and Hansen relationship predicted channel deposition on the order of 0.5 m/yr downstream of the sedimentation basin, which is not observed. On Upper Penitencia Creek, EH predicted consistent channel degradation in the range of 0.2 to 0.3 m/yr along the entire longitudinal profile. This does not agree with field observations on this stream.

Table 6.11 Comparison of the Yang and Engelund and Hansen transport functions to measurement of cross section erosion or deposition.

Berryessa Creek

Reach	River stationing	Observed aggradation or degradation	Computed aggradation or degradation (Yang)	Computed aggradation or degradation (EH)	RMSE (Yang)	RMSE (EH)
	(m)	(m/yr)	(m/yr)	(m/yr)	(m/yr)	(m/yr)
GCS 2	2298-2213	0.02	n/a	n/a		
GCS 4	2213-2020	0.02	-0.084	0.01	0.10	0.0
Upstream of Old Piedmont	2020-1854	-0.031	-0.25	-0.01	0.22	0.0
Old Piedmont to Cropley	1854-1521	-0.003	-0.06	0.07	0.06	0.1
Sediment basin	1521-1447	0.56	0.16	0.31	0.40	0.3
Sediment basin to Sweigert Creek outfall	1447-1247	-0.031	-0.29	0.33	0.26	0.4
Sweigert to footbridge	1247-768	-0.003	-0.16	0.51	0.16	0.5
Footbridge to Crosley Creek outfall	768-491	0.001	-0.11	0.27	0.11	0.3
Crosley to headcut	491-250	0.061	0.14	0.39	0.08	0.3
Downstream of headcut	250-0	0.035	0.18	0.45	0.15	0.4
Sum of RMSE					**1.53**	**2.2**

Upper Penitencia Creek

Reach	River stationing	Observed aggradation or degradation	Computed aggradation or degradation (Yang)	Computed aggradation or degradation (EH)	RMSE (Yang)	RMSE (EH)
	(m)	(m/yr)	(m/yr)	(m/yr)	(m/yr)	(m/yr)
GCS 1-5	5988-5622	0.031	-0.132	-0.49	0.15	0.52
GCS 6-12	5622-4745	0.013	-0.052	-0.24	0.11	0.25
GCS 12-16	4745-3484	0.038	-0.056	-0.22	0.12	0.26
GCS 16-I 680	3484-2523	0.133	0.173	-0.15	0.04	0.28
GCS 18-19	2523-2096	0.001	0.125	-0.23	0.12	0.24
GCS 20-22	2096-1051	0.011	-0.065	-0.33	0.07	0.34
GCS 23-24	1051-542	0.029	-0.150	-0.35	0.19	0.38
GCS 25-26	542-289	0.045	-0.066	-0.06	0.12	0.10
Sum of RMSE					**0.92**	**2.37**

The combination of the Yang (1973) and Yang (1984) transport functions was selected for the transport analysis. The EH relationship provided a better fit to the measured sediment transport data collected, but the Yang function had better agreement with the measured cross section data. The author has far greater confidence in the uncertainty related to the cross section measurements compared to the measurements of sediment transport rate collected. Furthermore, the Yang relationship fits the observed morphologic longitudinal trends and therefore offers a better chance of elucidating the relative changes in morphology to the urbanization and subsidence variables being investigated.

6.10 SEDIMENT TRANSPORT MODELING RESULTS

Twelve sediment transport models were created for each creek (a GSTARS-1D and SIAM model for each of the six scenarios described in Table 6.1), resulting in 24 models. These models will attempt to elucidate the relative effects of the hydrologic, subsidence, and engineered river infrastructure changes that have taken place on these streams. These processes are complex and inter-related therefore isolating each change within a given scenario is ideal. For each stream there are 3 scenarios that utilize historic conceptual models of the streams and a 30-year simulation length. Comparison of these scenarios will isolate the hydrologic changes due to urbanization and subsidence changes to valley base level. The existing conditions scenario for both streams will be compared to the observations collected in this study.

Three of the scenarios utilize the surveyed cross section data from 2004 with variations in hydrology and river infrastructure to determine the relative effect of each on channel stability. These models do not include subsidence as subsidence rates were halted in the late 1960s and urbanization began to increase rapidly in the 1970s. Certainly the streams were still responding to the base-level change as the urbanization impacts were starting, but given the data available, modeling concurrent channel response to base-level lowering and urbanization within the same model was not feasible. The GSTARS-1D models using the 2004 cross section data use a simulation length of three years.

6.10.1 COMPARISON OF EXISTING CONDITIONS MODELS TO FIELD OBSERVATIONS

Reach-average GSTARS-1D and SIAM model results were compared to the measured rates of cross section erosion and deposition observed from 2004 to 2006. Two estimates of erosion and deposition were formulated from the field measurements:

1. The change in cross sectional area below the bankfull stage divided by the bankfull width. This was termed the normalized erosion and deposition rate and reported in m/year. A negative value represents erosion.

2. The change in the thalweg elevation over the monitoring time. This was also reported in m/year. A negative value represents erosion.

The two values typically followed similar trends. The SIAM model was created to compare gross sediment balances between reaches. The depth of channel change can be estimated by assuming a mass density for the solid particles and porosity for the bed material and dividing the calculated volume by the reach length and average width. The bed material was assumed to have a mass density of 2650 kg/m^3 and a porosity of 0.3

(Dunne and Leopold 1978). The SIAM model results for the computed depth of channel change were compared with the normalized erosion and deposition rate parameter.

The GSTARS-1D models incorporate a time step and channel change throughout the simulations and the simulated thalweg depth at the end of the simulation can be extracted from the model results. Because this elevation was readily available from the model results, the final thalweg elevation from GTARS simulations was compared to the measured elevations collected from the field data. Summary data from the comparisons are presented in Tables 6.12 (Upper Penitencia) and 6.13 (Berryessa).

Table 6.12 Summary data for existing conditions model comparison to measured data on Upper Penitencia Creek.

Reach name	Reach stationing (m)	SIAM erosion or deposition (m/yr)	GSTARS erosion or deposition (m/yr)	Observed normalized erosion or deposition (m/yr)	Observed elevation change of thalweg (m/yr)	RMSE SIAM	RMSE GSTARS
GCS 1-5	5988-5622			0.013	0.031	x	x
GCS 6-12	5622-4745	0.159	-0.097	0.005	0.013	0.15	0.11
GCS 12-16	4745-3484	-0.060	-0.081	0.061	0.038	0.12	0.12
GCS 16-I 680	3484-2523	0.057	0.176	0.05	0.133	0.01	0.04
GCS 18-19	2523-2096	0.078	0.121	-0.015	0.001	0.09	0.12
GCS 20-22	2096-1051	0.019	-0.054	0.008	0.011	0.01	0.07
GCS 23-24	1051-542	-0.036	-0.162	0.016	0.029	0.05	0.19
GCS 25-26	542-289	0.099	-0.078	0.024	0.045	0.08	0.12
RMSE Sum						**0.51**	**0.77**
RMSE average						**0.07**	**0.11**

Table 6.13 Summary data for existing conditions model comparison to measured data on Berryessa Creek.

Reach name	Reach stationing (m)	SIAM erosion or deposition (m/yr)	GSTARS erosion or deposition (m/yr)	Observed normalized erosion or deposition (m/yr)	Observed elevation change of thalweg (m/yr)	RMSE SIAM	RMSE GSTARS
GCS 2	2298-2213			0.002	0.02	x	x
GCS 4	2213-2020	1.11	-0.08	0.011	0.02	1.10	0.10
Upstream of Old Piedmont	2020-1854	-0.34	-0.25	-0.037	-0.031	0.30	0.22
Old Piedmont to Cropley	1854-1521	0.11	-0.06	0.013	0	0.10	0.06
Sediment basin	1521-1447	0.63	0.16	0.56	0.56	0.07	0.40
Sediment basin to Sweigert Creek outfall	1447-1247	-2.01	-0.29	0.006	-0.031	2.02	0.26
Sweigert to footbridge	1247-768	0.70	-0.16	0.013	-0.003	0.69	0.16
Footbridge to Crosley Creek outfall	768-491	0.02	-0.11	-0.002	0.001	0.02	0.11
Crosley to headcut	491-250	0.22	0.14	0.088	0.061	0.13	0.08
Downstream of headcut	250-0	0.07	0.18	-0.058	0.035	0.13	0.15
RMSE Sum						**3.45**	**1.44**
RMSE average						**0.43**	**0.18**

The RMSE for the predicted channel change and simulated channel change in the existing conditions model indicates that the models provide reasonably close predictions to channel change for Upper Penitencia Creek. The average RMSE for the SIAM models was 0.07 m/year and the GSTARS-1D average RMSE was 0.1 m/year. The predicted and observed values show greater deviation for the Berryessa Creek models, which is to be expected because the system is much more complex in terms of the hydrologic changes and the engineered sedimentation basin. The GSTARS-1D models had better agreement with the measured data, with an average RMSE of 0.18 m/yr compared to 0.43 m/yr for the SIAM models. The average RMSE for the Berryessa SIAM models is skewed by some large outliers where predictions are much greater than the observed values. These outliers include the reach immediately downstream of the upstream boundary at GCS 4, which predicts deposition of 1.1 m/yr, and the reach immediately downstream of the sedimentation basin, where the model predicts erosion of 2.01 m/yr. The most upstream reach is quite steep (0.036 m/m) and it is likely that the amount of sediment supplied to the downstream reach is overestimated. Downstream of the sedimentation basin the bed material grain size becomes significantly smaller, with a D_{84} of 27 mm compared to 153 mm in the upstream reach. It is reasonable to expect erosion due to this change, but the amount of erosion is overestimated. The SIAM model is better suited to predict relative trends in erosion and deposition rather than specific depths of aggradation or degradation (Mooney 2007). This is particularly true in reaches were there are abrupt changes in channel hydraulics or bed material size. The SIAM model did show good agreement with the amount of sediment that would be deposited in the Berryessa sediment basin on an annual basis. Dredging records were available from the SCVWD from 1985 to 2004. Calculations made from this dataset indicate that the average amount of sediment dredged yearly is 1151 metric tonnes/yr and the median amount is 1693 metric tones/yr. The SIAM model predicts that 1303 metric tonnes of sediment will be deposited in the basin, a 13% difference from the average and a 29 % difference from the median. Given the degree of uncertainty in the dredging record, bed material mass density and porosity these estimates provide a good indicator of the amount of sediment that can be expected to deposit in this feature.

The GSTARS-1D models incorporate a time step for changes to the channel cross section as well as the bed material gradation of the active transport layer. This allows for more gradual transitions in the channel hydraulics and bed material gradations over the simulation. These are the main factors leading to better predictions simulated by the GSTARS-1D model for Berryessa Creek.

The Upper Penitencia Creek dataset has more gradual transitions in channel hydraulics and stream bed material caliber. Both of the models provide reasonable simulations of the erosion and deposition processes occurring at a reach scale The average RMSE values for these models are 70 mm/yr (SIAM) and 100 mm/yr (GSTARS-1D).

Figures 6.18 (Upper Penitencia) and 6.19 (Berryessa) show the predicted and observed trends for the modeled sediment reaches. The modeled scenarios generally follow the longitudinal trends observed in the streams. There are outliers in these trends. This is expected given the uncertainty inherent in sediment transport modeling. Estimates are oftentimes only within 1 or 2 orders of magnitude when compared to measured values (Alonzo 1980, Parker et al. 1982). The simulated erosion and deposition rates are typically exaggerated when compared to the observed values. However, these are reach-averaged values and erosion/deposition trends fluctuate, with the reach-scale dampening the values of measured erosion and deposition characteristics at individual cross sections.

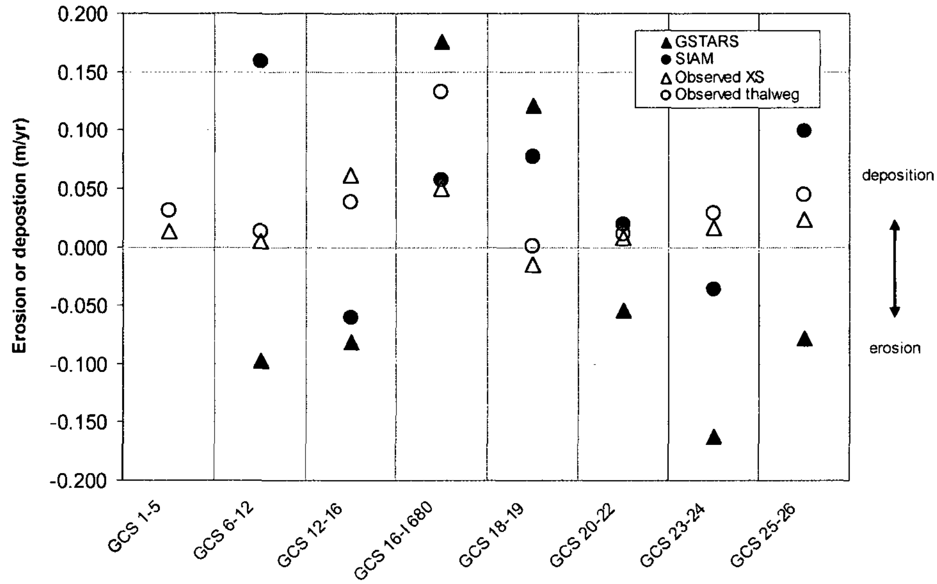


Figure 6.18 Modeled and observed values of erosion and deposition for Upper Penitencia Creek.

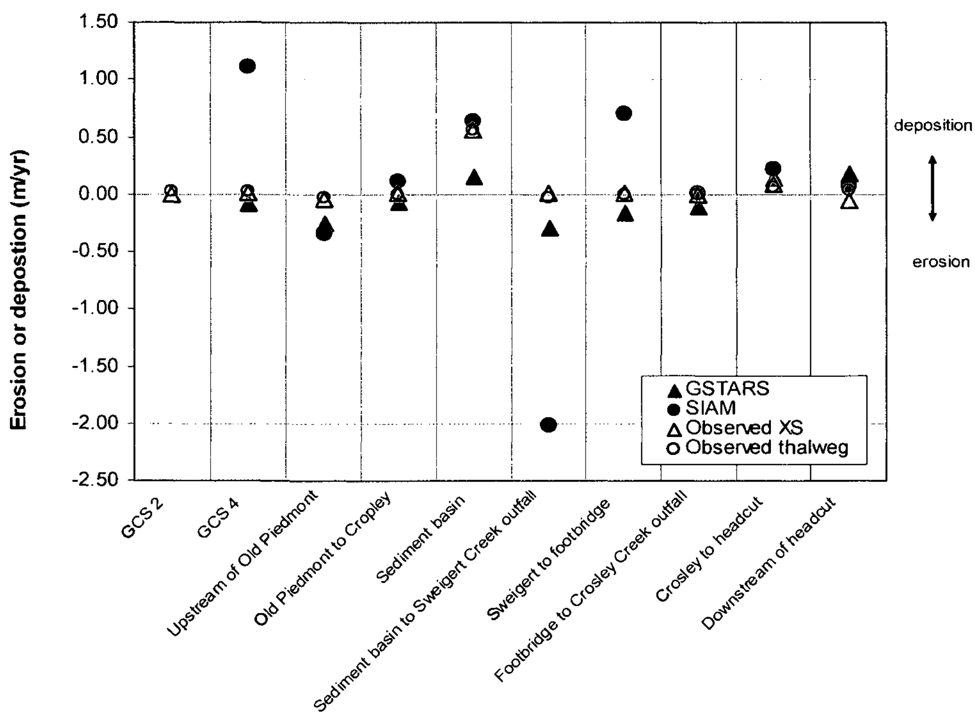


Figure 6.19 Modeled and observed values of erosion and deposition for Berryessa Creek.

6.10.2 INVESTIGATION OF HYDROLOGIC CHANGES DUE TO URBANIZATION

As stated previously and detailed in Chapter 5, hydrologic changes have occurred in both of the streams due to urbanization infill, effective catchment area changes to the drainage network, and flow diversion to groundwater percolation ponds. The relative effects of these changes were ascertained in two modeling scenarios.

1. Comparison of the sediment modeling results for the conceptual historic models without valley subsidence (one model has pre-urban hydrology and the other has post-urban hydrology).

2. Comparison of the sediment modeling results for the surveyed 2004 cross sections, including urban infrastructure (one model has pre-urban hydrology and the other has post-urban hydrology).

Comparison of these models will reveal the relative effects of urban hydrologic change on erosion and deposition processes. The historic models indicate the response of the original (circa 1939) stream to the hydrologic change. The historic cross sections with the historic flow regime represent a baseline condition for the erosion and deposition trends in an un-altered state. The current models indicate the potential for future channel change of the presently observed channels in response to the urban hydrologic regime change.

6.10.2.1 BERRYESSA HISTORIC MODELS WITH AND WITHOUT URBAN HYDROLOGIC CHANGE

The Berryessa historic model simulations do not include the sedimentation basin or the grade-control structure at the valley/upland interface currently in place. The results of this analysis are presented in Table 6.14. In the table, a negative number indicates erosion and a positive number indicates deposition. The results from the most upstream reach in the models (GCS 2) are not included because this was used as a supply reach to the downstream reaches; therefore stability was imposed by the boundary conditions. A negative number in the percent change column indicates the relative increase in erosion or deposition due to the hydrologic changes. The results of this analysis indicate that the hydrologic changes that have occurred on Berryessa Creek due to urbanization would be expected to induce significant channel change, particularly in the reaches downstream of the storm sewer outfalls and continuing up to the upland valley interface.

Table 6.14 Channel change modeled due to changes in hydrology for the conceptual historic Berryessa Creek models.

		Historic geometry historic flows		**Historic geometry urban flows**			
Historic reaches	River stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 2	2298-2192	-	-	-	-	-	-
GCS 4	2192-1996	1.00	-0.050	1.00	-0.059	0%	-18%
Upstream of Old Piedmont	1996-1813	-0.318	-0.050	-0.318	-0.071	0%	-42%
Old Piedmont to Sed basin	1813-1447	0.093	-0.025	0.093	-0.080	0%	-220%
Sed basin to Sweigert Creek	1447-1167	-0.066	-0.015	-0.066	-0.091	0%	-495%
Sweigert to footbridge	1167-609	0.040	-0.014	-0.030	-0.059	-174%	-335%
Footbridge to Crosley Creek	609-357	0.124	-0.011	0.144	-0.042	16%	-279%
Crosley to outlet	357-0	0.041	-0.012	-0.061	-0.032	-248%	-158%

The SIAM model indicates a change from deposition to incision downstream of both the Crosley Creek and Sweigert Creek culvert outfalls. The SIAM results indicate that the erosion rates downstream of these outfalls will increase 174% for the reach downstream of Sweigert Creek and 248% downstream of Crosley Creek. The GSTARS-1D models show a similar trend and they indicate that the incision will proceed headward into the upland reaches over the 30-year simulation period. The maximum increase in incision rate for the GSTARS-1D models is 500%. The final rate downstream of Sweigert Creek is 335% and the final rate downstream of the Crosley culvert is 158%.

The annual specific sediment yield (metric tonnes/yr-km^2) was computed at the outlet for both models. The GSTARS models were 30-year simulations. The annual sediment yield for the watershed was computed by dividing the cumulative sediment load for the simulation by 30. The GSTARS models predict a 9% increase (135 to 147 tonnes/yr-km^2) in the annual sediment yield due to the changes in the hydrologic regime. The SIAM models predict a 61% increase (75.5 to 121.3 tonnes/yr-km^2) in the annual sediment yield as a result of the urban hydrologic changes. Both models clearly indicate that by including Sweigert Creek and Crosley Creek, both of which are historically adjacent alluvial fan systems, in the current urban drainage structure, channel instability is incurred along Berryessa Creek. The SIAM models show that areas of historic deposition are transformed into incising reaches and the GSTARS models indicate that the channel response to the drainage alterations will be system-wide.

6.10.2.2 BERRYESSA CURRENT GEOMETRY MODELS WITH AND WITHOUT URBAN HYDROLOGIC CHANGE

The current geometry scenarios were run with and without the urban hydrologic changes to investigate the expected response of the current stream to hydrologic change. These models include the sediment basin and grade-control structure. The results are presented in Table 6.15. Results of this analysis indicate that in the present context the changes in channel stability due to the urban hydrologic changes will be smaller than those modeled in the historic models. The SIAM models indicate that the reaches downstream of the Sweigert and Crosley Creek outfalls will remain depositional. This is primarily a result of local sediment sources from failing stream banks in these reaches and the reduced gradient in the reach due to historic channel incision. The models indicate that the deposition is mitigated by the increased transport provided by the urban flow regime. The relative increases in transport downstream of the outfalls are 12% for Sweigert Creek and 27% for Crosley Creek.

The GSTARS-1D models do not simulate local sediment sources and the results are much different. The GSTARS-1D models predict incision proceeding headward in reaches that are depositional under the historic flow regimes. The reach below Crosley Creek remains depositional but the transport capacity is increased 15%. The upstream reaches transition from depositional to incising, with relative erosion rates increasing 150% to 234%. The reach downstream of the sediment basin has the highest erosion rates (0.29 m/yr), due to coarse bed material deposition in the sediment basin. However, the relative rate is only increased 29% in this reach. The presence of the sediment basin and grade-control structure prohibits the incision from moving further upstream.

Table 6.15 Channel change modeled due to changes in hydrology for the current geometry Berryessa Creek models.

2004 survey reaches	Reach stationing	Current geometry historic flows SIAM erosion or deposition	Current geometry historic flows GSTARS erosion or deposition	Current geometry urban flows SIAM erosion or deposition	Current geometry urban flows GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 2	2298-2213	-	-	-	-	-	
GCS 4	2213-2020	1.109	-0.084	1.109	-0.084	0%	0%
Upstream of Old Piedmont	2020-1854	-0.341	-0.247	-0.341	-0.247	0%	0%
Old Piedmont to Cropley	1854-1521	0.105	-0.063	0.105	-0.063	0%	-1%
Sediment basin	1521-1447	0.633	0.160	0.633	0.156	0%	-3%
Sed basin to Sweigert Creek	1447-1247	-2.007	-0.226	-2.007	-0.292	0%	-29%
Sweigert to footbridge	1247-768	0.800	-0.066	0.703	-0.164	-12%	-150%
Footbridge to Crosley Creek	768-491	0.012	0.083	0.016	-0.110	39%	-234%
Crosley to headcut	491-250	0.299	0.164	0.220	0.140	-27%	-15%
Downstream of headcut	250-0	0.057	0.181	0.068	0.184	18%	1%

The annual specific sediment yield (metric tonnes/yr-km^2) was computed at the outlet for both models. The GSTARS models were 3-year simulations, therefore to estimate the annual sediment yield for the watershed the cumulative sediment load for the simulation was divided by 3. The GSTARS models predict a 4% increase (73.4 to 76.4 tonnes/yr-km^2) in the annual sediment yield due to the changes in the hydrologic regime. The SIAM models predict a 59% increase (54.2 to 86.3 tonnes/yr-km^2) in the annual sediment yield as a result of the urban hydrologic changes. The predicted relative increases in sediment yield in these simulations are comparable to the results from the historic geometry models.

6.10.2.3 UPPER PENITENCIA HISTORIC MODELS WITH AND WITHOUT URBAN HYDROLOGIC CHANGE

Sediment transport models were run for the conceptual historic Upper Penitencia Creek watershed scenarios. These models did not include any of the grade-control structures present on the upstream portion of the watershed. The historic models were created from the historic reach discretization described previously, however data analysis was conducted in the context of the current geometry reach scenario to facilitate comparison amongst the various models. Bed material estimates were created using the existing conditions bed material measurements for the field sampling of the pavement and sub-pavement layers. The urban hydrologic change on Upper Penitencia differs from Berryessa Creek. The current effective catchment area is smaller than the historic topographic catchment area and a portion of flood flows are typically diverted into the off-channel percolation ponds in the upstream reaches. Both watersheds have seen drastic increases in impervious surface within the valley portion of the catchment, Upper Penitencia is 76% urban land use within the valley, while Berryessa is 85% urban within the valley. A summary of this analysis is provided in Table 6.16. The upstream reach is excluded from the analysis because it is a supply reach.

The most noteworthy point that can be deduced from these data is the degree of channel stability modeled for the historic geometry of Upper Penitencia Creek. The GSTARS-1D models simulate reach-average erosion rates ranging from -0.03 m/yr to 0.01 m/yr for the historic flow regime and -0.04 m/yr to 0.01 m/yr for the urban flow regime under historic geometric conditions. The SIAM models indicate more variability, but simulated reach-average erosion rates still indicate relative stability ranging from -0.05 m/yr to 0.12 m/yr for the historic flow regime and 0.0 m/yr to 0.1 m/yr for the urban flow regime under historic geometric conditions. In nearly all cases the urban flow regime provides greater stability from the results of the transport models. This stability in the historic geometric configuration illustrates two important points. First, areas of instability that are witnessed currently are likely due to valley subsidence or urban encroachment, not changes due to the urban flow regime. Secondly, management of groundwater drawdown in the region by flow extraction into off-channel percolation ponds did not adversely affect channel stability and it was successful in mitigating valley subsidence in the area. The SIAM model does predict bed material deposition in the reach from river stations 5622- 4745 m, where the peak flows are extracted. The GSTARS-1D model does not predict this response.

Table 6.16 Channel change modeled due to changes in hydrology for the conceptual historic Upper Penitencia Creek models.

		Historic geometry historic flows		Historic geometry urban flows			
Reach Name	Reach stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr)	(m/yr)	(m/yr)	(m/yr)		
GCS 1-5	5988-5622	-	-	-	-	-	-
GCS 6-12	5622-4745	-0.049	-0.030	0.036	-0.040	173%	-32%
GCS 12-16	4745-3484	0.018	0.004	0.001	-0.001	-93%	-131%
GCS 16-I 680	3484-2523	0.084	0.010	0.063	0.009	-25%	-13%
GCS 18-19	2523-2096	0.115	-0.001	0.104	-0.002	-10%	-39%
GCS 20-22	2096-1051	0.014	-0.008	0.002	-0.006	-89%	22%
GCS 23-24	1051-542	0.033	-0.017	0.026	-0.004	-20%	78%
GCS 25-26	542-289	0.005	-0.015	0.018	-0.005	247%	67%

The annual specific sediment yield (metric tonnes/yr-km^2) was computed at the outlet for both models. The GSTARS models were 30-year simulations. The cumulative sediment load for the simulation was divided by 30 to compute the annual sediment yield. The GSTARS models predict an 8% decrease (75.4 to 69.5 tonnes/yr-km^2) in the annual sediment yield due to the changes in the hydrologic regime. The SIAM models predict a 4% decrease (41.7 to 39.8 tonnes/yr-km^2) in the annual sediment yield as a result of the urban hydrologic changes.

6.10.2.4 UPPER PENITENCIA CURRENT GEOMETRY MODELS WITH AND WITHOUT URBAN HYDROLOGIC CHANGE

The 2004 cross section hydraulic models were run to investigate implications for flow regime change under the current geometric configuration for Upper Penitencia Creek. Results of this analysis are presented in Table 6.17. Results from the SIAM models indicate that there is a loss of transport in the reach where the diversion occurs (GCS 6-12). The SIAM model predicts increased deposition in this reach, whereas the GSTARS-1D model predicts that the reach will be degradational. The degradation predicted in the GSTARS models is a function of upstream erosion migration resulting from storm water inputs over time. Both models are in agreement with the prediction that incision should occur upstream of crossing with Upper Penitencia Creek Rd. and that deposition should occur in the vicinity of I-680, this trend is validated through field observations. Comparison of the modeling results does not indicate that the current urban flow regime is a strong driver of change in the trends of the modeling results. There is a signal in the SIAM results indicating the effect of the urban runoff flow augmentation in the downstream reaches. This can be deduced from river stations 34+84 m to 5+42 m., in these reaches reach average erosion rates show relative increases ranging from 17% to 52% as a result of the urban flow regime.

Table 6.17 **Channel change modeled due to changes in hydrology for the current geometry Upper Penitencia Creek models.**

		Current geometry historic flows		Current geometry urban flows			
Reach Name	Reach stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 1-5	5988-5622	-	-	-	-	-	-
GCS 6-12	5622-4745	0.103	-0.052	0.159	-0.097	55%	-87%
GCS 12-16	4745-3484	-0.063	-0.056	-0.060	-0.081	3%	-45%
GCS 16-I 680	3484-2523	0.073	0.173	0.057	0.176	-22%	2%
GCS 18-19	2523-2096	0.093	0.125	0.078	0.121	-17%	-3%
GCS 20-22	2096-1051	0.030	-0.065	0.019	-0.054	-35%	17%
GCS 23-24	1051-542	-0.024	-0.150	-0.036	-0.162	-52%	-8%
GCS 25-26	542-289	0.073	-0.066	0.099	-0.078	36%	-18%

The annual specific sediment yield (metric tonnes/yr-km^2) was computed at the outlet for both models. The GSTARS models were 3 year simulations. The cumulative sediment load for the simulation was divided by 3 to compute the annual sediment yield. The SIAM model results always represent an annual loading estimate. The GSTARS models predict a 1% decrease (86.5 to 85.3 tonnes/yr-km^2) in the annual sediment yield due to the changes in the hydrologic regime. The SIAM models predict a 4% decrease (38.7 to 37.3 tonnes/yr-km^2) in the annual sediment yield as a result of the urban hydrologic changes.

6.10.3 INVESTIGATION OF THE EFFECTS OF VALLEY SUBSIDENCE ON CHANNEL STABILITY

Both streams have been subject to base-level lowering as a result of groundwater extraction and subsequent valley floor subsidence. Data from Poland and Ireland (1988) were utilized to construct valley subsidence profiles for both streams along the study reach extents. Maximum base-level lowering has been greater for Upper Penitencia Creek (1.1 m) when compared to Berryessa Creek (0.23 m) within the surveyed study reaches. The effect of base-level lowering was simulated using the GSTARS-1D and SIAM models. The presently surveyed cross section data cannot be used to model base level lowering because subsidence was halted during the time period from the late 1960s to the early 1970s (Poland and Ireland 1988). The cross sections surveyed in 2004 have had approximately 25 years to adjust to the base-level lowering. Therefore, the geometry from conceptual historic models of the watersheds was used to simulate base-level lowering. The geometry in these models did use upstream surveyed cross sections that were outside of the zone of influence of both subsidence and urbanization. The effect of altered urban flow regime must also be eliminated to directly study the effect of base-level lowering; therefore, the historic geometry with the historic hydrology was chosen to model this process. The models were run with and without base-level lowering to investigate stream response to this forcing variable.

The rate of base-level lowering at each cross section calculated from the subsidence profiles was amortized over a 30-year time period for the GSTARS-1D models. The SIAM models do not incorporate a time step; therefore, full base-level lowering was applied to all cross sections within the zone of subsidence influence for this model.

6.10.3.1 BERRYESSA CREEK SUBSIDENCE MODELING RESULTS

Results of the sediment transport modeling of base level lowering for Berryessa Creek are provided in Table 6.18.

Table 6.18 **Summary data from subsidence comparison for Berryessa Creek.**

		Historic geometry no subsidence		Historic geometry with subsidence			
Historic reaches	River stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 2	2298-2192	-	-	-	-	-	-
GCS 4	2192-1996	0.999	-0.050	0.999	-0.051	0%	-2%
Upstream of Old Piedmont	1996-1813	-0.318	-0.050	-0.328	-0.050	-3%	0%
Old Piedmont to Sed basin	1813-1447	0.093	-0.025	0.091	-0.026	-2%	-4%
Sed basin to Sweigert Creek	1447-1167	-0.066	-0.015	-0.061	-0.016	7%	-5%
Sweigert to footbridge	1167-609	0.040	-0.014	0.035	-0.017	-12%	-25%
Footbridge to Crosley Creek	609-357	0.124	-0.011	0.162	-0.018	30%	-61%
Crosley to outlet	357-0	0.041	-0.012	0.003	-0.014	-93%	-12%

The Berryessa Creek data show that valley subsidence did have an effect on erosion trends in the lower portion of the valley. The effects are strongest in the reach upstream of the zone of maximum subsidence the GSTARS-1D models indicate a 61 % increase in erosion rates due to subsidence in the reach upstream of the Crosley culvert outfall. In this reach erosion rates increase from 0.011 to 0.018 m/yr due to the subsidence. The cumulative change in thalweg lowering due to subsidence is shown in Figure 6.20. The effect of the base-level drop proceeds and reaches a maximum of 0.27 m in the vicinity of river station 500 m, this incision is marginally larger than the overall base-level drop of 0.23 m. The incision dissipates in the upstream direction from this zone. The incision effects are minimal 1000 m upstream of the downstream boundary.

The SIAM model results indicate that the effect of base-level lowering is rather moderate; this is understandable because SIAM does not incorporate a time step and the resulting changes in channel hydraulics due to the 0.23 m base-level drop are rather moderate. The model indicates that there will be some increased transport in the most downstream reach, but SIAM models this reach as depositional and the base-level lowering actually improves channel stability in the lower reaches. Contrary to the GSTARS models the SIAM models indicate that the subsidence will result in increased deposition in the reach upstream of the Crosley culvert outfall.

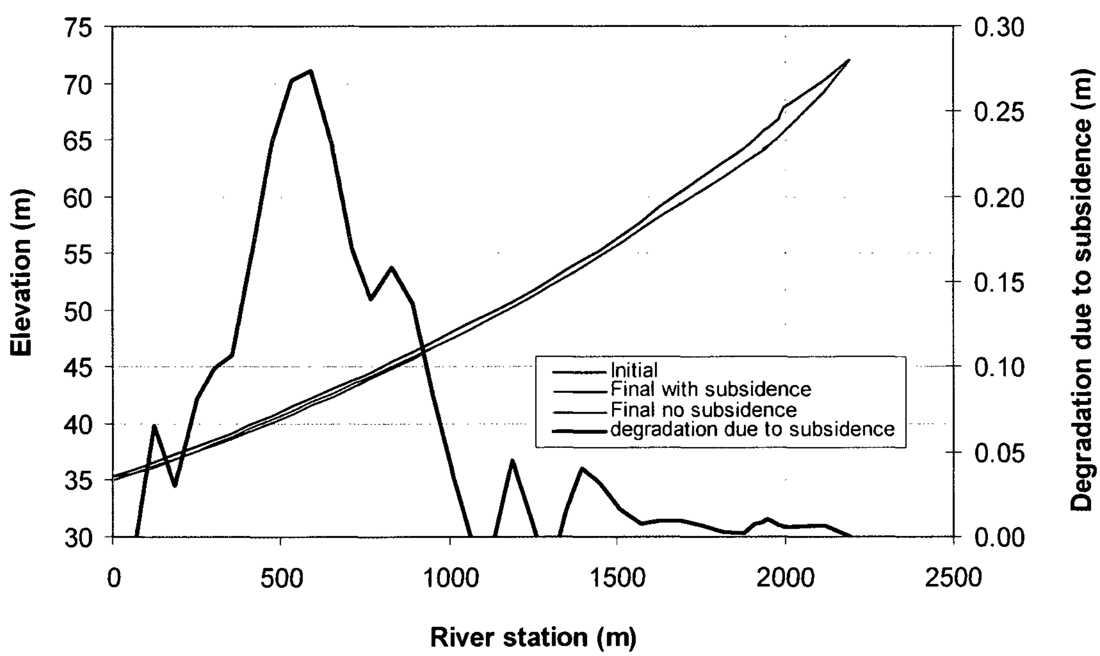


Figure 6.20 Thalweg lowering due to subsidence along the Berryessa Creek longitudinal profile.

6.10.3.2 UPPER PENITENCIA CREEK SUBSIDENCE MODELING RESULTS

Results of the sediment transport modeling of base level lowering for Upper Penitencia Creek are provided in Table 6.19. Rates of erosion modeled in GSTARS-1D increase from the pre-subsidence condition up to the GCS 12-16 reach near river station 4745 m, 4000 m upstream of the zone of maximum subsidence. The model results indicate that the reach GCS 18-19 that was historically stable is shown to be degradational due to the subsidence. The model results show that there is a thousand-fold increase in incision rate in this reach resulting from the subsidence over the 30-year simulation. Channel incision rates are also increased downstream of this reach, and the relative rate increases range from 69 to 224 %. The relative effect of incision due to the subsidence is shown in Figure 6.21. This figure shows the zone of maximum incision near station 1800 m, with incision due to subsidence reaching a maximum depth of 0.65 m. In the 30-year time period the zone of maximum incision has proceeded 1800 m upstream from the zone of maximum subsidence. Values for relative change in the GSTARS-1D models are skewed by the low rates of incision predicted under the no-subsidence condition.

It is important to note that maximum incision rates on Upper Penitencia Creek are smaller than the total base-level lowering depth, while the incision rates on Berryessa Creek are greater than the base-level lowering depth. This indicates the added resistance to erosion on Upper Penitencia Creek due to the coarser stream bed material and well established pavement layer. Berryessa Creek is less resilient and responds more dramatically to perturbation, in part due to the lack of streambed armoring in the lower reaches modeled.

Table 6.19 Summary data from subsidence comparison for Upper Penitencia Creek.

		Historic geometry no subsidence		Historic geometry with subsidence			
Reach Name	Reach stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 1-5	5988-5622	-	-	-	-	-	-
GCS 6-12	5622-4745	-0.049	-0.030	-0.049	-0.032	1%	-7%
GCS 12-16	4745-3484	0.018	0.004	0.013	0.000	-28%	-102%
GCS 16-I 680	3484-2523	0.084	0.010	0.082	0.000	-2%	-100%
GCS 18-19	2523-2096	0.115	-0.001	0.103	-0.016	-11%	-1330%
GCS 20-22	2096-1051	0.014	-0.008	0.020	-0.025	35%	-224%
GCS 23-24	1051-542	0.033	-0.017	0.040	-0.028	22%	-69%
GCS 25-26	542-289	0.005	-0.015	0.007	-0.029	47%	-88%

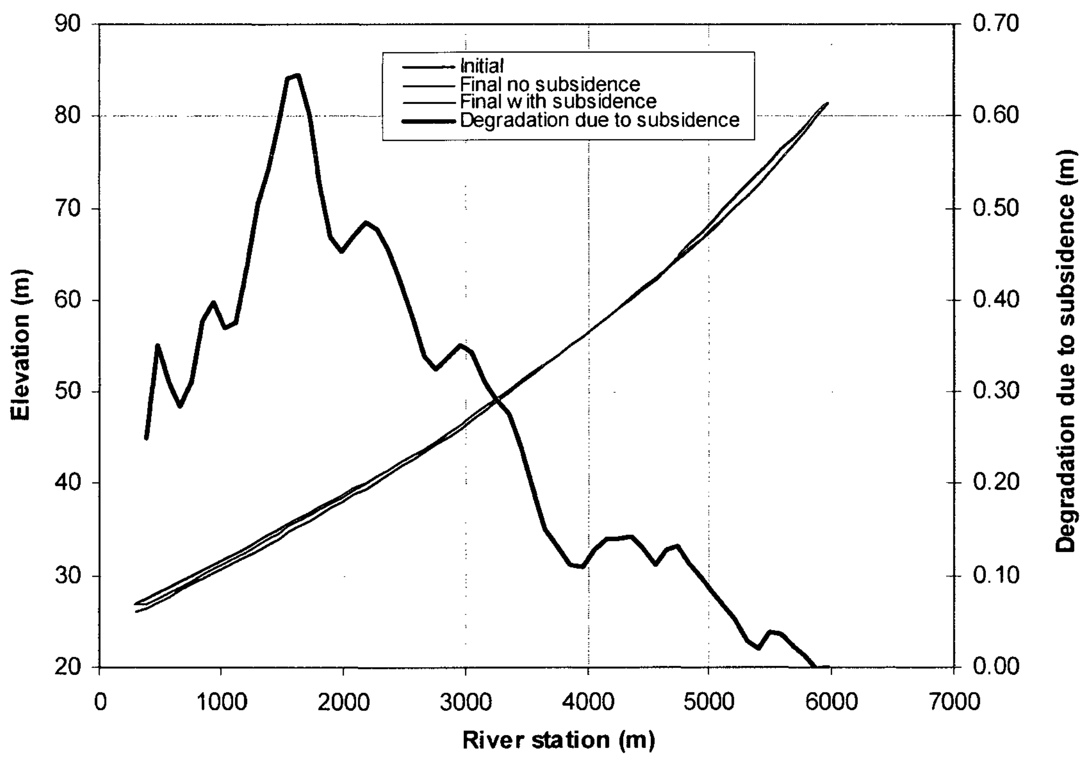


Figure 6.21 Thalweg lowering due to subsidence along the Upper Penitencia Creek longitudinal profile.

Changes in the specific sediment yield at the outlet location were calculated for both streams. Results indicate that the changes in the sediment yield will be minimal due to valley subsidence. The GSTARS models predict that the sediment yield at the outlet of Upper Penitencia Creek will show a slight increase of 0.5% from 75.3 tonnes/yr-km^2 to 75.6 tonnes/yr-km^2 and the SIAM models predict a more substantial increase of 4% from 41.7 tonnes/yr-km^2 to 43.5 tonnes/yr-km^2. In a similar fashion the GSTARS models predict a marginal increase in the sediment yield due to subsidence for Berryessa Creek. The results indicate a 0.3 % increase from 135 tonnes/yr-km^2 to 135.4 tonnes/yr-km^2. The SIAM models for Berryessa Creek predict a more substantial increase in sediment yield of 11 % (75.5 to 83.9 tonnes/yr-km^2).

The SIAM models for Upper Penitencia Creek indicate little morphologic response to the subsidence. This is unlikely due to the magnitude of the base-level lowering. Data from the current and historic longitudinal profiles illustrate this point (Figure 6.22). In this figure the measured stream bed elevation change extracted from archived construction drawings and the stream bed elevation change due to subsidence are plotted on the primary Y-axis. On the secondary Y-axis is the reach-average percent change in unit stream power (velocity and energy slope product) from the hydraulic modeling results. Unit stream power (Yang 1973) is a strong indicator of sediment transport capacity. This figure shows that the maximum increase in unit stream power is immediately downstream of channel degradation near river station 3000 m. Valley subsidence was halted in the late 1960s and the aggradation/degradation data shown are from 1985 to 2004. It is logical that incision would proceed upstream of the zone of maximum stream power increase over the 37-year time period extending from the last date of recorded subsidence in 1967 (Poland and Ireland 1988) to the date of the 2004 longitudinal survey.

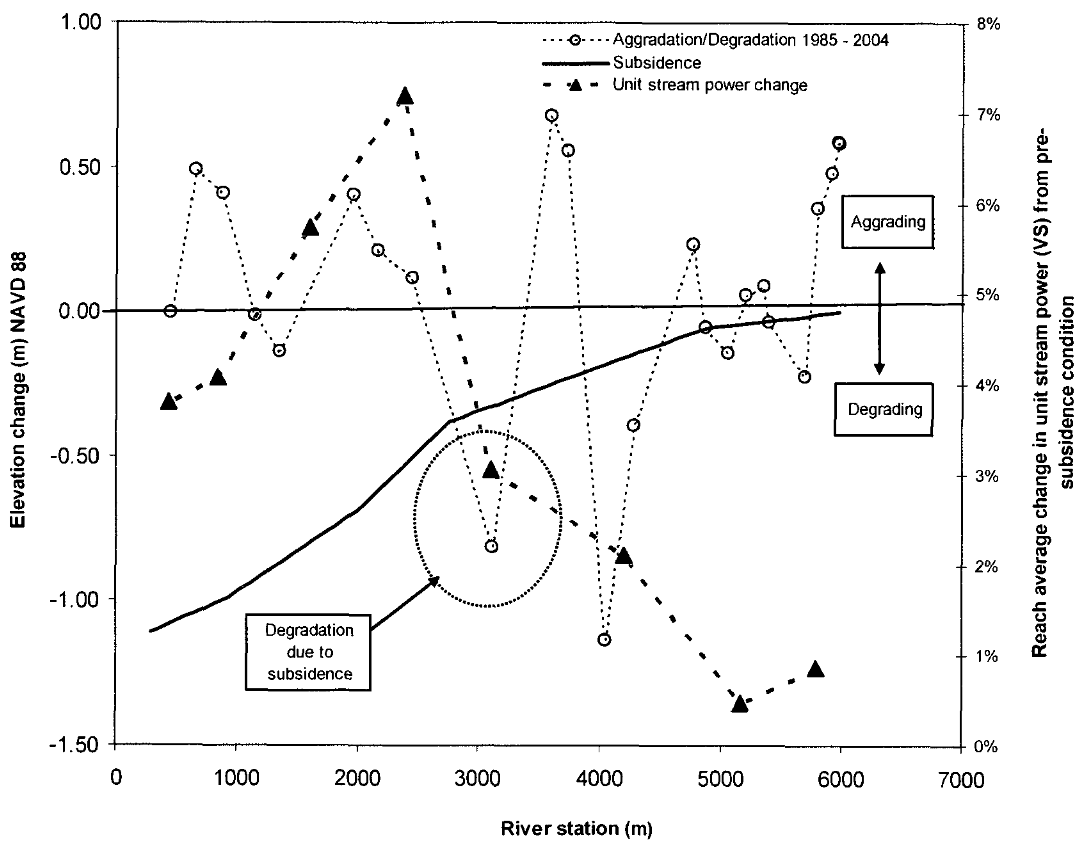


Figure 6.22 Base-level, aggradation/degradation, and stream power trends due to subsidence and slope change on Upper Penitencia Creek.

Another slope perturbation was stream re-alignment that was done during the construction of Interstate 680. In the vicinity of river station 2600 m the local slope was increased 16 % due to this realignment. Both of these slope changes have caused instability in the reaches upstream. This incision is corroborated by field observations (Figure 6.23). Reaches downstream of the incised reach show aggradation since 1985. This is a logical response since sediment that is eroded from the degrading reach is deposited downstream in the zone of maximum subsidence.

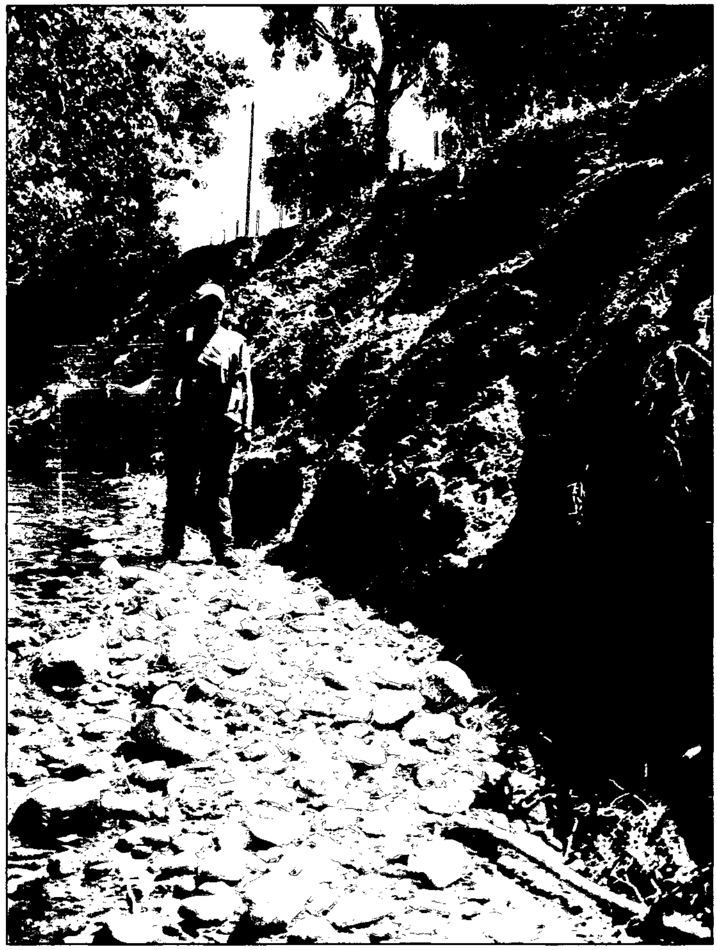
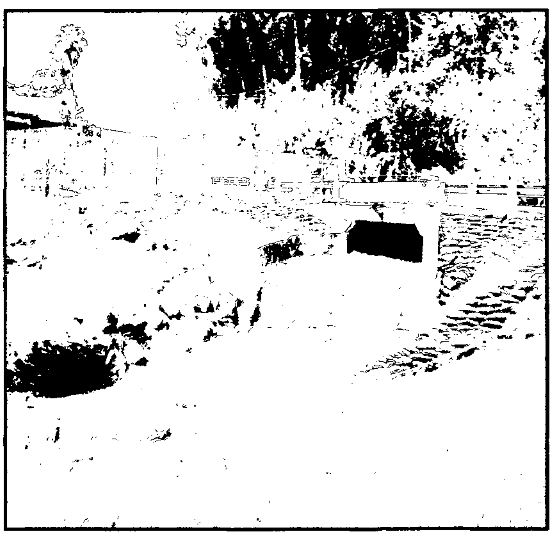


Figure 6.23 Incised reach upstream of I-680 Upper Penitencia Creek (approximate river station 2800 m).

6.10.4 SEDIMENT TRANSPORT INVESTIGATION INTO THE EFFECTS OF URBAN INFRASTRUCTURE ON CHANNEL STABILITY

Engineered river infrastructure is present on both streams. Berryessa Creek has a large grade-control structure at the urban/valley interface (Figure 6.24) and a 3.5 m wide, 155 m long box culvert that leads into a sedimentation basin located 350 m downstream of the drop structure (Figure 6.24). The primary infrastructure present on Upper Penitencia Creek is a series of grade-control structures that are present primarily in the upstream reaches (Figure 6.25). Sediment transport models were run to investigate the effect of these elements on channel stability. Model scenarios 4 and 5 were used to investigate the relative changes in channel stability if the structures were not present. Scenario 4 is the existing conditions model with the current survey data, current hydrology, and the infrastructure in place. Scenario 5 is exactly the same except that the structures were removed and replaced with cross sections that are similar to the adjacent cross sections in the vicinity of the structures. In the GSTARS-1D, models the grade-control structures were modeled with cross section data collected during the 2004 survey and the invert elevations were held constant during the simulations. The geometry of the sedimentation basin was also modeled using the survey data collected in 2004.



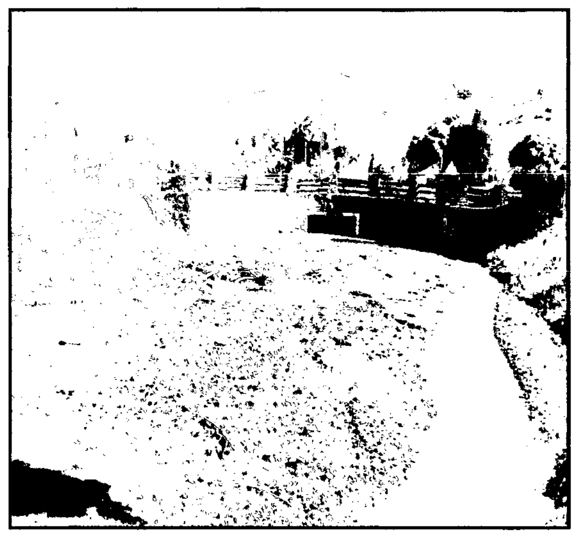


Figure 6.24 Grade control structure and sedimentation basin present on Berryessa Creek.

Figure 6.25 Examples of grade control structures located on Upper Penitencia Creek.

6.10.4.1 BERRYESSA CREEK RESULTS

Results of the infrastructure analysis for Berryessa Creek are presented in Table 6.20.

Table 6.20 Summary data from infrastructure comparison for Berryessa Creek.

		With Infrastructure		Without Infrastructure			
Reach	Reach stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 2	2298-2213	-	-	-	-	-	-
GCS 4	2213-2020	1.109	-0.084	1.150	-0.109	4%	-29%
Upstream of Old Piedmont	2020-1854	-0.341	-0.205	-0.986	-0.229	-189%	-12%
Old Piedmont to Cropley	1854-1521	0.105	-0.096	0.554	-0.049	427%	49%
Sediment basin	1521-1447	0.633	0.075	0.346	-0.006	-45%	-108%
Sed basin to Sweigert Creek	1447-1247	-2.007	-0.35	-1.773	-0.338	12%	3%
Sweigert Creek to footbridge	1247-768	0.703	-0.179	0.703	-0.082	0%	54%
Footbridge to Crosley Creek	768-491	0.016	-0.130	0.016	0.071	0%	154%
Crosley Creek to headcut	491-250	0.220	0.081	0.220	0.076	0%	-6%
Downstream of headcut	250-0	0.068	0.234	0.068	0.232	0%	-1%

Both models indicate that potential instability problems may be introduced to the upstream reaches by removing the grade-control structure present on Berryessa Creek.

The SIAM model indicates that the reach upstream of the grade-control structure (river stations 1854 to 2020 m) will have a 189% increase in degradation potential as a result of removing the grade-control structure. Incision rates increase from 0.34 m/yr to 0.99 m/yr. The GSTARS-1D model indicates that removing the grade control structure will marginally increase the likelihood of incision upstream. The percentage increase in the upstream incision rates range from 12 to 29%. These results are logical since 1.85 m of elevation is presently being held in place by the current grade-control structure. The magnitude in the difference between the SIAM and GSTARS-1D model results stems from the fact that in the GSTARS-1D model the bed material gradation of the active transport layer is updated with each time step. This enables coarse bed material to be recruited into the reach upstream of the grade control due to the increased slope in the reach. The SIAM model does not have this capability and likely over-predicts incision potential. If the grade-control structure were removed it is essential to assure bed stability, possibly by coarsening the stream bed with large boulders and implementing a step-pool channel morphology to hold the grade change.

The channel incision upstream of the grade-control location results in increased sediment supply to the immediate downstream reach located between Old Piedmont Rd. and Cropley Ave. The SIAM model indicates that deposition rates will increase in this reach from 0.105 m/yr to 0.554 m/yr and 427% increase. The rate of 0.554 m/yr is not reasonable, however the trend toward increased deposition in this reach is the most important finding. The GSTARS model predicts that this reach is degradational under existing conditions and that degradation will be mitigated by removing the structure. The degradation rate is predicted to decrease from -0.096 m/yr to -0.049 m/yr, a 49% relative change. Both models are in agreement with regard to the relative trajectory of increased deposition in this reach as a result of removing the current infrastructure.

The SIAM model predicts that altering the geometry of the sediment basin downstream of Cropley Ave. will decrease deposition rates at this location by 45%; the annual deposition rate is predicted to decrease from 0.63 m/yr to 0.35 m/yr. Likewise the GSTARS modeling results indicate that channel stability will be improved by altering the geometry of the sediment basin. Deposition in the sediment basin is predicted to decrease from 0.075 m/yr to a slight degradational trend of -0.006 m/yr. It is unlikely that the reach would be degradational if the sediment basin was decommissioned, but once again the fundamental insight that can be gleaned from the analysis and modeling is that the current aggradation at the site could be mitigated.

Downstream of the sediment basin channel stability is predicted to improve marginally as the SIAM models predicted incision rates drop from -2.01 m/yr to -1.77 m/yr, a 12% change. These incision rates are not realistic, however they do give a relatively indication of downstream channel response to the removal of this structure. The GSTARS models show relatively little morphologic response to the reach immediately downstream of the sediment basin, only a marginal 3% change from a degradation rate -0.35 m/yr to -0.34 m/yr. The reach downstream of the sediment basin is predicted to remain degradational, regardless of whether the structure is there or not. This may be a function of the parameterization of the bed material in this reach. The stream bed is much finer downstream of the sediment basin compared to the upstream reaches, because coarse bedload is currently deposited in the sediment basin. If the sediment basin was removed, over time the existing bed material will likely coarsen as a greater amount of coarse material will be routed through the sediment basin area. This may take many years and these model runs were only 3 year simulations. The SIAM model does not take this into account because there is no time step in the model. The GSTARS model does update the bed gradation of the active transport layer, therefore longer simulations may reveal this morphologic response. Figure 6.26 illustrates the effect of the sediment basin on the transport of gravels to the downstream reaches. These results were taken from the GTSTARS modeling immediately downstream of the sediment basin and they clearly show the increase in sediment yield for gravel sized bed material that results from decommissioning the sediment basin. The model results predict a three-fold increase in gravel sediment yield from 21 metric tonnes/yr to 64 metric tonnes/yr downstream of the existing sediment basin if the sediment basin were decommissioned.

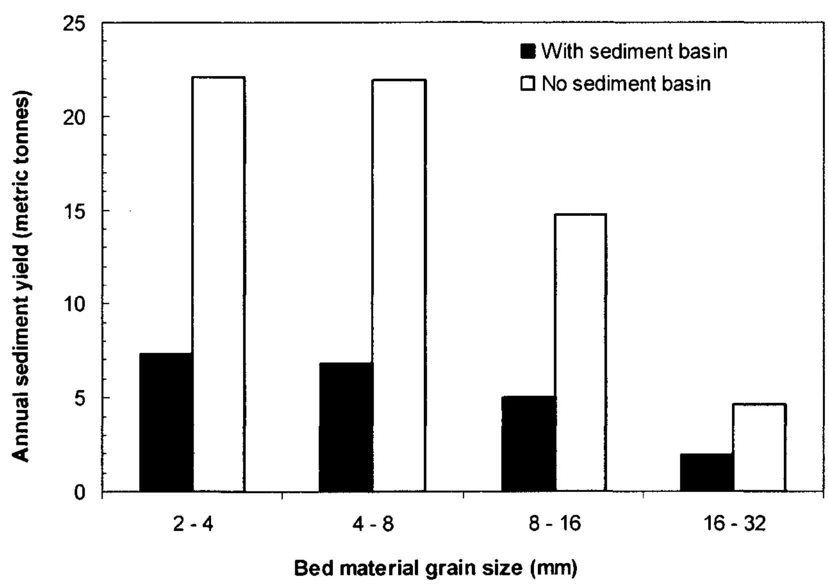


Figure 6.26 Gravel sediment yield changes downstream of the Berryessa Creek sediment basin predicted by GSTARS modeling.

Further downstream of the sediment basin (River stations 1247 to 0 m), channel stability predictions cannot be made with the SIAM modeling because there are no hydraulic alterations downstream of the sediment basin and changes in sediment supply are reflected only in the immediate downstream reach in the SIAM framework. The GSTARS modeling indicates a trend of improved stability. However, a noticeable difference in morphologic response is predicted in the reach from the pedestrian footbridge downstream to the Crosley culvert outfall location. Under existing conditions this reach is predicted to be degradational -0.13 m/yr, however if the sediment basin is removed the reach is predicted to aggradational 0.07 m/yr. This may be a result of the increased sediment supply and subsequent increase in sediment yield that would result from removing the current sediment basin. The changes in the annual specific sediment yield due to the removal of the engineered infrastructure elements were mined from the sediment transport models at the outlet location. The SIAM models do not simulate the changes in bed material load sediment yield at the outlet because the changes in reach scale sediment yield are only reflected in the immediate downstream reach of the change. The GSTARS-1D models indicate that annual specific sediment yield will increase 15% at the outlet from 76.4 to 88.0 metric tonnes/yr-km^2 if the current infrastructure elements are removed. This is logical because the current sediment basin captures are significant portion of the annual sediment load downstream of Cropley Ave.

6.10.4.2 UPPER PENITENCIA CREEK RESULTS

The results of the sediment transport analysis for Upper Penitencia Creek are presented in Table 6.21. The modeled infrastructure elements on Upper Penitencia Creek consist of a series of grade-control structure located between river stations 4096 to 5543 m and one drop structure located at river station 1495 m. The drop structures range in height from 0.3 to 1.25 m. It is proposed that these drop structures aid in channel stability in the upper reaches.

Table 6.21 Summary data from infrastructure comparison for Upper Penitencia Creek.

		With Infrastructure		Without Infrastructure			
Reach Name	Reach stationing	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM erosion or deposition	GSTARS erosion or deposition	SIAM % change	GSTARS % change
	(m)	(m/yr	(m/yr)	(m/yr)	(m/yr)		
GCS 1-5	5988-5622	-	-0.14	-	-0.36	-	-157%
GCS 6-12	5622-4745	0.16	-0.05	0.16	-0.21	-1%	-306%
GCS 12-16	4745-3484	-0.06	-0.06	-0.05	-0.08	21%	-41%
GCS 16 - I-680	3484-2523	0.06	0.17	0.12	0.22	104%	29%
GCS 18-19	2523-2096	0.08	0.13	0.08	0.14	0%	12%
GCS 20-22	2096-1051	0.02	-0.07	0.00	-0.07	-93%	-12%
GCS 23-24	1051-542	-0.04	-0.15	-0.01	-0.16	74%	-8%
GCS 25-26	542-289	0.10	-0.07	0.10	-0.06	0%	12%

The majority of the drop structures are located in the sediment reach named GCS 6-12. GSTARS-1D model results indicate that these structures do improve channel stability within this reach. Modeled erosion rates in this reach are 0.05 m/yr with the structures and 0.21 m/yr without the structures. This is a 306% increase in modeled incision rate without the structures. The upstream reach GCS 1-5 was included in the analysis of the GSTARS-1D model to investigate upstream response to the removal of the drop structures. Model results indicate that incision would migrate upstream into this reach as well, with an annual incision rate increasing from 0.14 m/yr to 0.36 m/yr, a 157% increase within this reach. The GSTARS-1D model indicates that these structures do provide added channel stability in the upstream reaches. The model also predicts that the increased incision will magnify downstream deposition rates. Deposition in the downstream reach (River stations 2523-3484 m) is predicted to increase from 0.17 m/yr to 0.22 m/yr, a 29% increase. Channel stability in the downstream reaches shows minimal change in the GSTARS-1D models.

The SIAM model does not indicate that channel stability will change in the GCS 6-12 reach if the grade-control structures in the upstream reaches are removed. The SIAM model utilizes reach-averaged hydraulic properties and the hydraulic effect of these structures is minimal if reach-average properties are used. The hydraulic impact of these structures is localized due to the relatively steep gradient of the stream and relatively small drop height of the structures. The stability they provide as fixed elevations along the longitudinal profile is not modeled in SIAM. SIAM does pick up the increase in downstream deposition rates in the vicinity of river stations 2523 to 3484 m. Deposition rates increase from 0.06 m/yr to 0.12 m/yr, a 104% increase, within this reach. The SIAM models indicate that channel stability would be improved by removing the downstream drop structure at river station 1495 m. Upstream sediment supply and transport capacity are in balance in the reach where the drop structure is located, GCS 20-22 (River stations 1051 to 2096 m), as well as the downstream reach (erosion rate of 0.01 m/yr), if the drop structure were not in place. However this is not feasible because the structure is currently utilized to divert flow into an offsite ground water percolation pond at the site.

The changes in the annual specific sediment yield due to the removal of the engineered infrastructure elements were mined from the sediment transport models at the outlet location. The SIAM models do not simulate the changes in bed material load sediment yield at the outlet because the changes in reach scale sediment yield are only reflected in the immediate downstream reach of the change. The GSTARS-1D models indicate that annual specific sediment yield will increase 3% at the outlet from 85.3 to 87.9 metric tonnes/yr-km^2 if the current infrastructure elements are removed.

6.11 SUMMARY POINTS FROM THE SEDIMENT TRANSPORT ANALYSIS

A sediment transport analysis was carried out for the Berryessa and Upper Penitencia Creek watersheds. Six modeling scenarios were simulated with the GSTARS-1D and SIAM sediment transport models to investigate the effects of the following changes on channel stability and sediment yield:

1. Hydrologic alteration to the historic flow regime due to increased impervious land cover, drainage area manipulation and water diversion;
2. Urbanization infrastructure elements including grade-control structures, sedimentation basins, and instream culverts and;
3. Historic valley subsidence from the period of time between 1939 and 1969.

The sediment transport models were also compared to measured observations to determine the efficacy of the models to simulate existing conditions and the efficacy of sediment transport relationships to model measured cross section aggradation/degradation data from a 3-year period. A summary table of the resulting changes in the annual specific sediment yield at the outlet location for all of the modeling scenarios is presented in Table 6.22.

Table 6.22 Sediment yield summary for sediment transport modeling simulations.

		Sediment yield (metric tonnes/yr-km2)	
Berryessa Creek	**Model**	**GSTARS**	**SIAM**
	Historic conditions (historic geometry and historic flow regime)	135.0	75.5
	Historic geometry/historic flows with subsidence	135.4	83.9
	Historic geometry with urban flow regime	147.0	121.3
	Current surveyed geometry with historic flow regime	73.4	54.2
	Current surveyed geometry with urban flow regime	76.4	86.3
	Current surveyed geometry with urban flow regime and no infrastructure elements	88.0	86.3
	Change in sediment yield due to subsidence (historic models)	**0.3%**	**11%**
	Change in sediment yield due to urbanization and drainage area capture (historic models)	**9%**	**61%**
	Change in sediment yield due to urbanization and drainage area capture (current geometry models)	**4%**	**59%**
	Change in sediment yield due to current infrastructure	**-15%**	**0%**
Upper Penitencia Creek			
	Historic conditions (historic geometry and historic flow regime)	75.6	41.7
	Historic geometry/historic flows with subsidence	75.3	43.5
	Historic geometry with urban flow regime	69.5	39.8
	Current surveyed geometry with historic flow regime	86.5	38.7
	Current surveyed geometry with urban flow regime	85.3	37.3
	Current surveyed geometry with urban flow regime and no infrastructure elements	87.9	37.3
	Change in sediment yield due to subsidence (historic models)	**-0.5%**	**4%**
	Change in sediment yield due to urbanization, drainage area reduction, and flow diversion (historic models)	**-8%**	**-4%**
	Change in sediment yield due to urbanization, drainage area reduction, and flow diversion (current geometry models)	**-1%**	**-4%**
	Change in sediment yield due to current infrastructure	**-3%**	**0%**

Key findings of this analysis are:

- A combination of the Yang (1973) and Yang (1984) sand and gravel transport functions provided the most realistic prediction of the observed longitudinal erosion and deposition trends among the transport equations available in GSTARS-1D and was therefore used to model the hypothetical scenarios.

- Model results indicate that alterations to the effective catchment area and urban flow regime in Berryessa Creek have greatly increased channel instability, particularly downstream of culvert outfalls from captured drainages. Reaches that were historically depositional become incised under the current urban hydrologic regime. All of the modeling scenarios predict significant increases in specific sediment yield at the basin outlet. The predictions of increased sediment yield range from 4 to 61% depending on the modeling scenario.

- Model results indicate that the current effective catchment network and urbanized flow regime have minimal effect on channel stability in Upper Penitencia Creek. All of the modeling scenarios predict a decrease in annual sediment yield resulting from the current hydrologic regime compared to the historic hydrologic regime. The predictions range from a 1 to 8% decrease in sediment yield resulting from the current Upper Penitencia hydrologic regime.

- Valley subsidence can be expected to induce channel incision in both streams due to increases in channel slope. Berryessa Creek experienced 0.23 m of base-level drop and the GSTARS models predict channel incision will reach a maximum of 0.27 m approximately 500 m upstream of the outlet location. Upper Penitencia Creek experienced 1.11 m of base-level drop at the outlet location and the GSTARS models predict channel incision will reach a maximum of 0.64 m approximately 1800 m upstream of the outlet location. GSTARS modeling results predict minimal changes in sediment yield for both streams due to the subsidence. A 0.3% increase is predicted for Berryessa Creek and a 0.5% decrease is predicted for Upper Penitencia Creek. The SIAM models predict an 11% increase in sediment yield for Berryessa Creek and a 4% increase for Upper Penitencia Creek.

- Results of the subsidence modeling and analysis of reach scale unit stream power changes coupled with historic longitudinal profile data and field observations indicate that valley subsidence and channel straightening in the vicinity of I-680 have resulted in increased stream power upstream of I-680. The combination of the subsidence and channel re-alignment are likely the primary causes of localized channel instability observed upstream of I-680 on Upper Penitencia Creek.

- Existing infrastructure elements on Berryessa Creek include a 1.85 m grade-control structure at the upland-valley interface and an on-line sedimentation basin downstream. Sediment transport modeling indicates that removal of the grade-control structure can result in the potential for upstream channel instability and downstream sedimentation problems. Model results also indicate that downstream channel stability can be improved if the sediment basin is re-configured to better transport gravel size bed material to downstream reaches. It is predicted that the annual sediment yield at the outlet (300 m upstream of Morrill Ave.) will be increased by 15% if the existing infrastructure elements are removed.

- Existing infrastructure present on Upper Penitencia Creek includes a series of drop structures in the upstream reaches. Modeling results indicate that these drop structures improve upstream channel stability by preventing incision in these reaches. GSTARS models predict a 4-fold increase in the channel incision rate if the structures were not present. Model results indicate that if the structures were removed the annual sediment yield at the basin outlet would be increased by 3%.

7.0 CONCLUSIONS AND RECOMMENDATIONS.

7.1 CONCLUSIONS

A detailed geomorphic assessment was conducted to investigate the comparative response of two adjacent watersheds to flow regime changes resulting from urbanization, valley subsidence, and constructed river engineering infrastructure. Components of the quantitative urban geomorphic assessment include historical analysis of the pre-urban geomorphic state, time-series morphometric analysis to gain insight into changes imposed by urbanization on the historic condition, investigation into historic data sources to quantify longitudinal profile change, field survey data to quantify the existing morphologic state and current rates of channel change, hydrologic analysis to quantify the altered urban flow regime, and sediment transport analysis to investigate channel response to the potential drivers of channel change.

Over 9 km of detailed longitudinal profile data were gathered, 128 bed material gradations were sampled and 90 permanent cross sections were monumented and surveyed on both streams, establishing a permanent network that can be monitored over many years to investigate channel change in an urban context.

The research objectives and major findings related to the objectives of the study are:

1. **Perform a comparative analysis of the factors leading to channel instability and/or stability in two adjacent watersheds that have encountered vastly different morphologic response to urbanization despite similar upland watershed characteristics. This will be accomplished through historical data**

analysis, field observations and measurements, and numerical hydrologic and sediment transport modeling.

- Field observations of channel stability indicate that Berryessa Creek is an unstable stream system and Upper Penitencia Creek is generally a stable stream system with areas of localized instability.

- The ephemeral flow regime of Berryessa Creek results in sparse riparian vegetation that provides little resistance to bank erosion process, while Upper Penitencia Creek is supplied with consistent base-flow that has promoted abundant riparian vegetation that is resilient to bank erosion processes.

- Berryessa Creek has a higher rate of sediment supplied from the upstream watershed which results in a more heterogeneous bed material composition ranging from sands to cobbles. This bed material gradation is more susceptible to erosion than the primarily cobble/gravel bed of Upper Penitencia Creek.

- Three of years of cross section surveys revealed that average yearly adjustments typically range from +/- 0.05 m/yr. Patterns in erosion and deposition typically oscillate around equilibrium values with greater oscillation observed on Berryessa Creek. Berryessa Creek cross sections are also more likely to be degradational compared to Upper Penitencia Creek. Areas of deposition are typically associated with failing stream banks and lateral channel migration indicating large amounts of sediment are introduced locally within the urbanized valley.

- Historical longitudinal profiles created by the investigating author revealed a system-wide degradational trend for Berryessa Creek from 37 years of data. Quasi-equilibrium with some localized areas of erosion and deposition were observed for Upper Penitencia Creek from 20 years of data.

- Morphometric analysis results indicate that while both basins have been subject to similar urbanization trends with regard to increases in impervious area, drainage area capture by the constructed storm sewer network has increased the contributing drainage area in directly hydraulic connectivity with Berryessa Creek by 20% for the entire watershed and 122% within the low relief valley from historic conditions. The storm sewer network in Upper Penitencia Creek has resulted in a net loss of 3% of the total contributing drainage area and a 29% net loss within the valley.

- Flow diversion has also taken place on Upper Penitencia Creek as peak flow shaving is used to export water into ground water percolation ponds modifying the downstream hydrologic regime from historic conditions

- The primary infrastructure elements on Berryessa Creek are a 1.85 m grade-control structure, a 155 m long box culvert and an online sedimentation basin. Sediment transport results indicate that the sedimentation basin contributes to downstream incision by capturing coarse bedload; this was corroborated with field measurement of stream bed material and cross section measurements.

- A series of drop structures ranging in height from (0.3 to 1.25 m) are in place on the upstream reaches of Upper Penitencia Creek. Modeling results indicate that these structures aid in the stability of the upstream reaches.

A summary table of the comparative analysis is provided in Table 7.1.

Table 7.1 Summary of comparative watershed analysis.

	Berryessa Creek	Upper Penitencia Creek
Basin characteristics		
	High sediment supply	Lower sediment supply
	Ephemeral flows result in sparse vegetation	Upstream reservoir and natural springs provide continous baseflow resulting in abundant riparian vegetation
	Bed material consists of heterogeneous mix of sand, gravel, and cobbles	Bed material consists of primarily cobbles and gravels
	Generally unstable	Generally stable
Urbanization		
	Drainage area capture resulting from the storm sewer network	Drainage area reduction resulting from the storm sewer network
	Engineered structures promote local sedimentation and downstream instability	Engineered structures promote upstream channel stability
	No flow diversion	Flow diversion of runoff to off-channel percolation ponds
	Watershed urban land use 14% (85% urban in valley)	Watershed urban land use 7% (76 % urban in valley)
	48% increase in water yield from historic conditions	7 % increase in water yield from historic conditions
	Increase in sediment yield due to urban flow regime (range 9 to 61%)	Decrease in sediment yield resulting from urban flow regime (range 4 to 8 %)
	Change in historic flow regime results in channel instability	Channel stability is un-affected by urban flow regime
Subsidence		
	0.23 m base-level drop at outlet of study area	1.11 m base-level drop at outlet of study area
	Subsidence effects are small relative to urbanization effects	Isolated channel instability due to subsidence and channel re-alignment

2. **Investigate the relative effects of drainage area manipulation via the storm sewer network, increased imperviousness due to urbanization infill and flow diversion on typical storm hydrographs. The effects of the urban hydrologic changes on water yield, sediment yield, and channel stability will be quantified via numerical modeling for both streams.**

    - Results indicate that the hydrologic regimes Upper Penitencia and Berryessa Creek have encountered distinctly different alterations from the construction of the urban storm sewer network and off-channel percolation ponds.

    - Flood peaks (47%) and volumes (37%) have been magnified on Berryessa Creek due to drainage area capture alone. Flood peaks (77%) and volumes (66%) have been increased from historic non-urbanized conditions at the outlet location of the study site.

    - At the downstream outlet the specific water yield for a series of typical yearly storm events increased from 31.2 to 46.1 ($1000m^3/km^2$), a 48% increase, due to drainage area capture and urban land use change. If drainage area capture were not considered the net increase in water yield due to urban land use change would only be 13%.

    - Model results for Upper Penitencia Creek at the downstream outlet location (Berryessa Industrial Park) show a 23% net decrease in flood peak and a 19% net decrease in flood volume due to flow diversion and topographic drainage area reduction. Modeling results indicate that in the current hydrologic regime the flood peak has decreased 12% and flood volume has increased 9% at the basin outlet compared to historic conditions. Without drainage area and flow diversion modification flood peaks (15%) and volumes (29%) would have increased due to watershed imperviousness.

- Specific water yield analysis indicates that the existing urban flow regime produces 7% more water than historic conditions at the gaging outlet, an increase from 64.3 to 68.6 ($1000m^3/km^2$). However if drainage area reduction and flow diversion were not present in this system, modeling results indicate that there would be a 28% increase in water yield at the outlet from historic conditions (64.3 to 82.2 $1000m^3/km^2$). This indicates that the water diversion and drainage area reduction effectively off-set the effects of urban land use change on the flow regime in Upper Penitencia Creek.

- These hydrologic changes have resulted in channel instability and increased sediment yield on Berryessa Creek validate by sediment transport modeling. Predicted increases in sediment yield range from 9 to 61%. Hydrologic changes transformed historically depositional reaches into incising reaches.

- The morphologic effects of the urban flow regime on Upper Penitencia Creek have been minimal. Sediment transport models predict a decrease in sediment yield ranging from 1 to 8 % depending on the modeling scenario. The urban flow regime has a minimal effect on channel stability as flow diversion to the percolation ponds is off-set by increased water yield from the impervious areas.

3. **Investigate the effect of valley subsidence on channel stability and sediment yield for both streams using numerical modeling, historic data sources and field observations.**

   - Valley subsidence can be expected to induce channel incision in both streams due to increases in channel slope. Berryessa Creek experienced 0.23 m of base-level drop and the GSTARS models predict channel incision will reach a maximum of 0.27 m approximately 500 m upstream of the outlet location. Upper Penitencia Creek experienced 1.11 m of base-level drop at the outlet location and the GSTARS models predict channel incision will reach a maximum of 0.64 m approximately 1800 m upstream of the outlet location. GSTARS modeling results predict minimal changes in sediment yield for both streams due to the subsidence. A 0.3% increase is predicted for Berryessa Creek and a 0.5% decrease is predicted for Upper Penitencia Creek. The SIAM models predict an 11% increase in sediment yield for Berryessa Creek and a 4% increase for Upper Penitencia Creek.

   - Results of the subsidence modeling and analysis of reach scale unit stream power changes coupled with historic longitudinal profile data and field observations indicate that valley subsidence and channel straightening in the vicinity of I-680 have resulted in increased stream power upstream of I-680. The combination of the subsidence and channel re-alignment are likely the primary causes of localized reach scale channel instability observed upstream of I-680 on Upper Penitencia Creek.

- Presently observed subsidence effects on Berryessa Creek are more ambiguous due to other processes affecting channel stability, namely flow and sediment regime alteration, after the subsidence drawdown period.

In summary hydrologic and river engineering infrastructure changes to Berryessa Creek have adversely affected channel stability. The instability is system-wide within the valley portion of the watershed. This instability was documented with field measurements and observations. Valley subsidence and local channel straightening have resulted in reach scale channel instability on Upper Penitencia Creek. This was documented with historic longitudinal profile data and current field measurements and channel observations. The urban hydrologic regime and river infrastructure have not negatively affected channel stability, particularly in the upstream reaches.

7.2 UNIQUE CONTRIBUTIONS PROVIDED BY THIS RESEARCH

1. The hydrologic effects of watershed urbanization have been well documented in previous studies; however these studies typically document a change in impervious land cover within a fixed catchment area and the subsequent effects of this land use change on the hydrologic regime. This study is unique,

in that it documents changes in the watershed structure due to drainage area capture via the constructed storm sewer network as an added component of watershed urbanization. The hydrologic and morphologic implications of the drainage area capture were quantified via numerical modeling for two adjacent watersheds with opposing tendencies with respect to this driving variable.

2. The effects of valley subsidence on channel form and process have been studied conceptually and in flume studies, however little research has been conducted on field documented channel response to valley subsidence. This study couples historical research, field data collection, and numerical modeling to document the effects of valley subsidence on channel stability and sediment yield.

3. An extensive field monitoring network and protocol for data collections, as well as a GIS based historical analysis have been established in two urban streams in the Santa Clara Valley region of California. Long-term monitoring (more than 10 years) of the monumented cross sections and longitudinal profiles will provide valuable information on channel response to urbanization, valley subsidence and river infrastructure changes.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

1. The cross section resurveys should be continued by SCVWD or other research staff on an annual or at least a biennial basis to continue to document channel change over a longer time scale.

2. Similar data sets should be collected by SCVWD or other research staff to develop a regional database that can be used for stream restoration design; it would be useful to collect data sets from differing hydrologic and hydraulic settings to investigate channel response under a variety of scenarios.

3. A centralized database should be developed in the area archiving both current field measurements as well as historic data sources and that dataset be made available to the scientific and restoration design community to inform future research and restoration design in the region.

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APPENDIX A

Bankfull cross section data

Berryessa Creek 3 year average bankfull channel characteristics.

XS ID	XS Type	Local slope (m/m)	Station (m)	BF area (m^2)	BF stage (m)	BF width (m)	Max BF depth (m)	Avg. BF depth (m)	Width/depth
2	Riffle	0.065	2298	1.61	77.19	4.50	0.52	0.36	12.62
4	Riffle	0.078	2192	1.83	72.76	4.28	0.64	0.42	10.10
5a	Bend	0.033	1997	2.84	68.36	6.28	0.69	0.44	14.50
5b	Bend	0.033	1988	2.45	67.97	6.19	0.72	0.38	16.53
5c	Bend	0.033	1982	2.54	67.69	5.22	0.76	0.46	12.06
6a	Bend	0.029	1948	1.49	66.64	4.06	0.56	0.35	11.72
6b	Bend	0.029	1940	2.04	66.60	4.31	0.78	0.45	9.98
6c	Bend	0.029	1932	2.48	66.37	4.84	0.78	0.48	10.86
7	Riffle	0.019	1912	1.53	65.68	4.11	0.61	0.35	11.62
8	Headcut_US	0.028	1808	2.07	61.17	4.18	0.76	0.47	9.36
9	Headcut_DS	0.007	1798	1.71	60.93	3.59	0.75	0.46	8.55
10	Headcut_US	0.007	1778	1.85	60.59	4.76	0.68	0.37	13.90
11	Headcut_DS	0.006	1768	1.61	60.22	4.47	0.60	0.36	12.61
12a	Bend	0.013	1447	1.29	55.51	4.25	0.43	0.29	14.51
12b	Bend	0.013	1436	1.20	55.39	4.73	0.40	0.24	22.04
12c	Bend	0.013	1431	1.43	55.43	5.52	0.51	0.25	22.57
14	Riffle	0.005	1321	1.10	53.50	3.97	0.47	0.27	14.99
15a	Bend	0.016	1265	1.18	52.49	3.80	0.58	0.31	12.24
15b	Bend	0.016	1254	1.97	52.42	5.47	0.56	0.36	15.42
15c	Bend	0.016	1247	1.81	52.24	5.05	0.53	0.36	14.12
16a	Bend	0.005	1168	1.09	50.54	2.87	0.58	0.37	7.92
16b	Bend	0.005	1157	0.98	50.48	2.48	0.73	0.38	6.59
16c	Bend	0.005	1153	1.39	50.56	2.68	0.92	0.49	5.50
16-2a	Bend	0.008	1108	1.54	49.69	3.88	0.74	0.39	9.98
16-2b	Bend	0.008	1103	2.25	49.76	4.28	0.87	0.52	8.32
16-2c	Bend	0.008	1099	1.85	49.68	3.41	0.89	0.54	6.30
17a	Bend	0.014	1095	1.62	49.56	3.71	0.71	0.43	8.87
17b	Bend	0.014	1091	1.40	49.37	3.69	0.52	0.37	10.77
17c	Bend	0.014	1087	1.45	49.38	3.35	0.67	0.43	8.00
19	Riffle	0.016	1039	1.42	48.53	4.10	0.51	0.34	12.33
20	Riffle	0.015	924	0.99	46.62	2.77	0.51	0.34	8.39

XS ID	XS Type	Local slope	Station	BF area	BF stage	BF width	Max BF depth	Avg. BF depth	Width/depth
		(m/m)	(m)	(m^2)	(m)	(m)	(m)	(m)	
21a	Bend	0.015	776	1.19	44.37	2.60	0.58	0.45	6.30
21b	Bend	0.015	773	1.22	44.28	2.38	0.69	0.49	5.56
21c	Bend	0.015	769	1.13	44.21	2.78	0.57	0.40	7.21
23	Riffle	0.010	610	2.15	42.29	4.18	0.66	0.46	9.20
24a	Bend	0.014	583	1.65	41.83	3.63	0.59	0.44	9.00
24b	Bend	0.014	577	1.45	41.70	3.59	0.52	0.38	10.05
24c	Bend	0.014	570	1.69	41.63	4.46	0.57	0.36	12.78
25	Riffle	0.006	526	1.41	41.15	3.20	0.58	0.43	8.05
26a	Bend	0.010	504	1.51	40.89	4.53	0.49	0.33	14.46
26b	Bend	0.010	498	1.51	40.90	4.03	0.60	0.38	11.35
26c	Bend	0.010	492	1.51	40.79	4.33	0.51	0.35	12.78
27a	Bend	0.011	357	3.15	39.11	7.48	0.63	0.40	20.84
27b	Bend	0.011	353	3.56	39.22	6.52	0.89	0.54	12.13
27c	Bend	0.011	349	2.37	39.06	5.96	0.80	0.38	18.77
28	Headcut_US	0.005	263	2.28	38.31	6.13	0.64	0.36	17.07
29	Headcut_DS	0.004	243	2.47	37.61	3.46	1.13	0.65	4.99

*BF=bankfull stage values

Upper Penitencia Creek bankfull channel characteristics.

XS ID	XS Type	Local slope (m/m)	Station (m)	BF area (m^2)	BF stage (m)	BF width (m)	Max BF depth (m)	Avg. BF depth (m)	Width/depth
1	Headcut US	0.027	5988	4.76	82.20	10.44	0.45	0.74	22.97
2	Headcut DS	0.010	5973	3.68	82.00	7.23	0.49	0.87	14.70
3	Riffle	0.010	5919	4.17	80.88	9.14	0.45	0.63	20.78
4-a	Bend	0.007	5797	3.85	78.99	7.21	0.52	0.90	14.61
4-b	Bend	0.007	5792	4.10	78.92	7.91	0.50	0.68	17.31
4-c	Bend	0.007	5787	4.59	78.78	9.18	0.48	0.70	20.08
5	Riffle	0.009	5699	3.43	77.61	5.46	0.61	0.93	9.71
6	Riffle	0.002	5394	4.93	72.25	7.66	0.64	0.98	14.19
7	Riffle	0.004	5348	5.96	71.77	11.01	0.54	0.72	20.82
8-a	Bend	0.006	5203	7.18	70.10	11.51	0.60	0.96	19.66
8-b	Bend	0.006	5198	6.16	70.06	10.13	0.59	1.00	17.38
8-c	Bend	0.006	5191	8.42	70.09	12.18	0.68	1.09	19.49
9-a	Bend	0.004	5054	5.75	68.21	8.81	0.65	1.15	13.69
9-b	Bend	0.004	5051	5.32	68.21	7.30	0.72	1.38	10.54
9-c	Bend	0.004	5048	5.82	68.14	8.58	0.67	1.19	13.31
10	Bend	0.018	4874	4.94	66.27	7.89	0.60	0.89	13.85
12-a	Bend	0.006	4758	3.74	64.73	8.87	0.43	0.79	21.15
12-b	Bend	0.006	4751	4.12	64.78	8.25	0.49	0.73	16.77
12-c	Bend	0.006	4745	3.69	64.63	8.00	0.46	0.71	18.91
13	Riffle	0.016	4284	4.03	58.69	6.61	0.60	0.85	11.26
14	Riffle	0.017	4048	4.52	56.06	7.51	0.59	0.93	12.98
15	Riffle	0.015	3733	3.64	53.33	7.35	0.48	0.66	16.80
16-a	Bend	0.028	3598	3.60	52.12	8.67	0.41	0.80	21.77
16-b	Bend	0.028	3590	4.73	52.17	8.64	0.54	0.89	16.19
16-c	Bend	0.028	3577	4.66	51.94	7.33	0.60	0.93	12.13
17-a	Bend	0.005	3112	4.47	46.80	6.81	0.64	0.85	11.03
17-b	Bend	0.005	3105	4.23	46.74	6.48	0.62	0.81	11.82
17-c	Bend	0.005	3102	5.29	46.80	6.96	0.73	1.01	11.22
18-a	Bend	0.010	2448	4.78	41.66	15.61	0.31	0.70	52.08
18-b	Bend	0.010	2437	5.27	41.57	10.83	0.46	0.93	23.76
18-c	Bend	0.010	2430	5.04	41.55	8.26	0.59	1.22	13.91

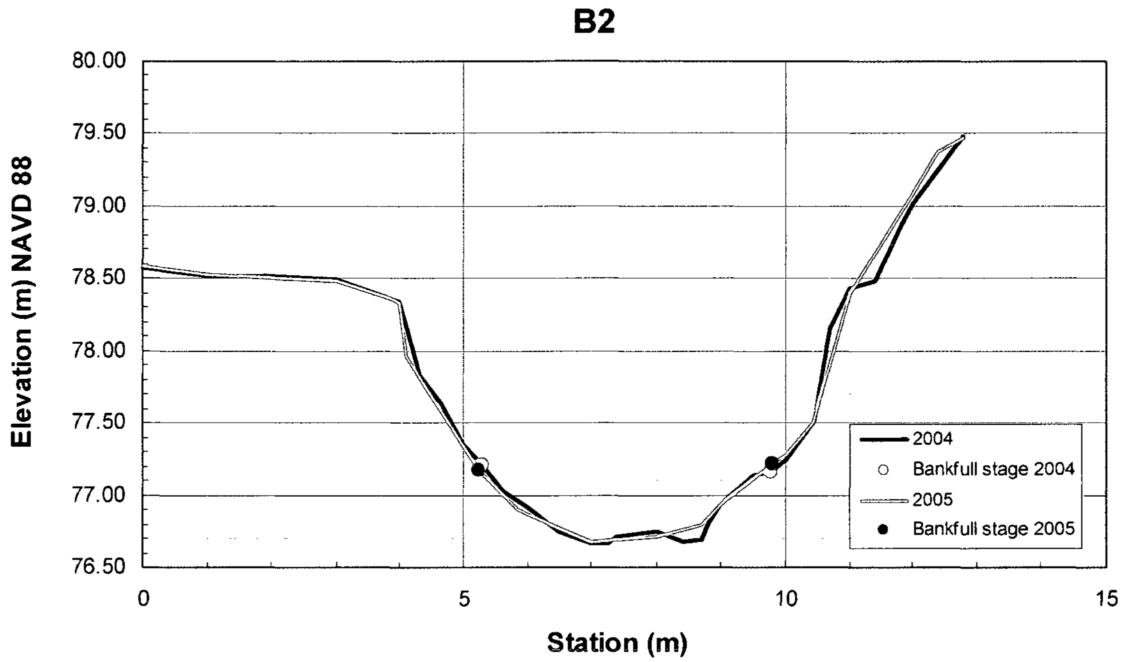
XS ID	XS Type	Local slope (m/m)	Station (m)	BF area (m^2)	BF stage (m)	BF width (m)	Max BF depth (m)	Avg. BF depth (m)	Width/depth
19	Riffle	0.010	2166	4.47	39.41	8.63	0.51	0.94	17.12
20	Riffle	0.009	1958	4.80	38.16	10.99	0.43	0.65	26.15
21-a	Bend	0.011	1346	5.05	33.24	7.55	0.65	0.88	11.73
21-b	Bend	0.011	1338	4.84	33.21	6.47	0.71	1.16	9.20
21-c	Bend	0.011	1325	6.32	33.29	9.93	0.62	0.96	16.85
22	Riffle	0.006	1141	3.52	31.83	6.22	0.57	0.87	11.18
23	Riffle	0.007	873	4.31	30.10	8.11	0.53	0.76	15.44
24-a	Bend	0.003	650	3.49	28.56	6.66	0.52	0.98	12.92
24-b	Bend	0.003	645	3.69	28.53	6.92	0.52	1.07	13.10
24-c	Bend	0.003	640	5.31	28.51	8.67	0.58	1.04	14.73
25	Riffle	0.010	445	3.21	26.77	6.41	0.50	0.75	13.05
26	Riffle	0.002	290	5.37	26.07	6.78	0.79	1.00	8.55

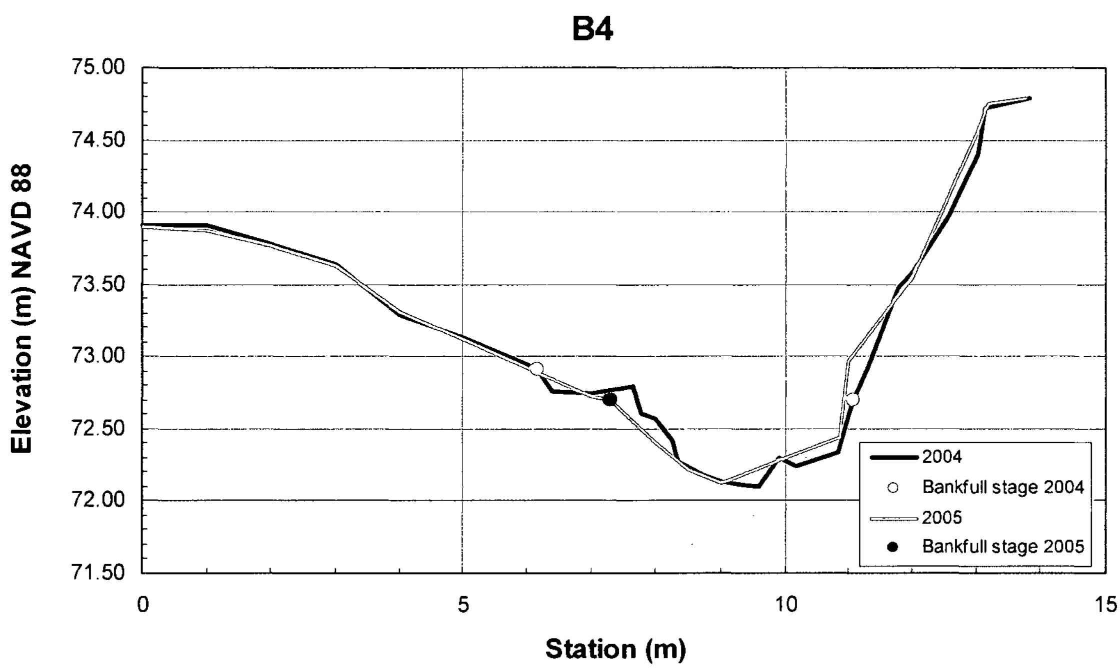
*BF=bankfull stage values

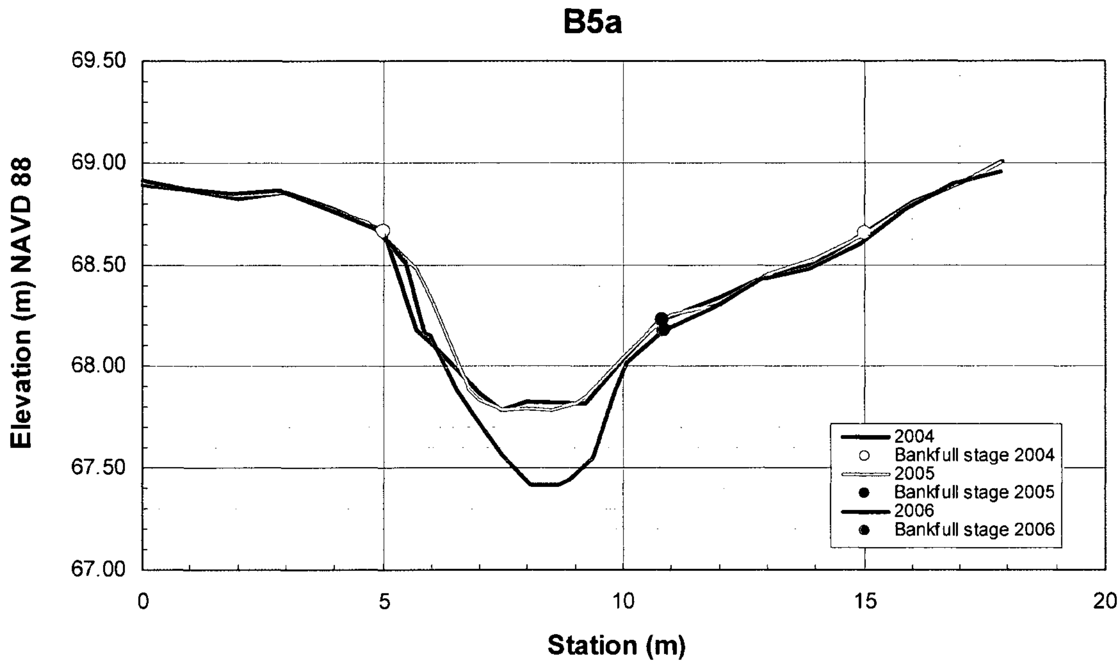
APPENDIX B

2004-2006 Cross Section Data

Berryessa Creek Surveyed Cross Sections



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68.50
68.00
67.50
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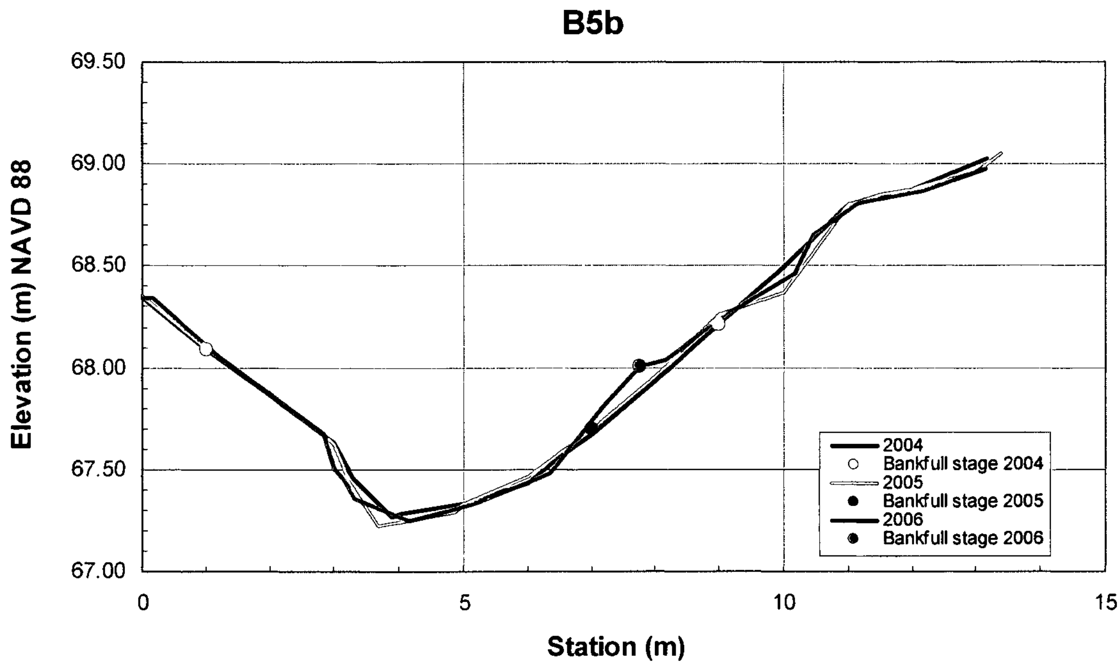
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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69.00
68.50
68.00
67.50
67.00
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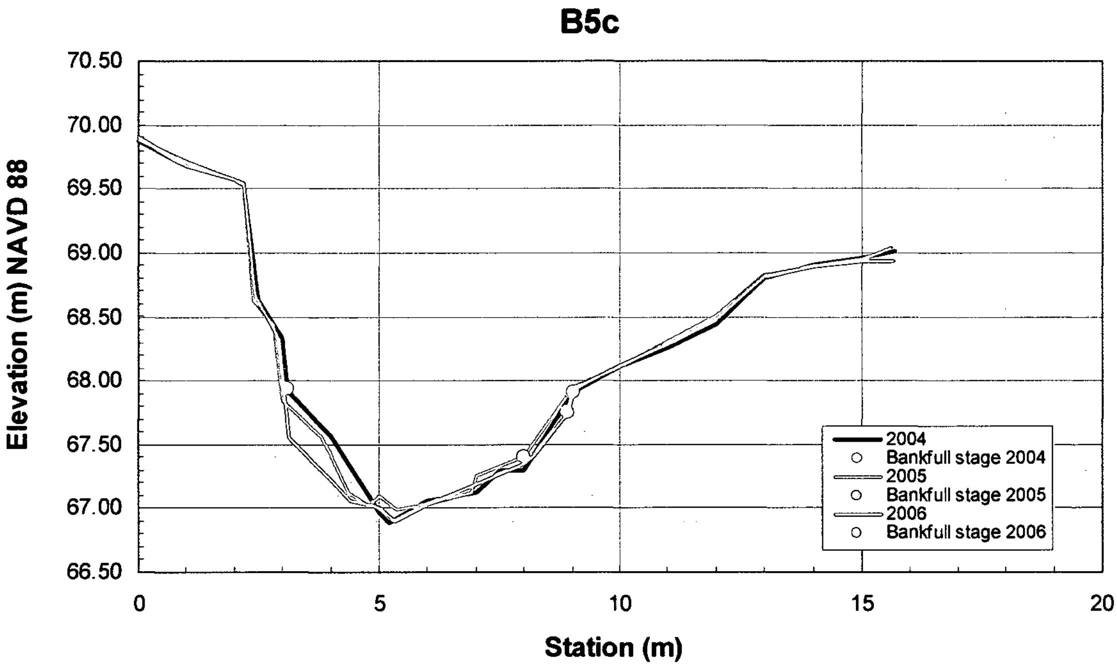
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



B5c
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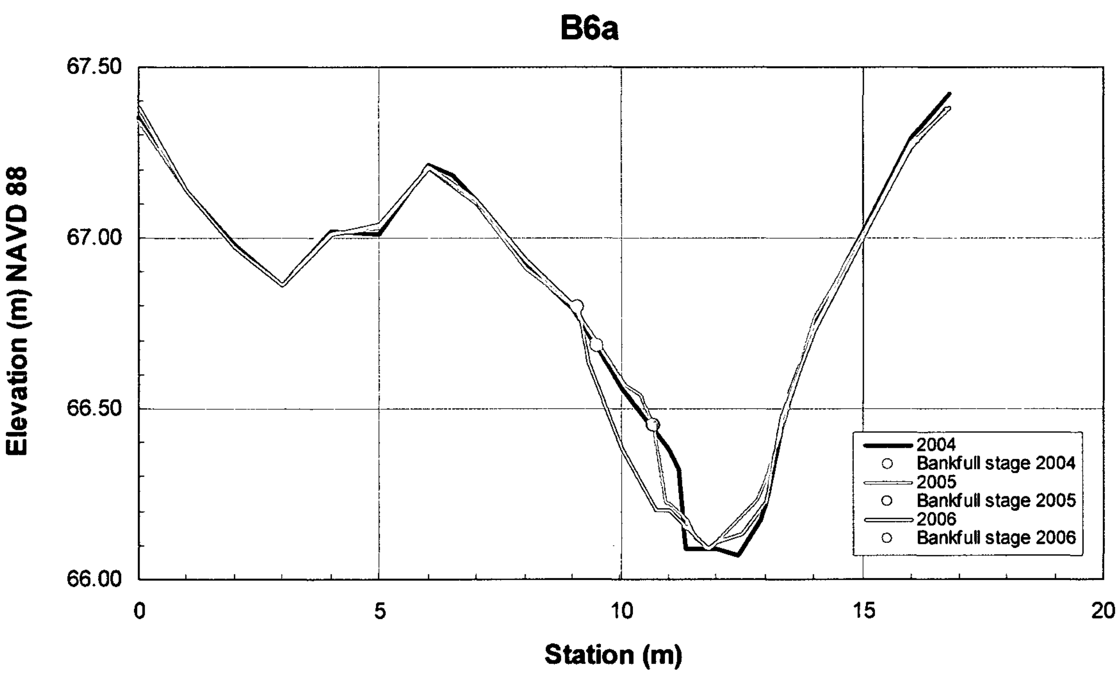
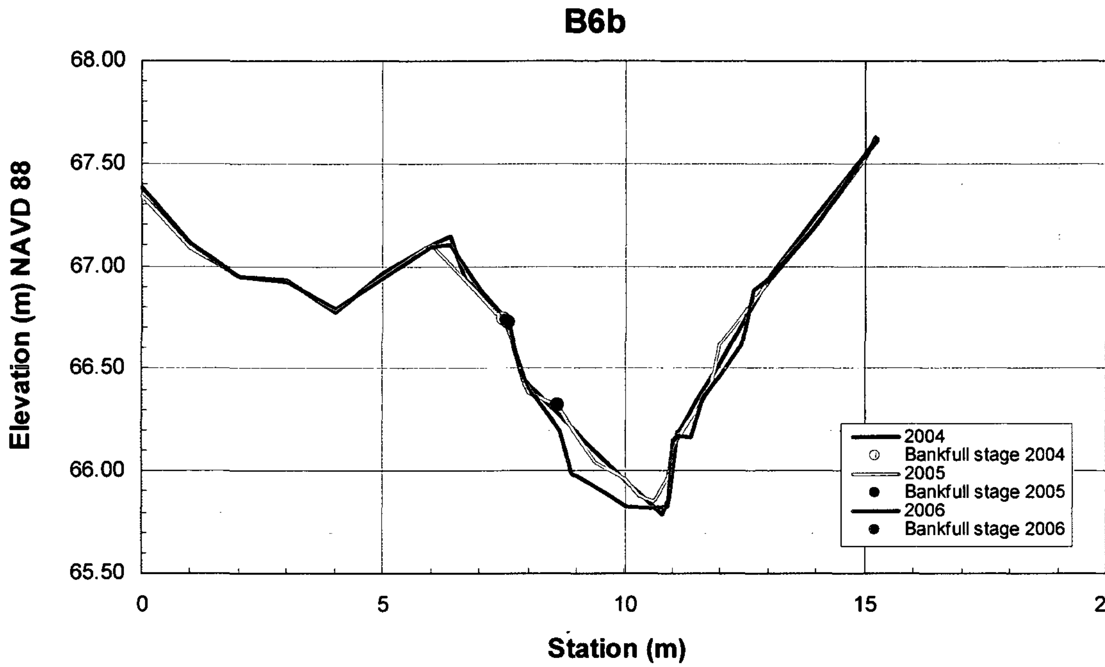
70.00
69.50
69.00
68.50
68.00
67.50
67.00
66.50
Elevation (m) NAVD 88
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



B6a
67.50
67.00
66.50
66.00
Elevation (m) NAVD 88
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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66.00
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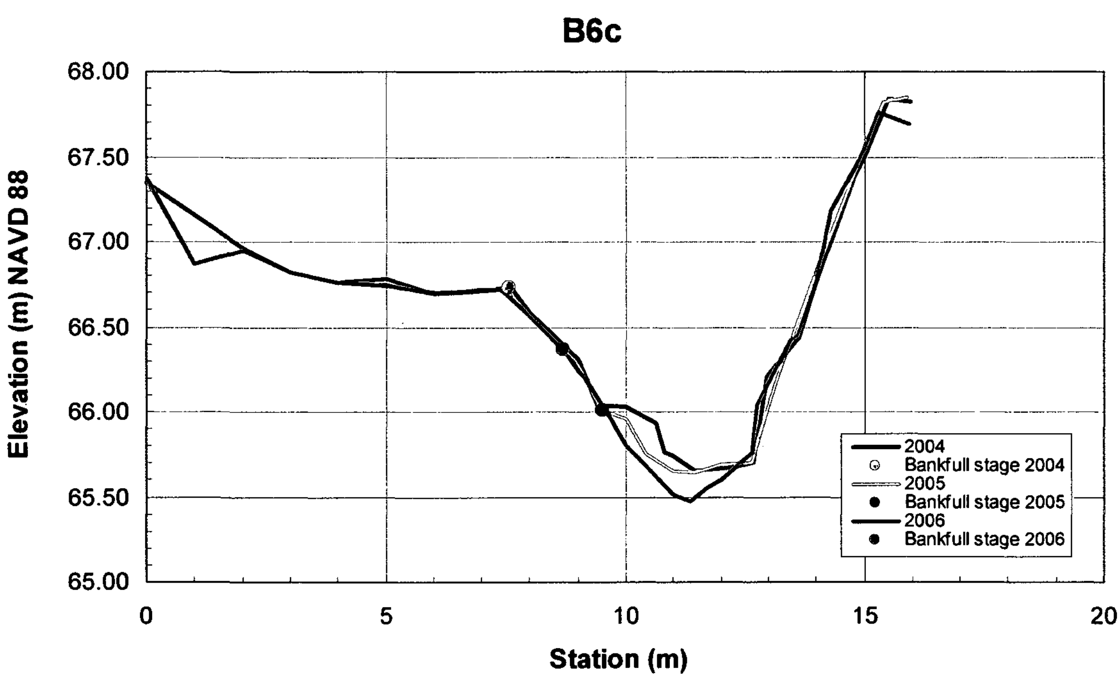
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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67.50
67.00
66.50
66.00
65.50
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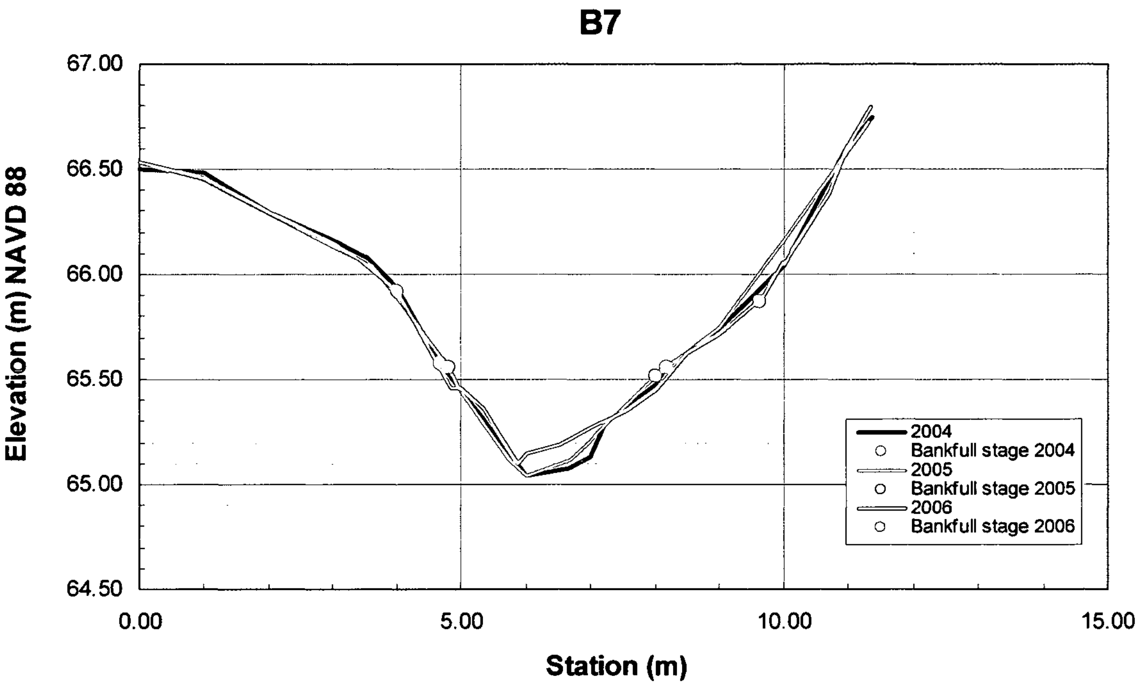
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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Station (m)
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66.00
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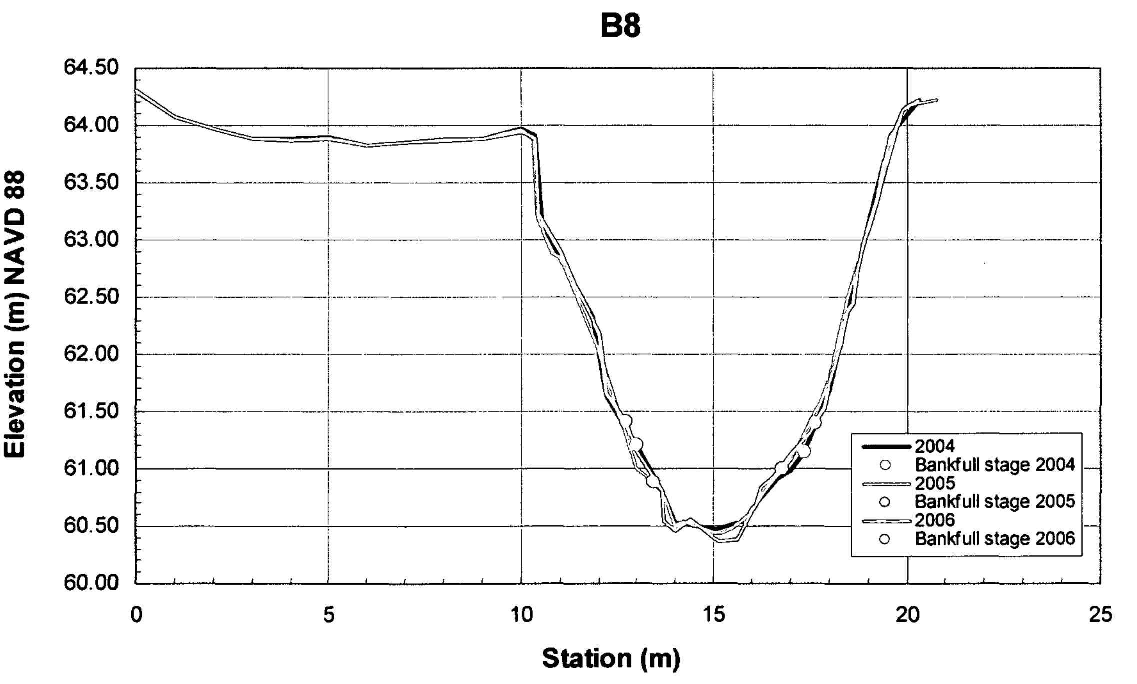
64.50
0.00
5.00
10.00
15.00
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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Station (m)
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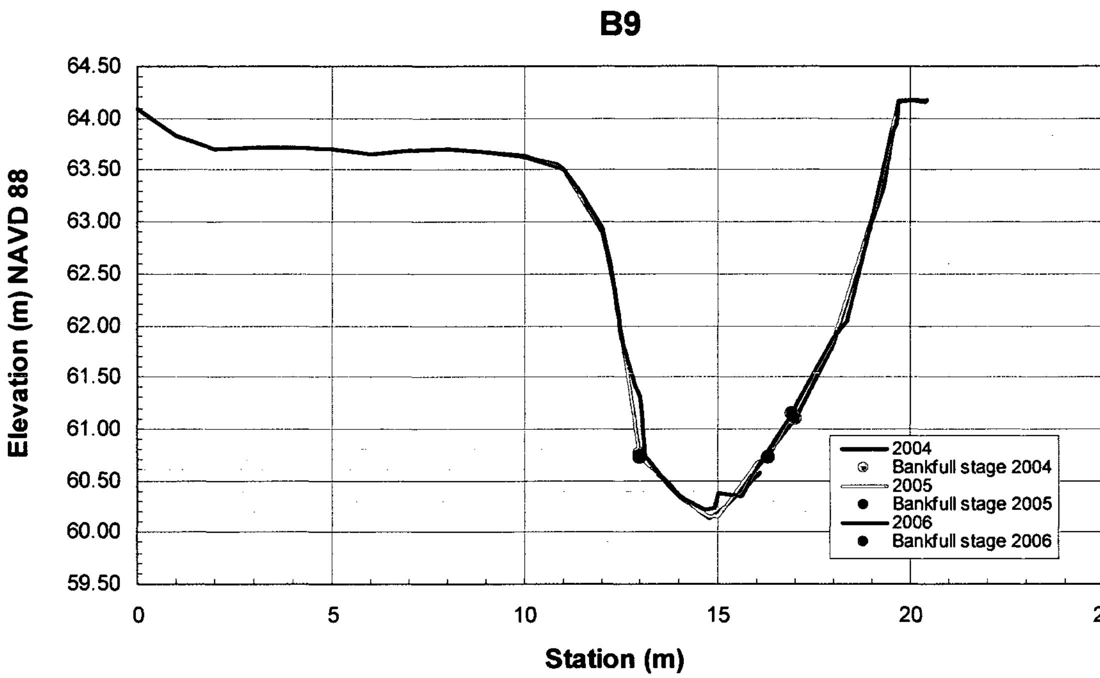
60.00
0
5
10
15
20
25
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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64.00
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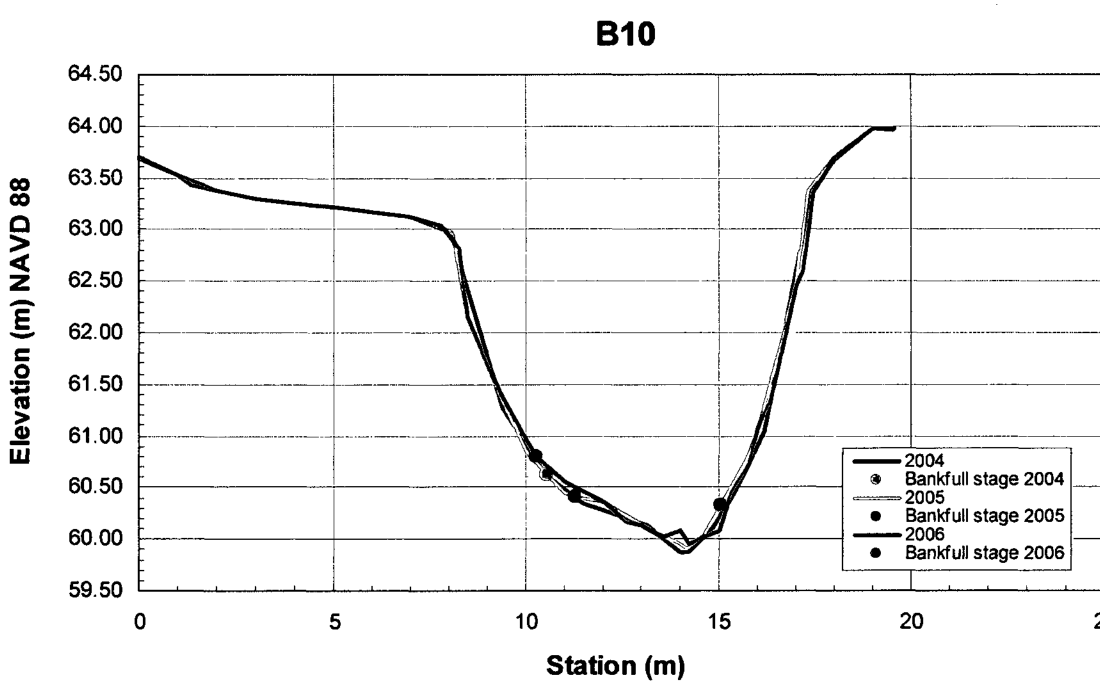
63.00
62.50
62.00
61.50
61.00
60.50
60.00
59.50
Elevation (m) NAVD 88
0
5
10
15
20
25
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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63.50
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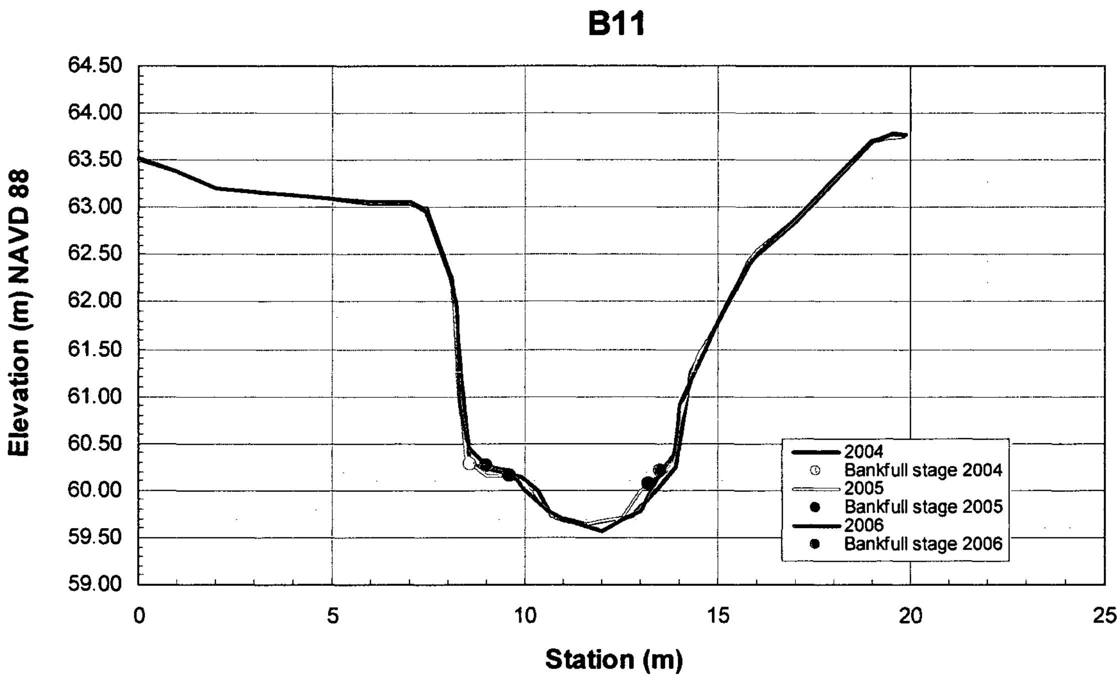
62.50
62.00
61.50
61.00
60.50
60.00
59.50
Elevation (m) NAVD 88
0
5
10
15
20
25
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



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Station (m)
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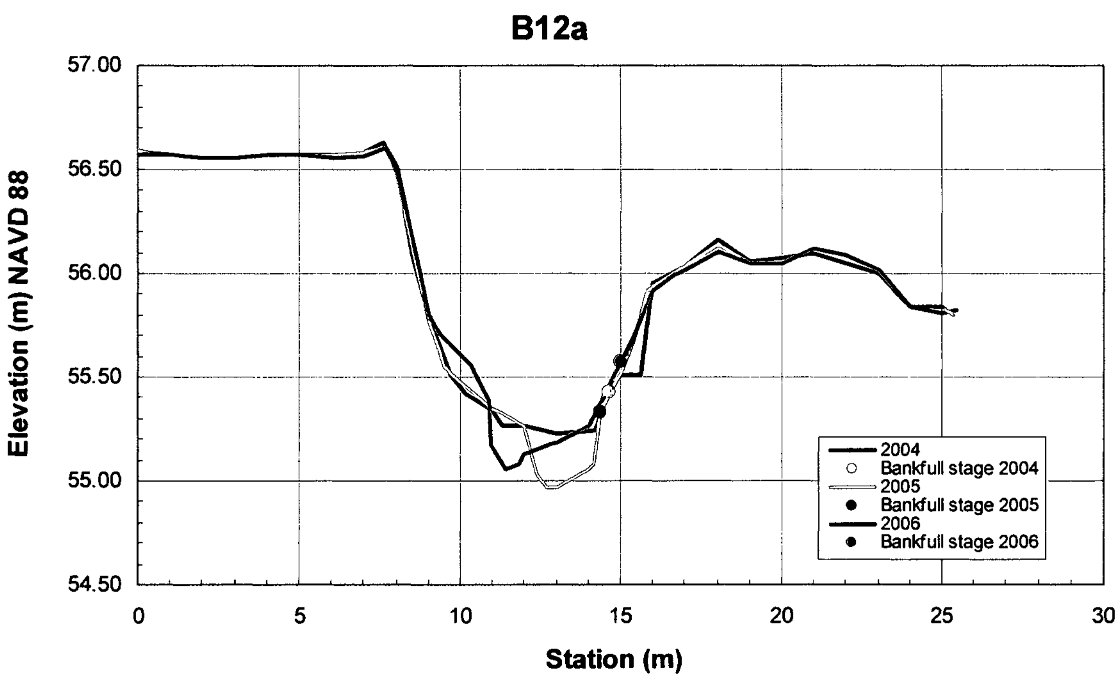
63.00
62.50
62.00
61.50
61.00
60.50
60.00
59.50
59.00
0
5
10
15
20
25
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



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Elevation (m) NAVD 88
Station (m)
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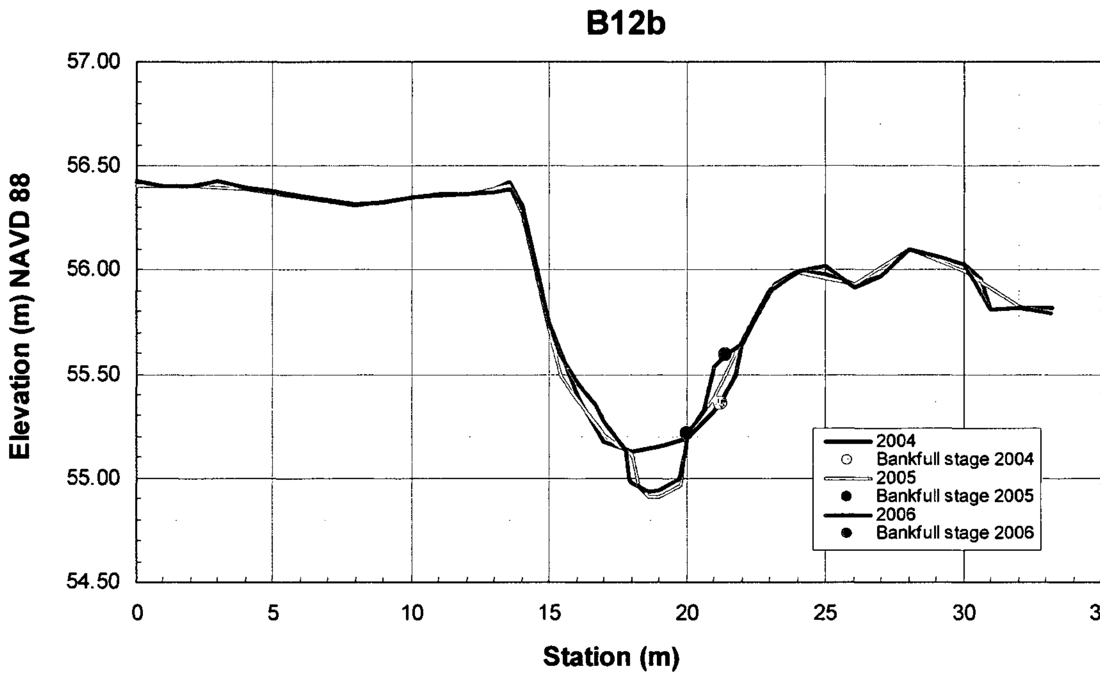
56.50
56.00
55.50
55.00
54.50
0
5
10
15
20
25
30
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B12b
Elevation (m) NAVD 88
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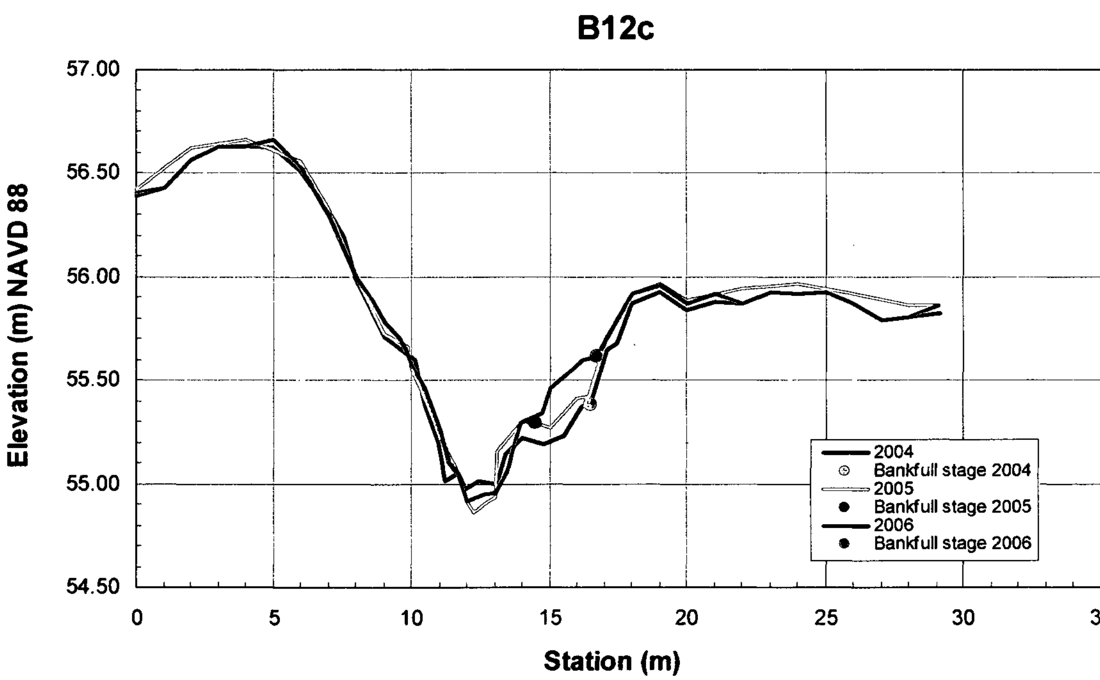
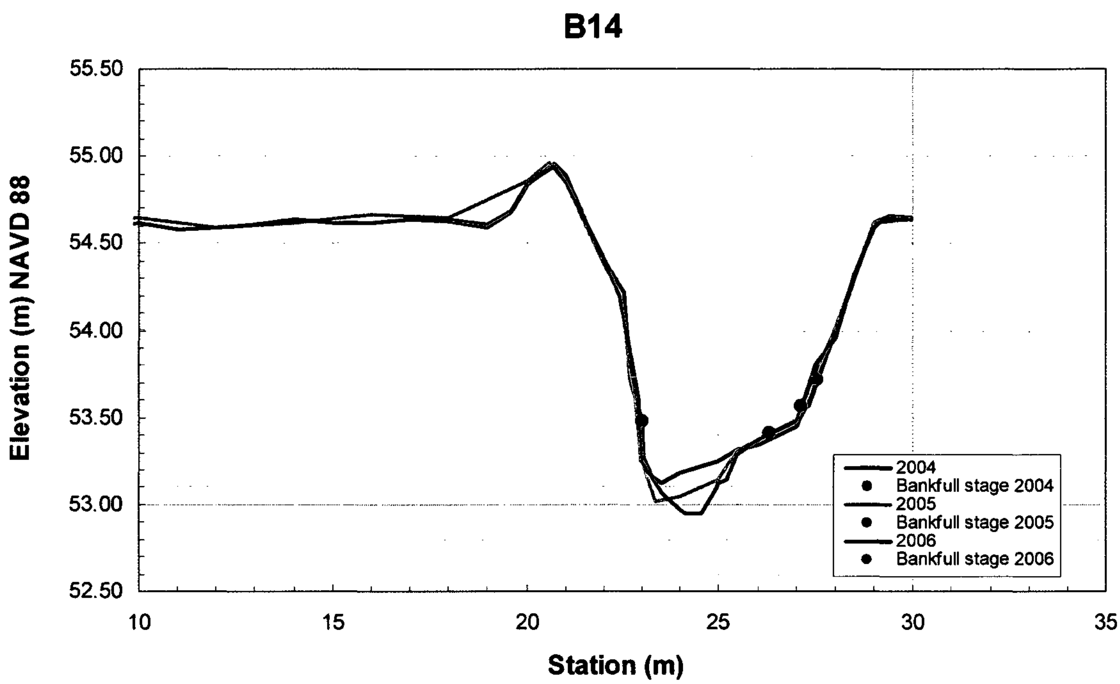
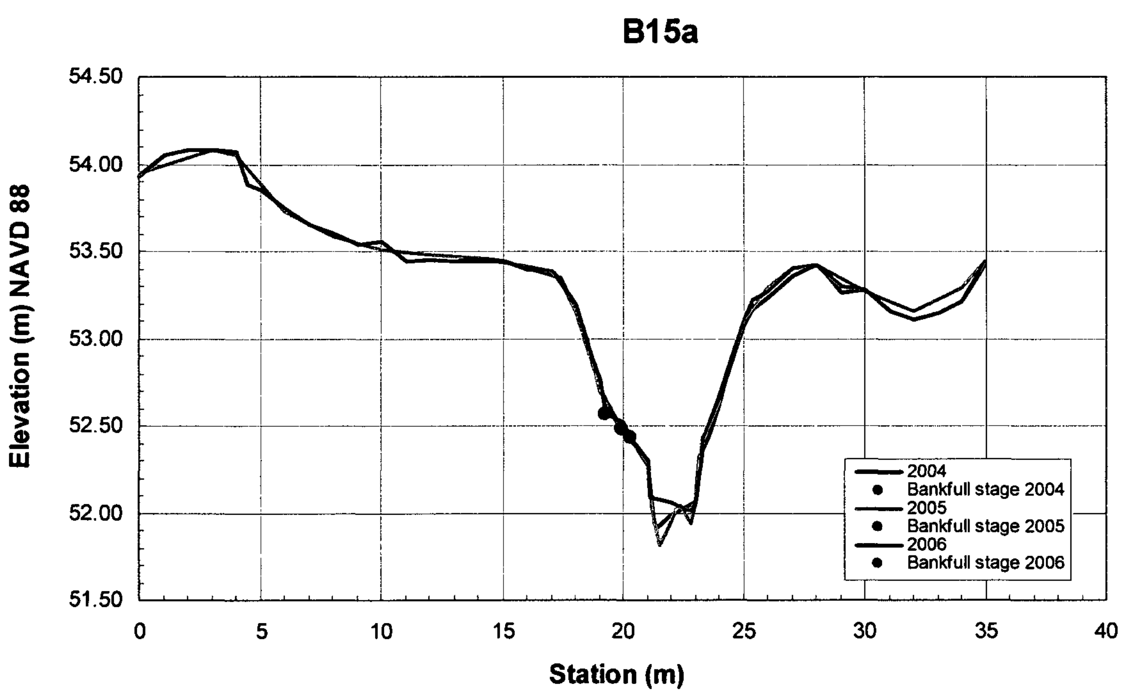
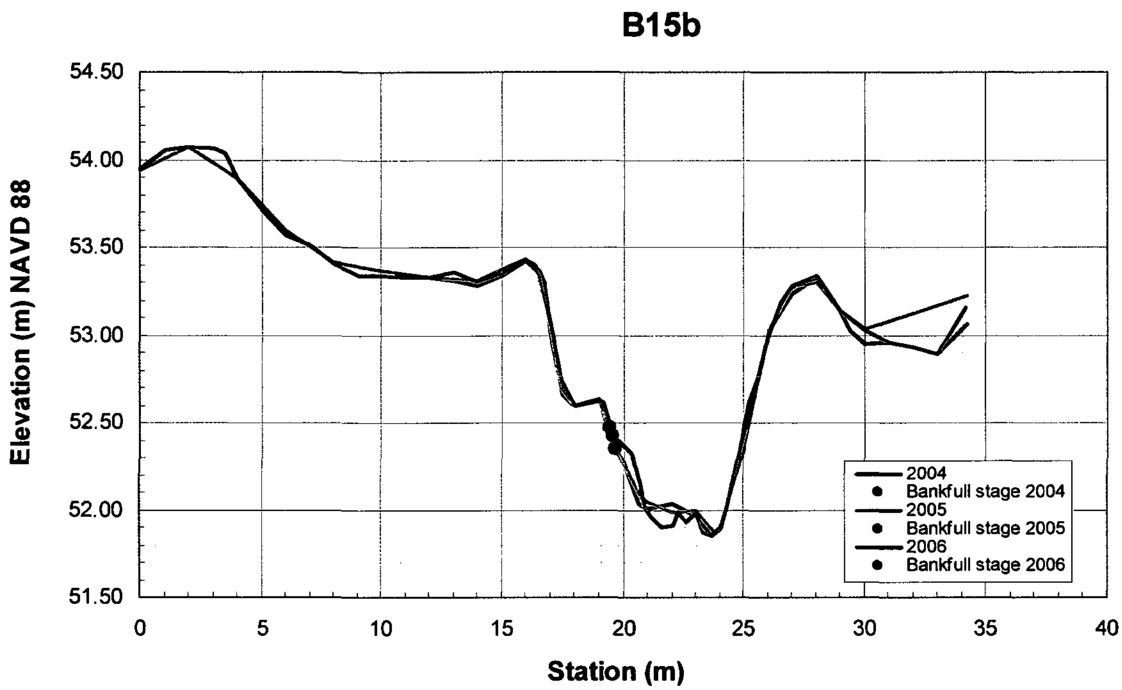
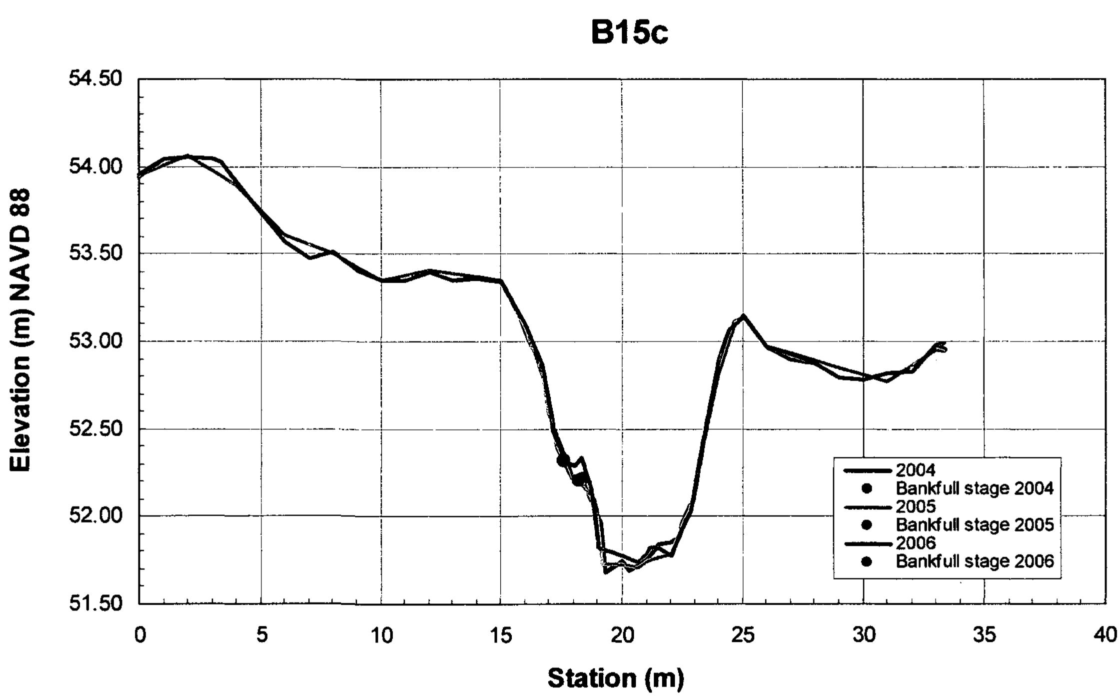
56.50
56.00
55.50
55.00
54.50
0
5
10
15
20
25
30
35
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

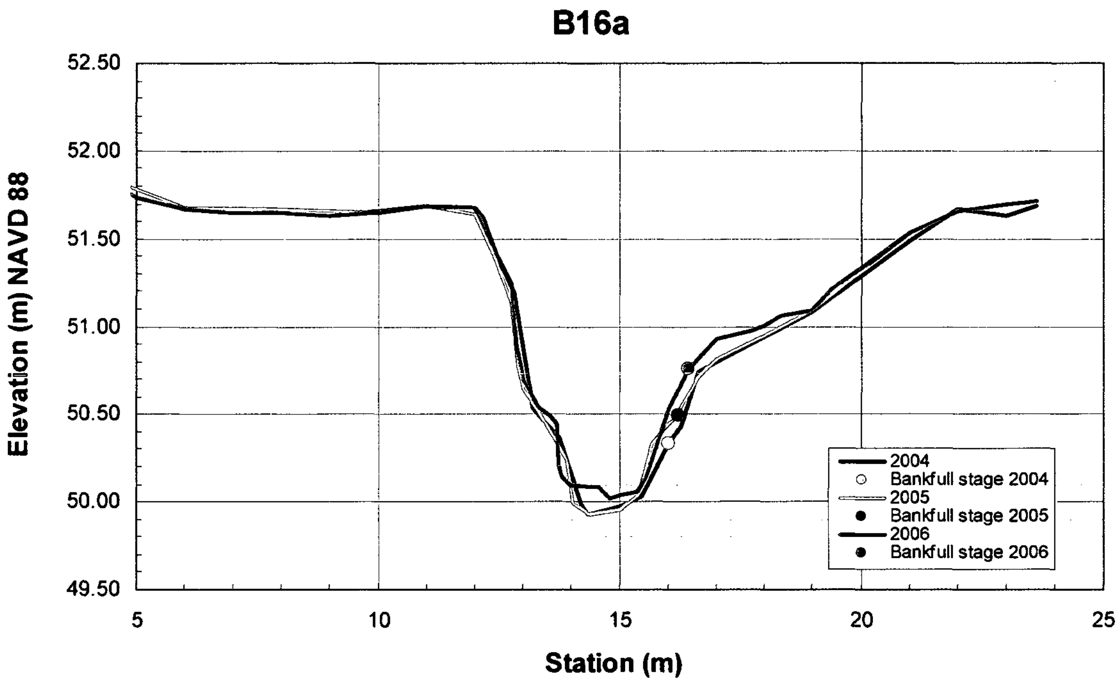

B12c
Elevation (m) NAVD 88
57.00
56.50
56.00
55.50
55.00
54.50
0
5
10
15
20
25
30
35
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B14
55.50
55.00
54.50
54.00
53.50
53.00
52.50
Elevation (m) NAVD 88
10
15
20
25
30
35
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

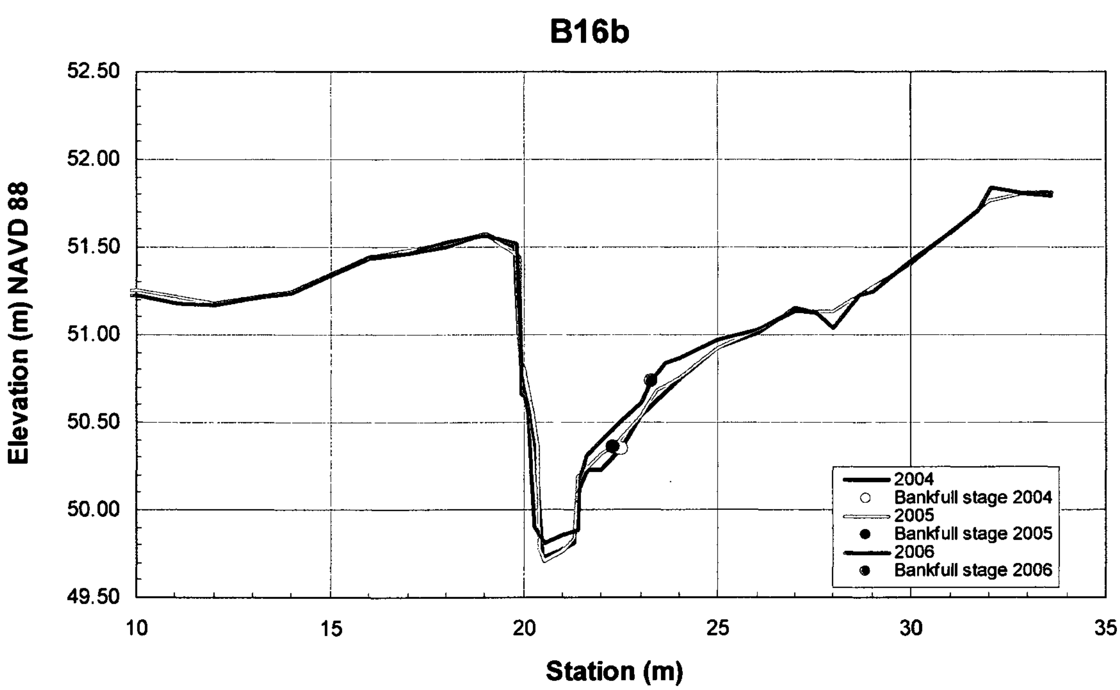

B15a
54.50
54.00
53.50
53.00
52.50
52.00
51.50
Elevation (m) NAVD 88
0
5
10
15
20
25
30
35
40
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B15b
Elevation (m) NAVD 88
Station (m)
54.50
54.00
53.50
53.00
52.50
52.00
51.50
0
5
10
15
20
25
30
35
40
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

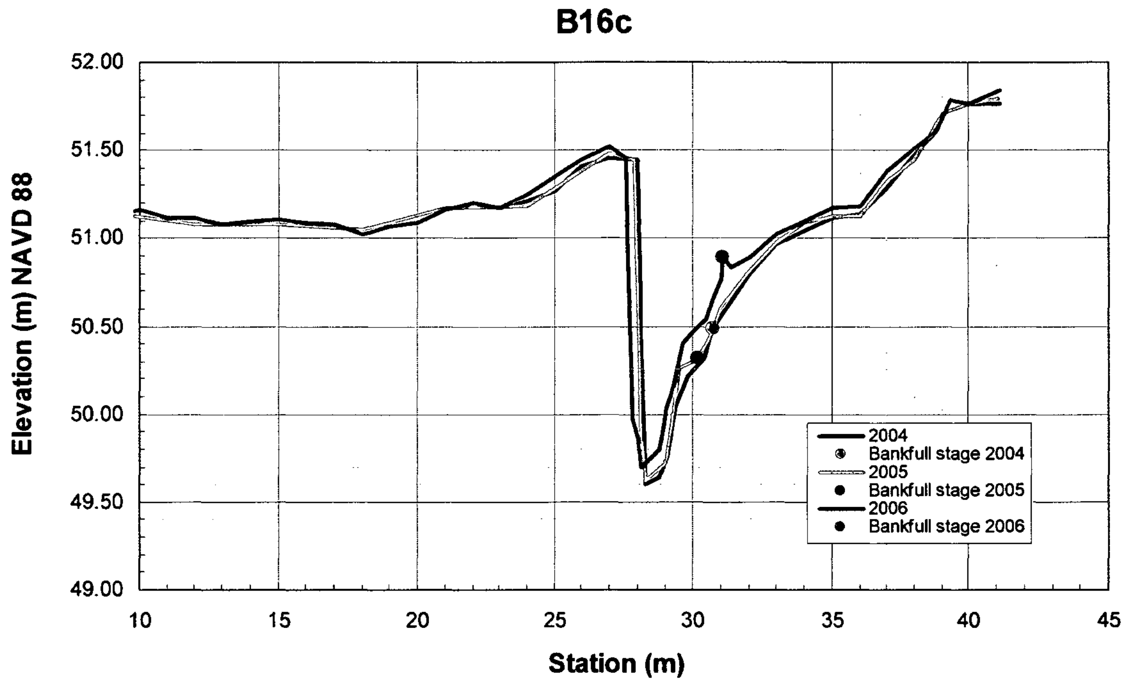

B15c
Elevation (m) NAVD 88
Station (m)
54.50
54.00
53.50
53.00
52.50
52.00
51.50
0
5
10
15
20
25
30
35
40
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

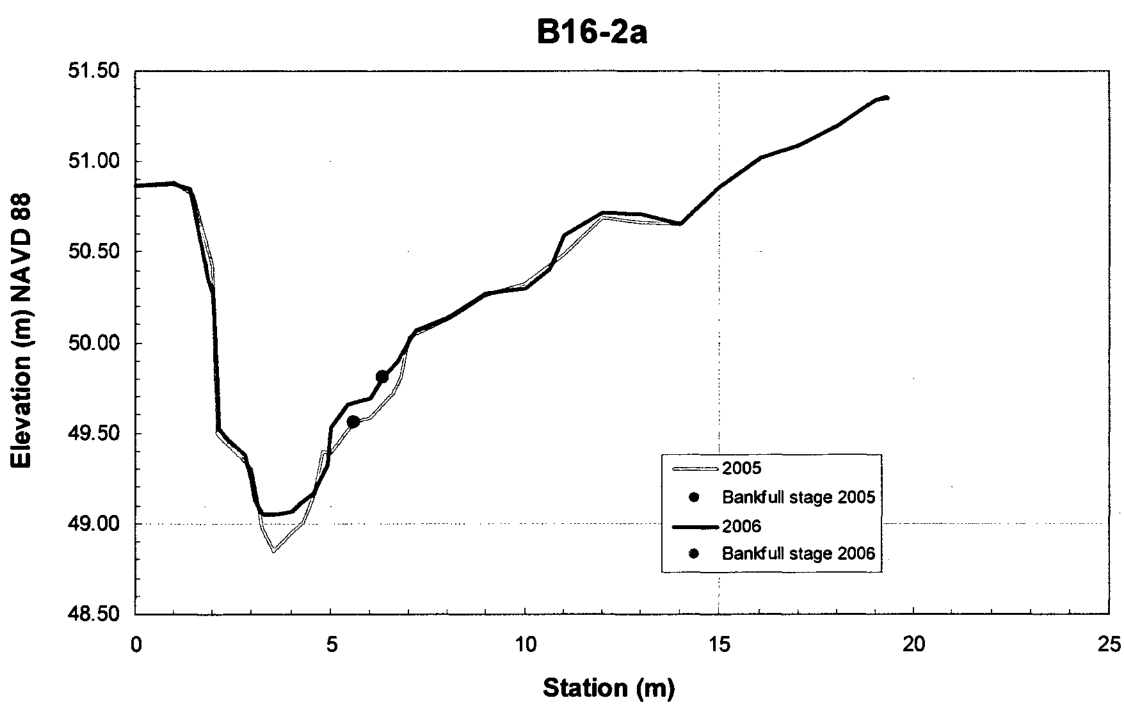


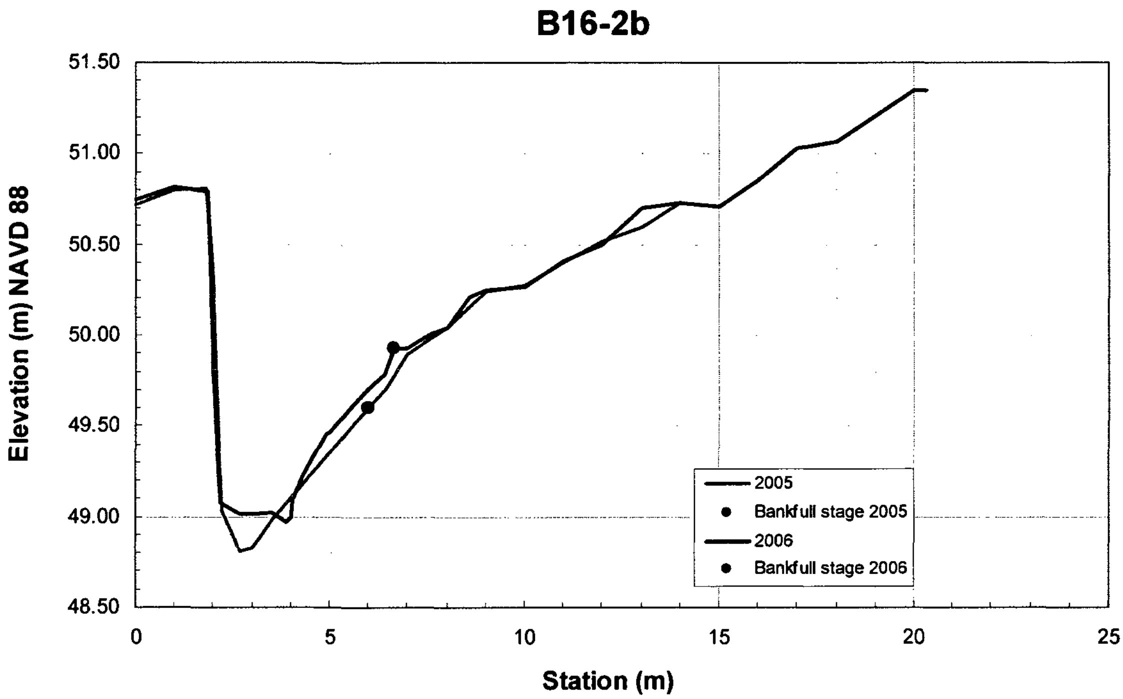
B16a
52.50
52.00
51.50
51.00
50.50
50.00
49.50
5
10
15
20
25
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

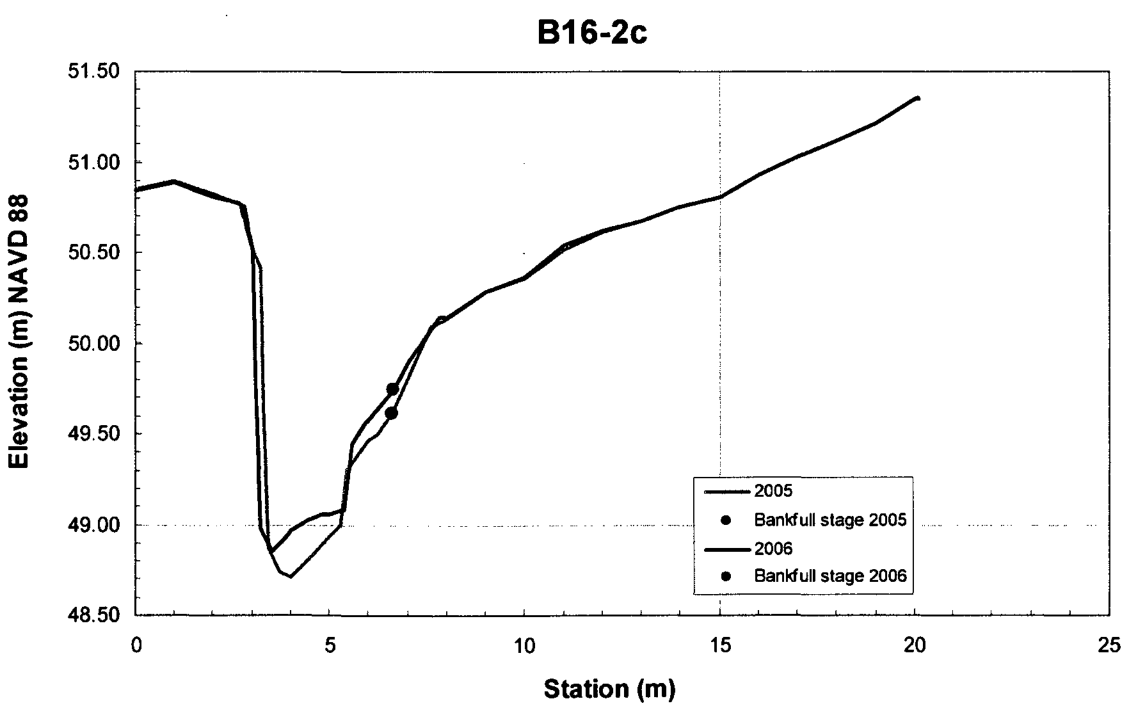


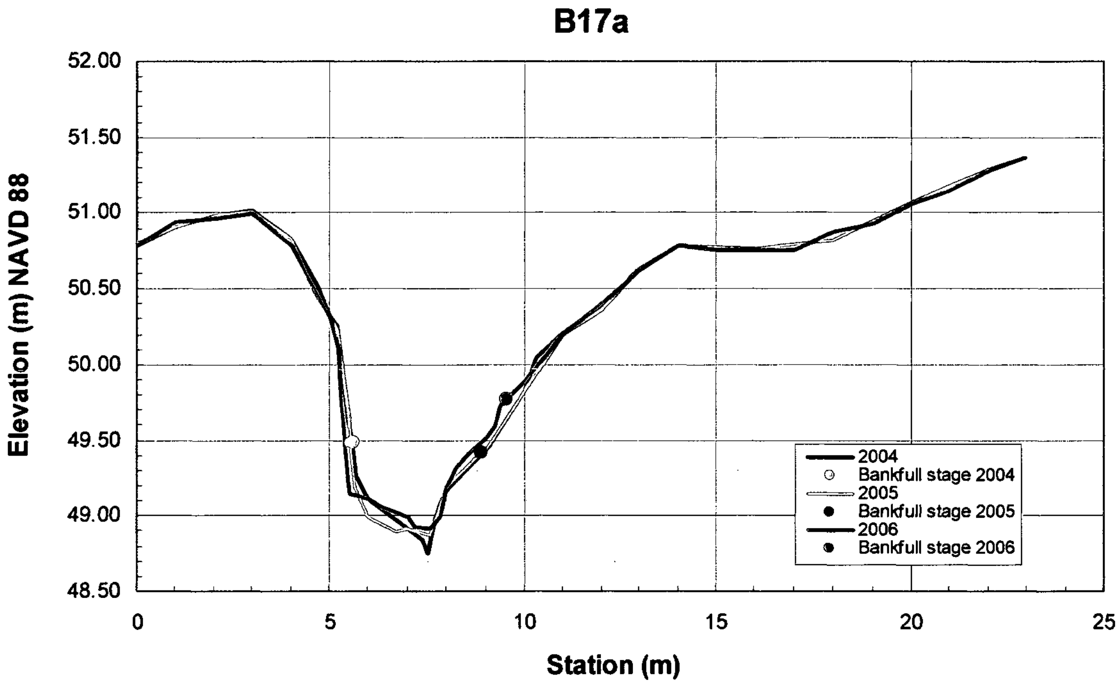
B16b
52.50
52.00
51.50
51.00
50.50
50.00
49.50
10
15
20
25
30
35
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

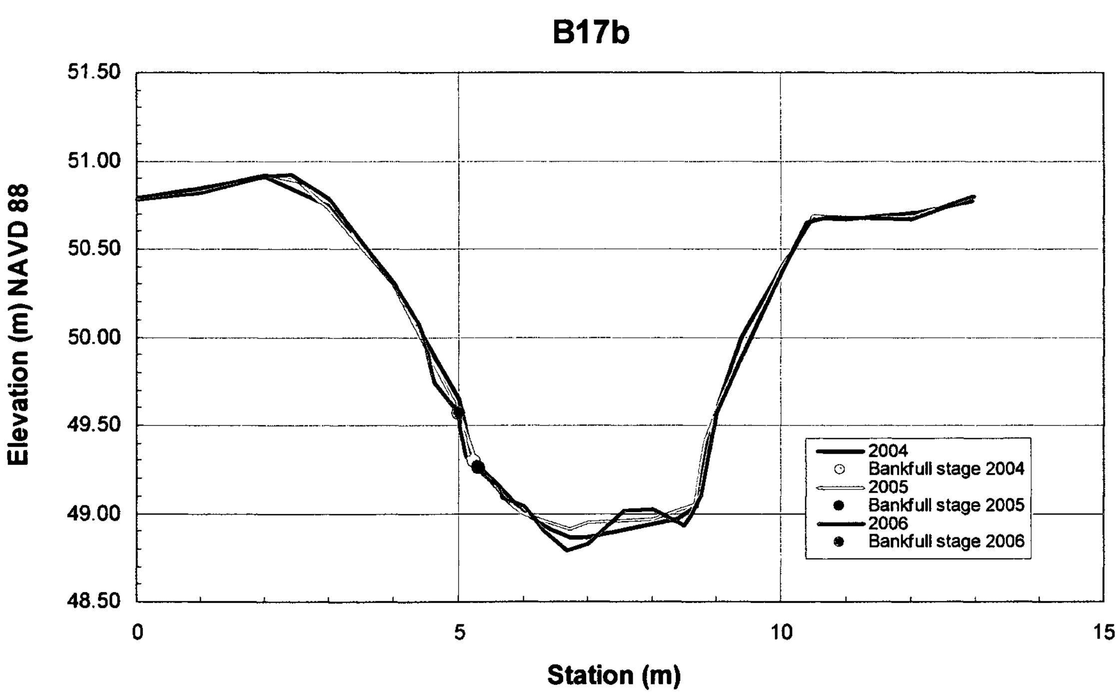

B16c
Elevation (m) NAVD 88
52.00
51.50
51.00
50.50
50.00
49.50
49.00
10
15
20
25
30
35
40
45
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

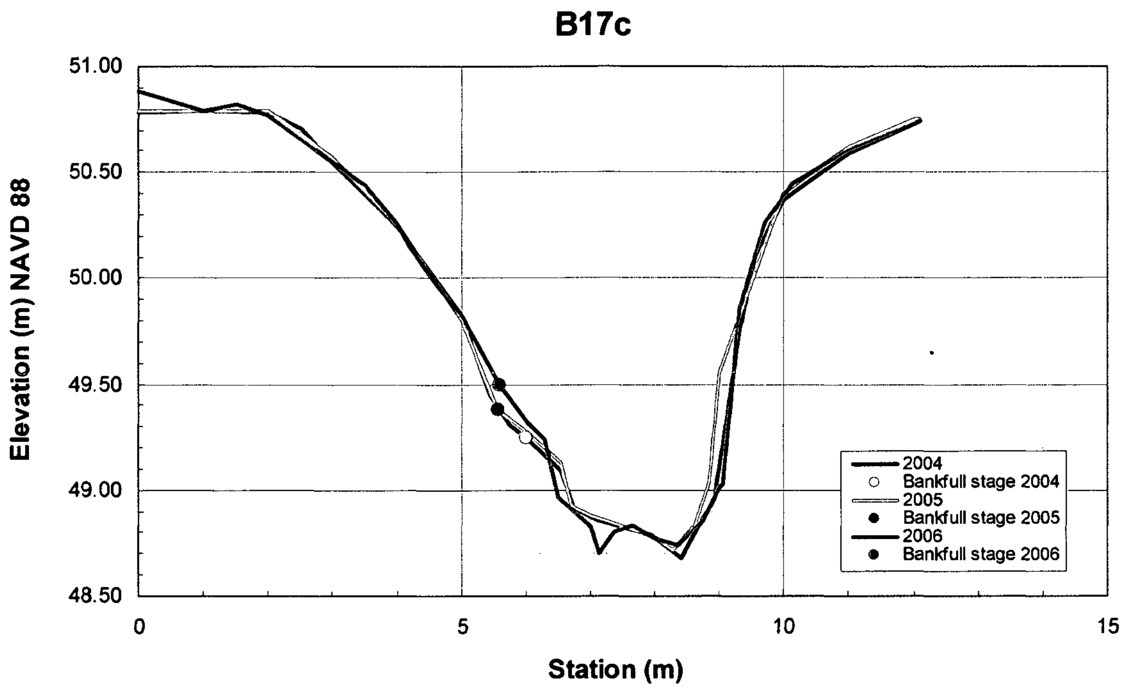

B16-2a
Elevation (m) NAVD 88
51.50
51.00
50.50
50.00
49.50
49.00
48.50
0
5
10
15
20
25
Station (m)
2005
Bankfull stage 2005
2006
Bankfull stage 2006

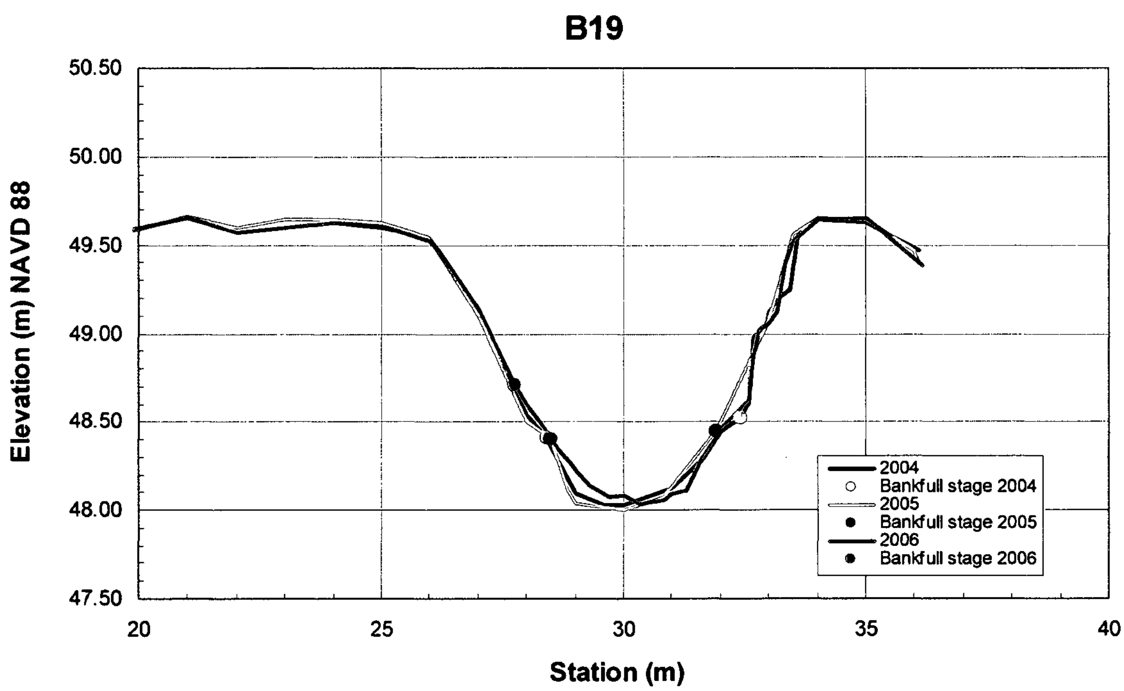

B16-2b
Elevation (m) NAVD 88
51.50
51.00
50.50
50.00
49.50
49.00
48.50
0
5
10
15
20
25
Station (m)
2005
Bankfull stage 2005
2006
Bankfull stage 2006

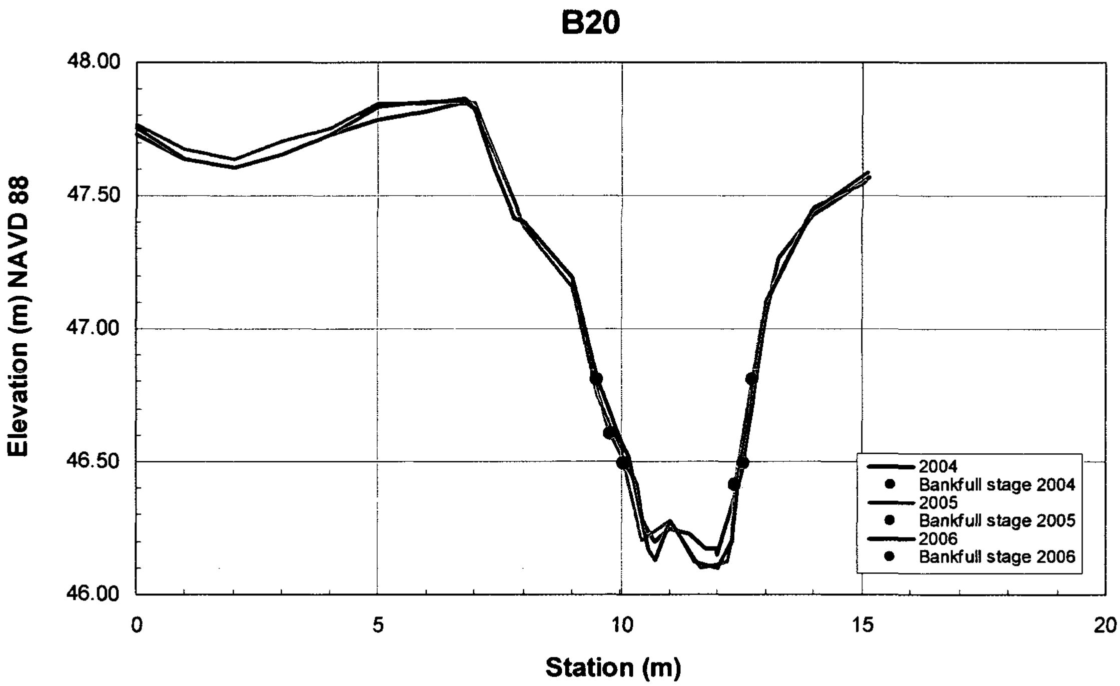

B16-2c
Elevation (m) NAVD 88
51.50
51.00
50.50
50.00
49.50
49.00
48.50
0
5
10
15
20
25
Station (m)
2005
Bankfull stage 2005
2006
Bankfull stage 2006

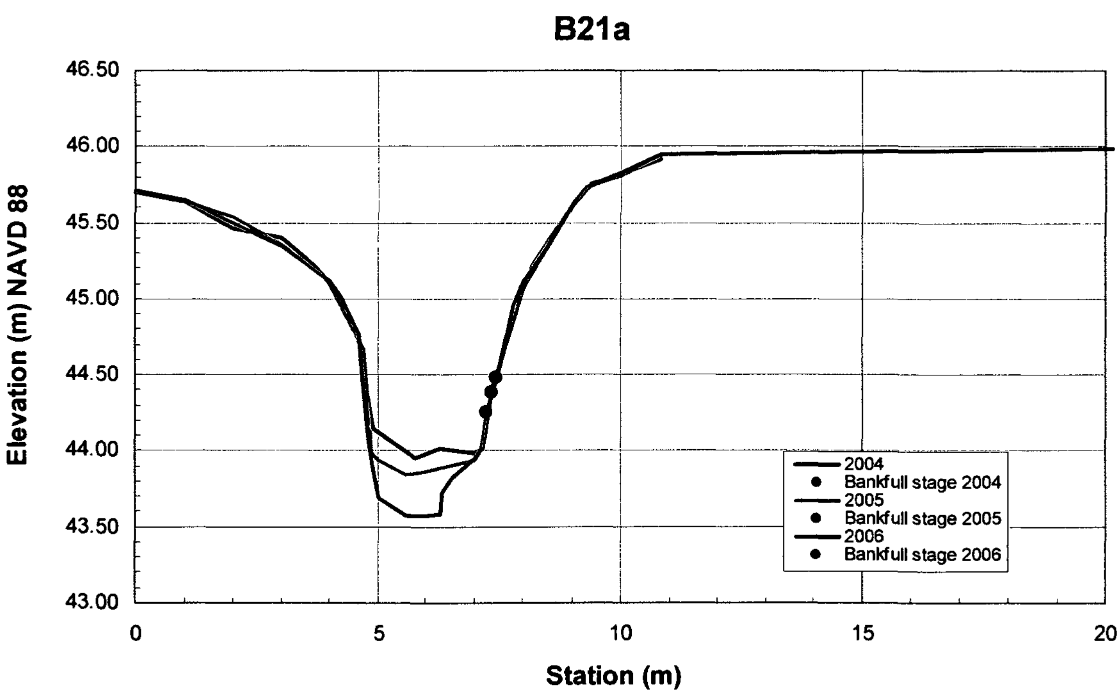

B17a
Elevation (m) NAVD 88
52.00
51.50
51.00
50.50
50.00
49.50
49.00
48.50
0
5
10
15
20
25
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

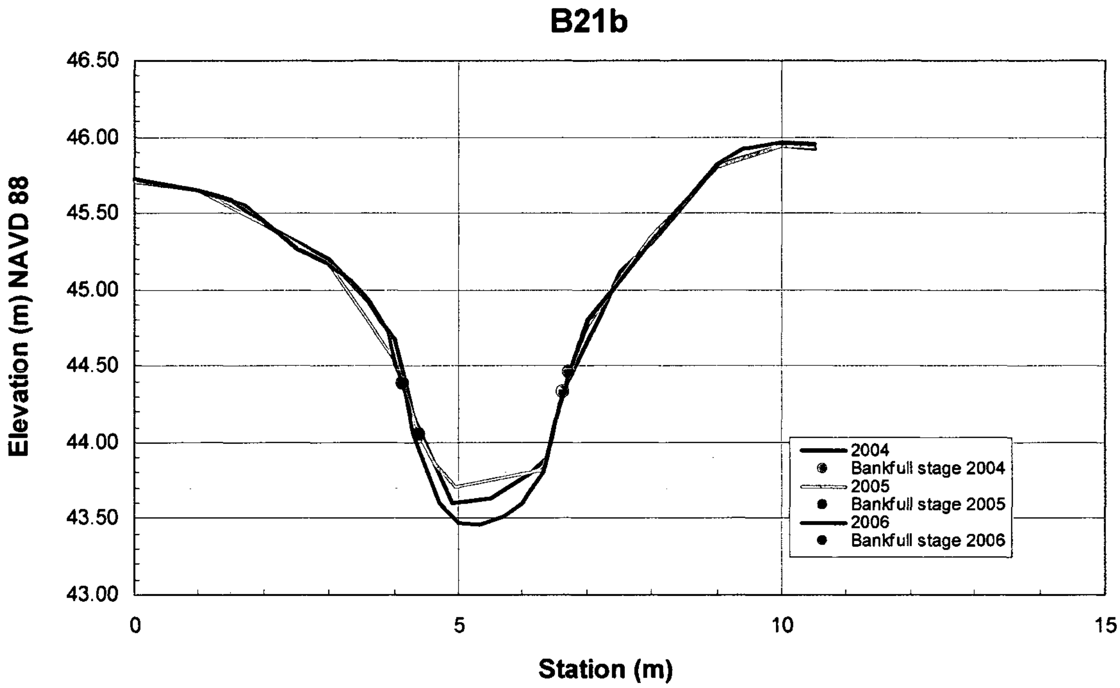

B17b
Elevation (m) NAVD 88
51.50
51.00
50.50
50.00
49.50
49.00
48.50
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

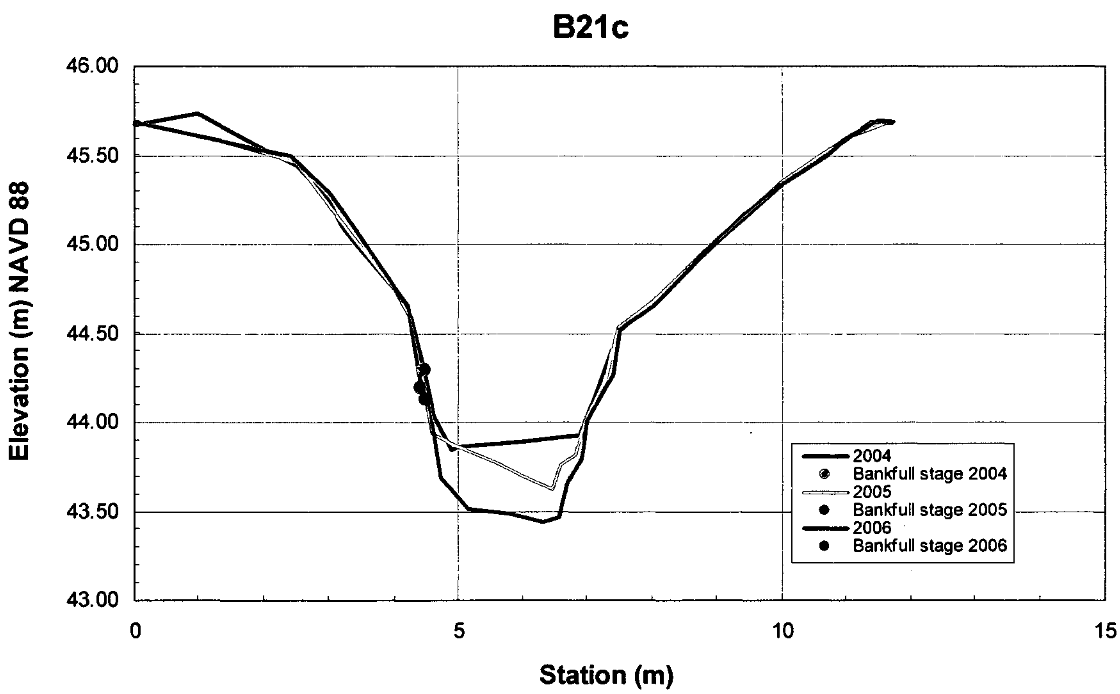

B17c
51.00
50.50
50.00
49.50
49.00
48.50
Elevation (m) NAVD 88
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

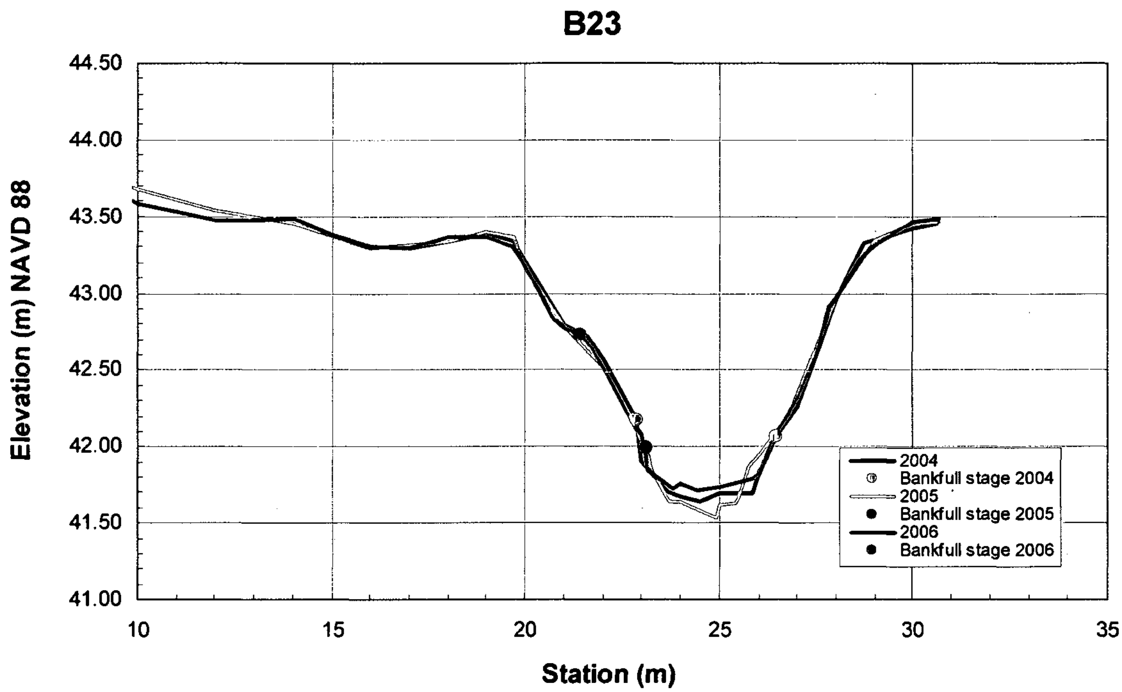

B19
50.50
50.00
49.50
49.00
48.50
48.00
47.50
Elevation (m) NAVD 88
20
25
30
35
40
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

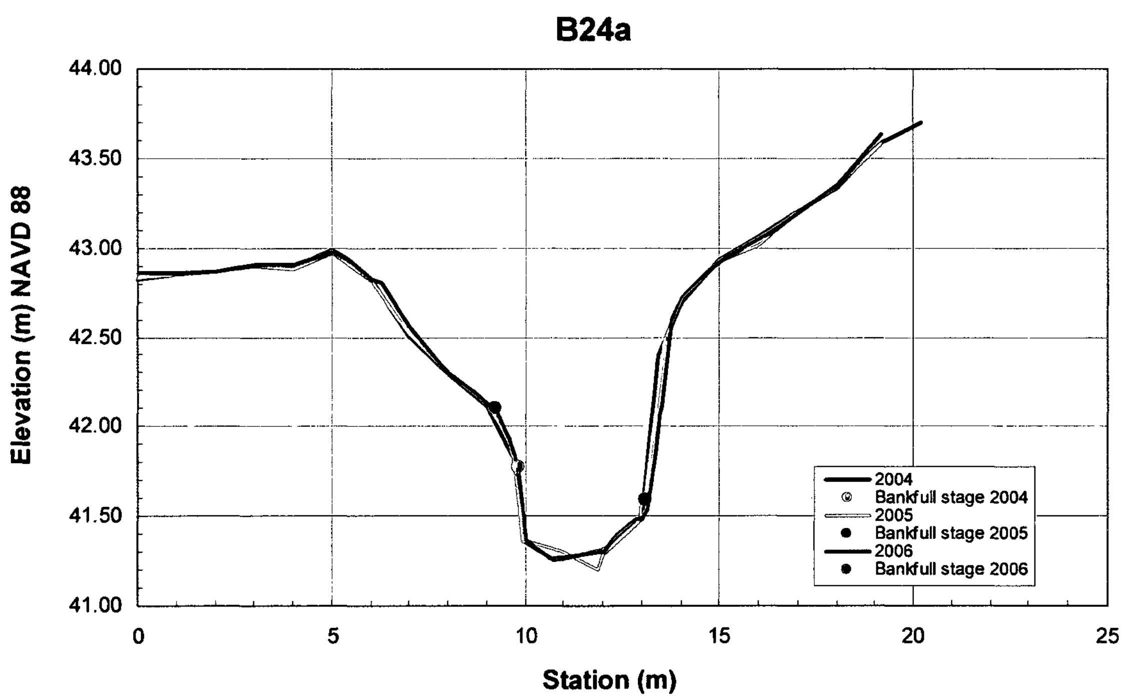

B20
48.00
47.50
47.00
46.50
46.00
0
5
10
15
20
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

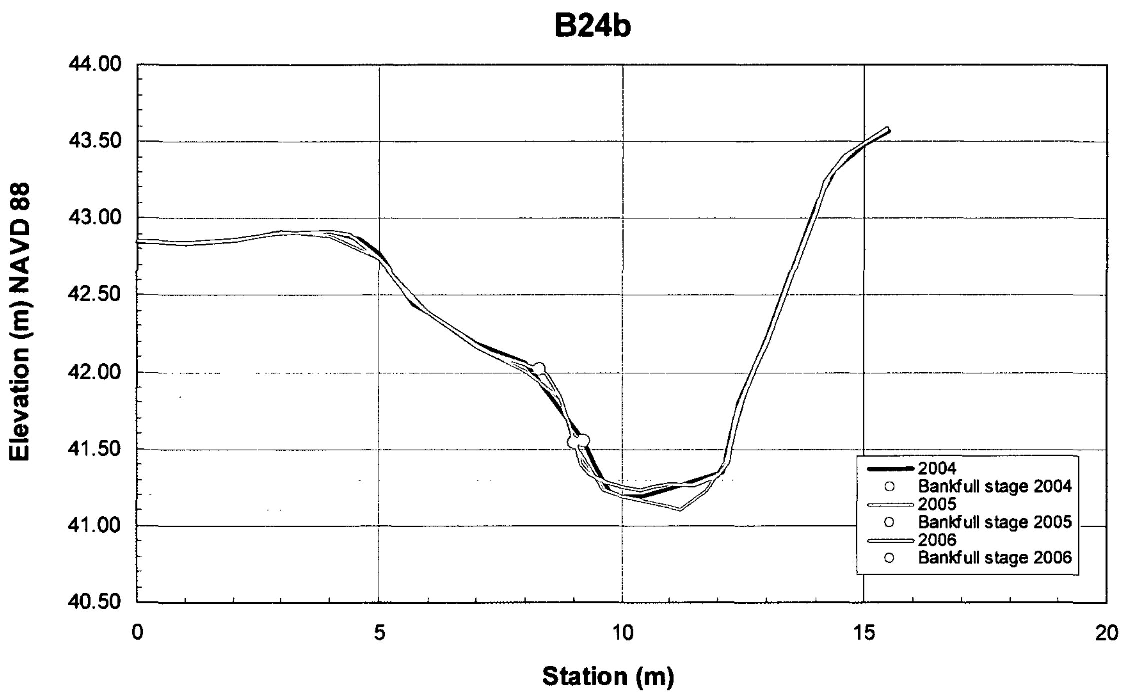

B21a
46.50
46.00
45.50
45.00
44.50
44.00
43.50
43.00
0
5
10
15
20
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

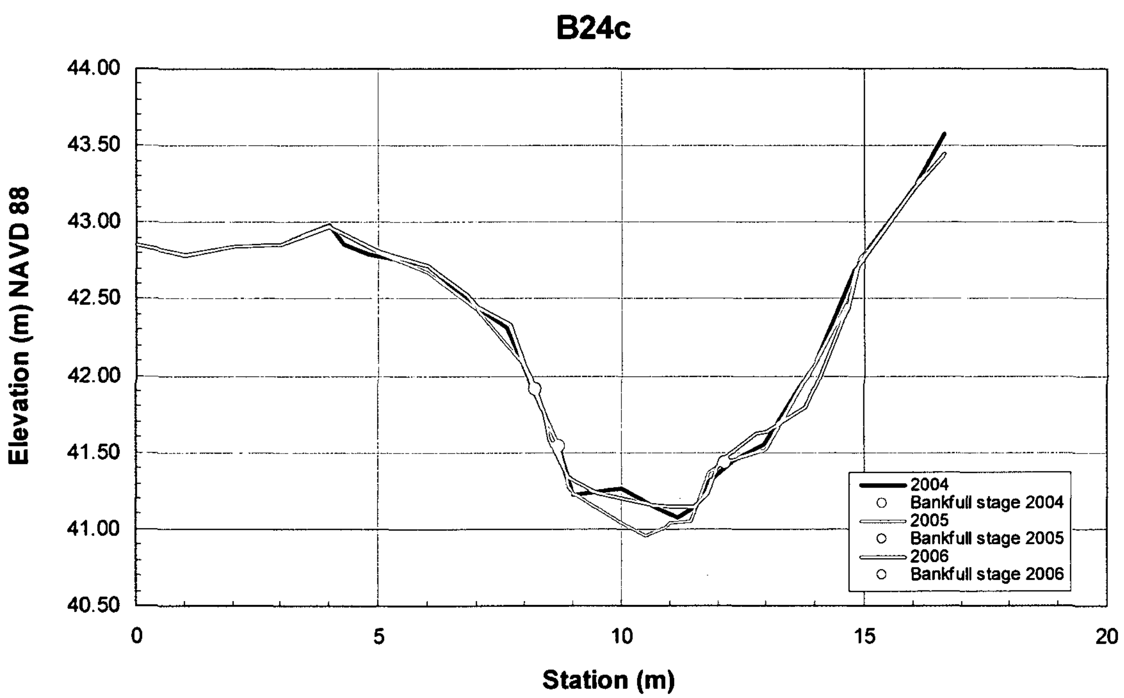

B21b
46.50
46.00
45.50
45.00
44.50
44.00
43.50
43.00
Elevation (m) NAVD 88
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

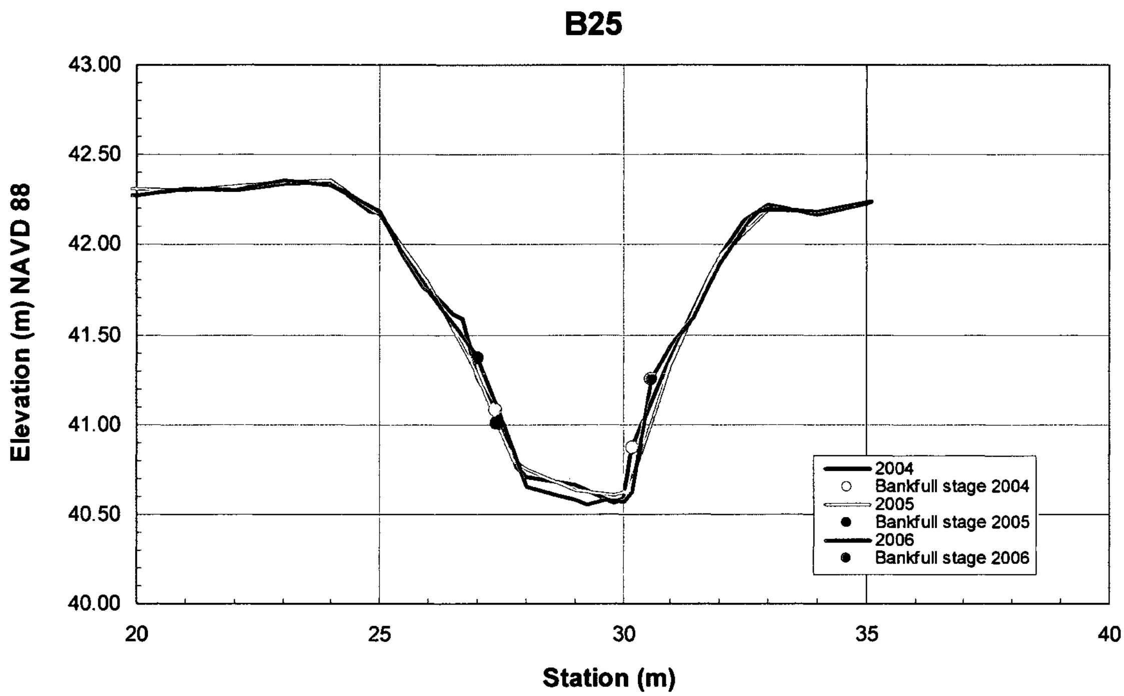

B21c
46.00
45.50
45.00
44.50
44.00
43.50
43.00
Elevation (m) NAVD 88
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

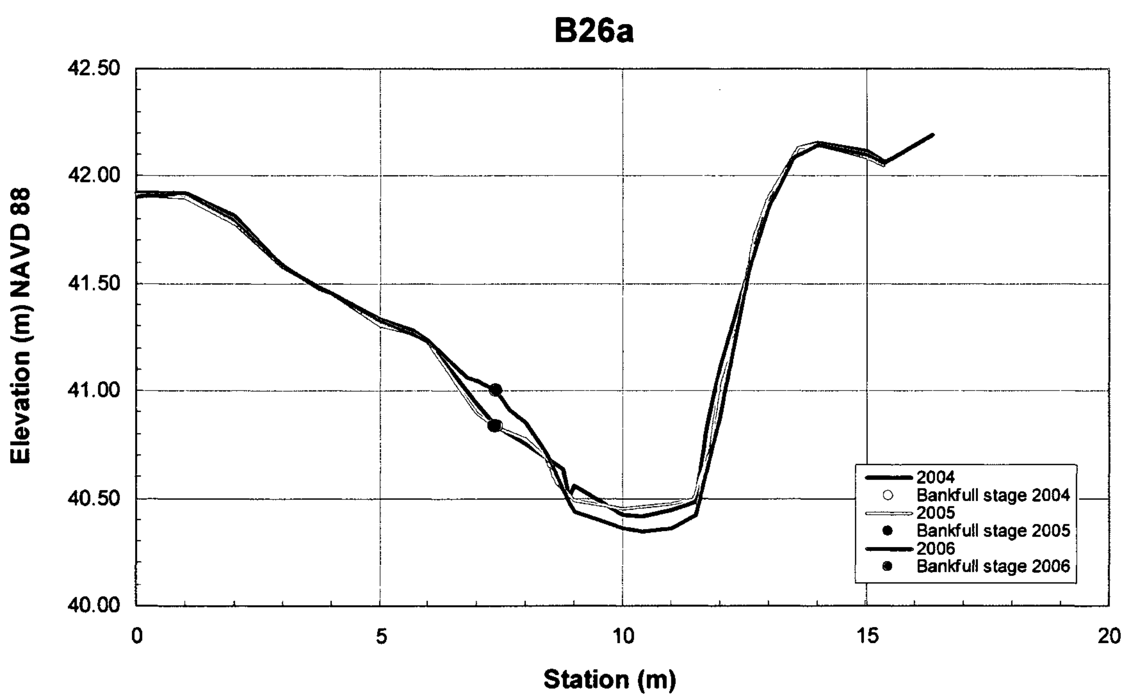

B23
Elevation (m) NAVD 88
Station (m)
44.50
44.00
43.50
43.00
42.50
42.00
41.50
41.00
10
15
20
25
30
35
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

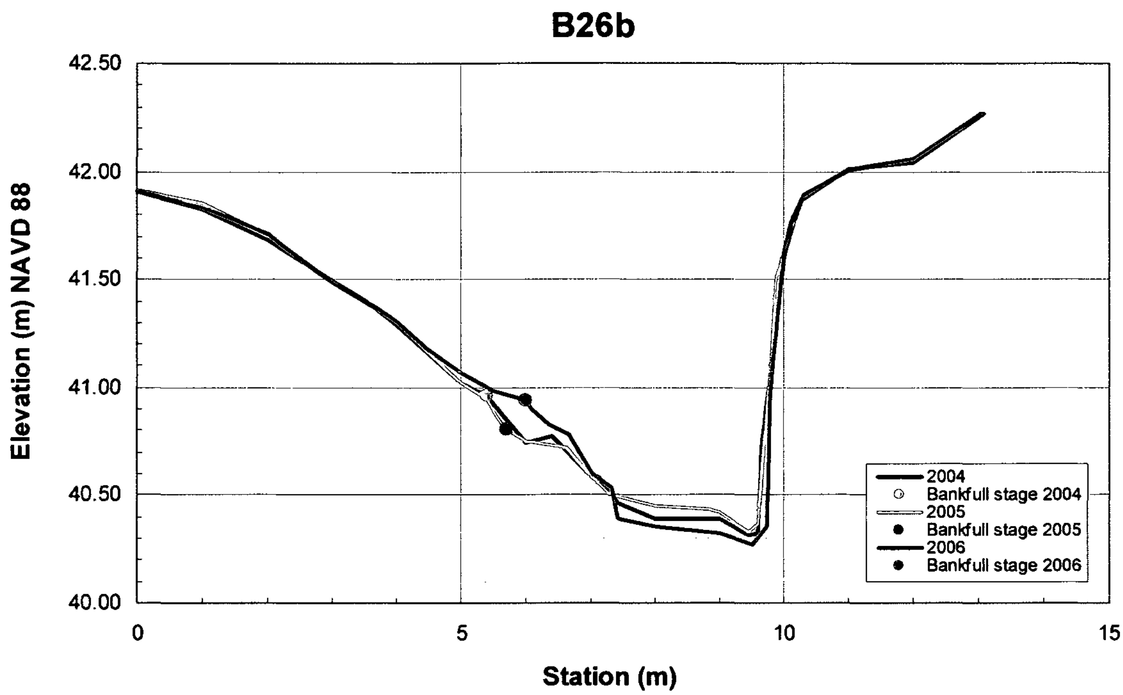

B24a
Elevation (m) NAVD 88
Station (m)
44.00
43.50
43.00
42.50
42.00
41.50
41.00
0
5
10
15
20
25
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B24b
Elevation (m) NAVD 88
44.00
43.50
43.00
42.50
42.00
41.50
41.00
40.50
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

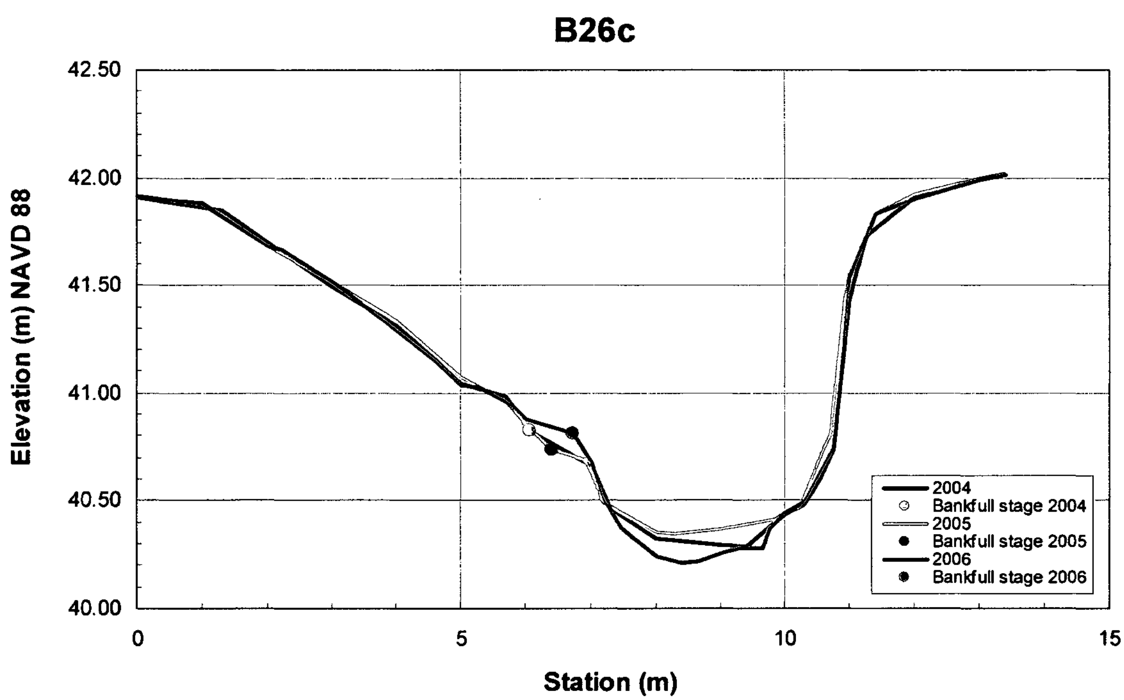

B24c
Elevation (m) NAVD 88
44.00
43.50
43.00
42.50
42.00
41.50
41.00
40.50
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B25
43.00
42.50
42.00
41.50
41.00
40.50
40.00
Elevation (m) NAVD 88
20
25
30
35
40
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

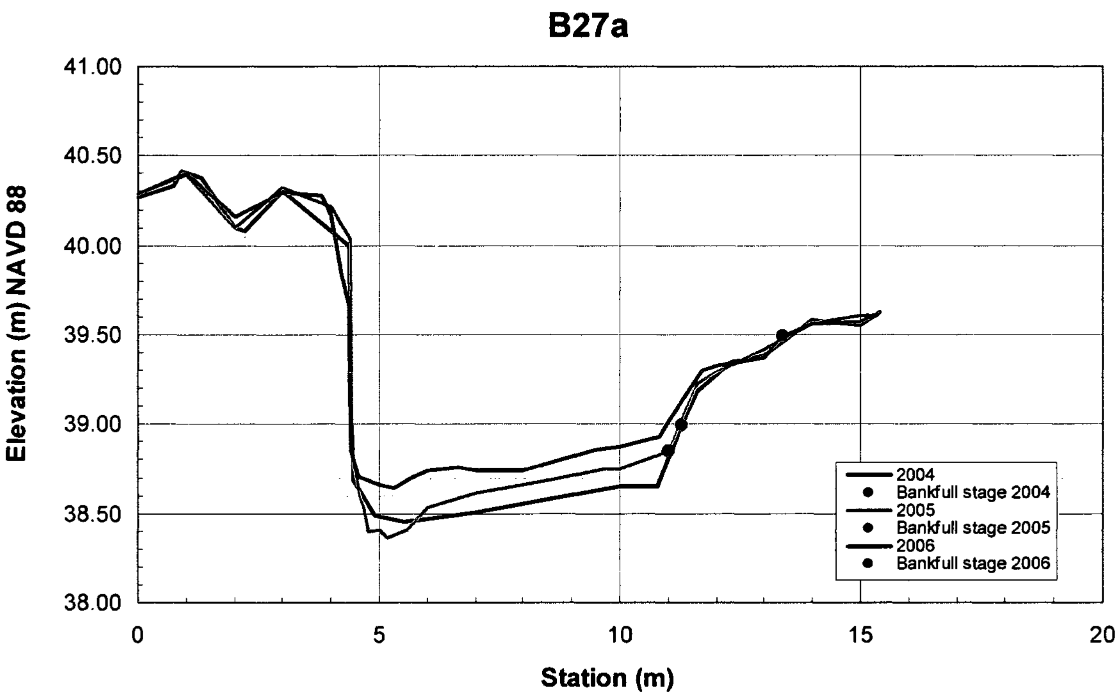

B26a
42.50
42.00
41.50
41.00
40.50
40.00
Elevation (m) NAVD 88
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

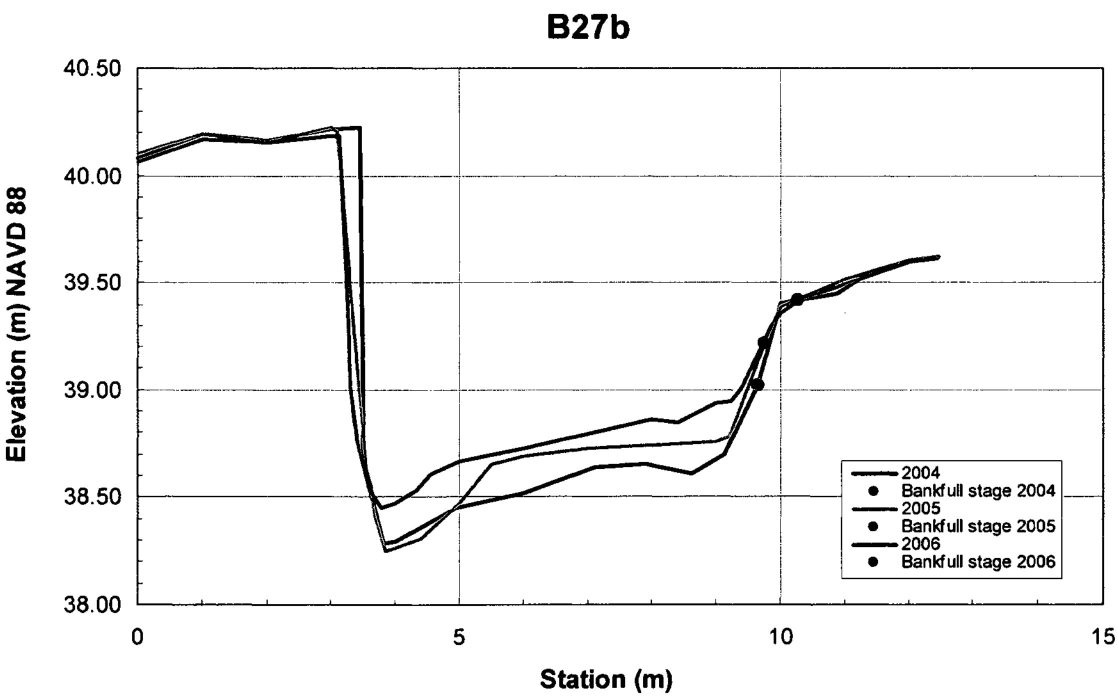


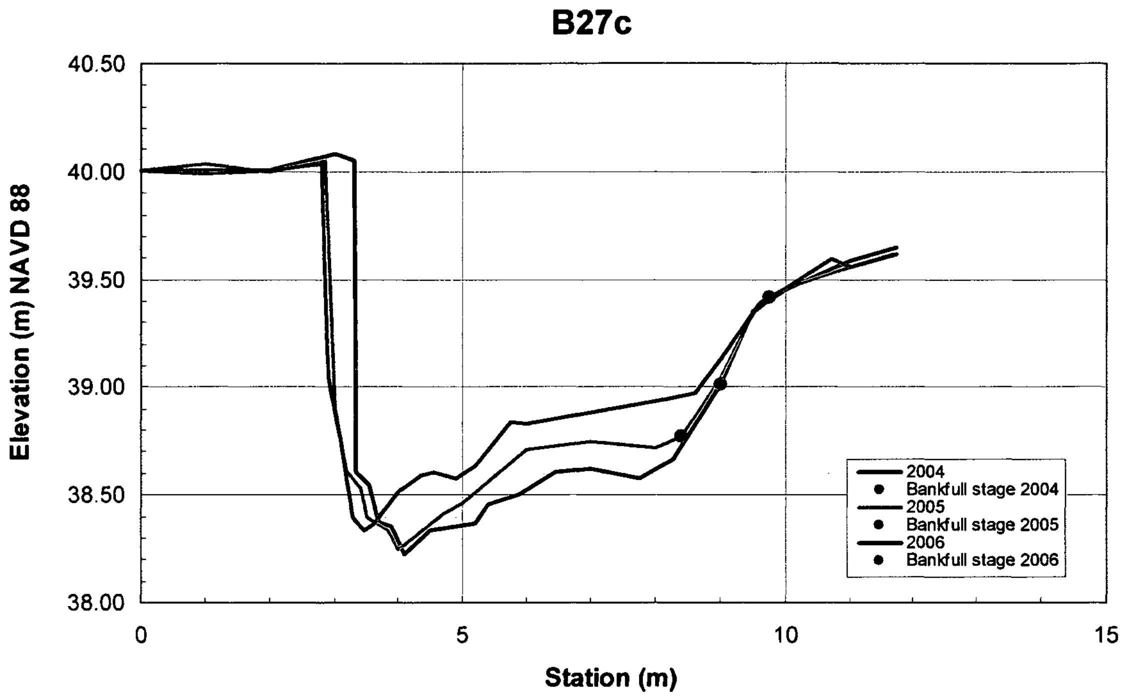
B26b
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

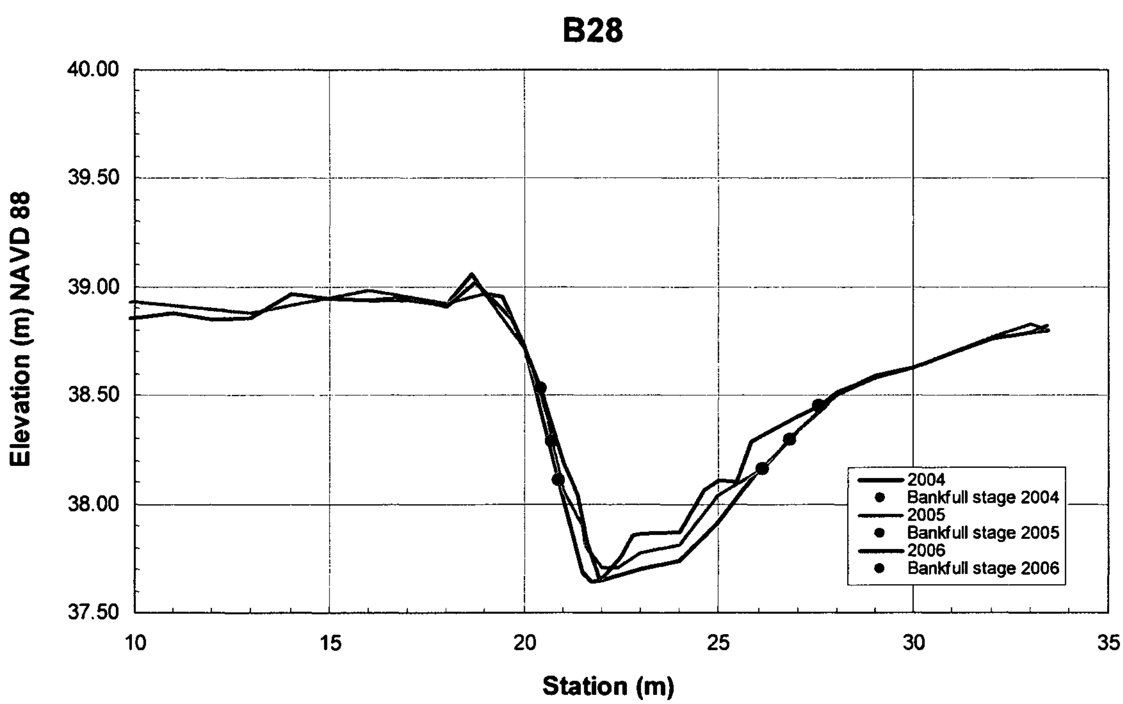


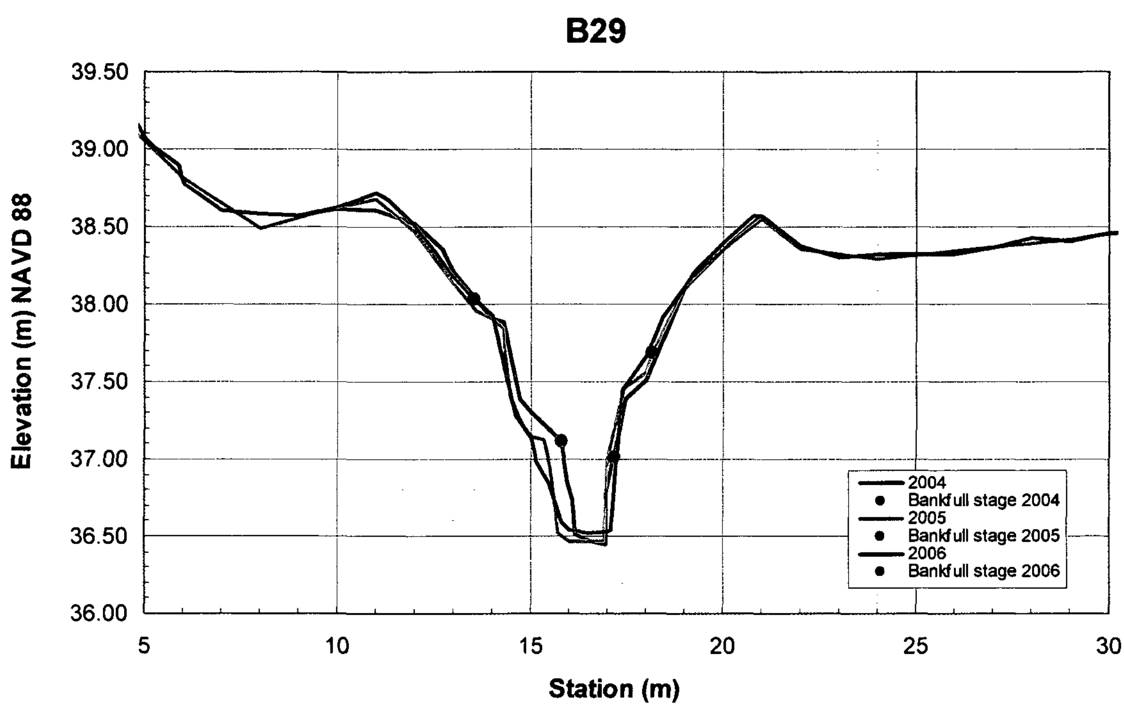
B26c
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


B27a
Elevation (m) NAVD 88
41.00
40.50
40.00
39.50
39.00
38.50
38.00
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

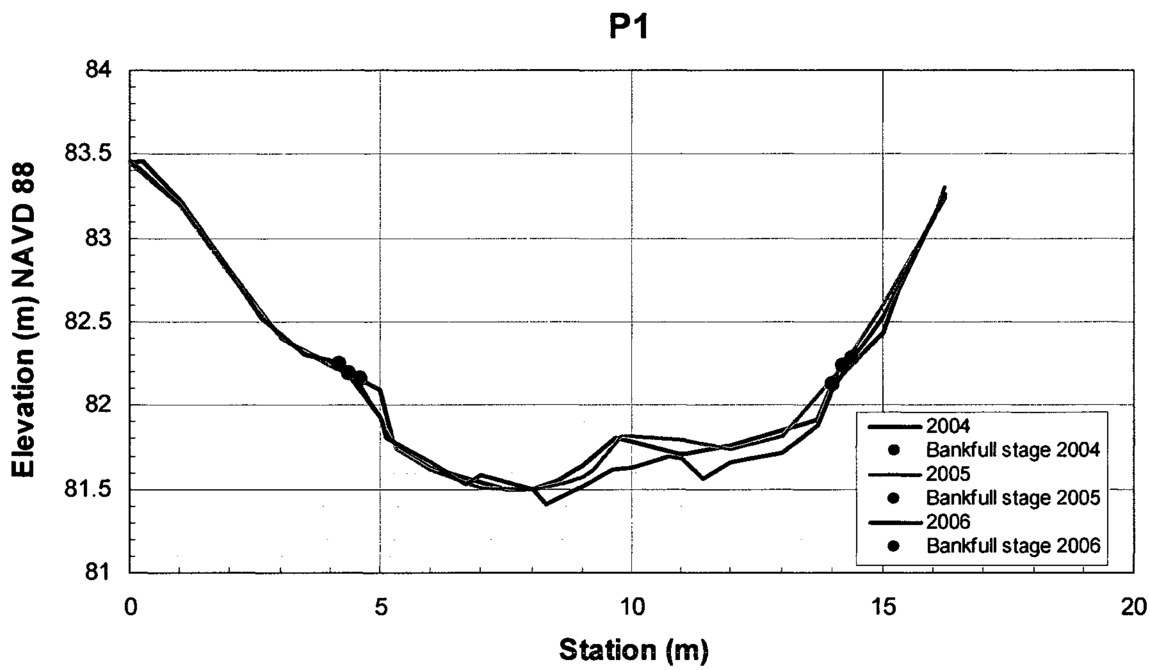

B27b
Elevation (m) NAVD 88
40.50
40.00
39.50
39.00
38.50
38.00
0
5
10
15
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

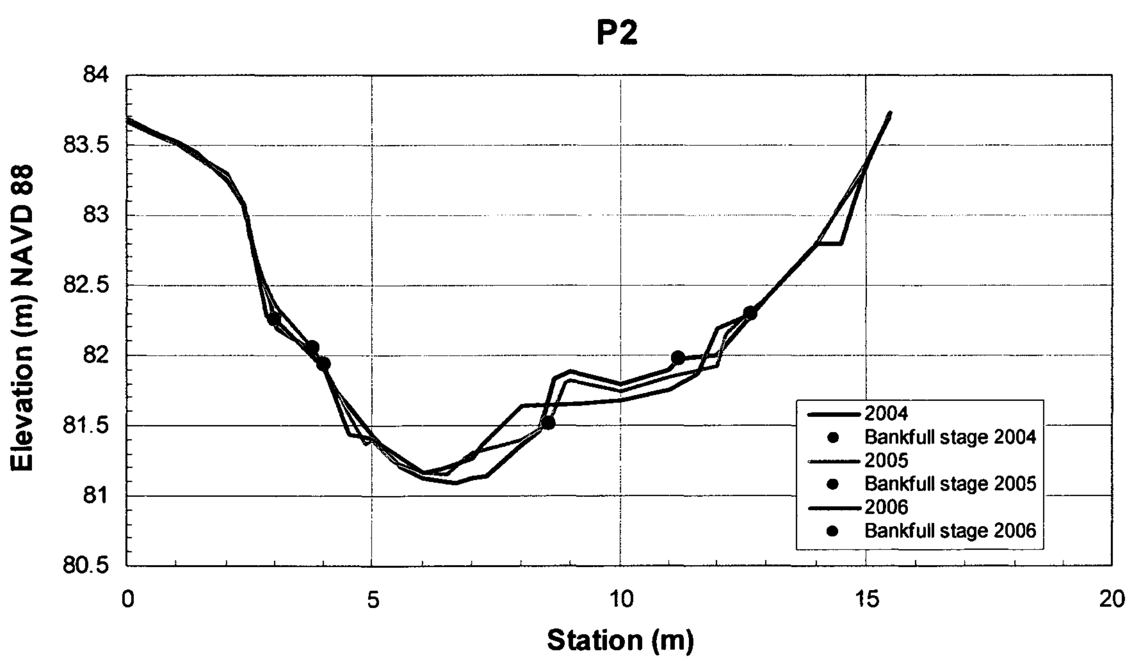

B27c
Elevation (m) NAVD 88
Station (m)
40.50
40.00
39.50
39.00
38.50
38.00
0
5
10
15
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

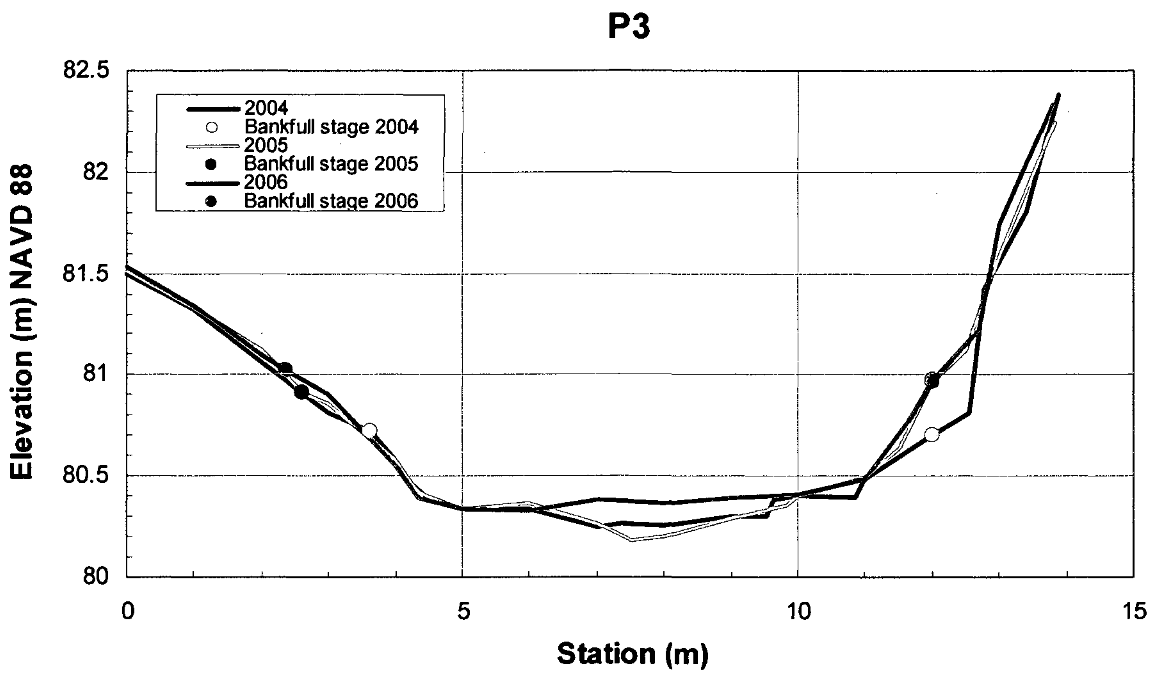

B28
Elevation (m) NAVD 88
Station (m)
40.00
39.50
39.00
38.50
38.00
37.50
10
15
20
25
30
35
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

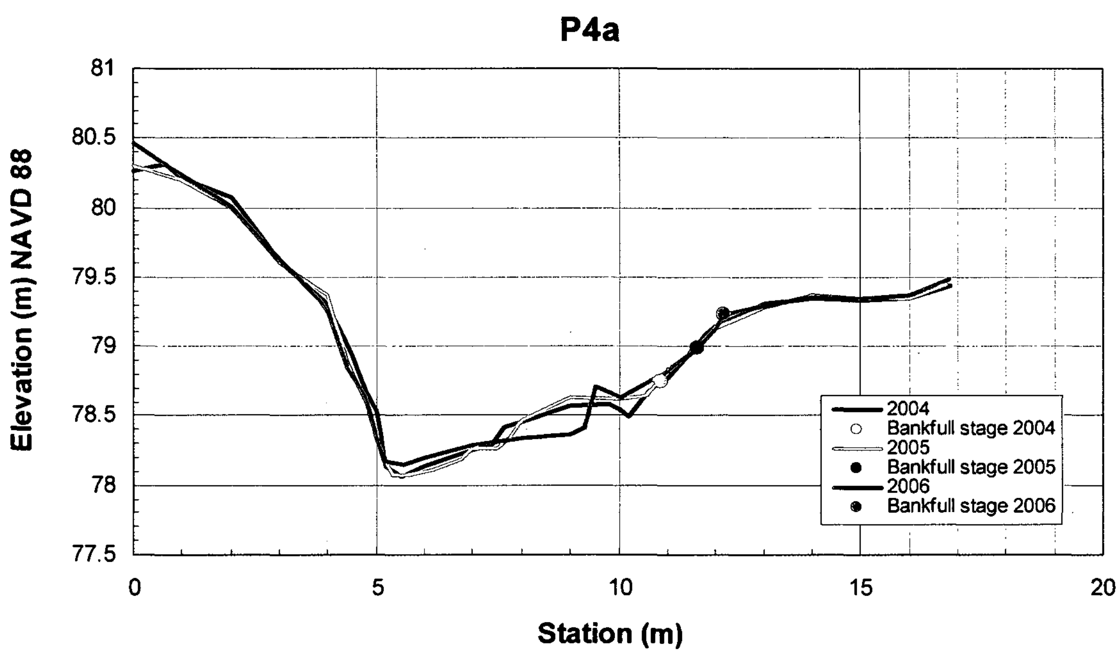

B29
Elevation (m) NAVD 88
Station (m)
39.50
39.00
38.50
38.00
37.50
37.00
36.50
36.00
5
10
15
20
25
30
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

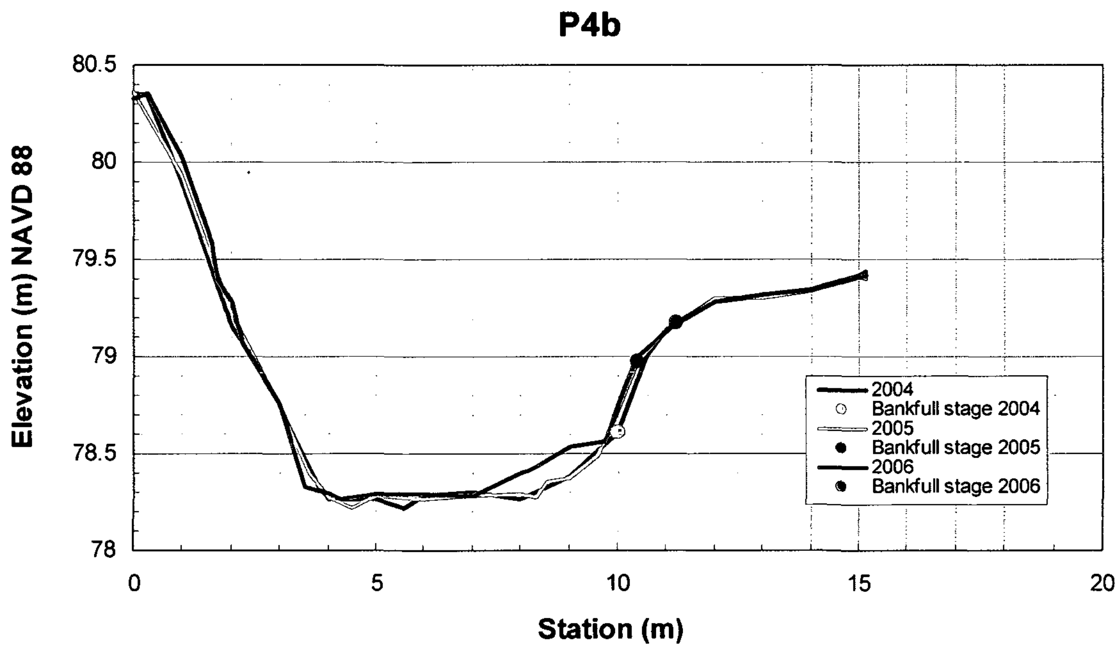
Upper Penitencia Creek Cross Section Data

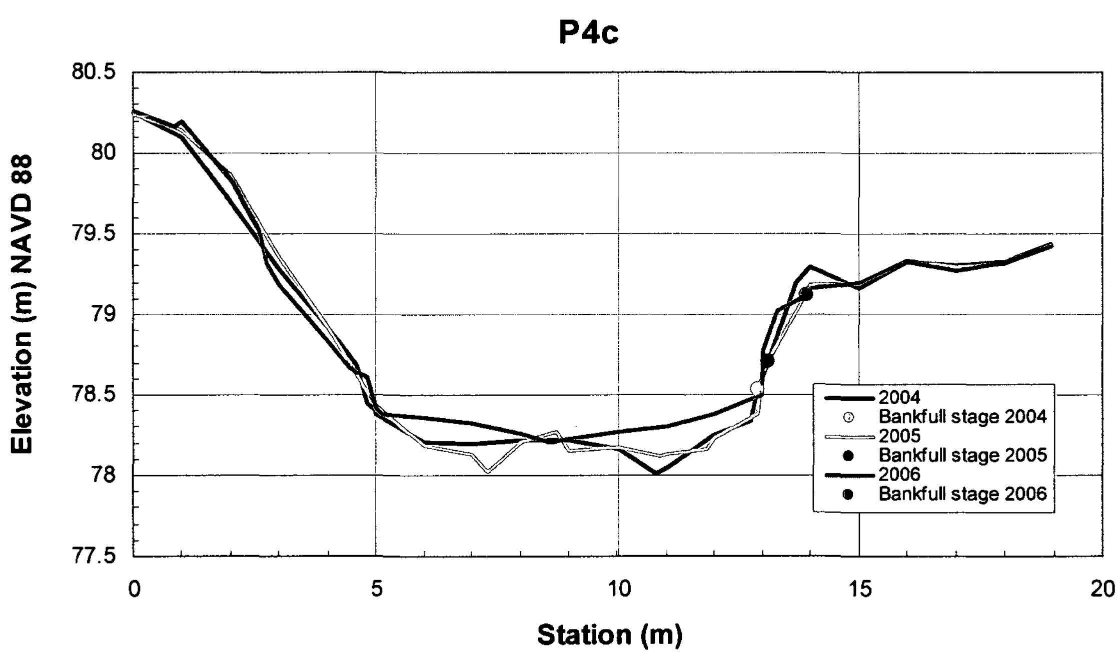


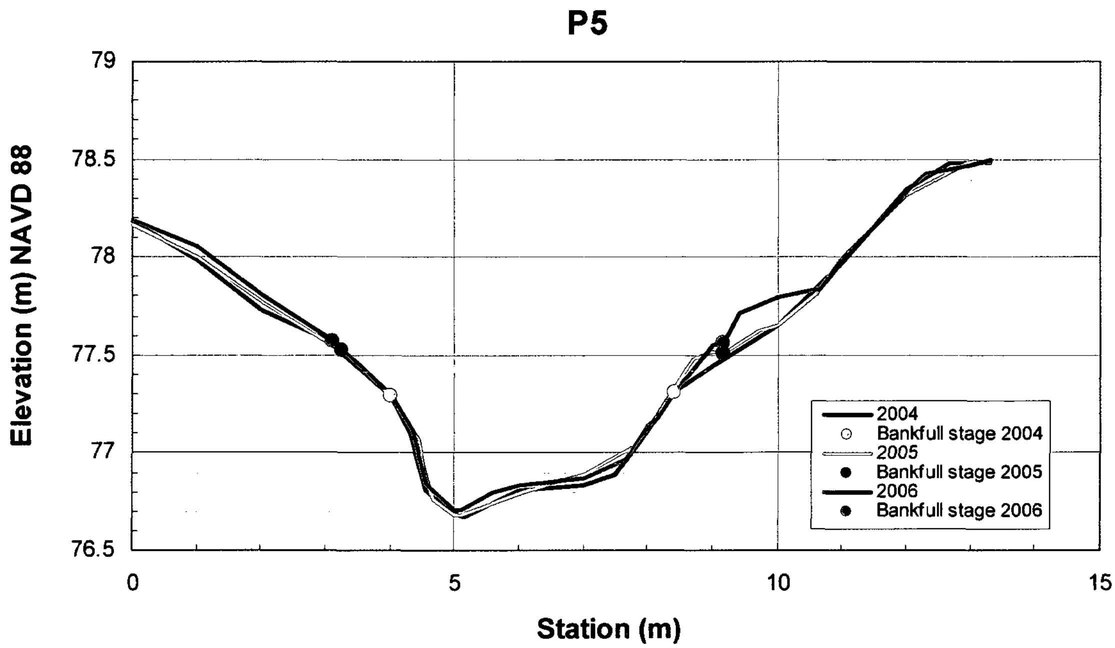


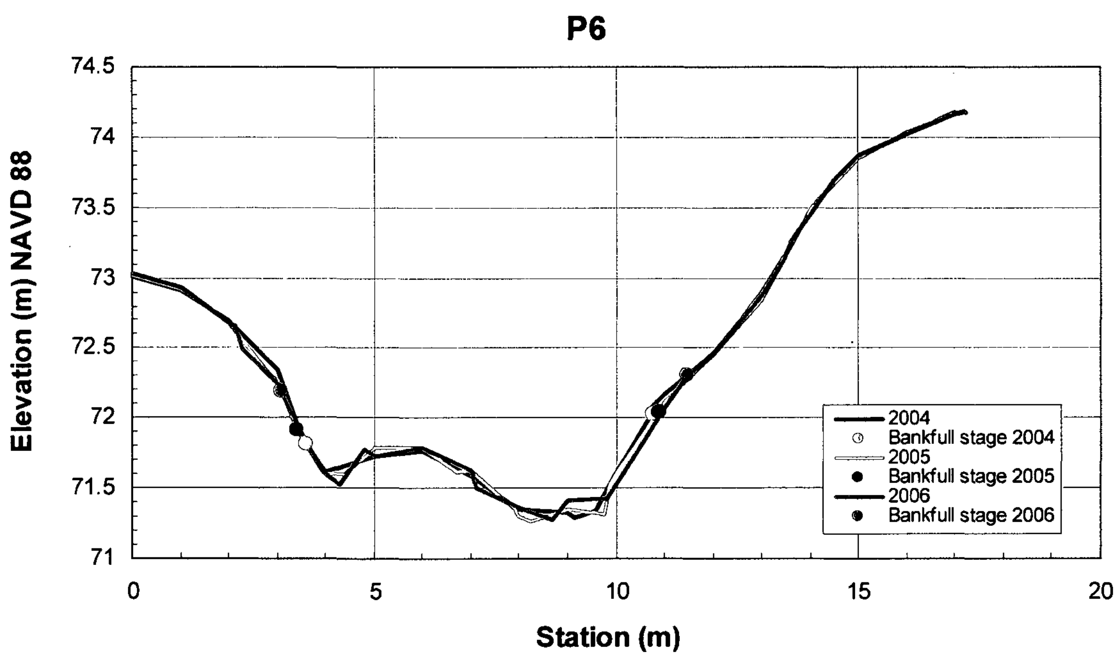

P3
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
Elevation (m) NAVD 88
Station (m)
82.5
82
81.5
81
80.5
80
0
5
10
15

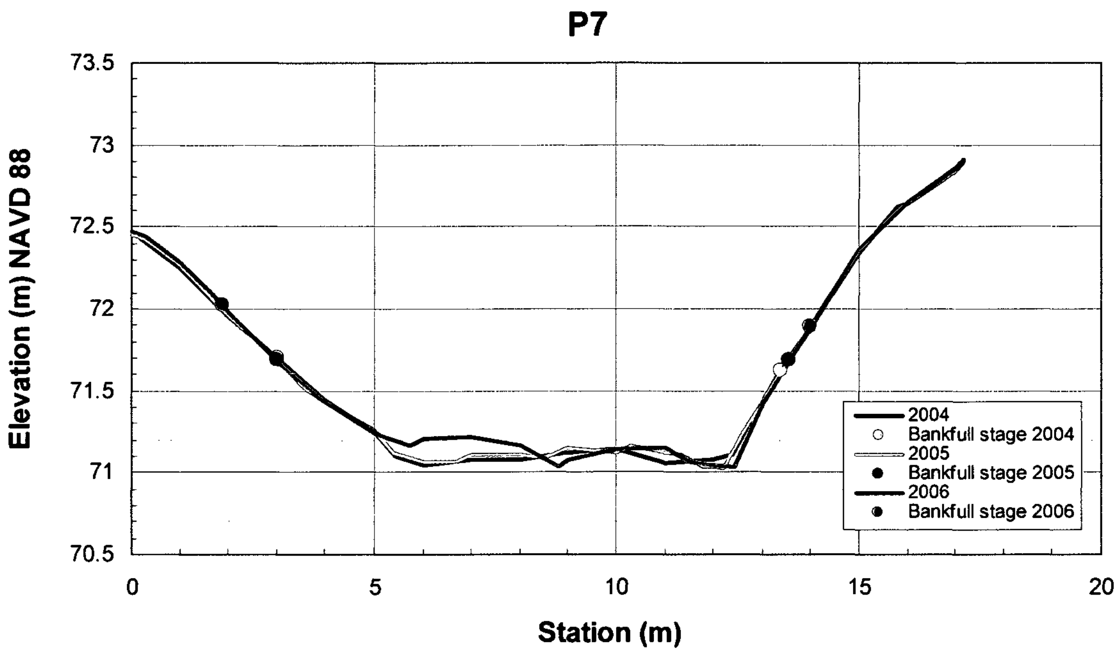

P4a
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
Elevation (m) NAVD 88
Station (m)
81
80.5
80
79.5
79
78.5
78
77.5
0
5
10
15
20

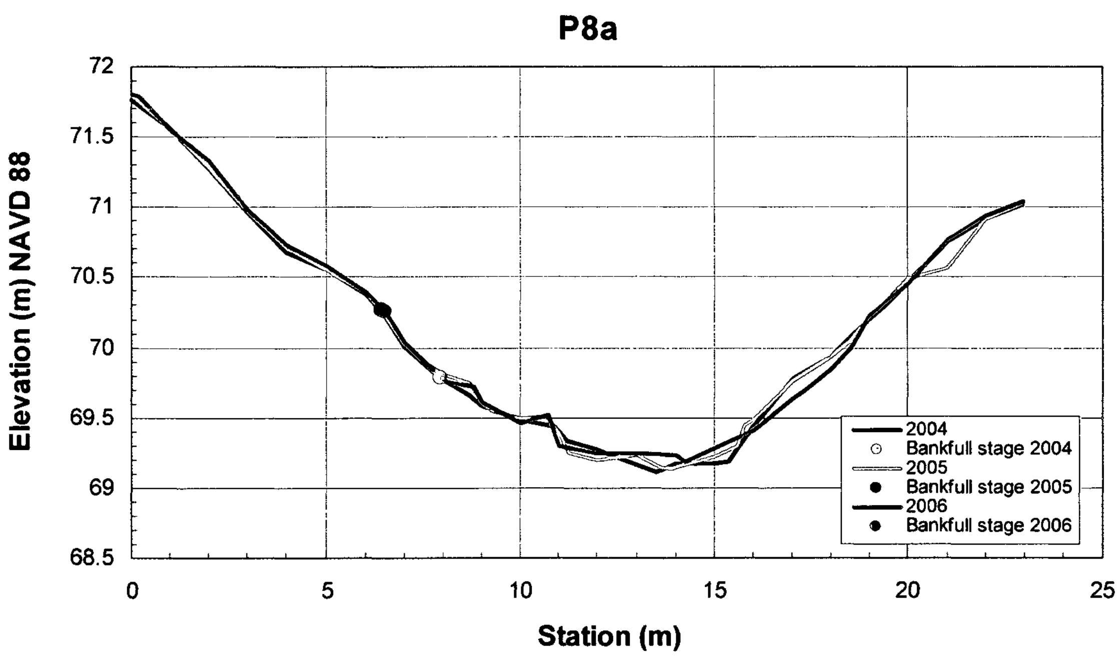

P4b
Elevation (m) NAVD 88
80.5
80
79.5
79
78.5
78
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

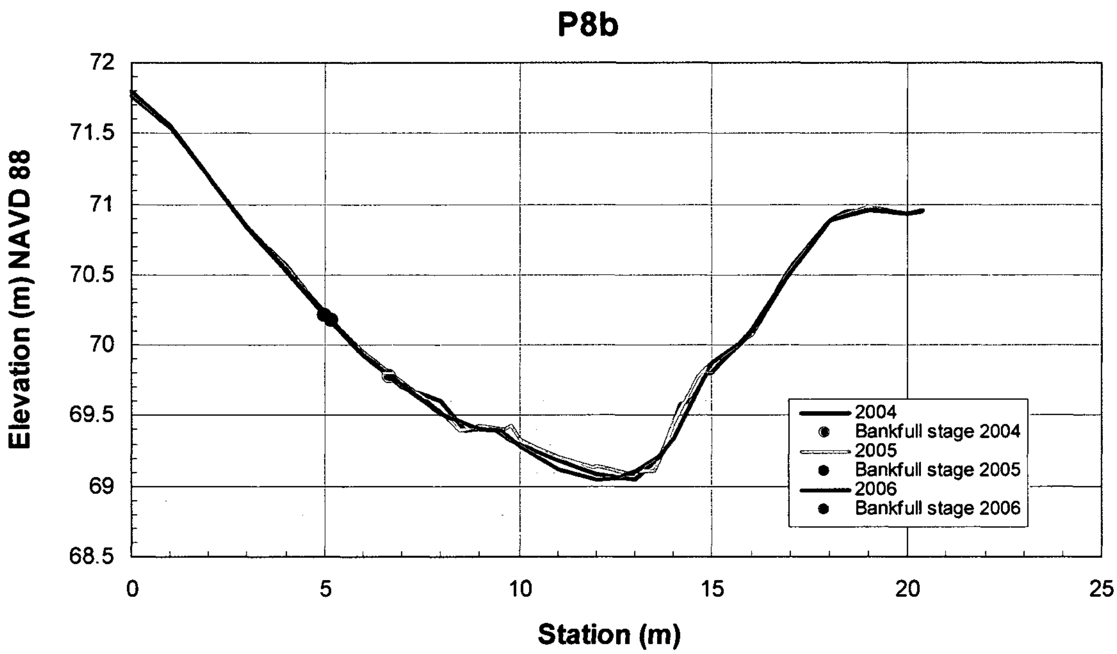

P4c
Elevation (m) NAVD 88
80.5
80
79.5
79
78.5
78
77.5
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P5
79
78.5
78
77.5
77
76.5
0
5
10
15
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P6
74.5
74
73.5
73
72.5
72
71.5
71
0
5
10
15
20
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P7
Elevation (m) NAVD 88
73.5
73
72.5
72
71.5
71
70.5
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P8a
Elevation (m) NAVD 88
72
71.5
71
70.5
70
69.5
69
68.5
0
5
10
15
20
25
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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Station (m)
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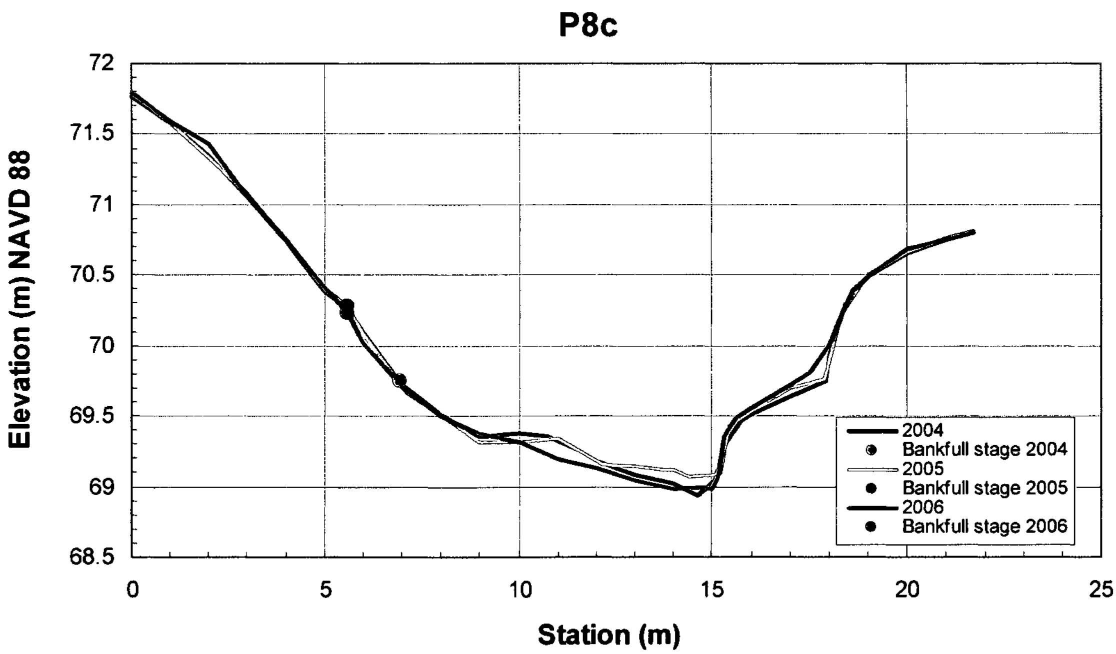
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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Station (m)
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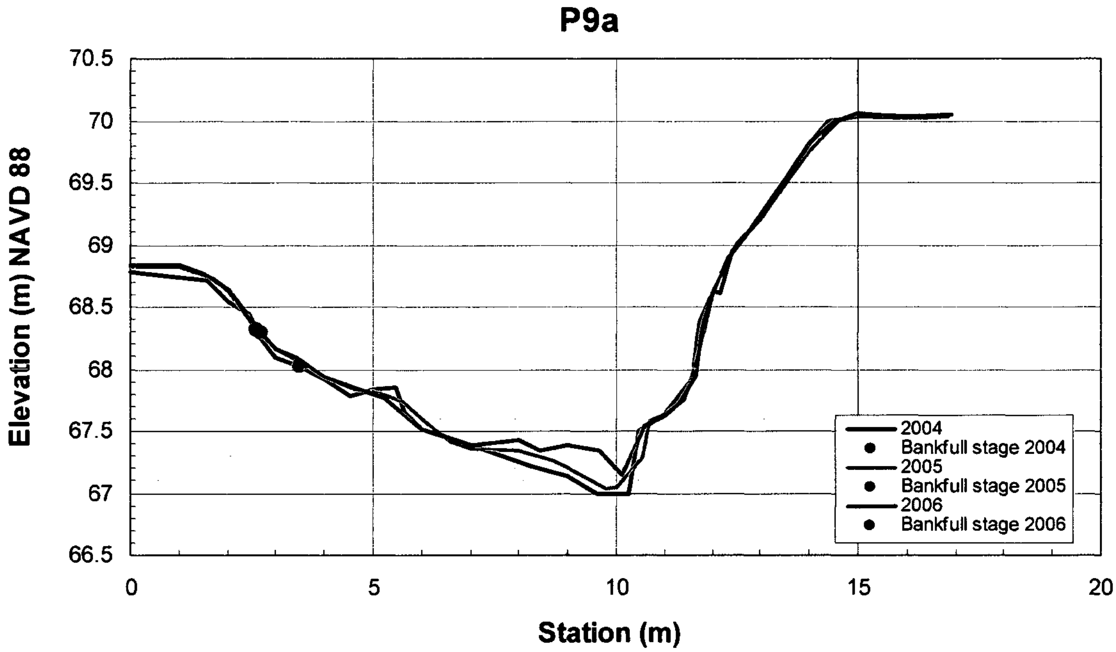
Bankfull stage 2005
2006
Bankfull stage 2006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70
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69
68.5
68
67.5
67
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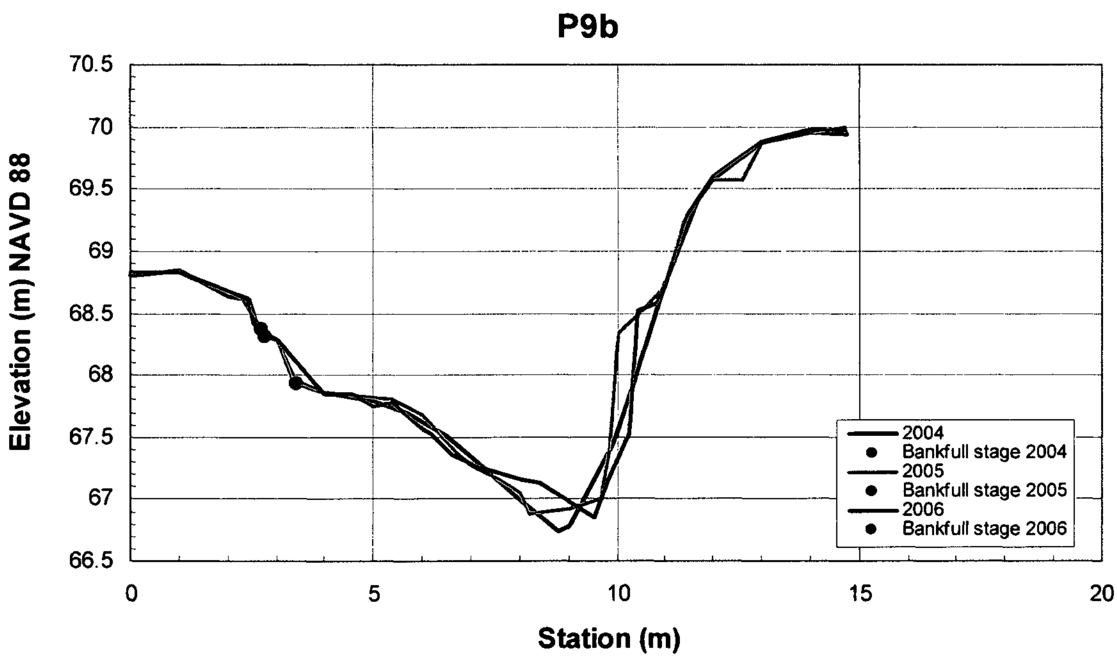
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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67
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Elevation (m) NAVD 88
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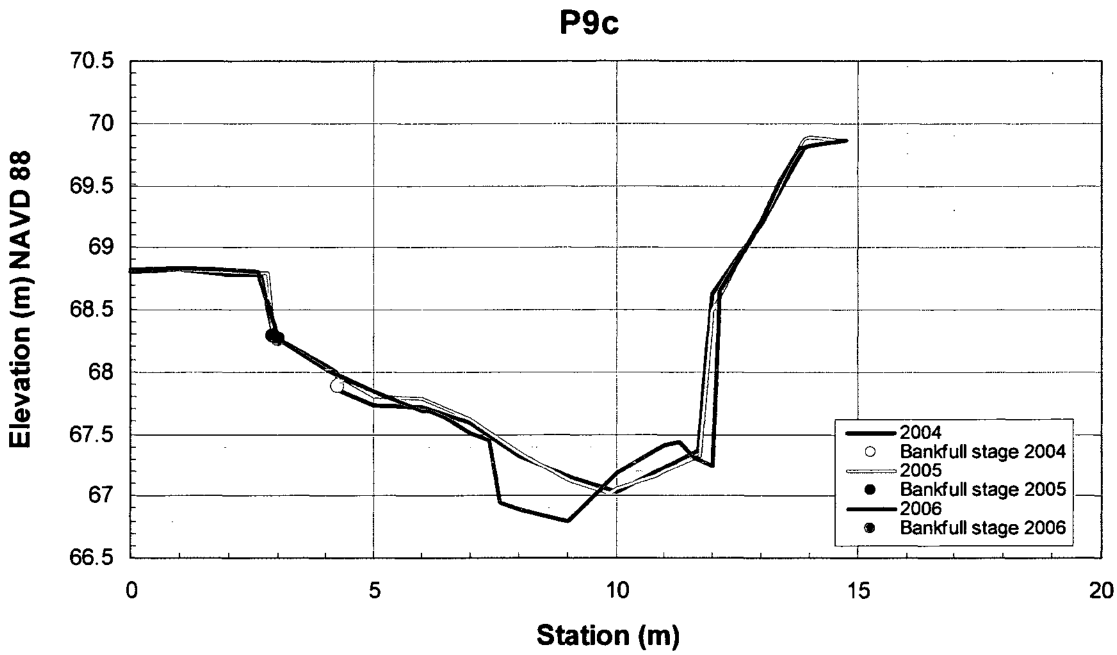
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P9c
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Station (m)
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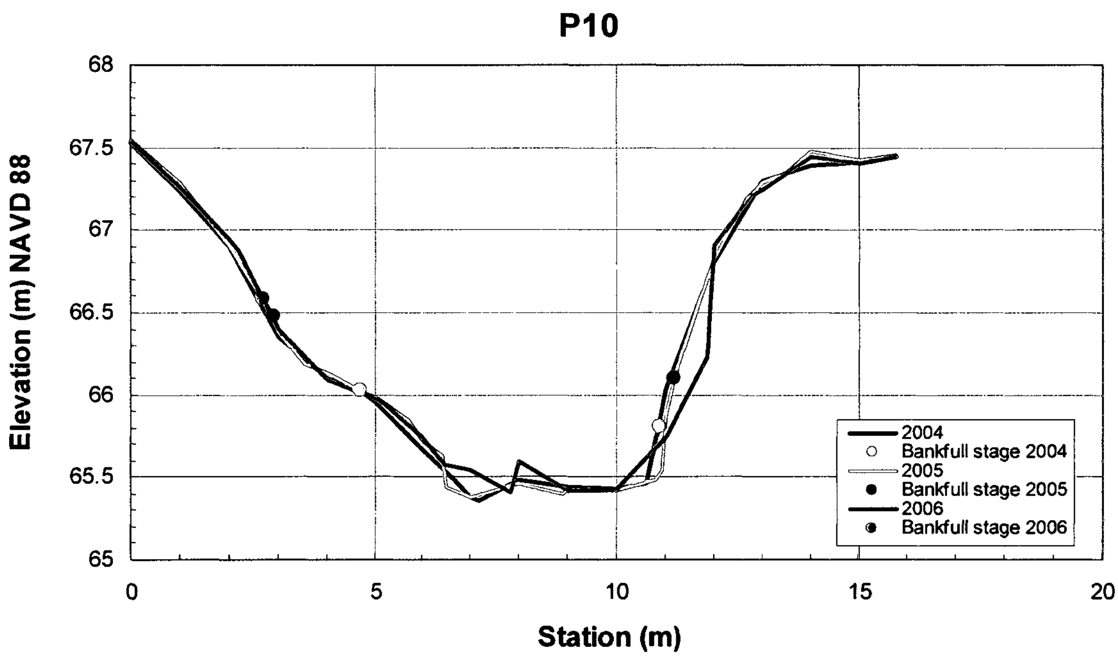
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006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Station (m)
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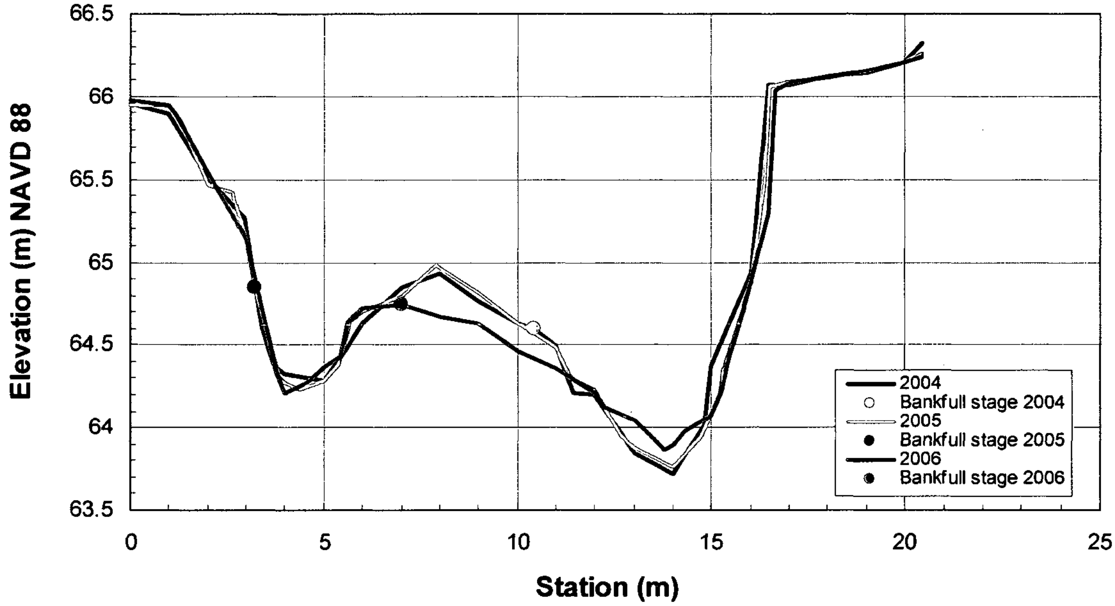
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

P12a


Elevation (m) NAVD 88
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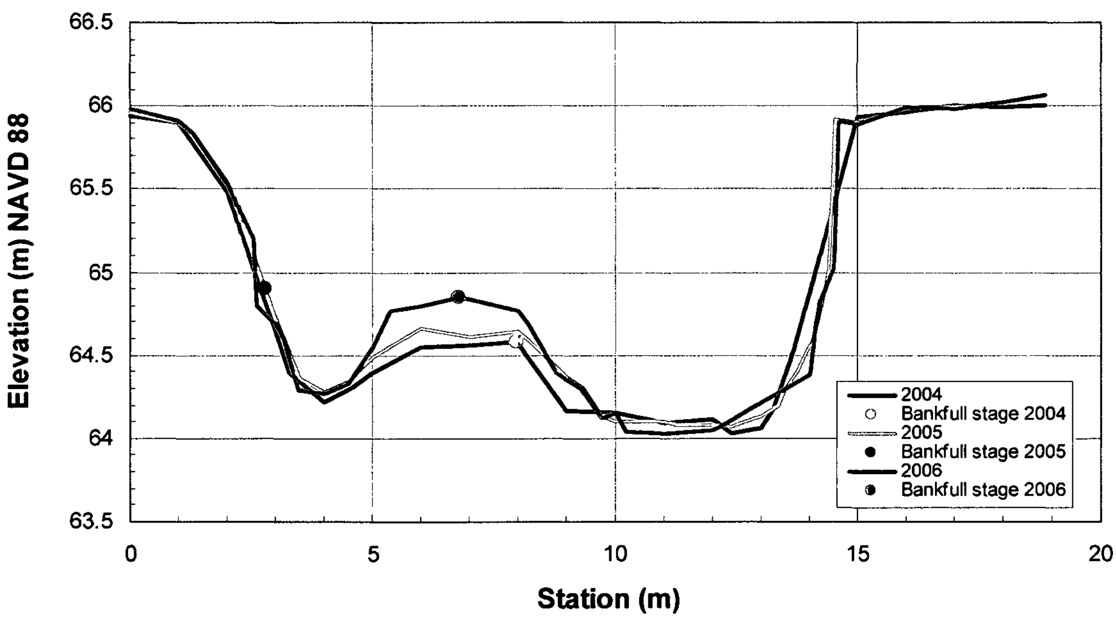
66
65.5
65
64.5
64
63.5
0
5
10
15
20
25
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006

P12b


Elevation (m) NAVD 88
66.5
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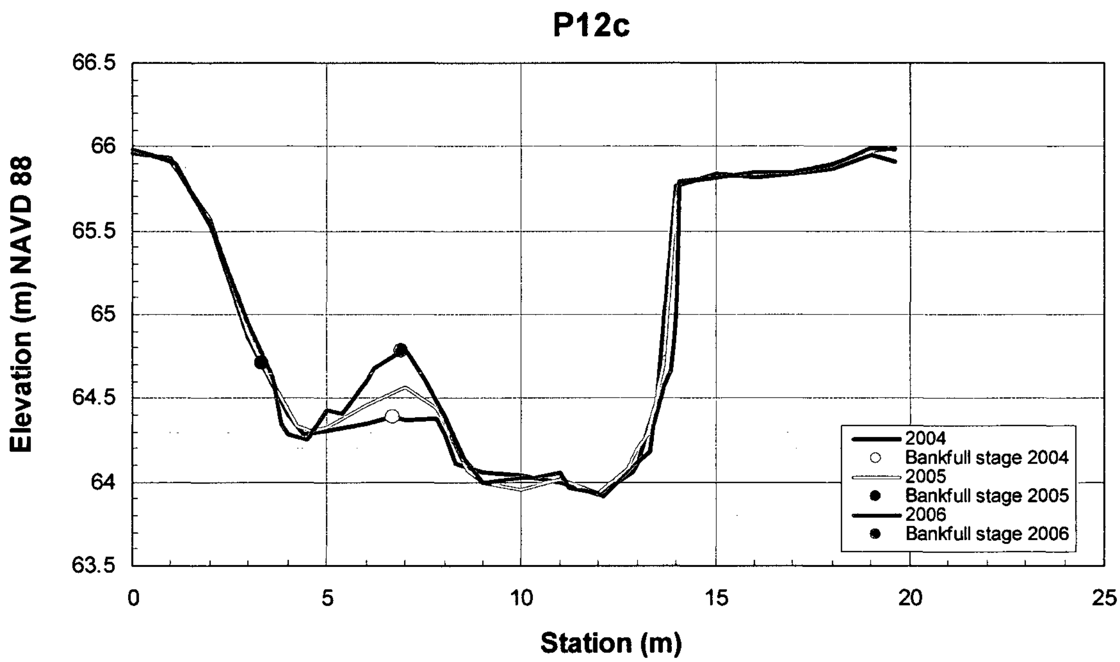
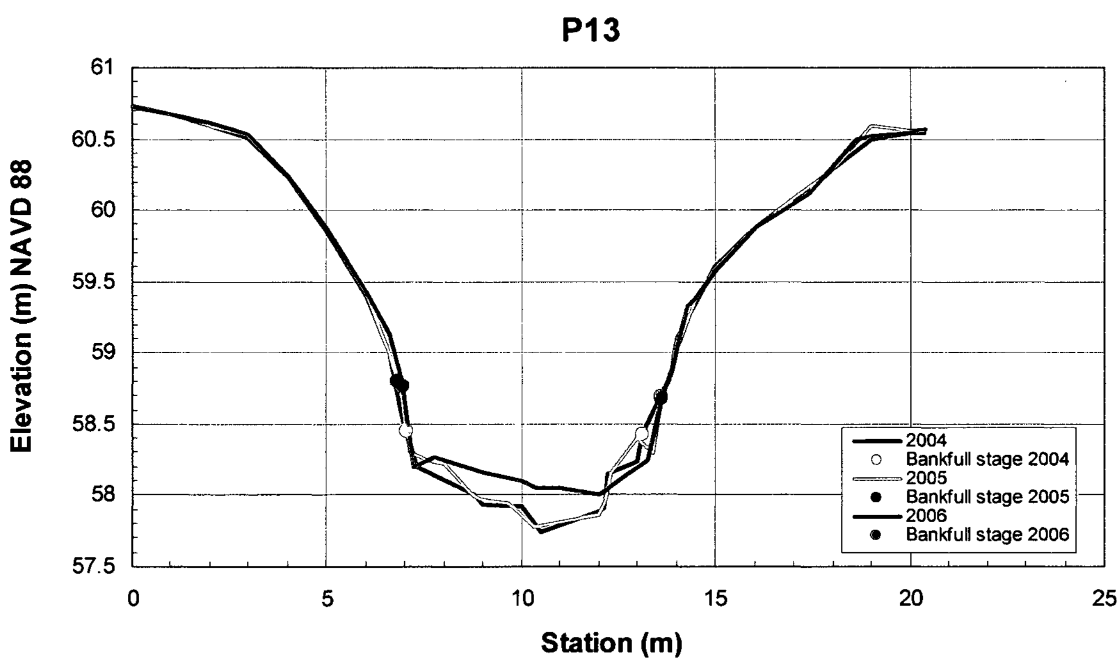
65.5
65
64.5
64
63.5
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



P12c
66.5
66
65.5
65
64.5
64
63.5
0
5
10
15
20
25
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006



P13
61
60.5
60
59.5
59
58.5
58
57.5
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5
10
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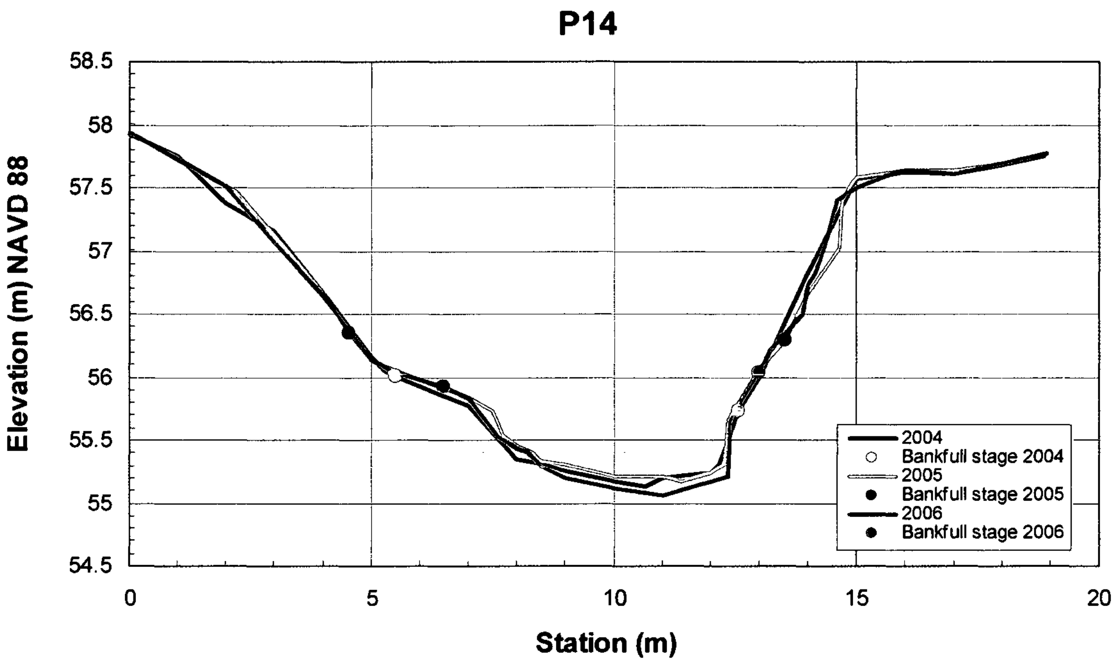
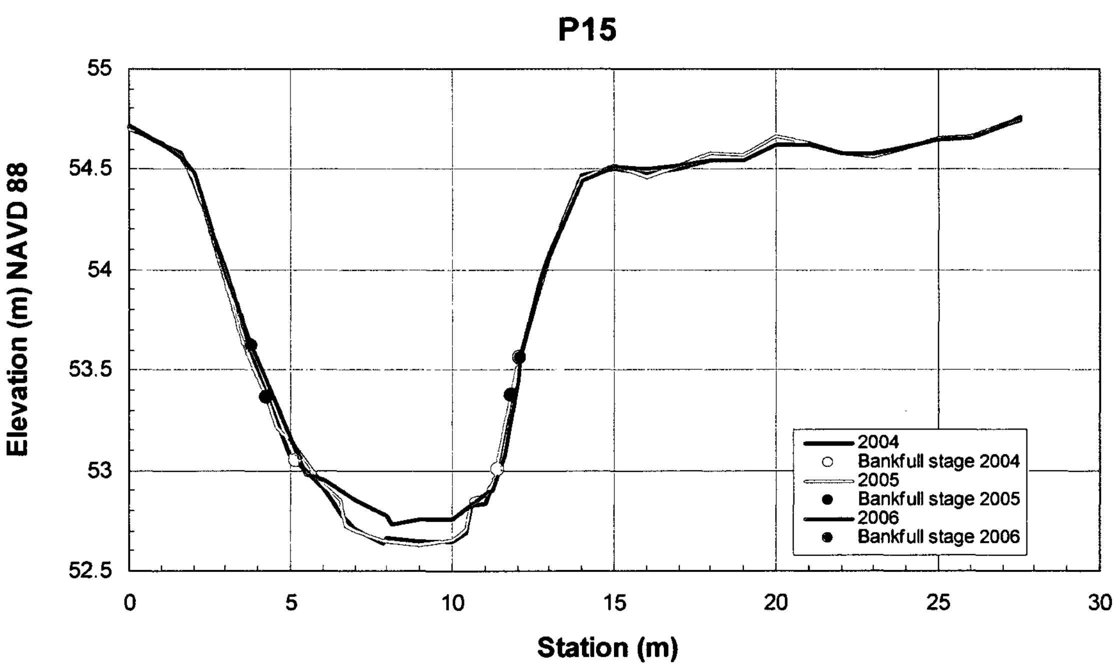
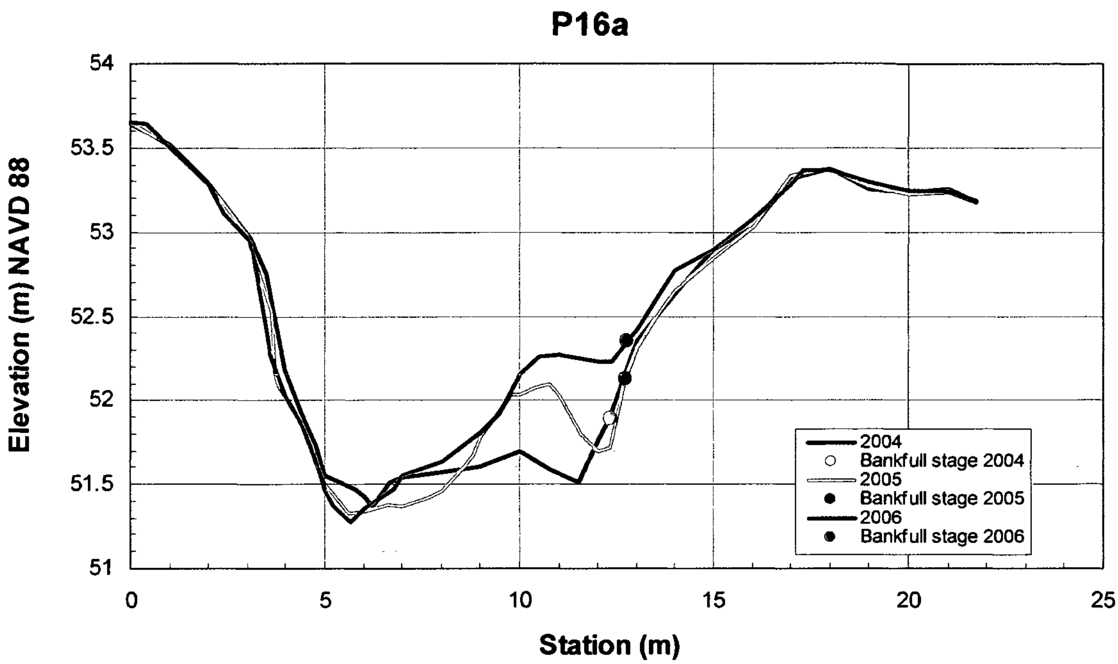
20
25
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P14
Elevation (m) NAVD 88
Station (m)
58.5
58
57.5
57
56.5
56
55.5
55
54.5
0
5
10
15
20
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P15
Elevation (m) NAVD 88
Station (m)
55
54.5
54
53.5
53
52.5
0
5
10
15
20
25
30
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P16a
Elevation (m) NAVD 88
Station (m)
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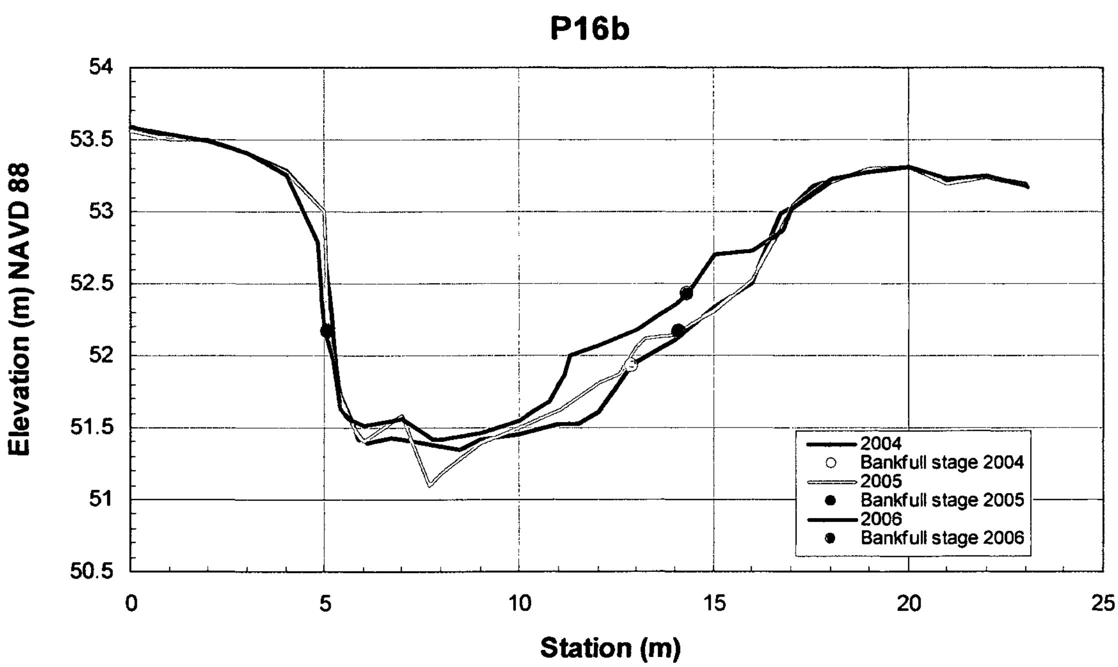
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P16b
Elevation (m) NAVD 88
Station (m)
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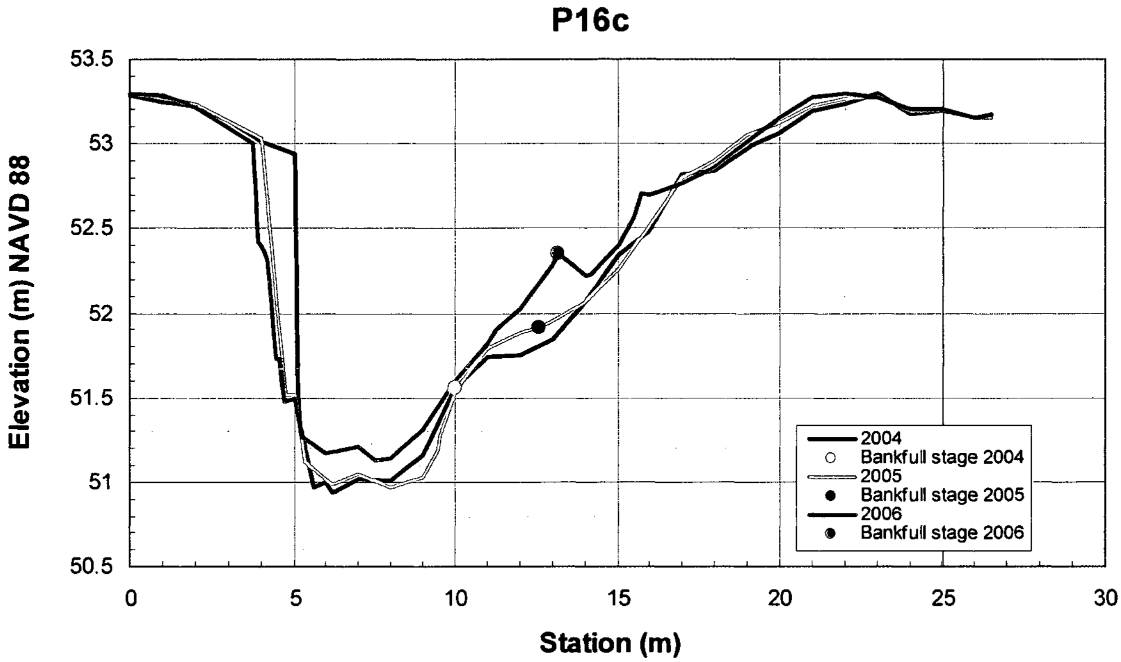
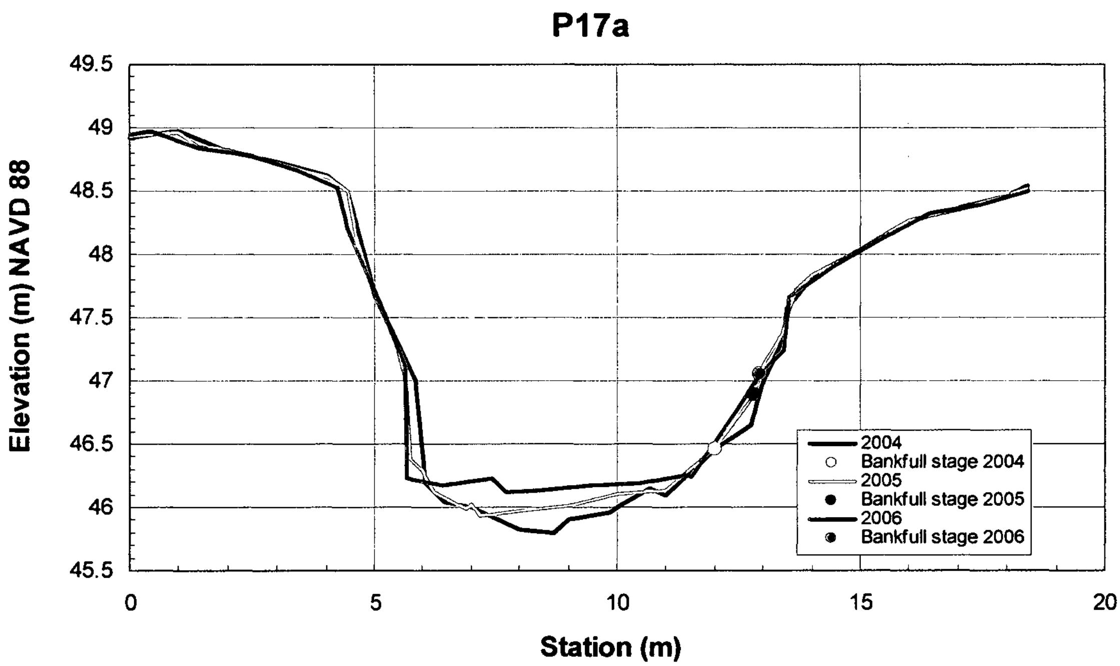
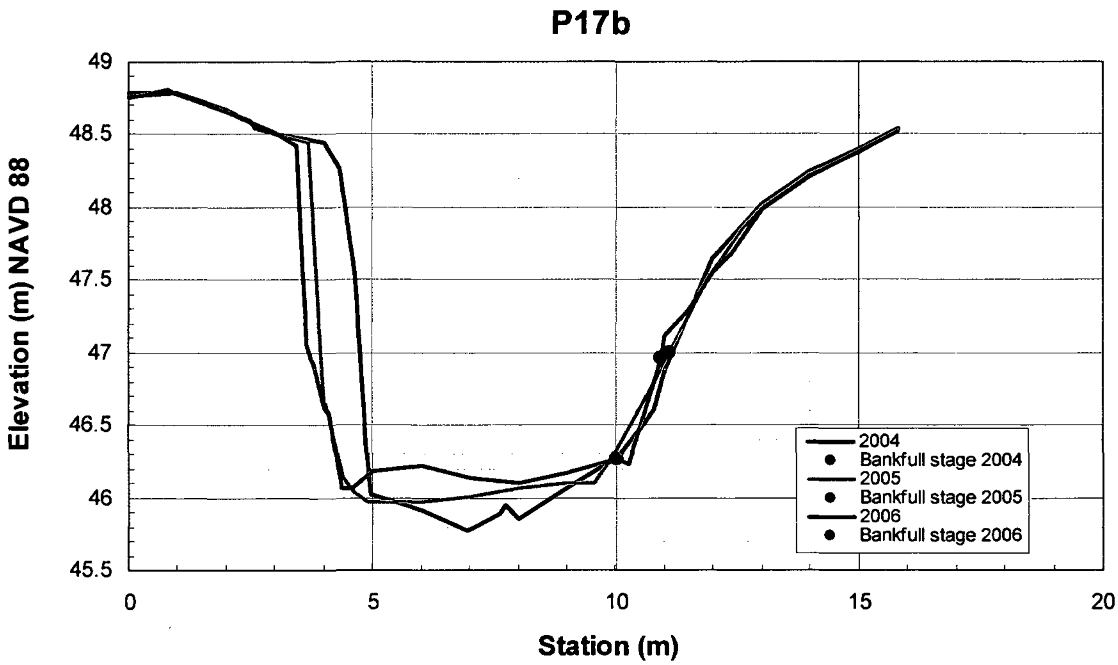
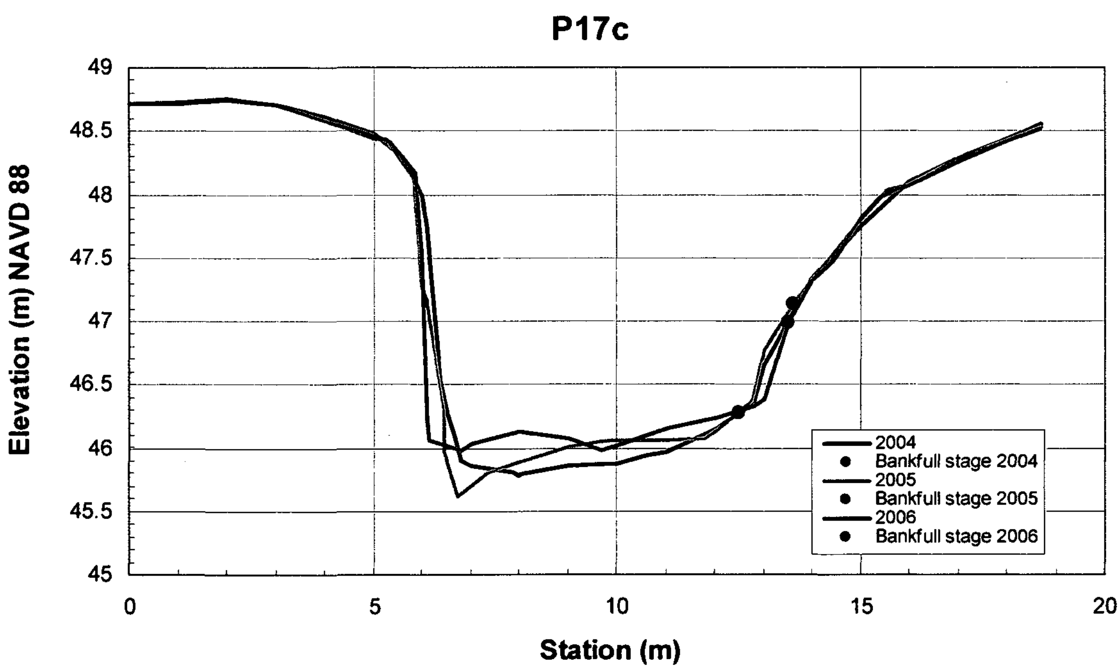
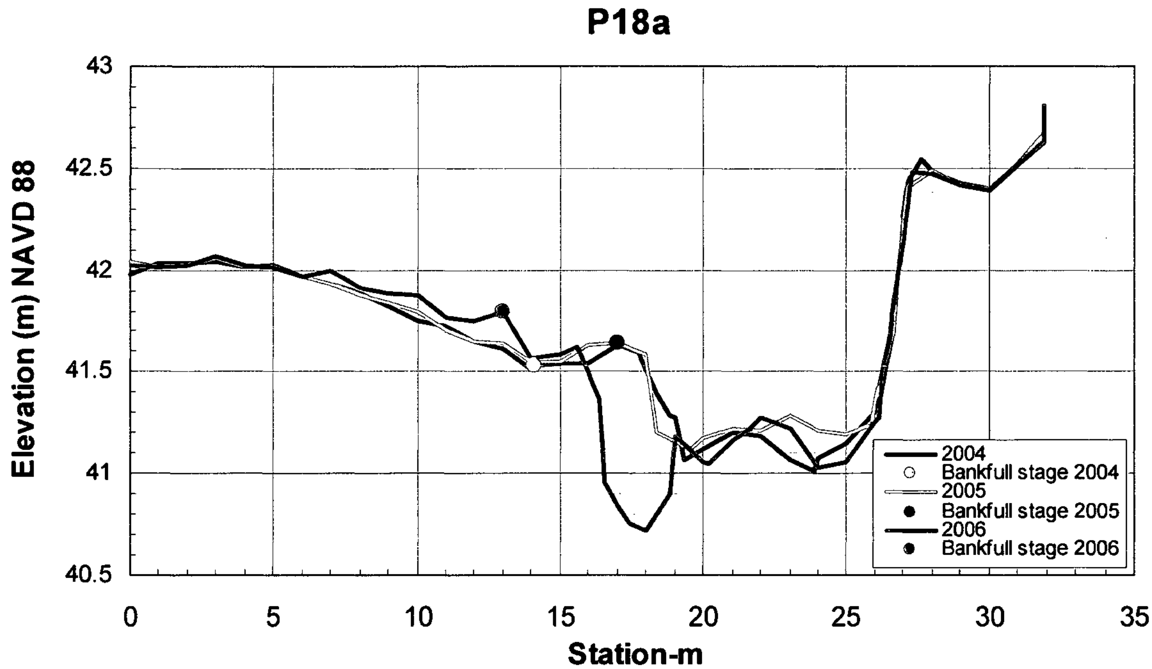
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P16c
Elevation (m) NAVD 88
53.5
53
52.5
52
51.5
51
50.5
0
5
10
15
20
25
30
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P17a
Elevation (m) NAVD 88
49.5
49
48.5
48
47.5
47
46.5
46
45.5
0
5
10
15
20
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P17b
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P17c
Elevation (m) NAVD 88
Station (m)
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P18a
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
43
42.5
42
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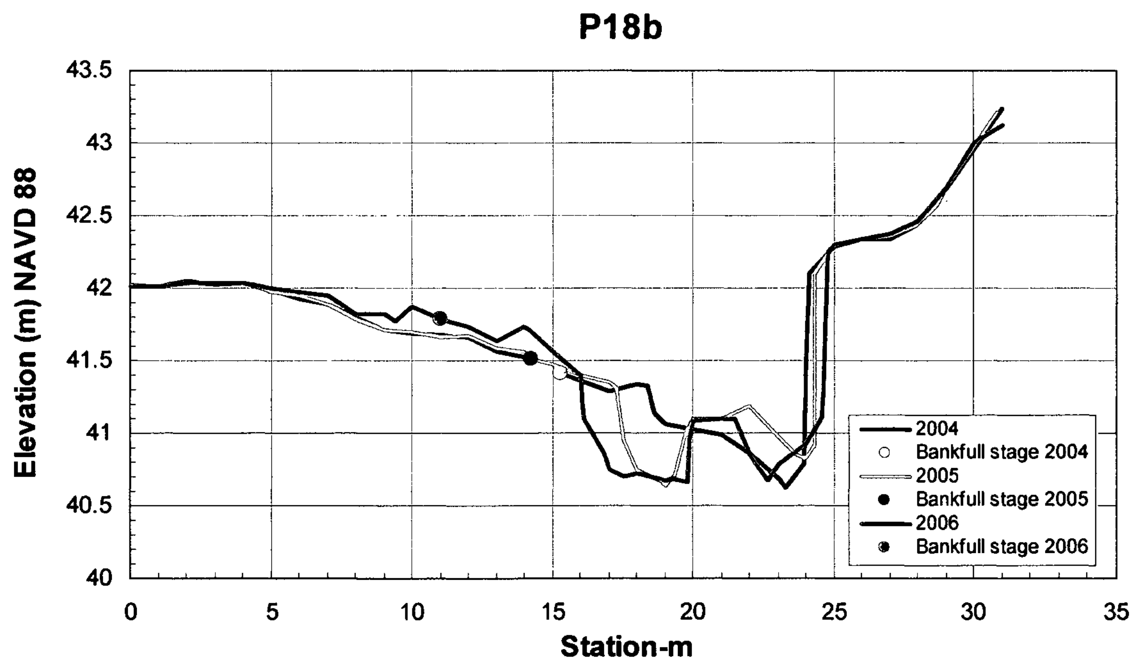
15
20
25
30
35


P18b
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
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42.5
42
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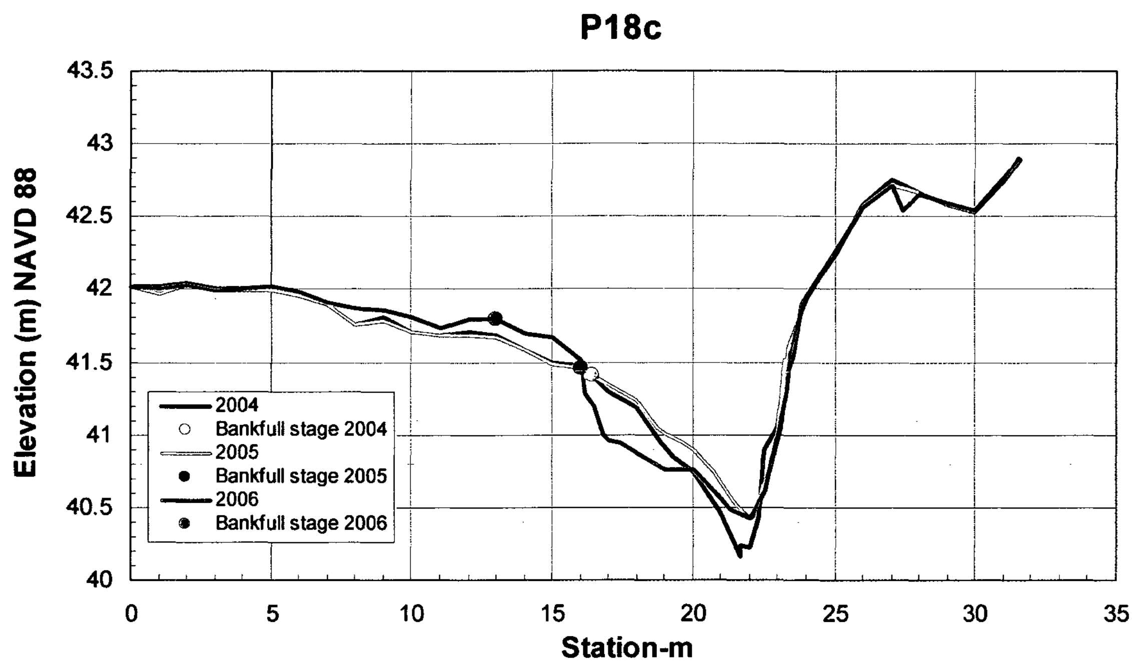
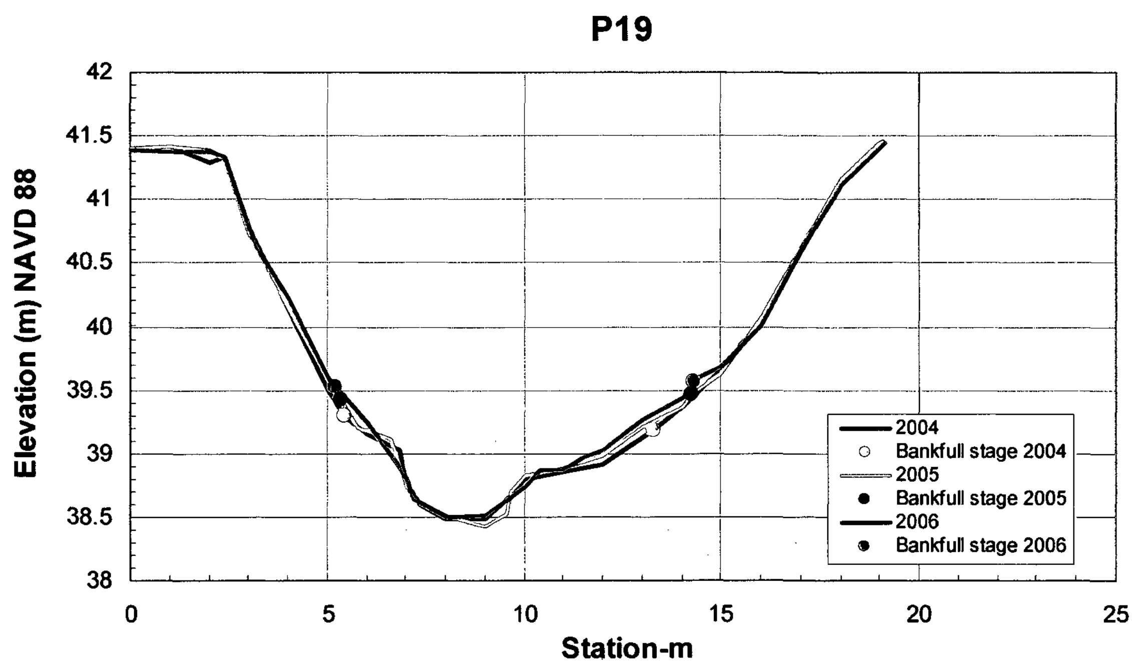
41
40.5
40
0
5
10
15
20
25
30
35


P18c
Elevation (m) NAVD 88
Station-m
43.5
43
42.5
42
41.5
41
40.5
40
0
5
10
15
20
25
30
35
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P19
Elevation (m) NAVD 88
Station-m
42
41.5
41
40.5
40
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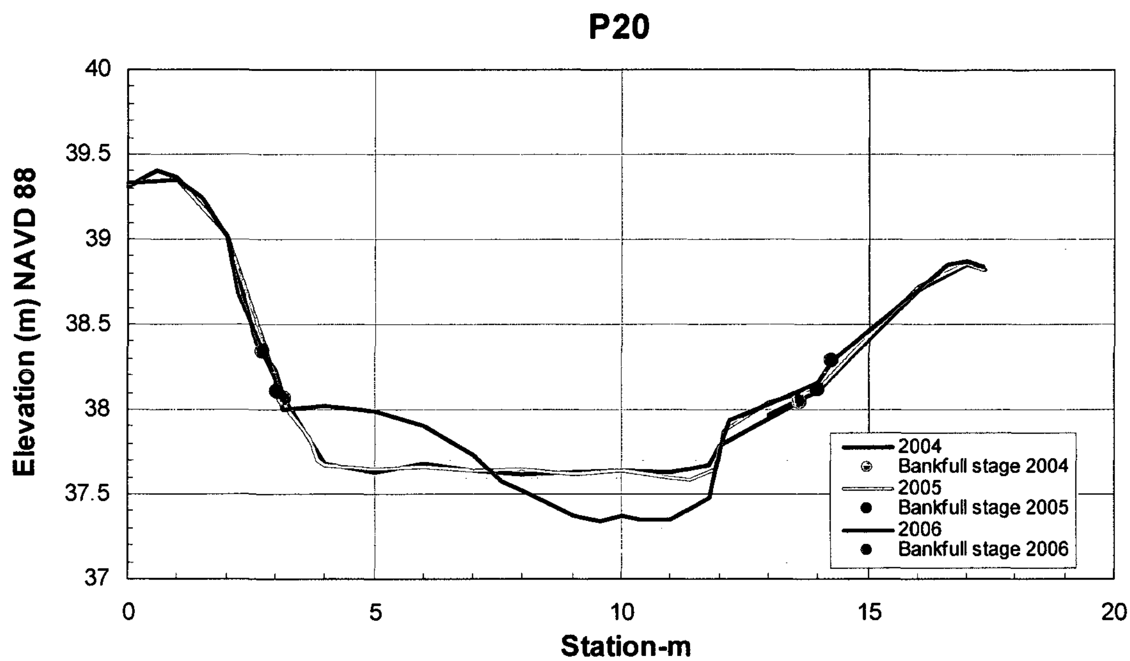
39
38.5
38
0
5
10
15
20
25
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P20
40
39.5
39
38.5
38
37.5
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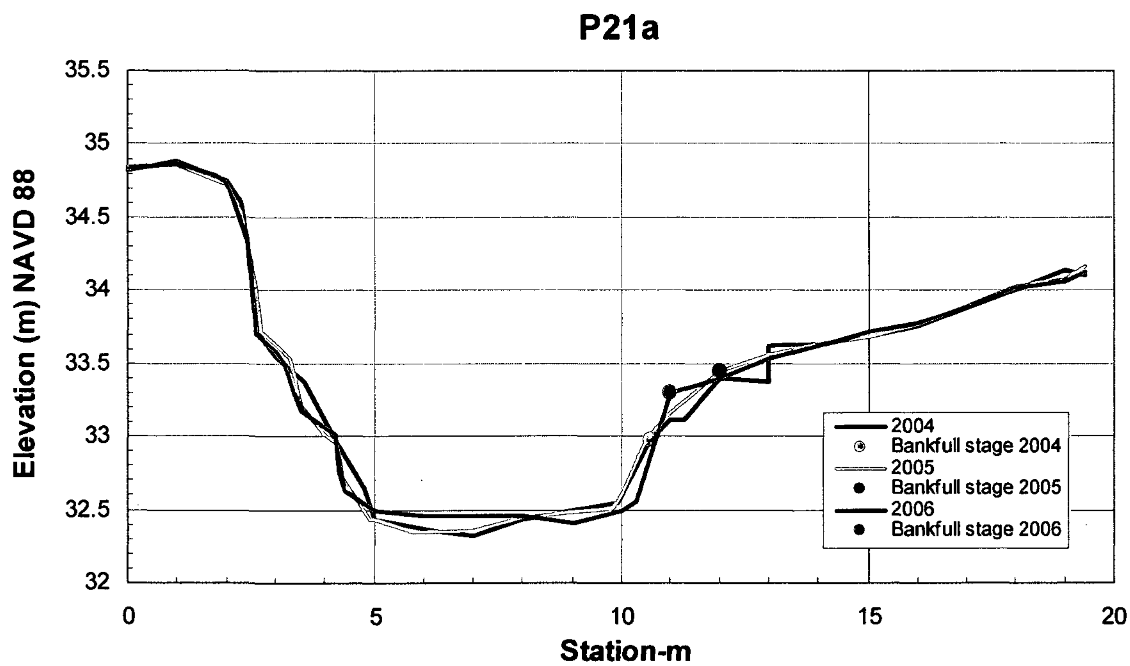
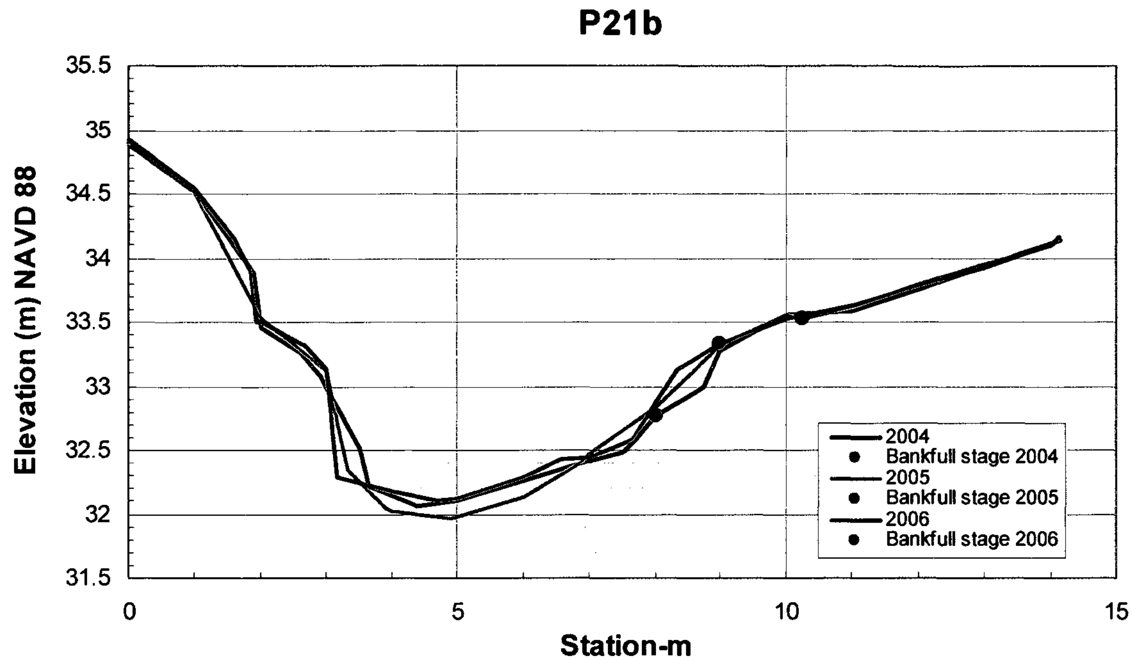
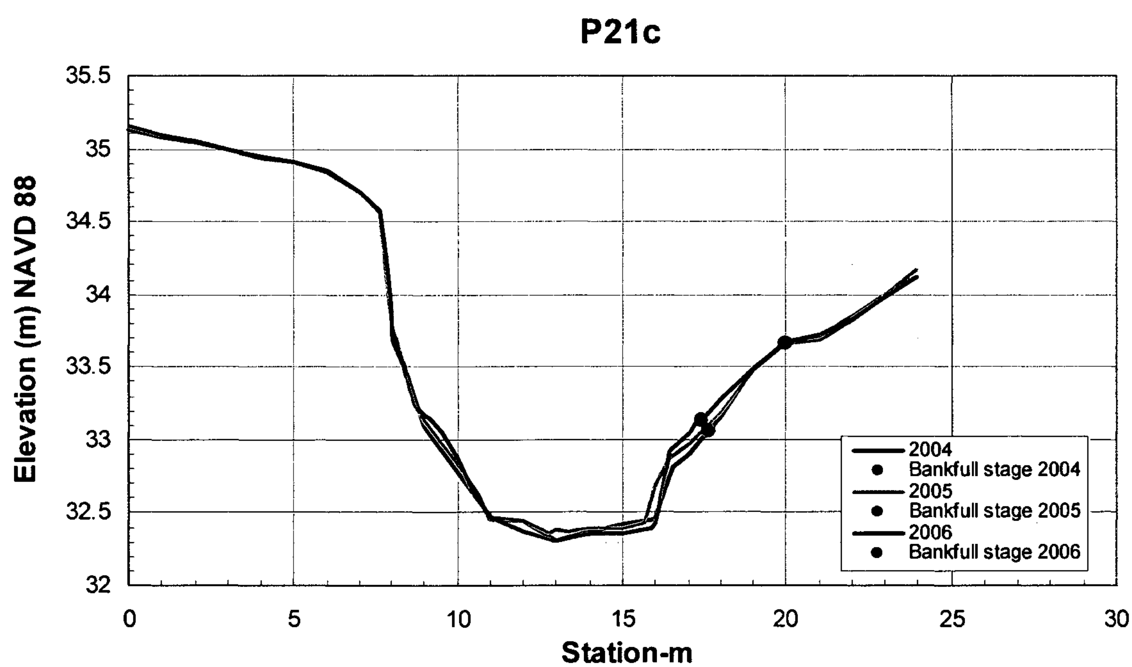
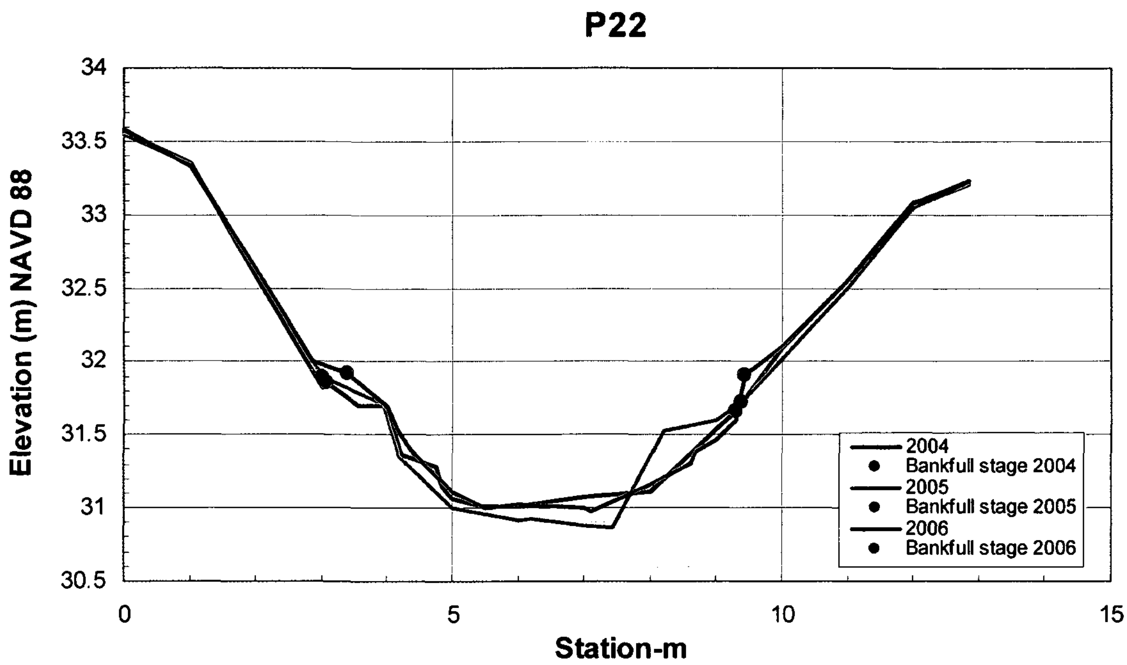
5
10
15
20
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P21a
35.5
35
34.5
34
33.5
33
32.5
32
0
5
10
15
20
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P21b
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P21c
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P22
Elevation (m) NAVD 88
Station-m
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Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
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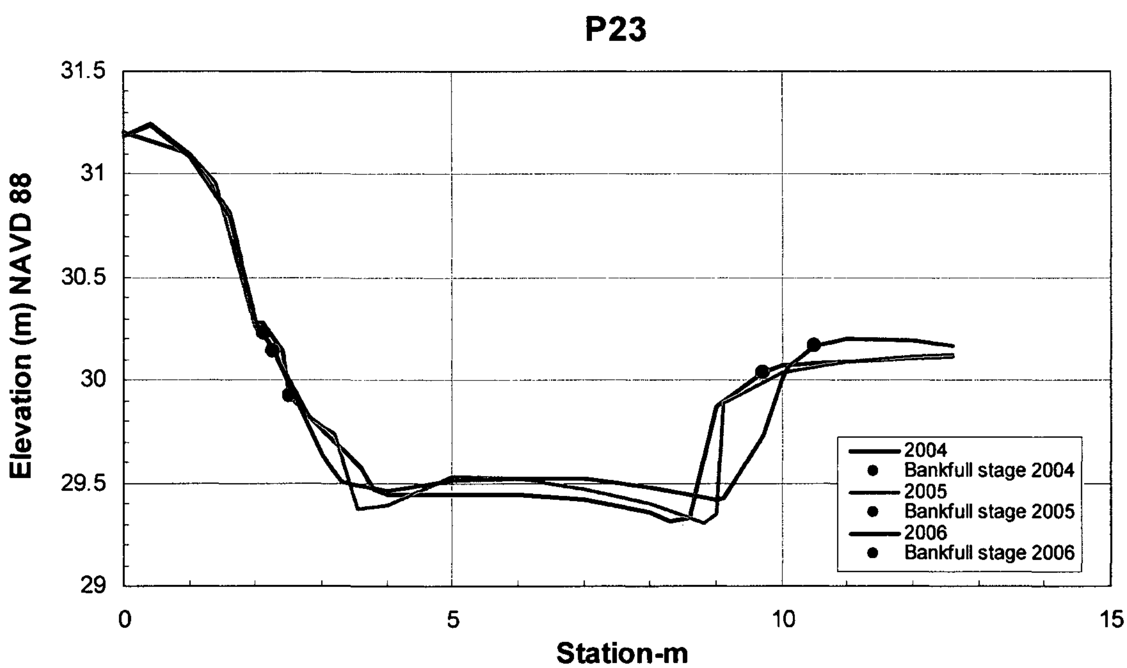
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Elevation (m) NAVD 88
Station-m
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Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
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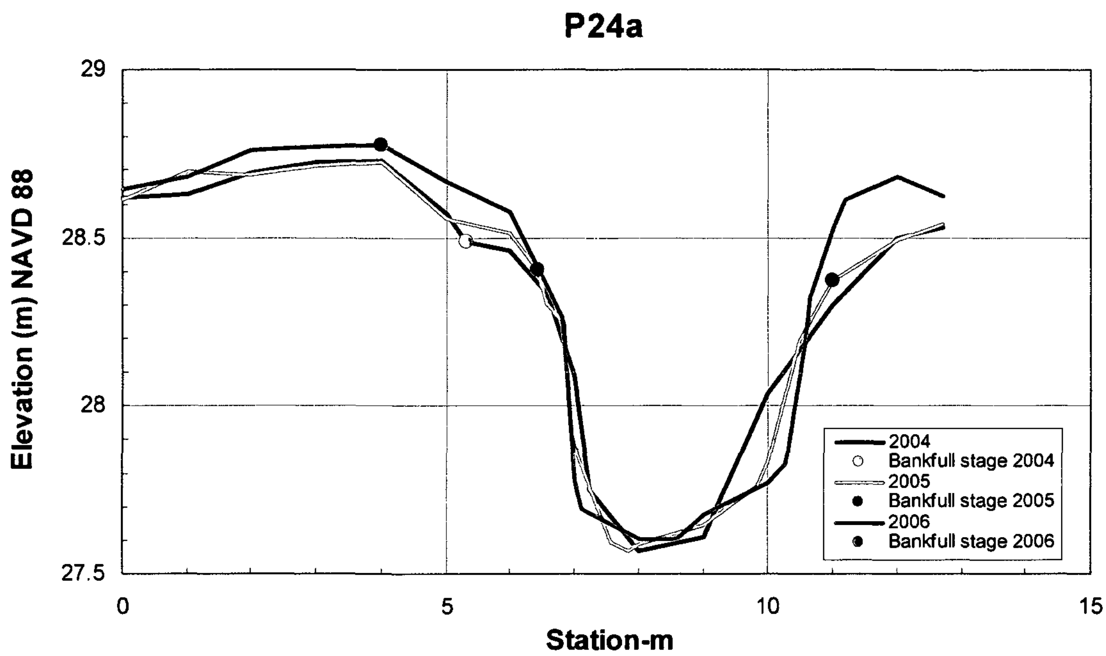
5
10
15


P24a
Elevation (m) NAVD 88
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27.5
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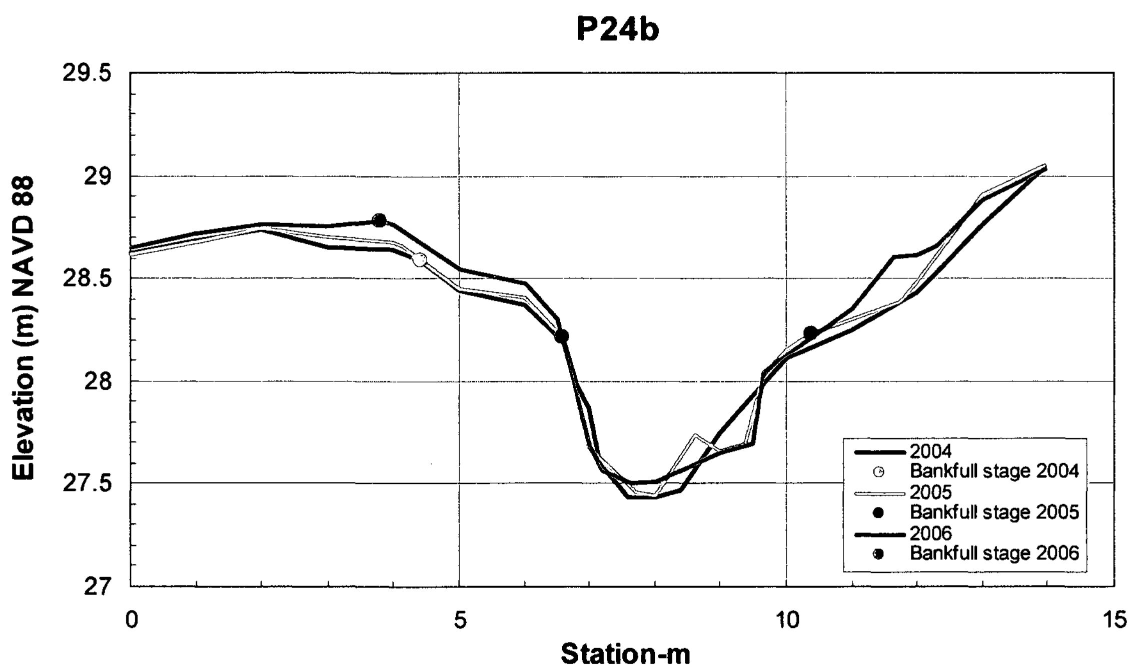
5
10
15
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P24b
Elevation (m) NAVD 88
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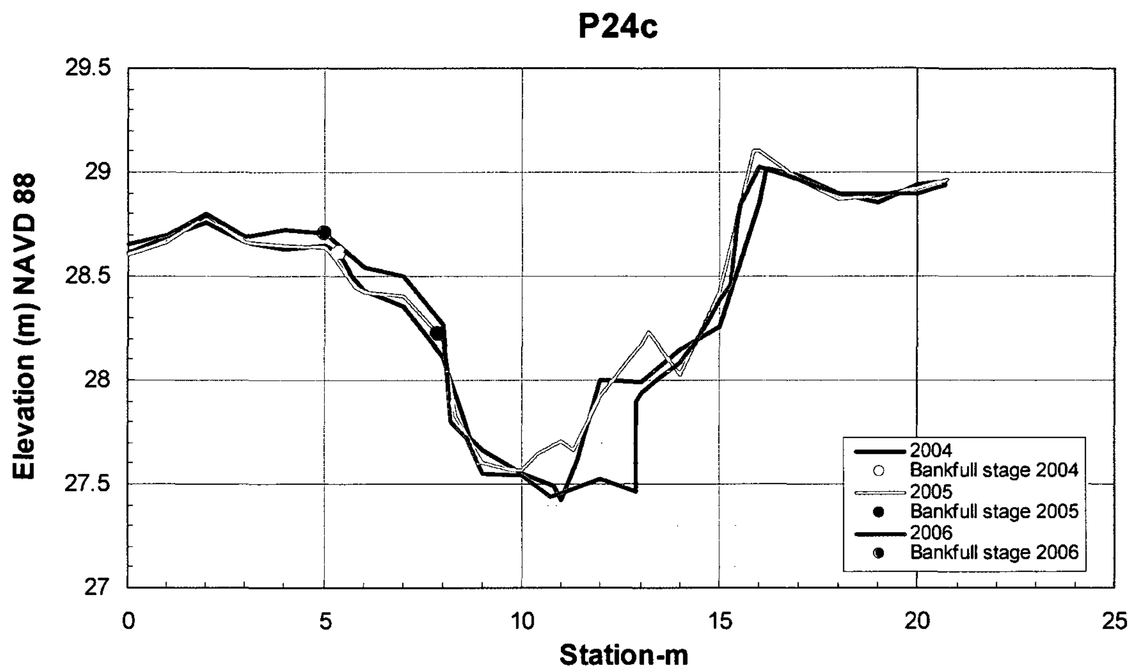
27.5
27
0
5
10
15
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006


P24c
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
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5
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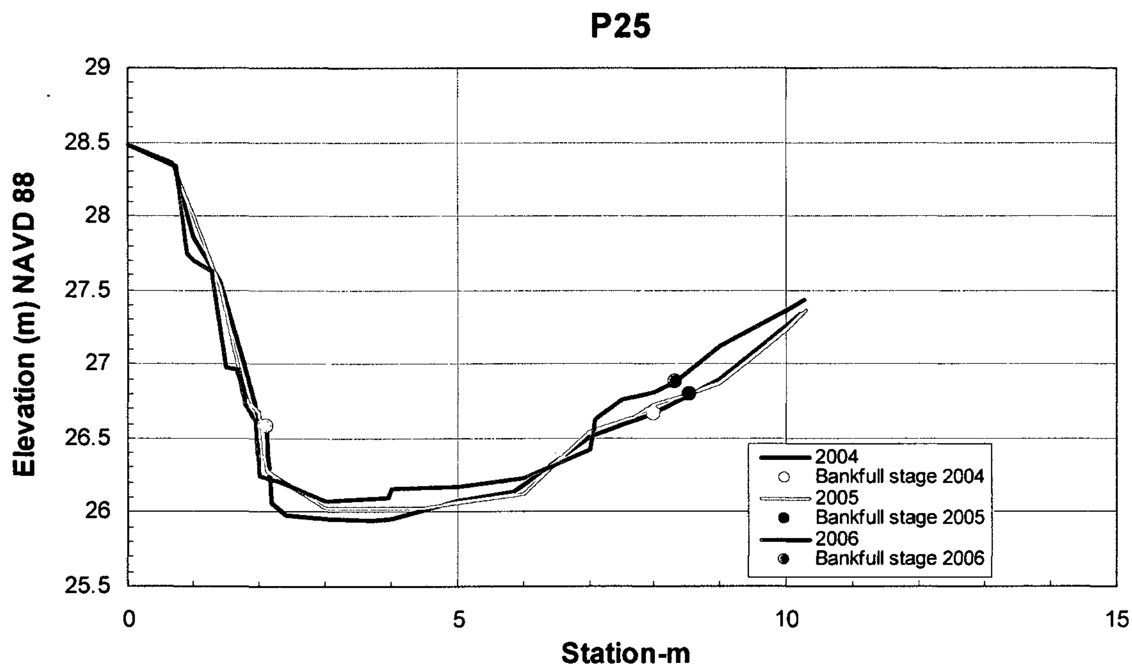
15
20
25


P25
Elevation (m) NAVD 88
Station-m
2004
Bankfull stage 2004
2005
Bankfull stage 2005
2006
Bankfull stage 2006
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26.5
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25.5
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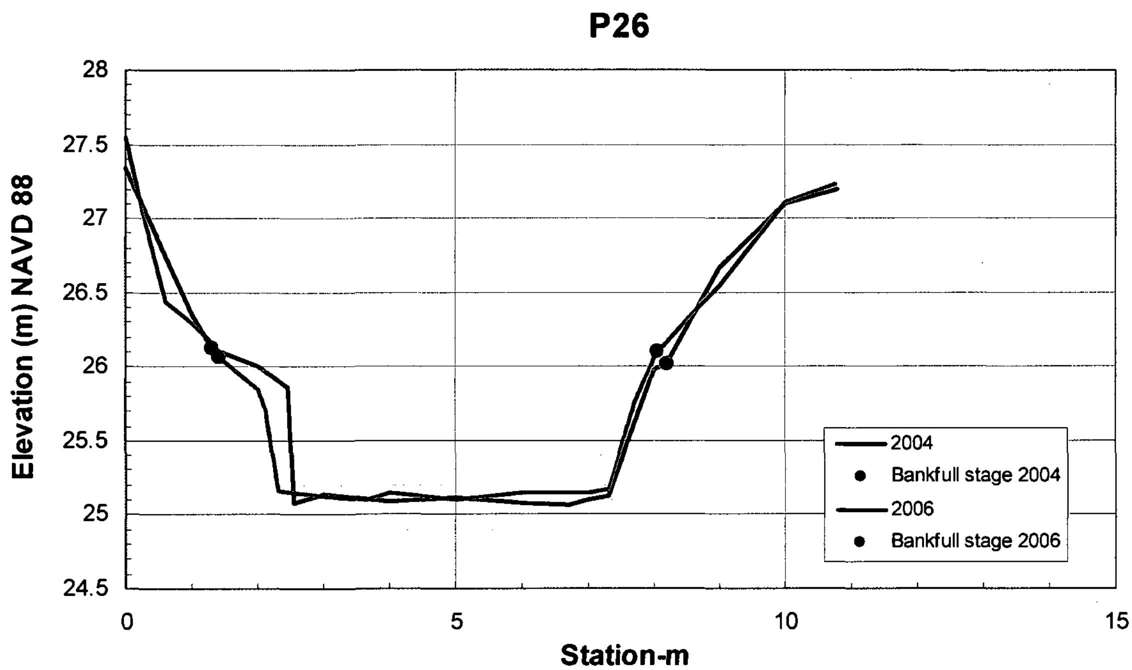
5
10
15


P26
Elevation (m) NAVD 88
28
27.5
27
26.5
26
25.5
25
24.5
0
5
10
15
Station-m
2004
Bankfull stage 2004
2006
Bankfull stage 2006

APPENDIX C
Bed Material Summary Data

Berryessa Creek Bed Material Data

					Pebble count			Pavement			Sub-pavement		
GCS	Morphology	Station	Local slope	Bankfull slope	D16	D50	D84	D16	D50	D84	D16	D50	D84
		(m)	(m/m)	(m/m)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2	Riffle	2298	0.065	0.028	0.2	5	45	17	64	109	1	10	42
4	Riffle	2192	0.078	0.028	0.6	25	84	24	144	305	1	5	15
5a	Bend	1997	0.033	0.028	x	x	x	x	x	x	x	x	x
5b	Bend	1988	0.033	0.028	4.7	26	126	x	x	x	x	x	x
5c	Bend	1982	0.033	0.028	x	x	x	x	x	x	x	x	x
6a	Bend	1948	0.029	0.028	x	x	x	x	x	x	x	x	x
6b	Bend	1940	0.029	0.028	0.2	34	164	x	x	x	x	x	x
6c	Bend	1932	0.029	0.028	x	x	x	x	x	x	x	x	x
7	Riffle	1912	0.019	0.028	0.2	20	142	5	45	136	1	4	19
8	Headcut_ US	1808	0.028	0.026	0.2	10	68	3	36	80	0.5	6	35
9	Headcut DS	1798	0.007	0.026	0.2	21	88	x	x	x	x	x	x
10	Headcut US	1778	0.007	0.026	0.2	3	85	x	x	x	x	x	x
11	Headcut DS	1768	0.006	0.026	0.2	9	61	17	80	165	1	8	25
12a	Bend	1447	0.013	0.015	x	x	x	x	x	x	x	x	x
12b	Bend	1436	0.013	0.015	0.2	4	18	x	x	x	x	x	x
12c	Bend	1431	0.013	0.015	x	x	x	x	x	x	x	x	x
14	Riffle	1321	0.005	0.017	0.2	11	28	1	11	27	1	8	23
15a	Bend	1265	0.016	0.017	x	x	x	x	x	x	x	x	x
15b	Bend	1254	0.016	0.017	0.1	6	26	x	x	x	x	x	x
15c	Bend	1247	0.016	0.017	x	x	x	x	x	x	x	x	x
16a	Bend	1168	0.005	0.017	x	x	x	x	x	x	x	x	x
16b	Bend	1157	0.005	0.017	0.1	1	18	x	x	x	x	x	x
16c	Bend	1153	0.005	0.017	x	x	x	x	x	x	x	x	x
17a	Bend	1095	0.014	0.017	x	x	x	x	x	x	x	x	x
17b	Bend	1091	0.014	0.017	0.2	14	50	x	x	x	x	x	x
17c	Bend	1087	0.014	0.017	x	x	x	x	x	x	x	x	x
19	Riffle	1039	0.016	0.017	0.2	13	52	2	21	89	2	16	41
20	Riffle	924	0.015	0.017	0.2	9	56	x	x	x	x	x	x
21a	Bend	776	0.015	0.017	x	x	x	x	x	x	x	x	x
21b	Bend	773	0.015	0.017	0.1	10	29	x	x	x	x	x	x
21c	Bend	769	0.015	0.017	x	x	x	x	x	x	x	x	x
23	Riffle	610	0.010	0.012	0.6	12	48	x	x	x	x	x	x
24a	Bend	583	0.014	0.012	x	x	x	x	x	x	x	x	x
24b	Bend	577	0.014	0.012	0.1	6	20	x	x	x	x	x	x
24c	Bend	570	0.014	0.012	x	x	x	x	x	x	x	x	x
25	Riffle	526	0.006	0.012	0.1	9	21	4	41	148	1	9	38
26a	Bend	504	0.010	0.012	x	x	x	x	x	x	x	x	x
26b	Bend	498	0.010	0.012	0.2	15	33	x	x	x	x	x	x
26c	Bend	492	0.010	0.012	x	x	x	x	x	x	x	x	x
27a	Bend	357	0.011	0.012	x	x	x	x	x	x	x	x	x
27b	Bend	353	0.011	0.012	0.1	10	24	x	x	x	x	x	x

					Pebble count			Pavement			Sub-pavement		
GCS	Morphology	Station	Local slope	Bankfull slope	D16	D50	D84	D16	D50	D84	D16	D50	D84
27c	Bend	349	0.011	0.012	x	x	x	x	x	x	x	x	x
28	Headcut US	263	0.005	0.012	0.1	6	19	x	x	x	x	x	x
29	Headcut DS	243	0.004	0.012	0.1	8	18	2	12	47	3	32	88

Upper Penitencia Creek Bed Material Summary Data

					Pebble count			Pavement samples			Sub-pavement samples		
GCS	Morphology	River station	Local slope	Bankfull Slope	D16	D50	D84	D16	D50	D84	D16	D50	D84
		(m)	(m/m)	(m/m)	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	Headcut_US	5988	0.027	0.014	0.1	14	45	153	275	395	3	27	81
2	Headcut_DS	5973	0.010	0.014	0.1	1	91	153	275	395	3	27	81
3	RIFFLE	5919	0.010	0.014	0.1	1	41	15	81	177	3	40	225
4-A	BEND	5797	0.007	0.014	x	x	x	x	x	x	x	x	x
4-B	BEND	5792	0.007	0.014	0.4	11	62	x	x	x	x	x	x
4-C	BEND	5787	0.007	0.014	x	x	x	x	x	x	x	x	x
5	RIFFLE	5699	0.009	0.014	0.1	9	90	27	131	268	2	11	40
6	RIFFLE	5394	0.002	0.014	0.1	1	92						
7	RIFFLE	5348	0.004	0.014	0.1	8	64	21	101	215	3	31	136
8-A	BEND	5203	0.006	0.014	x	x	x	x	x	x	x	x	x
8-B	BEND	5198	0.006	0.014	0.1	10	41	x	x	x	x	x	x
8-C	BEND	5191	0.006	0.014	x	x	x	x	x	x	x	x	x
9-A	BEND	5054	0.004	0.014	x	x	x	x	x	x	x	x	x
9-B	BEND	5051	0.004	0.014	0.1	1	55	x	x	x	x	x	x
9-C	BEND	5048	0.004	0.014	x	x	x	x	x	x	x	x	x
10	RIFFLE	4874	0.018	0.014	1.2	34	144	x	x	x	x	x	x
12-A	BEND	4758	0.006	0.014	x	x	x	x	x	x	x	x	x
12-B	BEND	4751	0.006	0.014	0.2	10	110	x	x	x	x	x	x
12-C	BEND	4745	0.006	0.014	x	x	x	x	x	x	x	x	x
13	RIFFLE	4284	0.016	0.014	0.1	11	133	x	x	x	x	x	x
14	RIFFLE	4048	0.017	0.014	0.1	10	135	14	74	137	3	23	92
15	RIFFLE	3733	0.015	0.011	0.2	28	83	x	x	x	x	x	x
16-A	BEND	3598	0.028	0.011	x	x	x	x	x	x	x	x	x
16-B	BEND	3590	0.028	0.011	0.2	18	92	x	x	x	x	x	x
16-C	BEND	3577	0.028	0.011	x	x	x	x	x	x	x	x	x
17-A	BEND	3112	0.005	0.011	x	x	x	x	x	x	x	x	x
17-B	BEND	3105	0.005	0.011	0.1	18	87	x	x	x	x	x	x
17-C	BEND	3102	0.005	0.011	x	x	x	x	x	x	x	x	x
18-A	BEND	2448	0.010	0.0074	x	x	x	x	x	x	x	x	x
18-B	BEND	2437	0.010	0.0074	0.1	7	40	x	x	x	x	x	x
18-C	BEND	2430	0.010	0.0074	x	x	x	x	x	x	x	x	x
19	RIFFLE	2166	0.010	0.0074	0.1	1	51	10	70	130	2	14	52
20	RIFFLE	1958	0.009	0.0074	0.1	16	50	15	71	138	2	17	48
21-A	BEND	1346	0.011	0.0068	x	x	x	x	x	x	x	x	x
21-B	BEND	1338	0.011	0.0068	0.1	17	70	x	x	x	x	x	x
21-C	BEND	1325	0.011	0.0068	x	x	x	x	x	x	x	x	x
22	RIFFLE	1141	0.006	0.0068	0.1	16	60	x	x	x	x	x	x
23	RIFFLE	873	0.007	0.0068	0.1	22	60	10	59	109	2	13	44
24-A	BEND	650	0.003	0.0068	X	x	x	x	x	x	x	x	x
24-B	BEND	645	0.003	0.0068	0.1	11	64	x	x	x	x	x	x
24-C	BEND	640	0.003	0.0068	X	x	x	x	x	x	x	x	x
25	RIFFLE	445	0.010	0.0068	0.2	21	66	18	66	109	3	21	52

					Pebble count			Pavement samples			Sub-pavement samples		
GCS	Morphology	River station	Local slope	Bankfull Slope	D16	D50	D84	D16	D50	D84	D16	D50	D84
		(m)	(m/m)	(m/m)	mm	mm	mm	mm	mm	mm	mm	mm	mm
26	RIFFLE	290	0.002	0.0068	0.1	13	40	x	x	x	x	x	x