EFFECTS OF URBANIZATION ON STORM RESPONSE IN THE NORTH FORK SAN PEDRO CREEK

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Geography

by

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San Francisco, California

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CERTIFICATION OF APPROVAL

I certify that I have read *Effects of Urbanization on Storm Response in the North Fork San Pedro Creek* by Paul Franklin Amato, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Geography at San Francisco State University

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IN THE NORTH FORK SAN PEDRO CREEK

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This study reviews the record of land use change in the San Pedro Creek watershed, in Pacifica California, focusing on the effects of 50 years of urbanization. Storm related discharge and turbidity were measured and compared for the undeveloped Middle Fork and partly developed North Fork tributaries to quantify differences associated with impervious surfaces and increased drainage density from hillside residential development. Continuous recording data loggers in both tributaries measured rainfall, turbidity, and stage (used to estimate discharge) during three storm events. Rainfall values were consistently higher in the Middle Fork drainage but response time of discharge in the North Fork was faster and resulted in peaks of greater magnitude and frequency. Middle Fork turbidity was, on average, 10 times greater than the North Fork. Bank erosion, measured downstream of the Middle and North Fork confluence, was the greatest per linear foot when compared to the rest of the San Pedro Creek main stem.

I certify that the Abstract is a correct representation of the content of this paper.

______________________________________ __________________
Jerry D. Davis Date

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CHAPTER 1 – INTRODUCTION

Stream processes are strongly related to the physical conditions of the watershed from which they flow. Alterations to physical conditions of a watershed manifest themselves through measurable responses of stream flow, sediment transport, channel erosion and aggradation, water quality, and the health of dependant flora and fauna. Human settlement has often led to an evolution of the landscape from undeveloped to agricultural to urban land use. This evolution has a significant influence on the physical conditions of a watershed and can be clearly linked to stream channel responses. Human alteration of the landscape in the form of urbanization increases impervious surface area and drainage channel networks, causing alterations in the response of stream flow and sediment dynamics. The intent of this study is to characterize and compare two sub-watersheds of a Central California coastal stream, one partly urbanized and the other dedicated open space, and to identify, measure, and quantify differences in stream flow, turbidity, and bank erosion attributable to urbanization.

San Pedro Creek watershed is located in the City of Pacifica, California approximately 20 miles (32.2 km) south of San Francisco (Figure 1). The steep headwater tributaries begin in the northern Santa Cruz Mountains forming the main stem that flows west across San Pedro Valley and into the Pacific Ocean.

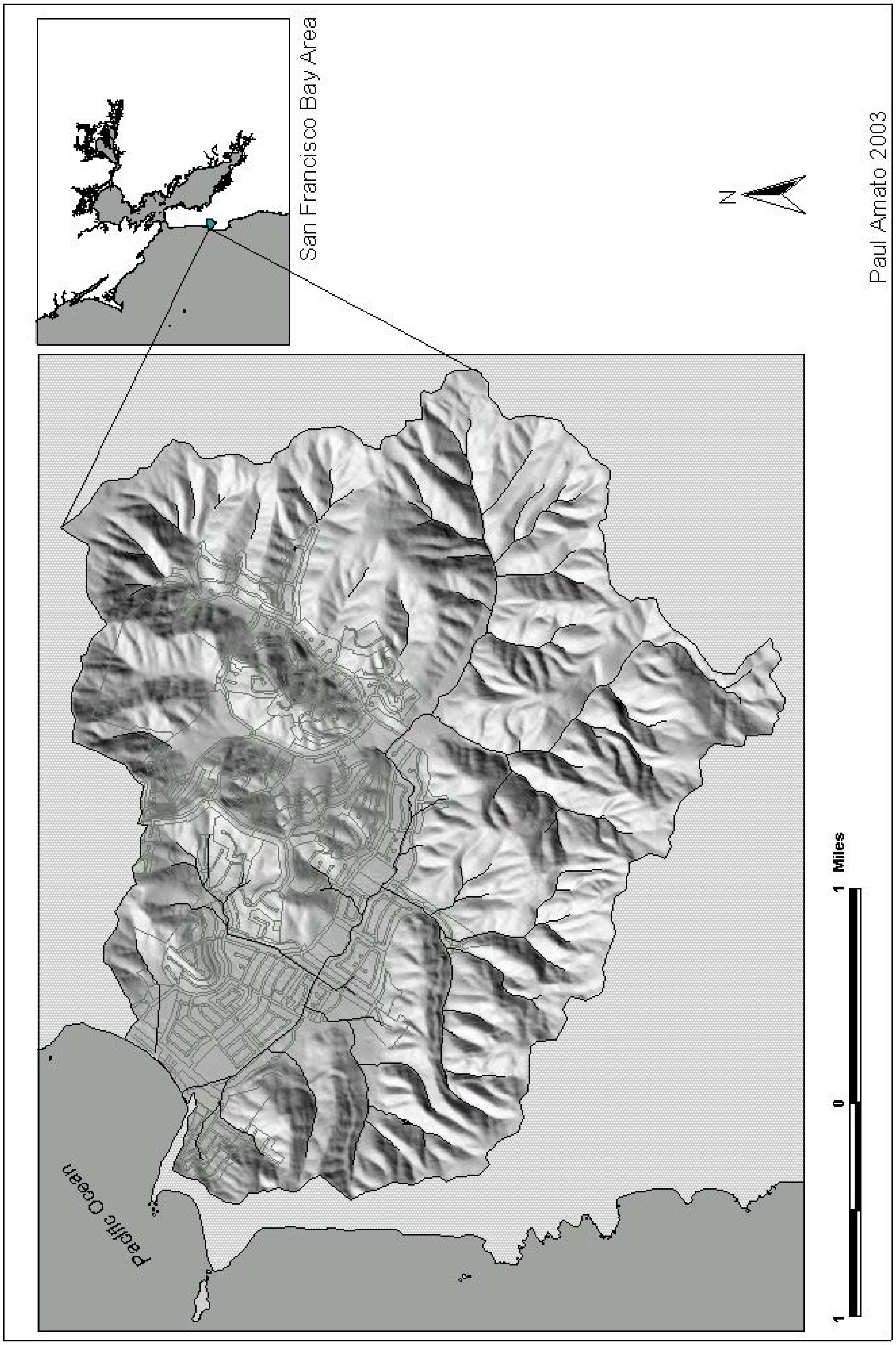

Figure 1. Location Map of San Pedro Creek Watershed

The entire watershed is approximately 8 square miles (20.7 km^2) and composed of 5 main tributaries. Residential development dominates the lower and middle watershed with light commercial and industrial facilities interspersed throughout the valley bottom. Headwater drainage areas are primarily dedicated open space.

The San Pedro Creek watershed was selected as the study site due to the potential to demonstrate contrasting stream responses in two neighboring sub-watersheds that are characterized by different land uses. San Pedro Creek is an especially interesting study location because it supports the central California coast evolutionarily significant unit, steelhead *(Oncorhynchus mykiss)*, a state and federally listed threatened species. In addition, the highly developed steep slopes in the North Fork tributary represent the ever-increasing land use practice of hillside development that threatens to continue throughout the California coast.

This investigation considers land use change throughout the watershed but limits measured stream response to the two largest tributaries, the Middle Fork and the North Fork. The main stem of San Pedro Creek begins at the confluence of these tributaries near the geographic center of the watershed. The Middle Fork watershed is about 2.39 square miles (6.19 km^2) and is composed primarily of undeveloped dedicated open space with the exception of some residential and commercial development at the downstream end. The Middle Fork channel is open and unlined with the exception of two box culverts and some revetment in the residential area. A riparian canopy is present along most of the channel length. The North Fork watershed is 2.37 square miles (6.13 km^2) with residential and light commercial facilities in the valley and open space in the headwaters. The North Fork channel is contained in a concrete pipe for most of its length with the exception of steep headward first and second order channels. The drainage area, topography, and vegetation of the tributary watersheds are similar, with notable variation in geology, and rainfall.

A properly functioning stream can be described as one that is in a state of equilibrium: it has “developed equilibrium size and shapes appropriate to the available discharge and character and quantity of sediment supplied” (Leopold et al. 1964). A stream that is neither aggrading nor eroding in excess is capable of adjusting to variations of discharge and sediment supply. When influences within the system alter the stream’s ability to transport water and sediment efficiently, excess erosion and aggradation occur. This condition has been referred to as disequilibrium. Landscape changes resulting from human activities often cause streams to enter a state of disequilibrium. A stream can move back and forth between these two states in response to changes to the physical setting. When changes cease or stabilize, the stream can eventually adjust to a state of quasi-equilibrium where erosion and aggradation rates re-stabilize. Though significant isolated erosion is still occurring, the main stem of San Pedro Creek appears to be capable of transporting its sediment load and may be in a state of quasi-equilibrium (Collins et al. 2001).

Prior to urbanization, the ground surface throughout the watershed was pervious, allowing infiltration of precipitation. When the natural surfaces were hardened with buildings and pavement, water infiltration potential was significantly reduced and runoff rate and volume to the stream increased. As is typical with urbanization, road gutters, stormdrain facilities, and hillside drainage ditches were constructed to convey the increased runoff, resulting in more frequent and greater flood peaks in the stream channel. Hardening watershed surfaces also reduced the amount of sediment available for transport by the stream, which increased the amount of energy sediment-free water could exert on the stream channel boundaries. Channel incision, already initiated by earlier cattle grazing and farming practices, increased vertical separation of the channel from its floodplain, further increasing energy directed at the channel banks during frequent high flow events. Stream banks were destabilized as the bed degraded and the channel was subjected to more erosive flows at a greater frequency. Human landscape modifications altered natural surfaces and hydrologic response of the watershed, disrupting conditions that previously formed the equilibrium channel size and shape.

Today, these changes are especially evident in the main stem of San Pedro Creek below the North and Middle Fork confluence. Here, creek side residents have responded to erosion of their property with a variety of bank revetments ranging from yard debris to concrete. This alteration to the channel has in many cases resulted in erosion of the channel bed and adjacent unprotected banks, leading to a perceived need for more revetments. As a result, channel morphology and ecology are degraded from urban landscape change as well as by the response of the urban creek side dwellers.

Water quality has also been impaired due to urban runoff pollutants, increased fine sediment from localized in-stream erosion, increased temperature and decreased dissolved oxygen due to loss of riparian canopy, yard and pet waste, and failing sewer lines (Matuk 2001).

Evidence from seminal works on the influence of urbanization on watershed processes (Wolman 1967; Leopold 1973; and Morisawa 1979) and visual field reconnaissance led to the assumption that the Middle and North Fork drainages would respond differently to storms and that the resulting influence on stream processes and channel characteristics would be evident. To quantify these differences, gaging stations and continuous data logging systems were installed near the downstream ends of both drainages to measure values of turbidity and discharge (derived from stage) during storms. Physical characteristics of the drainages and temporal change were measured using ancillary data, and established field techniques. Influence of urbanization on bank erosion was measured using a survey method that was developed and used in several San Francisco Bay Area streams (Collins et al. 2001).

CHAPTER 2 – PHYSICAL AND HUMAN SETTING

Physical Setting

Watershed Geology

San Pedro Creek watershed is located in the northern extent of the Santa Cruz Mountains in the Central California Coast Range. Tectonic compression and vertical displacement along the San Andreas Fault has resulted in structural and compositional diversity throughout the region. The 8 square mile (20.7 km^2) watershed is bisected longitudinally by the Pilarcitos Fault, an ancestral trace of the San Andreas Fault (Figure 2). Pilarcitos appears to have about 20 miles (32.2 km) of right slip with an unmeasured but probable vertical slip (Dibblee 1966). The trace of the Pilarcitos, running in a northwest to southeast direction, is very close to that of San Pedro Creek main stem and Middle Fork, suggesting that the stream course is in part, a result of past tectonic activity along this fault. This point is further supported by a dominant northwest structural grain in the geology of the San Pedro Valley (Howard Donley, Assoc. 1982).

The Pilarcitos Fault divides two structural blocks that lie beneath the watershed. To the northeast, delineated by the San Andreas and Pilarcitos Faults, is the Pilarcitos Block, and to the south is the La Honda Block, delineated by the Pilarcitos and Seal Cove-San Gregorio Faults (Figure 2). Basement rock of the Pilarcitos Block is composed primarily of Franciscan Complex.

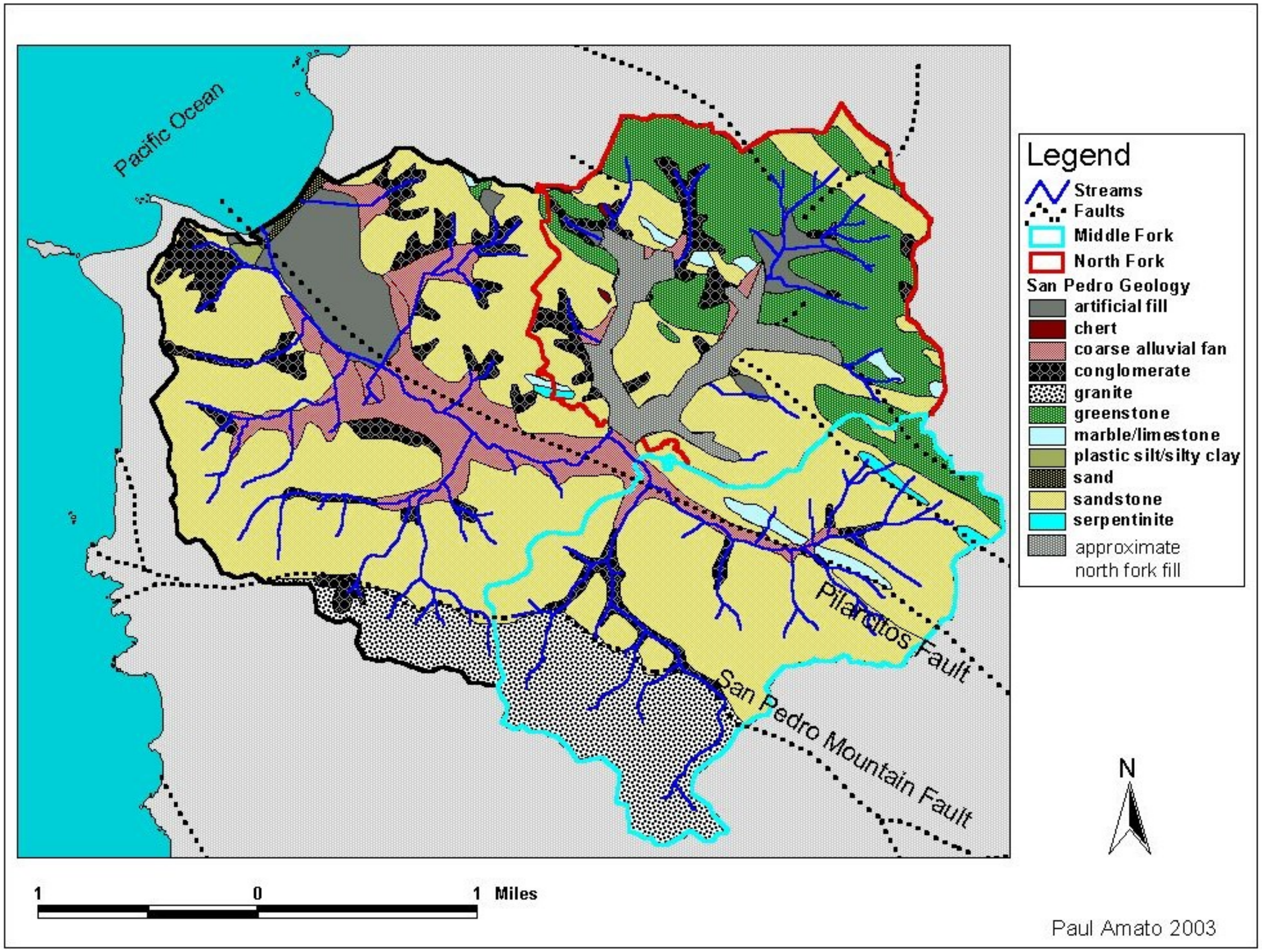

Figure 2. Geology Map of San Pedro Creek Watershed

This geologic assemblage is thought to be Jurassic and Cretaceous in age (Pampeyan 1994). The Franciscan Complex of the Pilarcitos Block is composed primarily of sandstone (greywacke) interbedded with pyroclastic greenstones, and a sheared rock section along the fault. Limestone, serpentine, conglomerate, chert, and glaucophane schist, in order of abundance, are also present. Igneous and sedimentary units of the Franciscan Complex are predominantly metamorphosed and thought to be amongst the oldest formations in the area (Pampeyan 1994). The greywacke is so severely crushed from tectonic activity that it weathers to depths of up to 50 feet (15.2 m) (Bailey et al. 1964). Significant weathering and shearing along the fault have resulted in unconsolidated soils and colluvium on the northern side of the watershed. This unit forms slopes that are “unstable, especially when wet.” (Pampeyan 1994).

The La Honda Block portion of the watershed is composed of Paleocene sandstone and conglomerate turbidites underlain by granitic bedrock thought to be pre-Cretaceous in age (Pampeyan 1994). The contact of these two formations is formed by the San Pedro Mountain Fault running nearly parallel to the Pilarcitos Fault. The granitic formation is so heavily fractured and weathered that representative samples have been difficult to find (Pampeyan 1994).

Watershed Soils

Significant portions of the Pilarcitos and La Honda Blocks are overlain by Holocene deposits described as slope wash, ravine fill, and colluvium. Deposits of up to 20 feet (6.1 m) in depth have been found over the Pilarcitos Block where sheared Franciscan Complex rock is present. Coarse-grained Holocene alluviums composed of unconsolidated, moderately sorted sands and gravels form the valley bottoms (Pampeyan 1994). Landslide investigations conducted after the 1982 storm that resulted in several slope failures were unable to identify any relationship between frequency of landsliding and bedrock type. Absence of a relationship between bedrock type and landslide frequency may indicate that susceptibility to failure is not controlled by the differing geologic units (Howard 1982).

Watershed Geomorphology

Geomorphic processes in the San Pedro watershed area are dominated by the interaction of tectonic compression and uplift with fluvial, colluvial, and aeolian erosion and deposition common to the central California coastal zone. The highest elevation in the watershed is the 1,898 feet (578.5 m) tall north peak of Montara Mountain. Together, Montara and the smaller San Pedro Mountains form the southern rim of the watershed. Cattle Hill and Sweeney Ridge form the northern extent with a maximum elevation of approximately 1,340 feet (408.4 m) near the southern extent of Sweeney Ridge. Steep slopes and deep headward channels are common throughout the area. Large gullies have formed on hillsides, primarily along the northern slopes (Photo 1). The flat alluvial valley floor is a stark contrast to the steep slopes of the surrounding range. From above, the watershed forms a distinctive bowl, along the coast.

Photo 1. Gully on Cattle Hill

Landslide activity is common in this part of the Coastal Range. Under saturated conditions, steep slopes and unconsolidated soils have led to several landslides in the watershed. In 1982, 6-8 inches (152.4-203.2 mm) of rain fell over the City of Pacifica in less than 30 hours, causing 475 detectable landslides (Howard et al. 1982). Half of these landslides were concentrated in the San Pedro Creek watershed with approximately 100 occurring in the North Fork and 60 in the Middle Fork. The majority of the landslides were classified as surficial failures because they were less than 10 feet (3 m) deep (Howard 1982). Though this was considered an unusual event, it is indicative of the potential for episodic earth movement in the watershed.

The main stem of San Pedro Creek supports perennial flows for its entire length of approximately 4 miles (6.4 km) from the mouth at Pacifica State Beach to the eastern headward extent of the Middle Fork tributary. Total channel length of the main stem and five main tributaries is approximately 35 miles (56.3 km).

Watershed Climate

The climate of Pacifica is Mediterranean, characterized by dry, mild summers and moist, cool winters (Wagner et al. 1961). Annual precipitation averages 33 inches (838.2 mm) ranging from 23 inches (584.2 mm) at the coast to 38 inches (965.2 mm) at the highest elevations (USACE 1997). Precipitation is greatest between November and March. Pacifica also experiences significant amounts of fog in the summer, keeping it much cooler and moister than areas further inland. Prevailing winds are on-shore from the west while dominant storm related winds are on-shore from the southwest.

Watershed Vegetation

Vegetation in the San Pedro Valley consists of a mix of communities with native and non-native species dispersed throughout. Coastal scrub, chaparral and European grasslands are common on the hillsides where they have not been replaced by exotic forest. Large groves of introduced eucalyptus (*Eucalyptus*), Monterey pine (*Pinus radiata*) and Monterey cypress (*Cupressus macrocarpa*) can be found throughout the area, with the largest groves occurring along the southern slopes. Introduced exotic landscaping plants dominate the valley floors while native species are still relatively common in riparian areas, especially in the headward reaches. The health and diversity of riparian species deteriorates downstream due to the spread of invasive ornamentals, eroding stream banks, and a lowered water table resulting from channel incision. Common native riparian species include red willow (S*alix laevigata*), arroyo willow (*Salix lasiolepis*), Sitka willow (*Salix sitchensis*), red alder (*Alnus rubra*), and Oregon ash (*Fraxinus latifolia*). Coastal chaparral is generally found at elevations above 500 feet (152.4 m) and is dominated by shrubs. Common plants include California Lilac (*Ceanothus*), Yerba Santa (*Eriodictyon*), Manzanita (*Arctostaphylos*), Coffee Berry (*Rhamnus californica*), and Golden Chinquapin (*Chrysolepis*). Coastal scrub is found below 500 feet (152.4 m) and is also dominated by shrubs. Common plants are Coyote Bush (*Baccaharis piluralis*), Coast Sagebrush (*Artemisia*), Sticky Monkey Flower (*Mimulus aurantiacus*), Coast Paintbrush (*Castilleja*), Seaside Daisy, (*Erigeron glaucus*), and Coast Buckwheat (*Erigonum latifolium*), (VanderWerf 1994). Introduced European annual grasses have replaced native bunch grasses and can be found amongst the hillside and valley vegetation communities.

Watershed Land Use

Land use in San Pedro Valley is dominated by residences on the valley floor as well as up the valleys of buried tributaries, especially in the North Fork. Light commercial and industrial uses are present on the valley floor, predominantly towards the coast near Highway 1. Stables operate in the upper reaches of the North Fork and on the southwest end of the watershed, and a cattle ranch may still be in operation in the North Fork though grazing activity appears to be minimal (Last observed by author in 1999). Pocket areas to the south are designated as evergreen forest, while most of the upper hillsides and ridge tops are designated shrub and brush rangeland. Public lands include San Pedro Valley County Park, and a portion of the Golden Gate National Recreation Area. These public lands are located predominantly at the ridge tops and the southeastern end of the valley. Private watershed lands include an in-holding of the North Coast County Water District, and the San Francisco Water Department Crystal Springs watershed (Figure 3).

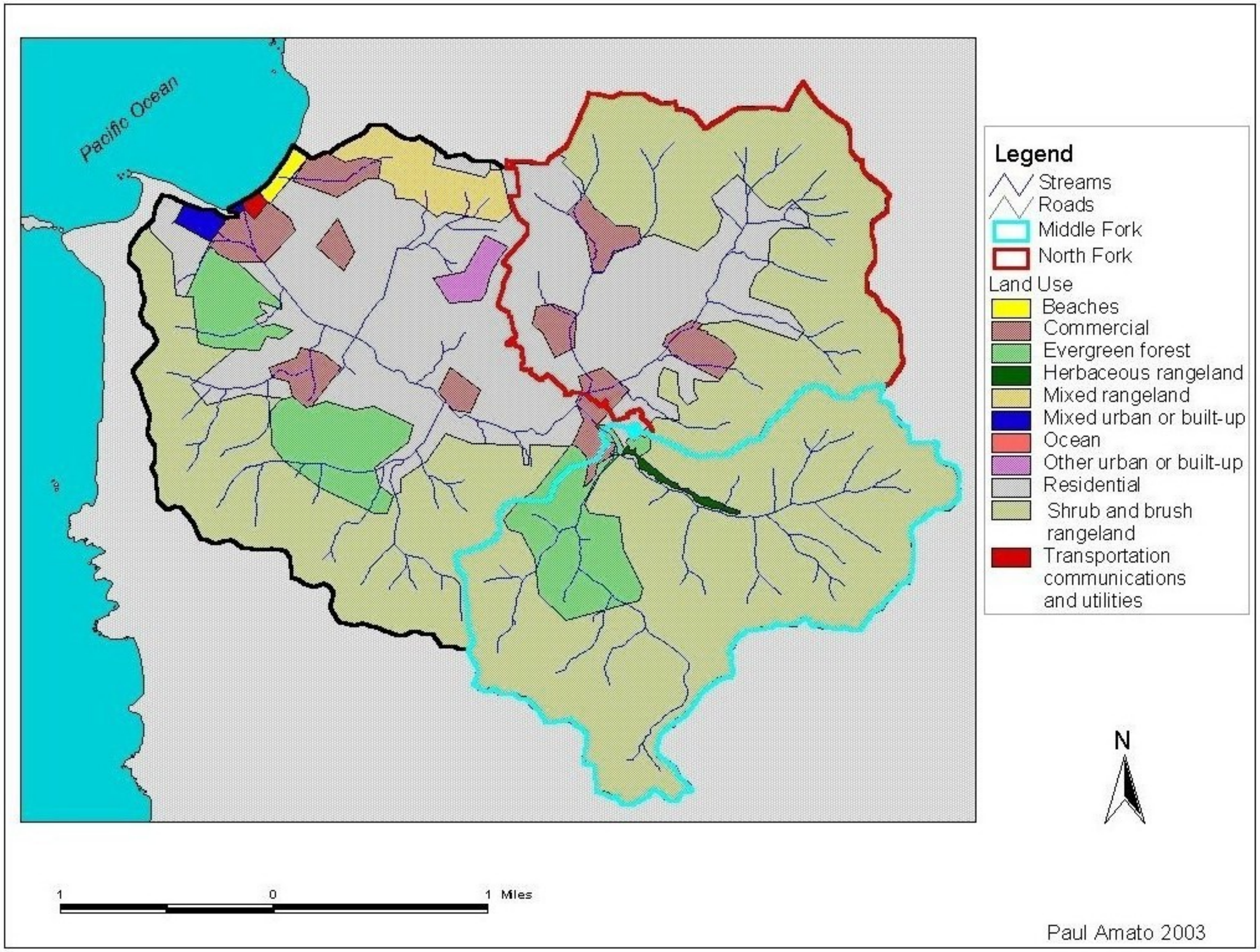

Figure 3. Land Use Map of San Pedro Creek Watershed

Human Setting

Like all of the San Francisco Bay Area, the human setting and accompanying land use practices in San Pedro Valley have changed considerably over the past 5,000 years. The following discussion attempts to recreate past conditions and to describe probable changes resulting from the various stages of human settlement leading up to the present.

Pre-Human Period, Preceding About 5,000 Years Before Present

Prior to human occupation of San Pedro Valley, the setting was very different from today. On the ridge tops grew large stands of Douglas fir (*Pseudotsuga*) as seen today at a smaller scale on the north slopes of Montara Mountain. Coastal scrub and coastal chaparral covered the hillsides. Small grasslands were dominated by perennial bunch grass communities like needlegrass (*Achnatherum*) prairie on south facing slopes, and California fescue (*Festuca californica*) and reed grass (*Calamagrostis*) prairie on the north facing slopes. Similar to historic Presidio lands in San Francisco, the valley may have supported coast live oak (*Quercus agrifola*) savannah. The valleys adjacent to the arroyos and the developed stream corridors were dominated by communities composed of arroyo willow (*Salix lasiolepis*), red alder (*Alnus rubra*), trailing blackberry (*Rubrus ursinus*), and California wild rose (*Rosa californica*) (Vasey 2001).

The creek transitioned from steep and confined in the headwaters to flat and sinuous with an established floodplain on the alluvial fans. The lower valley floor consisted of abundant reed grass freshwater marsh habitat intermixed with patchy willow thickets known later as “sausal”. This habitat surrounded a lake, later known as Lake Mathilda that covered a large portion of the lower valley where the meandering streams disappeared into large deposits of fine sediments carried from the hills above. This feature is evident in historic maps from the mid-nineteenth century (Figure 4). Sand dunes separated the marsh and lake from the beach except during winter storms when flood waters and beach erosion activated intermittent hydraulic connections (Collins et al. 2001). These events created opportunities for native steelhead (*Onchorhynchus mykiss*) and possibly Coho salmon (*Onchorhynchus kisutch*) to pass upstream to spawn while young-of-the year left the refuge of the marsh and lake to complete their growth cycle in the ocean.

A variety of wildlife thrived in and around the valley including such species as grizzly bear, black bear, mountain lion, bobcat, wolf, coyote, fox, deer, elk, sea lions, and otters. A great variety of resident and migratory birds and waterfowl were also very common.

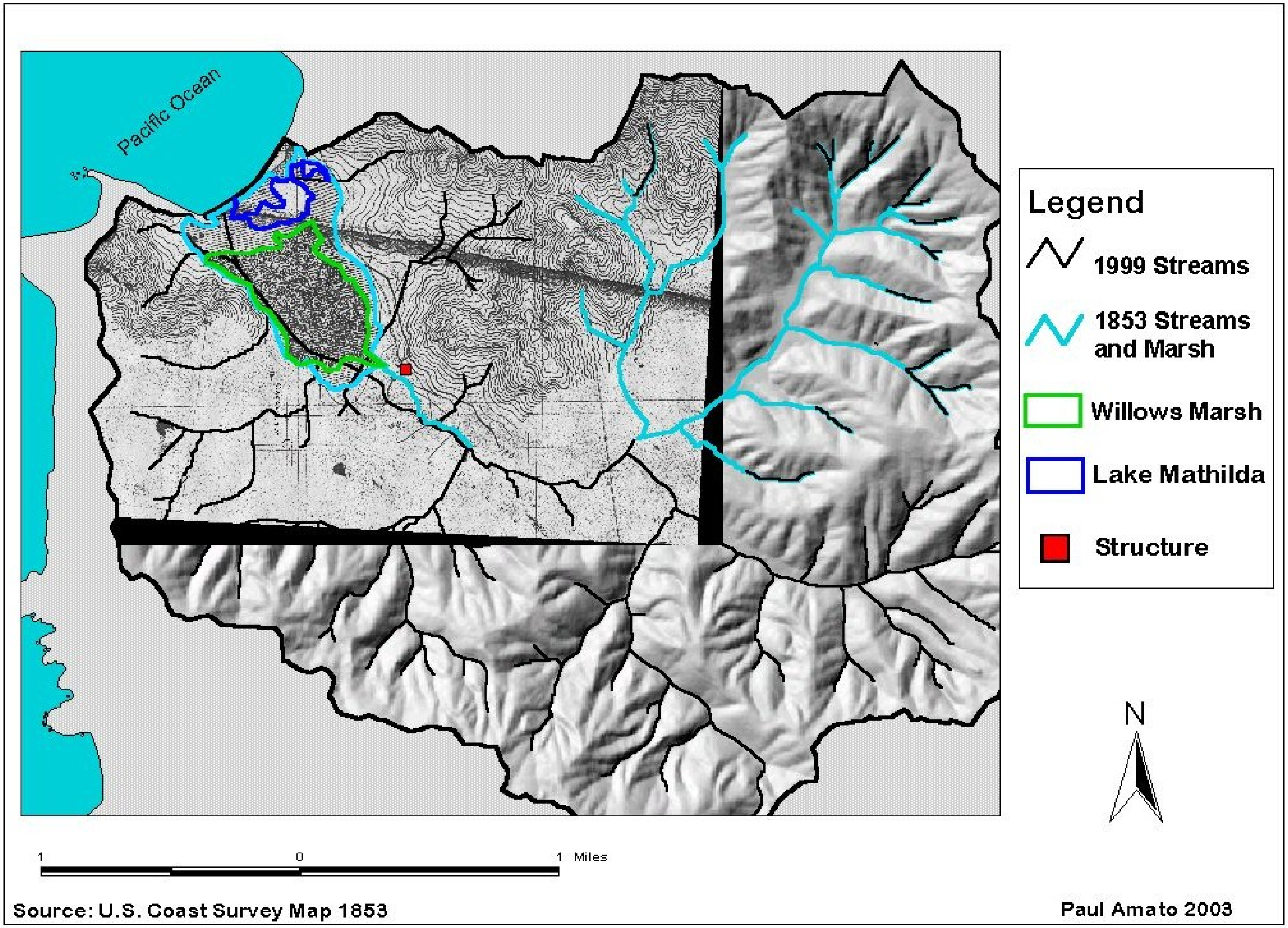

Figure 4. 1853 Historical Map of San Pedro Valley

Native American Period, About 5,000 Years Before Present to 1769

It is estimated that approximately 5,000 years ago marks the arrival of the Native American Ohlone to the central California Coast. With their appearance in the Bay Area came the introduction of the first human land use practices to change San Pedro Valley. The Ohlone lived in small tribelets of some 250 members each and were only loosely associated with other groups, so much so that languages sometimes varied greatly within short distances (Margolin 1978). The tribelet in Pacifica burned the land each fall to suppress development of coastal scrub and chaparral on the hills and to promote the summer yield of grasses and the germination of gray pines (*Pinus sabiniana*); important sources of seeds and nuts respectively (VanderWerf 1994; Culp 1999). Burning was also important for maintaining pasture that supported elk and deer. Early explorers of the 1769 Portola and 1774 Rivera expeditions noted frequent grass fires (Miller 1971). In the valley bottom, willow, grasses and sedges were harvested for many purposes including shelter, boats, baskets, and medicine.

It is not clear to what extent Ohlone practices changed the San Pedro Creek watershed. One possibility is that a long history of burning decreased soil-stabilizing cryptogrammic crusts (composed of algae, lichen, and moss), leading to increased runoff and increased hillside erosion (Loope et al. 1972). If this were the case, an increase in the transport of fine sediments to the stream may have resulted. It is probable that Ohlone land use practices did affect the San

Pedro Creek watershed, but these disturbances are assumed to have been insignificant compared to activities of the settlers that displaced them.

Mission Period, 1769 to 1822

Documented evidence of modern land use impacts began after 1769 when Captain Gaspar de Portola led his Spanish expedition to San Pedro Valley while searching for Monterey Bay. Early observations from this time help support the description of the valley prior to and during Ohlone occupation. Miquel Costanso recorded that:

> We went down to the harbor and set up camp a short way from the shore, (in a lush valley) close to a stream of running water which sank into the ground turning into a marsh of considerable extent (covered with cane grass) and reaching near the sea. The country was plentiful in grass, and all surrounded by very large hills making a deep hollow open only toward the bay of the north west (in Stranger et al. 1969).

Padre Crespi, of the same expedition wrote that:

> The valley has a great deal of reed grass and many black berries and roses; there are a few trees in the beds of the arroyos, and some moderate sized willows, but on the hills there was not a single tree to be seen except on a mountain range that encircles the bay (in Biosystems 1991).

The returning party in 1774 was sent to establish Catholic missions throughout California. A group sent to Pedro Valley was charged with establishing a support farm, or *assistencia* for the Mission Dolores in San Francisco. The following account describes San Pedro Valley, including the former Lake Mathilda. Padre Palou noted that:

> At eleven we came to a large lake between high hills, which are in the plain ending in a small bay on the beach, about a league distant from Point Angel de la Guarda. If the beach permits it and there is no precipice in the way, we will save a good stretch of road and avoid some bad spots. The lake compelled us to make detour of about half a league, and it was necessary for us to draw close to the beach and cross over the sand which surrounded the lake. We made a detour around the lake and stopped about one in the afternoon in a canyon of the valley near an arroyo of running water, one of the two in the valley from which the lake is formed. It is well covered with tule, and on its banks, there are some willows and blackberry brambles. The beds of both arroyos are the same, and on the slopes of the hills, I saw here and there a live oak. If the place had timber it would be suitable for a mission, on account of its proximity to the mouth of a port, for it does not lack land, water, or pasture for cattle (in Biosystems 1991).

The Spanish set up the support farm in 1782 at the site of the Ohlone village of Pruristac and began farming and ranching (Drye 1986). Some 90 acres (36.4 hectares) of the floodplain were cleared for crops. Irrigation ditches were dug to direct water and "opened to drain the water which spread on the field," (Dietz 1979) indicating that the channel bottom was closer to the elevation of the floodplain at the site of the historic Spanish settlement than the 22 foot (6.7 m) difference measured there today (Collins et al. 2001).

Accounts of a Padre Landeata report that as many as 6,000 head of cattle roamed the San Pedro watershed by 1800 and as many as 8,000 by 1801 as part of the mission cattle ranching operations (Landaeta 1949). Soil compaction from cattle and sheep eventually led to a reduction in the natural permeability of the soil, resulting in increased runoff rates and decreased time for flows to reach the channels. European annual grasses found more suitable for grazing gradually replaced native perennial bunch grasses. The shallower root system of the introduced grasses combined with surface soil disturbance from trampling led to soils more susceptible to erosion. Grazing and trampling animals also had an impact on the riparian areas as commonly seen in modern ranchlands of today. The combination of soil compaction and a reduction in soil stability caused an increase in surface erosion initiating several large hillside gullies still present in the watershed.

According to archeological investigations of the former Spanish settlement, the stream may have been moved to the south of its natural course to increase the area accessible for planting (Drye 1999). Channel straightening together with increased runoff from grazing initiated channel incision and bank erosion. Incision, hillside erosion, and eroding banks from riparian degradation led to increased in-channel and hillside sediment supply and downstream aggradation in the marsh, sausal, and Lake Mathilda.

The Mission Period also saw the destruction of the area’s native people as a result of mistreatment by the Spanish and the introduction of foreign diseases like smallpox. With the end of the Ohlone people in the valley came the end of burning practices, and the re-encroachment of coastal scrub and chaparral communities where grasslands had been maintained.

Mexican Rancho Period, 1822 to 1862

After the end of Spanish control in California, the Mexican Land Grant system was established. Prominent Mexican soldiers and officials that helped extricate the Spanish from California were awarded large parcels of land that had formerly belonged to the missions. In 1839 Francisco Sanchez was awarded the 8,926 acre (3612.2 h) Rancho San Pedro for his service as commandante at the San Francisco Presidio. Records do not indicate how many livestock Sanchez had at the time but it is known that cattle continued to graze the watershed under his ownership. His father owned the neighboring Buri Buri Rancho and reported having 2,000 cattle and 250 sheep that likely grazed between the ranchos (Collins et al. 2001).

Grazing continued to influence the watershed through the rancho period but to what degree is not known. When Sanchez built his house at the site of the mission outpost, it was reported that the creek meandered “a few feet” below ground level (Drake 1952). This report indicates that channel incision may have been rather insignificant compared to today. The 1853 map of the main valley that shows the marsh and sausal still functioning during this period further supports evidence that channel incision was minimal (Figure 4).

Farming Period, 1862 to 1953

In 1862, Francisco Sanchez died and the rancho was subdivided into several north-south running plots leased for dairy ranching and farms. In the years that followed, grazing continued in the hills while the valley flats were converted to small market gardens to serve the local communities. By the early 1900s, most of the ranchers had become farmers, leading to a reduction in cattle and an increase in crops including potatoes, watercress, pumpkins, and artichokes, which eventually dominated the fields in San Pedro Valley (VanderWerf 1994). To increase agricultural area, farmers drained Lake Mathilda, straightened the lower section of the channel and moved it to its current location along the southern side of the valley. This resulted in an increase of 0.8 miles (1.3 km) of channel from the upstream extent of the drained Lake Mathilda to the Pacific Ocean (Collins et al. 2001). Channel straightening of tributaries and the main stem of San Pedro Creek can be seen in the 1941 aerial photograph (Photo 2). Several flashboard dams were installed in the main channel for crop irrigation, providing local grade controls upstream and promoting incision downstream of the structures. These dams are no longer functioning.

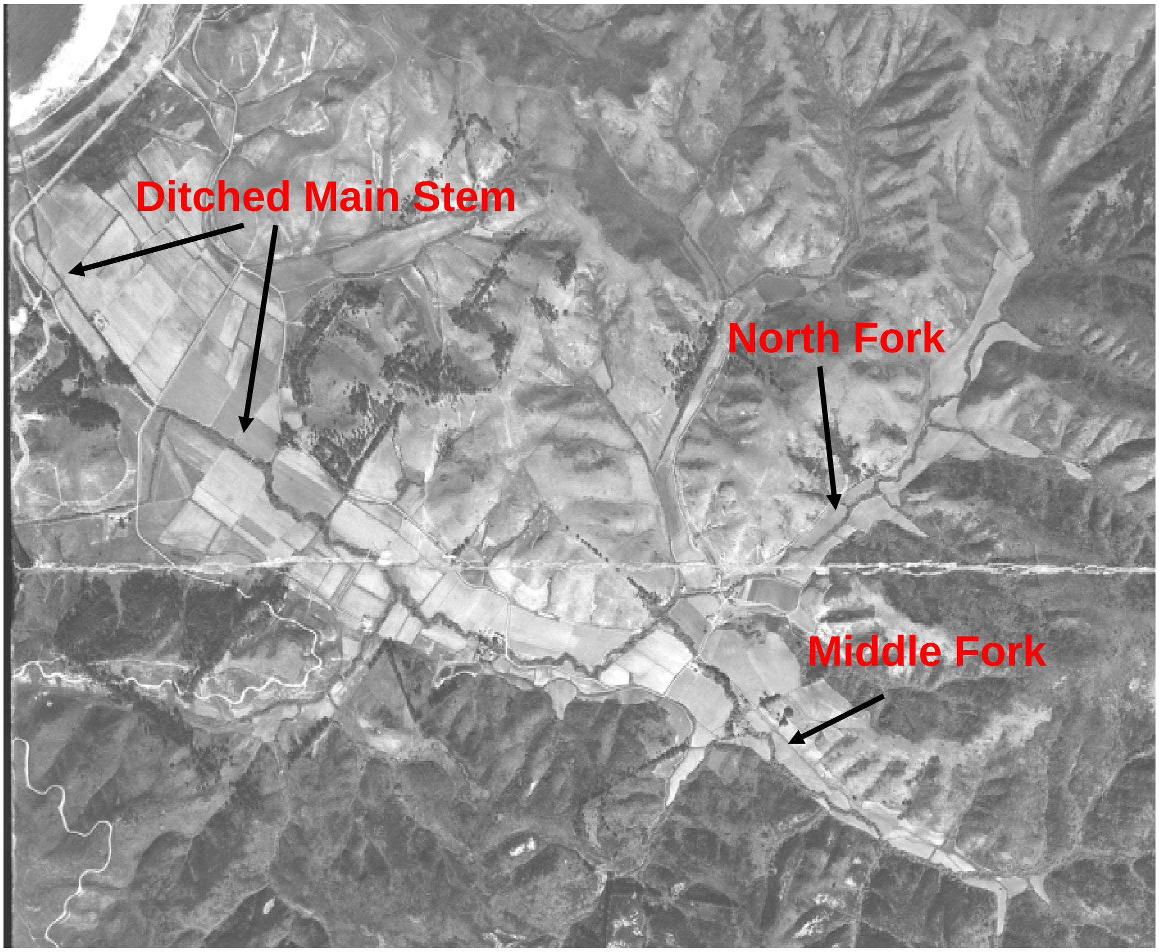

Photo 2. 1941 Aerial Photo of Agriculture in San Pedro Valley

More than a century of farming, cattle grazing, and appurtenant modifications to the channel and floodplain resulted in significant long-term alterations to the San Pedro Creek system. By the 1950s, Lake Mathilda was drained and the channel had been straightened and connected directly to the ocean. By making this connection, farmers had lowered the base level of the stream, resulting in a headcut that caused the channel to incise headward.

Irrigation wells and incision led to a lowering of the water table and a decrease in base flows during the summer dry season. The riparian corridor also experienced continued degradation due to grazing and farmland expansion. Land use practices of this period played a significant part in establishing the contemporary plan form, pattern, and profile of the creek.

Urbanization Period, 1953 to Present

The 1950s were the beginning of the era of development that formed the City of Pacifica much as we see it today (Photo 3). The first major residential development, called Linda Mar was built on the eastern side of the valley in 1953. Construction of housing developments continued into the early 1970s when the upper North Fork watershed was completed. Grading and construction, absent any of today’s erosion and sediment control requirements, caused an increase in sediment supply, reducing the capacity of the channel. As development progressed, an increase in impervious surface area combined with engineered runoff conveyance resulted in increased runoff rate and volume, increased flood peak frequency and discharge, and increased bed and bank erosion. Leopold (1972) described this cycle in urban streams. Increased development is a likely contributor to flooding in Pacifica in 1955, 1962, 1972, and 1982. Current conditions in the stream represent a trend towards a quasi-equilibrium state as the channel regains a sinuosity and channel geometry within the incised channel that is more suitable for transporting sediment and discharge supplied by the watershed.

Photo 3. Typical Residential Land Use in San Pedro Valley

San Pedro Creek has changed considerably in the 218 years between European settlement and this study. Today the main channel is incised from the headwaters to the mouth and tends to be deep and narrow with insufficient sinuosity and little to no active floodplain to accommodate larger flow events. Channel incision is the leading cause of bank instability throughout most of the creek. Pervasive bank instability has caused creekside residents to armor stream banks with cement, rock, and other materials (Collins et al. 2001). Bank armoring has reduced channel roughness, increased flow velocities, increased erosion on adjacent banks, and led to increased channel incision, which has undermined several attempts at bank protection and repair. Excessive erosion has also been observed in the vicinity of several stormdrain outfalls and undersized bridge structures.

San Pedro Creek and the surrounding watershed have been heavily modified and disturbed over the past several decades with the most significant impacts resulting from agriculture and development. Today, the hydrology, geomorphology, habitat, and water quality are compromised as a result of human activities.

The Study Area

The Middle Fork sub-watershed (including the smaller South Fork) and the North Fork sub-watershed form the study area (Figure 5). For the purposes of this investigation, the watersheds are delineated by the drainage area upstream from the gaging stations used for this study (Figure 5). The Middle Fork gaging station is located approximately 1,300 feet (396.2 m) upstream of its confluence with the North Fork at the downstream edge of San Pedro Valley County Park. The North Fork gaging station is about 350 feet (106.7 m) upstream of the confluence, near where the stream exits an 8-foot (2.4 m) diameter culvert. The “study” watersheds are thus slightly smaller than the true watersheds delineated by the area above their confluence.

The two watersheds are similar in area, relief, vegetation, and macro-climate but different in land use practices, geology, and precipitation. The most significant difference of interest for this study is the difference in land use.

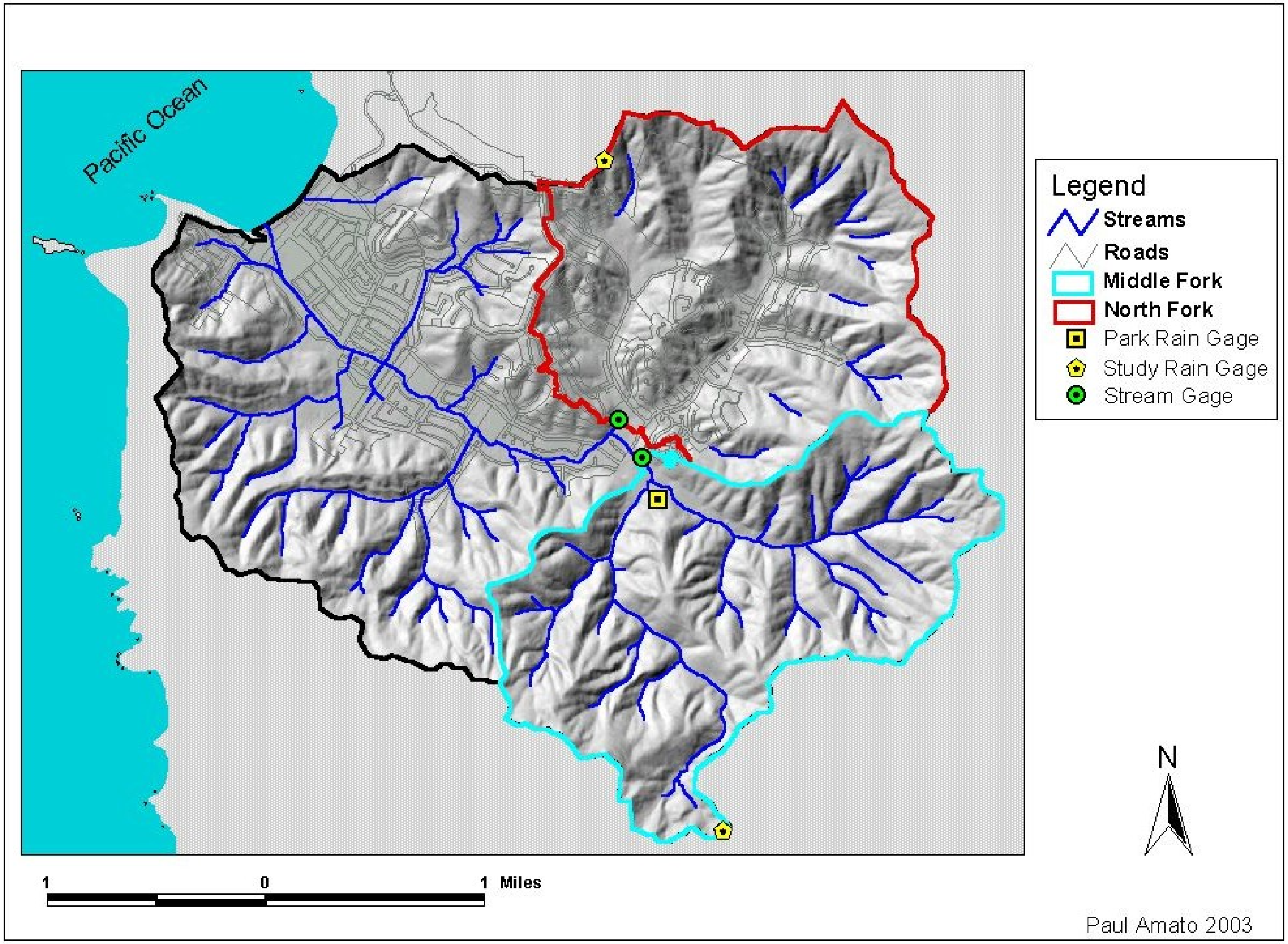

Figure 5. Study Area Map

Middle Fork Watershed

The 2.39 square mile (6.19 km^2) Middle Fork watershed is the southeastern most drainage of the San Pedro watershed. The southern portion, between Pilarcitos and Montara Mountain Faults, is located on the La Honda Block. North of Pilarcitos Fault is predominantly Holocene slope wash, ravine fill and colluvium with sheared Franciscan mélange sandstone, conglomerate and limestone intrusions (Figure 2). South of the Pilarcitos Fault is predominantly Holocene slope wash, ravine fill and colluvium with granitic and limestone intrusions. Throughout the watershed, the valleys are composed of coarse-grained alluvial Holocene deposits, though sedimentary bedrock can be seen in the bed and banks of portions of the Middle Fork just downstream of the South Fork confluence (Pampeyan 1994).

Landforms in the Middle Fork include steep slopes of Montara Mountain and Whiting Ridge eroding down to flat alluvial valleys formed by the drainage network. As stated earlier, the 1,898-foot (578.5 m) north peak of Montara Mountain is the highest elevation in the San Pedro watershed, rising almost 1,600 feet (487.7 km) from the upper extent of the Middle Fork valley. Steep tectonic topography has led to the development of deep tributary canyons throughout the watershed. Agricultural practices confined the channel to the southern side of its valley and caused it to incise several feet below the historic floodplain.

Landslide activity is significant in the Middle Fork drainage. The January storm of 1982 resulted in some 60 landslides throughout the drainage, accounting for about 12% of the total storm related landslides mapped in the City of Pacifica (Howard et al. 1982). Core samples taken in 1999 were used to date young alders located in portions of the Middle Fork. The age of the alders indicates that large deposits of sediment were introduced into the system in 1982, allowing the alders to establish soon afterwards on the deposits along the channel (Collins et al. 2001). The Middle Fork appears to be in a continuing state of incision through these, and perhaps earlier, landslide-related deposits of a major storm that occurred in 1962.

A rain gage on Whiting Ridge at the Middle and South Fork divide measured 26 inches (660.4 mm) of rainfall from February through May 2000, 13% more than the 22.7 inches (576.6 mm) measured at San Pedro Valley Park. During the 2000 water year (October 1, 1999 to September 30, 2000), precipitation at the Park totaled 40.7 inches (1033.8 mm). Monthly rainfall difference between the Middle Fork and the Park gages ranged from 9% to 23%. Based on the overall 13% difference from February to May, up to 46 inches (1168.4 mm) of rain may have fallen at the top of the Middle Fork drainage during the 2000 water year. This is 18% higher than the 38 inch (965.2 mm) average precipitation estimated by the U.S. Army Corps of Engineers (1997). Middle Fork rainfall measured 27% greater than the North Fork for the same four months, with a monthly difference ranging from 20% to 48%. A significant difference in rainfall in the two sub-watersheds is likely due to wind patterns and the direction from which storms typically approach the area. San Pedro watershed rainfall patterns are heavily influenced by topographic features. Storms approaching from the southwest typically stall, yielding heavier rainfall over Montara Mountain to the south before approaching the North Fork drainage. This topographic stall results in higher rainfall in the Middle Fork, gradually decreasing as the system passes over the Park and finally the North Fork watershed.

Vegetation of the Middle Fork watershed is heavily dominated by coastal chaparral and coastal scrub mixed with smaller grassland areas of European annuals. An introduced evergreen forest of eucalyptus is present along the lower portions of the South Fork watershed, extending below the confluence with the Middle Fork. The lower valley of the stream is primarily grassland with dense riparian vegetation growing in and along the channel.

The Middle Fork study watershed is almost entirely without impervious surface area with the exception of the San Pedro Valley County Park maintenance facility and a small adjacent paved area located a few hundred feet upstream of the gaging station, on the north side of the South and Middle Fork confluence. Due to the limited size of this facility, the influence of runoff on the stream is considered insignificant.

Notable land use impacts in the Middle Fork are limited to a long history of grazing and to crop farming of the farming period, when the valley flats were cleared and cultivated. Cattle would have grazed the hillsides and valleys from the time of the Spanish, through the ownership of Sanchez, and up to the early 1900s when dairies and ranches ended production in San Pedro Valley. Residential and commercial developments were never introduced to the Middle Fork drainage with exception of the most downstream extent.

As is the case throughout the region, the first human influence resulted from the controlled burns of the Native American Ohlone. Impacts on the stream channel are expected to have been minimal. The Spanish settlement of 1782 introduced cattle, sheep and horse to the area in relatively significant numbers, continuing the suppression of coastal scrub and greatly increasing soil compaction. This caused a decrease in soil permeability, possibly resulting in increased runoff rates. There is no documented evidence that the Middle Fork channel began to change during this period; however channel conditions in grazing lands of today illustrate that riparian buffers are compromised, runoff rates increase in volume and intensity, and channel bed and banks erode (Roath et al. 1982; Rauzi et al. 1966; and Reid 1993).

Air photos from 1941 illustrate that the extent of crop farming in the Middle Fork was limited to the valley flats, and that the riparian corridor remained intact during the farming period. Channel straightening by farmers cannot be confirmed, but a considerable portion of the channel in the alluvial valley appears to have been moved and straightened (Photo 2).

A significant degree of channel incision likely occurred as a result of grazing and farming. Today, the channel in the Park is incised as much as 18 feet (5.5 m) below the valley floor resulting in the formation of a terrace where a floodplain previously functioned. Historical accounts depict the downstream channel as a shallow stream that provided irrigation through hand dug ditches; this implies that significant down-cutting of the channel has occurred in the last 200 years.

Two activities unique to the Middle Fork drainage include earlier operation of a trout farm and a municipal water diversion on the South Fork. In 1962, the trout farm owned by John Gay was destroyed by a major storm that flooded several portions of the San Pedro Valley and initiated mudflows in the watershed. Remnants of a water diversion structure and off-channel concrete holding tanks are still evident. The North Coast County Water District operates an in-channel water diversion on the lower section of the South Fork. Approximately 10% of the water supply for the City of Pacifica was diverted from this facility and piped to the water treatment plant between December and March every year. These diversions may have caused ecological and physical impacts if reduced discharge caused excessive aggradation of sediments to occur in the channel bed.

<u>North Fork Watershed</u>

The 2.37 square mile (6.13 km^2) North Fork watershed is located on the Pilarcitos Block, composed of Franciscan basement rock. As stated earlier, greywacke sandstone and greenstone dominate the Franciscan assemblage, forming deep soil and colluvial horizons (Pampeyan 1994). Landslide mapping following heavy storms in January in 1982 identified approximately 100 individual earth movements in the North Fork alone (approximately 21% of the slides in Pacifica), indicating that heavy rainfall in a short period of time can cause substantial mobilization of sediments. Elevation ranges from approximately 135 feet (41.1 m) to a maximum elevation of 1,325 feet (403.8 m) at the ridge top. Steep slopes and deep V-shaped first order streams are common in the upper portions of the watershed while the lower valleys have been filled in for development.

Between November 1999 and May 2000, rainfall in the North Fork near the top of Sweeney Ridge totaled 30.7 inches (779.8 mm), 80% of the 38.5 inches (977.8 mm) measured in San Pedro Valley Park within the same time frame. The total rainfall in the park for the 2000 water year was 40.7 inches (1033.8 mm). Monthly differences in rainfall ranged from 8% to 45%. Based on the overall 20% difference in precipitation of the seven-month comparison, the total rainfall for year 2000 for the North Fork may have equaled approximately 32.5 inches (825.5 mm).

Vegetation communities in the North Fork are primarily coastal scrub and chaparral mixed with European annual grasses in the headward reaches, and ornamental landscape plants in the middle to lower reaches.

Based on a study performed in 1998, the surface area of the North Fork sub-watershed is 19.1% impervious as a result of human development (Randall 1998). Impervious surface can be defined as any surface which prevents infiltration of rainfall, causing immediate runoff during rainfall events. In contrast, pervious surface is characterized by having rainfall infiltration capacity, which varies with soil type and vegetation cover. After a saturated state is reached, a pervious surface can become effectively impervious (Boyd et al. 1993).

The North Fork drainage has been subjected to intensive land use practices. Like the entire watershed, the first human influence resulted from controlled burning by the Ohlone. Impacts to the North Fork are believed to have been similar to the Middle Fork and equally minimal. Cattle grazing from the time of the Spanish settlement to the early agricultural period are assumed to have caused the North Fork watershed and channel to change much like the Middle Fork.

As is the case with the main stem and Middle Fork of San Pedro Creek, significant impacts to the watershed first became obvious during the agricultural period, with the intensive row crops in the valleys and heavy modification of the channel. Regardless of major changes from agriculture, the most significant impact on the North Fork watershed and channel resulted from residential development in the 1960s and 70s. No land use practice imposed as profound and long-lasting impact on the stream channel and surrounding ground surface as residential development. As stated earlier, only about 2.8 miles (4.5 km) of open channel remain of the historic 9.4-mile (15.1 km) drainage network. The other 6.6 miles (10.6 km) have been put in concrete pipes and buried beneath roads, houses, and parking lots. These modifications, along with the accompanying impacts from a 19% increase in impervious surface area and increased drainage density, led to a significant increase in peak flow and channel discharge. Construction activities first increased sediment availability and later reduced it by paving over natural surfaces.

CHAPTER 3 – LITERATURE REVIEW

Human land use activities impose significant influences on watershed processes. It is well understood that urbanization alone can significantly alter the hydrology and sediment supply of streams (Wolman 1967; Leopold 1972; Graf 1976; Morisawa et al*.* 1979; Booth 1991). This literature review focuses upon investigations where parallels can be drawn with the land use changes observed in the San Pedro Creek watershed, and methods for understanding the effects of urbanization on fluvial processes.

Research into the impacts of urbanization on streams has a notable history. For some time, negative cumulative effects of human development have motivated researchers to theorize, study and evaluate these effects as they pertain to drainage systems. Early on it was proposed that:

> When an area is developed for housing or other urban purposes, the immediate hydrologic effect is to increase the area of low or zero infiltration capacity and to increase the efficiency or speed of water transmission in channels or conduits (Dunne and Leopold 1978).

Urbanization has steadily replaced open spaces and forced dramatic changes to watersheds in the process. Natural drainages have been replaced by human structures, or reengineered for human purposes.

Early Studies

Luna B. Leopold is one of the pioneers of scientific research evaluating the adverse changes humans can impose on streams. His work on the Watts Branch of the Potomac River near Rockville, Maryland is considered seminal among investigations of temporal fluvial geomorphic response to urbanization (Leopold 1973). Leopold helped to introduce the idea that urbanization is an impact on watersheds, geographic units that he considered significant environments in form and function.

William L. Graf focused on how changes in channel networks occur as a result of impervious surfaces, proposing that:

> Roofs, sidewalks, streets, parking areas, and sod lawns accelerate overland flow and restrict infiltration, resulting in flood discharges of greater magnitude and frequency than those that occurred before urbanization. In addition to changes in surfaces, however, suburban development introduces another significant change into the hydro-geomorphic systems in the form of radical alteration of channel networks (Graf 1976).

Graf's research (1976) found that an increase in impervious surface added a significant artificial channels to the previously existing natural drainage network. His early work references Leopold, among others, but is unique for its time because of its multi-variable approach. Graf examined several indicators of change and ranked the importance of their spatial relationships to the drainage network.

These two studies are significant not only for their relatively early publication but also for their uniquely geographic approaches. They helped formulate research standards and approaches that reappear in many later works.

Grazing and Farming

Grazing and farming can also result in watershed modifications and channel response. In western human landscape evolution, these two activities have often preceded urbanization. Such is the case with San Pedro Creek. Though it can be very difficult, or at times impossible, to quantify grazing's and farming's impacts separately from urbanization, it is still important to consider the influence these activities may have had on human landscape evolution and the resulting effects on watershed processes. This review only considers some of the significant effects that may have occurred in the San Pedro Creek watershed. There is an extensive body of literature on these subjects.

Grazing can result in soil compaction, soil erosion, and changes in vegetation communities and abundance. These changes to the watershed can result in reduced infiltration, increased runoff, and increased sediment supply and transport. The degree to which grazing practices can cause negative watershed impacts is directly related to the degree of over-grazing in the basin. According to Tate (1998) overgrazing occurs when the number of cattle per unit area, per unit of time exceeds the carrying capacity of the landscape. Though it is uncertain whether over-grazing occurred historically in the San Pedro watershed, the presence of livestock is known and some level of effect can be assumed.

The presence of cattle and the trampling that ensues can lead to a compaction of subsurface soil layers while loosening surface soils (Reid 1993). Liacos (1962) found that the shallow horizon of grazed soils in Berkeley, California typically had a higher density (expressed as bulk density) than nearby ungrazed soils. Several rangeland studies have found a strong correlation between increased bulk density and water infiltration (Packer 1953, 1963; Rauzi et al. 1966). Given enough precipitation, reduced infiltration resulting from subsurface compaction will increase surface runoff's capability of eroding and transporting loosened surface sediments to nearby streams. This process may be responsible for the initiation or exacerbation of the gullies identified on the northern hill slopes of San Pedro Valley. Increased runoff also leads to increased peak discharge and more erosive instream flows (Allen-Diaz et al. 1998). Increases in peak discharge can be compounded by the concentration of flows in terracettes or "cattle tracks", as observed by Stephenson (1994).

Grazing has had a permanent impact on the grassland community of the San Pedro watershed and could have altered the riparian community as well. Burcham (1982) described how California Coast Range grasslands changed from perennial bunchgrasses to European annuals with the introduction of grazing. According to Reid (1993) changing the longevity of roots through conversion from perennial to annual grasses can play a part in changing soil texture and surface roughness. Reid also reported that grazing could lead to decreased ground-cover density due to consumption of plants, as well as trampling. Reducing soil-binding benefits of roots, and exposing more surface area to rain-splash erosion could have generated more sediment supply to San Pedro Creek.

As for riparian impacts, cattle have been found to spend significantly more time in riparian areas than in drier upland areas (Harper et al. n.d.). Similarly, Roath and Krueger (1982) found that 81% of forage use was sustained by a riparian area that made up only 1.9% of the cattle range in an Oregon basin. Consumption of young riparian plants and trampling stream banks likely increased channel instability and erosion in San Pedro Creek.

Crop farming has also been observed to have measurable impacts on watershed processes. Common changes include increased runoff and peak discharge, increased sediment supply and channel erosion, and direct channel alteration. Farming occurred for approximately 170 years in the San Pedro Creek Watershed, peaking between the late nineteenth and mid twentieth centuries. During this later period, all of the level valley areas had been converted to farms.

Converting land to agricultural use has often meant draining wetlands and extirpation of the native vegetation community (Reid 1993). In the Willamette Valley, Oregon, for example, the natural drainage network of bayous and floodplain channels were drained and confined into a single channel to increase arable land (Sedell and Froggatt 1984). This conversion typically initiates processes resulting in other direct and indirect impacts.

Plowing can reduce soil compaction near the surface (Voorheese 1983) while subsurface compaction increases (Blake et al. 1976). Surface compaction can also increase where roads and other agricultural service areas are established (Reid 1993). This change in the earth surface, along with appurtenant drainage and irrigation facilities, leads to increases in runoff and peak discharge in streams. In a study reported by Dunne and Leopold (1978), overland flow resulting from saturation developed more frequently on soils used for growing crops. Similarly, but throughout a larger study area, Knox (1977) observed that conversion from natural vegetation to crops led to an increase in flood magnitudes in several watersheds.

Exposed soils and increased surface roughness results in greater sediment supply to streams when overland flow occurs (Reid 1993, Woltemade 1994). Woltemade (1994) found that sediment eroded from upland farms in the Grant River in southern Wisconsin were deposited as overbank levees in the lower river reaches. Knox (1977) who observed this same phenomenon in the Platte River found that raised channel banks concentrated discharge and increased stream power within the channel. Increased downstream erosion caused upstream reaches to incise and peak discharges to increase up to five times pre-settlement levels. Woltemade (1994) showed that 33 out of 69 upstream locations in agricultural areas had incised enough to containe the 10-year frequency flood. Of these sites, almost half could contain a 25-year frequency flood. Knox (1989) summarized this process:

> The enlarged channels now contain most floods that once overflowed stream banks, and because these channels perform a “flume-like” function with relatively little hydraulic roughness compared to that experienced when shallow flood waters are spread across wide floodplains, the floods are quickly routed downstream with considerable velocity and erosive force… (Knox 1989).

Intentional channel straightening typically shortens the stream channel by cutting off natural meanders. This is often done to maximize land for crops, as occurred throughout San Pedro Creek (Collins 2001). Yet the channel length of lower San Pedro Creek was actually increased by approximately 0.8 mile (1.3 km) with the ditching and draining of the lake and surrounding marsh creating a discrete channel where no channel had existed (Collins 2001). In either case, channel slope is steepened, causing an increase in erosive flows and channel incision. Emerson (1971) studied the channelized Blackwater River in Missouri and found that the channel had been incising for 60 years with no sign of stabilizing. According to Dunne and Leopold (1978) the change of a rivers slope can cause a long-term, irreversible condition of instability that may be the most difficult impact to correct without significant effort.

Urbanization

Perhaps the most obvious landscape-level change to accompany urbanization is the extent to which previously natural surfaces are covered by engineered, impervious ones (May 1997). Once vegetation and soils are replaced with buildings and paved surfaces, the infiltration potential for precipitation is greatly reduced, resulting in increased runoff, decreased lag time and increased peak discharge in streams. Sediment source areas and supply dynamics are modified when impervious areas cover the natural earth. Increased peak discharge and reduced sediment supply often result in accelerated erosion leading to increased aggradation in depositional zones. These effects have generated negative impacts on fluvial geomorphic processes, riparian habitat, and water quality, leading many researchers to investigate and improve our understanding of how urbanization alters streams.

Impervious Surface Area

Impervious surfaces associated with urbanization include roads, sidewalks, parking lots, and buildings- any artificial, hardened surface that reduces permeability and infiltration of water into the soil (Arnold and Gibbons 1996). A study in the Puget Sound region of Washington (1994) indicated that approximately 60% of the impervious cover in a suburban area was related to transportation (City of Olympia 1994). Schueler (1994) described impervious surface area as a good indicator of development that can be used to characterize the current state of water quality and biological diversity of a stream. He developed categories of stream condition in terms of beneficial uses and impervious area. As shown in Figure 6, watersheds with 10% or less cover are considered sensitive, 11% to 25% are considered impacted and anything above 26% impervious cover is a non-supporting creek.

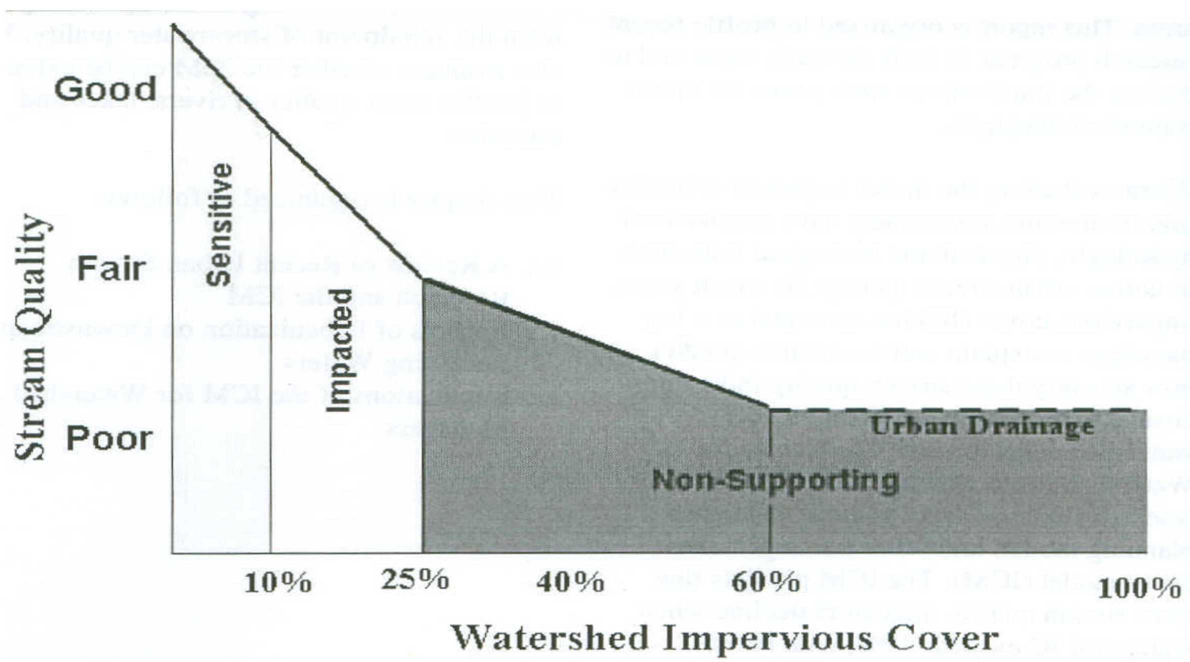

Figure 6. Impacts of Impervious Cover. Center for Watershed Protection, 2003:2

The location and connectivity of impervious cover to the receiving water body is also significant. Boyd, Bufill, and Knee (1994) defined the impervious area draining directly to the natural drainage system as the “effective impervious area”. They distinguished drainage pathways, observing that “connected” impervious areas drain directly to the natural drainage system, while “unconnected” impervious areas drain to pervious areas. For example, a street draining to a stormdrain system that flows to a creek is “connected”, while a school yard that drains to the surrounding playfields is “unconnected”. Impervious areas that are unconnected can still contribute to runoff when the surrounding pervious areas become saturated. Leopold (1991) reported a significant increase in runoff in Cerrito Creek, Berkeley, California due to saturated overland flow, implying that the pervious areas could become effectively impervious.

Investigations of Boyd, Bufill, and Knee (1993) observed a high degree of effective impervious area in 26 urban basins in Canberra, Australia. They plotted total storm rainfall depth against runoff depth for a range of storm events and found that the effective impervious area remained fairly constant for all storms, plotting as a straight line with minimal scatter from pervious area contribution. Conversely, Stephenson (1994) found that 70% of the 25% impervious area found in developments near Johannesburg, South Africa was unconnected, so the effective impervious area was considerably less prior to saturation.

In addition to causing changes in drainage surfaces, urbanization may radically alter channel networks. Graf (1976) focused on how changes in channel networks occur as a result of impervious surfaces, proposing that roofs, sidewalks, streets, parking areas, and even sod lawns accelerate overland flow and restrict infiltration, resulting in flood discharges of greater magnitude and frequency than those that occurred before urbanization. At the same time, Graf described how an increase in impervious surface increases the length of artificial channels to the previous network of natural channels. An increase in channel network results in higher drainage density, defined as the length of the drainage network divided by the drainage area (Dunne and Leopold 1978). Graf (1977) described changes to a drainage network in a developing area near Iowa City, Iowa, including a 50% increase in drainage density due to artificial channels. Dunne and Leopold (1978) found that high drainage density commonly result in high peak flows due to more efficient capture and transport of runoff. May (1997) measured artificial and natural drainage density in watersheds of the Puget Sound ecoregion in Washington and used the ratio of artificial to natural as an indicator of urban impact.

Runoff

Elements that control runoff include frequency and intensity of rainfall, and ground infiltration potential which is in turn controlled by soil type, soil moisture, antecedent rainfall, surface cover type, percentage of impervious surfaces and surface retention. Travel time is determined by slope, the length of the flow path, the depth of flow and surface roughness. These elements in different combinations result in variations in peak discharge values. Other significant factors include the size of the watershed, the location and size of a development, and the distribution and intensity of rain events (Cronshey 1986). When a portion of a watershed is urbanized, some of these controlling factors are altered to the point of having a significant influence on runoff. Generally speaking, surface cover type, surface retention, length of flow path, and surface roughness are most affected, resulting in increased runoff reaching the natural drainage channel in less time.

Replacing native soils and vegetation with engineered, impervious surfaces has been clearly linked to increases in the amount of runoff that is generated during rainfall events. Schueler (1994) for example, compared the runoff of a parking lot with runoff of a meadow and found that the parking lot produced more than 15 times the runoff of the meadow. On a larger spatial scale, Schueler (1987) compiled runoff data from 44 small urban catchments across the United States and found that runoff increases were directly related to amount of impervious cover. In his comparative study of an urbanized watershed with one that was grassland dominated, Stephenson (1994) observed that total surface runoff from the urbanized drainage was four times greater than from the grasslands.

Urbanization also has a measurable effect on the runoff rates in a watershed, which can be expressed as *lag time*, or the time period between a burst of rainfall and the resulting hydrograph downstream (Leopold 1991). A hydrograph plots discharge over time at a specific point in a stream (Dunne and Leopold 1978). When rain falls on urbanized regions, smooth impervious surfaces cause immediate runoff that in turn flows through engineered drainage systems, resulting in reduced lag time. Two ways of measuring lag time are lag-to-peak, which is the time between the center of mass of rainfall and the peak of the hydrograph, and centroid lag which is the time between the center of mass of rainfall and the center of mass of the resulting hydrograph (Leopold 1991). Lag time is an important hydrologic measurement that describes the response of a watershed to rain. Leopold (1991) described the measurement of lag time as a better expression of the degree of urban landscape alteration than the direct measure of impervious cover. Lag time can also be influenced by antecedent wetness, or the amount of water already contained in pervious surfaces. As described earlier, when otherwise pervious surfaces become saturated, or close to saturation, they can produce rapid runoff much like an artificial impervious surface.

Peak discharge, a measurement or predictor of the highest discharge during a specific rain event or specific period of time, is linked directly to runoff and lag time. Compiled data from Carter (1961) indicate that an area that has been urbanized might show an increase in peak discharge of from 2 to 6 times the pre-urban conditions. Later work by Hollis (1975) compiled peak discharge data from fifteen studies, which showed a relationship of increasing peak discharge with increasing impervious surface area and decreasing storm magnitude. Neller (1988) also reviewed data from several studies and found that small floods may increase 10-fold due to urbanization. In his work in King County, Washington, Booth (1990) found a two- to three-fold increase in peak flows in typical low-density urban areas with 10-20 % impervious cover. Leopold (1978) compiled data from seven different studies, concluding that a 20 % increase in impervious surface area generated enough runoff to double the frequency of bankfull flows. These results were consistent with his findings in the Watts Branch where urbanization led to an increase of more than two-fold for flows with a recurrence interval of 1.5 to 5 years (Leopold 1972).

These works are only a few among many demonstrating that reduced infiltration from impervious surfaces is directly related to the amount of runoff that eventually flows to nearby water bodies. In the case of San Pedro Creek, the North Fork, and a significant percentage of the flatlands have experienced dramatic increases in the percentage of impervious surface area since the onset of urbanization in the early 1950s.

Sediment

Urbanization also affects the sediment supply of a stream, often in cycles. Wolman (1967) described three stages; 1) an initial state of equilibrium in which the watershed is primarily agricultural or forested, 2) the construction period which exposes land to erosion and increased sediment supply, and 3) the final stage consisting of an urbanized landscape which reduces sediment supply by increasing impervious surfaces. Figure 7 illustrates these stages.

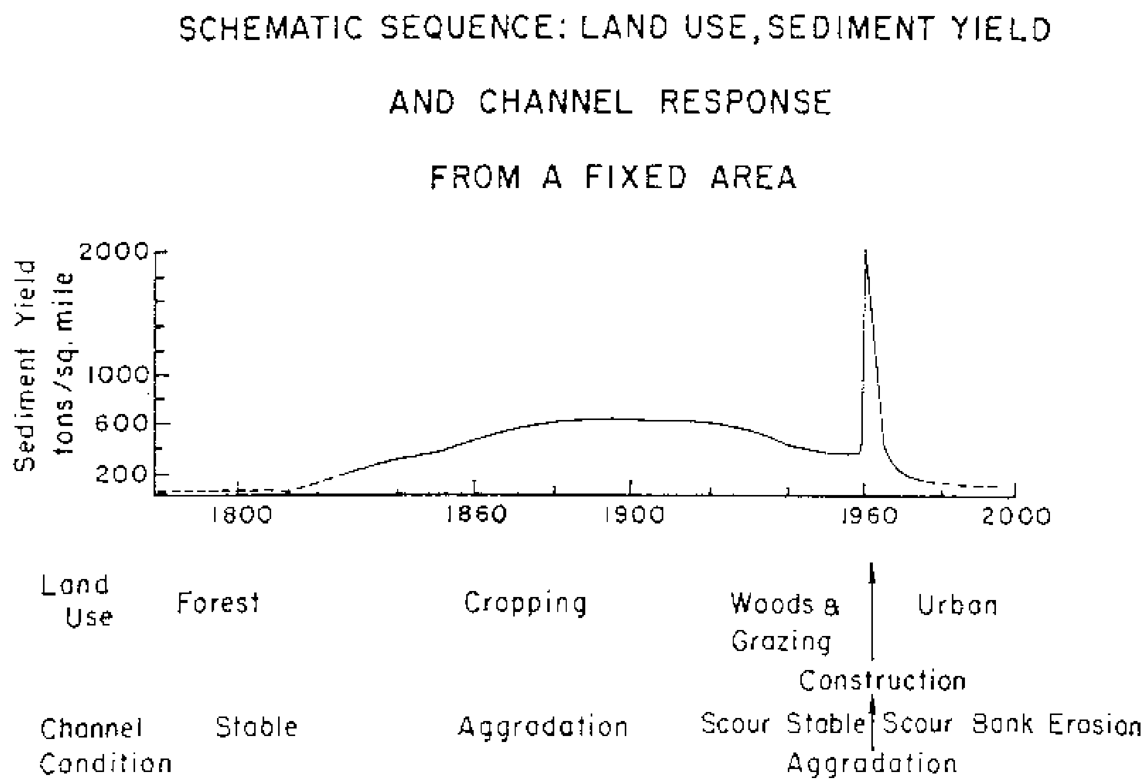

Figure 7. Land Use and Sediment Yield. Wolman, 1967

Parts of the San Pedro Watershed have experienced this same cycle, though the initial stage of equilibrium is thought to have preceded the agricultural stage, which is assumed to have caused an increased sediment supply. Leopold (1972) agreed with Wolman finding that sediment concentrations increased during the construction phase (second stage) followed by a decrease after buildings and paved roads were finished (third stage). It should be noted that modern developments, unlike those in San Pedro Valley or observed by Leopold and Wolman, are legally obligated to comply with the Federal Clean Water Act of 1972 which requires permits and best management practices designed to protect streams and other water bodies of the United States from pollution. Though not infallible, this protection does include measures for preventing increased sediment supply to streams from construction sites.

Leopold's efforts to quantify channel change over time measured cross-sections in the Watts Branch between 1953 and 1970 and found a decrease in cross-sectional area of 32% (Leopold 1994) due to "plastering" of excess silt onto the channel banks. This loss corresponded with rapid development in the basin. Wolman indicated that sediment yields from areas subject to construction might be several hundred times that of forested lands and grazed areas, or several times that of agricultural areas. He also reported data from Keller (1962) who found sediment concentrations in channel discharge to be 3 to 5 times greater in a watershed under construction when compared to a rural stream.

Following the construction stage, impervious surfaces cover previously exposed soils and vegetation, and pipes and lined ditches replace a portion of the drainage network. These changes reduce the amount of sediment available for transport to and through the natural stream network. The North Fork and the greater San Pedro Watershed, with the exception of an occasional minor construction project, are built out and any major developments in the future are prevented by the dedication of protected open space.

Literature reporting sediment concentrations following construction are not as available as for sediment concentrations following other land use impacts. Wolman (1967) did compare three watershed conditions on two streams representing pre-development, active construction, and post-development. He found that suspended solids in the post-development stream reach were lower than the pre-development reach 85% of the time and that active construction concentrations were 5 times greater than pre-development. Wolman also surveyed fourteen stormwater outfalls draining urban areas. Of these facilities, only three showed sediment accumulation of 20% or more and of these, two were draining developments that had just been constructed a year prior to observation. Where development had been complete for five or more years, sediment accumulation only filled 10% or less of the outfall cross-section. Wolman’s work supported the assertion that sediment yields during construction are greater than pre-development and agricultural conditions, and suggested that post-development conditions led to very low sediment yields equal to or less than those from forested lands.

Fluvial Geomorphic Response

Stream channels will respond to alterations of the hydrologic and sediment regimes that maintained the pre-disturbance equilibrium state. According to Wolman (1967):

> Upon completion of streets and sewerage systems sediment derived from the watershed decreases while the rapidity of runoff is increased. Channel bars and vegetation may be removed by flows of clear water. At the same time the absence of a fresh supply of sediment may result in progressive channel erosion without concomitant deposition.

As suggested by Wolman, typical fluvial geomorphic responses include channel incision, and bank erosion. These adjustments occur as a result of increased frequency and duration of peak flows exposing the channel to increased shear stress that exceeds the critical threshold needed to move bank and bed sediments (Schueler et al*.* 2003). These conditions are further exacerbated by an absence of sediment supply from outside the channel boundary.

During periods of adjustment following urbanization, receiving channel cross-sections can increase in both width and depth (Wolman 1967; Morisawa 1979; Booth 1990; and Pizzuto et al. 2000). Several studies compiled by Schueler (2003) found that channel enlargement in response to urbanization can result in cross-sectional area that is 2 to 8 times greater than pre-urbanization conditions. Gregory (1992) observed channel capacity increases in the Monks

Brook in southern England on the order of 2 to 2.5 times after urbanization. Channel adjustments resulted in width increases up to 2.2 times and bed incision up to 0.4 meters. Morisawa (1979) found that streams in several urbanized drainages in the Pittsburgh, Pennsylvania area were enlarging by incision, bank erosion, or both and attributed variations in enlargement to the complex interactions of hydrology and differing resistance of bed and bank material to erosion. Channels with more resistant bed material will erode laterally while channels with more resistant banks will tend to incise. Booth (1990) indicated that the immediate increase in discharge may, with time, cause an increase in stream channel cross-sectional area or potentially catastrophic channel incision depending on slope and geology.

Channels can yield significant amounts of sediment from bank erosion and bed incision, especially when they are in an unstable state. Trimble (1997) hypothesized that 60% to 75% of the sediment yield from watersheds he observed in California and Texas was derived from bank erosion. Collins (2001) reported that within the 2.6-mile (4.2 km) study reach of San Pedro Creek, sediment supplied from bed incision was 7 times greater than from bank erosion. Significant instream erosion may continue until development of the watershed has stopped long enough for the channel to adjust to a more stable geometry suited to post-urbanization flow and sediment regimes. Morisawa (1979) and Ebisemiju (1989) suggested that once development ceased, the stream channel would adjust to the post-urbanization flow and sediment regime resulting in a new equilibrium state. Finkenbine (2000) observed these conditions in Vancouver streams that stabilized 20 years following completion of construction.

Impacts of Urbanization

Urbanization has many negative impacts on many aspects of watersheds. May (1997) conducted studies in the Pacific Northwest and found that urbanization changed the physical, chemical, and biological characteristics of streams. Matuk, 2001 reviewed the impacts of urbanization on water quality in San Pedro Creek. For the purposes of this study, a brief review is provided for work related to physical channel impacts that occur as a result of increased impervious surface area.

When urbanization results in bank erosion, bed incision or both, alterations in stream channel geometry can be significant. Impacts associated with these alterations are often defined by the boundary conditions of the affected reaches. Ferguson (1991) explained:

> Such accelerated lowering and bank erosion can cause destruction of aquatic habitat; excavation or dewatering of riparian zones; undercutting of structures, such as buildings and bridges; and loss of streamside yards, gardens, trees, parks, open spaces, and mature riparian vegetation.

Schueler (1992) emphasized impacts to riparian and instream habitat. Erosion destabilizes riparian vegetation on channel banks, while sand and silt deposits smother streambed habitat features. Alteration of riparian and instream channel habitats threatens dependent species such as salmonids (May 1997). Pools, riffles, and gravel beds critical to aquatic fauna are scoured by increased shear forces or smothered by increased fine sediments from bank erosion. Increased fines could be correlated with decreased aquatic species health (May et al. 1997). Loss of riparian vegetation from undercut and eroding banks reduces cover, reducing water temperature in winter and increasing it in the summer (Galli 1991). Reproduction and survival of aquatic species are compromised.

Stream bank erosion and loss, or potential loss of property leads public and private entities to respond with channel armoring projects that often include riprap, gabions, concrete, or some other sterile material. Channel armoring reduces habitat potential and transfers accelerated velocity vectors to downstream banks. Sauer (1983) observed that channel armoring influenced peak discharge rates, increased the efficiency of instream runoff transport, and amplified shear stress velocities and channel erosion. Collins (2001) identified various types of revetment covering 20% of the length of the main stem of San Pedro Creek. An additional 37% of the bank length was considered to be actively eroding and potentially subject to new revetment projects.

Research Methods

Interest in measuring the effects of urbanization on streams and the complexities inherent in watershed systems has produced a variety of research methods. Because watershed processes are controlled by several variables, an oversimplified approach is at serious risk of missing important information. A clear understanding of the physical and human characteristics of a given watershed is critical if a method is expected to produce valuable results.

Ebisemiju (1989b) describes four widely recognized methods for identifying changes in stream channels. He associates these techniques with relevant works of specific authors: the deductive method comparing pre- and post disturbance conditions (Wolman 1967), the monitoring of channel cross sections at established sites over time (Leopold 1973), the regime theory involving the comparison of relationships between channel form, water discharge and sediment yield (Schumm 1969; Rango 1970; and Blench 1972), and the spatial interpolation technique involving the comparison of a modified stream with an adjacent “natural” stream or the comparison of an unaffected reach with a modified reach on a single stream (Hammer 1972; Gregory et al. 1976; and Park 1978a). Gregory, Davis and Downs (1992) add that the most common “historical” method for identifying channel change is the comparison of historical large-scale maps and remotely sensed data with current data to establish modifications in channel planform. The cross-sectional, regime theory, and spatial interpolation methods are discussed further because of their relevance to this study.

The cross sectional monitoring approach conducted by Leopold, involved measurement of 14 cross sections of a stream channel about every other year for 20-years (1953-1972). Changes in cross sectional area were compared to ascertain changes in channel size resulting from erosion and deposition attributed to increased flood frequency relative to urbanization in the watershed (Loepold 1973). Results of some of the years are represented in Figure 8.

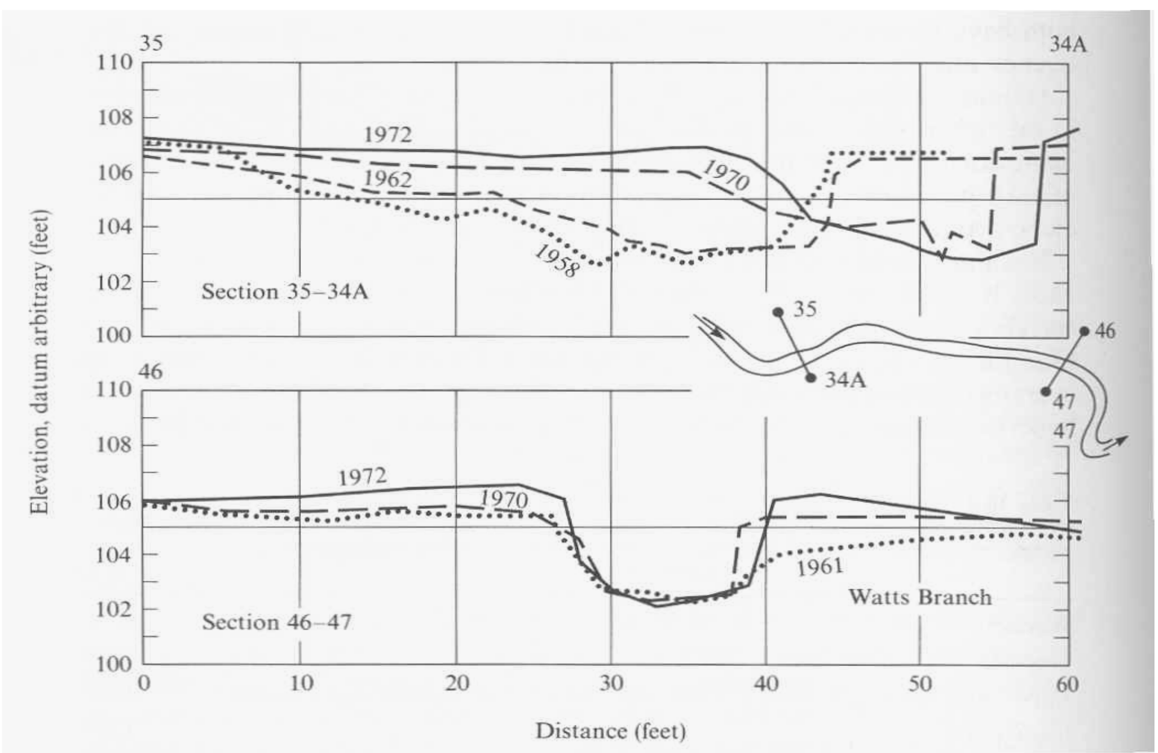

Figure 8. Watts Branch Cross-Sections. Dunne and Leopold, 1978:698

It is impractical for most researchers to collect cross sectional data over twenty years, and the effectiveness of this method is strongly correlated with length of time measured, but even on a shorter time scale one can observe localized or systematic changes in the channel form.

Beyond comparing the changes in cross sections, Leopold utilized the regime method by calculating lag time and comparing it to precipitation data, drainage size, drainage density, discharge, sediment yield, increased urbanization and changes in stream channel geometry. These methods became standard practice, aiding researchers in determining the response of a channel to urbanization and other land use changes.

In a study designed to indicate the irregularity of stream response to urbanization in a humid tropical basin, Odemerho (1992) employed the spatial interpolation technique to measure whether downstream propagation of influences from urban land use was detectable (Odemerho 1992). Odemerho set up ten stations along the Ikpoba River in Nigeria for the purpose of measuring changes in the bankfull channel cross-section. He placed the stations upstream, adjacent to, and downstream from the urbanized area and monitored changes in channel depth and width finding that channel dimensions varied with different proximity to the urban area. Upstream, increasing drainage area corresponded with larger cross-sections until reaching the urban section, which was constricted by sedimentation from urban inputs. He then interpreted the changes in channel dimensions to determine the impact of urbanization.

Like Odemerho, Ebisemiju (1989b) used the spatial interpolation method to measure channel geometry in developed and undeveloped drainages. Different from Odemerho, Ebisemiju distributed measuring sites in seven urbanized and six natural headwater catchments throughout the Elemi and Ireje watersheds, also in Nigeria. Ebisemiju also found that channel cross-sections in and downstream of urban areas were reduced by sedimentation and noted that the model of urban induced erosion and incision proposed by Morisawa (1967) may not be appropriate in the humid tropics.

To better understand the changes that resulted from development, Gregory, Davis and Downs relied on the comparisons of large-scale (1:2500) topographic maps. By examining stream reaches on maps produced in different years, they could trace the changes in channel width and channelization that resulted from urbanization. They cited Gregory and Brooks (1983 and 1992) who used large-scale maps from different dates to measure increases in channel width downstream of bridges.

Close attention must also be paid to the location of urbanization in a watershed and how different spatial relationships with the stream can result in different responses of the stream channel. In a study of the impacts of urbanization in Nigeria, Ebisemiju (1989a) hypothesized that:

> The location of urbanization in a watershed should influence the magnitude of runoff and sediment delivered to a stream from urban surfaces during rainstorms of comparable intensity, duration and erosivity. It should also influence variations in peak-flow discharges and stream velocity along a channel…

It has been shown that the placement of the urbanized area within a watershed can result in different effects on the stream. This has become a widely accepted precept that should be considered regardless of what method the researcher is using.

The methods discussed above represent only four of the many methods that exist for determining the changes in a watershed due to human development. Computer modeling and manipulation of digital information present two examples (not discussed here) of advancing methods that will continue to provide better datasets for both comparative and non-comparative studies. Several of the methods have been rigorously tested over time, both in the field and on the computer, and all of them have potential for refinement and improvement. Based on the literature, however, it is clear that the best research will employ a combination of methods well suited to the individual study.

Proposed Solutions

In order to frame any discussion of mitigating and ultimately avoiding the potential impacts of urbanization on streams, it is necessary to understand what has been sacrificed, what will be saved and why it is important.

> To define our goals in watershed management requires first that we articulate the values we associate with watersheds and the stream channel network. These values include the function of the natural stream-and-floodplain network in flood runoff and drainage in general, the ecological values of the aquatic and riparian systems, and the recreational and aesthetic values of these systems. Urbanization affects all these, but they can all be managed for (Kondolf et. al 1991).

Several possibilities have been suggested for avoiding degradational urban influences on streams as well as the potential catastrophic and economic influences of streams on urbanization. At the same time, limited suggestions are given for after-the-fact repairs, perhaps due to economic barriers and the potential for negative environmental impacts resulting from the current dependence on engineered solutions. Methods most commonly suggested in the reviewed literature can be divided into two categories: better land use planning and continued research aimed at a clearer understanding of the watershed as a natural system and an urban-nature interface.

Kondolf recognized the necessity of identifying the channel-floodplain prior to the consideration of development in the valley bottom. He suggested the use of historical records to indicate previous stream migrations and areas of flood inundation (Kondolf et al. 1991). By understanding the natural floodplain and avoiding it as an area of "prime real-estate" both the channel and development can be more successful.

When the floodplain is not preserved, the changes in urbanized streams often lead to unattractive and even dangerous conditions due to increased flows, flooding and environmental degradation. As a result, channels are paved, fenced off and made unavailable or undesirable to the public and dependent wildlife. In this way, streams become "invisible" when they should be valued aesthetically, recreationally and as habitat.

As an alternative, planners should consider the design of streamside parks as uses that can be flooded with less cost to humans. Such parks could also reduce the potential for flooding downstream and provide areas of beneficial use for people and wildlife (Dunne and Leopold 1978). Odemerho (1992) speculated that:

> The development of green belts/lawns and other options that encourage infiltration in urban areas will be more successful than development of storm sewers both because of capital constraints and the need to reduce rapid flows into the existing river channel.

He suggested this as a method of reducing flows downstream from the development and as a long-range strategy for stream channel stability and downstream impact mitigation.

When a development is already complete, the community and planner must employ measures that recognize areas sensitive to flooding and channel instability. Booth's study in King County, Washington (1990) led him to believe that "[f]low diversion, piping, adequate detention, or extensive upland infiltration buffers…" are all possible proactive solutions to problem areas that may not have been adequately considered before planning and construction.

Research-based solutions are suggested to provide necessary data to support proper land use decisions. Investigations in and away from the field must focus not only on the location of the floodplain but also on the location of change and amount of change expected. Much of the literature indicates that alterations due to human influence may be varied and spatially discontinuous. Consequently, it is essential that successive studies identify the location of stream channel responses to aid in developing proper avoidance measures (Gregory et. al 1992). Ebisemiju also suggests giving more attention to the pattern of stream response to urbanization (Ebisemiju 1989b).

Finally, Luna Leopold cites a need for closer study and better understanding of small drainage basins. "The land planner may be interested in the hydrologic effects in a basin the size of a housing development or even a single house" (Leopold 1991). It has become common practice to place developments in smaller valleys as large-scale development sites have been built out. By understanding the hydrology of small basins in varying environments, the land planner will be better equipped to avoid serious problems. By estimating natural lag time and projecting post-urbanization lag time, planners can better design to avoid hydrologic impacts or "hydromodification" to streams and protect from flooding to the community.

CHAPTER 4 – METHODS

Previous and Concurrent Studies

This study builds on previous works of other researchers that considered changes to the culture, water quality, and physical changes as well as current conditions of the San Pedro Creek watershed. A considerable amount of attention has resulted from an active community watershed group and an academic interest driven to better understand the past and how it has affected the present and future of a still relatively intact urban stream.

The cultural landscape was reported by Culp (2002) in an attempt to piece together several phases of cultural history in the San Pedro Valley, starting with the Native Americans and ending with present conditions. Culp examined landscape changes with each series of cultural periods including the Ohlone Landscape, the Mission Period Landscape, the Rancho Landscape, the Truck Farming Landscape, the Early Suburban Landscape, the Modern Suburban Landscape, and Today.

Matuk (2001) looked at seasonal water quality data from San Pedro Creek in an attempt to characterize physical, chemical, and biological parameters and found that the urban landscape was a significant contributor to water quality impacts in all three areas.

Eisenberg, Olivieri, and Associates (EOA 1998) had been hired by the San Mateo Countywide Stormwater Pollution Prevention Program to assess impervious surfaces in five different watersheds in San Mateo County; one of which was the San Pedro Creek watershed. EOA used digitized 1995 land use data generated by the Association of Bay Area Governments (ABAG) to calculate the total impervious area for the watershed (ABAG had designated twenty land use categories and estimated their total area within the San Pedro Watershed based on aerial photos flown in 1997). Impervious surfaces were digitized and displayed for direct measurement and assigned an impervious percentage category of 0, 30, 45, 60, 65, 70, and 100 percent. EOA performed some field checks to ground truth their determinations and to increase the overall accuracy of their measurements.

Collins, Amato, and Morton (2001) surveyed 2.6 miles (4.2 km) of main stem from the mouth at the Pacific Ocean to the upstream confluence with the South Fork tributary, and conducted historical ecology research combined with field data of physical conditions to describe the evolution of the human and natural landscapes, and to assess present fluvial geomorphic conditions. Detailed survey data were collected to describe bed and bank conditions including erosion, incision, sediment size class distribution, in-stream habitat features, and stream reach classification based on Rosgen (1994). Observations and results of this geomorphic investigation elucidated the importance of a more detailed understanding of the influence of urbanization on San Pedro Creek and further emphasized a need to monitor the storm response of the Middle and North Fork watersheds.

Methods Specific to this Study

To compare how the North and Middle Forks responded differently in storms, data for several watershed variables were collected. Percent cover of impervious surfaces and length of artificial channels were quantified; monitoring equipment was installed to collect continuous precipitation, water level, and turbidity data; discharge was measured in the field to estimate continuous storm response; and longitudinal profiles and cross-sections were surveyed before and after the 2000 rainy season to demonstrate short-term channel response. Bank erosion data was previously assessed under a separate study.

Engineered drainages were measured using ArcView geographic information system (GIS) software and street and stormdrain data from the U.S. Geological Survey and City of Pacifica respectively. Engineered drainages included street gutters, mapped ditches for hillside drainage, and stormdrains. Pre-urbanization drainage density was derived by dividing the pre-development channel length by drainage area. Post-urbanization, or current drainage density was derived by combining the measured length of natural and artificial channels and dividing by the drainage area.

A rain gage tipping bucket was placed at the ridgeline near the headwaters of each drainage, as shown in Figure 5, to record precipitation during the course of the study as well as during storm events. The buckets were factory calibrated to record an event after collecting 0.01 inch (1.37 mm) of rain. Data loggers were installed in the rain gages to record date, time, and event, and to allow for periodic data downloading. This data was collected and rainfall events were plotted over time, showing total rainfall and intensity for a given period based on the frequency of each recorded event.

Water level and turbidity stream gage stations were established at representative sites near the downstream terminus of both tributaries, just upstream of their confluence (Figure 5). Gage location selection criteria consisted of the site's ability to represent stream response due to the land use of the sub-watershed, physical characteristics of the watershed, proximity to the downstream end of the individual tributary, channel stability along bed and banks, access, and protection from vandalism. Most pertinent to this study was the location's ability to represent the effects of land use on the response of flow and turbidity during storms.

The Middle Fork gage station was located in San Pedro Valley County Park upstream from the urbanized portion of the watershed. The only man-made structures upstream of this station were a small maintenance yard and two small bridges located upstream of the gage. Residential and commercial facilities in the lower 1,300 feet (396.2 m) of stream contribute urban stormwater runoff to the Middle Fork and were thus excluded from the study area so that data collected at the gage would more accurately represent the undeveloped open space that dominates the Middle Fork watershed. The maintenance yard and pedestrian bridges were expected to have negligible influence on the stormwater runoff response and turbidity levels in the Middle Fork. The effects of trails on runoff and turbidity rates were considered beyond the scope of this study.

The gage station was located on the north bank at the end of a long riffle with earthen banks and gravel substrate. The bed and bank at the gage were relatively stable but did exhibit some signs of active erosion. As shown in Photo 4, sensors were housed in a black 5-inch (127 mm) diameter PVC pipe mounted perpendicular to the channel bed. Several holes were drilled into the bottom of the pipe to allow water-level equalization and through-flow while protecting the sensors from debris and sediment impact during storm flows. The sensors were connected to a data logger in a waterproof bucket hidden in a pit in the terrace above the channel, an accessible but secure location that allowed for regular data downloads and maintenance while protecting the equipment from tampering or theft. A staff gage was placed next to the sensors for calibrating the water level data measured by the sensor with actual measured water level.

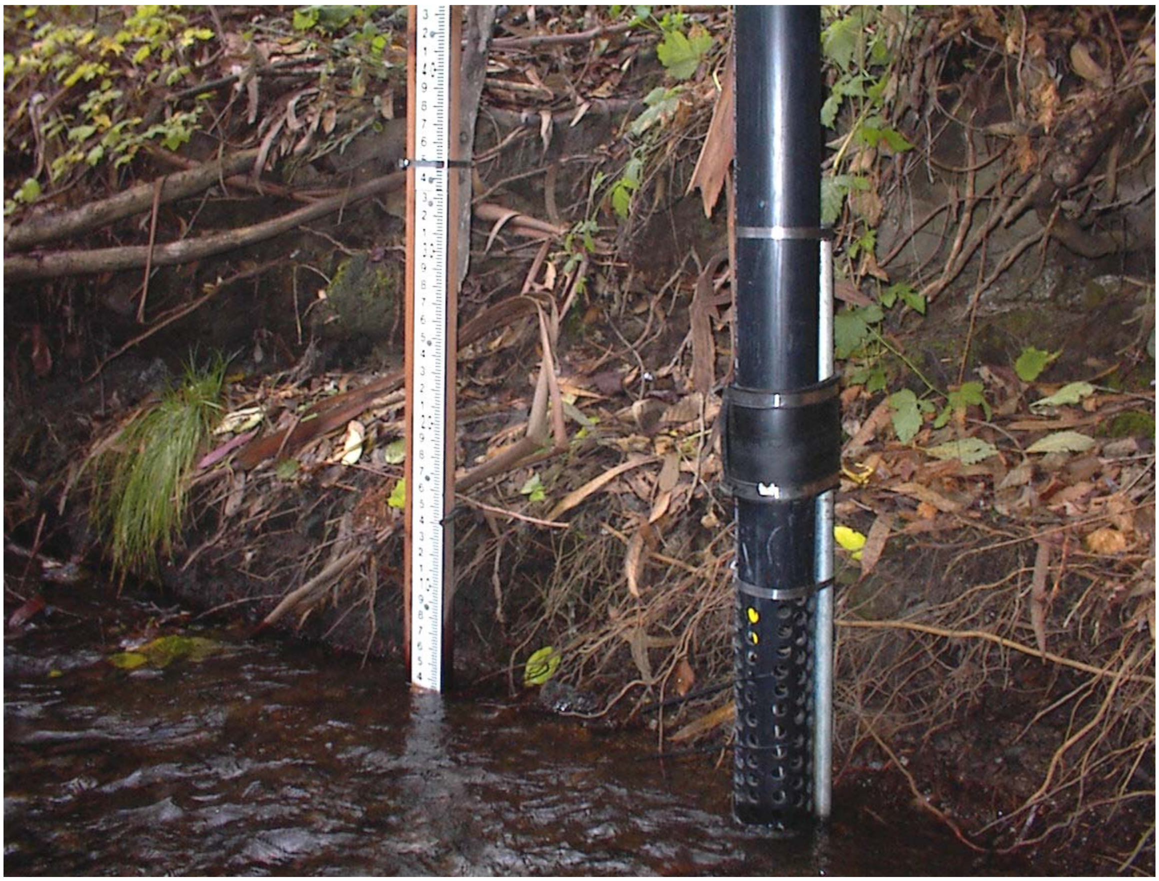

Photo 4. Middle Fork Gage Station

The North Fork gage station was located inside the 8-foot (2.4 m) diameter concrete pipe that forms the lower reach of the tributary, approximately 350 feet (106.7 m) upstream of its confluence with the Middle Fork. As shown in Photo 5 and 6, sensors were installed inside the pipe, 50 feet (15.2 m) from the end so they would be out of sight and safe from potential vandalism by juveniles and transients known to frequent the area. The need for this precaution was reinforced by personal encounters and observations of conditions at the site. The sensors and data cables were bolted to the concrete pipe and routed to a waterproof bucket containing the data logger. A PVC sensor well was originally installed but was washed out by minor storm flows prior to installation of the sensors, providing a timely indication of the velocities at which the culvert conveys flow. The sensors were re-mounted near the bottom of the concrete pipe without any housing.

A Global Water WL300 Water Level Sensor Pressure Transducer was used at both gage stations to record water depth, or *stage* (Photo 7). Stephenson (1994) used pressure transducers for measuring runoff from water depth in a similar watershed comparison near Johannesburg, South Africa. The WL300 creates an output in milliamps (mA), which must be calibrated to actual depth of water. The water level on the staff gage in the Middle Fork, and water depth measurements in the North Fork were observed at specific times during various depths and compared to the mA output recorded at the same time.

Photo 5. North Fork Gage Station Inside Culvert

Photo 6. North Fork Culvert

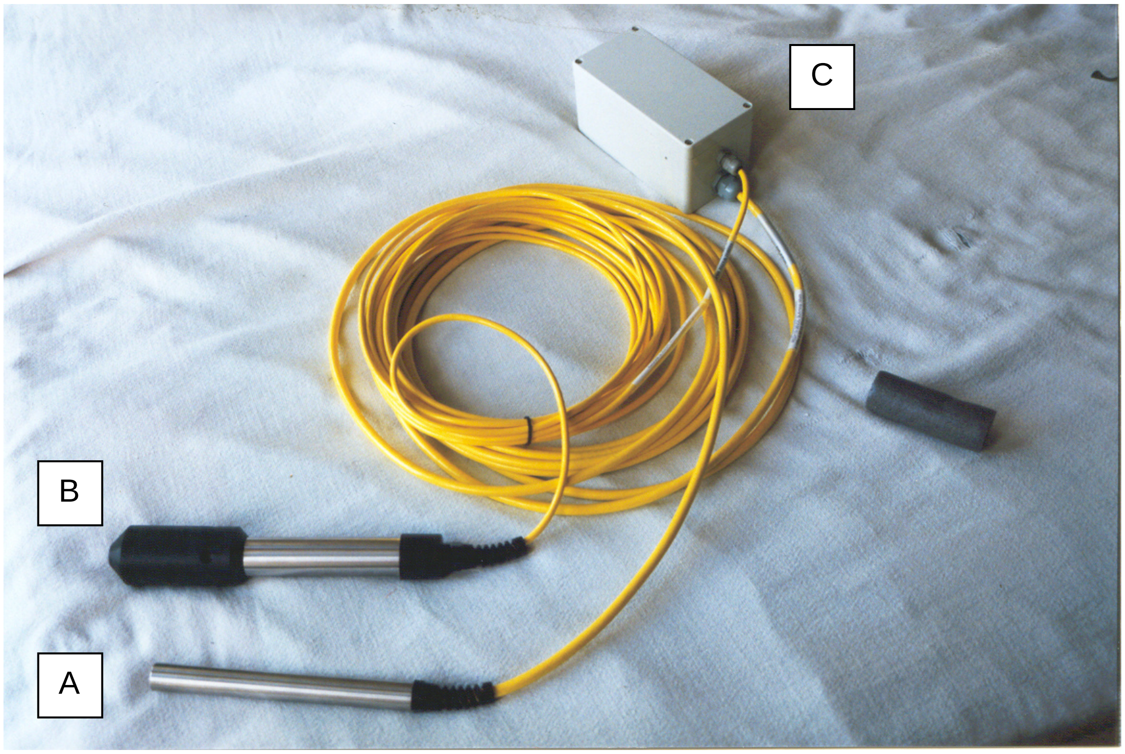

Photo 7. A) Pressure Transducer B) Turbidity Sensor C) Data Logger

Records in mA were converted to stage by running a regression analysis of actual measured water depths at various flows against water level sensor outputs in mA recorded at or within minutes of the same time. A strong correlation of r^2=0.98 in the Middle Fork, and a weaker correlation of r^2=0.69 in the North Fork were used to estimate discharge in both basins during the study period.

Turbidity was measured using a Global Water WQ700 Turbidity Sensor (Photo 7). The WQ700 is factory calibrated to measure turbidity in nephlometric turbidity units (NTUs) with a range of 0 to 2000.

> Particles scatter light through defraction, refraction, and reflection in all directions. A detector with a limited EPA (Environmental Protection Agency)-specified acceptance angle collects light at 90° to the focused beam resulting in a measurement of particle concentration or water cloudiness. The measured light level is converted to an electrical signal, filtered and displayed, resulting in the raw 4-20 mA output (Global Water 1999).

Consistent with criteria used by Lewis (1996) the sensors were installed close enough to the channel bottom to try and ensure they would remain submerged during all flows of interest.

Data output was recorded using a custom-built computer from Electronically Monitored Ecosystems. The computer was needed to turn on the water level and turbidity sensors three seconds prior to the preprogrammed data logger recording interval to allow for the manufacturer's required sensor warm-up time. Once the event was recorded, the computer turned the sensors back off until three seconds before the next recording event. Turning the sensors off between recording intervals was necessary to preserve the 12-volt power supply, avoiding power supply changes, and to prevent missed data collection. Onset Computer Hobo event loggers and Boxcar Pro Version 3.5 software were used for data recording from the sensors and the rain gages.

Data logging intervals for water level and turbidity were originally set for every ten minutes at both the Middle and North Fork stations. Lewis used the same interval in Caspar Creek, a small, mountainous, coastal stream in northern California (Lewis, 1996). This interval was thought to be frequent enough to capture the changing water levels in these small drainages. Visual observations of rapid water level rise and fall in the North Fork led to an increased frequency recording interval resolution of every five minutes in the North Fork only, to better capture system response. The Middle Fork recording interval remained ten minutes for the duration of the data collection period.

Discharge was measured at various flows using a Swoffer Instruments model 2100 flow meter, and multiplying measured velocity by the cross-sectional area of water in the channel. Continuous water depth (stage) was derived by establishing the relationship of observed stage on a staff gage to mA outputs responding to water depth (pressure) at the same time. Continuous discharge was then derived by plotting derived stage over discharge measured in the field at the same time. This effort yielded estimated discharge only due to the inability to measure enough discharge calibration points during a wide enough range of flows. Many storms occurred at night when measurement in the stream was difficult or unsafe, and mechanical breakdown and repair of the flow meter mid-study meant that the instrument might have had a different calibration before and after repair.

Longitudinal profiles and cross-sections were measured in the same reaches where the stream gages were located. Monumented surveys were done in 1999, prior to the study period, and in 2000, following data collection. The intent of the surveys was to plot the channel thalweg and cross-sections to see if channel geometry changed during the course of the study. It was important to survey cross-sections at the Middle Fork gage to measure any significant changes in geometry that could influence stage throughout the study period. Several previous studies (e.g., Leopold 1973; Ebisemiju, 1989; Odemerho 1992; and Gregory et al. 1992) have used channel geometry surveys to measure channel change.

Profile surveys were measured using a survey level and stadia rod for elevations, and a 100-meter (328.1 ft) tape measure for marking discrete points, or “stations” along the channel bed. Both the 1999 and 2000 surveys started and ended at the same fixed elevations (at concrete box culverts) so they could be plotted together and assessed for change. By recording fixed elevations at the upstream and downstream extent, changes in the elevations and features of the earthen channel in between could be measured. The level was mounted on a tripod and elevations were sighted on the rod at locations in the thalweg that defined the upstream and downstream extent of riffles, pools (including maximum depth), distinct changes in bed elevation, knick points, and concrete bridge aprons for elevation control. Stations on the tape measure were recorded for each elevation sighting. Points were then plotted for comparison.

Cross-sections were surveyed using the same method and equipment as for the longitudinal profile with the addition of rebar stakes for elevation control points. Once the cross-section locations were identified, rebar benchmarks were hammered into the ground on opposite banks. The measuring tape was stretched between the stakes to designate stations across the channel. The level was set up and sightings were taken on the rod at stations that represented changes in bed elevation. Like the profile data, cross-section data were plotted for comparison. These methods are commonly used for surveying stream geometry and have been described in several studies (e.g., Leopold 1973; Harrison 1994; and Rosgen 1996).

Bank erosion had been measured in 1999 as part of a geomorphic assessment of the San Pedro Creek Watershed. The author of this thesis assisted Laurel Collins, a local geomorphologist, and Donna Morton in measuring several in-channel characteristics related to physical conditions of the creek. Eroding bank sections were identified and referenced to continuous longitudinal stations along the centerline of the channel. Banks were separated into segments including bank, below the bankfull elevation; and terrace, landslide, or gully above bankfull. Depth, length, and height of bank erosion were estimated for the period since European settlement of the area in 1782 when land use impacts were believed to have begun affecting the channel. Bank erosion per linear foot was then determined by dividing cubic yards of eroded bank by linear feet of the channel reach. The Linda Mar reach extending from the confluence of the Middle and North Fork to the Linda Mar Bridge approximately 510 feet (155.4 m) downstream, was observed for bank erosion effects of the North Fork flows. The 764 linear feet (232.9 m) North Fork Confluence reach and the 1,217 linear feet (370.9 m) Oddstad reach were considered to be comparative reaches in the Middle Fork upstream of the influence of North Fork flows.

CHAPTER 5 – RESULTS AND DISCUSSION

Impervious Surface Area and Drainage Density

EOA (1998) measured a total impervious surface of 13% in the whole San Pedro Creek watershed, 1.8% in the Middle Fork and 19.1% in the North Fork, (Figure 9). The stream gage station in the Middle Fork was located *upstream* of nearly all impervious surfaces, with the exception of the San Pedro Valley Park maintenance and parking facilities, representing a small fraction of total impervious cover. Conversely, in the North Fork, impervious area downstream of the gage station represents only a small fraction of the total basin. According to the water quality and biological diversity based categories developed by Schueler (1994) the Middle Fork above the gage could be considered sensitive but good (0-10% impervious) though the near absence of impervious cover likely makes these categories inapplicable. The North Fork would be considered impacted and nearing non-supporting. The majority of the developed area (>0% impervious cover) in the North Fork was determined to be 60% impervious in the residential areas with smaller fractions of 30% for Frontierland Park which was built on a former landfill; 70% at Terra Nova and Ortega schools, a horse stable, and residential pocket; and 100% at the Park Mall.

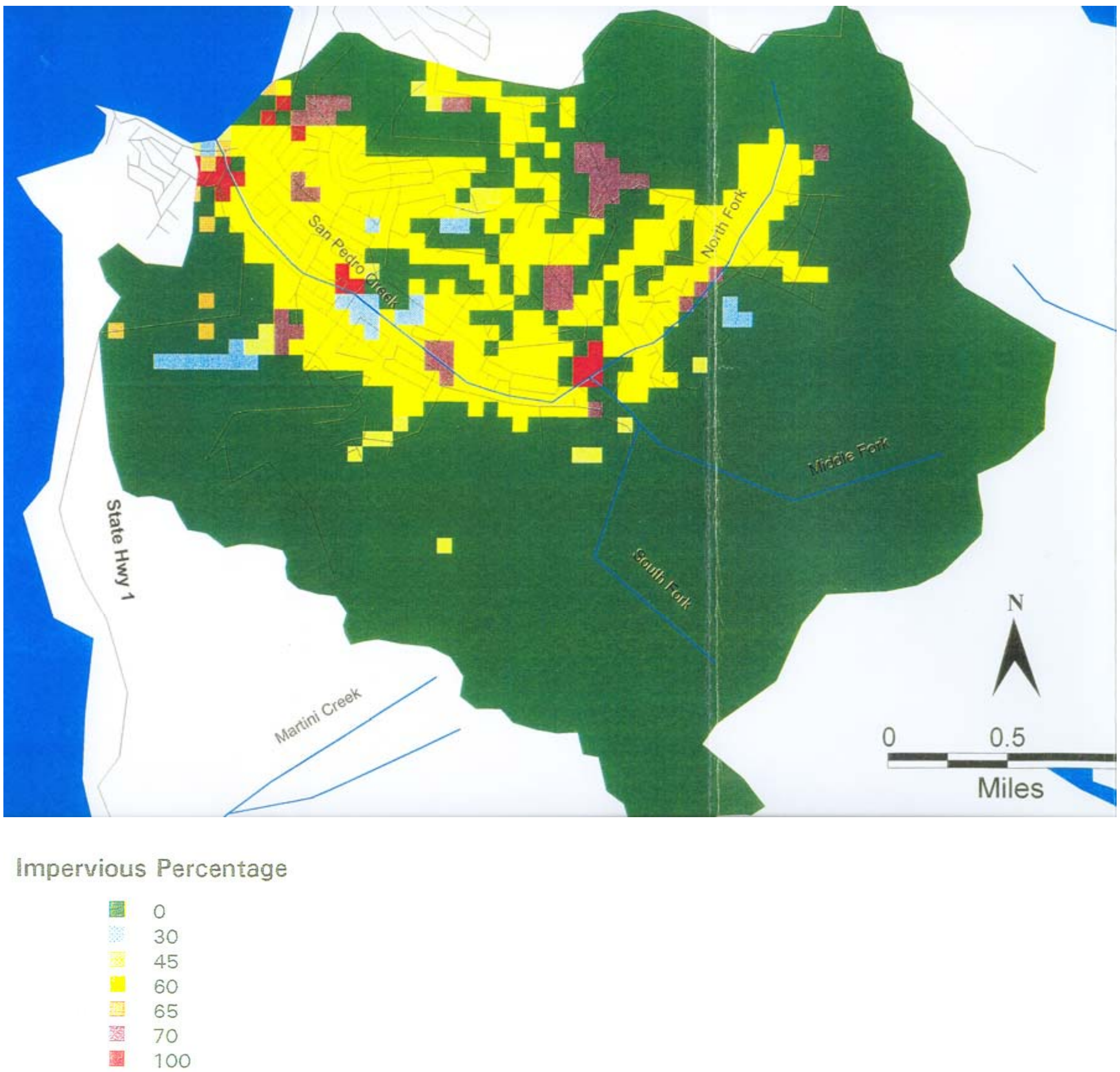

Figure 9. Impervious Cover in the San Pedro Watershed (EOA 1998)

Based on stormdrain data from the City of Pacifica, impervious surface area is predominantly connected, or effective at all times (Figure 10). Gutters, ditches, and storm drains service drainage needs of all the developed portions of the watershed as well as the upper, undeveloped watersheds. First and second order headward channels and hillside drainage have been connected directly to the storm drain system where stream channels once flowed openly. As a result, upland flows are accelerated downstream as soon as they reach the upstream opening of the stormdrains.

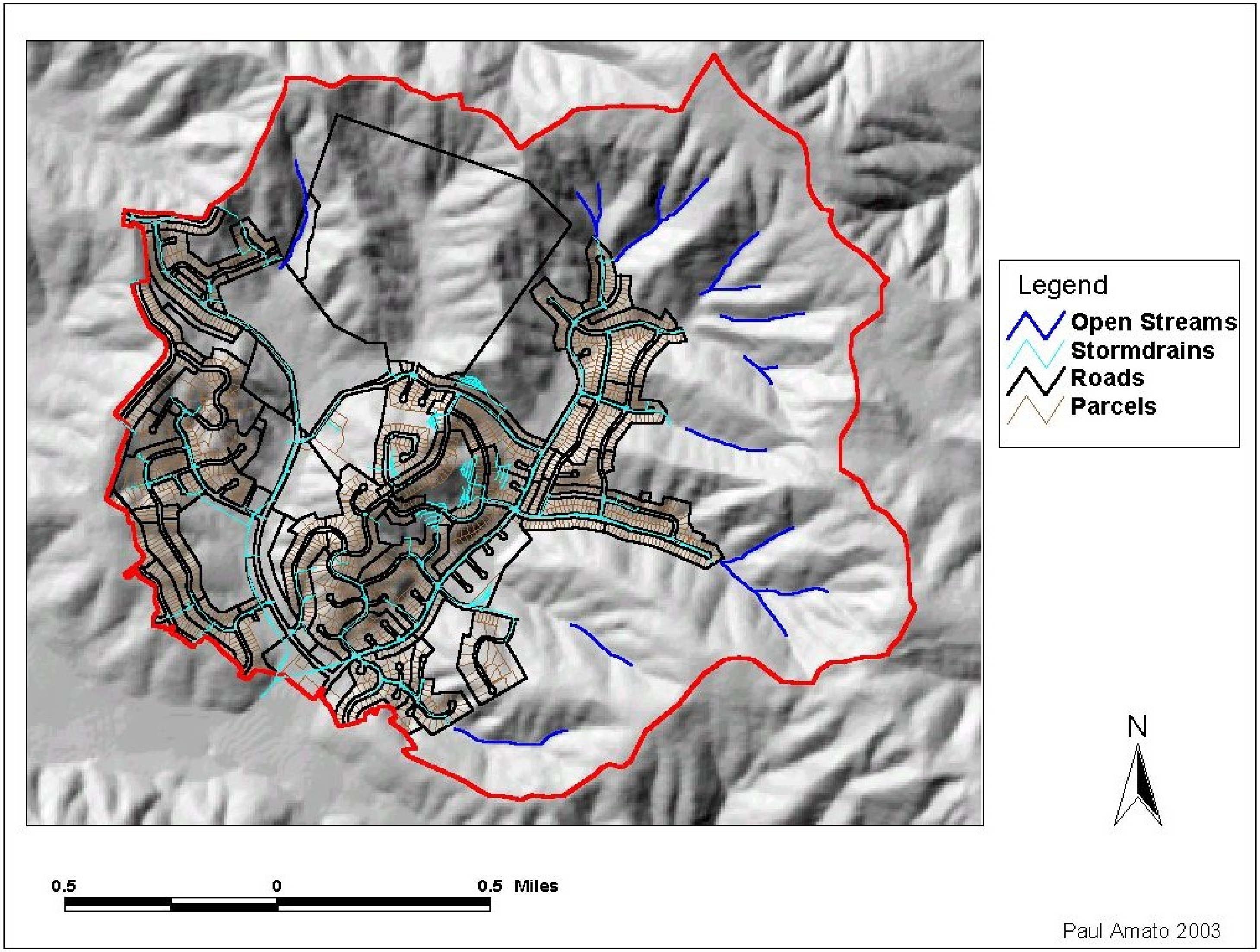

Figure 10. North Fork Stormdrain Network

Drainage density of the Middle Fork is approximately 4.5 miles/miles^2 (2.8 km/km^2) or 10.7 miles (17.2 km) of channel divided by 2.39 square miles (6.19 km^2) of drainage area. This may not be an exact representation of pre-European drainage density but it is assumed to be close since Middle Fork land use modifications to the channel length are relatively minor.

The North Fork channel network was historically about 9.4 miles (15.1 km) in length. This channel length divided by the 2.37 square mile (6.13 km^2) drainage area results in a drainage density of about 4.0 miles/mile^2 (2.5 km/km^2). Channel length has been increased dramatically by engineered drainage facilities. Currently, only about 2.8 miles (4.5 km) of open channel remains in the North Fork drainage confined to first and second order headward channels; only about 300 feet (91.4 km) of open channel remains between the downstream extent of the North Fork culvert and the confluence with the Middle Fork. In turn, approximately 24.6 miles (39.6 km) of culverts and drainage ditches and 6.28 miles (10.1 km) of road gutters have been added to the drainage network for a total length of 30.9 miles (49.7 km) of engineered drainage and a total North Fork drainage network of approximately 33.7 miles (54.2 km); this represents a drainage density of 14.3 miles/miles^2 (8.9 km/km^2) a 72% increase over natural conditions.

Increased impervious surface area and increased drainage density have significantly modified the hydrologic and turbidity responses of the North Fork. These modifications have caused an increase in bank erosion downstream of the Middle and North Fork confluence. The following analysis describes the data that supports these conclusions.

Rainfall

During the 2000 water year, (the time of this study) rainfall records at San Pedro Valley Park measured 40.72 inches (1034.3 mm). Howard (1982) reported that mean annual precipitation in Pacifica was 25 inches (635 mm) with the majority of rain falling between the months of October and April. Forty-two years of recorded rainfall had exceeded this amount 18 times. The USACE (1998) used 13 nearby gages to estimate mean annual rainfall of 33 inches (838.2 mm) ranging from 23 inches (584.2mm) at the coast to 38 inches (965.2) at the ridge tops. Twenty-one years of daily rainfall records at San Pedro Valley Park indicate that mean annual precipitation is 38.2 inches (970.3 mm). Based on these reports, rainfall during the 2000 water year was higher than previous averages and about 10% above the average derived from the Park data, the longest continuous record in the watershed.

Rain data were collected for this study using a tipping bucket rain gage installed on the ridge top of each sub-watershed from February through May and November through June respectively. Simultaneous rain data collection occurred at the Park, and the Middle and North Forks from February to May only. A comparison of data for the Middle and North Forks and San Pedro Valley Park shows that monthly totals were consistently highest on the Middle Fork and lowest on the North Fork (Figure 11). Additional months when only Park and North Fork rain data were available are consistent with this pattern. On average, from February through May, rainfall in the Middle Fork was approximately 31% greater than the North Fork and 17% greater than the Park. The Park gage measured 17% greater than the North Fork gage. Monthly variability can be seen in Table 1. Though the data are compared over a short period of time, it appears that the Park rain gage is a good indicator of average rainfall for the Middle and North Fork drainages. Additional years of data are needed to confirm this.

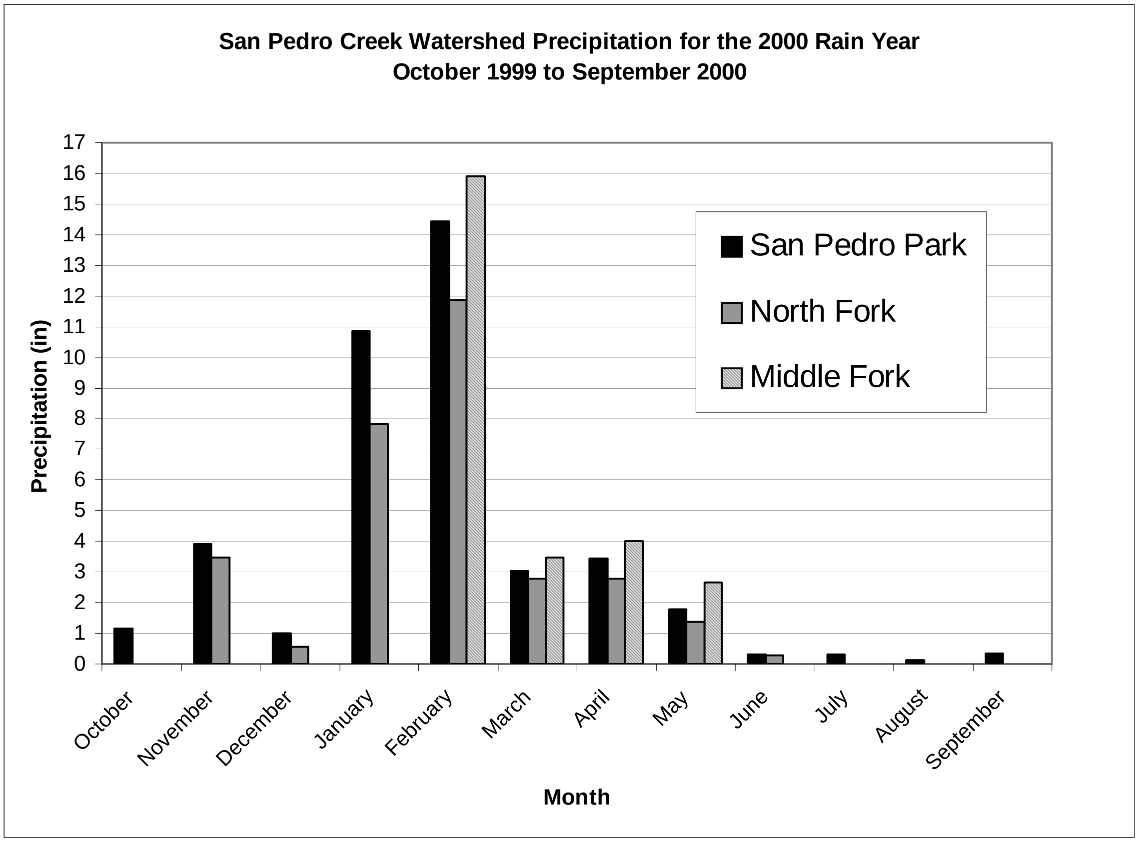

Figure 11. Monthly Rainfall Comparison for Three Rain Gages

Month	MF > Park	MF > NF	Park > NF
February	9.40%	25.40%	17.70%
March	13.20%	19.40%	8.30%
April	14.50%	30.61%	18.90%
May	33.00%	48.20%	23.00%
Average	17.50%	30.90%	16.97%

Table 1. Monthly Rainfall Comparison Showing Percent Greater by Gage

Daily and monthly rainfall recorded at the Park during the 2000 water year can be seen in Figure 12. The wettest months by far were January (10.86 inches (274.3 mm)) and February (14.4 inches (365.8 mm)). January 24 was the wettest day with nearly 4.5 inches (114.3 mm) of rain, approximately 60% to 75% of the estimated rainfall that fell in less than 30 hours in 1982, causing 475 landslides throughout Pacifica.

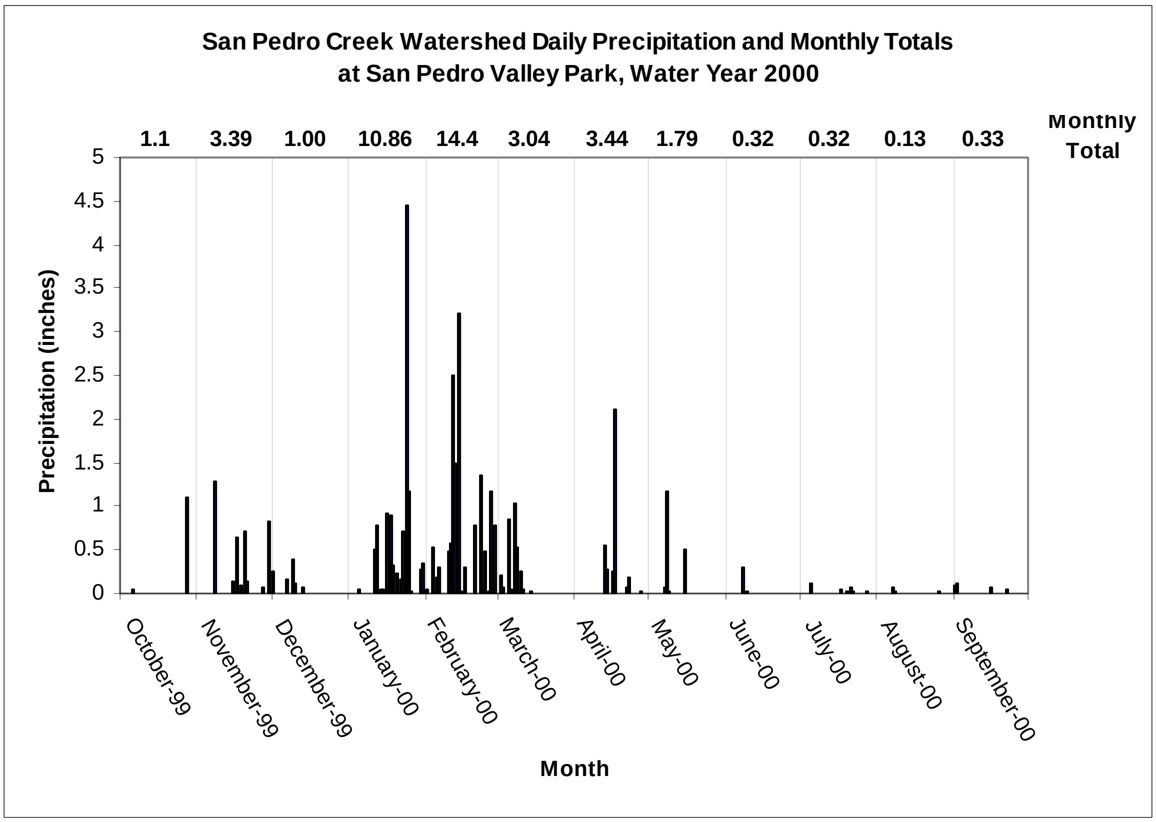

Figure 12. Daily and Monthly Precipitation at San Pedro Valley Park, 2000 WY

Figure 13 shows daily rainfall for all three gage sites during the month of February, which was selected for additional analysis of rainfall, and storm response because it was the only month in which all the in-stream gaging stations and rain gage tipping buckets were in simultaneous operation. Rainfall, stage (to estimate discharge), and turbidity were all collected from January 30 to February 23, 2000. Of the 24 days where precipitation was measured at all three rain gages, the Middle Fork was wettest on 14 days, the Park on 13 days, and the North Fork only once. This seems to be consistent with the differences in measured monthly totals supported by the observation that coastal storms typically move in from a southwesterly direction, stall over the Middle Fork and then over the Park before reaching the North Fork watershed. Rainfall data appears to indicate that duration and total rainfall are weaker by the time most systems reach the North Fork.

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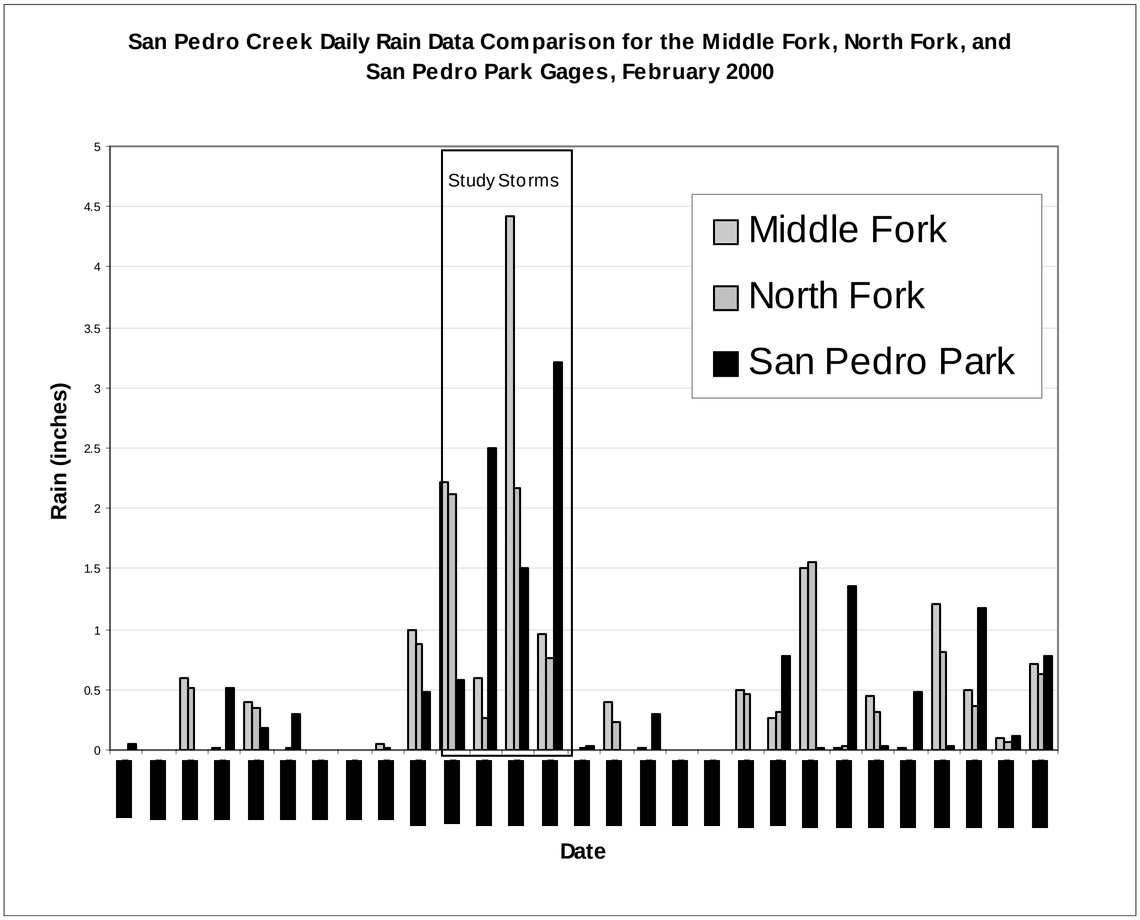


Figure 13. Daily Rain Comparison for the Month of February, 2000

The four highest rainfall days of February are represented on Figure 13. From February 11 to February 14, three distinct storms were delineated based on a lapse between a recorded rainfall event at the Middle and North Fork gages. The three storms of February 11, 13, and 14 were selected for further analysis of channel response and are described later in this section. Combined rainfall from the three storms totaled 8.2 inches (208.1 mm) at the Middle Fork, 7.8 inches (198.1 mm) at the Park and 5.3 inches (134.6 mm) at the North Fork. Time between storms averaged 9.5 hours in the Middle Fork and 13 hours in the North. This was considered adequate time for the peak of the hydrograph to recede significantly, especially in these smaller, steep drainages. Lag-to-peak times recorded by Leopold (1991) in several drainages in the San Francisco Bay Area were consistent with this.

February 11 Storm Rainfall

As shown in Figure 14, the February 11 storm lasted for approximately 10 hours and resulted in 2.2 inches (55.9 mm) at the Middle Fork gage and 2.1 inches (53.3 mm) at the North Fork. In each of the three storms, rainfall started earlier in the Middle Fork and ended about the same time in both drainages. On the 11th, rainfall intensity was steady for about the first five hours, peaked two hours later, and ended three hours after that. The most significant difference, when comparing the two gages, was the intensity during the third to last hour of the storm when the Middle Fork dropped 50% and the North Fork hardly dropped at all. Discharge readings are included in Figure 15 for a subsequent discussion of measured discharge.

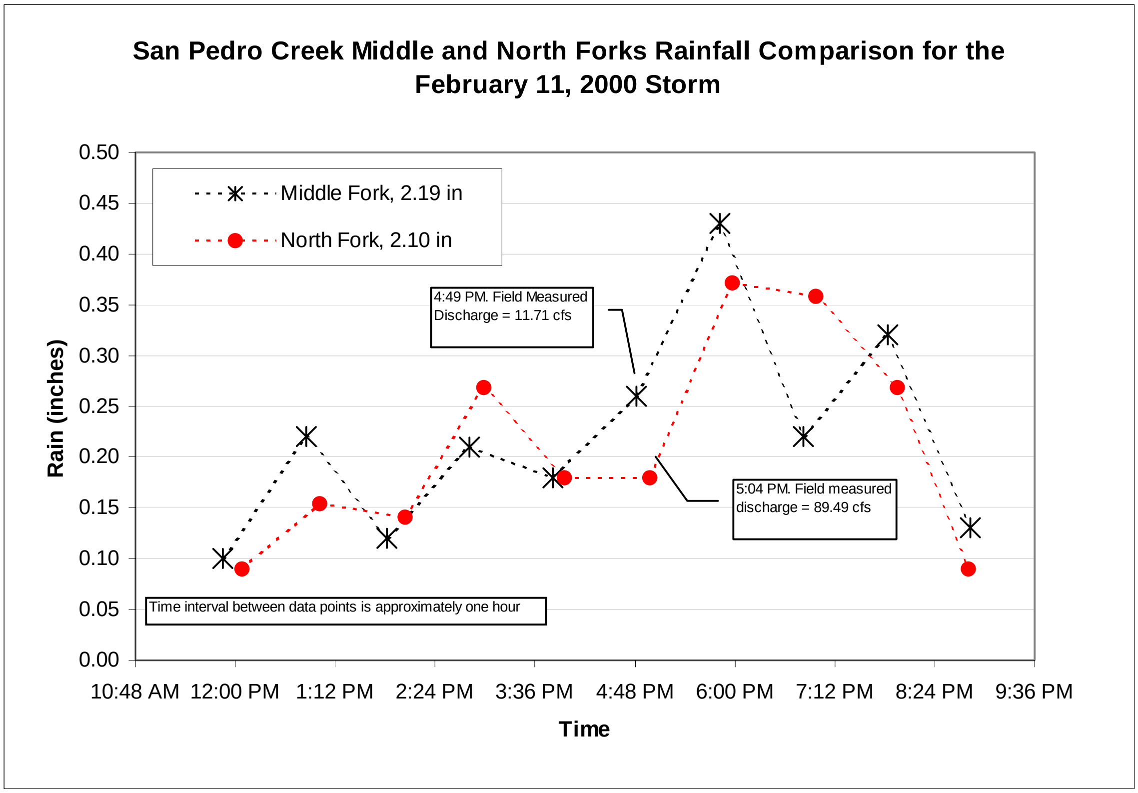


Figure 14. Rainfall Intensity and Duration for the February 11, 2000 Storm

February 13 Storm Rainfall

The February 13 storm lasted approximately 21 hours, resulting in 4.48 inches (113.8 mm) of rain in the Middle Fork, twice the 2.23 inches (56.6 mm) in the North Fork. This storm was 2.3 times longer than the February 11 storm, resulted in more rainfall, and measured significantly different rainfall totals at both gages. Rainfall intensity of the North Fork was noticeably less than that of the February 11 storm. Peak intensity was about the same for the Middle Fork.

Rainfall distribution on the 13th was similar to the earlier storm in that it was steady for most of the event, followed by a significant peak prior to ending. Specifically, rainfall was steady for about the first 12 hours, peaked over the next five, and ended four hours later (Figure 15).

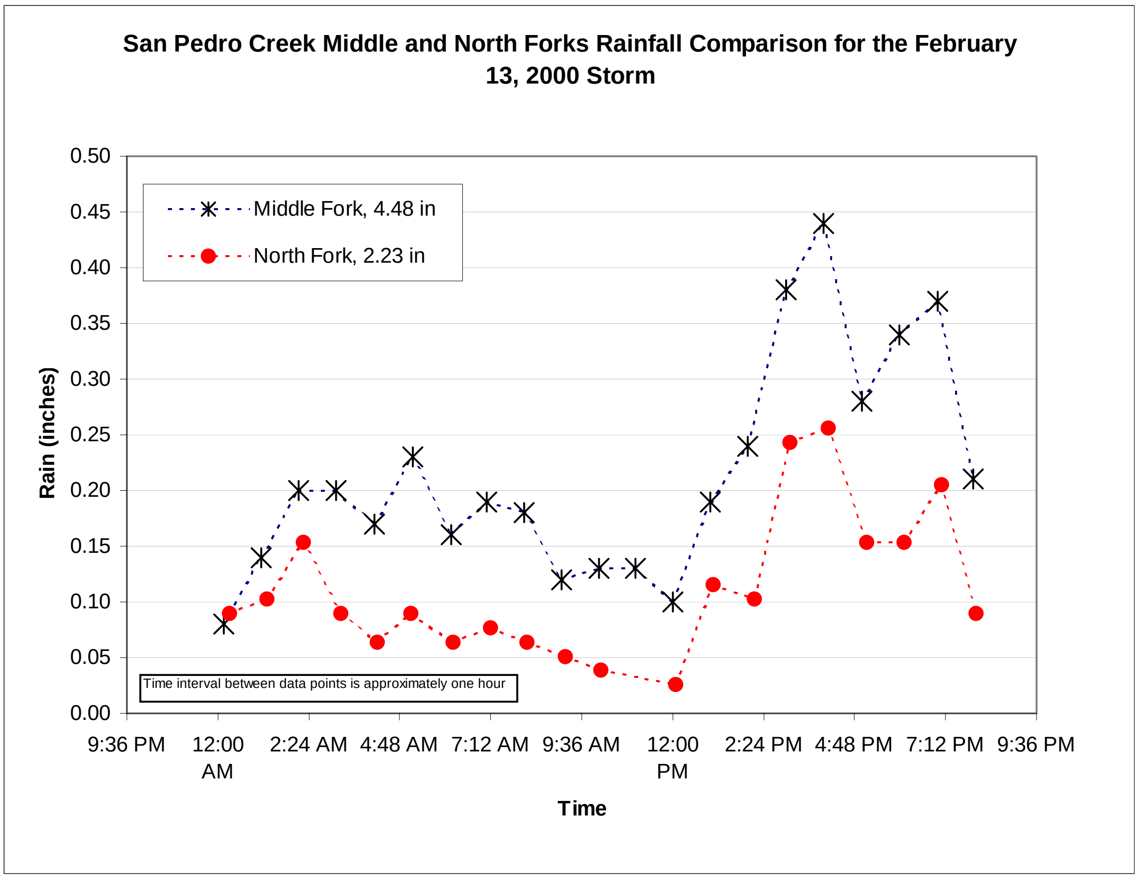


Figure 15. Rainfall Intensity and Duration for the February 13, 2000 Storm

February 14 Storm Rainfall

The February 14 storm lasted 5 hours in the Middle Fork and only four in the North Fork, with rainfall totals of 0.92 inch (23.4 mm) and 0.74 inch (18.8 mm) respectively. In both storms, rainfall intensity was greatest at about the middle of the storm (Figure 16). This storm was much shorter than the two previous, resulting in much less overall rain. Peak rainfall intensity of the Middle Fork was very similar to the February 11 storm and February 13 storms. Peak intensity in the North Fork was about average the February 11th and 13th.

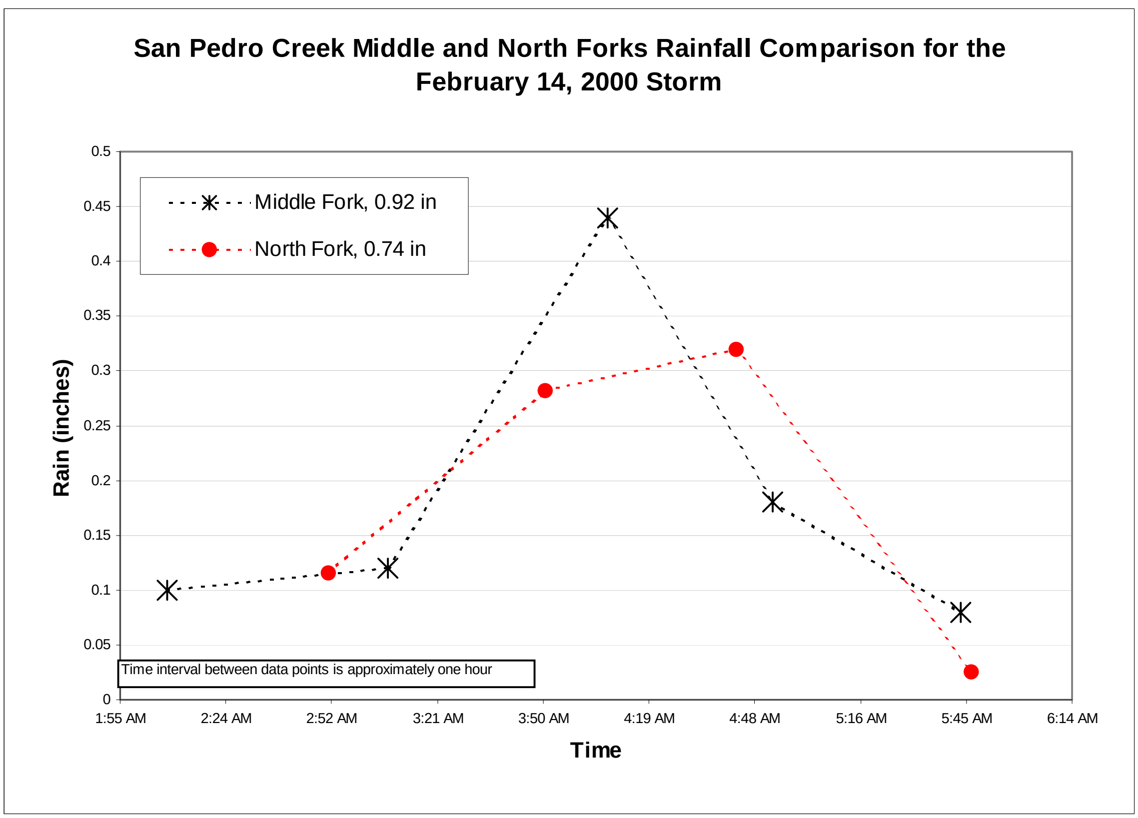


Figure 16. Rainfall Intensity and Duration for the February 14, 2000 Storm

Overall, the three measured storms exhibited notable similarities and differences both between individual events and between watersheds. During each storm there was similarity in the distribution of rainfall for both the Middle and North Fork watersheds. Cumulative rain values were similar in both watersheds for only the first storm, and greater in the Middle Fork for the two later events. Peak hourly rainfall intensities were similar in the Middle Fork for all three events and exceeded the North Fork each time. Intensities were similar for both watersheds during the first and third storm and two times greater in the Middle Fork for the second storm.

In comparing each storm event, rainfall distribution was similar for the first two storms. All three storms differed in length. Cumulative rainfall also varied with the exception of the first and second storm experiencing the same rainfall in the North Fork. Intensity was also similar for all three storms with the exception of a lower value in the North Fork during the second storm.

Field Measured Discharge

Discharge was measured at the Middle and North Fork gage stations eight times between November 6, 1999 and February 27, 2000. This data were used to establish the relationship between real discharge and the continuous stage measurements at the gage stations. Accuracy of this relationship was limited by the low number of discharge measurements over a small range of flows but it was considered sufficient to provide an estimate of continuous discharge during the study period. Figure 17 shows daily rainfall by gage location and measured discharge at the Middle and North Fork stations. Middle Fork rain data were not available for the first four discharge measurements as this period predates installation of the rain gage tipping bucket. North Fork rain data were not available until November 7. Data from the beginning of the rainy season were only available for the Park gage. Discharge measurements were not taken during this time but rainfall was recorded for the North Fork and the Park equaling 9 inches (228.6 mm) and 12 inches (304.8 mm) respectively. Because field measured discharge was not measured from November 22, 1999 to January 28, 2000, this period is not represented.

November Discharge Measurements

The first four discharge measurements were taken early in the rainy season and indicate that there was no discernable increase in base flows for either fork. The first recording occurred on November 6, 1999 after only 1.17 cumulative inches (29.7 mm) of rain had been measured at the Park. The fourth measurement on November 21 occurred after 4.45 cumulative inches (113 mm) of rain. Middle Fork discharge is consistently higher than the North Fork drainage, which can be attributed to greater groundwater or spring fed inputs. Consistently low base flows in both watersheds are expected during this time due to the increased soil infiltration potential following the dry season. Relatively dry soils are much more capable of absorbing the first few rains, preventing surface runoff or significant increases in groundwater inputs

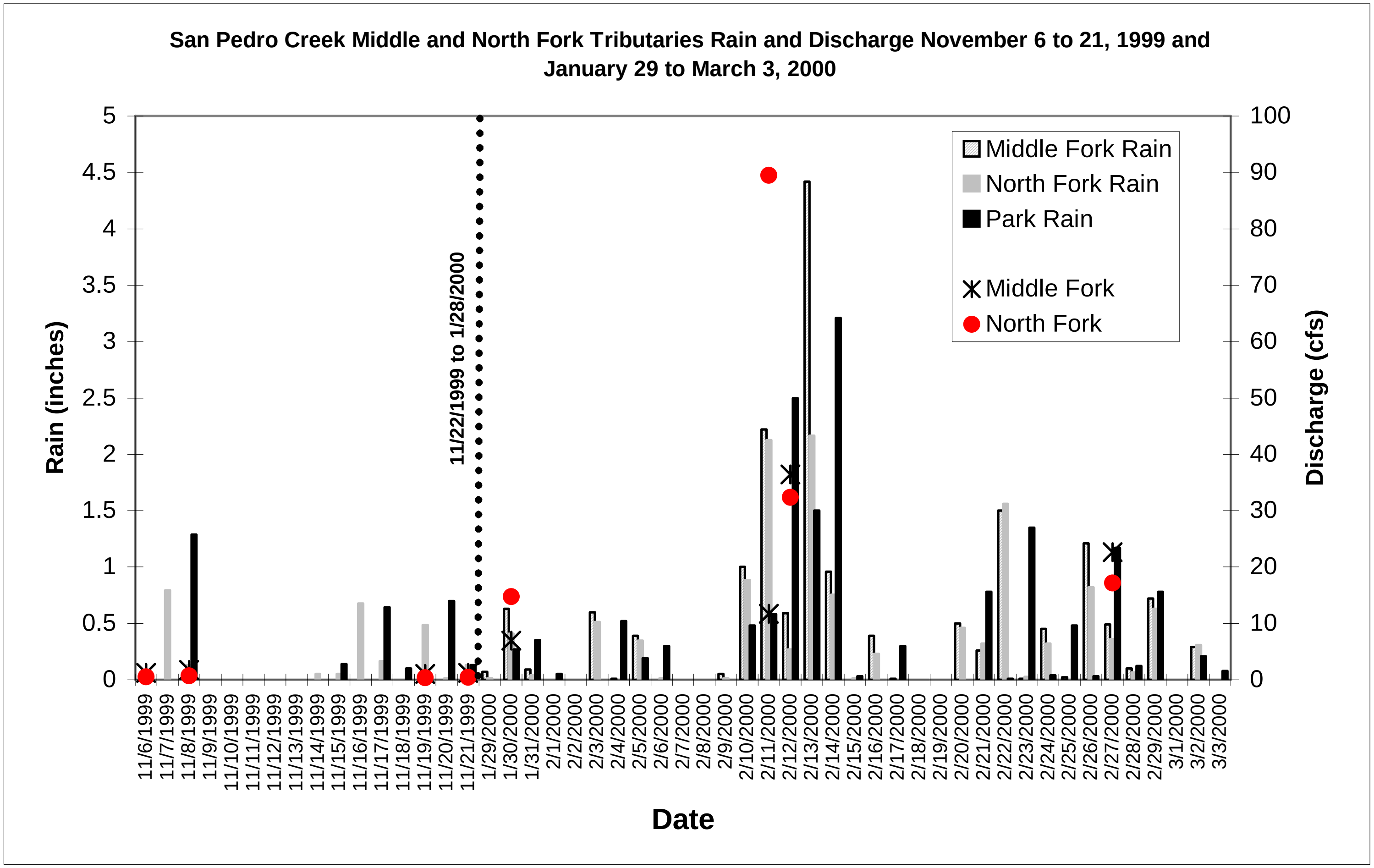


Figure 17. Daily Rainfall and Periodic Field Measured Discharge

January 30 Discharge Measurements

By the fifth discharge measurement on January 30, 16.58 inches (421.1 mm), or nearly 41% of the water year rainfall had been recorded at the Park; 4.5 inches (114.3 mm) were recorded on January 24th alone. It is likely that antecedent wetness in the drainages was enough to produce surface runoff as well as subsurface inputs to the channel, resulting in increased base flows. Rain was falling at the time discharge was measured at 14.78 cfs (0.42 cms) in the North Fork. By the time discharge of 6.92 cfs (0.2 cms) was measured in the Middle Fork, rain had stopped for approximately one hour. Presumably, the North Fork discharge was almost double that of the Middle Fork due to increased runoff reaching the gage via impervious surfaces and engineered conveyance, at the time the discharge measurement was recorded.

February 11 Discharge Measurements

The sixth discharge measurement taken on February 11coincides with one of the three selected study storms. Figure 18 shows a significant difference in the discharge readings of both forks, with 11.71 cfs (0.33 cms) in the Middle and 89.49 cfs (2.53 cms) in the North. Both readings were taken while it was raining; Figure 14 shows measured discharge values relative to the rainfall distribution and intensity of the storm event. Nearly half the water year precipitation had occurred by this time, providing sufficient antecedent wetness to increase runoff rate and volume in both drainages.

Middle Fork rainfall equaled 2.11inches (53.6 mm) for the hours between February 10 at 12:00 AM and February 11 at 4:49 PM. Discharge was 40% greater than the previous reading on January 30 and can be attributed to increased groundwater input, and channel response to the concurrent storm-related rainfall runoff.

North Fork peak discharge exceeded that of the Middle Fork by approximately 7.5 times, exceeding the early findings of Carter (1961) who found that peak discharge of an urbanized area might exceed pre-urbanized conditions by 2 to 6 times. Steep hills and a highly culverted channel network may contribute to the even greater exceedence. As described previously, rainfall had been steady for several hours prior to discharge measurements, allowing significant runoff to reach the gage stations. As with January 30 values, North Fork discharge is expected to be greater due to increased runoff rate and volume from impervious surfaces and engineered conveyance.

Rainfall intensity in the North Fork watershed was significantly greater during the February 11 storm when compared to the February 13 storm. Six hours into the 10-hour storm event, more rain had fallen in the North Fork than had fallen in 13.5 hours on the 13th. Intense rainfall falling on steep hills and paved surfaces of the North Fork drainage resulted in far greater discharge than in the unurbanized Middle Fork. Photos 8 and 9 compare the energy and discharge of the North Fork and the Middle Fork during this event. The North Fork photo shows water backing up against the two remaining 4-foot tall reinforced-concrete energy dissipaters (three have fallen during earlier flows). Super critical flows can be seen in the form of a reverse wave (hydraulic jump) in the Middle Fork just downstream of the gage station. The Middle Fork may appear to have greater flows, but the photo was taken from in the channel; North Fork velocities were far to high too stand in.

Photo 8. North Fork Culvert flows During the February 11, 2000 Storm

Photo 9. Middle Fork Super Critical to Sub-critical Transition Flows During the February 11, 2000 Storm (view looking downstream)

February 12 Discharge Measurements

February 12 discharge measurements were much more similar in the two watersheds: 36.41cfs (1.03 cms) in the Middle Fork and 32.37 cfs (0.92 cms) in the North Fork. Most of the rain fell in the morning, ending approximately 2.5 hours prior to the North Fork measurement and 2.75 hours prior to the Middle Fork. The discharge values were likely similar because of significant differences in lag time. Flow in the Middle Fork was continuing to respond to the morning rainfall and to a lesser degree, to rainfall during the previous two days. Continued inputs from the unurbanized upper watershed and groundwater seepage into the pipes may also have elevated the discharge value in the North Fork close to that of the Middle Fork. Contrary to the February 11 measurement taken during rainfall and active runoff, the February 12 discharge in the North Fork was probably lower because a significant portion of the runoff had already passed the gage.

North Fork discharge measured on February 12 was only 36% of that measured on the 11th, and illustrates the relationship of rainfall intensity and duration to impervious surfaces as well as the principle of lag-to-peak. At the time the measurement was made on the 12th, the storm had dropped 0.93 inches (23.6 mm) of rain over a period of 12 hours, resulting in a discharge of 32.37 cfs (0.92 cms). The measurement on the 11th was made after 1.11 inches (28.2 mm) of rain had fallen in 6 hours, resulting in 89.49 cfs (2.53 cms). Greater rainfall in a shorter time interval before measurement, combined with the affect of recording discharge during rainfall, resulted in a much higher discharge measurement at the time of the February 11 recording.

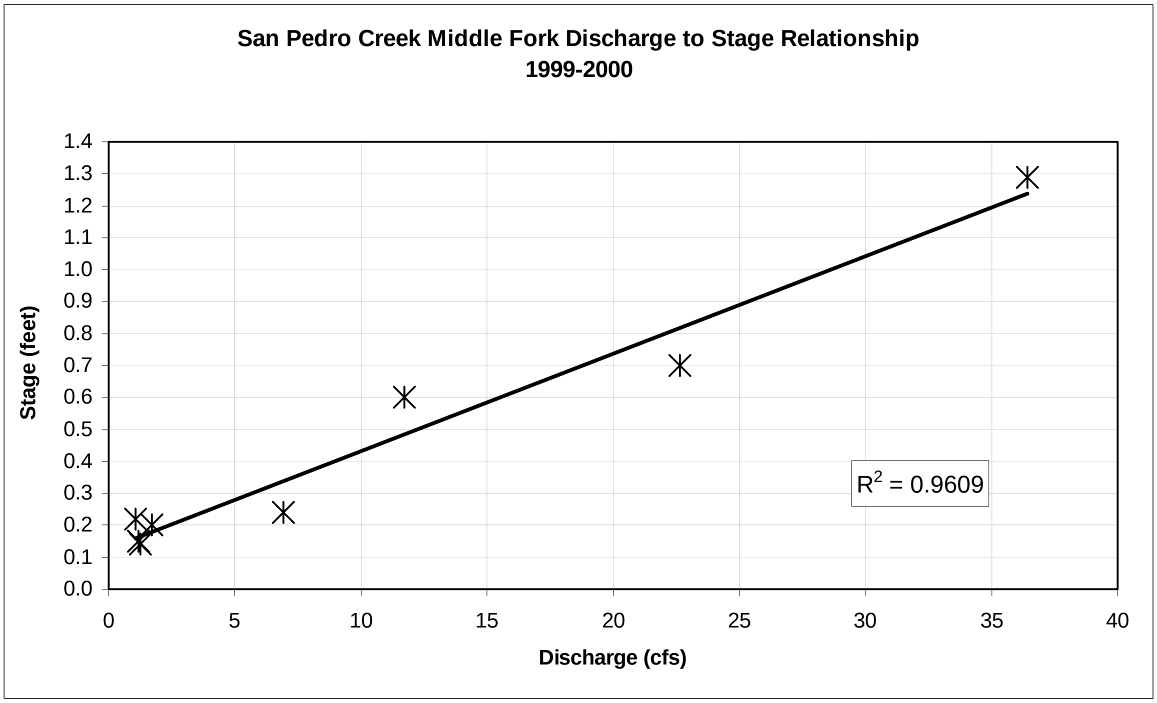
February 27 Discharge Measurements

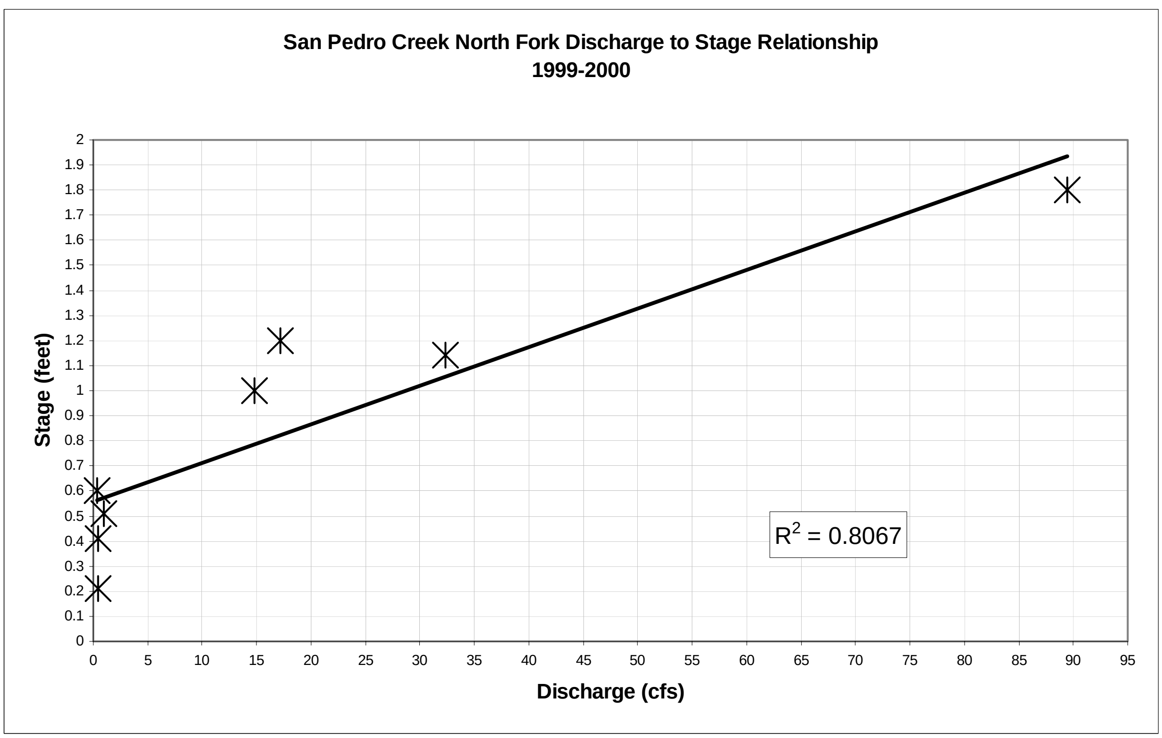
The eighth and final discharge measurement occurred on February 27, and found 22.63 cfs (0.64 cms) in the Middle Fork and 17.17 cfs (0.49 cms) in the North. The rainfall and discharge patterns are very similar to those of

February 12. The discharge values are lower due to less rainfall in the hours preceding the discharge recording.

Discharge to Stage Relationships

As described in the Methods section of this study, the relationship of measured discharge and stage was used to estimate discharge values for continuously logged stage (recorded in mA) measured at both gage stations. Discharge and stage were measured at the same time in the field and plotted to demonstrate correlations. For both locations, measured discharge increased with stage. Figures 18 and 19 show these relationships; this correlation yielded an r^2 of 0.96 in the Middle Fork and 0.81 in the North Fork. A weaker correlation in the North Fork may be caused by highly variable cross-sectional area and stage that can visibly change during the course of a reading. This is a direct result of increased “flashiness” in an urbanized system.





Figures 18 & 19. Middle & North Fork Relationship of Discharge and Stage

Storm Response

As described earlier, the three rainfall events of February 11, 13, and 14, 2000, were identified and analyzed for this study for the purposes of demonstrating how an urbanized watershed responds differently than an unurbanized watershed during storms. Rainfall totals, duration, and intensity of these storms were described above. The following discussion presents each event and considers relationships between rainfall, discharge, and turbidity. A summary of these measurements is provided in Table 2.

<u>February 11 Storm Response</u>

The February 11 storm represents a moderate event, producing about 2.2 inches (55.9 mm) of rain at the Middle Fork gage over a period of 10 hours. Figure 20 represents the period of time from storm initiation to just before the start of the next rainfall event. The storm graph clearly shows a relationship of rainfall to discharge. Discharge responded to rainfall 4.5 hours after the storm began and peaked in 10 hours. The lag-to-peak time, or time between peak rainfall and peak discharge was approximately 3.3 hours. Pre-storm discharge was 6.7 cfs (0.2 cms) eventually peaking at 51.2 cfs (1.4 cms). Average discharge for the duration of the graph equaled 31 cfs (0.9 cms). Discharge did not return to pre-storm levels due to contributions of runoff from the next storm event (not shown in the graph). The relationship of discharge to rainfall for this storm is indicative of anticipated hydrologic response in a small, steep, unurbanized watershed. The rising limb is steep and regular as runoff accumulates before reaching a peak and gradually returning towards pre-storm levels.

Turbidity levels rose in parallel with discharge during this event with periodic spikes. Pre-storm levels were 33 NTU and began to rise 3 hours after the start of rainfall. In-stream turbidity responded approximately 1.5 hours faster than discharge, probably because rainsplash erosion and overland transport carried enough fine sediment particles to the channel to show a measurable response in advance of a measurable change in discharge. Turbidity levels peaked at 247 NTU, 7 hours after the beginning of the storm, before falling again to previous levels. Turbidity and discharge peaked at about the same time, indicating that the lag time between peak rain and both peak discharge and peak turbidity was 3.3 hours for this event. Levels remained at or above 100 NTU from about 5:30 PM on February 11 to noon the following day. Average turbidity levels equaled 127 NTU. Consistently elevated levels of turbidity represent the various upland and instream sediment sources that contribute to the system during rainfall. Periodic spikes in turbidity occurred over the course of the falling limb of discharge. These spikes may be explained by increases in rainfall intensity, or bursts occurring after the storm peak, or by anomalous inputs of sediment from upstream bank erosion and upland slope failure.

The North Fork response to this storm, and to the following storms, is more difficult to interpret. As described previously, the flashiness of this drainage was immediately evident and required that the recording interval for stage (to estimate discharge) and turbidity be increased from every 10 minutes to every 5. As a result, twice as many data points are plotted for the North Fork during the same period to better represent the irregular patterns of discharge and turbidity response. Figure 21 plots rainfall, discharge, and turbidity from the beginning of the storm (11:08 AM) to just prior to the next rainfall. The storm was 10 hours in duration and resulted in 2.1 inches (53.3 mm) of rain. Though the range of values is significant, the general pattern of the North Fork, like to the Middle Fork, was to rise, peak, and fall to a level higher than pre-storm conditions.

Discharge first responded to rainfall at 11:18 AM, a period of only 10 minutes. Approximately 6.5 hours passed between the start of the storm and the initial peak of discharge. Peak discharge occurred three separate times concurrent with the period of peak rainfall. The highest recorded discharge was 170.8 cfs (5 cms). Pre-storm discharge was approximately 0.25 to 0.5 cfs. (0.007 cms to 0.01 cms). Peak values were recorded at 5:33 PM, 6:43 PM and 7:23 PM during the 2.5 hours of peak rain falling from 5:30 PM to 8:30 PM. Based on this observation, it appears that at this point in the storm, discharge response to increased rainfall was almost instantaneous. This is consistent with field observations that flows in the North Fork culvert increased rapidly with rainfall intensity. Average discharge was derived for the same time interval as the Middle Fork to allow for comparison. The average discharge was 40 cfs (1.1 cms). Discharge levels dropped almost immediately after rain stopped, but not to pre-storm conditions as might have been expected in such a flashy system. This may be due to continued upper watershed surface runoff and groundwater inputs to the system.

Like discharge, turbidity in the North Fork responded quickly. Pre-storm levels were very low and during the storm exceeded 50 NTU eight times, and 100 NTU only twice. A peak turbidity of 246 NTU was uniquely high for this storm event; the average turbidity value was derived for the same period defining the Middle Fork graph, and totaled 14.6 NTU. Relationships to discharge are apparent though not consistent. Turbidity levels can both increase and decrease with discharge, which seems to signify that concentrations of suspended matter in the water column increase or decrease with discharge. If sediment inputs are low (as expected in an engineered system), the mass of material in transport may remain relatively constant. Rapid fluctuations in discharge could cause rapid fluctuations in turbidity as flow increases dilute and flow decreases concentrate sediments.

The February 11 storm event and recorded responses of discharge and turbidity help demonstrate that the urbanized North Fork watershed and the unurbanized Middle Fork watershed behaved quite differently. Urbanization has not only greatly decreased the time it takes for the North Fork to respond to rainfall, it has resulted in an almost immediate response to increased rainfall intensity. Middle Fork discharge peaked after approximately 10 hours and had a lag-to-peak time of 3.3 hours. The North Fork discharge peaked after 6.5 hours and had an indiscernible lag-to-peak time. The North Fork is also much flashier, with higher variability in discharge. Average discharge is about 30% greater in the North Fork and peaks are almost three and a half times higher. Equal rainfall and duration resulted in very different channel responses with faster, more variable discharge response in the North Fork due to effects of impervious surface area on runoff.

Response in turbidity was also very different between the two drainages. The relationship of turbidity to discharge in the Middle Fork was direct and consistent, showing a nearly parallel response between the two. The North Fork was somewhat erratic, more a function of supply, dilution, and concentration. Average turbidity in the North Fork was only 14.6 NTU while the Middle Fork averaged 127 NTU, or 9 times greater, demonstrating that sediment sources are greatly reduced by impervious surfaces and engineered concrete channels.

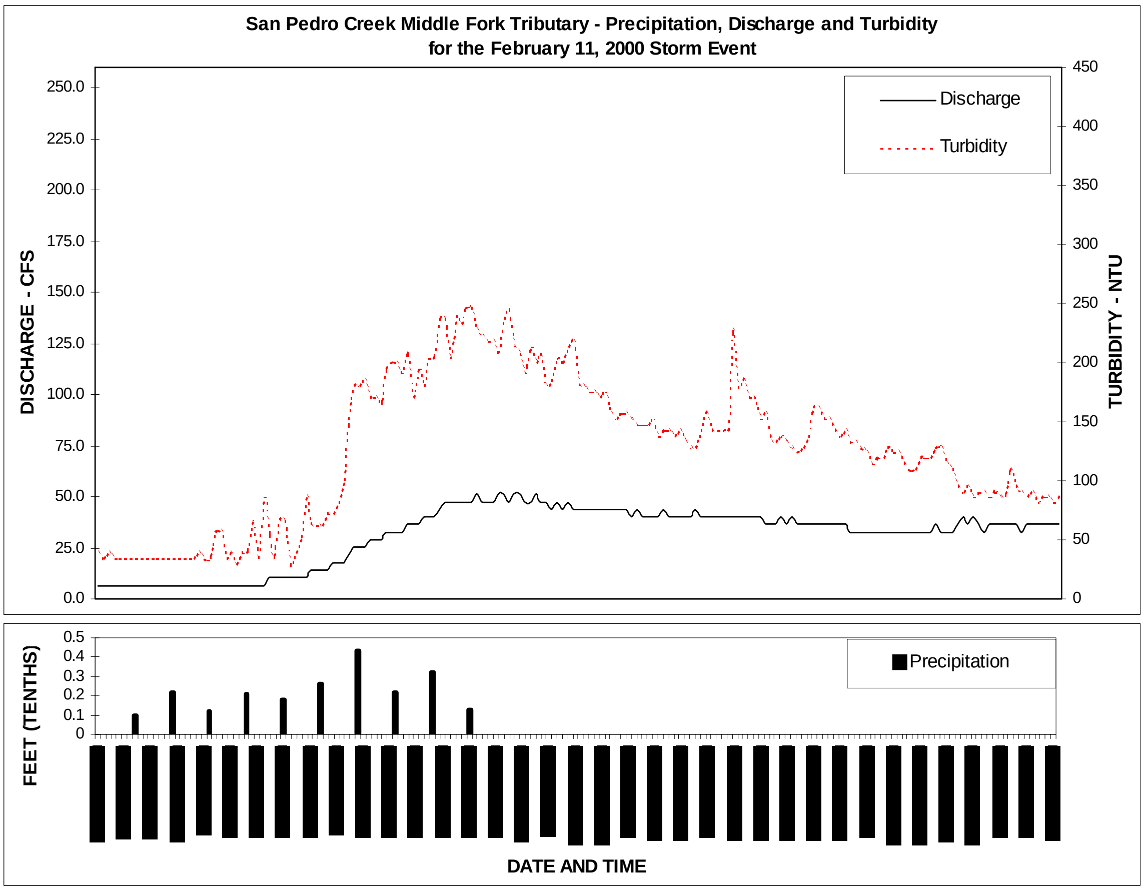


Figure 20. Middle Fork Rain, Discharge and Turbidity, February 11, 2000 Storm

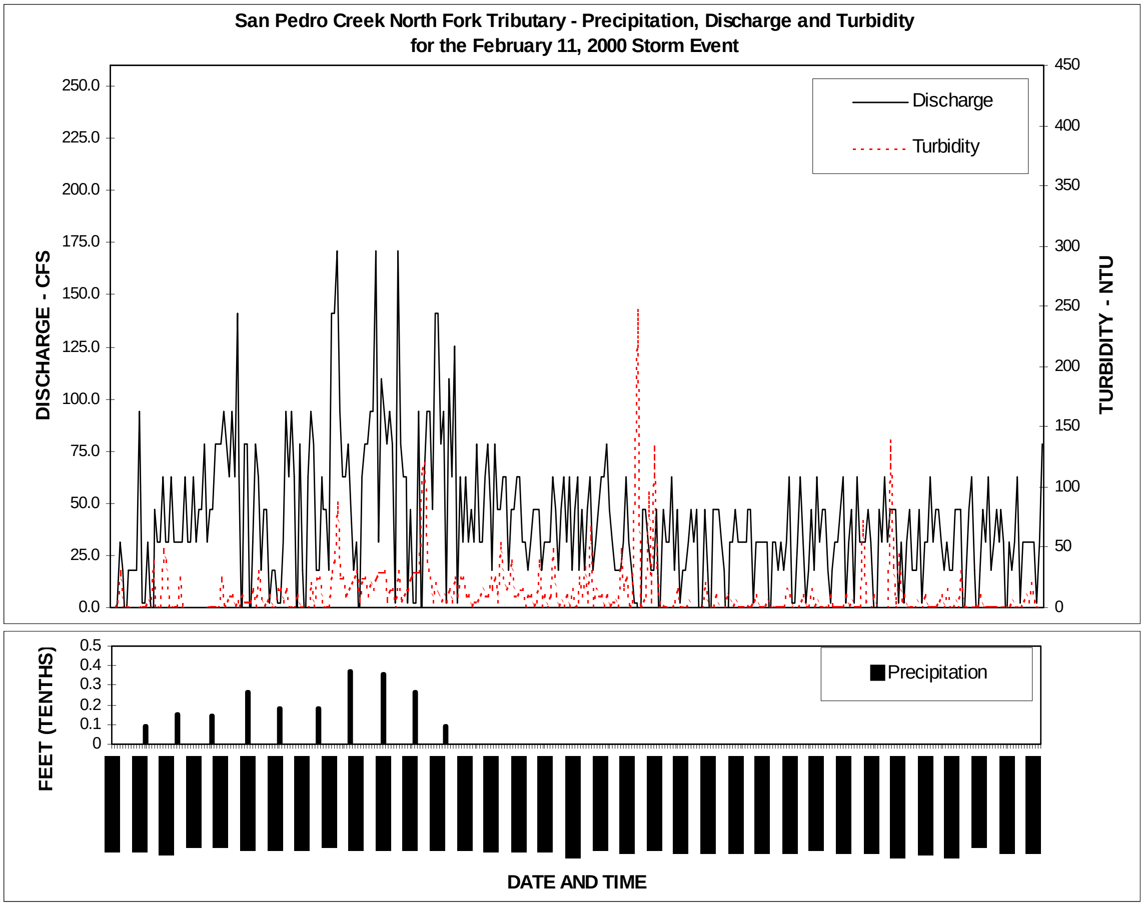


Figure 21. North Fork Rain, Discharge and Turbidity, February 11, 2000 Storm

February 13 Storm Response

This storm was relatively significant in size, lasting 21 hours and producing 4.5 inches (113.8 mm) of rainfall in the Middle Fork. Figure 22 depicts the event from the start of rainfall to immediately prior to the next rainfall episode. Like the February 11 graph, Figure 22 shows a clear relationship between rainfall and discharge. The first response of discharge occurred at 1:54 AM on February 13, almost 3 hours following the first recorded rainfall. Peak discharge did not occur for approximately 18.5 hours. Time between the peak rainfall and peak discharge was 4.75 hours. At the height of storm response, discharge rose from approximately 29 cfs to 130 cfs (0.8 cms to 3.7 cms). Average discharge during this event equaled 70 cfs (2 cms). Following the storm, discharge dropped to 81 cfs (2.3 cms) before responding to subsequent rainfall (not shown on the graph). This event was similar to the storm of February 11 in that the discharge plot shows a steady response to rainfall before peaking and falling. The most significant differences are that peak discharge took almost twice as long to occur and reached a level 2.5 times greater. These differences are a function of greater rainfall intensity during the storm of the 11th and greater duration and volume on the 13th and are representative of the hydrologic response expected for this watershed.

As with the previous storm, turbidity levels paralleled discharge for a significant portion of the event. Prior to rainfall and discharge response, turbidity ranged from 67 to 90 NTU. It did not show a consistent upward trend until 1:54 AM, when discharge also first responded. This immediate response of turbidity to discharge differs from the February 11 storm, which showed increasing turbidity in advance of discharge response. A possible explanation for this difference may be that with an increase in discharge comes the incipient motion of finer sediment particles causing turbidity in the water column to rise. The storm of the 11th may have shown a turbidity response in advance of discharge due to upland inputs transported by overland flow following drier conditions from February 6th to the 9th. The peak turbidity level was 385 NTU and did not occur for almost 12.75 hours after the storm began. Prior to this peak, turbidity had experienced an inverse relationship with discharge, which is very obvious on the graph. From 3:59 PM to 4:24 PM, turbidity levels suddenly dropped from 337 NTU to 100 NTU as discharge rose from 88 cfs to 92 cfs (2.5 cms to 2.6 cms). At 6:04 PM, discharge reached 118 cfs (3.3 cms) and turbidity rose again to 271 NTU. When peak storm discharge of 130 cfs (3.7 cms) occurred at 8:04 PM, turbidity fell again to 0 NTU. At 9:54 PM, after the peak, discharge fell to 100 cfs (2.8 cms) turbidity again rose to 304 NTU. As described earlier for the North Fork, this appears to be a result of dilution. Assuming that sediment inputs were relatively stable, the peak discharge may have produced enough flow to dilute turbidity in the water column to a negligible level but without mobilizing enough sediment to maintain high turbidity as happened in the earlier storm. After peak discharge, water levels began to recede fairly quickly and turbidity exceeded levels prior to the rapid decline. Reduced discharge and lower water surface elevation may have been enough to increase turbidity concentrations, and initiate sapping of saturated bank sediments, causing additional increases in turbidity levels.

The North Fork storm shown in Figure 23 indicates that like the Middle Fork, the event lasted for approximately 21 hours. Unlike the storm of February 11, when both drainages experienced similar rainfall, only 2.23 inches (56.6 mm) was recorded at the North Fork gage, less than half the rainfall on the Middle Fork. Discharge is more difficult to interpret for this event. As expected, rainfall caused an immediate response in discharge, and a rapid fall and rise is evident at approximately 4:00 AM and 11:00 AM concurrent with reduced and paused rainfall. But the decline in discharge between 2:48 PM and 8:18 PM is puzzling as this same interval saw the highest rainfall intensity of the storm. Based on other observations discharge should peak during this period. One possible explanation could be that the storm system was most intense in the upper watershed near the rain gage location. If the storm were stalled over the upper watershed during this time period, rainfall might have measured high but runoff rates and volume might have been retarded by unpaved and vegetated ground surfaces with greater infiltration potential. Additional rain gage data from other locations in the drainage could support this hypothesis. Another explanation could be that the sensor was temporarily fouled for an unknown reason. The peak discharge was 200 cfs (5.8 cms), which occurred in a little less than 9 hours from beginning of rain, and the lag-to-peak time is not apparent based on the data. Average discharge equaled about 35 cfs (1 cms). This value is suspect due to the unusual period of decline in discharge during increased rainfall.

Again, turbidity was highly variable, often rising with reduced discharge and falling with increased discharge. This inverse relationship is especially evident during the 5-hour period when rainfall increased and discharge was generally lower than expected. This result could support the theory that the storm system was isolated over the vicinity of the rain gage and that lower discharge increased turbidity concentrations in the water column. The peak turbidity of 247 NTU was very unique and occurred during the unexplained period of high rainfall intensity and low discharge. Average turbidity equaled 34 NTU.

A review of discharge and turbidity during this second storm further demonstrates how urbanization has altered the response of the North Fork. Though the storm duration was equal at both gages, rainfall in the Middle Fork was twice that of the North gage. Even with greater rainfall, initial discharge response to rain did not occur for hours in the Middle Fork while the North Fork responded right away. Discharge in the Middle Fork rose gradually over the course of the storm, peaked and fell following the end of rainfall. North Fork discharge was highly variable and responded immediately to rainfall. The lag-to-peak time in the Middle Fork was approximately 4.75 hours, while at the North Fork it was undetectable. Clearly, impervious surfaces and storm drains have reduced the North Fork response time dramatically.

Peak stage at both gage stations was almost equal but it should be noted that the Middle Fork cross-section is approximately double the width of the North Fork pipe. Equal stage within the wider cross-section suggests that greater discharge was conveyed in the Middle Fork. But peak discharge was 45% greater in the North Fork. This could be attributed to increased velocities due to a lower roughness coefficient in the smooth concrete pipes. Conversely, average discharge in the Middle Fork was more than double that of the North Fork. Higher rainfall, antecedent wetness, increased groundwater inputs, and higher pre-storm flow conditions in the Middle Fork are potential explanations.

Peak and average turbidity in the Middle Fork were higher than the North Fork. Average turbidity was over 5 times greater demonstrating that sediment inputs from the earthen channel and natural watershed surfaces was much more substantial.

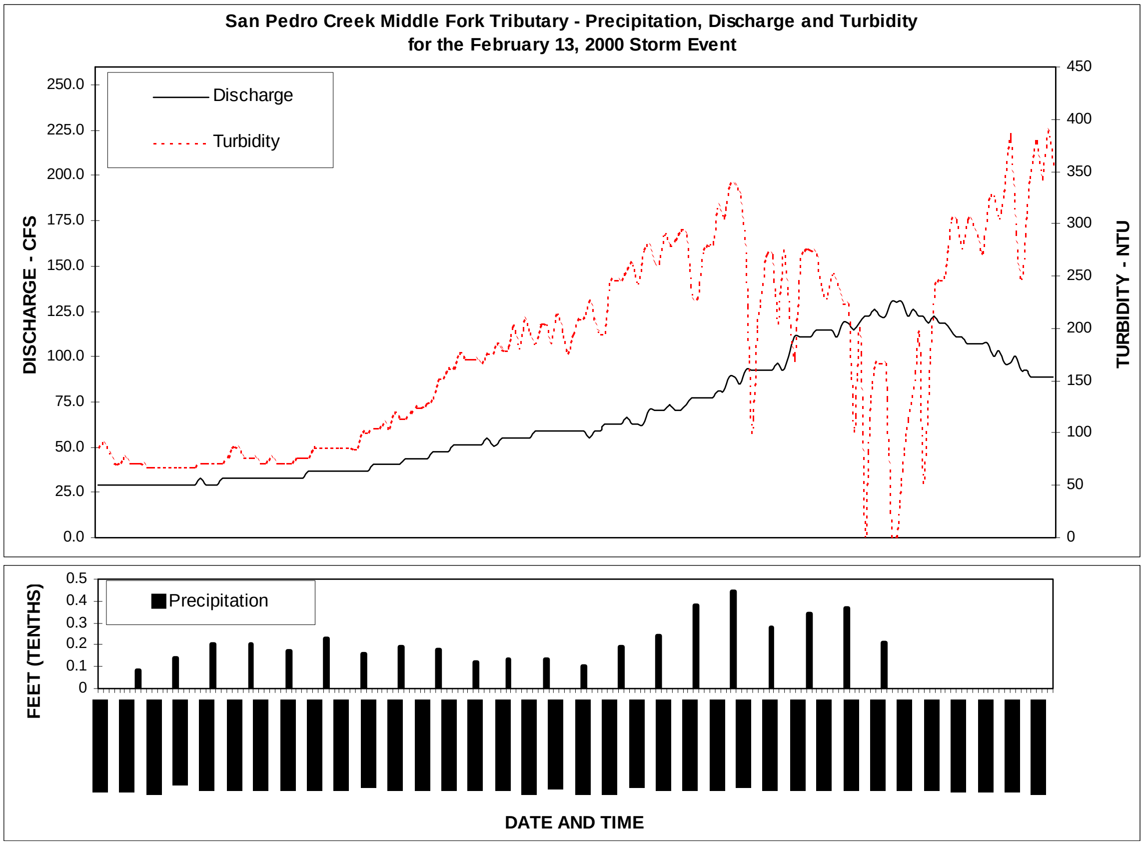


Figure 22. Middle Fork Rain, Discharge and Turbidity, February 13, 2000 Storm

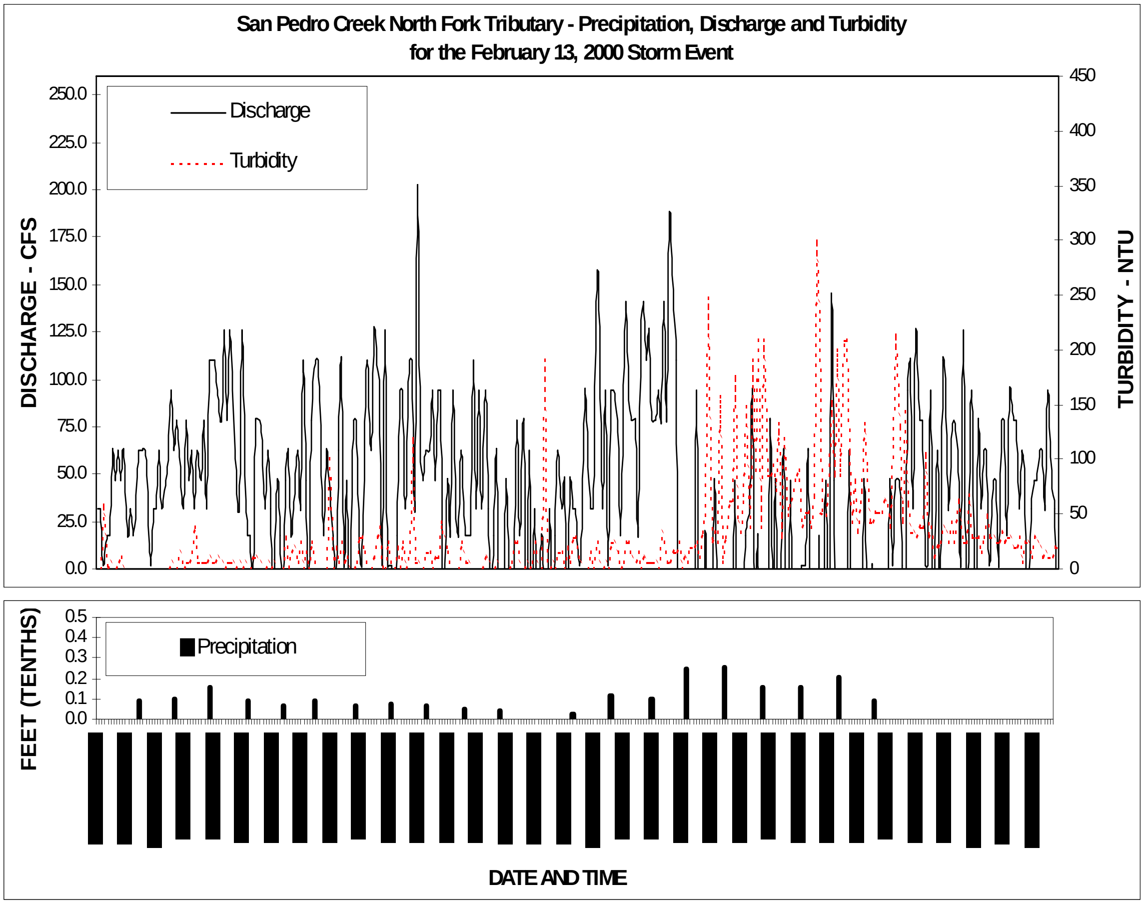


Figure 23. North Fork Rain, Discharge and Turbidity, February 13, 2000 Storm

February 14 Storm Response

Figures 24 and 25 portray the final study storm that occurred on February 14, producing only 0.92 inches (23.4 mm) of rain over 5 hours in the Middle Fork and 0.74 inches (18.8 mm) over 4 hours in the North Fork. The additional hour of record suggests that the storm paused over the Middle Fork before moving north. During this relatively small event, discharge first responded about 2 hours following the first rainfall record at the Middle Fork rain gage. Similar to the previous two storms, the North Fork discharge responded immediately. Lag-to-peak in the Middle Fork was about 1.25 hours and only 10 minutes in the urbanized North Fork. The Middle Fork gage station measured a peak discharge of 107 cfs (3 cms). The North Fork was significantly higher measuring 265 cfs (7.5 cms). Average discharge in the Middle Fork was again about double that measured in the North Fork.

Peak and average turbidity remained lower in the urbanized drainage with a peak of 251 NTU and average of 19.9 NTU. The Middle Fork measured a peak of 427 NTU and an average of 321.7 NTU. Average turbidity was 16 times greater in the Middle Fork.

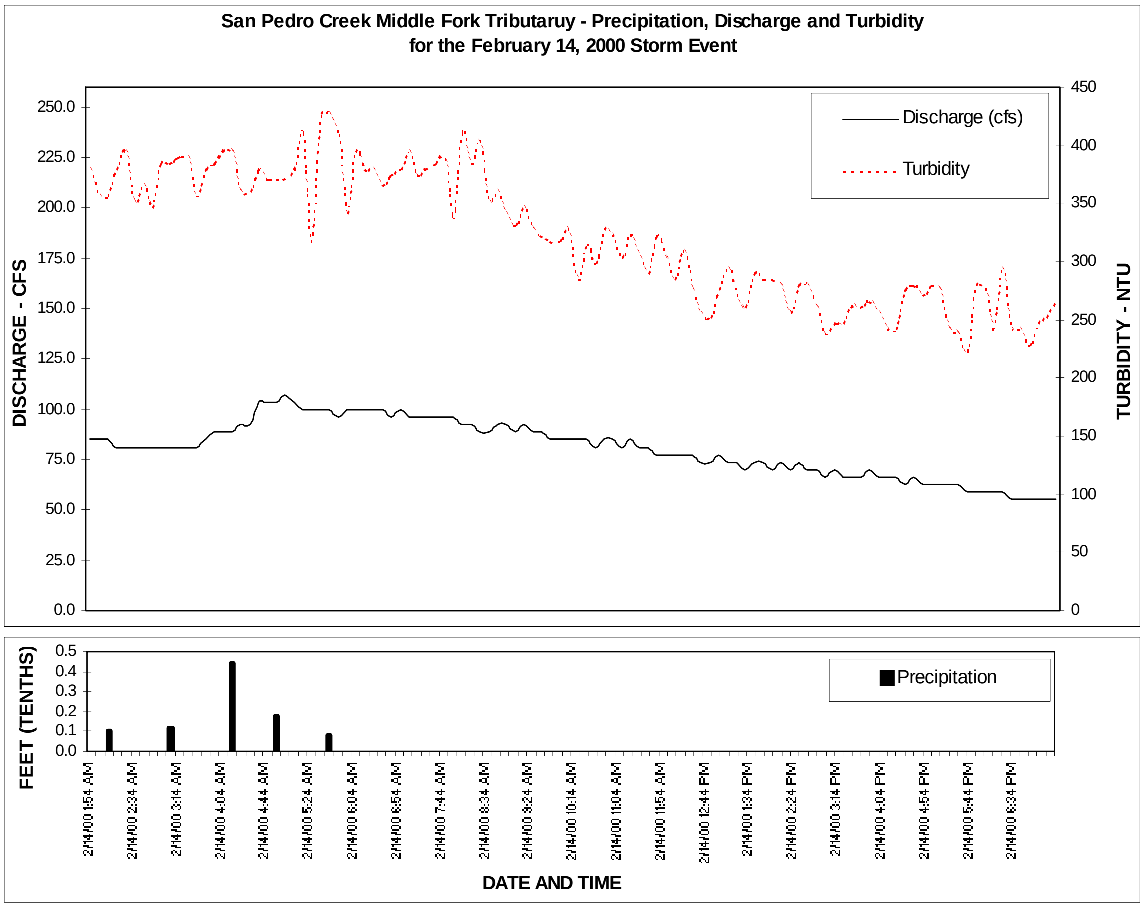


Figure 24. Middle Fork Rain, Discharge, and Turbidity, February 14, 2000 Storm

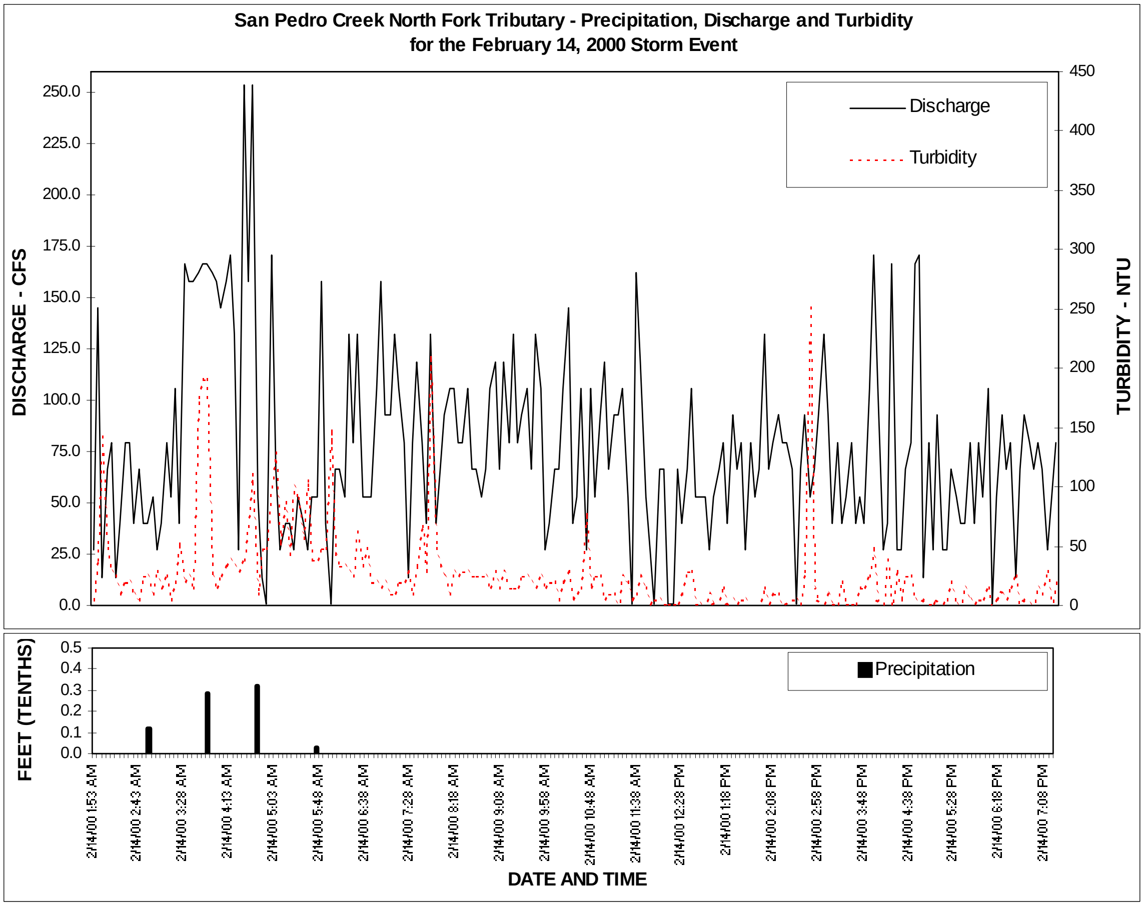


Figure 25. North Fork Rain, Discharge, and Turbidity, February 14, 2000 Storm

Storm Response Summary

The influence of urbanization on storm response was dramatic during the study storms. Perhaps the most obvious influence is on lag-to-peak time, which ranged from 1.25 to 3.3 hours in the Middle Fork compared to almost instantaneous response in the North Fork. Initial increases in discharge also responded to rainfall almost immediately in the North Fork while the Middle Fork took from 2 to 4.5 hours. For the three events, peak discharge was 35% to 75% greater in the North Fork and occurred more frequently. Average discharge was higher in the North Fork during the first storm but was exceeded by the Middle Fork during the last two due to increased runoff from antecedent wetness conditions, and higher groundwater inputs.

Paved surfaces and concrete pipe channels have also had a significant influence on the availability of sediment supply and delivery to the urbanized system. Figure 26 helps demonstrate that there is a dearth of turbidity in the North Fork when compared to the more natural conditions of the Middle Fork. Peak turbidity was generally higher in the Middle Fork as was average turbidity, which measured 10 times higher than the North Fork during the three storms.

Having established that the influence of urbanization has been a measurable alteration to the response of discharge and turbidity (a surrogate for sediment) the logical next step is to consider how the physical channel itself is affected.

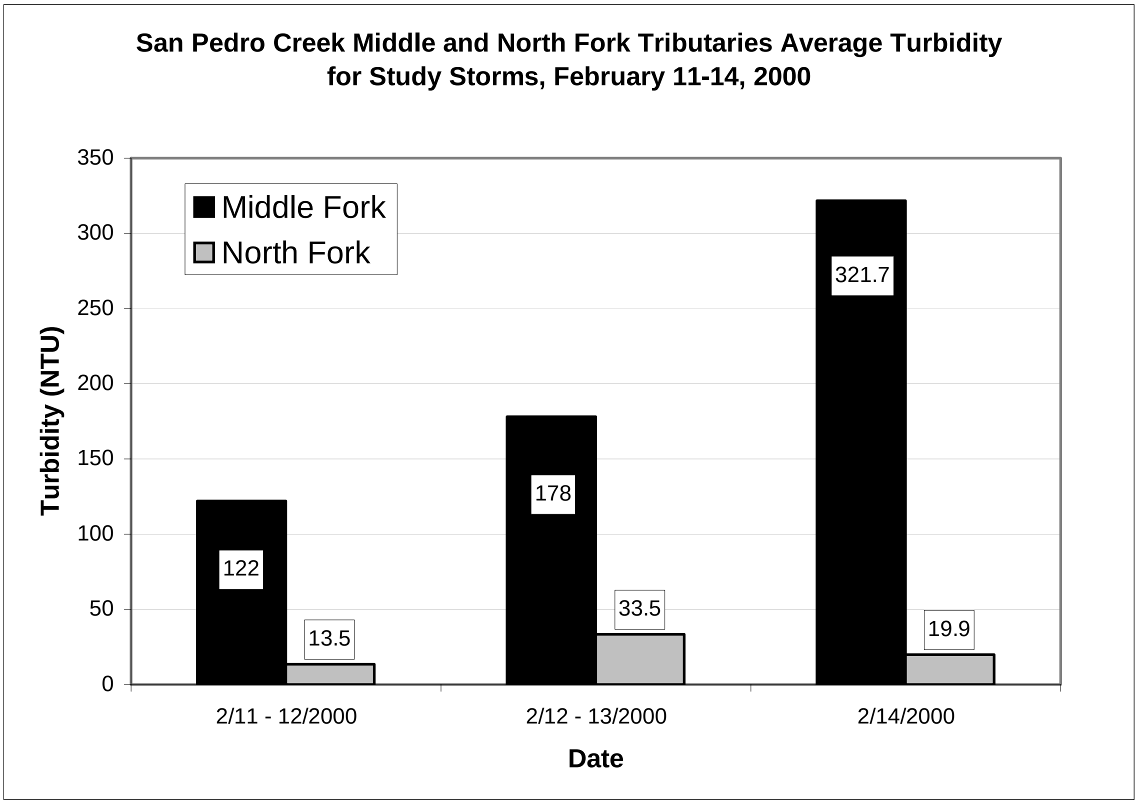


Figure 26. Average Turbidity for the Three Study Storms

Storm and Watershed	Total Rain (inches)	Storm Length (hours)	Discharge Response to Rain (hours)	Lag-to-Peak (hours)	Peak Stage (feet)	Peak Discharge (cfs)	Average Stage (feet)	Average Discharge (cfs)	Peak Turbidity (NTU)	Average Turbidity (NTU)
February 11, Middle Fork	2.19	10	4.5	3.3	1.74	51	1	31	247	127
February 11, North Fork	2.1	10	0.6	0.05	3.74	171	1.3	40	246	14.6
February 13, Middle Fork	4.48	21	3	4.75	4.2	130	2.3	68	385	178
February 13, North Fork	2.23	21	0	0	4.3	200	1.1	35	247	34
February 14, Middle Fork	0.92	5	2	1.25	3.5	107	2.7	80	427	322
February 14, North Fork	0.74	4	0	0.6	5.5	265	1.3	40	251	19.9

Table 2. Summary of Characteristics for the Three Study Storms

Channel Response

Profile and Cross-Section

An accurate determination of long-term trends in channel erosion and aggradation requires several years of observation similar to Leopold's research from 1953 to 1972 in the Watts Branch (Leopold 1973). This study included only two consecutive years of channel cross-section and profile surveys in the Middle and North Forks. As a result, observations from this data are limited to short-term, seasonal change. The 1,200 linear feet (365.8 m) Middle Fork Profile, beginning at Oddstad Boulevard and ending at the first upstream San Pedro Park bridge, experienced both incision and aggradation during the 2000 water year. Figure 27 shows the thalweg profile for 1999 and 2000 as well as the location of surveyed cross-sections and the stream gage station. According to the profile, this reach of the Middle Fork experienced localized incision and aggradation but was not particularly dominated by either. Minor deposition occurred just downstream of the Park bridge, downstream of the Middle and South Forks confluence, and in short sections near the stream gage station. Incision was evident up and downstream of the confluence, and for most of a 375 linear feet (114.3 m) section ending just downstream of cross-section #1. Overall, the bed did not exhibit a strong trend in either direction.

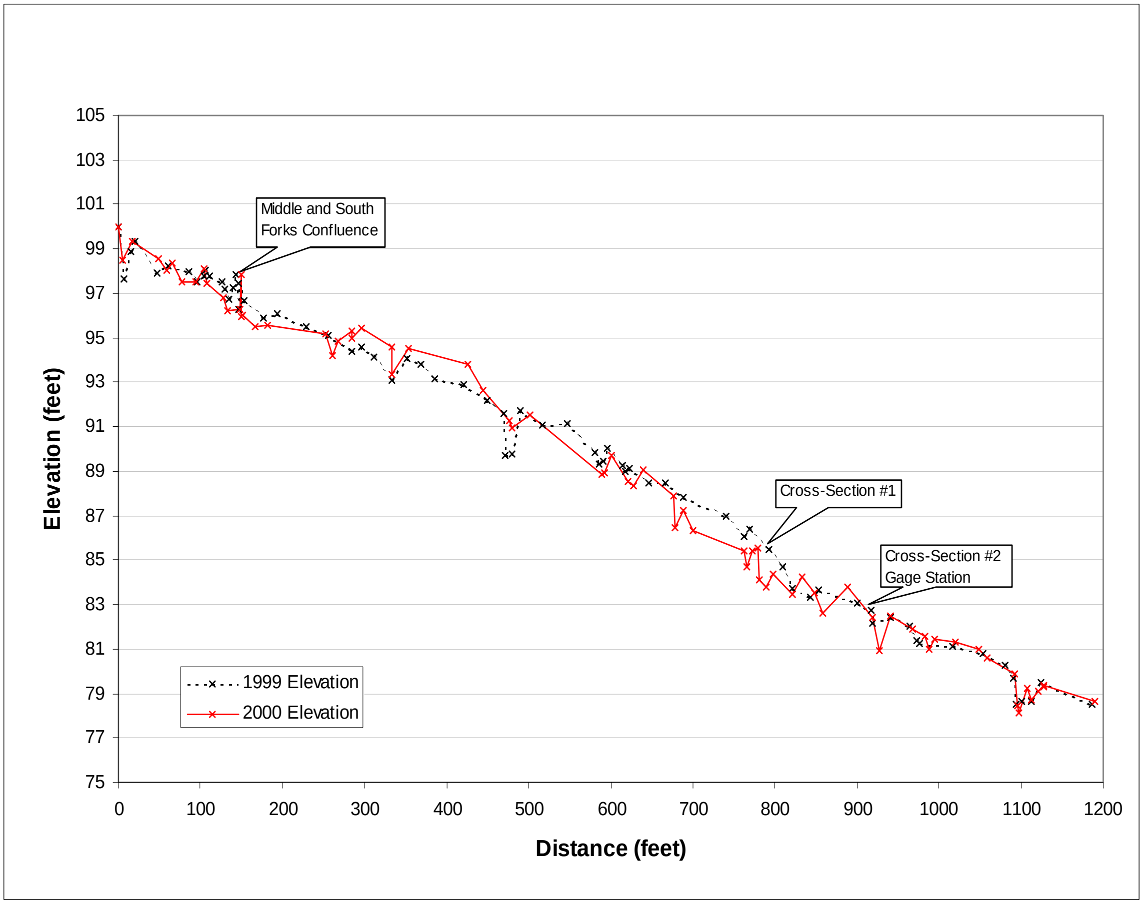


Figure 27, Middle Fork Longitudinal Profile, 1999 and 2000

Figures 28 and 29 show two surveyed cross-sections which confirm channel response to wet season flows during the study period. Cross-section #1, located about 100 feet (30.5 m) upstream from the gage station, was in a section of stream where the channel appeared to be incising through sandstone and conglomerate bedrock. Active channel incision at the cross-section is evident in Photo 10. Large storms reported in 1956, 1962, and 1982 (Collins et al. 2001) moved large amounts of sediment into the channels, covering the bed with alluvial deposits. Tree cores taken from young alders growing on a gravel deposit at the upstream end of the Oddstad Bridge showed them to be 18 years old, indicating they colonized the gravel bar following the 1982 storm. The Middle Fork appears to be incising through these deposits at this location. The area of vertical and lateral incision shown in the cross-section is consistent with incision shown at the same location on the profile and in the area of incision shown in the photo.

Photo 10. Middle Fork Cross-Section #1 - Showing Incision

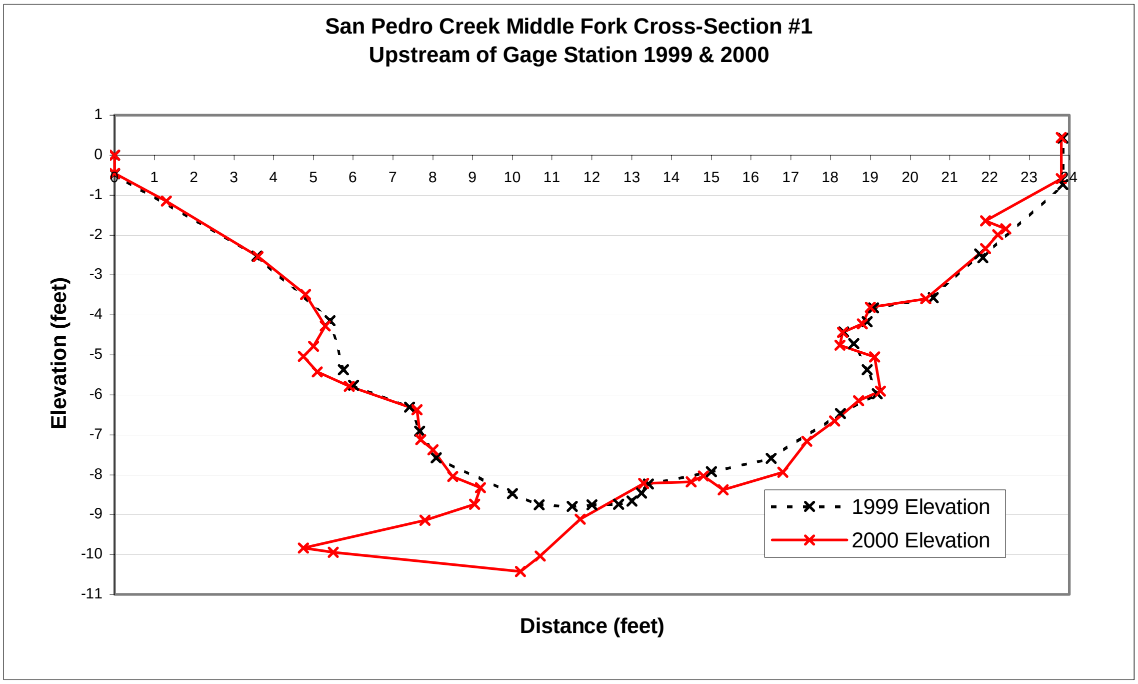


Figure 28. Middle Fork Cross-Section #1, 1999 and 2000

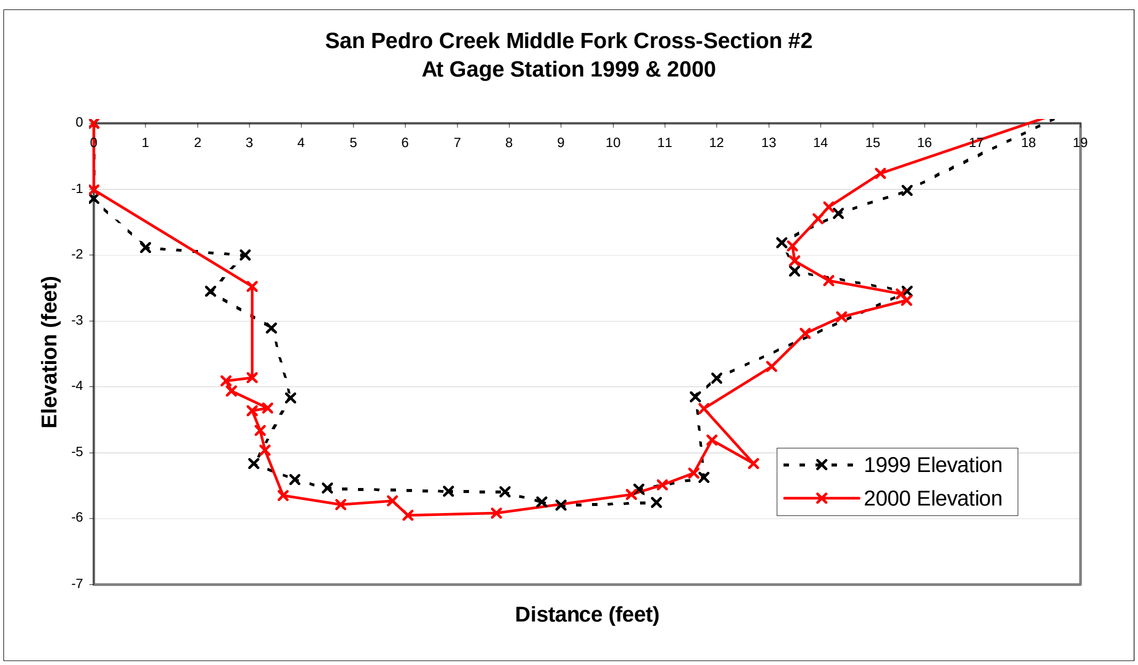


Figure 29. Middle Fork Cross-Section #2, Stream Gage Station, 1999 and 2000

Cross-section #2 at the stream gage station was relatively stable during the 2000 water year. Only minor bank erosion and bed incision (on the order of a few inches) occurred. A small gravel bar continued to develop immediately upstream of the gage station as seen in Photo 11, perhaps due in part to minor flow obstruction from the gage itself. Like cross-section #1, channel change at cross-section #2 at the stream gage is also consistent with the profile and photo.

Photo 11. Middle Fork Cross-Section #2 Looking Downstream at Stream Gage

During the 2000 water year, the Middle Fork, in the vicinity of the stream gage, exhibited signs of incision and deposition. Maximum recorded incision and aggradation were approximately 1.7 feet (0.45 m) and 1.6 feet (0.49 m) respectively. The Middle Fork appears to be in a state of minor adjustment as seen by continued bank and bed erosion.

The North Fork longitudinal profile was surveyed for 350 linear feet (106.7 m). Of that, only the downstream 250 feet (76.2 m) are earthen channel; much of this is armored with concrete rubble of undetermined origin. The upper 100 feet (30.5 m) are in the 8 feet (2.4 m) diameter concrete pipe. The entire reach length begins at the stream gage station and ends just downstream of the confluence with the Middle Fork as shown in Figure 30. This short reach of the North Fork experienced both incision and aggradation during the 2000 water year. All pools and a 25 feet (7.6 m) long riffle show some deepening with a range of 0.2 foot to 0.7 foot (0.06 m to 0.2 m). Aggradation was less both longitudinally and vertically with a few localized sections exhibiting accretions of 0.3 foot to 0.6 foot (0.09 m to 0.18 m). The most notable deposition was at the location of the one North Fork cross-section (Figure 31), which captures both the Middle and North Fork at their confluence

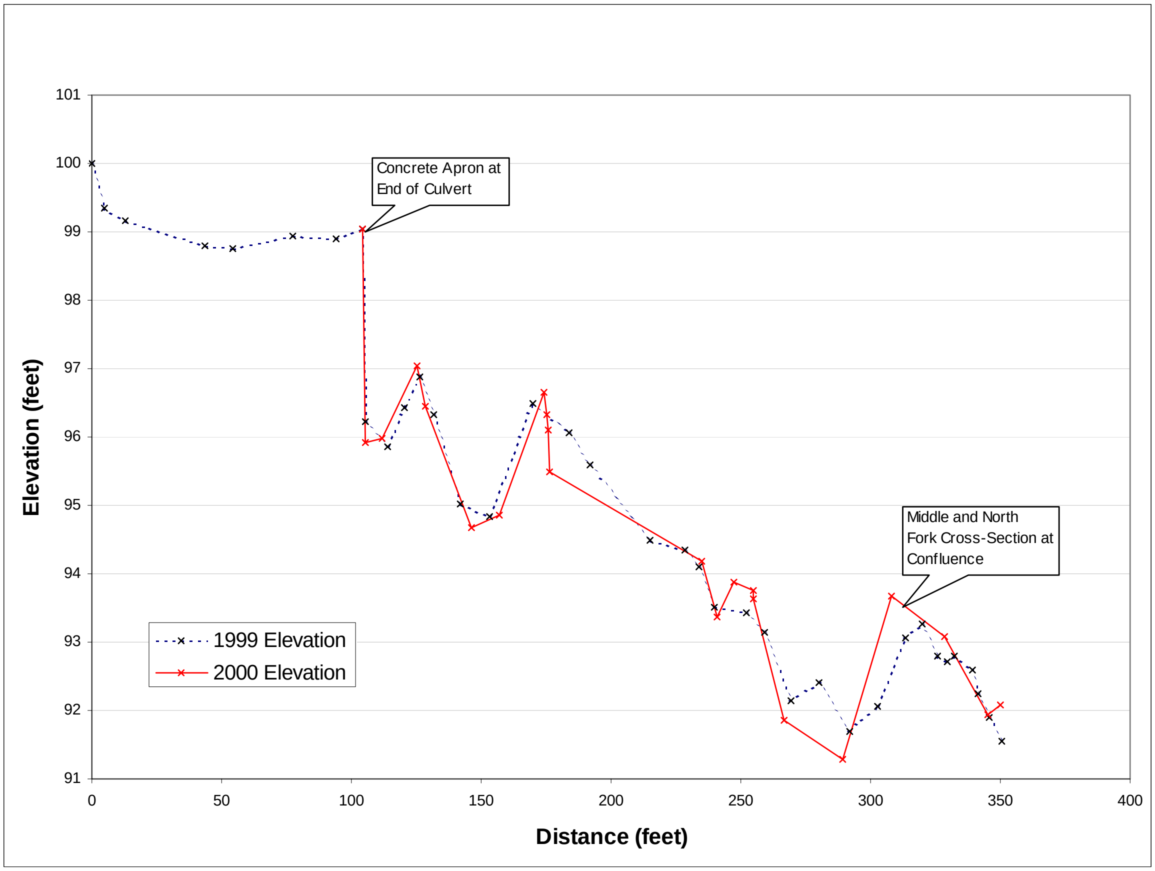


Figure 30. North Fork Longitudinal Profile, 1999 and 2000

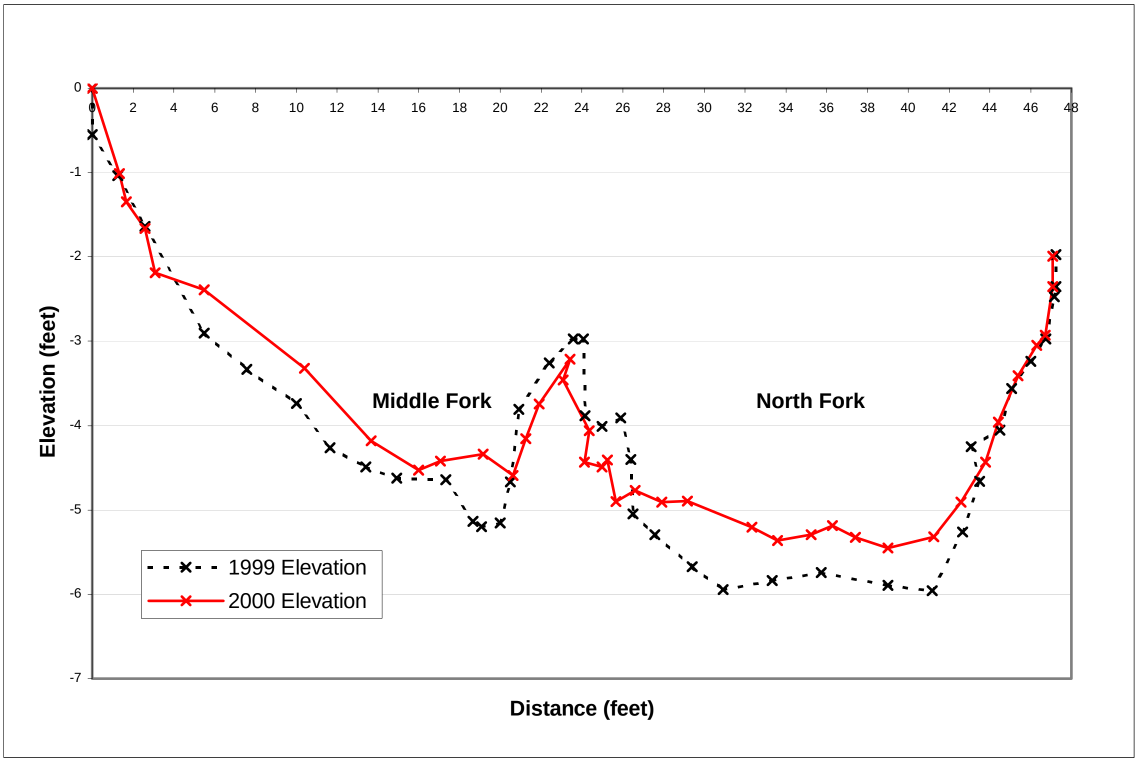


Figure 31. Middle and North Fork Cross-Section at Confluence, 1999 and 2000

Both the Middle and North Fork beds aggraded, on average, half a foot following the 2000 water year, although the banks of the “island” separating the channels were eroded. As is evident in the cross-section, the North Fork bed is on average about one foot deeper than the Middle Fork. The island separating the channels will continue to erode away, eventually lowering the base level of the Middle Fork to that of the North Fork and initiating a head cut upstream. Consistent with the findings of Schueler (2003) and Gregory (1992), the North Fork channel bed is also about double the width of the Middle Fork indicating that it has had to adjust to a larger cross-section to accommodate the flashy response of the urbanized watershed.

Localized incision and aggradation were measured in both forks during the 2000 water year but the data are not sufficient to suggest any specific trends. It is difficult to say how Middle and North Fork channel geometry changes from year to year but based on the survey information and observed active erosion, it is reasonable to assume that some adjustment to past and current land use activities is occurring.

Bank Erosion

The geomorphic survey conducted in 1999 (Collins et al. 2001) divided the main stem of San Pedro Creek into reaches based on road crossings, where bridges impose local grade control. For the purposes of this study, an additional reach was delineated to separate specific characteristics of the channel downstream of the confluence of the Middle and North Fork channels. The 1999 survey separated the Middle Fork into two reaches. The 1,217 linear feet (371 m) Oddstad Reach started at the pedestrian bridge in the park and ended at the downstream box culvert at Oddstad Boulevard. The remainder of the Middle Fork Reach was included in the 1,275 feet (388.6 m) Linda Mar Reach starting at Oddstad Boulevard and ending downstream of the Middle and North Fork confluence at Linda Mar Boulevard. The 200 feet (61 m) of open North Fork channel between the culvert and the confluence with the Middle Fork was not assessed in 1999 or for this study. To demonstrate the impact of urbanized North Fork flows on the main stem of San Pedro Creek, the Linda Mar Reach is divided into two sections upstream and downstream of the confluence. The Oddstad Reach remains the same; the 764 linear feet (233 m) North Fork Reach extends from Oddstad Boulevard to the confluence; and the new Linda Mar Reach starts at the confluence and ends at Linda Mar Boulevard.

Figure 32 shows the estimated volume of combined bank erosion per linear foot for all seven reaches of the 2.6-mile (4.2 km) San Pedro main stem study reach. Of all the reaches, the North Fork Confluence Reach has experienced the most significant bank erosion at 55.2 cubic feet (1.5 cm) per foot from the bed to the top of bank. This erosion volume value is 41% greater than the Oddstad Reach upstream of the confluence. Higher erosion volume downstream of the confluence can be attributed to the excess energy, flashy high peak flows, and low sediment (sediment starved) concentrations observed at the North Fork stream gage.

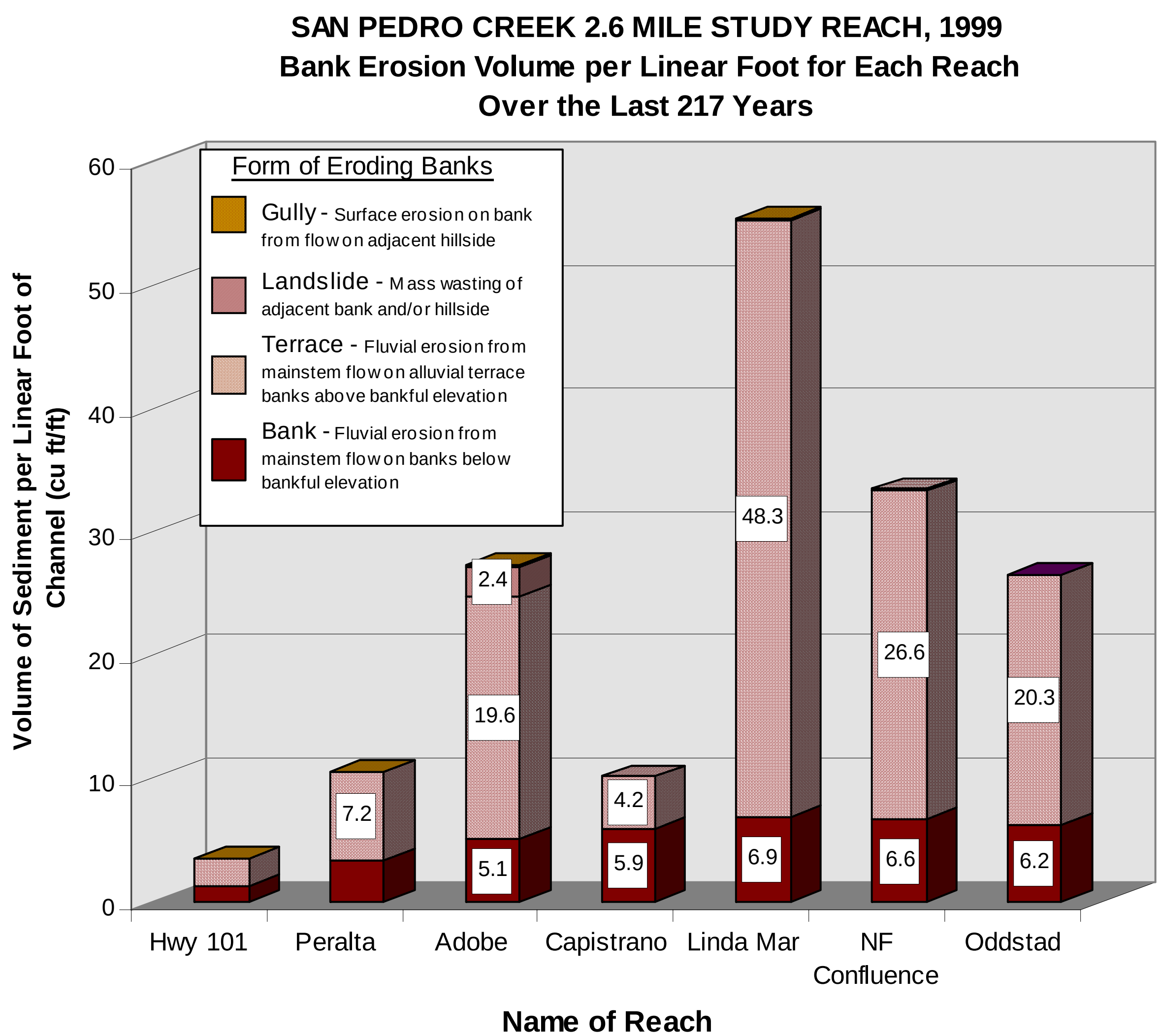


Figure 32. Bank Erosion Volume Per Linear Foot (Collins et al. 2001)

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

A significant body of research supports the finding that an urbanized watershed will cause negative impacts to the stream that drains it. Often these impacts can be measured in the form of process-related changes such as discharge, sediment supply, sediment transport, and alterations to channel geometry. That these process-related changes are directly linked to riparian and aquatic habitat and water quality is well understood. Furthermore, it can be said that land uses such as farming and grazing often initiate watershed and channel processes that cause streams to become unstable or in a state of disequilibrium.

Human landscape evolution typically begins with a relatively benign indigenous occupation; it is followed by conversion to agriculture by either native or exotic populations, and eventually reaches, a state of development including multiple land uses such as residential, commercial, industrial, and open space. With the introduction of development in the form of urbanization comes an increase in impervious surface. As described by this study and several earlier works (Wolman 1967; Leopold 1973; Graf 1976; Booth 1991; and Schueler 1994), the presence of impervious surfaces is an indication that hydrologic and sediment related processes have been altered and local waterways degraded. Humans are just beginning to recognize the real need to change the typical paradigms under which we populate, and consequently modify our landscape, but without aggressive planning and recovery efforts, watershed and stream channel impacts will continue unabated.

San Pedro Creek watershed is a classic example of human landscape evolution and the negative environmental impacts that accompany it. It serves as an appropriate and effective case study for urban impacts not only because of the relevance of the historical and physical context in which it changed, but also because of its ecological significance today. Though significant alterations to the system have occurred, San Pedro Creek continues to support a riparian corridor complete with the only steelhead trout fishery within 30 miles (48 km) of San Francisco. It has inspired several concerned members of the community to form the San Pedro Creek Watershed Coalition with the goal of protecting, preserving, and restoring stream functions and ecology, and promoting public awareness of watershed issues (SPCWC 2002). Studying present contrasts between the Middle and North Fork sub-watersheds also improves our understanding of how a severely engineered drainage network responds to storms and increased downstream impacts. Lastly, the study area displays impacts of hillside development, which will likely continue in the San Francisco Bay Area and coastal California, with the complete development of the flatlands.

Historical analysis of the San Pedro Creek watershed reveals distinct human periods of influence, each with unique physical modifications of the watershed and its drainage network. For centuries, Ohlone people managed vegetation communities with fire, perhaps with some change to runoff and sediment supply. Channel condition during this period was not documented, although the Spanish settlers who displaced the Ohlone described a system very different than seen today. Spanish occupants of the Mission period introduced farming and grazing and were perhaps the first to directly modify the stream channel through diversion and realignment. Runoff and erosion rates from farming and grazing also modified the stream by increasing incision and the supply of fine sediments.   Mexicans of the Rancho period who replaced the Spanish continued agricultural practices and associated impacts and introduced even greater numbers of cattle to the watershed through the late nineteenth century. The commercial farming period (late 1800s to the mid 1950s) saw the most significant modifications up to that time, as intensive row crops filled the valley flats and dairy cattle grazed the hillsides. Increased runoff and sediment supply were prompted by the installation of diversion dams, straightening and realignment of the stream channel, and a major drop in base level by ditching the lower valley to drain Lake Matilda and the surrounding, marsh. But no period in the human landscape evolution chain saw as dramatic physical and process-related changes as the period of suburban development. Introduction of impervious surfaces and engineered drainage over a 20-year period buried most of the North Fork tributary main stem, increased drainage density, reduced rainfall infiltration, increased runoff rates and volume, increased flood frequency and channel erosion, and led to pervasive channel armoring to protect property from ongoing bank erosion. These modifications of course caused further degradation to the riparian and aquatic habitat of the creek adding to present day conditions of polluted water and threatened species habitat decline.

Research performed in 1999 and 2000 was designed to measure and compare the response of flows and turbidity during storms in the unurbanized Middle Fork and the urbanized North Fork tributaries, and to quantify changes to channel geometry. Impervious surface area in the North Fork was measured at 19% of total drainage area, and considered highly connected to the drainage network. Drainage density increased from 4.0 miles/mile^2 (2.5 km/km^2) to 14.3 miles/miles^2 (8.9 km/km^2), a 72% increase due to the introduction of road gutters, drainage ditches, and stormdrains. Increases in Middle Fork impervious area and drainage density were considered negligible.

Rainfall measurements in the tributaries and the San Pedro Valley Park indicated that on average the Middle Fork received 31% more rainfall than the North Fork and 17% more than the Park. This appears to be a result of the wind patterns that move storm systems from the southwest to the northeast. Under natural conditions, a watershed with greater precipitation would be expected to have greater storm discharge than a physically similar watershed with less rainfall. This was likely the case with the Middle and North Fork tributaries prior to development. Discharge measured in the field under current conditions shows that early rainy season base flows for the Middle Fork are slightly higher than the North Fork, possibly demonstrating more significant groundwater inputs from the more pervious basin. Conversely, measurements taken during or shortly following rainfall indicate approximately 2 to 7.5 times more discharge in the urban drainage due to direct runoff from impervious surfaces into an engineered stormdrain network.

Stream gage stations with electronic sensors and continuous record data loggers were installed in each tributary and the data used to plot discharge and turbidity levels with hourly rainfall intensity, during three consecutive storms on February 11, 13, and 14, 2000. Discharge was derived from recorded stage based on the relationship of observed stage to measured discharge.

In the Middle Fork, time measured between the peak rainfall intensity and peak discharge ranged from 1.25 to 4.75 hours, depending on the duration and total rainfall measured. The longest storm with more rainfall had the longest lag-to-peak time, while the shortest storm with the least rainfall had the shortest lag-to-peak time. Based on the data, the response period between the beginning of rainfall and the initial rise in discharge in the urbanized North Fork was only minutes or an undetectable period of time. The relationship between peak rainfall and peak discharge was the same. Peak stage was also significantly greater in the North Fork because the Middle Fork has a wider cross-section causing water surface elevation to rise more slowly.

During the February 11 storm, average discharge was higher in the North Fork. This appears to be due to reduced infiltration potential in the impervious areas resulting in greater runoff while more rainfall was infiltrated in the Middle Fork. The Middle Fork lag time is also significantly greater. The two later storms exhibited higher average discharge in the Middle Fork. This inversion is likely a result of increased antecedent wetness conditions from the February 11 rainfall, causing a rise in runoff rate and volume in the Middle Fork drainage.

Turbidity data were collected as a surrogate of sediment response for both drainages. In the Middle Fork, the turbidity curve typically paralleled discharge with the exception of the February 13 storm when turbidity exhibited an inverse relationship to peak discharge. This response appears to be a result of dilution of the water column as flows increase at a faster rate than suspended matter. This same relationship was evident in the North Fork, though at a much more frequent and shorter time interval. The Middle Fork also transported significantly more suspended load than the North Fork during all three measured events.

The data presented help illustrate how the influence of urbanization in the North Fork has caused a change in storm response when compared to the pre-urbanization conditions of the Middle Fork. In the North Fork, water levels and discharge increase rapidly and are highly variable, peak discharge and average discharge are higher than the Middle Fork prior to sufficient antecedent wetness conditions. Following enough rainfall, the graphs indicate that the Middle Fork will convey almost double the amount of discharge of the North Fork for the same period of time. This was a result of higher rainfall and increased effective impervious area following soil saturation.

Observations of increased bank erosion downstream of the North Fork and Middle Fork confluence also show how high energy, low sediment flows of the urbanized drainage cause an increase in channel degradation when compared to bank erosion in the Middle Fork above the confluence. Surveyed channel cross-sections of the tributaries reveal that the North Fork cross-section is approximately double that of the Middle Fork. The larger North Fork cross-section is indicative of channel adjustment to urban storm flows and sediment starved water, and is expected downstream of the culvert.

To halt, or at least reduce stream impacts associated with urbanization, significant changes must be made in the way societies view streams and their connection to the surrounding land. In the American west, the advent of water reclamation projects in the form of intra- and interstate level water supply systems eliminated the need for urban and suburban dwellers to draw their water locally. Over this short period in history, controlled water supply opened the door for increased population and floodplain development, which introduced the need for flood protection. Streams were reduced to modifiable conduits for flood conveyance instead of life-giving water and food sources. Today, in communities like the San Pedro Valley, residents may drive across local creeks without even knowing they are there. Getting people to understand that they live, work, and play in a watershed that forms a stream with ecological and social significance is the first step toward creating public interest in protecting and restoring these important natural resources.

With public interest comes the public funding necessary to improve the planning process and avoid channel impacts like those described in the San Pedro Creek system. Public interest will also result in academic programs that better train our politicians, planners, engineers, environmental regulators, and watershed managers to recognize the watershed as an important geographic and ecological unit. As perception and understanding improve, direct measures can be taken to achieve new stream protection and enhancement goals. Developments will have reduced impervious surfaces, reduced effective impervious area, and increased rainfall infiltration, runoff retention and detention; adequate riparian buffers will be preserved to control runoff, allow flood conveyance and improve water quality; drainage networks will no longer be filled, channelized, or put in culverts to maximize the amount of developable space; and drainage density will be preserved in or close to an undeveloped state. Many people are currently working towards public education and adoption of federal, state, and local government regulations intended to meet goals, but will continue to face a significant challenge until public perception is improved.

San Pedro Creek changed significantly as a result of past land use practices but most degradation has been caused by urbanization. Still, a relatively intact riparian corridor traverses the valley and sensitive species like steelhead continue to rely on the system for their survival. Completely undoing changes of the past is virtually impossible but opportunities for several improvements should be studied for implementation. The lower reaches of San Pedro Creek have already been given a head start towards improvement through the design and construction of the fluvial geomorphic design of the U.S. Army Corps of Engineers flood protection project. Now improvements should migrate upstream, bettering passage for steelhead as they go. Certain recommendations apply to the entire watershed but would best serve San Pedro Creek if first implemented in the North Fork drainage.

Continuous recording discharge and rainfall gage stations should be installed to monitor the flows of San Pedro Creek. At a minimum, a discharge gaging station would be put at the mouth of the creek, but if resources allowed, additional stations in the Middle and North Forks would better quantify the influence of urbanization on the watershed as a whole.

Areas should be identified where existing impervious surfaces can be minimized and disconnected from the drainage network. Parking areas can be reduced in size and their pavement partly or entirely replaced with pervious materials like gravels or paver stones. Where possible, vegetated planting medians should be introduced to large paved surfaces and roadways to capture rainfall and improve infiltration. Rainfall runoff from paved surfaces can be directed to bio-retention areas that support vegetation instead of stormdrains that flow directly and rapidly to the creek. Rooftop gutters can be directed to yards, landscaped areas or into private irrigation cisterns, which will also reduce water consumption. These features not only increase infiltration and reduce runoff; they also improve the appearance and environment of sterile paved areas.

The North Fork tributary should be assessed for “day-lighting” and restoration for a few hundred feet between the downstream end of the North Fork culvert and the connection of the Terra Nova tributary with Terra Nova Boulevard upstream. Existing open space at this location could provide opportunity to recreate riparian habitat and to excavate an adjacent floodplain to help reduce velocities exiting the concrete pipe.

The main stem of San Pedro Creek in the Linda Mar reach should be assessed for extensive bank repair using biotechnical methods. Efforts should be made to replace existing armored bank revetments, and eroding banks with appropriate bank stabilization techniques that use natural materials and native riparian vegetation. The proper bankfull channel cross-sectional geometry should first be determined based on upstream discharge to determine requirements to maximize long-term geomorphic stability.

The North Fork watershed should be surveyed for locations of storm detention facilities. Off-stream ponds or floodplain areas that can slow the movement of flows through the drainage network can reduce peak discharge frequency and extent during storms, reducing erosive flows downstream.

Open space in the watershed should be protected in perpetuity. This is already the case for significant portions of the upper watershed that are established county and federal park space, but privately owned lands may be candidates for future development. Additional increases in impervious surfaces and stormdrain contributions to the creek could further prevent establishment of a new post-development equilibrium and further exacerbate erosion and incision.

Finally, municipal and private parties should continue to collaborate on grant applications for funding sources to support special studies and corrective measures that improve the watershed and health of San Pedro Creek.

Given adequate time, and attention from economic and social resources, the physical, chemical, and biological conditions of San Pedro Creek can be enhanced for humans and wildlife in the San Pedro Valley. But let this study of the current conditions and response of the Middle and North Forks, as well as the channel below their confluence, serve as a reminder of what can happen when urban planning and development disregards the physical processes of a watershed.

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