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.

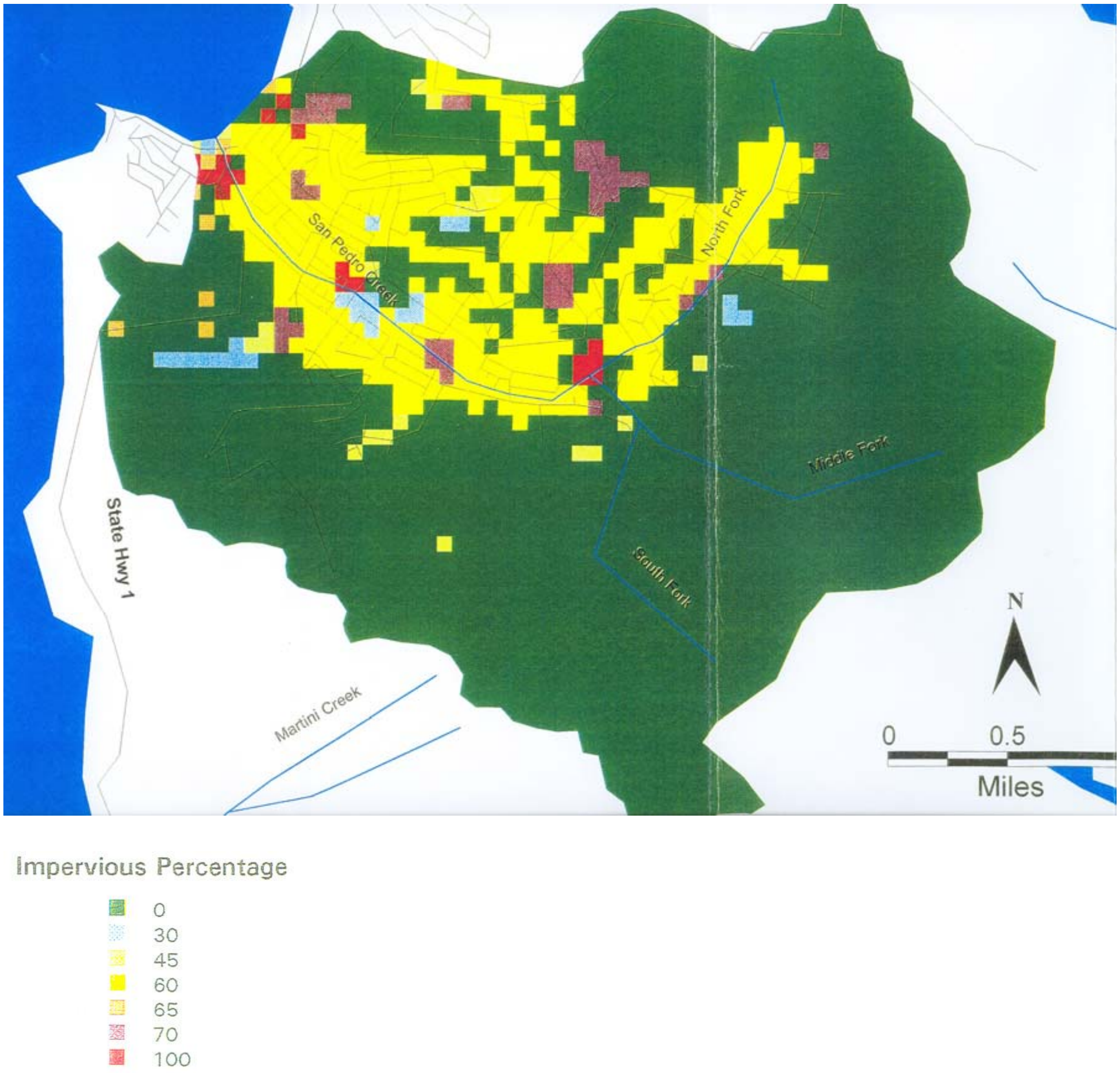
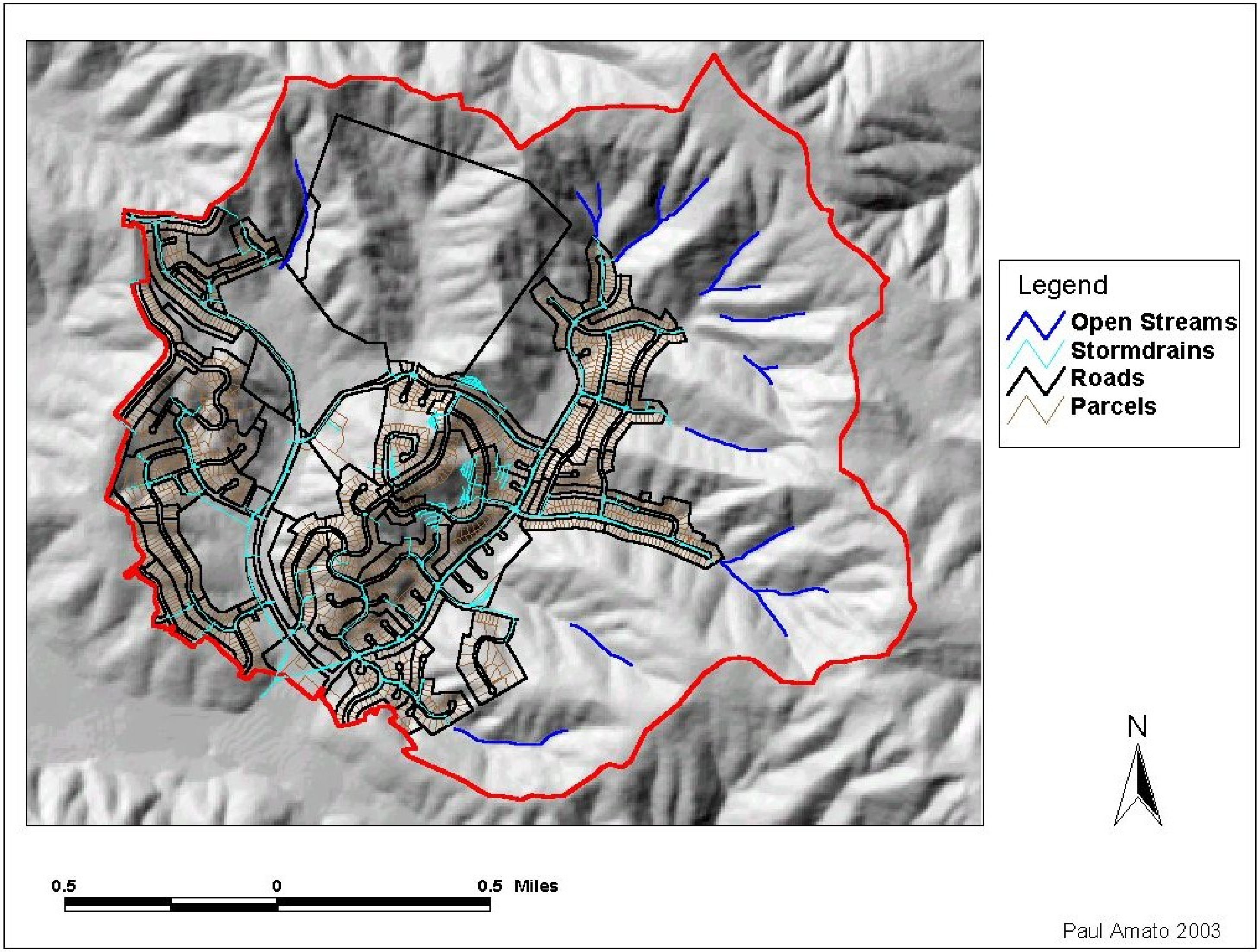


Figure 9. Impervious Cover in the San Pedro Watershed (EOA 1998)

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.



Paul Amato 2003

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.

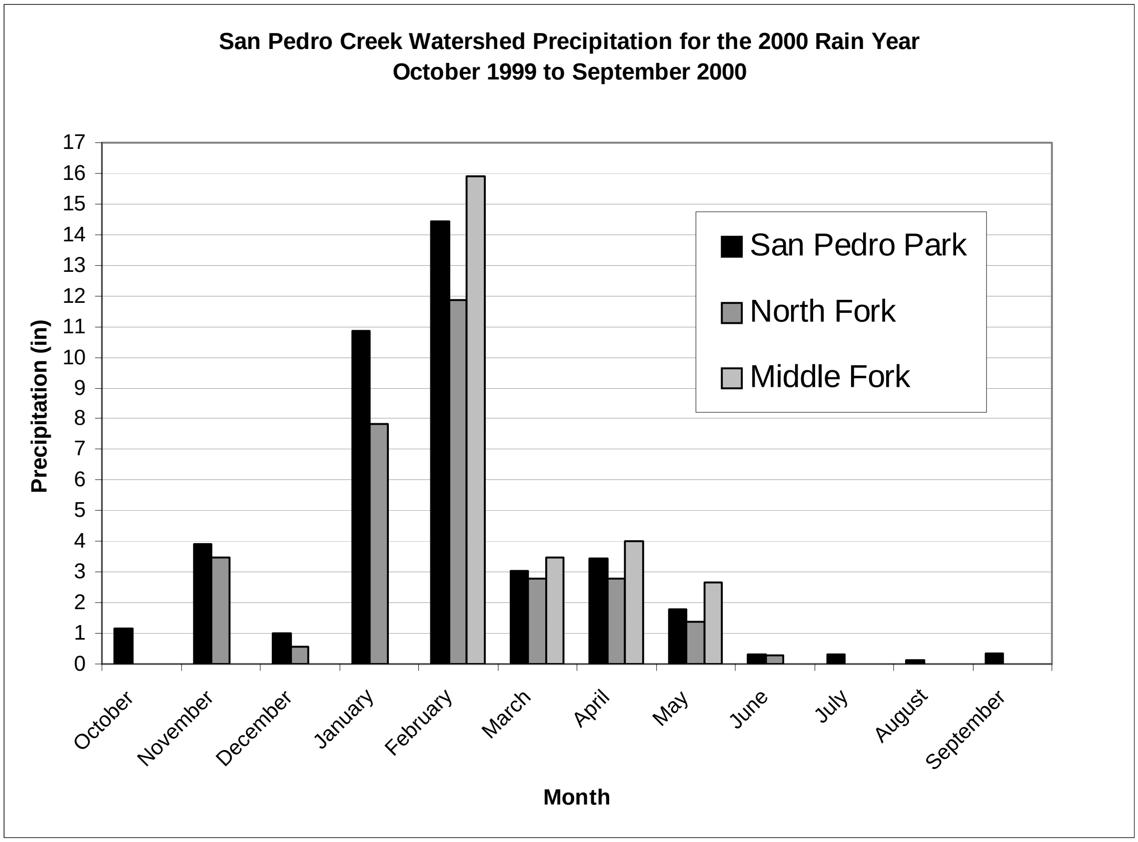


Figure 11. Monthly Rainfall Comparison for Three Rain Gages

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.

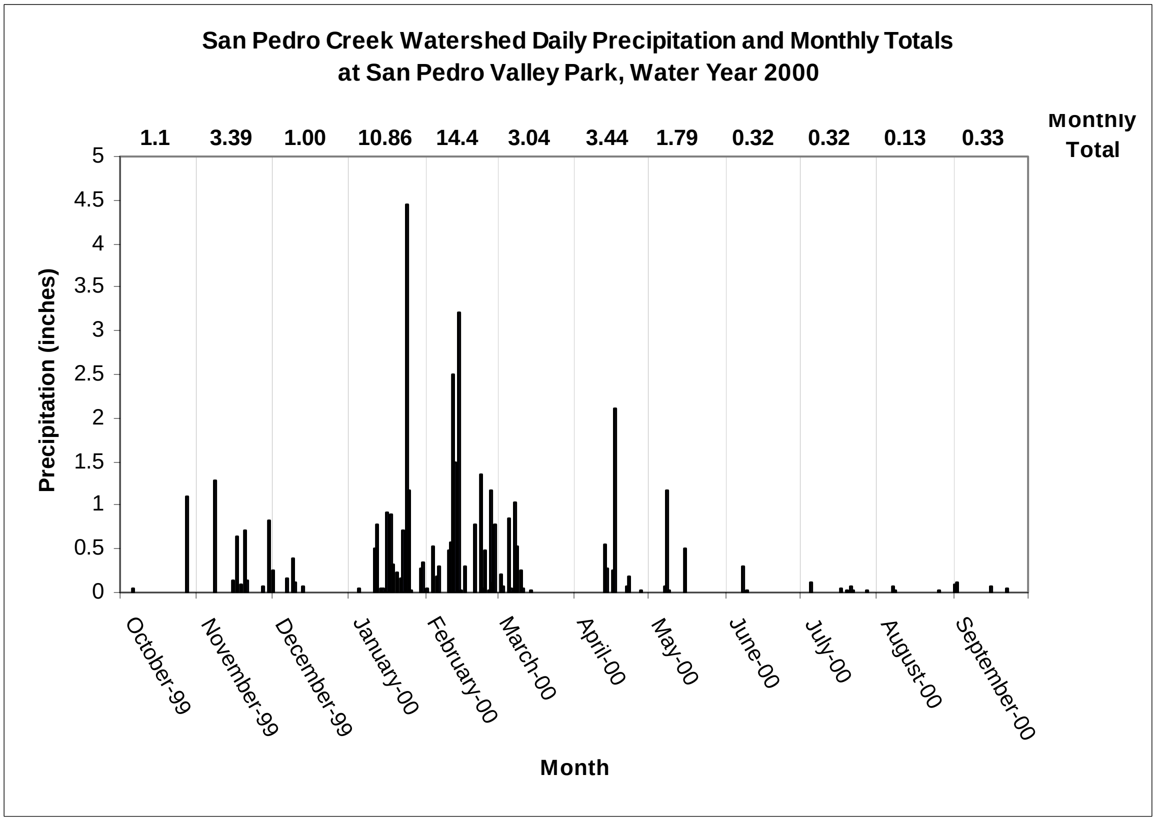


Figure 12. Daily and Monthly Precipitation at San Pedro Valley Park, 2000 WY

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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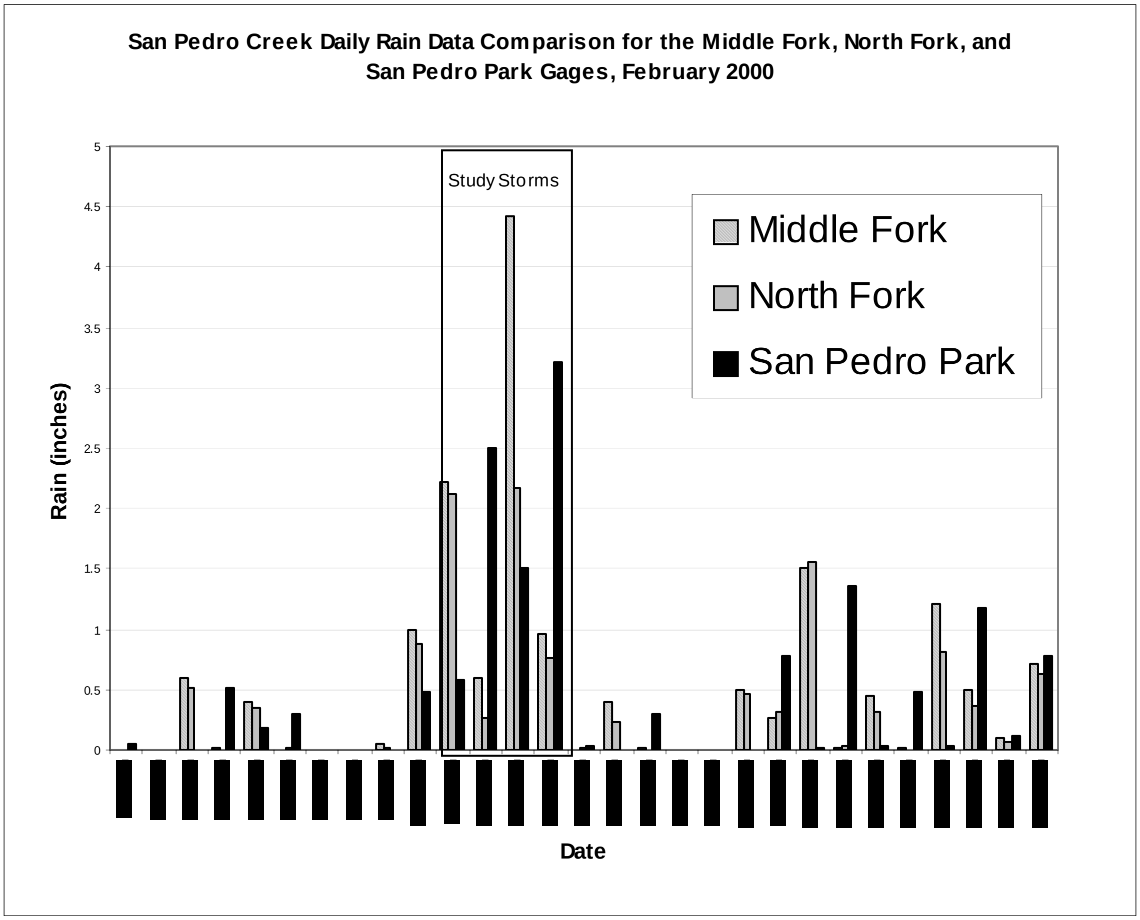


Figure 13. Daily Rain Comparison for the Month of February, 2000

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.

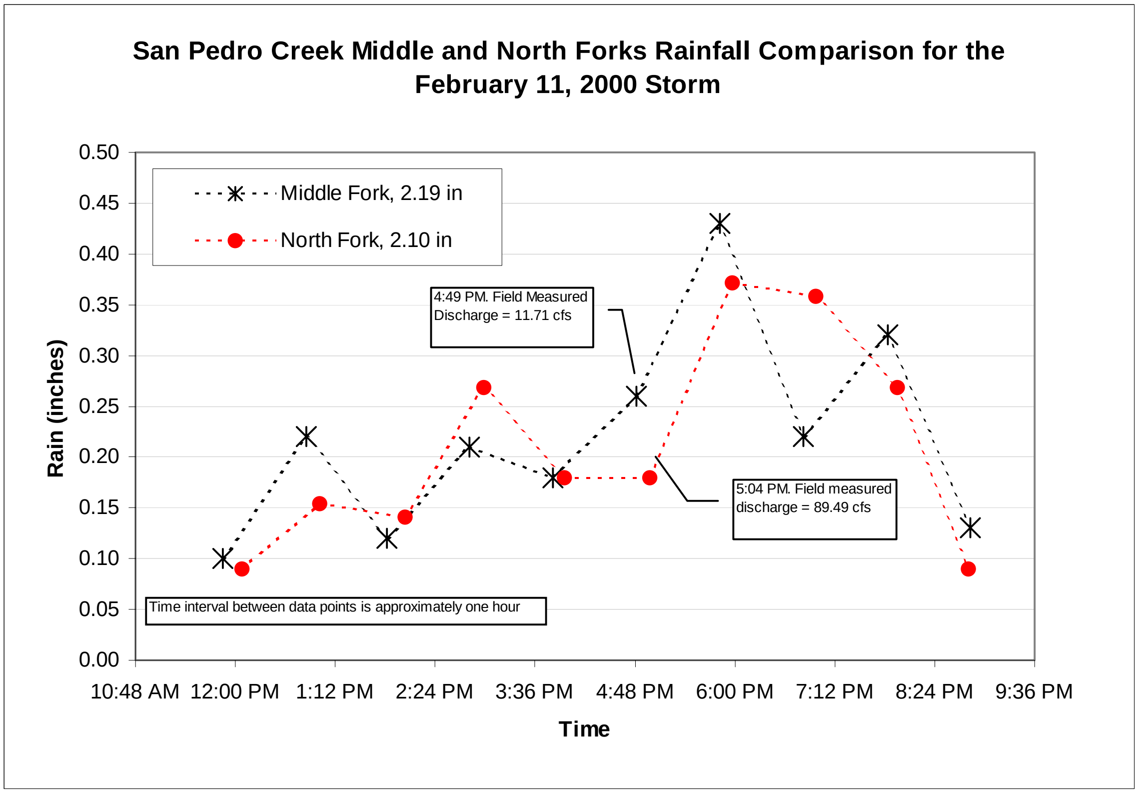


Figure 14. Rainfall Intensity and Duration for the February 11, 2000 Storm

<u>February 13 Storm Rainfall</u>

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).

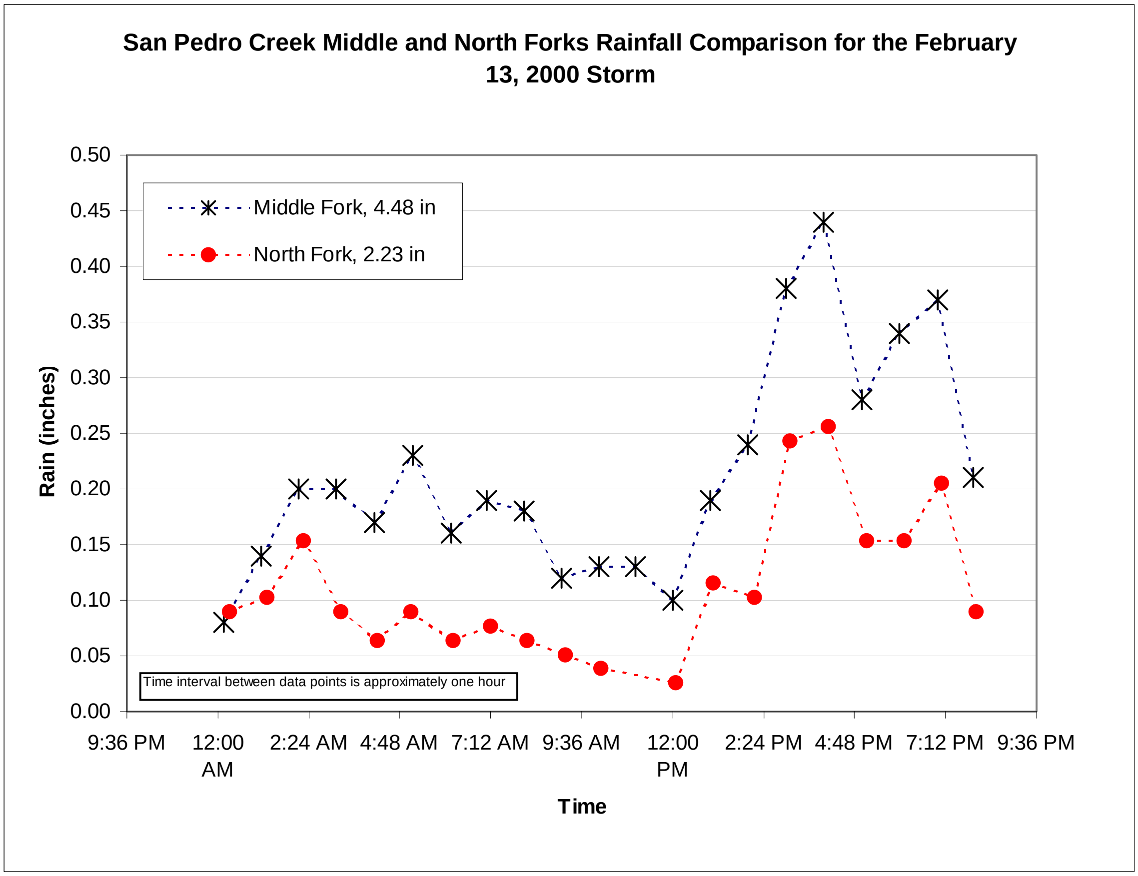
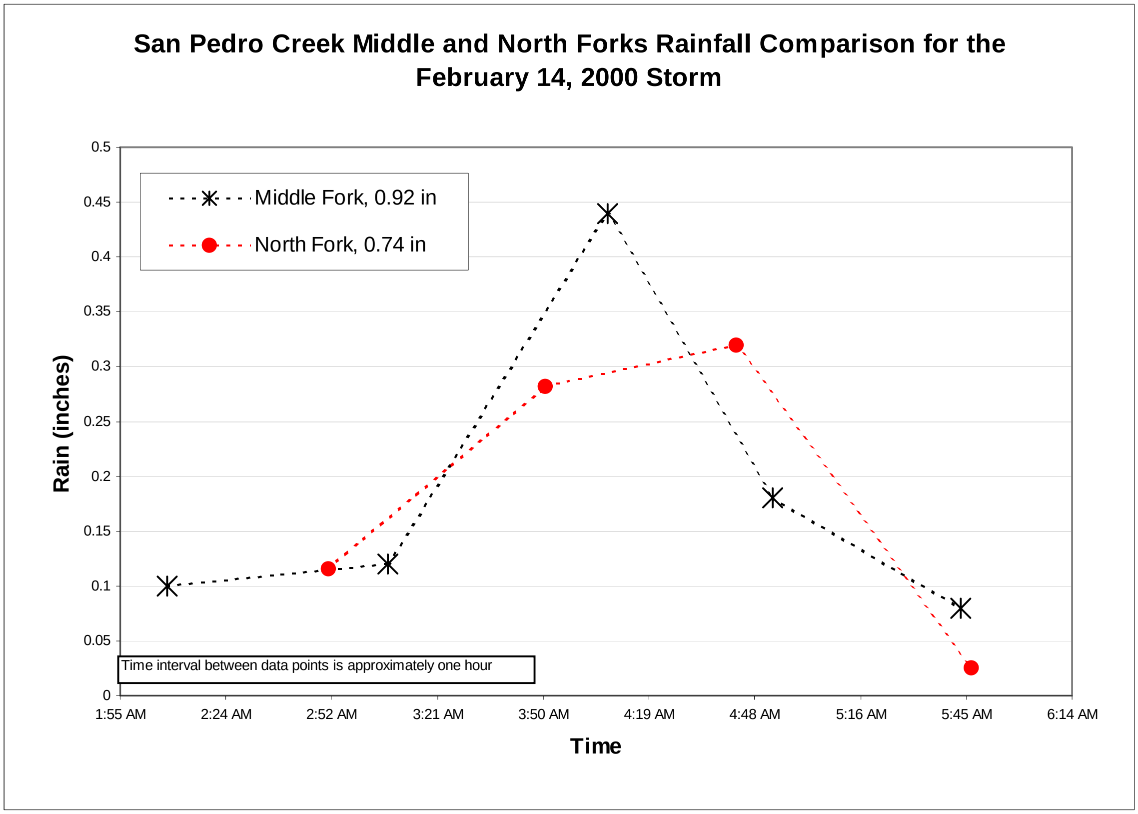


Figure 15. Rainfall Intensity and Duration for the February 13, 2000 Storm

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.



San Pedro Creek Middle and North Forks Rainfall Comparison for the February 14, 2000 Storm

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

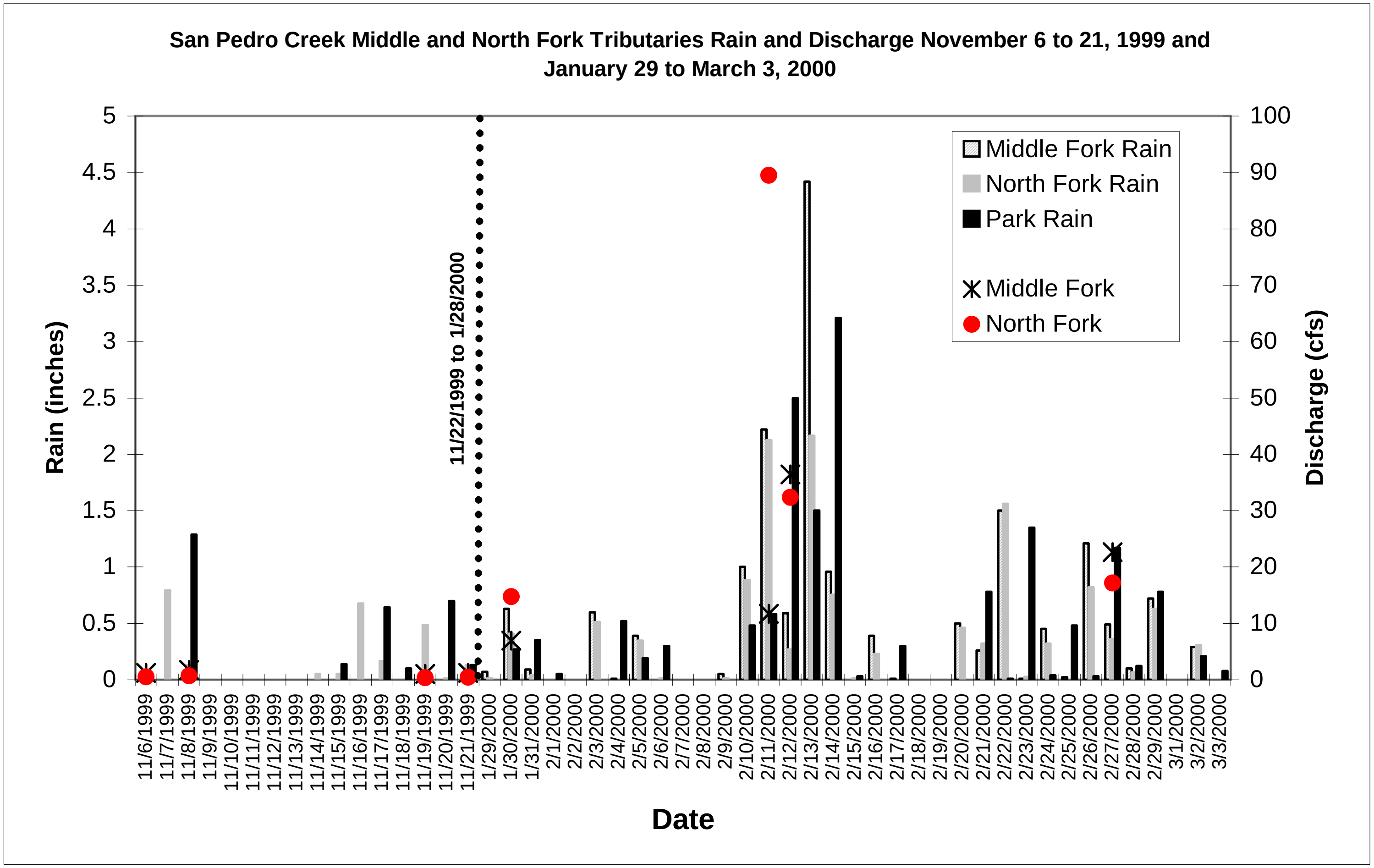


Figure 17. Daily Rainfall and Periodic Field Measured Discharge

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.

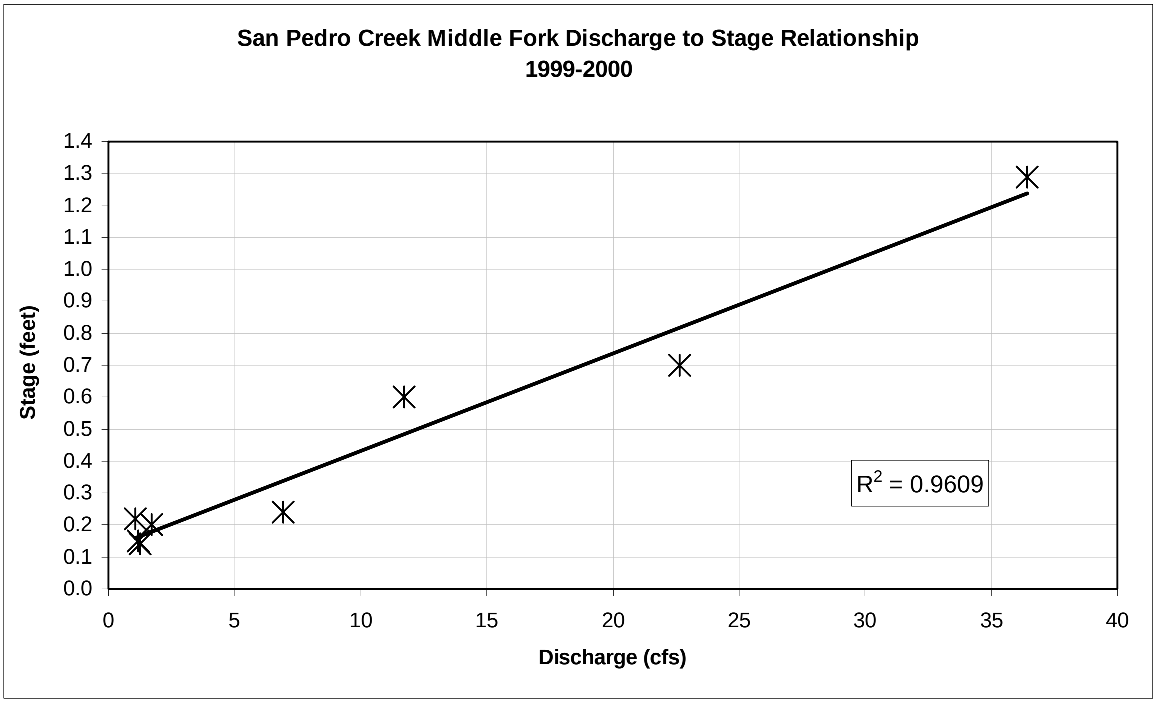
February 27 Discharge Measurements

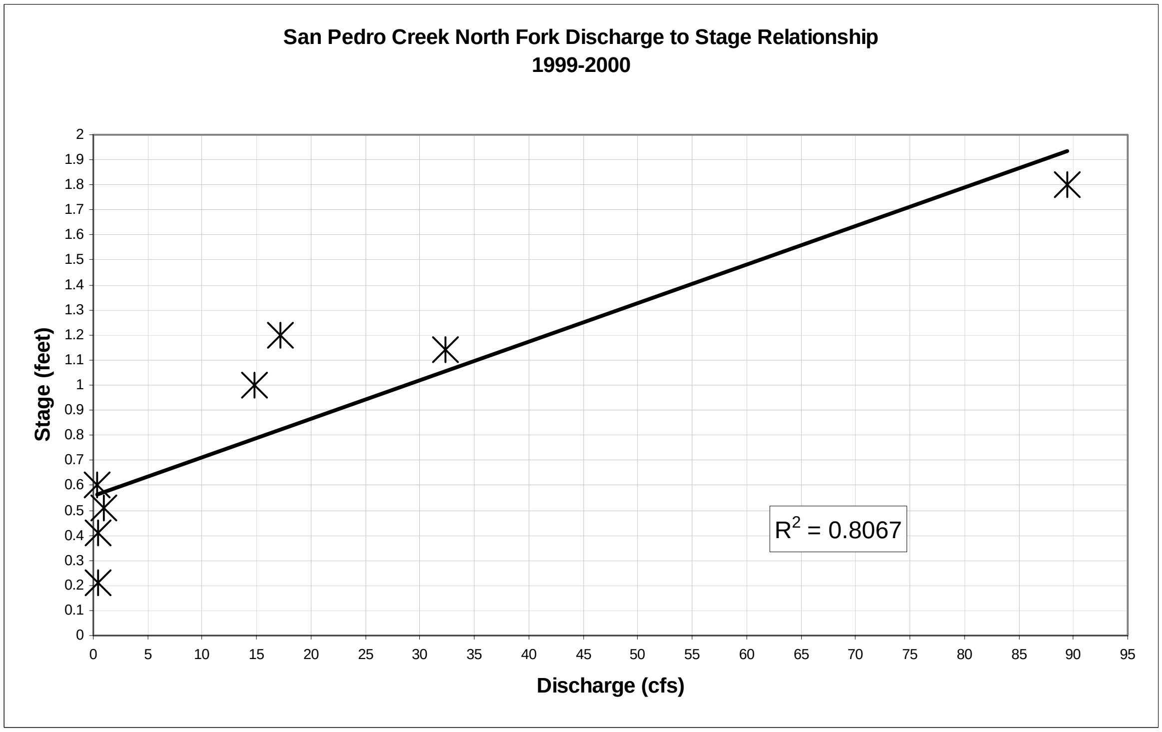
The eighth and final discharge measurement occurred on February 27, and found 22.63 cfs (0.64 cms) in the Middle Fork and 17.17 cfs (0.49 cms) in the North. The rainfall and discharge patterns are very similar to those of

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.

February 11 Storm Response

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.

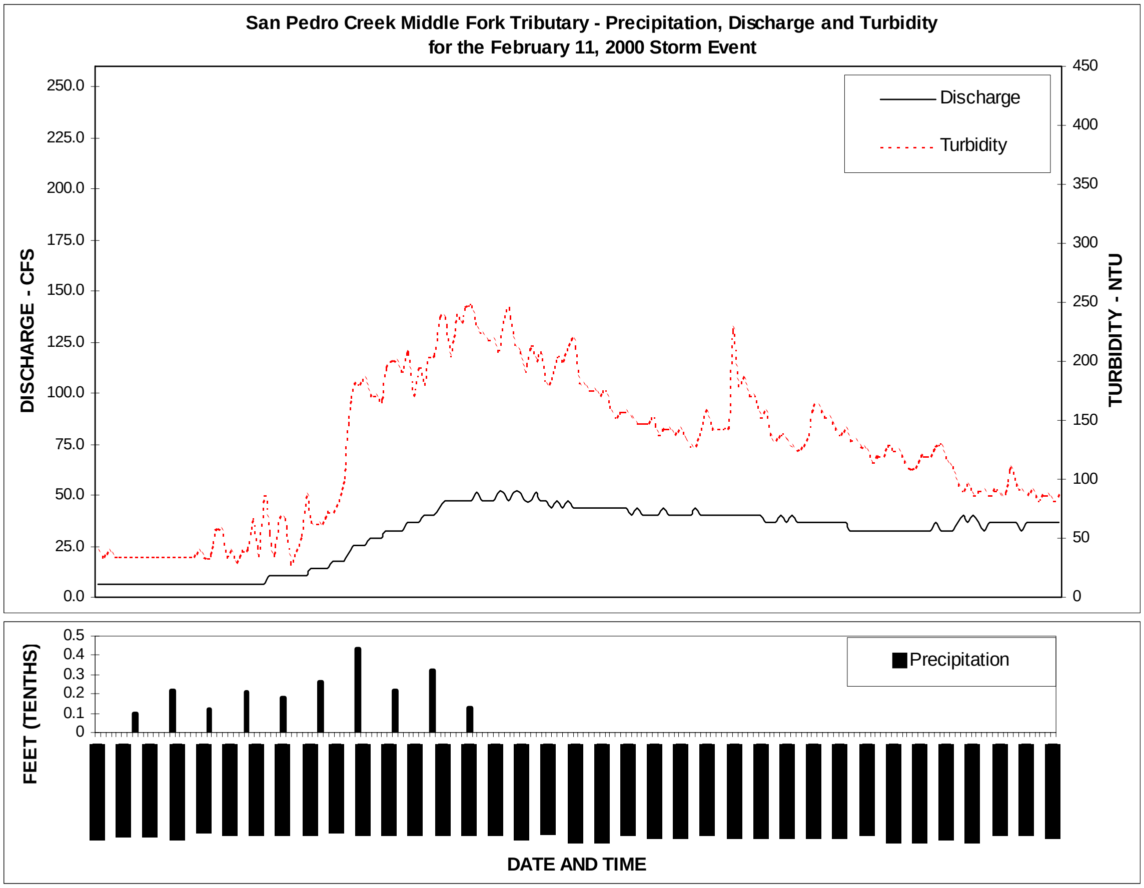


Figure 20. Middle Fork Rain, Discharge and Turbidity, February 11, 2000 Storm

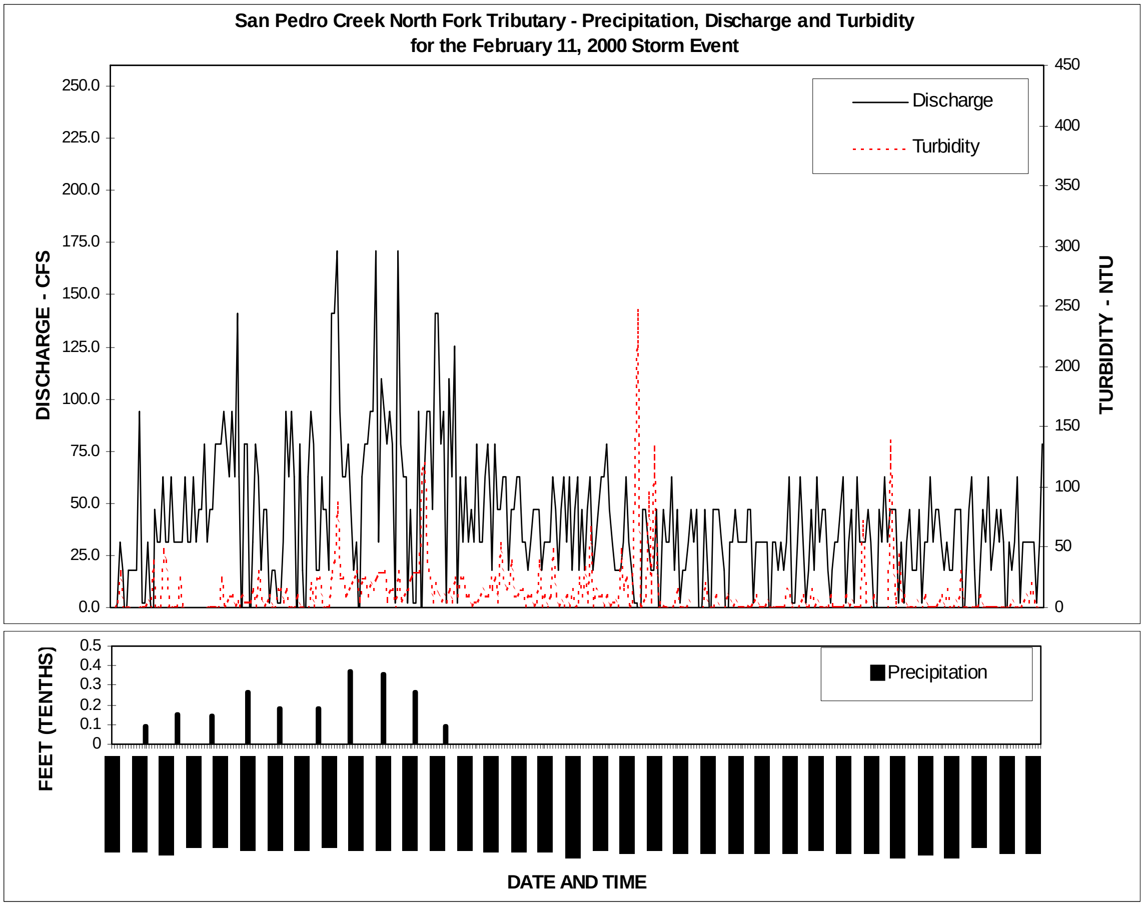


Figure 21. North Fork Rain, Discharge and Turbidity, February 11, 2000 Storm

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.

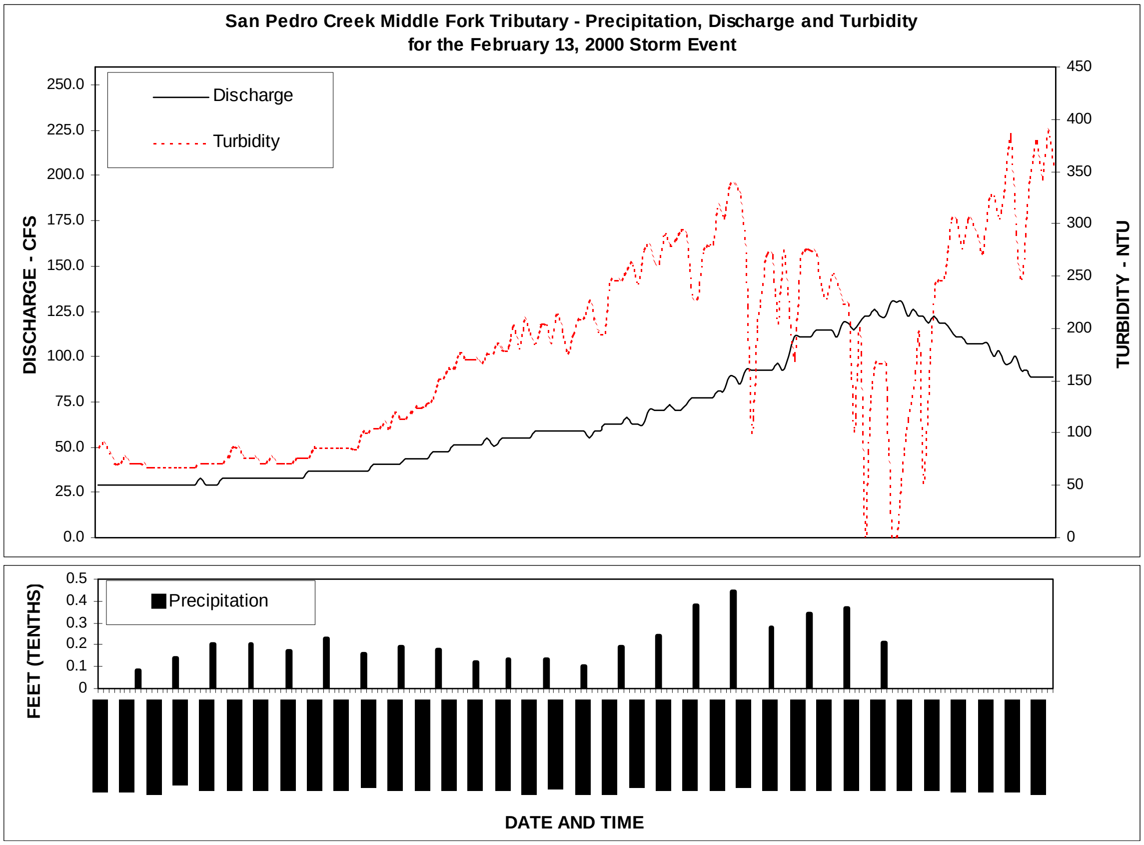


Figure 22. Middle Fork Rain, Discharge and Turbidity, February 13, 2000 Storm

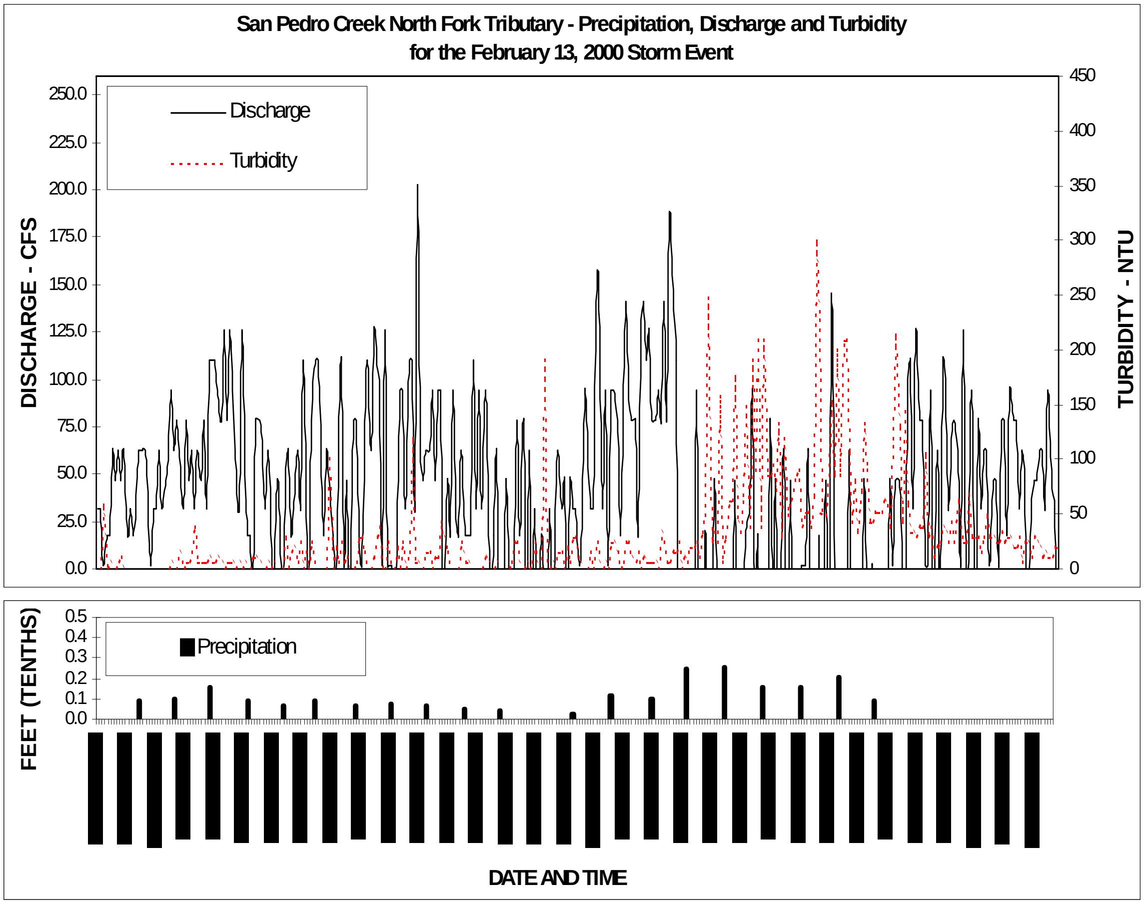


Figure 23. North Fork Rain, Discharge and Turbidity, February 13, 2000 Storm

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.

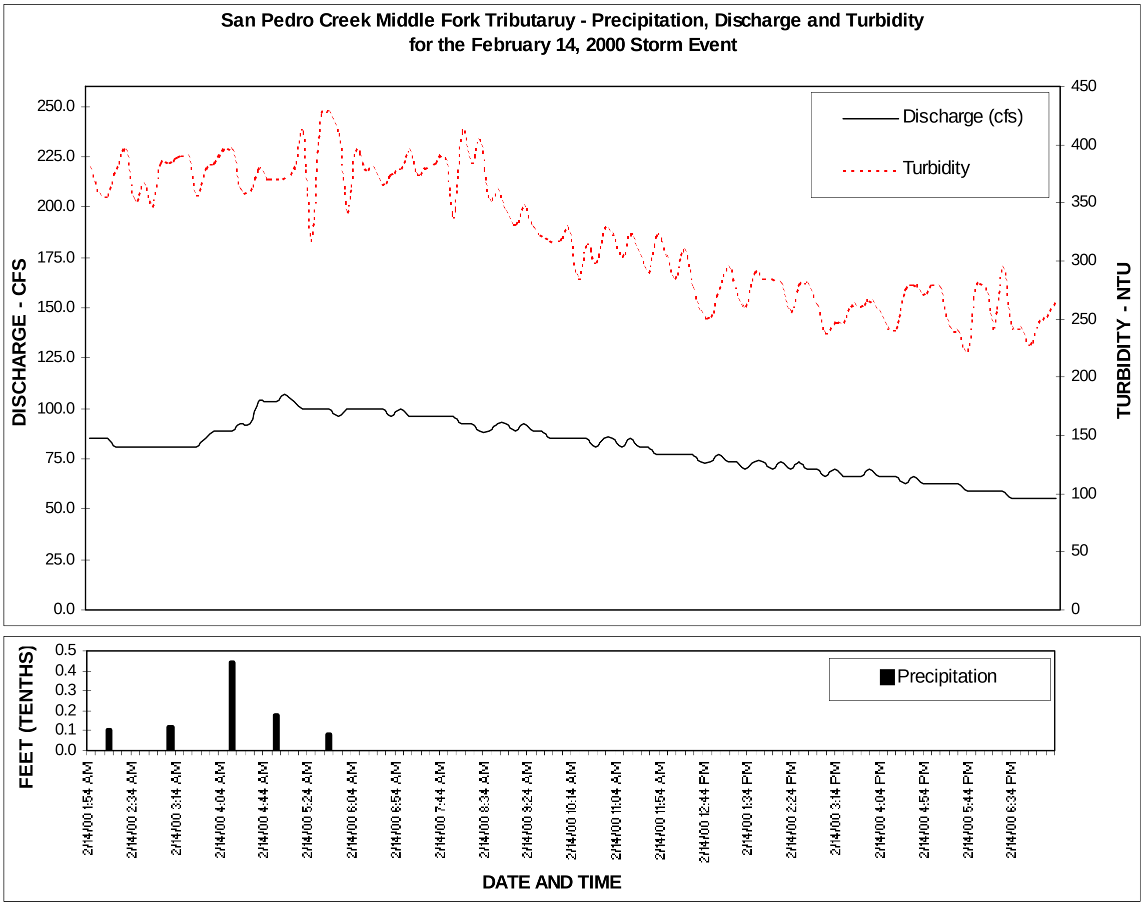


Figure 24. Middle Fork Rain, Discharge, and Turbidity, February 14, 2000 Storm

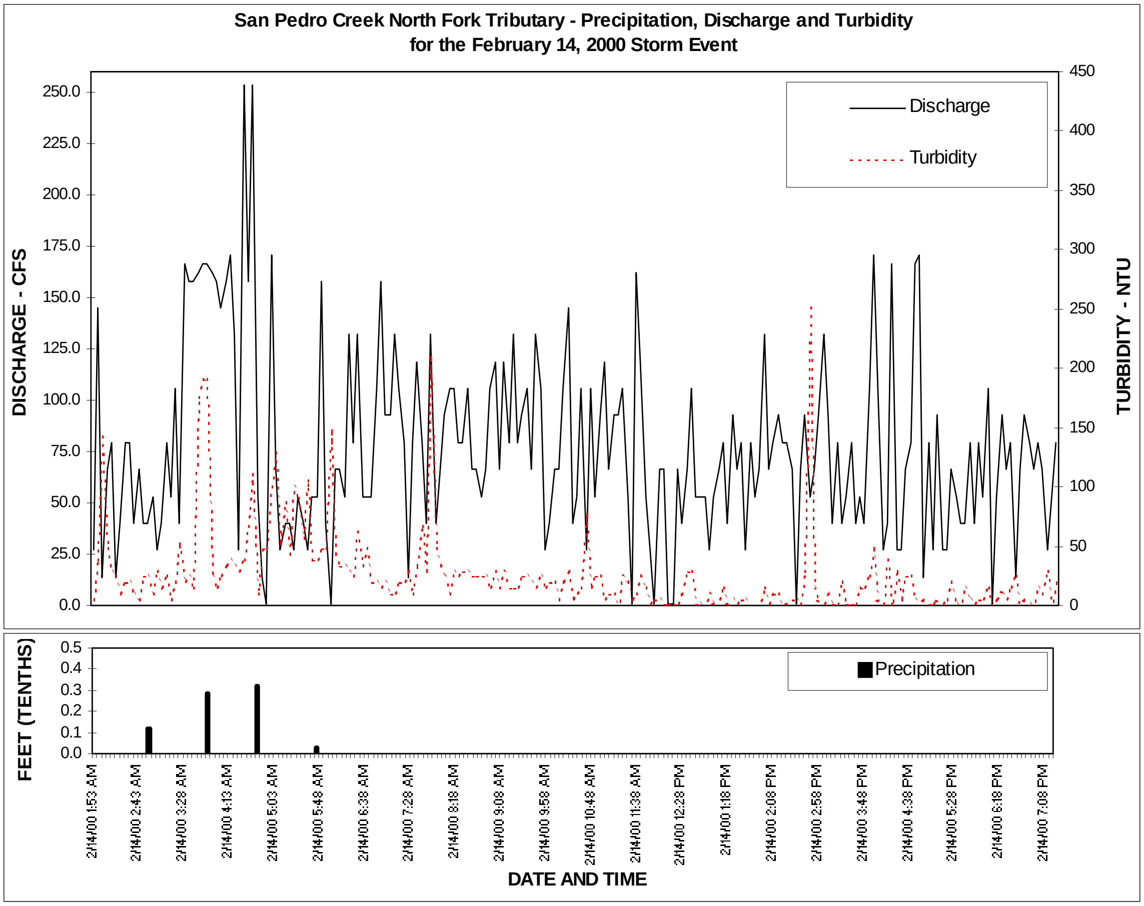


Figure 25. North Fork Rain, Discharge, and Turbidity, February 14, 2000 Storm

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.

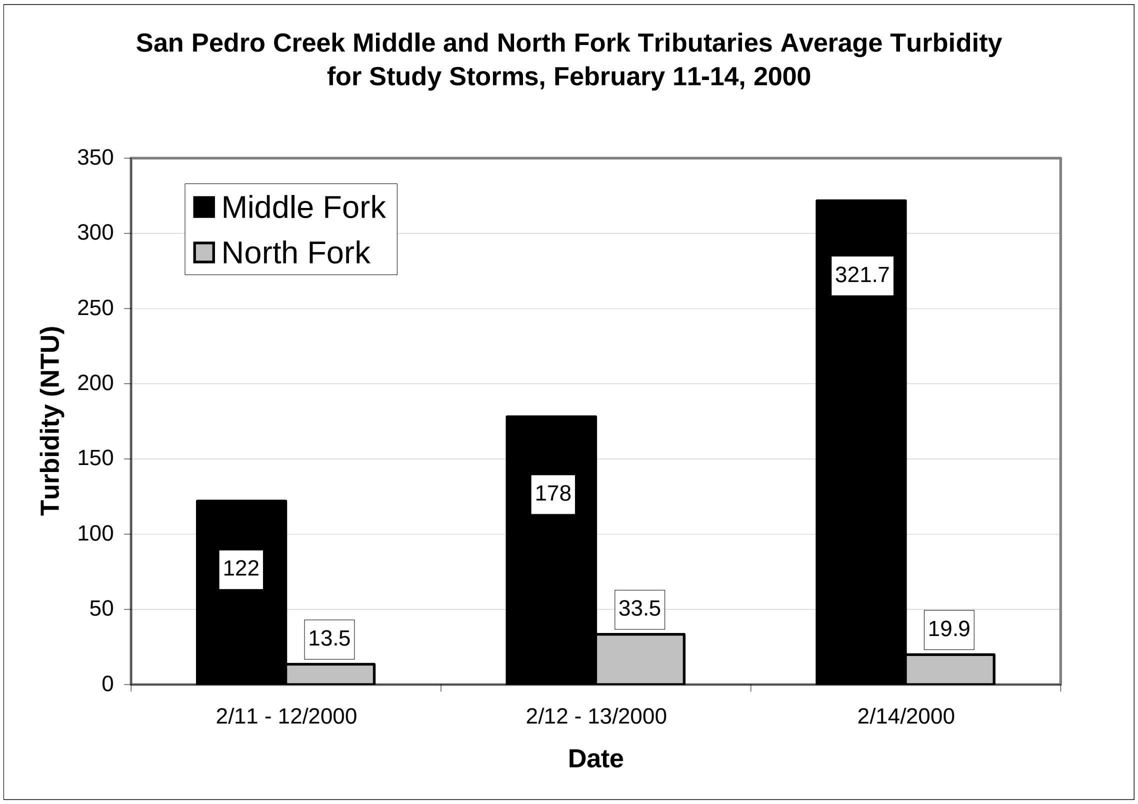


Figure 26. Average Turbidity for the Three Study Storms

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.

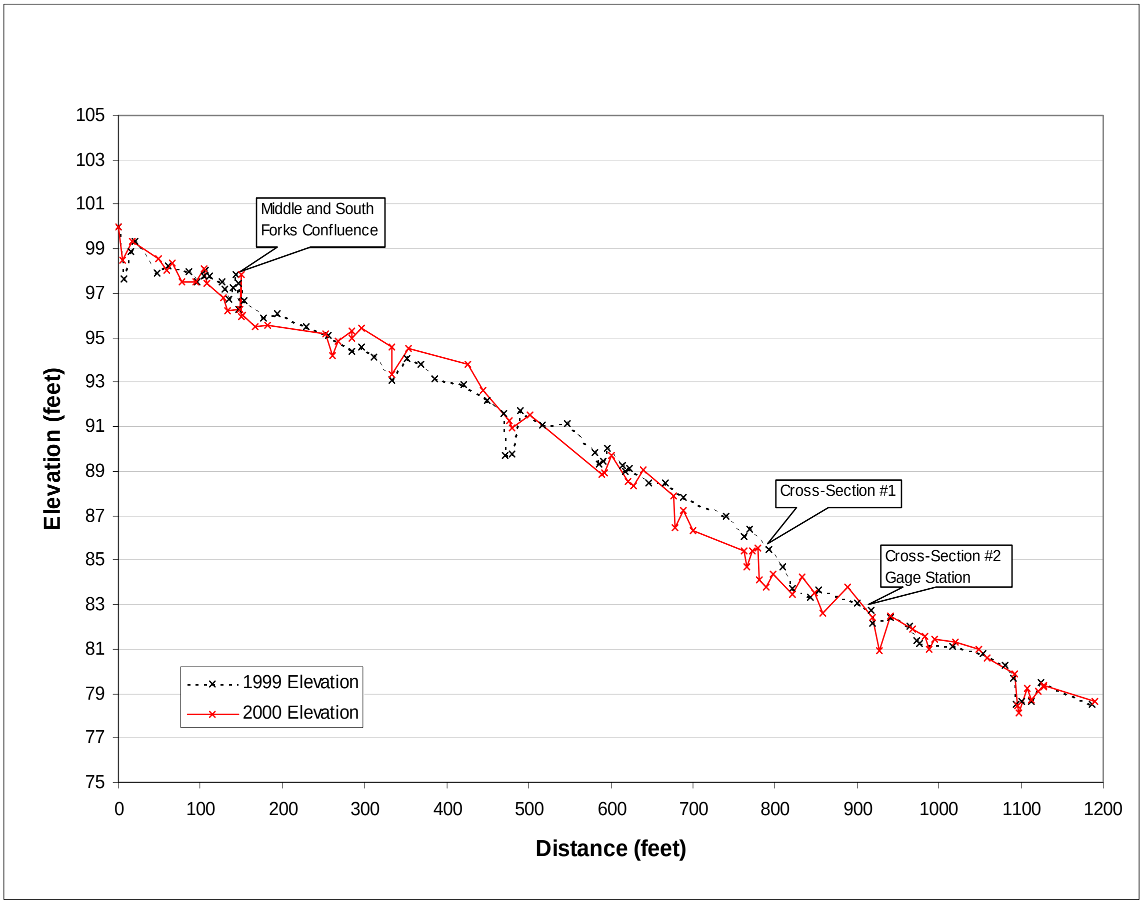


Figure 27, Middle Fork Longitudinal Profile, 1999 and 2000

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

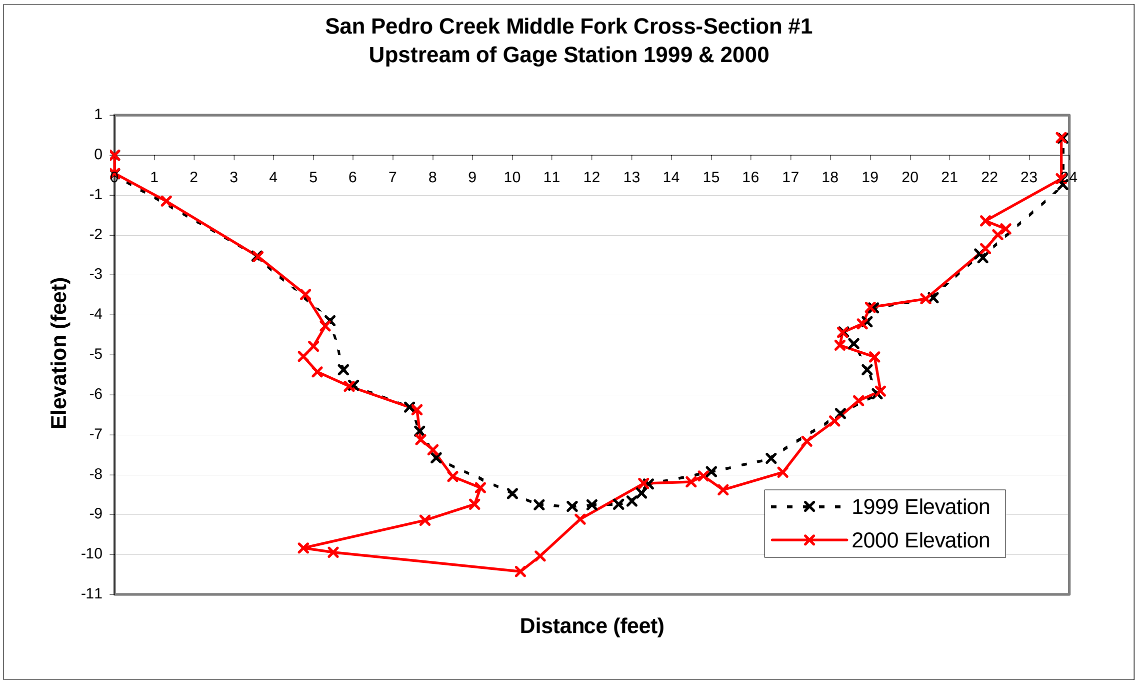


Figure 28. Middle Fork Cross-Section #1, 1999 and 2000

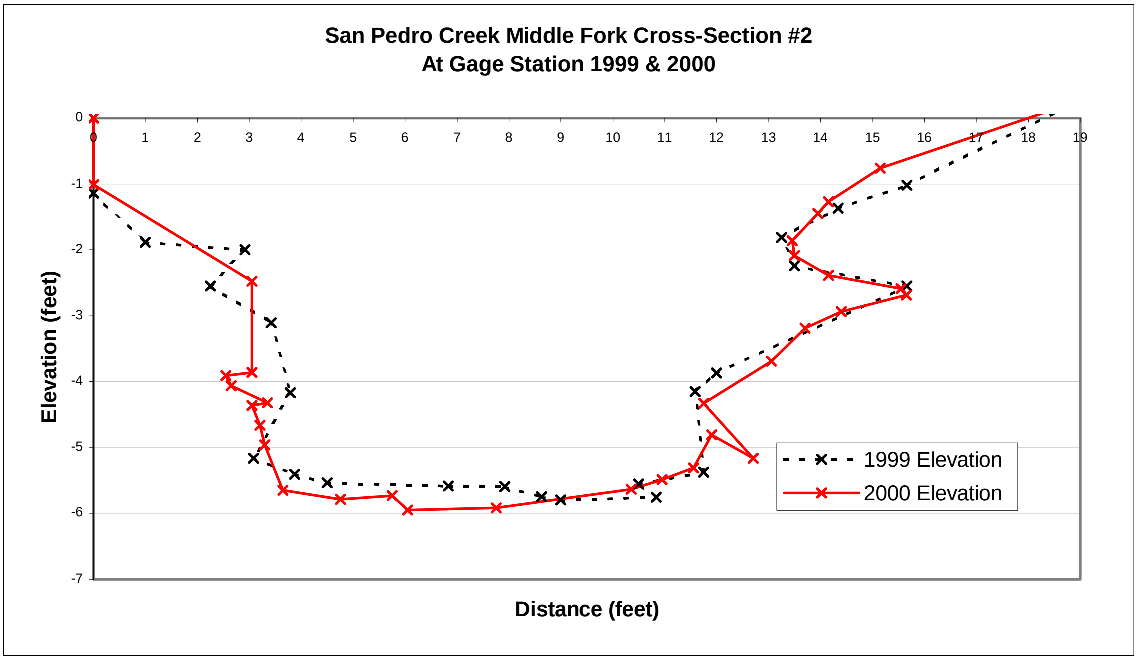


Figure 29. Middle Fork Cross-Section #2, Stream Gage Station, 1999 and 2000

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

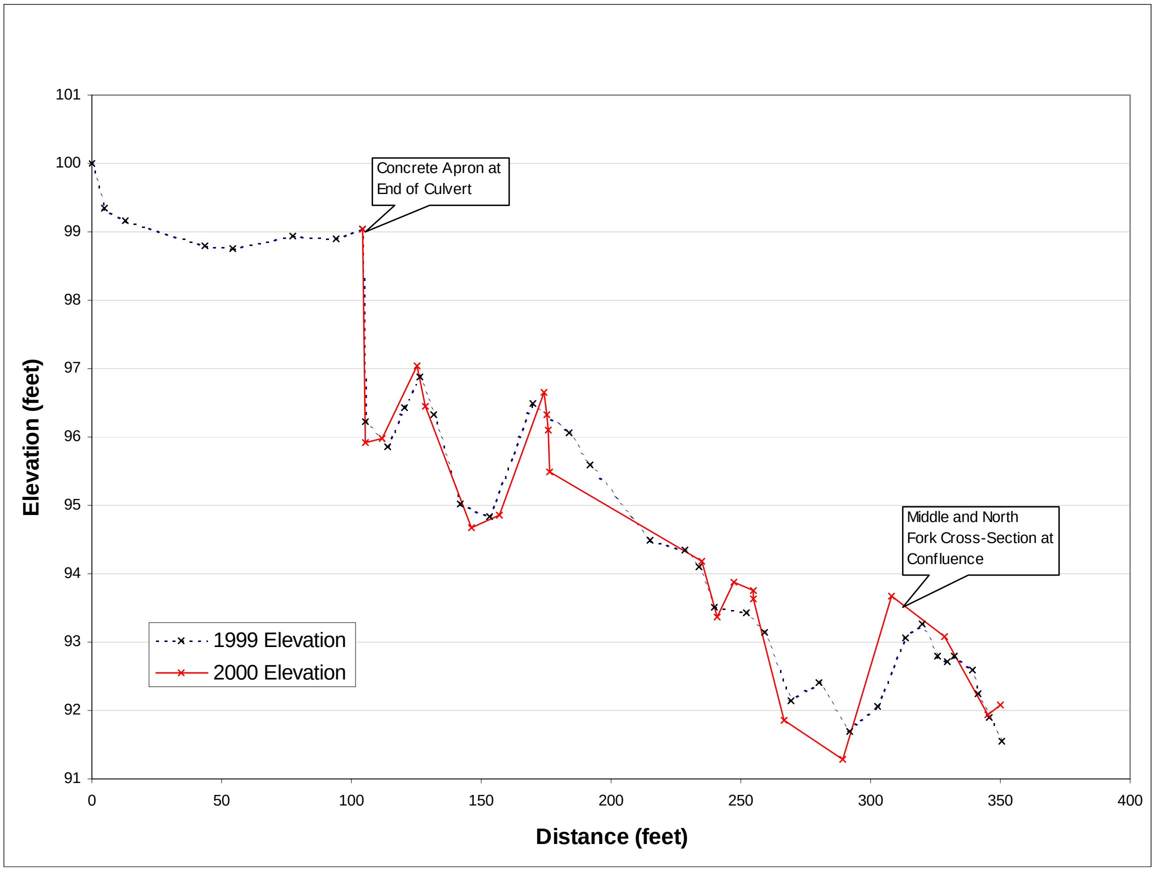


Figure 30. North Fork Longitudinal Profile, 1999 and 2000

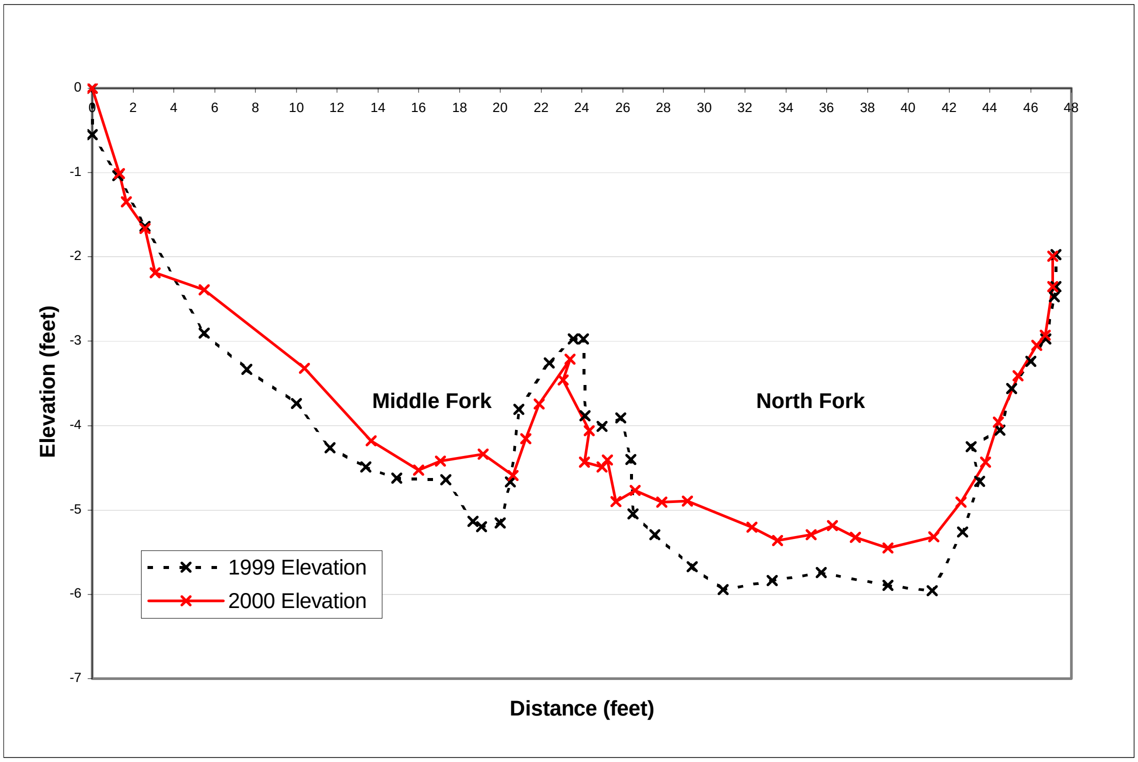


Figure 31. Middle and North Fork Cross-Section at Confluence, 1999 and 2000

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.

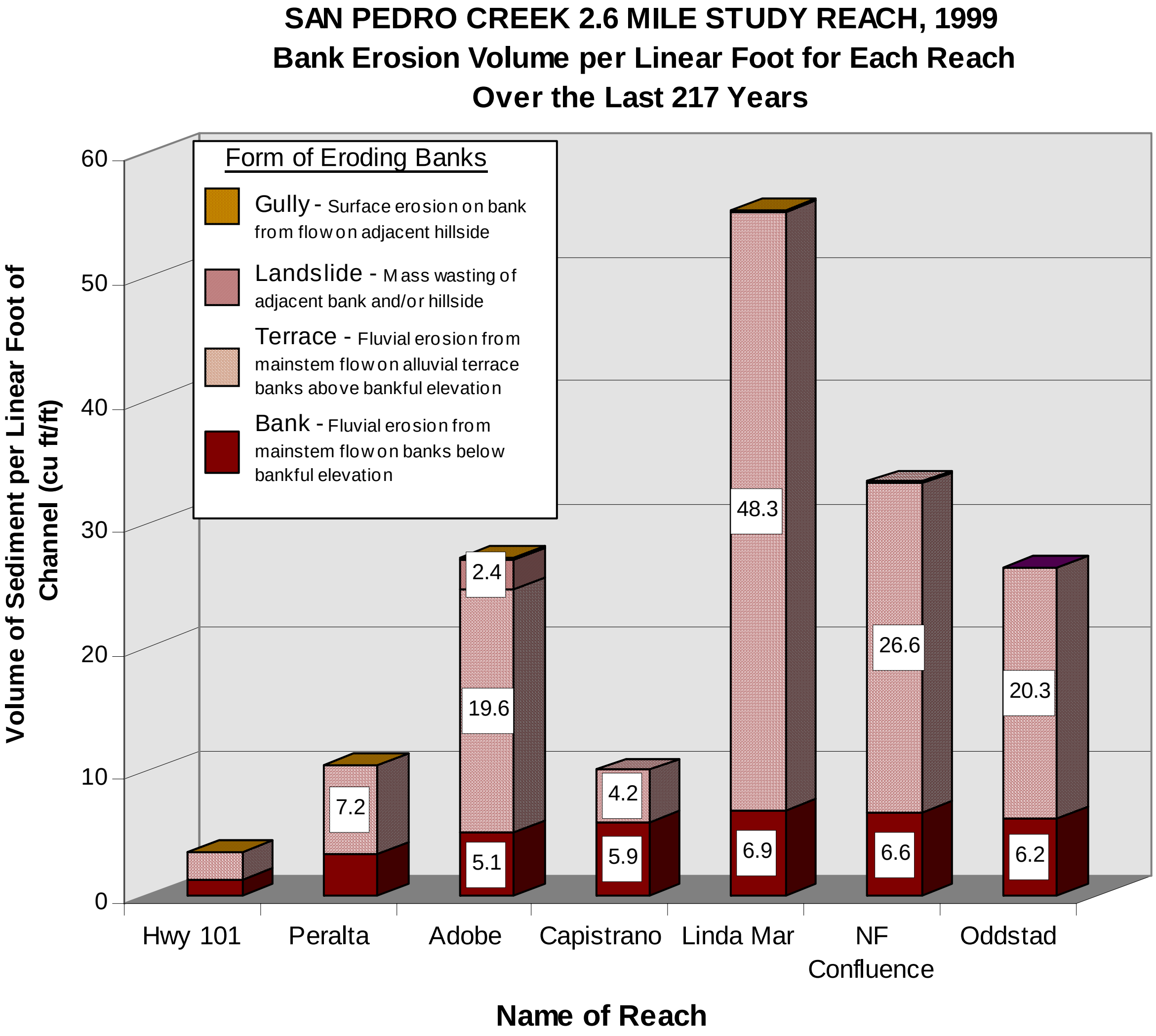


Figure 32. Bank Erosion Volume Per Linear Foot (Collins et al. 2001)