Flood Control Failure: San Lorenzo River, California

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ABSTRACT / The San Lorenzo River on the central California coast was the site of a major US Army Corps of Engineers flood control project in 1959. By excavating the channel below its natural grade and constructing levees, the capacity of the river was increased in order to contain approximately the 100 year flood. Production and transport of large volumes of sediment from the river's urbanizing watershed has filled the flood control project with sand and silt. The natural gradient has been reestablished, and flood protection has been reduced to containment of perhaps the 30 year flood. In order for the City of Santa Cruz, which is situated on the flood plain, to be protected from future flooding,it must either initiate an expensive annual dredging program, or replan and rebuild the inadequately designed flood control channel. It has become clear, here and elsewhere, that the problem of flooding cannot simply be resolved by engineering. Large flood control projects provide a false sense of security and commonly produce unexpected channel changes.

As a result of disastrous flooding within the City of Santa Cruz during December 1955, the US Army Corps of Engineers (COE) proposed a flood control project along the lower San Lorenzo River. The project consisted of levee construction and channel dredging for 4 km (2.5 mi) upstream from the river mouth. Since the 1959 completion of the flood control channel, heavy siltation has become a problem. Annual dredging to project depth has not been performed by the city as was originally agreed upon. Instead, the city has relied on river scour to remove the silt. Santa Cruz cannot now afford to remove the accumulated sediment, and as a result, cannot control the San Lorenzo River.

The San Lorenzo River drains 357 km^2 (138 mi^2) of the central California Coast Ranges (Figure 1). Annual rainfall in the redwood forested basin averages 120 cm (47 in). Flooding has been common within the communities that occupy the river's flood plain. Steep slopes, landsliding, and unstable soils combined with high intensity precipitation have led to severe erosion in certain parts of the basin. Logging, quarrying, and the grading and vegetation removal that accompany urban and rural developments have compounded the erosion and sediment production problem.

Excluding the population of the City of Santa Cruz at the river's mouth, the watershed is home to 33,000 people. Most of the population is concentrated along the stream bottoms of the river and its tributaries. This study utilizes hydrologic data collected over the past 30 years in the English unit system. For consistency, tables and figures utilize this original data, and conversion factors to

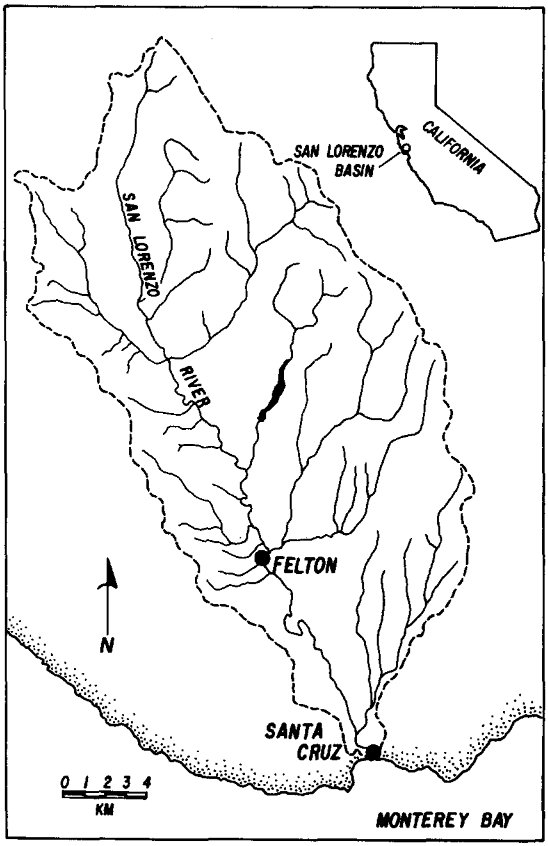

Figure 1. Index map showing the San Lorenzo River watershed and its location in California.

KEY WORDS: Flood control; Sediment transport; San Lorenzo River

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metric units are included. Within the text, the metric system is used exclusively.

Flooding

Within the United States, flooding, on an annual average, ranks second among all geologic hazards in property damage and first in fatalities (Costa and Baker 1981). Despite the construction of ever-increasing numbers of dams for flood control purposes, losses from flooding have continued to increase due primarily to expanded use, re-occupation, and development of downstream flood plains.

There is little doubt that river control works accelerate flood plain development. Once a sense of security from flooding has been established, the conversion of open space to densely populated areas becomes commonplace. Although flood control projects do offer protection from all events smaller than the design flood, (a flood of a certain size which a structure is designed to withstand or control) if properly designed, they will not be effective against the infrequent larger events. In other words, all flood control ends somewhere; we simply cannot afford to provide protection from the 500 or 1000 year flood (a flood which would only be expected to occur every 500 or 1000 years on the average). Thus as protected flood plain areas are more intensively developed, the potential damage from a great or catastrophic flood, which cannot be contained, continues to rise.

There is, in addition, a tendency for river control works to become self-perpetuating. Low-lying land that has been protected from the 20 year flood (the flood of such a size that would be expected to occur every 20 years on the average), because of that degree of safety, tends to become even more intensely developed. Eventually residents and property owners will demand protection from the 100 year flood. Any engineering protection, however, is both limited and temporary.

Overflowing rivers and streams regularly cause significant flooding in about half of the country's communities, spreading over at least 7% of the total land area in the United States (Griggs and Gilchrist 1977). Flooding and flood-control on the San Lorenzo River contribute to these statistics.

Although floods are natural events, their magnitudes and impacts can be intensified by human activity. Increased impervious surface and the channelization of storm runoff serve to increase both the frequency and magnitude of flood flows (Leopold 1968). At the present degree of urbanization, about 6% of the San Lorenzo basin above Santa Cruz is now impervious.

Developments located in the flood plain are not only more susceptible to damage, but also reduce the capacity of the flood plain to transport and store flood waters. They may actually increase the depth and areal extent of inundation. Virtually the entire downtown portion of Santa Cruz lies within the 100 year flood plain of the San Lorenzo River, (that area which would be inundated by a 100 year flood) as do certain residential areas along the river's upper reaches.

Logging and land clearing activity can contribute to flooding problems. Logjams can form as logs and other debris are swept downstream during high flows. Considerable damage during past floods in the densely wooded and heavily logged San Lorenzo basin was apparently caused by log jams occurring at bridges followed by river back-up and overbank flooding.

Flood season for the San Lorenzo River extends from November through April, although most historic floods have occurred in either December or January. These floods have generally been of short duration due to the small size and steepness of the basin. Although flood flows can rise very quickly, damaging stages do not last for more than 18–36 hr. Historic flooding occurred in January 1862, 1869, 1890, 1895, 1909, 1911, and in December 1931. It is not possible to establish magnitudes for these early events because flood levels were not accurately measured. Peak discharges have been recorded during major flooding in February 1940, December 1955, and April 1958, following the establishment of a gauging station near Felton in 1940. Flood frequency calculations have been developed for this station by both the US Geological Survey and US Army Corps of Engineers (Table 1).

Continued heavy rainfall during December 1955 led to severe flooding throughout the San Lorenzo basin. Fifty cm of rain fell between the 15th and 28th of December at Boulder Creek, with almost half of that (23 cm) falling on the 22nd of December. The gauging station at Big Trees recorded a 6.88-m stage with a discharge of 861 m^3/sec (30,400 cfs). Overflow occurred from the headwaters to the mouth, resulting in the maximum flood on record. Numerous log jams and other channel obstructions diverted the flood flows, causing streams to change from their normal alignment, undercut and scour out numerous bridges, road fills, and private developments (Corps of Engineers 1973). Seven persons lost their lives,

Table 1. Flood frequency data for San Lorenzo River (from US Geological Survey—Observed Peaks—extrapolated according to basin area downstream).

	Big Trees	Above Branciforte Creek	Below Branciforte Creek
Drainage area	105 mi^2	118.7 mi^2	137 mi^2
		Flood magnitude	
Recurrence interval			
2 yr	5,583 cfs	6,311 cfs	7,258 cfs
5 yr	12,972 cfs	14,658 cfs	16,864 cfs
10 yr	18,750 cfs	21,188 cfs	24,375 cfs
25 yr	26,398 cfs	29,830 cfs	34,317 cfs
50 yr	32,075 cfs	36,245 cfs	41,698 cfs
100 yr	37,586 cfs	42,472 cfs	48,862 cfs
Maximum flood on record	30,400 cfs	33,820 cfs	39,820 cfs
Standard project flood		46,800 cfs	53,000 cfs

1 mi^2 = 2.59 km^2; 1 cfs = 0.028 m^3/sec.

2830 people were displaced from homes, and damages amounted to $8.7 million, most of this within the City of Santa Cruz itself.

Flood Control

Almost two years before the 1955 flood, in the spring of 1954, the US Army Corps of Engineers (COE) applied to Congress for $2.265 million for the construction of a flood control project on the lower 4 km of the San Lorenzo River and lower Branciforte Creek in the City of Santa Cruz (Figure 2). Preliminary designs had already been completed using discharge from a 1940 flood. Channel capacities were projected as 1042 m^3/sec (36,800 cfs) above the confluence with Branciforte Creek, and 1150 m^3/sec (40,600 cfs) below this point, or approximately 113 m^3/sec (4000 cfs) input from Branciforte Creek.

The December 1955 flood apparently interrupted work and necessitated a re-evaluation of the Standard Project Flood, but also provided the COE with even stronger justification for proceeding with the project. Construction began in 1957 after revisions in the discharge capacities of the project: a 25% increase for the San Lorenzo and a 110% increase for Branciforte Creek, to 1303 m^3/sec (46,000 cfs) and 238 m^3/sec (8400 cfs), respectively (Corps of Engineers 1957).

The COE project consisted of the construction of levees for 4 km upstream from the mouth, and the excavation of about 590,000 m^3 (770,000 yds^3) of sediment from the existing channel, to increase the slope and capacity of the new channeled reach. The design channel bottom was lowered as much as 2.1 m below the natural or original river bottom (Figure 3). In conjunction with the excavation, the COE design utilized flow velocities of 2.4–7.5 m/sec (7.9–24.7 ft/sec) to move the necessary water volumes through the various design cross-sections.

In July 1959 the project was completed and was deeded to the City of Santa Cruz by the COE. The City agreed to maintain the channel to design specifications and was provided with a maintenance plan and procedure. In order to assure compliance with the terms of the agreement, the COE reserved only the rights of inspection. Annual maintenance costs were estimated by the COE as $25,000. Total project cost at time of completion was $6,466,000. The Corps departed at this point, absolved of all further responsibility. No one at the time questioned the wisdom of altering the channel gradient, the velocities used in the design, or the size of the channel. Because the Corps presumably had the most experience in the field, it was assumed that the project as planned was the best long-term solution.

Flood protection assured, Santa Cruz intensively redeveloped the former flood plain of the now tamed San Lorenzo River over the next ten years. A shopping mall became the showpiece of a downtown renovation project.

Figure 2. The City of Santa Cruz and the San Lorenzo River Flood Control Project in 1971. Dashed line delineates the flood plain. Numbers refer to individual bridges. (1) Highway 1, (2) Water Street, (3) Soquel Avenue, (4) Riverside Avenue. Arrow indicates point where Branciforte Creek enters San Lorenzo River.

The early seventies, however, brought some threatening revelations about the safety of downtown Santa Cruz and the condition of the channel. A 1975 channel centerline survey showed that at least 306,000 m^3 (400,000 yds^3) of sediment had accumulated, reducing the project's capacity significantly. Annual dredging to project depth was not performed by the city; public works officials felt that high winter flows would scour the accumulated sediments out to sea. This scour did not occur. Subsequent surveys have shown only minor variation in the amount of channel fill that now stands at about 350,000 m^3 (Figures 3 and 4).

The State Department of Water Resources discovered the situation in 1976, and threatened to assume responsibility for clearing the channel and charge the City of Santa Cruz for the dredging later. Responding to these official warnings, the city began to pile up sediment within the channel over the last four years, (again hoping for winter scour to remove the sand—Figure 5), and also started to remove sediment on a small scale. (As of December 1981 less than 76,000 m^3, [100,000 yds^3] had been removed). However, the city is now unable to finance the removal of the accumulated sediments, which has been estimated to cost as much as $3 million initially and at least $200,000 annually to maintain. These are considerably different figures (even allowing for inflation) than the Corps estimated in 1959 ($25,000/yr). As a result, the city is concerned both about the cost of removing the sediment and the potential flood hazard of leaving the sediment in the channel.

If the present channel bottom does not change significantly from scouring during a large storm, it has been determined that some individual cross-sections could only contain the 25–30 year flood (Table 2). This is of

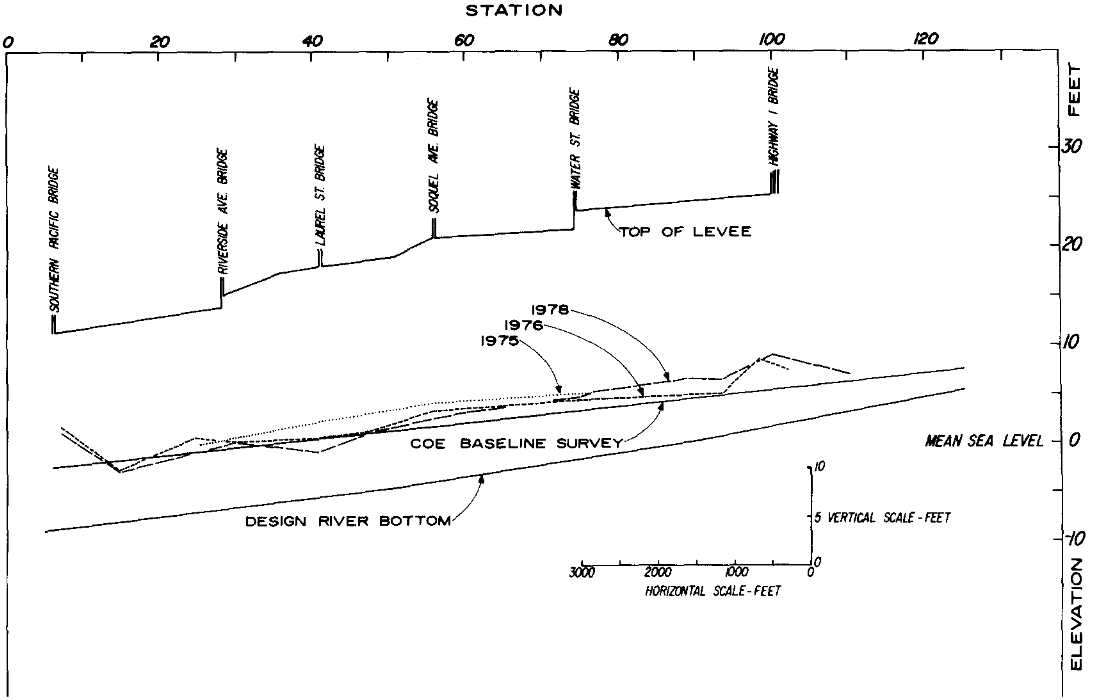

Figure 3. Changing gradient of the San Lorenzo River as it passes through Santa Cruz. Note contrast between original or design river bottom and surveys taken in late 1970's. Baseline survey refers to channel condition prior to Flood Control Project commencement in 1959. Station numbers refer to distance upstream from the river mouth in hundreds of feet (station 20 = 2000 feet).

immediate concern for insurance purposes because the city is no longer protected from the 100 year flood. Santa Cruz participates in the Federal Flood Insurance program. Unfortunately the Flood Insurance Administration (FIA) at this point has only preliminary 100 year flood plain maps for the city, which are now outdated; as a result the only area officially included within the 100 year flood plain lies between the levees within the river channel. Thus new construction continues to occur on the flood plain. An updated map delineating the present flood hazard and a city ordinance dealing with this situation are at least two years away. When this update is completed, however, much of the downtown area will fall within the 100 year flood plain. Federal loans may no longer be available for buying, building, or repairing structures in the flood plain because other non-hazardous sites are available (1972 Executive Order). In addition, during the present or emergency phase of the program, until final maps have been prepared, maximum federal insurance coverage amounts to only $35,000 for single family homes; $100,000 for multiple housing units. These amounts are less than one third of average existing values in the area. Santa Cruz is thus stuck with a poorly designed project, a difficult dilemma, and the potential for financial disaster. Why has this happened? Are they any solutions, and can we learn something from this expensive mistake?

The Effect of Altering the Natural Channel Gradient

An equilibrium condition in fluvial systems is referred to as graded or at grade. In 1948 Mackin defined a graded stream as one in which, over a period of years,

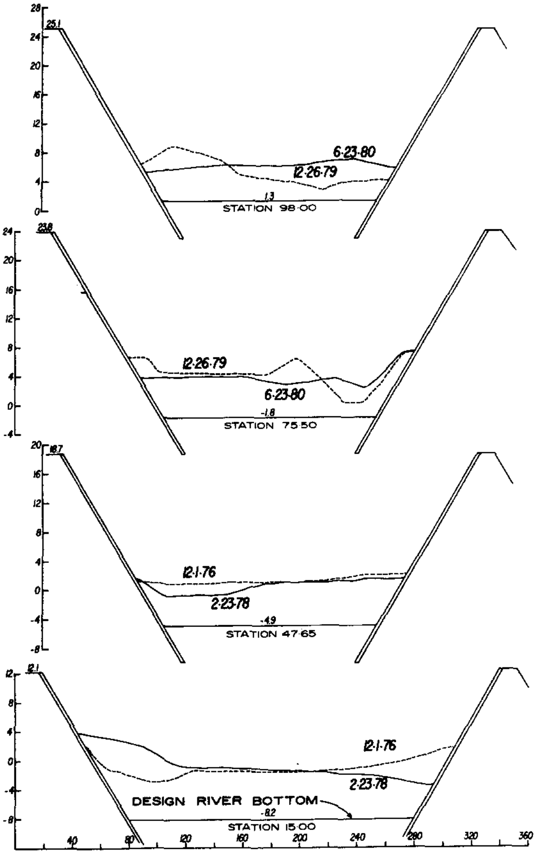

Figure 4. Selected channel cross-sections along San Lorenzo River in Santa Cruz showing extent of channel fill above original design channel bottom. Station locations refer to Figure 3. Vertical scale and elevations of levee and channel base are in feet relative to MSL.

slope is delicately adjusted to provide with available discharge and prevailing channel characteristics, just the velocity required for the transportation of the load supplied by the basin. This equilibrium is a dynamic process that is continually reacting to changing hydraulic conditions and basin sediment production. Water velocity, channel slope, and sediment transport capacity are adjusted in response to variations in the discharge, channel morphology, and sediment availability.

Figure 5. San Lorenzo River channel immediately upstream from the Water Street bridge showing efforts by the City Department of Public Works to pile up sediment in hopes of flushing by high flows.

It is assumed that the lower San Lorenzo gradient of 0.00083 was in equilibrium at the time the COE began their project. The removal of 590,000 m^3 of material increased the slope over the last 4 km to 0.0011, a 32% increase. This involved deepening the channel bottom below the existing thalweg (deepest part of a channel or stream bottom) some 0.9–2.1 m (3–7 ft). To either side of the thalweg up to 4 m of material was removed (Figure 4). The beach berm at the mouth of the river was apparently left intact except for a small pilot channel excavated to −0.6 m MSL (0.6 meters below mean sea level). The design was based on this berm being scoured out by high flows, which was based on past experience. However, just upstream, the channel had been deepened to −2.7 m MSL.

The base level that controls the channel grade is the ocean. The channel was initially dredged to 0.3 m MSL at the Highway 1 bridge (4 km from the mouth) such that the semi-diurnal tide extended to the upper reaches of the project. During a spring tide of 2 m MSL, 1.7 m of standing water would occur at the bridge.

The anticipated hydrologic response of flowing water entering a standing body of sea water would be a reduction in velocity with accompanying deposition of sediment load. The improved channel was actually a sink that would eventually be filled with sediment from the watershed, much like how a dam or reservoir traps

Table 2. Flood magnitudes and recurrence intervals for various river channel cross-sections within the city of Santa Cruz.

Station	Bottom width (ft)	Top width (ft)	Depth (ft)	Channel area (ft^2)	Wetted perimeter	Hydraulic radius	Water surface slope	Velocity (ft/sec)	Discharge (ft^3/sec)	Recurrence interval (yrs)
98 + 00									@n = .025	
June 1980	182	292	18.6	4408	300	14.7	0.00075	9.8	43,213	~100
Aug. 1979	191	292	17.0	4106	298	13.8	0.00075	9.4	38,592	68
94 + 00										
June 1980	182	293	18.8	4465	301	14.8	0.00062	9.0	39,979	75
Aug. 1979	204	293	15.2	3777	300	12.6	0.00062	8.0	30,376	26
90 + 00										
June 1980	184	298	19.4	4675	307	15.2	0.0005	8.2	38,265	65
Aug. 1979	199	298	16.8	4175	305	13.7	0.0005	7.6	31,884	30
80 + 00										
June 1980	177	298	20.2	4798	305	15.7	0.00065	9.5	45,754	>100
Aug. 1979	186	298	18.6	4501	304	14.8	0.00065	9.2	41,264	90
74 + 91										
Feb. 1978 Branciforte Creek enters	190	310	18.9	4725	310	15.2		~9	~42,525	~ 95
59 + 75										
Feb. 1978	283	392	18.2	6142	398	21.9		~9	~55,278	>100
40 + 80										
Feb 1978	187	290	17.3	4126	353	11.7	0.0011	8.1	40,126	42
15 + 00										
Feb. 1978	244	320	12.5	3525	323	10.9	0.00135	8.8	37,277	32

1 ft = 0.304 m; 1 cfs = 0.028 m^3/sec.

sediment; this process continues until the channel returns to an equilibrium slope. Periodic surveys of the channel center line and various cross sections suggest that equilibrium has been reached. However, the new equilibrium channel has a different profile than either the original or the design channel in the reach between Soquel and Highway 1 bridges (See Figure 3). The increased channel width and an increase in river sediment load have created a new equilibrium gradient in this reach. The channel bottom is now 2 m above the initial design bottom and 0.9 to 1.2 m above the original natural channel. That these conditions represent equilibrium is substantiated by the survey observations that indicate that the channel has undergone no major changes between 1974 and 1979, a period which has included both wet and dry years.

The estimated quantity of sediment that must now be removed in order to restore the design channel is about 350,000 m^3 (450,000 yds^3). The Corps made no mention of deposition problems in their design manual except to note frequent dredging would be required to maintain the channel grade. The basis for the Corp's estimate of annual dredging cost is unknown, but no sediment discharge measurements from the watershed has been made at the time the project was initiated.

Sediment Yield and Transport

Sediment yield within the San Lorenzo watershed is high; volumes of material transported by major runoff events can be very large. The natural basin conditions (steep and unstable slopes, highly erodible soils, and high intensity precipitation) combined with the vegetation removal and soil disturbance accompanying logging, quarrying, roadbuilding, and construction activities have all contributed

Table 3. Summary of sediment load measurements at Big Trees, 1973–1979.

	Suspended sediment (tons)		Bed load (tons)	Total sand-sized load		Total load	
Water year	Total	Sand-sized		Tons	Cubic yards 100 lb/ft^3	Tons	Tons/mi^2 106 Mi^2
1973	483,212	197,195 (45%)	14,827	212,022	157,000	498,039	4698
1974	93,350	49,475 (53%)	11,608	61,083	45,200	104,958	990
1975	66,194	23,829 (36%)	6,108	29,937	22,200	72,302	682
1976	532	122 (23%)	104	226	170	636	6
1977	563	28 (5%)	5	33	24	568	5
1978	335,581	97,318 (29%)	13,624	110,942	82,097	349,205	3294
1979	28,877	3,465 (12%)	722	4,187	3,098	29,599	279
1980	422,780	198,706 (47%)	4,120	202,826	147,454	426,900	4027
Annual average	178,886	71,267	6,391	77,701	57,136	185,275	1747

1 ton = 0.907 metric tons; 1 yd^3 = 0.76 m^3; 1 ton/mi^2 = 0.29 metric tons/km^2.
Source: US Geological Survey (1973–1980).

to high erosion rates and the production of large volumes of sediment. Much of the construction and population growth in the watershed (population has tripled from 1960 to 1979, from 11,600 to 33,000 people) has occurred in areas with soils that are particularly erosion prone. The Santa Cruz Office of Watershed Management (1976) estimates that the 2- to 4-fold increase in sediment production during these years is directly attributable to human disturbance of the basin's soils.

Suspended sediment and limited bedload measurements have been collected at two stations within the basin by the US Geological Survey and the University of California, Santa Cruz intermittently since 1973 (Table 3 and Figure 6). Using the sediment transport curves, flood frequency distribution, and particle size breakdown, projections can be made for the magnitude of sediment transport under various flood conditions as the river passes through Santa Cruz (Table 4). For example, the ten year flood can carry over 800,000 metric tons/day (520,000 m^3) of sand-sized or larger material in suspension. Bed load would increase this by 5 to 10%. If a sink (as was created in the flood control project), or tide water was encountered by material of this size in transit, it seems probable that much of it would be deposited. Again, although flood conditions would not normally persist for 24 hours, even 8 hours of the ten year storm could produce 173,000 m ^{3} (228,000 yds^3). Significant volumes of sediment can be transported by the two or five year events. Although the annual discharge of sand-sized material is highly variable, a reasonable estimate for a long-term average is 45,000 m^3/yr (60,000 yds^3, see Table 3). Even if the channel were to be dredged to original project design, sediment carried by one large flood flow (or even the cumulative effect of several years of moderate flow conditions) could soon fill the channel back to an equilibrium grade. This raises serious questions about the effectiveness of annual dredging as a solution to the flood control problem.

Flood Flows and Channel Capacities

In reviewing the COE design manual for the San Lorenzo River Flood Control project it became apparent that some of the velocities utilized were unrealistic. Flow velocities of 2.4–7.5 m/sec (7.9–24.7 ft/sec) were used in design calculations. These velocity changes are projected to occur within the last 4 km of river course. The extre

Table 4. Sediment transport capacity of San Lorenzo River below Branciforte Creek in the City of Santa Cruz.

Event recurrence interval	Discharge (cfs)	Suspended sediment (tons/day)	Suspended sediment (>sand size–tons/day)	Suspended sediment (sand size-yds^3/day @100 lb/ft^3)
2 years	7,528	175,000	56,000	41,000
5	16,864	1,000,000	320,000	237,000
10	24,375	2,600,000	832,000	616,000
25	34,317	5,000,000	1,600,000	1,185,000
50	41,698	7,000,000	2,240,000	1,659,000
100	48,862	12,000,000	3,840,000	2,844,000

cfs = 0.028 m^3/sec; 1701 = 0.807 metric tons; 1 yd^3 = 0.76 m^3.

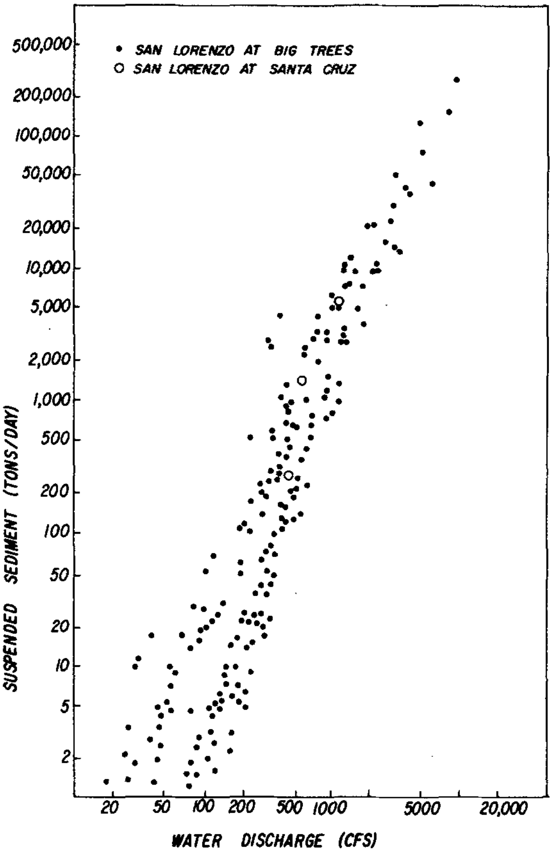

Figure 6. Suspended sediment rating curve for the San Lorenzo River at Big Trees (Felton). Three samples from the Santa Cruz reach of the river have been added.

changes in velocity detailed in the design manual would require dramatic changes in physical characteristics of the channel that do not occur. Recent modeling of flood flows under design channel conditions indicates that the 10 year flood would have velocities of only 2.4–3.7 m/sec (8–12 ft/sec), and that the Standard Project Flood (SPF) would attain a velocity of 5.5 m/sec (18 ft/sec) at the river mouth (Jones-Tillson and Associates 1979). This same study, which reviewed the flood control problem, concludes that current data indicates that the Standard Project Flood selected was close to the 100 year event. Utilizing 1979 channel conditions, Jones-Tillson and Associates used a Corps of Engineers computer program (HEC-2 and HEC-6) to pass various flood flows through the channel under differing scour and friction conditions. Some major finds were that with no scour and a friction factor of 0.025, the maximum flow that can be passed by the channel with 3 ft of freeboard is as low as the 10 year event (24,300 cfs); and that even if scour down to design project bottom is assumed to occur at the Riverside Bridge, the 50 year flood (40,700 cfs) cannot be contained (see Figure 7). Manual calculations using the Chezy-Manning equation, and cross-sectional profiles surveyed in 1978–1980 along the entire channel indicate that flood flows as small as the 30 to 40 year event would top the levees at some locations (see Table 2).

The unavoidable conclusions are that 1) the San Lorenzo River channel is now at equilibrium grade, and the sediment fill appears from all evidence to be stable; 2) the channel can no longer carry the 100 year event, and in fact, cannot in all probability hold the 30–40 year flood; and 3) downtown Santa Cruz is endangered, and has far less protection than is required by the Federal Flood Insurance Act. The $6.5 million flood control project designed by the Corps grossly underestimated the sediment load being carried by the river, and also

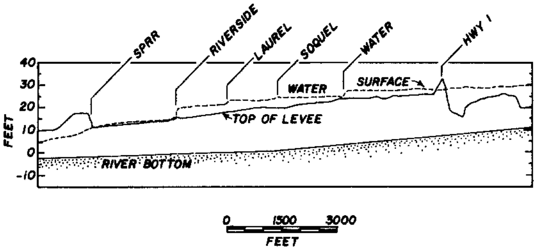

Figure 7. Projected water surface profile for 50 year flood assuming friction factor of 0.025 and no scour (from computer runs by Jones-Tillson and Associates (1979)).

failed to account for the changes in channel equilibrium gradient which would be produced by the alteration of channel morphology.

Future Options

There are no simple solutions to the current flooding dangers from the San Lorenzo River. One important factor to consider in any proposal to alleviate the problem is whether the solution is permanent and deals with the root cause or is simply a temporary stop gap approach. Although the latter may appear to be easier and cheaper over the short term, it will never resolve the real problem.

Option 1

Dredging and removal of all the accumulated sediment from the channeled reach of the river would cost about three million dollars today. Although this would reduce the immediate flood threat to the city, it would offer only temporary protection. At an average annual sand transport rate of 45,000 m^3, either channel capacity would soon be reduced, or expensive (estimated $100–200,000) yearly dredging would be required. During dry years the required sand removal would be minimal, but after a winter of high discharge, costs would be considerable. Inflation would also raise the removal costs per cubic meter each year. The city currently is using this dredging approach, but has only been removing sediment from the channel on a very modest scale. Channel surveys indicate that upstream sand input from winter flows are keeping pace with the sand removal operations.

Option 2

A combination of erosion control measures and sediment or debris basins could be used to reduce downstream sediment transport in the San Lorenzo River. This effort would have to be accompanied by initial dredging of the channel reach through Santa Cruz in order to provide the required flood protection. The logical approach would be to concentrate on the retention of sediment being produced in high erosion areas. Although the amount of coarse-grained sediment reaching the downstream channel could be greatly reduced by sediment traps, maintenance dredging of these basins will be required. Stream traps of this sort would definitely have an impact on fish populations. Although any erosion control measures in the watershed would be beneficial, the cost, maintenance, and biological effects of a number of large sediment traps on the San Lorenzo River or major tributaries are serious negative factors. Construction costs at present for debris dams impounding watersheds less that 1 mi^2 have been estimated at $50,000 to $100,000 with annual sediment removal costs of perhaps $12,000 (Jones-Tillson 1979). For comparison, costs for 20 such structures would approximate the initial outlay and annual costs of maintaining the downtown channel.

Option 3

A single large dam on the San Lorenzo itself or several smaller dams on major tributaries could reduce flood peaks by 20,000 cfs such that the present channel could convey the reduced flood flows. No suitable site exists on the San Lorenzo for a dam of this sort without inundating populated areas. Construction costs and environmental impacts of the number of smaller dams required make this alternative an unattractive one.

Option 4

The levees and bridges could be raised in order to increase the channel capacity such that the 100 year flood could be effectively contained. This option essentially enables the channel gradient to remain at its equilibrium position and allows for increased flood capacity through raising the banks. The cost for the replacement of four bridges and a 6-ft increase in levee heights is estimated to be $20 million, over 3 times the cost of the original project (Jones-Tillson and Associates 1979). Any flood control project of this sort has an obvious economic limitation and the 100 year flood may well occur and top the banks despite the expenditure of $20 million. Should a flood large enough to breach the levees occur, the height of the flood waters above the channel floor would provide a hydraulic head that could quickly erode the levee and inundate downtown Santa Cruz.

Option 5

Widening the existing channel to accommodate major floods is a final approach that may make the most hydrologic, biologic, and economic sense in the long run. A width increase of about 18-m along the reach between the Highway 1 and Water Street bridges would increase channel capacity to original design conditions. Closer to the mouth where present channel capacity is lower than it is just upstream, the width increase required would be about 34 m. This proposal presents some challenges and also opportunities. Widening would allow for reconstruction of some of the river's natural meanders.

Utilizing a meandering pattern would only require rebuilding one of the levees at any particular location. A survey of land adjacent to the river shows that streets, parking lots, used car lots, parks, and tennis courts occupy much of the 18 to 34 m of land in question. These uses could be continued after excavation. The widening of the river could be designed such that a smaller pilot channel could hold perhaps the *5 to 10 year event*. Much of the remaining channel could be vegetated as a downtown park and green belt such as the recessed park which presently exists between Soquel and Water Streets adjacent to the river. Other higher flood plain land could be used for the previously mentioned parking and streets except during and immediately after major flood events. The pilot channel could also provide an adequate flow depth for anadromous fish migration.

Existing bridges could probably be extended, obviating the complete bridge replacements necessitated by Option 3. Some houses and small commercial buildings may have to be removed, but initial investigation indicates that displacement need not be extensive. Much of required land is city property, which would lower acquisition costs.

Conclusions

In any analysis of flood control on the San Lorenzo River, three major flaws stand out. The first is the gradient alteration of the COE flood control project design. The second is the computations of flood flow velocities. The third occurred as a result of the first two design errors, and that is the size of the channel.

While the excavation of the natural channel's equilibrium gradient initially increased the project's capacity and slope, it also created disequilibrium to which the river had to re-adjust. The design velocities estimated by the Corps were too high, and as a result, the channel was too small at the onset to hold the design flood. The sediment fill in the channel has reduced its capacity to the point of possibly containing only the 30 to 40 year event along its upper reaches, and even less near the mouth at the Riverside Avenue bridge. In 1978 the 5 year event came within a meter of overtopping the bridge. Owing to the small cross sectional area beneath the bridge, a high tide combined with slightly higher discharge (than the 1978 event) would lead to flooding in this area. Because the channel can no longer contain the 100 year event, federal loans or funding may no longer be available for buying, building, or repairing buildings in the downtown area.

Any solution that will resolve the initial design problem is going to be expensive and controversial. All options should be considered for both their short- and long-term impacts and protection provided, as well as for their economics. As hydrologists, engineers, and planners, we must begin to focus our efforts on controlling our own activity and land use, rather than our ineffective historical approach of an increasingly expensive system of dams, channels, and levees. We can never afford complete flood protection, either as a community, state, or nation. The continued increase in annual flood losses despite the construction of an ever increasing number of flood control structures is clear testimony to the failure of river control. The San Lorenzo River and countless others are at a crossroads; we cannot afford a repeat of past mistakes in the years ahead.

Addendum: January 1982 Flooding along the San Lorenzo River

On January 3, 1982 two storm fronts converged on the central California coast and produced intense rainfall that lasted about 28 hours. Twenty-four hour rainfall reached as high as 11–19 inches in upper parts of the San Lorenzo River watershed and exceeded the 100 year storm. Prior rainfall had already been considerably above the seasonal average so that the intense rain fell on saturated ground. As a result, flooding and mass movements such as landslides and mudflows were widespread in the area.

The upper reaches of the watershed were hit particularly hard; hundreds of homes were damaged or destroyed, and at least 20 lives were lost. Within the City of Santa Cruz the river rose to 4 to 5 feet of the top of the levees, and actually overflowed onto parklands and a roadway at one point (see Figure 8). The large logs and trees (up to 60 ft long (see Figure 9)) that were swept

Figure 8. San Lorenzo River looking upstream from the Riverside Avenue Bridge at 1:00 P.M. January 4, 1982. Overflow actually occurred at Arrow, and much of the old roadway along left side of photo was undercut.

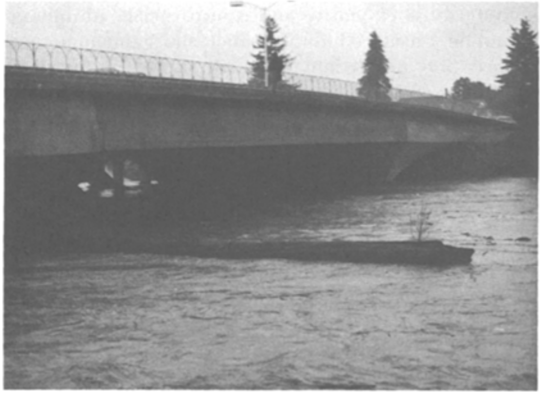

Figure 9. San Lorenzo River at Water Street bridge at 1:00 P.M. January 4, 1982. Redwood log is approximately 50 feet long. Logjams and flooding were averted at bridges by utilizing large cranes throughout the peak flows on the evening of January 4.

Figure 10. The Riverside Avenue bridge nearing capacity. River stage peaked about 2 feet above this point. Although no overflow occurred, the bridge foundation was damaged by scour.

Figure 11. Failure of one downstream span of the Soquel Avenue bridge. Note high water mark. Scour led to settling of an older pier supporting the down stream span.

down the river piled up at bridges, but prompt action by the City with heavy equipment prevented damming and flood water back up. Maximum discharge capacity beneath the Riverside Avenue bridge was reached, but no overflow occured (see Figure 10). Cracking of the bridge, perhaps from scouring, did lead to its closure. Severe scouring around bridge piers did lead to collapse of one span of the Soquel Avenue bridge (see Figure 11). Unfortunately half of Santa Cruz' telephone circuits passed beneath the span and were severed when collapse occurred. Bridge repairs are estimated at $1.75 million.

Fortunately for Santa Cruz, the flood peaked at low tide and Branciforte Creek peaked several hours before the main San Lorenzo. These two events may have saved the entire downtown area from inundation. Preliminary calculations by the US Geological Survey indicate a peak discharge at the Big Trees gauging station of 29,700 cfs, slightly less than the greatest historic peak recorded during the 1955 floods (30, 400 cfs). Research is now underway to evaluate what return period this flood represents. A follow up article on the magnitude and significance of the flood, as well as its impact on the flood control project will be forthcoming.

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