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UPSTREAM CHANGES AND DOWNSTREAM EFFECTS OF THE SAN MARCOS RIVER OF CENTRAL TEXAS

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Abstract.—Changes in the headwaters of the San Marcos River, with an area of 247 km^2, have caused major sedimentation and exotic plant invasion problems in its course through the city of San Marcos. Construction of upstream flood control dams, with insufficient flow-through provisions, has reduced the effective unregulated upstream drainage to 47 km^2 and reduced mean annual flood from 510 m^3/sec (18,000 ft^3/sec) to 42 m^3/sec (1,500 ft^3/sec) which is less than the threshold value required for scouring the river channel. Headwaters area construction downstream of the flood control structures, particularly on the Southwest Texas State University campus, has increased sediment production from 160 m^3 to 920 m^3/year. Since 1990, the combined effects of these changes have produced up to 0.50 m sedimentation in the main channel and an increase in exotic riparian and aquatic vegetation. Of the remedial actions proposed, the only likely option involves increased efforts to reduce sediment production from construction sites. The October 1998 flood, triggered by a larger than 100-year precipitation event (401mm/24hr), demonstrated that the flood control structures reduced peak discharge in San Marcos to a discharge that would have been approximately a twenty-five year event. This event did not produce the sediment scour that would have been expected which suggests that sediment increases and not a reduction of flows are the major cause of the sedimentation.

San Marcos, Texas, like many rapidly growing Sunbelt cities, faces the often conflicting goals of protecting aesthetic and recreational resources while providing flood protection. In 1970 the city had a population of 18,900; the 1995 estimate was 37,000 (City of San Marcos 1996) and the 1999 estimate was 41,000 (Greater San Marcos Economic Development Council 2000) even though the "official" 2000 census value was 34,733, which has prompted a city drive for a higher readjusted value (U.S. Bureau of the Census 2001). Southwest Texas State University (SWT), totally within the city limits, has grown from 9,900 students in 1970 to more than 22,000 in 2000 (Southwest Texas State University 2001). The San Marcos River was singled out in the 1996 city comprehensive plan as a unique resource that needs to be protected for the aesthetic benefit of residents and as a basis of the city's tourism industry (City of San Marcos 1996). Each year, the San

Marcos River draws more than an estimated five hundred thousand visitors for water based recreation and civic activities adjacent to its banks (Greater San Marcos Economic Development Council 2000). Baseflow for the river flows from springs draining the Edwards Aquifer; floodflow is produced by a 247 km^2 headwaters with ephemeral flow.

Management and protection of the San Marcos River not only is motivated by concern for its benefit to the city; it is habitat to four federally listed endangered species, two fish, a salamander and Texas wild rice (Texas Parks and Wildlife Department 1993). In response to a 1992 federal court order to develop a habitat protection plan, the State of Texas has created the Edwards Aquifer Authority that has imposed pumping limits and has developed additional drought management pumpage restrictions (Votteler 1998). Characteristic of its location along the Balcones Escarpment, the San Marcos River has the potential for generating huge flood discharges (Baker 1975). The flood of May 15, 1970, which had an estimated discharge of 2,170 m^3/sec (76,600 ft^3/sec), resulted in two drownings and the city being declared a federal disaster area (Upper San Marcos Watershed Reclamation and Flood Control District 1991).

The 1970 flood was the stimulus for efforts to create the Upper San Marcos Watershed Reclamation and Flood Control District (USMWRFCD) in 1971. A flood on June 13, 1981 that forced the evacuation of 1,800 people provided the political catalyst for the funding of US Soil Conservation Service flood control dams upstream of San Marcos. The last of five flood control dams on the upper San Marcos watershed was completed in 1991 (USMWRFCD 1991). These dams have a combined capacity of 23 million m^3 (19,000 acre feet) and reduced the uncontrolled drainage area from 247 km^2 to 47 km^2. (U.S. Soil Conservation Service 1978). Construction in the upstream area, but mostly downstream of the flood control dams, has produced sedimentation in the perennial flow reaches of the river in San Marcos (Miller 1996). Also, the public has increasingly complained about clogging of the channel by vegetation (Wood 1998). The flood control project received a major test in October 1998 when a storm with an official San Marcos 24-hour total of 401 mm (15.78 in) produced runoff amounts that exceeded the 254 mm (10 in) standard project flood design and produced considerable flooding in San Marcos (U.S. Soil Conservation Service 1978; U.S. Natural Resources Conservation Service 1999).

The purpose of this paper is to report on the changes in the headwaters of the San Marcos River and their downstream effects, both planned for and unplanned, since the construction of the five upstream flood control structures that began in 1981. A particular focus of this paper will be the effects of these flood structures on the October 1998 flood. Not included in this analysis are effects of the damming of San Marcos Springs in 1849 to form Spring Lake, which was developed into the popular commercial site known as Aquarena Springs (Mays et al. 1996), nor will this paper analyze the effects of the construction of small irrigation and hydroelectric dams (Rio Vista and Cape's Camp dams) downstream of San Marcos Springs during the late 1890s and early 1900s (McGehee 1982; Stovall 1986; Spain 1994). This paper is intended to complement the recent study on water quality characteristics of the San Marcos River by Groeger et al. (1997) and contains updated bibliographic references to augment those in Saunders (1992).

Methods and Materials

After describing the basic hydrology of the upper San Marcos River basin, this paper will analyze the changes in the watershed since 1970 and the efforts to mitigate the flood hazard and also summarize the discharges generated by the October 1998 event in upstream tributaries as well as the main channel in San Marcos. An analysis of the flood frequency of the modern stream will provide for an assessment of the stream's ability to transport the increased sediment supply that construction within the basin has produced. A series of management options for the stream under its new regime of reduced peak discharges and high sediment production will also be presented. Major data sources include the flood control project (U.S. Soil Conservation Service 1978; USMWRFCD 1991) and discharge data for the San Marcos River from the U.S. Geological Survey (USGS) gaging stations in San Marcos (USGS 1921; 1956-1999). Basic surveying methods were used to measure channel geometry and metal rod penetrometers to measure sediment depth to the nearest 0.1 m (Goudie 1990; Wood & Gilmer 1996). Currently available models were used for the calculation of hydrologic relationships for the basin and the channel. These included the Universal Soil Loss Equation model, which calculates annual sediment yield as a function of basin characteristics and the U.S. Soil Conservation Service TR 55 Runoff model, which calculates storm runoff as a function of storm intensity and basin characteristics, (Dunne & Leopold 1978; US Soil Conservation Service 1986; Chow et al. 1988; Dingman

1996). The U.S. Geological Survey Slope-Area method (Dalrymple & Benson 1967) was used to estimate peak discharge at ungaged sites for the October 1998 storm.

THE SAN MARCOS RIVER BASIN

The study area includes the 247 km^2 area within the Upper San Marcos Watershed Reclamation and Flood Control District (USMWRFCD) which includes the entire drainage of the San Marcos River upstream of its confluence with the Blanco River approximately 3 km southeast of Interstate Highway I-35 (Fig. 1). Discharge data for the basin has been provided since 1956 by U.S. Geological Survey (USGS) gage no. 08170000, which has been located at several sites along the river between the confluence with the Blanco River and downtown San Marcos, approximately one kilometer west of I-35 (Fig. 1). In 1994 the USGS installed another gage (08170500) where the river crosses under Aquarena Drive, approximately 1.5 kilometer west of I-35. This latter gage provides direct measurement of discharge whereas the original gage (08170000) was replaced by a well monitor in 1988 to estimate spring-flow/river baseflow from piezometric elevations. Approximately 124.7 km^2 of the basin is upstream of San Marcos Springs, formerly known as "Aquarena Springs," and another 121.9 km^2 comes from tributaries that enter the stream between San Marcos Springs and the Blanco River confluence, most of which comes from Purgatory Creek that drains the southern and western portions of San Marcos and adjacent areas. The changing of gaging station location necessitates consideration of where discharge measurements/values are based when analyzing the discharge record for the "San Marcos River at San Marcos." The area of former station no. 08170000 was listed by the USGS as 233.4 km^2, whereas station no. 08170500 has a drainage area of 129.7 km^2.

Virtually all of the non-flood flow in the river is supplied by San Marcos Springs, located on SWT property on the former Aquarena Springs commercial recreation site. These springs are the lowest natural piezometric outlet for the San Antonio section of the Edwards Aquifer (Hanson & Small 1995). In August 1956 (during the 1950s drought) the flow decreased to 1.3 m^3/sec (46 ft^3/sec), less than one third the 1957-1995 mean spring flow of 4.8 m^3/sec (170 ft^3/sec) (Table 1).

Near world-record rainfall intensities, provided by direct access to maritime tropical air from the Gulf of Mexico, and thin clay-rich soils

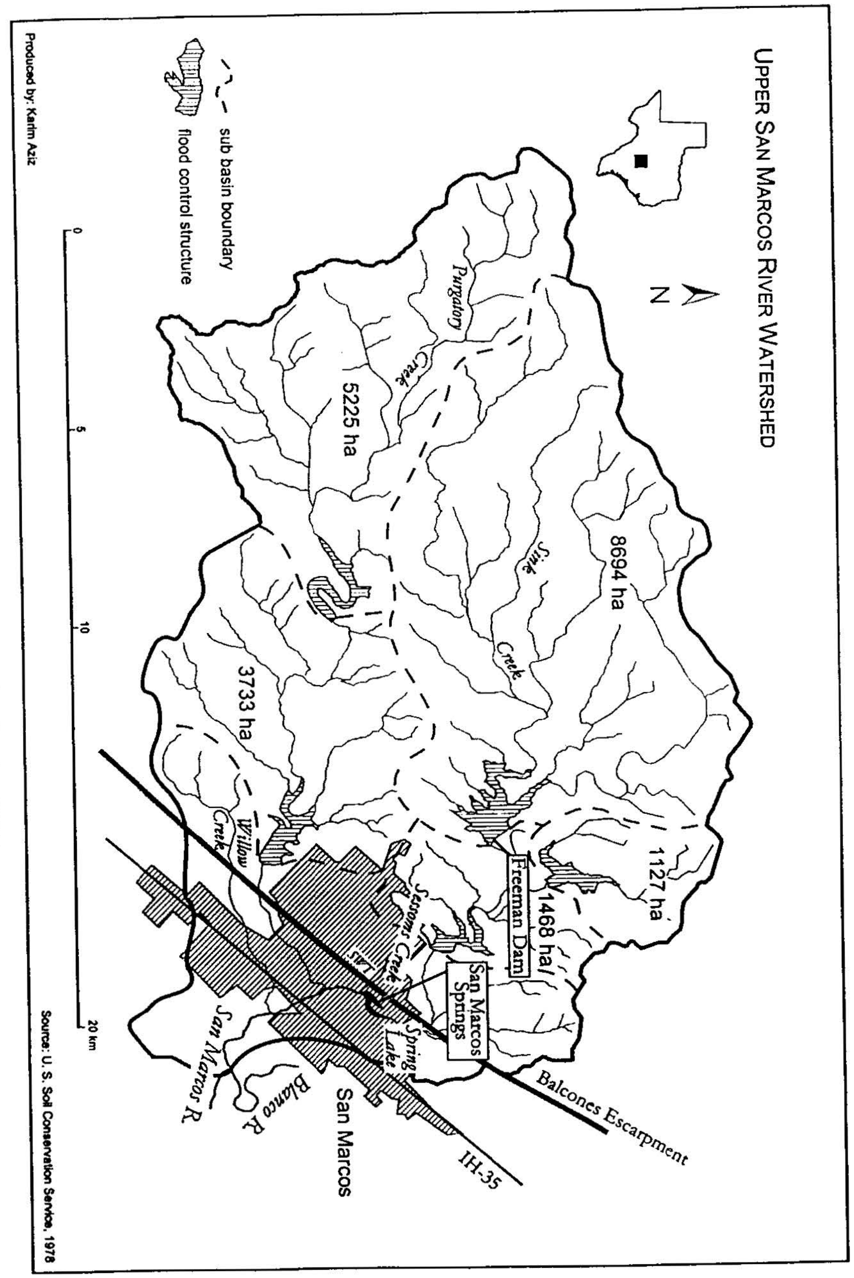

Figure 1. Upper San Marcos River Watershed (U.S. Soil Conservation Service 1978).

Table 1. Springflow and peak discharge for the San Marcos River (USGS 1956-1974; 1971-1999).

Water Year	% Basin Control	Springflow mean m^3/sec (ft^3/sec)	Flood Stage m (ft.)	Flood Discharge m^3/sec (ft^3/sec) (Rank)
1921		—	11.8 (38.6)	2700 (97,000) (1)
1956		—	1.7 (5.7)	15 (540)
1957		3.3 (117)	7.8 (25.6)	960 (34,000) (7)
1958		6.1 (215)	8.7 (28.5)	1300 (45,000) (4)
1959		4.8 (171)	3.7 (12.0)	130 (4,500)
1960		5.0 (178)	6.1 (20.0)	510 (18,000)
1961		5.9 (209)	7.7 (25.2)	910 (32,000) (8)
1962		3.8 (134)	4.1 (13.4)	170 (6,100)
1963		3.5 (124)	1.8 (6.0)	18 (630)
1964		2.6 (92)	2.1 (7.0)	28 (1,000)
1965		4.4 (156)	3.0 (9.7)	71 (2,500)
1966		4.6 (164)	4.8 (15.9)	270 (9,600)
1967		2.9 (103)	1.6 (5.4)	13 (460)
1968		5.5 (194)	5.0 (16.3)	280 (10,000)
1969		4.6 (162)	1.7 (5.7)	15 (540)
1970		(191)	11 (35.1)	2200 (76,600) (2)
1971		3.9 (138)	1.4 (4.6)	7.9 (280)
1972		4.5 (158)	8.0 (26.1)	990 (35,000) (6)
1973		5.4 (190)	3.3 (10.7)	93 (3,300)
1974		5.7 (200)	5.2 (16.9)	310 (11,000)
1975		6.7 (237)	6.5 (21.3)	590 (21,000) (10)
1976		5.5 (194)	4.7 (15.5)	250 (9,000)
1977		7.1 (252)	5.3 (17.4)	340 (12,000)
1978		3.5 (125)	2.1 (7.0)	28 (1,000)

Table 1 cont.

Water Year	% Basin Control	Springflow mean m^3/sec (ft^3/sec)	Flood Stage m (ft.)	Flood Discharge m^3/sec (ft^3/sec) (Rank)
1979		5.5 (195)	5.9 (19.5)	480 (17,000)
1980		3.9 (137)	2.4 (8.0)	42 (1,500)
1981		4.8 (169)	9.7 (31.8)	1700 (59,000) (3)
1982		4.1 (144)	4.4 (14.3)	200 (7,200)
1983	36.0	4.0 (143)	4.0 (13.0)	160 (5,600)
1984	36.0	3.1 (108)	1.3 (4.2)	5.7 (200)
1985	57.7	4.4 (157)	5.7 (18.7)	420 (15,000)
1986	62.5	5.7 (202)	7.4 (24.3)	820 (29,000) (9)
1987	62.5	7.1 (250)	4.5 (14.7)	220 (7,800)
1988	62.7	4.6 (163)	3.6 (11.9)	120 (4,400)
1989	78.0	3.1 (109)	****	
1990	78.0	3.0 (105)	****	
1991	84.1	5.0 (178)	****	
1992	84.1	9.4 (331)	****	
1993	84.1	5.9 (208)	****	
1994	84.1	4.0 (140)	****	
1995	84.4	4.5 (160)	—	—
1996[a]	84.4	3.1 (110)	2.1 (6.8)	16 (550)
1997[a]	84.4	4.8 (170)	2.3 (7.7)	22 (787)
1998[a]	84.4	5.1 (179)	2.0 (6.6)	13 (449)
1999[a]	84.4	7.8 (274)	6.5 (21.3)	610[a]/1300[b] (21,500[a] / 45,000[b])(4)

**** Springflow only data available; discharge based on well level.

a Discharge at Aquarena Drive new USGS gage no. 08170500

b Discharge estimate for gage no. 08170000 location based upon USGS slope area method (Dalrymple & Benson 1967).

make the Balcones Escarpment region of Texas known for its large flood discharges from seemingly small watersheds (Baker 1975). The San Marcos River is no exception. A hurricane-spawned flood in September 1921 produced a peak discharge of approximately 2750 m^3/sec (97,000 ft^3/sec), which is nearly 30% greater than the 1970 flood that provided the stimulus for the flood control project (Table 1). The peak flood discharge has exceeded 280 m^3/sec (10,000 ft^3/sec) at least 13 times in the last 30 years. There have been five precipitation events [1909, 1913 (two events), 1981, 1998] that have exceeded 254 mm/24 hours during the twentieth century (Slade 1986; Sands 1998; U.S. National Climate Data Center 2002).

Urban Growth and Flood Control

San Marcos and Southwest Texas State University have experienced considerable growth during the 1970-1995 period. Virtually all of this growth has occurred downstream of the USMWFCD dams. In a comparison of landuse using 1966 and 1989 air photos, Pulich et al. (1994) calculated more than a doubling of urban landuse, from 10.2% to 23.0%, along the uppermost 18.4 km of the San Marcos River from San Marcos Springs to Martindale. The City of San Marcos has implemented a series of grading ordinances that are intended to reduce runoff and sediment production from urbanized land both during and after construction. City regulations require adherence to US SCS guidelines as stated in *Erosion and Sediment Control Guidelines for Developing Areas in Texas* (U.S. Soil Conservation Service 1976). Besides these SCS rules, the city has designated a special "San Marcos River Corridor," which is defined as the area within 60 to 300 m of the center of the river, depending on drainage and terrain (City of San Marcos 1995). Even though the main SWT campus is entirely within the city limits, because it is a state institution, it is not subject to the city grading ordinances. This issue has particularly become apparent with the onset of construction for the new Lyndon B. Johnson Student Center and associated parking facilities that began in the spring of 1995. A large delta now occupies the confluence of Sessoms Creek and the San Marcos River; cobbles from the construction site are found as far as 60 meters below the confluence.

Until the October 1998 flood, there had been only one flow greater than 570 m^3/sec (20,000 ft^3/sec) since 1982 (Table 1). This absence of flooding correlates to the 1981-1991 construction of the headwaters flood control dams that decreased the unregulated watershed area to less than one fourth its previous value. This flooding hiatus also correlates to an absence of flood producing storm events for nearby basins in the size range of the upper San Marcos River. For the Comal River drainage at New Braunfels, with a 337 km^2 basin, the largest flood between 1983 and 1998 was only 10.9% of the largest event since 1957 with a discharge of 1720 m^3/sec (60,800 ft^3/sec) in May 1972. The largest flood between 1983 and 1998 for the Blanco River at Wimberley, Texas, with a 921 km^2 drainage, was only 46% of the 30 year storm of record with 2730 m^3/sec (96,400 ft^3/sec) in May, 1958 (USGS 1999).

October 1998 Flood

The October 1998 flood was among the largest flood events in the history of the region (EARDC 1999; LCRA 1999; US NRCS 1999; USGS 1999). The official 401 mm (15.78 in) recorded on October 17, 1998 at the "San Marcos, Texas" weather station was the greatest 24-hr total recorded since records began in 1901 (Sands 1998), but the fifth event to equal or exceed the "official" 254 mm 100-year 24-hour total designated for this region by U.S. Weather Service Technical Paper 40 (Hershfield 1961; Baker 1975). The headwaters of the upper San Marcos River received 24 hour totals in the 400 to 500 mm range with the greatest amounts over the southern portions of the upper San Marcos basin that are drained by Purgatory Creek (LCRA 1999; US NRCS 1999). Runoff produced exceeded the design standard project flood of the Upper San Marcos River Project but did not exceed the maximum probable flood spillway capacities of the project flood control dams. Thus, whereas there was considerable "spill" from the event, the flow downstream of the flood control structures was considerably less than it would have been without the project dams.

Even with the flood control project, the storm generated impressive peak discharges. Runoff and maximum discharge on tributaries upstream of the Freeman Ranch dam showed peak runoff between 46 (1.8 in) and 86 (3.4 in) mm/hr and that peak inflow into the dam was 1870 m^3/sec (66,000 ft^3/sec) (Table 2). Maximum "spill" from Freeman Ranch dam was 331 m^3/sec (11,700 ft^3/sec), less than 20% of the maximum inflow. Farther downstream, the calculated inflow (Table 3) into Spring Lake was 420 m^3/sec (15,000 ft^3/sec) and the peak inflow of Purgatory Creek into the San Marcos River was 280 m^3/sec (10,000 ft^3/sec). Downstream of Spring Lake, but upstream of the confluence with Purgatory Creek, the USGS employing similar slope-area methods

Table 2. October 1998 peak runoff and discharge calculated for upstream tributaries of the Freeman Ranch Dam on the SWT Freeman Ranch employing the slope-area method (Dalrymple & Bensen 1967).

Basin	Basin Area (ha)	Peak Discharge m^3/sec & mm/hr (ft^3/sec & in/hr)
Sink Creek (Main Channel)	4,863 (48.6 km^2)	1040 & 79 (36,700 & 3.1)
Sub-Basin B	76	9.8 & 46 (345 & 1.8)
Sub-Basin C	220	39.6 & 53 (1400 & 2.1)
Sub-Basin D	1,542	362 & 86 (12,800 & 3.4)
Sub-Basin E	144	22.7 & 56 (800 & 2.2)
Freeman Dam	8,692 (86.9 km^2)	est. 1870 (66,000)
Freeman Dam Spill	—	331 (11,700)

Table 3. Calculation of Peak Discharge for October 1998 storm corrected to the location of USGS Gage 08170000 (downstream of I-35 bridge) (This study).

Location	Discharge m^3/sec (ft^3/sec)
Inflow to Spring Lake from Sink Creek (124 km^2)	420 (15,000)
USGS Hopkins St. Estimate (155 km^2)	610 (21,500)
Purgatory Creek inflow (78 km^2)	280 (10,000)
Unregulated RO 31 km^2	400 (14,000)
Estimated Peak	1270 (45,000)

calculated a peak discharge of 610 m^3/sec (21,500 ft^3/sec) at the Hopkins Street bridge (USGS 1999). When peak runoff coefficients are applied to other downstream areas below the flood control dams, plus the observed peak flows, an estimated value of 1270 m^3/sec (45,000 ft^3/sec)

was obtained for the peak discharge of the event as measured at the location of the former USGS gage no. 08170000 just east of the I-35 bridge (Table 3). If peak runoff values of 51 to 76 mm (2-3 in)/hr such as those measured upstream of the Freeman Ranch dam are applied to the whole basin, the peak discharge at the I-35 location would have been between 3370 and 4110 m^3/sec (119,000 and 145,000 ft^3/sec) had there been no flood control project. Rather than being the fourth largest event on the San Marcos River at San Marcos, the event would have exceeded the record 1921 event by a considerable margin (Table 1). The record discharges of the event are verified by the period of record/or near record period of record discharges measured on nearby streams with less or no flood control facilities such as on the Blanco at Wimberley and the Comal and Guadalupe Rivers at New Braunfels (Table 4) (USGS 1999; USNRCS 1999).

Changes in the River

Until the October 1998 event, the largest flood since completion of the first, and largest, flood control dam in 1983 was 38% of the 1970 event (Table 1). Between 1983 and 1998 flood damage along the river had been mostly limited to debris clean-up and gravel trail repair in areas immediately adjacent to the river. As discussed above, the flood control project dramatically reduced the flood magnitude of the 1998 event. West of Hopkins Street, damage from the flood was mostly restricted to structures at Aquarena Center, the first floor of the University Apartments on Aquarena Drive, and parks immediately along the river. Between Hopkins Street and I-35, more than 51 ha of residential and commercial areas were inundated and produced an estimated $12,100,000 in property damages (Adamietz 1999; US NRCS 1999).

Since 1990, the San Marcos River has been closely monitored by both the Texas Parks and Wildlife Department (TPWD) and the Parks and Recreation Department of the City of San Marcos. The TPWD studies supported the critical habitat monitoring for the stream's endangered species. The City of San Marcos studies, under the title of the "River Stewardship Project," have supported the development of a management plan for the river as a part of the Parks and Recreation Department master plan and as a part of the monitoring and management of this aesthetic and tourism resource for the city.

A major problem verified by these studies and observed by the public has been the increase in exotic river vegetation, particularly *Hydrilla*

Table 4. Peak discharges for the October 1998 storm observed at other gages on the Guadalupe River system as compared to earlier events (USGS 1956-1974; 1971-1999; 1999).

Year	Location	Stage m (ft)	m^3/sec (ft^3/sec)
1998	San Marcos at San Marcos	est. 8.7 (28.5)	1300 (45,000)
1921	San Marcos at San Marcos	11.8 (38.6)	2700 97,000
1998	Blanco at Wimberley	—	2500/3300* (88,500/116,000)
1929	Blanco at Wimberley	—	3200 (113,000)
1998	Blanco at Kyle	—	3000 (105,000)
1929	Blanco at Kyle	—	3900 (139,000)
1998	San Marcos at Luling	12.7 (41.8)	5800 (206,000)
1869	San Marcos at Luling	12.3 (40.4)	>2800 (>100,000)
1998	Guadalupe at Gonzales	15.4 (50.4)	9600 (340,000)
1929	Guadalupe at Gonzales	15.0 (49.3)	—
1998	Guadalupe at New Braunfels	11.7 (38.5)	6300 (222,000)
1913	Guadalupe at New Braunfels	12.0 (39.5)	—
1869	Guadalupe at New Braunfels	12.0 (39.5)	—
1998	Guadalupe at Victoria	10.3 (33.8)	13,200 (466,000)
1936	Guadalupe at Victoria	9.5 (31.1)	5100 (179,000)

* USGS Flood peaks data base gives lower value than USGS 1999 report.

verticillata (hydrilla), *Potamogeton illinoiesnsis* (pondweed) and *Colacasia escuelenta* (elephant ear) (Lemke 1989; Staton 1992; Angerstein & Lemke 1994). In an analysis of this problem, Spain (1994) concluded that any program to control these exotics, including mechanical removal, biologic controls or herbicides, would be either expensive, controversial or illegal.

Another change observed by the public and verified by quantitative measurement has been sedimentation of the channel. Between 1990 and 1995, the City conducted annual sedimentation measurements at sites between University Drive and Hopkins Street. Employing a 0.63 cm diameter rod-penetrometer, sediment depth to the closest 0.1 m was measured every 3 meters across the channel at cross-sections every 25 meters in SWT Sewell Park and every 50 meters farther downstream. Between the scouring floods December 1991- January 1992 and 1995, there was an average channel deposition of 0.50 meters or 13,000 m^3 in the 800 meter reach of the stream immediately downstream from Spring Lake (Wood & Gilmer 1996).

ANALYSIS OF HEADWATER CHANGES

A hypothesis of this study is that the decrease in drainage area has reduced the number and maximum energy of stream erosional events. Furthermore, continued construction in the headwaters area downstream of the flood control dams has increased sediment input introduced into the river. Employing the slope-area method (Dalyrimple & Bentson 1967) for calculating bankfull discharge from channel geometry, the bankfull discharge in Sewell Park, immediately downstream of Spring Lake, is 33 m^3/sec (1150 ft^3/sec). Because of the changes in the location and instrumentation of gage number 0817000, it is difficult to determine the number of times that this discharge has been exceeded since the completion of the upstream dams. According to the formulas developed by Slade et al. (1995) for calculating peak discharge for a given recurrence interval ($Q_2 = 252A^{0.721}\ (SF)^{-0.326}$ where A = area in mi^2 and SF = shape factor) with the tributary area of this segment reduced from 77.0 to 15.6 km^2, the bankfull discharge for the two-year event comes out to 35 m^3/sec (1240 ft^3/sec) or approximately bankfull discharge. As shown in Table 1, only the October 1998 event exceeded bankfull discharge since the December 1991 flood.

In contrast, prior to closure of the dams, bankfull discharge was exceeded in over 82% (23/28) of the years with a mean annual flood of 510 m^3/sec (18,000 ft^3/sec). This 510 m^3/sec (18,000 ft^3/sec) value has a recurrence interval of 3.6 years. If Slade et al.'s (1995) equations are used, the present-day 3.6 year flood or mean annual flood with the reduced basin comes out to 43 m^3/sec (1,500 ft^3/sec). The maximum drain release from the "Site #3 Sink Creek" dam, approximately two kilometers upstream of Spring Lake is 27 m^3/sec (936 ft^3/sec) but this discharge is only produced when the structure has received 254 mm basin precipitation, the "100-year, 24-hr" event (US SCS 1978). Consequently, significant runoff below the flood control dams would be required to produce bankfull discharge in the main channel. Employing the TR 55 model, with a curve number of 75, between 38 and 54 mm/hr of precipitation is required to produce sufficient runoff to yield bankfull discharge (33 m^3/sec or 1150 ft^3/sec) downstream of Spring Lake (US SCS 1986). This precipitation rate has a recurrence interval of approximately two years, and thus, the decrease in bankfull events is at least partially due to a climatic perturbation that produced few high-intensity rainfalls between 1991 and 1998 (Hershfield 1961). Thus, both hydrologically (Slade et al. 1995) and rainfall frequency based models suggest that the 1991-1997 period of stream sedimentation was noted for its lack of large flood events.

Sedimentation results when sediment supply exceeds the ability of flood events to remove the sediment supply. A major source of the sediment introduced into the river is Sessoms Creek, with a basin area of 147 ha (363 acres) and which receives runoff from much of the SWT campus. Particularly noteworthy has been the recent construction on campus. An analysis of the sediment production from the site of the new student union and other facilities was undertaken with the Universal Soil Loss Equation (USLE) (Dunne & Leopold 1978). These areas had a bare, disturbed surface area of 7.3 ha and produced an estimated sediment yield of 121 tonnes/ha/year in contrast to an estimated pre-construction value of 0.22 tonnes/ha/year. Based upon a density of 2.0 g/cm^3, the annual sediment production from the construction site would have a volume of 780 m^3 compared to 15 m^3 for the remaining 140 ha of the basin. This sediment production rate over the three years of construction that began in 1995 would produce an annual sedimentation in the channel of the San Marcos River of 16 cm/year in the upper 250 meters of the river or at least 48 cm since 1995. The failure of the 1998 flood event to scour this sediment suggests that the sediment volume from Sessoms Creek is greater that the ability of even a major flood of the San Marcos River to erode and transport in the concrete lined main channel and farther downstream.

A potentially beneficial impact of the flood control project is the enhanced recharge to the Edwards Aquifer that occurs behind the USMWRFCD dams. Water that would have flowed down the San Marcos River as quickflow is now infiltrated and contributes to the water that is withdrawn by wells or emerges from San Marcos Springs.

The actual amount of enhanced recharge is a function of the mean annual runoff estimate. Interpolation between the 51 and 127 mm runoff lines on the runoff map produced by the USGS in 1970 produces an estimated 76 mm runoff for the region (USGS 1970). If runoff is calculated from the nearby gaged discharge/drainage basin area relationships, the regional runoff is approximately 127 mm (USGS 1921; 1956-1999). Lastly, if the regional annual runoff equation ($Q_{ann} = 10^{0.211} A^{0.846}$) developed by Lanning-Rush (2000) is employed, the 217 km^2 above the dams have an estimated 287 mm runoff. If one uses the value of 127 mm runoff calculated from the adjacent basins, the mean annual runoff from the controlled 217 km^2 regulated portion of the upper San Marcos basin is 27 million m^3 (22,000 acre feet) /year. Other than aquifer seepage, the only natural outlet for this water is San Marcos Springs. If all of this enhanced recharge were to become springflow, it would increase the average baseflow of the river by 0.8 m^3/sec (30 ft^3/sec) or about 18%. Unfortunately, this recharge is dependent upon precipitation and this enhanced flow could not be expected during drought times when little surface runoff is produced. Looking at this enhanced recharge in terms of water supply, this additional water, based upon a value of \$0.37 to \$1.10/ m^3 (\$100 to \$300/acre foot), is worth between \$2.2 and 6.6 million per year. Presently, Texas law does not grant ownership to the party responsible for enhanced recharge, but the volatile status of Texas water law forced upon a reluctant state by increasing demand for water and periodic droughts will probably clarify the ownership of enhanced recharge (Kaiser 1986; Votteler 1998). Once this issue is resolved, the increased groundwater would become a resource for future water demand for San Marcos or could generate revenues.

Management Options

The altered hydraulic regimen of the San Marcos River brought about by the upstream flood control project can be accepted and adjusted to, or can be modified. Already the City and SWT have implemented a hydrilla "mowing" program to reduce vegetation clogging (Anonymous 1994). Other than accepting the sedimentation, a channel dredging program has been proposed and could be implemented. Dredging would raise legal concerns over the "taking" of endangered species, and consequently, other options need to be considered to shift the sediment supply/stream energy relationship. A different stream regime with some combination of increased total stream energy or a reduction of sediment supply is necessary to reverse the persistent sedimentation. Dam design and operation could be modified to increase the amount of flow passed through the flood control dams on Sink Creek. On the other side of the equation, the amount of sediment entering the river could be reduced by enhanced efforts to reduce erosion and or implementation of a series of sediment check dams immediately upstream of where high sediment load tributaries enter the San Marcos River. The failure of the 1998 storm to produce a net scour of sediment deposited since 1991 suggests that with the present stabilized channel, the only means to reduce/reverse the sedimentation problems is to reduce sediment yield from the contributing watersheds.

An unresolved issue is the near autonomous status of SWT in terms of its actions affecting the river. University land constitutes 192 of the 940 ha of the drainage of Sessoms Creek, which includes the potential to cause considerable changes or damage to the river such as the leaky gasoline storage tank incident of 1994 proved (Dreckman 1994). City, county and even some state agencies cannot force SWT to modify its actions to protect the river because it is a state entity. This presents a fundamental problem for management in that such a significant landuser is immune from rules that are designed to protect such a valuable resource. With implementation of the next set of federal Water Quality Act (1987) rules in 2003, SWT will formally be required to treat its runoff from all new developments and be required to implement sediment control measures from all construction sites larger than 0.4 ha (1 acre) (U.S. Environmental Protection Agency 2000). Perhaps, enforcement of these rules on the SWT campus and elsewhere in the watershed of the upper San Marcos River watershed will significantly reduce the hydrologically overwhelming sediment load presently introduced into the river.

DISCUSSION

The recent changes in the San Marcos River illustrate a number a principles in environmental management. Hydrologically, the dams have reduced the magnitude and frequency of scouring flood events. Landuse changes downstream of the flood control dams have increased sediment yield so that the channel has adjusted through deposition. The reduction in peak flood energy has also led to in increase in exotic vegetation. These changes mimic those observed in the Grand Canyon of the Colorado following the closure of Glen Canyon Dam (Graf 1985; Carothers & Brown 1991). The trunk stream is unable to remove the sediment that is deposited at the mouths of the tributaries and there is

insufficient energy to flush out undesirable vegetation. Perhaps, a program as dramatic as the recent peak flood simulation in the Grand Canyon would be required (Webb et al. 1999). Public authorities would be reluctant to create or increase a flood that would further endanger lives and increase property damage for some uncertain benefit to the river. Sediment control through expanded implementation of the Water Quality Act (1987) will help with the sediment problem but other measures, perhaps more costly or controversial, will be required to deal with the increase in exotic vegetation. The recent changes in the San Marcos River brought about by the upstream flood control project illustrate the hydrologic and ecologic principle that reducing flood discharges establishes an entirely new stream regime that is often associated with a new set of management problems.

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GENERAI

THE GHOST-I
MORMOOPS MEGALOPHYLLA, (C
FROM THE DAVIS M

Robert S. DeBaca

Department of Biological
Texas Tech
Lubbock, Texa

The ghost-faced bat (*Mormoops r*
in the tropics of southwestern North
South America. The North Americ
southern three-fourths of Baja Califo
Central America (Hall 1981; Came
tional limit of *M. megalophylla*
southern Texas near the Rio Grand

In Trans-Pecos Texas, *M. mega*
Brewster, Presidio and Culberson
This new record from Jeff Davis
between northern, extralimital re
Elephant Mountain in Brewster Co
Apache Mountains in Culberson Co
respectively, 72 km SE and NW of

On 4 October 2000, two female
adult and one sub-adult) were capt
set across Limpia Creek at Davis M
tion 1522 m, UTM coordinates: 1
ghost-faced bat came in at 2122 hr
sunset, and the second came in at
temperature was 24°C, and the wi
times of capture. Eighty-four c
Nyctinomops macrotis and 61 *Tadar*
net between 2010 hr and 2300 hr.

The net was located over an ope
was 13 m wide by about 55 m long.
sloping canyon with a mosaic of oa
had been invaded by shrubs.