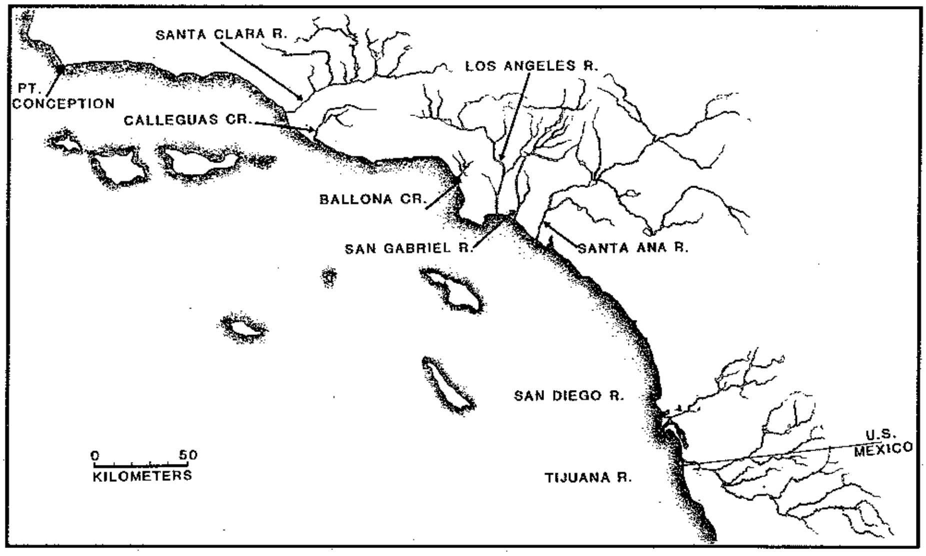
Surface Runoff to the Southern California Bight

Twenty creeks and rivers drain the coastal mountains, valleys and plains between Point Conception and the U.S./Mexican border and discharge into the Southern California Bight (SCB). A large portion of this discharge is urban runoff. Although a significant amount of data have been collected on contaminant concentrations in surface runoff, there are few published estimates of the mass of contaminants delivered to the ocean (e.g., SCCWRP 1973, Eganhouse and Kaplan 1982, SCAG 1988).

The objective of this study was to measure the concentration of selected constituents in runoff samples from the largest channels in Southern California and to estimate the mass carried to the ocean. We collected samples from eight channels during storms and low flows, and estimated the annual load of contaminants delivered to the ocean.

Figure 1.
Runoff samples were collected from the eight largest rivers and creeks that discharge to the ocean off Southern California.



Materials and Methods

Sampling Method and Locations. Samples were collected between September 1986 and April 1988 with a sampling device patterned after the U.S. Geological Survey suspended sediment pint sampler that has been in use in Southern California for two decades (Young and Bodeen 1991). About 10 samples were collected during each storm and were distributed over rising and declining flows. Samples were collected in the middle of each channel at the same location throughout the study. The sampling device and sampling method are described in SCCWRP (1990). The sampling locations were (Figure 1):

- *Santa Clara River:* Highway 101 8 km from the ocean.
- *Calleguas Creek:* above the tidal prism at Highway 1.
- *Ballona Creek:* Inglewood Boulevard 4 km from the ocean.
- *Los Angeles River:* above the tidal prism at the Willow Street bridge in Long Beach.
- *San Gabriel River:* College Park Drive bridge 4 km above the tidal prism and below confluence of the San Gabriel River and Coyote Creek.
- *Santa Ana River:* Hamilton Street on the border between Huntington Beach and Costa Mesa.
- *San Diego River:* 4 km above the tidal prism east of Fashion Valley Road in San Diego.
- *Tijuana River:* 6 km above the ocean at Dairy Mart Road.

Analytical Methods.
The samples were analyzed for suspended solids, selected trace metals, and selected trace organics. Sampling handling and analytical methods are described in SCCWRP (1990).

Load estimates.
The load of a particular constituent in a river is the total mass of the constituent passing the point of measurement over some period of time. We estimated the load of selected constituents transported by the eight rivers with a flow-weighted ratio estimator. Where sufficient contaminant data existed, we stratified the estimates into low and high flows. The inflexion point on the flow duration curve was the cutoff between low and high flow days (SCCWRP, unpublished data). Contaminant data from the two

years were pooled to increase sample sizes.

The flow-weighted ratio estimator is based on the relation between flows and loads:

$$L = Q\,T\,\frac{\sum_{i=1}^{n} c_i q_i}{\sum_{i=1}^{n} q_i}$$

where L is the load of the constituent, Q is the mean period flow, T is the total time in the period, c_i is the ith concentration, and q_i is the corresponding flow rate. The method assumes that flows are continuously monitored, mean flow can be determined accurately, concentrations are related to flows, and the underlying distributions are approximately normal. The estimation method and its assumptions and shortcomings are described in more detail in SCCWRP (1990).

River flow data were obtained from the U.S. Geological Survey, the Ventura and Los Angeles County Departments of Public Works, and the International Boundary Water Commission. Flow data are reported by water year (October 1 to the following September 30). We modified the

Table 1.
Flow-weighted mean constituent concentrations for runoff samples collected between 1986 and 1988 from rivers and creeks that discharge into the Southern California Bight. SS=suspended solids in dry weight.

	SS	Cd	Cr	Cu	Ni	Pb	Zn	ΣDDT[1]	ΣPCB[2]
	(mg/L)	(µg/L)						(ng/L)	
Santa Clara River	995	1.4	60	55	34	90	264	248	51
Calleguas Creek	667	3.0	111	80	62	28	195	176	187
Ballona Creek									
High Flow	402	3.3	38	138	39	286	766	183	166
Low Flow	136	1.3	12	60	19	52	206	25	75
Los Angeles River									
High Flow	1194	3.3	43	138	49	242	618	155	308
Low Flow	71	4.2	11	17	13	23	81	8	21
San Gabriel River	820	3.6	54	87	36	124	408	50	133
Santa Ana River	3,298	2.6	99	141	91	103	719	57	78
San Diego River	283	0.02	10	15	2.4	27	85	90	26
Tijuana River	4,313	5.1	184	416	116	988	1,150	243	634

[1]o,p'-DDT + p,p'-DDT+ o,p'-DDE + p,p'-DDE+ o,p'-DDD + p,p'-DDD
[2]Aroclor 1242 + Aroclor 1254

Table 2.
Spearman rank correlation coefficients (r_s) among constituent concentrations and instantaneous flow in runoff samples collected between September 1986 and January 1987 from rivers and creeks that discharge into the Southern California Bight. Only r_s significant at p<0.05 (*) and p<0.01 (**) are shown. SS=suspended solids.

	Santa Clara River		Calleguas Creek		Ballona Creek	
	Flow	SS	Flow	SS	Flow	SS
SS	.732**					
Cd	.637*	.782**		.940**		.855**
Cr	.684*	.976**		.966**		.722**
Cu	.653*	.988**		.862**		.946**
Ni	.578*	.802**		.904**		.809**
Pb	.639*	.888**		.944**		.793**
Zn	.615*	.939**		.962**	.556*	.862**
DDT[1]		.834**	.794**	.821**		.695**
PCB[2]			.638*			.840**

[1]o, p'-DDT + p, p'-DDT + o, p'-DDE + p, p'-DDE + o, p'-DDD + p, p'-DDD
[2]Aroclor 1242 + Aroclor 1254

water year to run from September 1 to August 31 because the first storm of the study occurred in September 1986 after five months of no precipitation.

Results

Santa Clara River

The Santa Clara River is 155 km long, drains an area of 4,219 km^2, and empties into the ocean south of Ventura. The drainage basin is moderately developed with large reservoirs, extensive levees, and agricultural diversions along the coastal plain. In the last 50 km, the river flows over a permeable, sandy, alluvial plain and flow rarely reaches the ocean except during storms. Annual rainfall ranges from 35 cm at the mouth of the river to 90 cm in the mountains (Brownlie and Taylor 1981).

Discharge from the Santa Clara River during the 1987 water year (0.9 x 10^6 m^3) was 0.2% of the total gauged runoff to the SCB; discharge during the 1988 water year (28.4 x 10^6 m^3) was 4.2% of the total discharge to the SCB. Discharge during the 2-year study was <1% and 19% of the long-term annual mean (1950-88: 146.2 x 10^6 m^3). The flow gauge on the lower river registered flow on only 18 days in 1987 and 22 days in 1988. Runoff from one storm in February 1988 was 72% of the gauged flow for that year. Most of the discharge from the river occurred from January through March.

Eleven runoff samples were collected from storms that occurred in September 1986 and January 1987. The flow increase during the September 1986 storm was small and not recorded by the flow gauge. Discharge during the January 1987 storm (3.6 x 10^6 m^3) was 13% of the annual discharge. One non-storm sample was collected in October 1986. Eleven samples were analyzed for suspended solids and chlorinated hydrocarbons and 10 samples were analyzed for trace metals (Table 1). Most constituents were correlated with flow and suspended solids (Table 2). The volume of discharge from the Santa Clara River increased by nearly 3200% from the first study year to the second. Estimates of constituent mass emissions increased by a similar amount (Tables 3a,b).

Calleguas Creek.

Calleguas Creek drains 837 km^2, including the rapidly growing Simi Valley, Thousand Oaks, and Camarillo, and empties into the ocean through Mugu Lagoon. The channel is moderately developed due to levees, agriculture, and urban and suburban development. Five municipal wastewater treatment plants discharged 87,000 m^3/day (23 mgd) into the creek during the study.

Discharge from Calleguas Creek during the 1987 water year (21.7 x 10^6 m^3) and the 1988 water year (31.3 x 10^6 m^3) was 5% of the total gauged runoff to the SCB. Discharge during the 2-year study was 59% and 93% of the long-term annual mean (1969-89: 35.2 x 10^6 m^3). High flows (>0.8 m^3/s) occurred 12% of the days during 1987 and 17% of the days during 1988, and accounted for 29% and 51% of the the annual discharge. Most of the discharge from Calleguas Creek occurred from December through March.

Nine runoff samples were collected from Calleguas Creek

Los Angeles River		San Gabriel River		Santa Ana River		San Diego River		Tijuana River	
Flow	SS	Flow	SS	Flow	SS	Flow	SS	Flow	SS
.720**		.797**		.830**		.656**		.600**	
				.604**	.730**			.761**	.547**
.507**	.787**	.514*	.787**	.872**	.891**		.811**	.560**	.642**
.659**	.829**			.934**	.910**		.730**	.664**	.606**
.481**	.813**			.872**	.926**		.508**	.544**	.652**
.691**	.736**			.905**	.883**		.734**	.509**	.428*
.671**	.845**			.908**	.914**		.648**	.572**	.471**
.764**	.697**	.673**	.533*	.527*	.690**	.674**	.692**	.557**	.397*
.492**	.408**							.611**	.407*

during storms in September 1986 and January 1987. These storms accounted for 1.4% of the discharge volume in 1986-87 and 1.8% of the discharge volume in 1987-88. One non-storm sample was taken in October 1986. Ten runoff samples were analyzed for suspended solids and chlorinated hydrocarbons, and nine samples were analyzed for trace metals (Table 1). The concentrations of most constituents were correlated with suspended solids, but not with flow (Table 2). The total volume discharged from Calleguas Creek increased 44% from 1987 to 1988 and so did the mass emission estimates (Tables 3a,b).

Ballona Creek.
Ballona Creek drains 232 km^2 of urbanized, predominantly residential, Los Angeles. The creek originates northeast of Baldwin Hills and empties into the ocean through Ballona Wetlands. The creek was once the outlet of the Los Angeles River. The channel is extensively developed as a result of urbanization and concrete channelization.

Discharge from Ballona Creek during the 1987 water year (21.8 x 10^6 m^3) was 4% of the total guaged runoff to the SCB; discharge during the 1988 water year (51.5 x 10^6 m^3) was 8% of the total guaged runoff to the SCB. Ballona Creek contributed 58% of the total runoff to Santa Monica Bay in 1987 and 71% in 1988. Discharge during the 2-year study was 48% and 133% of the long-term annual mean (1928-89: 38.7 x 10^6 m^3). High flows (>0.06 m^3/s) occurred 5% of the days during 1987 and 11% of the days during 1988, and accounted for 54% and 82% of the annual discharge. Most of the discharge from the creek occurred from November through March.

Fifteen runoff samples were collected from Ballona Creek during storms in September 1986, January 1987, and March 1987. Discharge during the storms averaged 2.4 x 10^6 m^3 (range: 0.7-4.5 x 10^6 m^3). The three storms accounted for 3.4%, 9.1%, and 20.5% of the total annual discharge volume. Two non-storm samples were collected in October 1986 and September 1987. Seventeen samples were analyzed for suspended solids, 16 samples were analyzed for trace metals, and 15 samples were analyzed for chlorinated hydrocarbons (Table 1). The concentrations of most constituents were correlated with suspended solids, but not with flow (Table 2). Flow-weighted mean concentrations at high flow were two to seven times greater than flow-weighted mean concentrations at low flow (Table 1).

High flow discharge accounted

Table 3a

Estimates of the mass emission of selected contaminants from rivers and creeks that discharged into the Southern California Bight between September 1, 1986 and August 31, 1987. VOL=annual discharge volume; SS=suspended solids in dry weight.

	VOL	SS	Cd	Cr	Cu	Ni	Pb	Zn	ΣDDT[1]	ΣPCB[2]
	(x 10^6 m^3)	(x 10^3 kg)	(kg)							
Santa Clara River	0.87	862	1	52	48	29	78	227	0.2	0.04
Calleguas Creek	21.7	14,452	65	2,407	1,735	1,344	607	4,228	3.8	4.1
Ballona Creek										
High Flow	11.8	4,708	39	440	1,632	462	3,354	8,976	2.1	2.0
Low Flow	10.0	1,390	13	117	604	194	518	2,067	0.3	0.7
Los Angeles River										
High Flow	61.0	72,437	202	2,609	8,372	2,973	14,682	37,492	9.7	18.8
Low Flow	95.4	6,799	402	1,053	1,628	1,245	2,202	7,756	1.0	1.9
San Gabriel River	139.2	114,127	501	7,516	12,109	5,010	17,258	56,785	7.0	18.5
Santa Ana River	17.6	58,060	46	1,742	2,481	1,601	1,812	12,650	1.0	1.4
San Diego River	20.0	5,667	<1	192	300	48	541	1,702	1.8	0.5
Tijuana River	10.2	43,883	52	1,870	4,231	1,178	10,051	11,706	2.5	6.4

[1]o, p'-DDT + p,p'-DDT + o, p'-DDE + p, p'-DDE + o, p'-DDD + p, p'-DDD
[2]Aroclor 1242 + Aroclor 1254

for 70-97% of the estimated annual constituent loads (Tables 3a,b). Total runoff volume increased 137% from 1987 to 1988 and high flow runoff volume increased 259%. Mass emissions estimates increased 100% to 300%. Low flow volume and estimates of the constituent mass emissions were similar in both years.

Los Angeles River. The Los Angeles River is the largest single source of gauged runoff to the SCB. It originates in the Santa Susana and Santa Monica mountains in the western part of the San Fernando Valley and also receives runoff from the western San Gabriel Mountains and the Santa Monica Mountains. The river enters the ocean in San Pedro Bay, but historically it has changed course several times and entered the ocean as far north as Ballona Creek and as far south as the San Gabriel River (Brownlie and Taylor 1981).

The Los Angeles River drains 2,155 km^2 and, for its size, is one of the most extensively controlled rivers in the world. All of the river has been channelized below the upland catchments (Brownlie and Taylor 1981). In 1982, nearly 60% of the river basin was urban and suburban, 40% was native vegetation, and 1% was agriculture (Department of Water Resources 1982).

Discharge from the Los Angeles River during the 1987 (156.4 x 10^6 m^3) and 1988 (217.3 x 10^6 m^3) water years was 33% of the total gauged runoff to the SCB. Discharge during the 2-year study was 83% and 115% of the long-term annual mean (1929-88: 189 x 10^6 m^3). High flows (>5 m^3/s) occurred 8% of the days during 1987 and 9% of the days during 1988, and accounted for 39% and 57% of the annual discharge.Most of the discharge occurred from November through March.

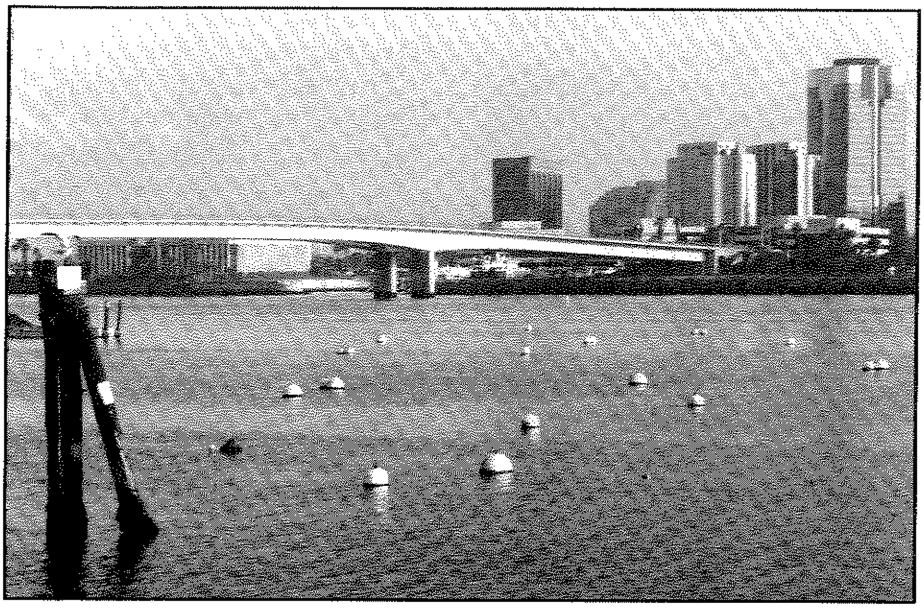
Fifty-three runoff samples were collected from the Los Angeles River during six storms that occurred in September 1986, January 1987, March 1987, October 1987, December 1987, and January 1988. Mean discharge during the storms was 12.9 x 10^6 m^3 (range: 2.9-21.3 x 10^6 m^3) was 6-8% of the annual discharge. One non-storm sample was collected in October 1986. Fifty-four samples were analyzed for suspended solids, trace metals, and chlorinated hydrocarbons (Table 1). The concentrations of all constituents except cadmium were correlated with flow and suspended solids (Table 2). Concentrations at high flow were three to 17 times greater than concentrations at low flow for all constituents except cadmium (Table 1).

Table 3b.

Estimates of the mass emission of selected contaminants from rivers and creeks that discharged into the Southern California Bight between September 1, 1987 and August 31, 1988. VOL=annual discharge volume; SS=suspended solids in dry weight.

	VOL (x 10^6 m^3)	SS (x 10^3 kg)	Cd (kg)	Cr (kg)	Cu (kg)	Ni (kg)	Pb (kg)	Zn (kg)	ΣDDT[1] (kg)	ΣPCB[2] (kg)
Santa Clara River	28.4	28,236	40	1,702	1,560	965	2,554	7,490	7.0	1.4
Calleguas Creek	31.3	20,893	94	3,408	2,508	1,944	878	6,113	5.5	5.9
Ballona Creek										
High Flow	42.2	16,971	140	1,584	5,850	1,667	12,093	32,356	7.7	7.0
Low Flow	9.3	1,305	12	110	567	182	486	1,940	0.2	0.7
Los Angeles River										
High Flow	123.9	148,011	409	5,330	17,107	6,074	29,998	76,609	19.8	38.4
Low Flow	93.4	6,628	392	1,027	1,587	1,213	2,147	7,560	0.9	1.9
San Gabriel River	138.6	113,671	499	7,486	12,060	4,990	17,189	56,558	6.9	18.4
Santa Ana River	25.8	85,294	67	2,559	3,644	2,352	2,662	18,584	1.5	2.0
San Diego River	30.5	8,620	<1	292	457	73	822	2,589	2.7	0.8
Tijuana River	40.2	173,270	205	7,385	16,706	4,653	39,684	46,221	9.8	25.5

[1]o,p'-DDT + p,p'-DDT + o,p'-DDE + p,p'-DDE + o,p'-DDD + p,p'-DDD
[2]Aroclor 1242 + Aroclor 1254



Mouth of the Los Angeles River in Queensway Bay, Long Beach

Except for cadmium, 66-95% of the estimated annual constituent loads was discharged during high flow days (Tables 3a,b). One third to one half of the estimated annual load of cadmium went out during high flow days. Total high flow volume increased 104% from 1987 to 1988. Consequently, the mass of solids and contaminants discharged during high flow days more than doubled (Tables 3a,b). Low flow volume and constituent mass emission estimates were similar in both years.

The Los Angeles-Glendale, Tillman, and Burbank water reclamation plants discharge tertiary effluent (disinfected) into the Los Angeles River. Their effluents constituted 69% of low flow, 9% of high flow, and 45% of total river discharge in the 1987 water year and 85% of low flow, 6% of high flow, and 39% of total river discharge in 1988 (SCCWRP 1990). Except for cadmium and nickel, the combined mass emissions from the three water reclamation plants accounted for less than 30% of the estimated loads delivered to the SCB by the Los Angeles River.

San Gabriel River.
The San Gabriel River drains 1,663 km^2 between the San Gabriel Mountains and the ocean and is the second largest single source of gauged runoff to the SCB. The river travels nearly 90 km from the junction of the East and West forks in the San Gabriel Valley to its mouth east of Long Beach. Annual rainfall ranges from 35 to 50 cm in the valleys and coastal plain, to 50 to 120 cm in the mountains (Brownlie and Taylor 1981). The San Gabriel River basin is extensively developed and the river is the second most controlled river in Southern California. Most of the river below the upland catchments has been channelized (Brownlie and Taylor 1981). The river receives tertiary treated wastewater from four water reclamation plants.

Discharge from the San Gabriel River was 30% of the total gauged runoff to the SCB during the 1987 water year (139.2 x 10^6 m^3) and 21% of the total gauged runoff to the SCB in 1988 (138.6 x 10^6 m^3). In both years, discharge was 115% of the long-term mean annual (1964-88: 120.9 x 10^6 m^3). Most of the discharge occurred from November through March. High flows (>5 m^3/s) occurred 10% of the days during 1987 and 11% of the days during 1988, and accounted for 31% and 39% of the annual discharge.

Sixteen runoff samples were collected from the San Gabriel river during storms in September 1986 and January 1987. These storms accounted for 5% and 9% of the flow for the year. Two non-storm samples were collected in October and November 1986. Sixteen samples were analyzed for suspended solids and chlorinated hydrocarbons, and 13 samples were analyzed for trace metals (Table 1). The concentrations of few constituents were correlated with flow or suspended solids (Table 2).

The San Gabriel River was the only channel where discharge did not increase from 1987 to 1988. Mass emission estimates for all nine constituents in 1988 declined by an amount proportional to the decline in discharge (Tables 3a,b).

Santa Ana River.
The Santa Ana River drains 4,406 km^2 and receives runoff from the San Bernardino, San Jacinto, and San Gabriel mountains. The river travels over 250 km before it empties into the ocean north of Newport Bay. Annual rainfall ranges from 30 to 45 cm in the plains and valleys to 50 to 120 cm in the mountains (Brownlie and

Taylor 1981). The Santa Ana River basin is extensively developed with water diversions for municipal and agricultural uses, flood control, and hydroelectric plants. Inputs from four municipal wastewater treatment plants (5.7 x 10^5 m^3/day, 150 mgd) augment the flow. Approximately 33% of the basin is urban and suburban, 10% is agriculture, and 57% is native vegetation (Department of Water Resources 1982, 1985).

Discharge from the Santa Ana River was 3% of the total gauged runoff to the SCB during the 1987 water year (17.6 x 10^6 m^3) and 4% of the total gauged runoff in 1988 (25.8 x 10^6 m^3). Discharge during the 2-year study was 36% and 63% of the long-term annual mean (1924-88: 40.7 x 10^6 m^3). Control facilities, spreading grounds, and the sandy river channel prevent everything but storm flow from reaching the ocean. There were no low flow days during the 2-year study; all of the flow went out in about 30% of the year. Most of the discharge from the river occurred from January through April.

Nineteen runoff samples were collected from two storms in January and April 1988. The January storm was 17%, and the April storm was 2%, of the annual flow. One non-storm sample was collected in December 1987. Twenty samples were analyzed for suspended solids and trace metals, and 19 samples were analyzed for total DDT and total PCB (Table 1). The concentrations of all constituents except total PCB were correlated with flow and suspended solids (Table 2). Total runoff volume increased nearly 50% from 1987 to 1988; annual mass emission estimates increased by a proportional amount (Tables 3a,b).

San Diego River

The San Diego River drains 1,119 km^2 extending from the Laguna Mountains in east San Diego County to the ocean near Mission Bay. The San Diego River is moderately developed. Only the last few kilometers of the channel are lined with concrete. Annual rainfall varies from 23 cm on the coastal plain to 81 cm in the mountains (Brownlie and Taylor 1981). Approximately 21% of the basin is urban and suburban, 2% is agriculture, and the remaining 77% is native vegetation (Department of Water Resources 1987).

Discharge from the San Diego River during the 1987 water year (20.0 x 10^6 m^3) and the 1988 water year (30.5 x 10^6 m^3) was 4% of total gauged runoff to the SCB. Discharge during the 2-year study was 48% and 23% of the annual mean (1982-86: 36.5 x 10^6 m^3). Most of the discharge from the river occurred from November through April. Unlike the other seven channels, the flow duration curve had no inflexion point so flows were not stratified.

Twenty-nine runoff samples were collected from storms that occurred in October 1987, January 1988, and April 1988. Discharge during the storms averaged 1.1 x 10^6 m^3 (range: 0.04-2.4

Table 4a

Constituent mass emissions as percent of total for channels that discharged into the Southern California Bight between September 1, 1986 and August 31, 1987. Vol=volume of discharge, SS=suspended solids in dry weight. Total is the volume (m^3) discharged and the estimated mass emission (kg).

	Vol	SS	Cd	Cr	Cu	Ni	Pb	Zn	ΣDDT[1]	ΣPCB[2]
Santa Clara River	0.2	0.1	0.1	0.3	0.1	0.2	0.2	0.2	0.7	<0.1
Calleguas Creek	5.6	2.4	4.9	13.4	5.2	9.5	1.2	2.9	12.9	7.6
Ballona Creek	5.6	14.8	3.9	3.1	6.7	4.7	7.6	7.7	8.2	5.0
Los Angeles River	40.3	23.4	45.6	20.3	30.2	29.9	33.0	31.5	36.4	38.1
San Gabriel River	35.9	45.0	38.0	41.8	36.5	35.6	33.8	39.5	23.8	34.1
Santa Ana River	4.5	2.9	3.5	9.7	7.5	11.4	3.5	8.8	3.4	2.6
San Diego River	5.2	1.8	<0.1	1.1	0.9	0.3	1.1	1.2	6.1	0.9
Tijuana River	2.6	9.6	3.9	10.4	12.8	8.4	19.7	8.2	8.5	11.8
Total	387.8x10^6	1.33x10^6	1,319	17,997	33,131	14,084	51,103	143,590	29.4	54.3

[1]o, p'-DDT + p, p'-DDT + o, p'-DDE + p, p'-DDE + o, p'-DDD + p, p'-DDD
[2]Aroclor 1242 + Aroclor 1254

x 10^6 m^3). The three storms accounted for 0.1%, 2.6%, and 7.9% of the total annual discharge. Two low-flow samples were collected in September and December 1987. Thirty-one samples were analyzed for suspended solids, 30 samples for trace metals, and 29 samples for chlorinated hydrocarbons (Table 1). The concentrations of most constituents were correlated with suspended solids, but not with flow (Table 2). Concentrations of cadmium, nickel, and total PCB were especially low because of the high proportion of non-detectable measurements. Runoff volume increased by 53% in 1988 and mass emission estimates increased by a proportional amount (Tables 3a,b).

Tijuana River.
The Tijuana River straddles the border between the United States and Mexico. Twenty-seven percent of the drainage basin (4,483 km^2) lies in Mexico and 73% lies in the United States. The channel is moderately developed and water is diverted to San Diego and Tijuana on its way to the ocean through Tijuana Slough. On the U.S. side, 3% of the land is urban and suburban, 2% is agriculture, and 95% is native vegetation (Brownlie and Taylor 1981).

Approximately 16.6 x 10^6 m^3/yr (12 mgd) of raw sewage and industrial and agricultural wastes are discharged into the Tijuana River south of the International Border (International Boundary and Water Commission, personal communication, October 16, 1990). This was 163% of the total discharge from the river in 1987 and 41% of the total discharge in 1988.

Discharge from the Tijuana River was 2% of total gauged runoff to the SCB during the 1987 water year (10.2 x 10^6 m^3) and 6% of total gauged runoff during the 1988 water year (40.2 x 10^6 m^3). Discharge during the 2-year study was 24% and 94% of long-term annual mean (1950-88: 42.9 x 10^6 m^3). Discharge during high flows (>0.5 m^3/s) occurred 7% of the days in 1987 and 24% of the days in 1988, and accounted for 48% and 82% of the annual river discharge. Most of the discharge from the river occurred from January through April.

Twenty-seven runoff samples were collected from storms in October 1987, January 1988, and April 1988. Discharge during these storms was 1-15% (0.4-6.0 x 10^6 m^3) of the annual discharge volume. Two non-storm samples were collected in September and December 1987. Twenty-nine samples were analyzed for suspended solids, 28 samples for trace metals, and 27 samples for chlorinated hydrocarbons (Table 1). The concentrations of all constituents were positively correlated with flow and suspended solids (Table 2). The volume of discharge from the Tijuana River increased by 300% from 1987 to 1988; mass emission estimates increased by the same amount (Tables 3a,b).

Table 4b

Constituent mass emissions as percent of total for channels that discharged into the Southern California Bight between September 1, 1987 and August 31, 1988. Vol=volume of discharge, SS=suspended solids in dry weight. Total is the volume (m^3) discharged and the estimated mass emission (kg).

	Vol	SS	Cd	Cr	Cu	Ni	Pb	Zn	ΣDDT[1]	ΣPCB[2]
Santa Clara River	5.0	1.5	2.2	5.5	2.5	4.0	2.4	2.9	11.3	1.4
Calleguas Creek	5.6	2.0	5.1	11.2	4.0	8.1	0.8	2.4	8.9	5.8
Ballona Creek	9.1	25.3	8.2	5.5	10.3	7.7	11.6	13.4	12.7	7.5
Los Angeles River	38.6	21.8	43.1	20.5	30.2	30.2	29.6	32.9	33.5	39.5
San Gabriel River	24.6	24.7	26.8	24.2	19.4	20.7	15.8	22.1	11.1	18.0
Santa Ana River	4.6	2.4	3.6	8.3	5.9	9.8	2.5	7.3	2.4	2.0
San Diego River	5.4	1.5	<0.1	0.9	0.7	0.3	0.8	1.0	4.3	0.8
Tijuana River	7.1	20.8	11.0	23.9	26.9	19.3	36.6	18.1	15.8	25.0
Total	563.6x10^6	2.41x10^6	1,859	30,955	62,046	24,144	108,514	256,020	62.1	102.0

[1]o, p'-DDT + p, p'-DDT + o, p'-DDE + p, p'-DDE + o, p'-DDD + p, p'-DDD
[2]Aroclor 1242 + Aroclor 1254

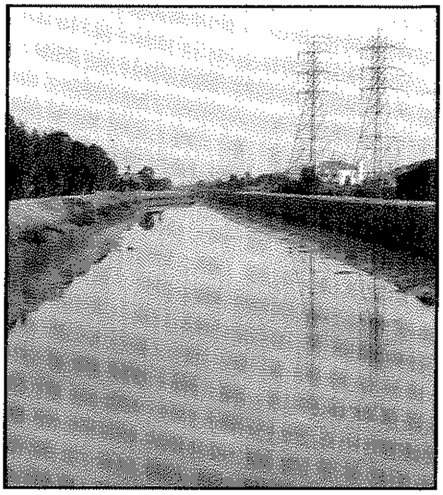
Discussion

Hydrography.
The rivers in this study occupy basins that are either moderately developed (Santa Clara, San Diego, and Tijuana rivers and Calleguas Creek) or extensively developed (Los Angeles, San Gabriel, and Santa Ana rivers and Ballona Creek) (Brownlie and Taylor 1981). In the most developed and manipulated basins, river discharge was extremely variable. The Santa Clara and Santa Ana rivers had no measurable flow for most of the year. River discharge was a combination of surface and groundwater runoff, releases from control facilities, and inputs of domestic and industrial wastes. Most of the flows resulted from winter rains; storms are short and intense, and discharge is variable from year to year.

The eight channels sampled during this 2-year study contributed about 80% of the total gauged runoff to the SCB. Annual river discharge during the study ranged from 0.9×10^6 m^3 for the Santa Clara River to 217×10^6 m^3 for the Los Angeles River. Annual discharges were, on average, 61% below their long-term means during the 1987 water year (range: 17-99% below), and 31% below their long-term means in 1988 (range: 75% below to 33% above). Rainfall in Los Angeles was 48% below its long-term average (1877-1988: 37.5 cm) during 1987 and 15% below average during 1988.

Constituent Concentrations.
Between September 1986 and April 1988, 191 runoff samples were collected from eight channels and analyzed for nine constituents; 179 samples were collected during storms and 12 samples were collected during non-storm periods. Constituent concentrations varied from one to two orders of magnitude among the channels (Table 1).

The Tijuana River, which is dominated by raw sewage, had the highest concentrations for eight of the nine constituents, and the second highest concentration for the remaining constituent. The Santa Clara River, a predominantly agricultural watershed, had the highest concentration of total DDT. The San Diego River, which drains a less developed basin, had the lowest concentrations for four of the nine constituents, and the second lowest concentrations for three of the remaining constituents. Low flow in the Los Angeles River had the lowest concentrations for five constituents and the second lowest concentrations for three of the remaining constituents. Interestingly, most of the water in the Los Angeles River at low flow is tertiary effluent from water reclamation plants.



Storm channel in Orange County

The concentrations of most constituents were correlated with suspended sediment, and to a lesser extent with river discharge (Table 2). The average rank correlation among constituent concentrations was 0.53. The average rank correlation among constituent mass emissions was 0.86 in 1987 and 0.80 in 1988 indicating that within a channel, conditions that result in high concentrations and mass emissions for one constituent hold for the other constituents. As river discharge rises, sediment mobilization increases. Suspended sediment, usually the constituent present in the greatest amount, comes from soil erosion and, in urban areas, particles produced by automobiles, industry, and commercial activities. Contaminant concentrations and mass emissions increase with increasing sediment loads because the surface area available for adsorption increases (Williams *et al.* 1966, Bradley and Lewin 1982).

Constituent Mass Emissions.
Mass emissions varied from one to three orders of magnitude among the channels (Tables 4a,b). The Los Angeles, San Gabriel, and Tijuana rivers had the highest mass emissions, and the Santa Clara and San Diego rivers had the lowest. Mass emission estimates generally increased from 1987 to 1988 in proportion to the increase in volume discharged. For Ballona Creek and the Los Angeles River, most of the increase was associated with the increased frequency of high flows; low flow volumes and constituent mass emissions estimates were similar between years.

Not all of the channels sampled discharge directly into the ocean. Several channels discharge into harbors and lagoons; it is possible to calculate the load delivered by the river to the harbor or lagoon, but because of modifications due to processes in the receiving body of water, this is not necessarily the load delivered to the ocean. Harbors and lagoons can be a partial trap for many substances, especially sediment.

Conclusions

Urbanization has had a dramatic impact on the landscape of southern California during the past century. Rivers and streams have been extensively modified to conserve water for a growing population and to control floods (Brownlie and Taylor 1981). Urbanization increases the quantities of pollutants that reach rivers and streams. The type and concentrations of pollutants in runoff are determined by the degree of urbanization, types of land use, densities and types of vehicle traffic and animal populations, atmospheric quality, municipal cleaning practices, and specific storm characteristics (Randall and Grizzard 1983, Ellis 1986). Most river discharge and contaminant transport in southern California happens during winter storms that occur intermittently and unpredictably. ■

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Acknowledgements

Authors Jeffrey Cross, Kenneth Schiff, and Henry Schafer thank the present and former staff of SCCWRP who participated in the sampling, analyses, and data reduction: Azra Khan, Charles Ward, Dario Diehl, Darrin Greenstein, David Tsukada, Harold Stubbs, Jim Laughlin, Karen Englehart, Pat Hershelman, Peter Szalay, Richard Gossett, Rika Jain, Robert Eganhouse, Skip Westcott, Steve Bay, Valerie Raco, and Tara Beaton. The authors thank Michael Sowby, Alan Chartrand, and Shirley Birosik of the Los Angeles Regional Water Quality Control Board; John Mitchell and Nellie Gonda of the Los Angeles County Department of Public Works; Ventura County Department of Public Works; San Diego City Water Supply Dive Group; Walter Knopka, Patty Vainik, and the chemistry and microbiology staff of the Point Loma Treatment Facility Laboratory; Lucy Jao of Hyperion Wastewater Treatment Plant; and Mike Moore and John Lightfoot of County Sanitation Districts of Orange County for help with sampling and analyses, and for guidance along the way.