Estuaries Vol. 14, No. 1, p. 80–93 March 1991

Responses of Fish and Macrobenthic Assemblages to Hydrologic Disturbances in Tijuana Estuary and Los Peñasquitos Lagoon, California

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ABSTRACT: Changes in the assemblages of fishes and benthic macro-invertebrates were evaluated in relation to wastewater inflows at Tijuana Estuary and impounded streamflows and mouth closure at Los Peñasquitos Lagoon. Freshwater from sewage spills or winter rains lowered water salinities and had major impacts on the channel organisms of both southern California coastal wetlands. Benthic infaunal assemblages responded more rapidly to reduced salinity than did fishes, with continued salinity reduction leading to the extirpation of most species. Both the fish and benthic invertebrate assemblages became dominated by species with early ages of maturity and protracted spawning seasons. Between-system comparisons showed that good tidal flushing reduced negative impacts on both the fish and benthic assemblages.

Introduction

Southern California estuaries and lagoons are subject to interannual variability in rainfall, streamflow, and disturbances such as sedimentation, dredging, and wastewater inflows. Two San Diego County wetlands, Tijuana Estuary (TJE; 32°34′N, 117°7′W) and Los Peñasquitos Lagoon (LPL; 32°56′N, 117°15′W) differ in many respects, including size and watershed, but especially in disturbance and tidal histories.

TJE has been open to tidal flushing except for periodic closures in the early 1960s and prolonged closure in 1984 (Zedler and Nordby 1986). LPL has been primarily closed to tidal flushing for most of this century (Bradshaw, unpublished report). A comparison of primary productivity of the two systems (Zedler et al. 1980) demonstrated higher accumulation of biomass of vascular plants at LPL, possibly due to impoundment of freshwater during the growing season. TJE and LPL represent extremes in southern California coastal wetlands (e.g., mouth usually open vs. usually closed) and the differences between the two systems could be explained in terms of the reliability of communication with the Pacific Ocean. In the last decade, human disturbance of these systems has intensified. A comparison of the channel communities of these two wetlands was undertaken to understand the responses to the wider range and increased severity of stresses resulting from these multiple disturbances.

Study Sites

TIJUANA ESTUARY

Tijuana Estuary is located in the southwestern corner of the continental U.S. (Fig. 1) and is included in the Tijuana River National Estuarine Research Reserve, administered by the National Oceanic and Atmospheric Administration (NOAA). The reserve includes approximately 1,012 ha (2,500 acres), 60 ha of which are tidal channels. The Tijuana River, with a watershed of 1,731 km², bisects the estuary into a northern and southern portion and rarely provides much freshwater input except in years with sewage-augmented flows.

In recent years, several disturbances at Tijuana Estuary have changed the salt marsh and channel communities dramatically (Zedler and Beare 1986; Zedler and Nordby 1986; Nordby 1987, 1988). Coastal dune sands were destabilized by trampling, and high tides coupled with sea storms washed large volumes of sand into the main channels of the estuary in 1983 (Zedler and Nordby 1986). The sedimentation events immediately affected channel biota through burial and increased turbidity (Nordby 1987). Later, the reduced tidal prism allowed sand to accumulate, and the tidal inlet closed in April 1984. Dredging to reopen the inlet (in December 1984) removed large numbers of channel organisms, and affected others by suspending sediments. During the eight-month closure of the estuary, hy-

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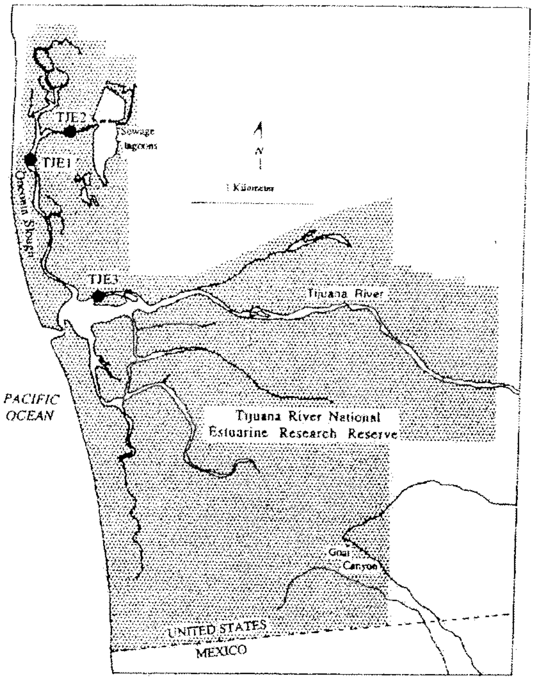

Fig. 1. Fish and invertebrate sampling stations at Tijuana Estuary (TJE). Stippled area represents the boundaries of the Tijuana River National Estuarine Research Reserve.

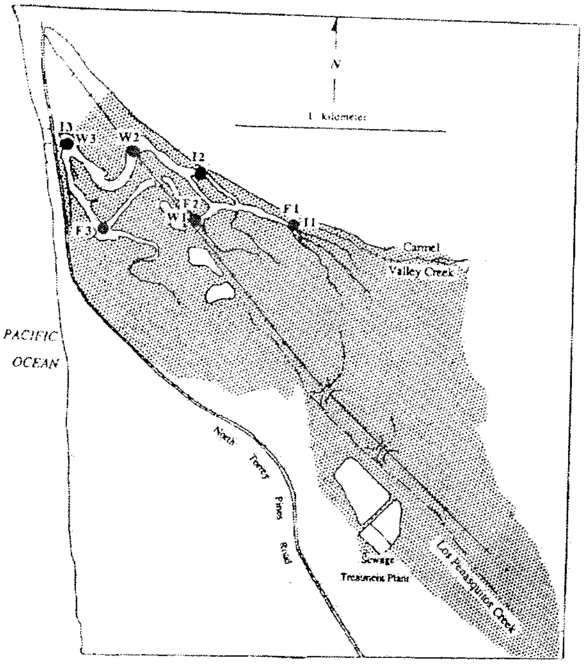

Fig. 2. Fish, invertebrate, and water quality sampling stations at Los Peñasquitos Lagoon (LPL). F = Fish site. I = Invertebrate site. W = Water quality site. Stippled area represents the approximate extent of coastal wetland habitat.

persaline conditions (60‰ in channels) developed through the long dry season, roughly May through November. Three fish species *Gillichthys mirabilis* (longjaw mudsucker), *Paralichthys californicus* (California halibut), and *Hypsopsetta guttulata* (diamond turbot) declined in abundance, and the dominant bivalve species *Nutallia nuttallii* (purple clam) became extinct at Tijuana Estuary (Nordby 1987).

The Tijuana River usually has very little or no flow in summer months when rainfall is low and evaporation rates are high (Zedler et al. 1984). For over 50 years, the river has received raw sewage flows from the City of Tijuana, Mexico (City of San Diego 1988), increasing in volume to an estimated average of 10–12 million gallons per day (MGD) in recent years (Seamans 1988). It has been estimated that a prolonged input of 12.5 MGD of raw or treated sewage would negatively impact the channel biota of the system (Zedler et al. 1984). Renegade flows were estimated at 22 MGD in 1987–1988 (Seamans 1988). Intermittent sewage flows also enter the estuary from Goat Canyon and Smuggler's Gulch. The latter conveyed 4–5 MGD of sewage to the estuary in recent years (City of San Diego 1988). In 1988 the International Boundary and Water Commission built an interceptor to collect and return those flows to the Tijuana treatment system. No interceptor was built at Goat Canyon, which carries intermittent sewage spills to the southern arm of Tijuana Estuary (Fig. 1).

Los Peñasquitos Lagoon

Los Peñasquitos Lagoon is a small coastal wetland of approximately 142 ha, 12 ha of which are channel habitat. The lagoon is the terminus of a small watershed (246 km^2) and is fed by two creeks: Carmel Valley Creek to the east and Los Peñasquitos Creek to the southeast (Fig. 2). Historically, both streams were seasonal, with little or no flow during summer and autumn. Recently, agricultural and residential run-off have increased flows of Carmel Valley Creek to year-round so that brackish marsh has encroached into the salt marsh.

In recent decades, LPL has evolved from a tidal estuary to a lagoon that is usually closed to tidal flushing. Construction of a railroad embankment across the center of the lagoon in 1925 isolated channels and thereby greatly reduced tidal volume and circulation. In 1932–1933, construction of a highway along the barrier beach resulted in more fill and constriction at the mouth. The tidal prism of the lagoon is no longer large enough to maintain an opening to the ocean. Consequently, mechanical removal of the sand and cobble sill at the mouth is necessary to provide occasional tidal circulation. The lagoon is nearly always nontidal in summer, and impounded seawater increases in salinity through the summer and autumn due to evaporation. In the cool wet season, storm run-off flows into the lagoon and decreases water salinity. Only major rainfalls raise the lagoon water level high enough to break through the sand berm at the mouth. The extremes in salinity cause conditions that are stressful to channel organisms (Bradshaw, unpublished report).

Wastewater flows also affect this lagoon. From 1962 to 1972 a sewage treatment facility discharged 0.5–1.0 MGD of treated effluent into the lagoon, increasing nitrate and phosphate loads and reducing water salinity. While the wastewater line was connected to the metropolitan sewer system in 1972, the pumps transporting the sewage to the treatment facility on Pt. Loma have failed repeatedly. A raw sewage spill of about 20 MGD occurred in March 1987. There were flood events during the wet seasons of 1986, 1987, and 1988. Organic matter from sewage spills, tidal closure, and floods probably interact to cause both salinity and oxygen stress to organisms. Persistence of these conditions for 2 to 3 d can eliminate most of the channel fauna. Only species that survive rapid reduction in salinity and dissolved oxygen or reinvade from the nearshore habitat via extreme high tides, storm waves, or brief tidal openings, persist from year to year.

Sampling Stations and Methods

Tijuana Estuary Stations

This study was conducted primarily in the northern arm of the estuary known as Oneonta Slough (Fig. 1). Sampling stations were chosen to reflect differences in channel morphometry (width, depth, and substrate type) and distance from the mouth. During the study, chronic wastewater inflows entered the system via the Tijuana River, while sewage spills from broken pipelines intermittently flowed across the southern portion of the marsh to the mouth. Areas near the mouth received more sewage than did areas further from the mouth.

Station TJE1 was 15 m wide, usually less than 1 m deep during sampling and had a sand substrate. This site was located about 900 m from the mouth. At station TJE1, extremely high tides (2.38 m MLLW) and coincident storm-induced waves washed dune sand into the channel on two occasions during the study period: December 31, 1986, and December 31, 1987. Several centimeters of dune sand were deposited at this sampling site on those dates. In April 1987, the north arm of the estuary was dredged to restore the tidal prism lost from sediment deposited that winter. Dredging was performed by drag line from the western bank of the channel beginning approximately 0.25 km north of TJE1 and ending roughly adjacent to TJE3 (Fig. 1). Following the dune wash-over of 1987, a shorter length of the southern main channel was bulldozed to remove sediment.

Station TJE2 was located in a man-made channel that was excavated in the early 1900s to link the former sewage lagoons with the main channels (Fig. 1). This was the deepest site (usually about 1 m), with eroding banks. The channel was 10 to 11 m wide at this site with a substrate that was composed of a clay/mud mixture with broken shell fragments in the upper 10 to 15 cm over a bed of coarse sand/gravel. TJE2 was located approximately 1,800 m from the mouth.

Site TJE3 was situated in the mouth region on a side channel paralleling the Tijuana River. This was the shallowest site (<0.5 m) and had sloping banks. The channel was 6 to 7 m wide with a sand substrate. TJE3 received sewage flows directly from the Tijuana River.

Los Peñasquitos Lagoon Stations

Sampling stations at LPL were chosen to represent a spatial continuum from the mouth to the terminal tidal creeks in the eastern end of the lagoon (Fig. 2). Station LPL1 was located in the extreme eastern end of the lagoon. The channel at this site was 5 to 7 m wide, 40 to 90 cm in depth depending upon season, with a clay substrate. Station LPL2 was located in a blind diverticulum which resulted from the construction of the railroad berm. This site was approximately half-way between the mouth and LPL1. The channel was 8 m wide and 30 to 90 cm deep with a clay/mud substrate. Station LPL3 was the widest site (>40 m), 30 to 100 cm deep with a mud substrate and was located in the mouth region.

Sampling Protocol

Fishes and benthic invertebrates were collected quarterly from each wetland. All samples were collected during daylight hours on moderate to low tides. Each system was sampled within the same 1-wk period. TJE has been sampled for 3 yr, from June 1986 to March 1989, while LPL has been sampled for 2 yr, from June 1987 to March 1989. However, due to different start-up times for various stages of invertebrate sampling, and due to a lag in the analysis of some benthic invertebrate samples, the numbers of samples are not identical (Table 1).

At each site, two "blocking nets" (13.7 m long, 1.8 m deep, 3-mm mesh) were used to confine all fishes within a section of the channel. A beach seine (3.7 m long, 1.8 m deep, with a 2 × 2 m bag, 3-mm mesh) was then drawn in a circular manner

TABLE 1. Sampling schedule for the collection of fishes and benthic invertebrates at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL).

	TJE	LPL
Fishes	12 quarterly samples June 1986–March 1989	8 quarterly samples June 1987–March 1989
Bivalves	10 quarterly samples September 1986–December 1989	7 quarterly samples June 1987–December 1988
Polychaetes and other benthic forms	7 quarterly samples June 1987–December 1988	7 quarterly samples June 1987–December 1988

within the two blocking nets and pulled to shore. Hauls were repeated until the number of fish captured declined to near zero, usually 4–5 hauls. The blocking nets were then drawn together in a semicircle to catch any fishes that were hiding in the blocking nets.

The areas sampled differed both within each wetland and between the two systems. The earliest samples at TJE were taken from relatively large areas. For example, June 1986 samples at TJE1, TJE2, and TJE3 were taken from areas of 520 m^2, 300 m^2, and 150 m^2, respectively. These areas were reduced to a standard area of 110 m^2, 110 m^2, and 70 m^2 for TJE1, TJE2, and TJE3, respectively, after preliminary analysis demonstrated that the number of species collected was not affected and densities were not significantly reduced.

The areas sampled at LPL were modeled after those at TJE. Thus, stations LPL1–LPL3 included areas of 70 m^2, 70 m^2, and 110 m^2, respectively. The numbers of fishes collected are expressed as densities (number m^{-2}) for comparative purposes.

To test the effectiveness of the fish sampling method and to demonstrate the catchability of individual species, the numbers of fish captured per haul were compared. A test of the number of hauls required to provide an adequate sample was also performed by plotting the number of fish caught against the prior cumulative catch. These tests were performed in March 1987.

Benthic invertebrates were collected using a 15-cm diameter (177 cm^2) coring device pressed into the sediment to a depth of 20 cm. The core was then sieved through a 1-mm mesh screen, with large organisms tallied in the field and the remaining specimens fixed in 3% formalin and transported to the laboratory for identification. Three replicate samples consisting of three pooled cores each were taken per site for a total of nine cores (0.16 m^2) per station. Sampling sites corresponded to fish sampling stations at TJE. At LPL, three stations within the main channel were sampled (Fig. 2).

Water quality was monitored approximately biweekly at LPL and quarterly at TJE. Sampling sites at TJE were the same as benthic invertebrate and fish sampling sites. Sampling stations at LPL were chosen to reflect extremes in water quality. These extremes represent a spatial continuum from the mouth of the lagoon to the terminal creeks (Fig. 2). Station LPL1 was nearest the freshwater inflows from Carmel Valley Creek, while station LPL3 was nearest the mouth and was the most affected by seawater when the mouth was open.

Water temperature and dissolved oxygen were measured using a Yellow Springs Instrument Model 51B DO/temperature meter. Salinity was measured to the nearest part per thousand using an American Optical salinity refractometer.

Sediments were analyzed for grain size using the Emery Settling Tube (Emery 1938), a 164-cm long water-filled glass tube that allows differential settling and separation of particles into size classes. This analysis was employed at TJE1 and TJE2 only.

Statistical tests of patterns of fish and benthic invertebrate distributions and abundances were conducted for each wetland. To test for differences in the number of fish species collected at each sampling station, a two-way ANOVA without replication was performed with stations and surveys as treatments. Because the assumption of no interaction may not have been met, these results are presented as an index of species distributions rather than a strict test of the null hypothesis. A one-way ANOVA was employed to test for differences in the sizes of *Atherinops affinis* (topsmelt) present each June at TJE1. A two-way ANOVA was performed on the square roots of bivalve densities using stations and surveys as treatments. Density data for bivalve assemblages were transformed to make the variances equal and distributions normal ($n = 3$ pooled cores).

Results

Environmental Conditions

The streamflow of the Tijuana River is characterized by high variability in both mean annual and monthly flows. Streamflow records from 1937 to 1977 document a mean annual discharge of 5,500 MGD with a coefficient of variability of 325% (Zedler and Beare 1986). Due to high variability in both

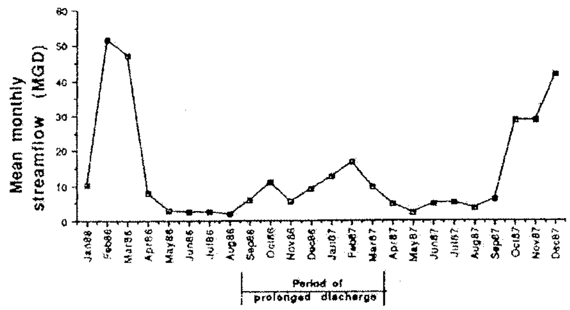

Fig. 3. Mean monthly streamflow for the Tijuana River 1986–1987. Data from the International Water and Boundary Commission (IBWC).

streamflow and rainfall, there is no means of separating "normal" streamflow from wastewater flows. For this study, we will refer to all flows as wastewater flows, realizing that considerable amounts of freshwater may enter the system following winter rainfall events.

The volume of wastewater entering the United States via the Tijuana River varied widely from 1986 through 1987 (Fig. 3). A peak discharge in winter 1986 was followed by about 6 months of low flow. Flow volumes were on the order of 5 to 20 MGD in late 1986 and early 1987 but increased again in late 1987.

At LPL, water salinity and dissolved oxygen levels fluctuated widely when the mouth was closed (Fig. 4). During this study period rapid reductions in salinity and dissolved oxygen occurred during October 1987 and December 1988.

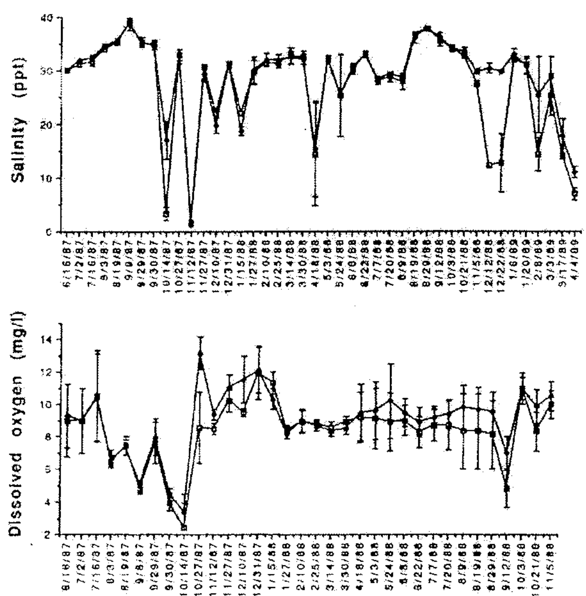

Fig. 4. Mean water salinity and dissolved oxygen at three sampling sites at Los Peñasquitos Lagoon (LPL). Error bars = ± one standard error.

TABLE 2. Fish species collected at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL).

Taxon	Common Name	TJE 1986–1988	LPL 1987–1988
Atherinidae			
Atherinops affinis	topsmelt	15,437	1,875
Blennidae			
Hypsoblennius gentilis	bay blenny	4	0
Hypsoblennius gilberti	rockpool blenny	1	0
Hypsoblennius jenkinsi	mussel blenny	1	0
Bothidae			
Paralichthys californicus	California halibut	283	12
Cottidae			
Leptocottus armatus	staghorn sculpin	1,431	346
Artedius sp.	sculpin	2	0
Cyprinodontidae			
Fundulus parvipinnis	California killifish	2,367	107
Engraulidae			
Anchoa compressa	deepbody anchovy	11	67
Girellidae			
Girella nigricans	opaleye	82	0
Gobiidae			
Clevelandia ios	arrow goby	60,097	816
Gillichthys mirabilis	longjaw mudsucker	275	877
Ilypnus gilberti	cheekspot goby	50	22
Lepidogobius lepidus	bay goby	0	9
Quietula y-cauda	shadow goby	3	0
Mugilidae			
Mugil cephalus	striped mullet	5	3
Pleuronectidae			
Hypsopsetta guttulata	diamond turbot	83	14
Pleuronichthys ritteri	spotted turbot	4	0
Poeciliidae			
Gambusia affinis	mosquitofish	0	937
Rhinobatidae			
Rhinobatos productus	shovelnose guitarfish	2	0
Serranidae			
Paralabrax clathratus	kelp bass	12	0
Sciaenidae			
Seriphus politus	queenfish	1	0
Syngnathidae			
Syngnathus leptorhynchus	bay pipefish	14	2
Total fishes collected		80,165	5,087
Total species encountered		21	13
Total sampling effort (cumulative area in m^2)		4,795	1,985
Number of quarterly samples		12	8

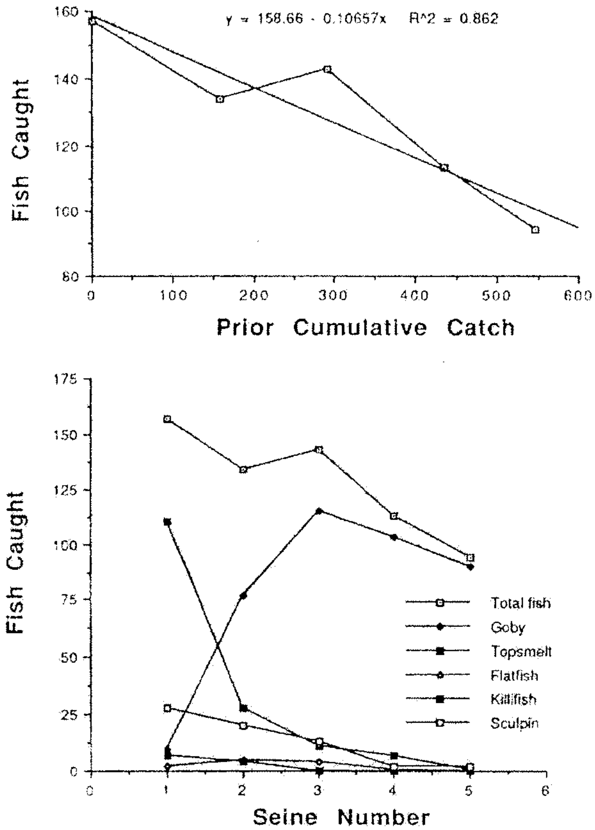

Fig. 5. Tests of the sampling efficiency of the method of collecting fish used in this study. Top: repeated seining of a blocked channel plotted against prior cumulative catch. Bottom: species composition of repeated seinings.

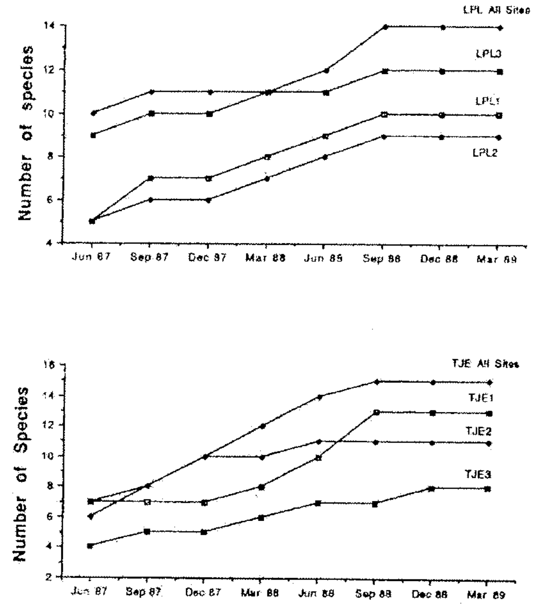

Fig. 6. Cumulative species curves for fishes collected at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL) from June 1987 to March 1989.

Fishes

The two wetlands exhibited obvious differences in fish assemblages (Table 2) in terms of dominants (total individuals collected) and species richness (number of species). At TJE, 21 species of fish representing 14 families were collected over the 3-yr period. Three species dominated the samples: 75% were *Clevelandia ios* (arrow goby), 19% *Atherinops affinis*, and 3% *Fundulus parvipinnis* (California killifish). The remaining 18 species comprised only 3% of the total combined. In contrast, 13 species from 10 families were collected at LPL. Dominants included four species: 36% were *Atherinops affinis*, 18% *Gambusia affinis* (mosquitofish), 17% *Gillichthys mirabilis*, and 16% *Clevelandia ios*.

A test of the sampling procedure used in this study illustrates its effectiveness in capturing the majority of the fishes contained within the two blocking nets (Fig. 5). Repeated seining was especially needed to sample the small, numerically dominant *Clevelandia ios*. The number of *C. ios* captured per seine increased on the second and third sweeps and remained high throughout the fourth and fifth efforts. Conversely, *Atherinops affinis* densities declined dramatically after the first seine, illustrating the relative ease with which this pelagic species was captured.

The differences in the number of species encountered in each wetland are partially due to a greater sampling effort at TJE. Many of the species taken at TJE were collected in 1986, a year before sampling began at LPL. There was also some disparity in areas sampled, with the total area at LPL somewhat smaller than at TJE. When the 1986 data from TJE are omitted from comparisons, the cumulative species curves for each wetland are similar with curves leveling after the sixth quarterly sample (Fig. 6), suggesting that both wetlands were adequately assessed for species richness.

A comparison of absolute and relative abundances demonstrated system-wide changes at TJE during the study (Table 3). The fish assemblage shifted from one codominated by *Atherinops affinis* and *Clevelandia ios* in 1986 to one in which *Clevelandia ios* was by far the numerical dominant. The relative abundance of *Atherinops affinis* remained fairly constant in LPL (Table 3). While *Clevelandia ios* dominated TJE, it was a relatively minor species at LPL. Conversely, *Gillichthys mirabilis* was important at LPL but rare at TJE. *Atherinops affinis* was common in both wetlands but declined throughout

TABLE 3. Annual relative abundance (% of total) of the dominant channel organisms collected at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL). X = no data.

Species	TJE			LPL	
	1986–1987	1987–1988	1988–1989	1987–1988	1988–1989
Fishes					
Atherinops affinis	52%	14%	7%	38%	36%
Clevelandia ios	41%	58%	90%	22%	14%
Fundulus parvipinnis	4%	19%	1%	4%	2%
Gillichthys mirabilis	0%	<1%	<1%	28%	14%
Gambusia affinis	0%	0%	0%	<1%	24%
Total fishes collected	20,888	4,976	54,301	1,253	3,834
Bivalves					
Tagelus californianus	73%	33%	27%	35%	50%
Protothaca staminea	19%	34%	42%	2%	8%
Macoma nasuta	2%	17%	19%	7%	5%
Cryptomya californica	0%	6%	4%	0%	8%
Total bivalves collected	658	490	651	55	40
Polychaetes					
Capitellidae	X	33%	50%	22%	36%
Spionidae					
Boccardia spp.	X	<1%	5%	19%	7%
Polydora spp.	X	18%	20%	28%	21%
Nephtys spp.	X	16%	1%	0%	0%
Pseudopolydora spp.	X	0%	0%	5%	3%
Spiophanes missionensis	X	0%	8%	0%	0%
Opheliidae					
Armandia brevis	X	<1%	5%	<1%	<1%
Euzonus mucronata	X	0%	0%	<1%	25%
Unidentified taxa	X	3%	0%	4%	0%
Total polychaetes collected		276	1,422	709	659

the study period at TJE. *Gambusia affinis* was common at LPL but absent from TJE.

The total numbers of fish species have also changed. At TJE, species richness fell from a high of 14 in September 1986 to a low of 6 in December 1988 and March 1989 (Fig. 7). The most dramatic change in species richness occurred between September 1986 and June 1987, a time of prolonged sewage discharge. Each quarterly sampling period in 1986–1987 yielded more species than the corresponding sampling period in 1987–1988. The number of fish species differed significantly with sampling station ($p < 0.05$; Fig. 8).

At LPL, species richness was highest in June and September and lowest in December (Fig. 7). There were no significant differences among stations ($p > 0.05$). A maximum of 10 species was collected from LPL during any single sampling period.

Fishes also declined in density and size. At TJE,

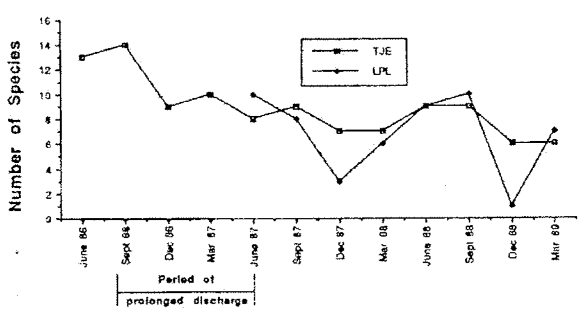

Fig. 7. Total number of fish species collected from each of three sampling sites at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL).

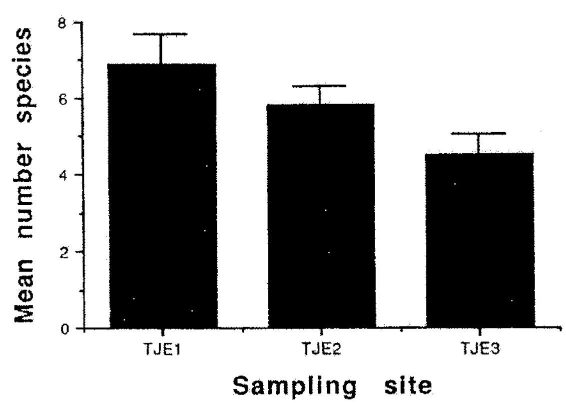

Fig. 8. Mean number fish species (n = 12) collected at three sampling sites at Tijuana Estuary (TJE). Error bars = ± one standard error.

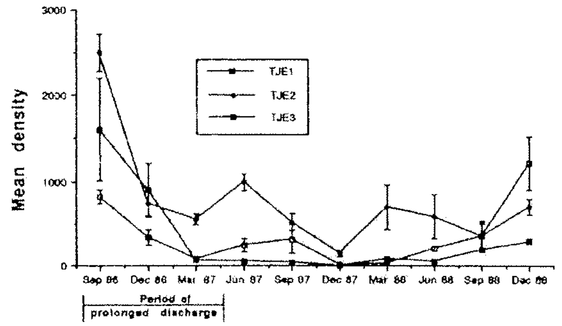

Fig. 10. Mean densities (no. m^{-2}) of all bivalves collected from each of three sampling sites at Tijuana Estuary (TJE). Error bars = ± one standard error.

(two-way ANOVA, $p < 0.01$); the interaction was also significant ($p < 0.01$), primarily because there were zero bivalves collected on some dates at some stations.

Two of the three dominant bivalve species were found in highest densities at station TJE2 compared to TJE1 and TJE3 (Fig. 11). Both *Protothaca staminea* and *Macoma nasuta* showed a strong site

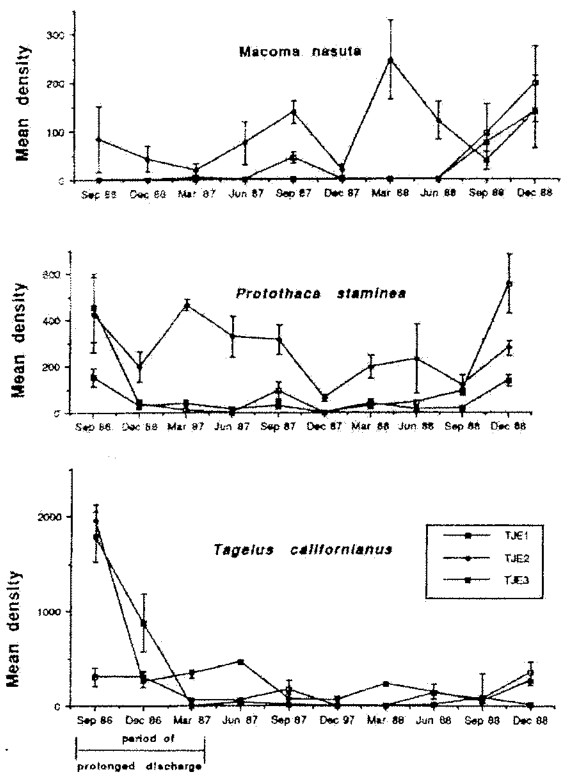

Fig. 11. Mean densities (no. m^{-2}) of the dominant bivalve species collected at each of three sampling sites at Tijuana Estuary (TJE). Error bars = ± one standard error. Note different vertical scales.

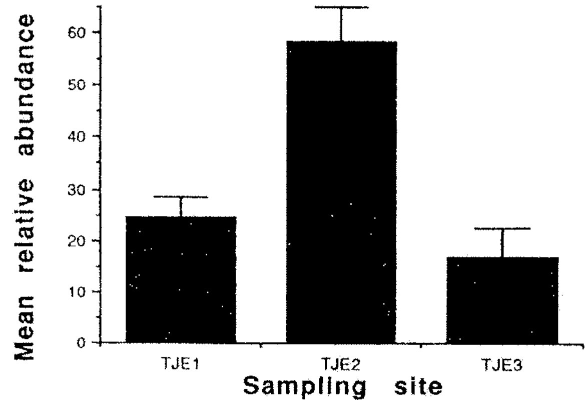

Fig. 12. Mean number of bivalve species collected from each of three sampling sites at Tijuana Estuary (TJE). Data are means for 10 sampling dates. Error bars = ± one standard error.

preference for TJE2. *Tagelus californianus* did not demonstrate a clear site preference but occurred at all sampling stations. TJE2 also supported higher mean relative abundances of bivalves than did stations TJE1 and TJE3 (Fig. 12).

Sediments analyzed at TJE2 had ϕ values (Table 6) that indicated a very coarse grain size and a high degree of variation about the mean grain size (sorting and skewness). Sediments from station TJE1 were coarse and well sorted. This site was buried with several centimeters of dune sand on two occasions during the study and was dredged once to remove sediments.

As with the fish assemblage, benthic invertebrates at TJE showed a shift in dominance and an overall decline in total number of individuals collected (Table 3). In 1986, *Tagelus californianus* dominated the collections while *Cryptomya californica* was absent. *Callianassa californiensis*, a commensal of *Cryptomya*, was collected in low densities in 1986. By 1987, *T. californianus* had declined

TABLE 6. Phi values determined from sediment analysis for Tijuana Estuary site TJE1 (from Duggan 1989).

Station	Date	Mean Grain Size[a] (mm)	Sorting[b]	Skewness[c]
TJE1	Sept. 1986	2.22	0.65	−0.11
TJE1	Jan. 1987	1.90	0.81	0.05
TJE2	May 1987	1.04	1.65	0.09
TJE2	Sept. 1987	0.75	1.81	−0.41

[a] 2 mm to 1 mm indicates very coarse grain size, 0.5 to 1.00 indicates coarse sand (from Krumbein and Pettijohn 1938).

[b] 0.5 to 1.0 indicates moderately well to moderately sorted; 1.0 to 2.0 indicates poorly sorted, with sorting a measure of dispersion of grain size around the mean grain size of that sample (from Folk and Ward 1957).

[c] −0.10 to +0.10 indicates nearly symmetrical distribution of grain size around the mean; −1.0 to −0.3 indicates negatively skewed (from Folk and Ward 1957).

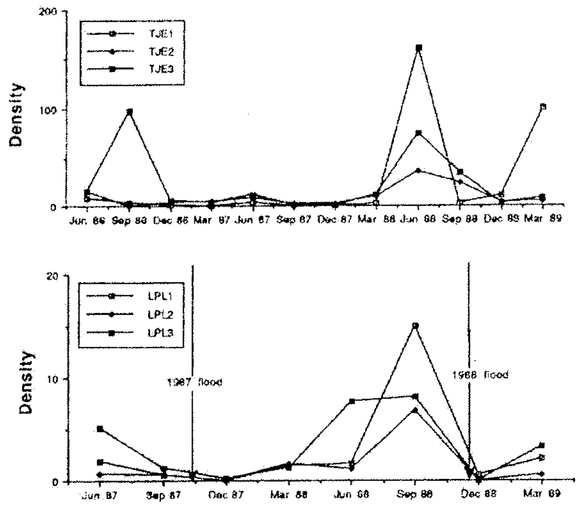

Fig. 9. Mean densities (no. m^{-2}) of all fishes collected at each of three sampling sites at Tijuana Estuary (TJE) and three sites at Los Peñasquitos Lagoon (LPL). Note different vertical scales.

the density of fishes collected decreased from a peak in September 1986 to relatively low values throughout 1987 before rising dramatically in March and June 1988 (Fig. 9). Mean density of fishes at LPL declined after a June peak to levels near zero in December, following the 1987 flood, and peaked again in September 1988, before crashing as a result of the 1988 flood (Fig. 9).

The maximum and mean sizes of *Atherinops affinis* captured at station TJE1 in June of each year declined dramatically (Table 4). There were significant differences in sizes present each June ($p < 0.001$). Station TJE1 was chosen for this example because it typically yielded the highest numbers of this species.

Benthic Invertebrates

Fifty-eight taxa of benthic invertebrates were collected from TJE from September 1986 to June 1988 (Table 5). The collections were nearly equally represented by polychaetes and bivalves. The dominant bivalve species included *Tagelus californianus*, *Protothaca staminea*, and *Macoma nasuta*, while capitellids and spionids dominated the polychaete fraction. The decapod crustacean *Callianassa californiensis* was also abundant.

TABLE 4. Sizes of *Atherinops affinis* (fork length in mm) collected at station TJE1 during June of three consecutive years. SE = ± one standard error.

Year	Maximum Size	Mean Size	SE	n
1986	188	110.3	±1.2	292
1987	121	91.6	±2.8	109
1988	68	47.2	±0.6	124

TABLE 5. Numbers of individuals of benthic invertebrates collected at Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL). Taxa comprising less than 5% are presented as "others."

Taxon	TJE 1986–1988	LPL 1987–1988
Sipunculid worms		
Themiste sp.	17	0
Echinoid echinoderms		
Dendraster excentricus	6	3
Nemertean worms	93	3
Polychaete worms		
Capitellidae	814	399
Spionidae		
Boccardia spp.	68 (5 spp)	183 (4 spp)
Polydora cornuta	124	18
Polydora ligni	143	92
Polydora spp.	63 (2 spp)	210 (2 spp)
Spiophanes missionensis	117	0
Opheliidae		
Euzonus mucronata	0	162
Other taxa combined	437	161
Total polychaetes collected	1,698	1,207
Total families collected	13	11
Total species collected	35	20
Bivalve molluscs		
Tagelus californianus	797	40
Protothaca staminea	554	4
Macoma nasuta	221	6
Laevicardium substriatum	30	8
Spisula sp.	0	17
Other species combined	227	17
Total bivalves collected	1,799	92
Total species collected	18	12
Decapod crustaceans		
Callianassa californiensis	234	3
Phoronida		
Phoronis sp.	1	114
Total sampling area (cumulative area in m^2)	5.25 m^2	3.82 m^2
Total number quarterly samples	11	8

By comparison, 37 taxa of benthic invertebrates were collected from LPL (Table 5). There, the benthic assemblage was dominated by three taxa of polychaetes and had relatively few bivalves. Polychaetes were dominated by capitellids, spionids, and the opheliid, *Euzonus mucronata*. Only 95 individual bivalves representing 12 species were collected from LPL.

Bivalves

At TJE, bivalve densities were greatest in September 1986 when as many as 2,500 m^{-2} were collected at station TJE2 (Fig. 10). Densities declined during the prolonged period of wastewater discharge. There were significant differences in bivalve densities among stations and on different dates

TABLE 7. Mean length (in mm) of the dominant bivalves collected from Tijuana Estuary November 23, 1986, and January 24, 1987. SE equals one standard error (from R. Duggan 1989).

Species	11/23/86			1/24/87		
	Mean	SE	n	Mean	SE	n
Tagelus californianus	40.3	2.2	302	38.4	0.4	164
Protothaca staminea	11.2	0.3	126	10.8	0.6	90

while *Protothaca staminea*, *Cryptomya*, and *Callianassa* had increased. In the three quarterly samples analyzed for 1988, *T. californianus* continued to decline and *P. staminea* continued to increase. *Cryptomya californica* and *Macoma nasuta* remained near 1987–1988 levels (Table 3).

A comparison of the mean sizes of the two dominant bivalve species (Table 7) suggests that the majority of the individuals encountered in this study were 0 to 1 year old with a few specimens slightly older (Shaw 1986; R. Duggan, SDSU, personal communication). Thus, newly recruited individuals comprised the majority of those collected.

Polychaetes

The abundance of polychaetes collected at TJE increased from 1987 to 1988, especially at station TJE3, nearest the Tijuana River (Fig. 13). The dominant taxa during this peak were capitellids and spionids, primarily *Polydora nuchalis* and *P. cornuta*.

At LPL, polychaetes were the dominant benthic form during the 2-yr study period. Capitellids, spionids (*Polydora* spp.) and the opheliid, *Euzonus mucronata*, dominated. Prior to the October 1987 flood, mean polychaete densities were highest near the mouth (station LPL3, Fig. 14). After flooding, mean densities fell to levels near zero at all sites. By September 1988, peak densities were encountered with the greatest values again at station LPL3.

A comparison of the annual relative abundances demonstrates the instability of both systems (Table 3). The relative abundance of each of the dominant taxa at TJE changed substantially, especially among the spionids where *Nephtys* spp. decreased and *Boccardia* spp. and *Spiophanes missionensis* increased from the previous year. The changes at LPL were less dramatic but included the decrease of *Boccardia* spp. and the sudden increase of *Euzonus mucronata*.

Discussion

Three lines of reasoning lead us to conclude that hydrologic disturbances, especially reduced salinity, are responsible for the patterns that have been found at both Tijuana Estuary (TJE) and Los Peñasquitos Lagoon (LPL). The trends over the course of the study are reduced species richness and abundances, population structures skewed toward young animals, and dominance by species with early reproductive maturity and prolonged spawning periods. First, an examination of historic data in southern California coastal wetlands, including TJE, shows that summer streamflows were rare or absent prior to the late 1970s. At that time, a very different benthic assemblage was present at TJE consisting of larger, and presumably older, bivalves (Hosmer 1977). Second, comparison of sampling sites within TJE indicates that the least-disturbed station (farthest from wastewater and not dredged) serves as a refuge for species that have been eliminated elsewhere. Finally, comparison of TJE with LPL, where reduced salinity is more severe due to annual impoundment of flood waters, shows that the fauna is most depleted where the hydrologic disturbances have been greatest. The history of impacts leads to concern regarding future planned modifications to regional streamflows.

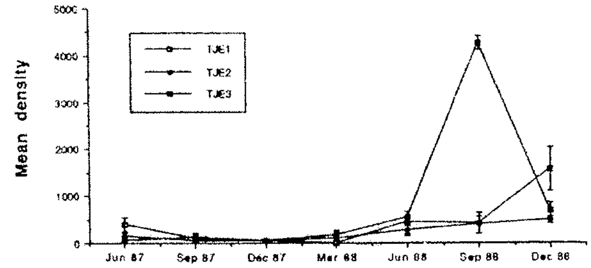

Fig. 13. Mean densities (no. m^{-2}) of polychaetes collected from each of three sampling sites at Tijuana Estuary (TJE). Error bars = ± one standard error.

Historic Comparison

Weather and streamflow records for the San Diego area (Zedler et al. 1984) show that there were no major flood years between 1944 and 1978. Streamflow in the lower Tijuana River was minimal, even in winter, with many years of no measurable flow entering Tijuana Estuary. It is reasonable to assume that the channels were essentially

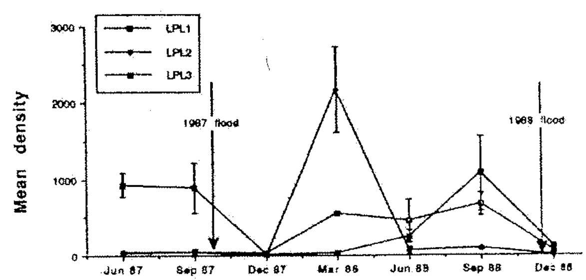

Fig. 14. Mean densities (no. m^{-2}) of polychaetes collected from each of three sites at Los Peñasquitos Lagoon (LPL). Error bars = ± one standard error.

marine at this time. The only historic salinity measurements were made by Purer (1942) in 1939 during a year of average (approx. 25 cm) rainfall and near-average streamflow. The lowest salinity she found at Tijuana Estuary in monthly sampling of three stations was 24‰ in March 1939. Even in a month with 10 cm of rainfall (March 1940), salinities were above 30‰.

The responses of the macrobenthic invertebrates of coastal wetlands to salinity reductions are more apparent than those of the fish assemblages, largely because of their inability to avoid exposure to unfavorable conditions. For this reason, we have concentrated our discussion of the historic comparison on the these assemblages. As previously mentioned, there was some disparity in sampling area with TJE1 and TJE2 equal at 110 m^2 and TJE3 at 70 m^2. While such disparity might have influenced fish distribution and abundance, it would not have affected benthic assemblages that were collected from equal areas and equal effort at all stations at all times. Thus, the strong intra-wetland patterns in the benthos at TJE are not artifacts of sampling design.

The benthos of Tijuana Estuary and Mugu Lagoon (34°N, 119°W) were sampled in the 1970s by Peterson (1972, 1975). His data for live bivalves characterize the low-disturbance assemblage in saline habitats. *Nuttallia* (*Sanguinolaria*) *nuttallii* and *Protothaca staminea* were the most abundant bivalves at both study sites. *Tagelus californianus*, *Cryptomya californica*, *Macoma nasuta*, and *Laevicardium substriatum* were also present but in lower numbers. Samples from Mugu Lagoon taken before and after the 1969 flood suggested that the population of *Tagelus californianus* was reduced by freshwater inflows (Peterson 1972). To test the tolerance of different bivalves to reduced salinity, Peterson simulated flood conditions in the laboratory (6-h periods with seawater diluted to increasing degrees). He found that *Tagelus californianus* and *Laevicardium substriatum* were intolerant of the lowest salinities (3–10‰) while *Protothaca staminea* and *Macoma nasuta* survived 0‰.

Our findings for Tijuana Estuary under continuous wastewater inflows are consistent with Peterson's conclusion that bivalve communities are strongly affected by lowered salinity. The species that are now dominant, *T. californianus*, *P. staminea*, and *M. nasuta*, were least abundant at TJE3, the site nearest the source of wastewater inflow (Fig. 11).

Hosmer (1977) examined bivalve composition and size structure at Tijuana Estuary before wastewater flows were a consistent problem. Large individuals were abundant. The mean sizes for the dominant bivalves were 71 mm for *Nuttallia nuttallii*, 22 mm for *Protothaca staminea*, and 27 mm for *Tagelus californianus*. His results contrast strongly with those of the present study. *Nuttallia nuttallii* no longer exists at Tijuana Estuary, and *P. staminea* is, on the average, half as large (Table 7). The mean size of *Tagelus californianus* in 1986–1987 was larger than that reported by Hosmer (1977), but he had problems in sampling this species and suggested that larger specimens may have eluded him.

While predisturbance data on fishes at TJE are lacking, the effects of a major winter storm on the fishes of Mugu Lagoon have been documented (Onuf and Quammen 1983). They found that *Atherinops affinis* and *Cymatogaster aggregatus* (shiner surfperch), the two dominant preflood fishes, suffered heavier reduction in numbers than did other species. They concluded that fishes that spend the majority of their time in the water column were more affected than were benthic fishes, and attributed this to the reduction of low tide volume within the lagoon as a result of flood-induced sedimentation. The sewage flows at TJE have not resulted in a noticeable decrease in tidal prism. The decline in *A. affinis*, the formerly dominant pelagic species, thus appears to be the result of salinity rather than loss of open water habitat.

Comparison of Stations Within Tijuana Estuary

At TJE, continual wastewater inflows pose a threat to the channel biota. However, the influx of nonsaline water to this tidal wetland had less drastic impacts than the flooding at LPL when it is nontidal.

The importance of salinity reduction is suggested by comparisons of the sampling stations near to and far from the freshwater inflows. At the mouth station (TJE3), channel organisms declined throughout the study period but increased in late 1988. Bivalve densities declined drastically from highs of more than 2,500 m^{-2}, mostly *Tagelus californianus*, in September 1986 to much lower densities for the remainder of the study (Fig. 10). Bivalves at the other two stations did not show similar responses. Polychaete densities were low until September 1988, when mean densities greater than 4,000 m^{-2} were encountered (Fig. 13). Fishes likewise declined at TJE3 throughout the study until June 1988, with the assemblage shifting from one co-dominated by *Atherinops affinis* and *Clevelandia ios* to one in which *Clevelandia ios* was the sole dominant. The highest densities of fish encountered in the study occurred in June 1988 (Fig. 9). This increase may have been a response to the elimination of wastewater flows in Smuggler's Gulch. The Smuggler's Gulch sewage interceptor was completed in April 1988 and operated throughout the 1988 summer; however, it failed to return flows on several occasions in fall 1988.

Station TJE1, which was disturbed by dredging, also demonstrated a general decline in channel organisms. Overall bivalve density declined from peaks in 1986, with little recovery until December 1988. Polychaete densities rose in 1988 to a peak mean density greater than 1,500 m^{-2}. Fish densities declined from 1986 until spawning peaks in June and December 1988.

Analyses of sediments before and after the 1988 dune washover (Table 6) showed that the substrate at TJE1 changed little, possibly because sedimentation events have long recurred at this site. Any impacts to the channel organisms at TJE1 were probably due to conditions other than sediment type, such as changes in water quality or direct disturbance due to dredging.

Station TJE2 acted as a refuge for two of the three important bivalves, *Protothaca staminea* and *Macoma nasuta*. Although the channel was not formed naturally (it was dredged in the early 1900s to connect the former sewage lagoons to the main channel and, ultimately, the ocean), it has had several decades to develop a rich fauna. The strong site preference of *M. nasuta* and *P. staminea* for station TJE2 is not explained by sediment type, since all three species inhabit a wide range of sediment types at TJE (Hosmer 1977), and each of the sampling stations contained sediments suitable for all three species. The high bivalve abundances at TJE2 are more likely due to isolation from wastewater and dredging disturbances. Mean polychaete densities were lowest at TJE2, a pattern that may be explained by their preference for finer sediments.

Station TJE3, at the mouth of the estuary, was directly in the path of the wastewater conveyed by the Tijuana River. This site supported the lowest mean density of bivalves and, at least in September 1989, very high densities of opportunistic polychaetes. In addition, the fewest fish species were collected here.

Populations of southern California coastal wetland fishes have marked seasonality, with highest densities in summer and low densities in winter; however, there are inconsistencies in TJE populations that suggest that this system did not display typical seasonality. These include the low densities encountered in June 1986 and June 1987 (Fig. 8) and the low species richness in June 1987 and March 1989 (Fig. 7). We suggest that this departure from typical seasonal patterns can be attributed to the impacts of modified hydrology.

The shift in the structure of the fish assemblage at TJE to one dominated by *Clevelandia ios* may be due partly from reduced predation pressure. *Clevelandia ios* is preyed upon by a number of estuarine species including *Paralichthys californicus, Hypsopsetta guttulata, Leptocottus armatus* (Pacific staghorn sculpin), and *Fundulus parvipinnis*, according to MacDonald (1975). Although not reported as a predator of *Clevelandia ios, Gillichthys mirabilis* has been observed to be an aggressive predator and cannibal. All of these potential predators have declined in density following mouth closure in 1984 (Nordby 1987) and the multiple disturbances discussed herein. An additional factor that may allow *Clevelandia ios* to dominate disturbed areas is its life history strategy. *Clevelandia ios* matures within one year (Brothers 1975) and spawns from September through June. In 1981, peak spawning at TJE occurred in March, April, and May, with lesser peaks in September and January (Nordby 1982). Larvae were collected in densities greater than 60 m^{-3} in April 1981.

Other components of the channel assemblage are also quick to mature. The dominant polychaetes at both LPL and TJE were species that reach sexual maturity rapidly. Some capitellid species mature sexually in as little as one month and may reproduce year-round (Grassle and Grassle 1976).

High densities of capitellids and *Polydora* spp. may have been encouraged by sewage spills. Both taxa are associated with pollution. Capitellids are considered enrichment opportunists (Pearson and Rosenberg 1978) while *Polydora cornuta* has been reported from areas of high organic matter (Pearson 1975).

In Los Angeles Harbor, Crippen and Reisch (1969) found that *Capitella* sp. and *Polydora cornuta* were most abundant in polluted to very polluted areas. Capitellids have also been shown to increase in density when the source of disturbance ceases, for example, abatement of a pollution source (Rosenberg 1976; Sanders et al. 1980). Thus, the reason for their sudden increase at TJE3 in September 1988 does not necessarily indicate increased wastewater flows.

Tijuana Estuary-Los Peñasquitos Lagoon Comparison

Hydrologic disturbances had a greater impact on the channel assemblage at LPL than TJE. During nontidal conditions at LPL, both fish and benthic invertebrate assemblages experienced seasonal storms and changes in water quality. Populations plummeted following flooding in fall 1987. In spring and summer 1988, the channel organisms recovered, until the December storm event in 1988, which again decimated populations.

There were few spatial patterns in fish and benthic invertebrate distributions within LPL despite stations specifically chosen near the mouth and near freshwater inflows. The small size of the lagoon and its usual closure made its waters relatively homogeneous. Polychaetes were generally more dense at the mouth (LPL3) but were also found in high densities at the other stations at some times of the year. *Gambusia affinis* was found in highest densities at the station most affected by freshwater (LPL1).

Freshwater input to LPL is increasing as the watershed is developed. Flows from Carmel Valley Creek continued throughout the summer and autumn of 1988, a period that is usually dry. This flow has resulted in the encroachment of brackish marsh into the salt marsh and introduced high numbers of *Gambusia affinis* to the landward edges of the lagoon. A long-term increase in freshwater input into the lagoon may jeopardize this coastal wetland.

Future Hydrologic Disturbances

Several municipalities and water utility districts in San Diego County are proposing to discharge treated wastewater into coastal streams, since the ocean outfalls are now at capacity. The California Regional Water Quality Control Board, San Diego Region (1988) projects releases of 10 to 30 MGD by the year 2015 for 10 county streams. All of these streams have natural flow peaks in the winter and many have little or no flow in summer. While plans call for the reuse of treated wastewater for irrigation, streamflows would still be augmented in winter, and the period of heavy flow would no doubt be extended. Shifts in wetland vegetation from dominance by salt marsh halophytes to brackish marsh species (*Typha* and *Scirpus* spp.) have been predicted previously (Zedler et al. 1984). Based on our analyses of channel assemblage responses to hydrologic disturbances, we now predict major impacts to fishes and macroinvertebrates. Discharge of treated wastewater to small coastal wetlands such as LPL, which are frequently closed to tidal flushing, will likely result in the extermination of most or all of the channel biota or replacement with fresh/brackish water species. In many cases these include exotic fish species such as *Acanthogobius flavimanus* (yellowfin goby) and *Gambusia affinis* and invertebrates such as the Asian bivalves *Corbicula fluminea* and *Musculista senhousia*.

Conclusion

The two coastal wetlands compared in this study differ in types and degrees of disturbance. Tijuana Estuary (TJE) has been subjected to continuous, long-term wastewater inflows while Los Peñasquitos Lagoon (LPL) has had flooding once in 1987 and once in 1988. The channel biota of each system were altered by these events, but short-term recovery appears to be greater at TJE, where tidal flushing is now continuous.

At TJE, the structure of the fish assemblage has shifted toward dominance by species with an extended spawning season and rapid maturity. Bivalve populations are composed of young individuals as the result of disturbance events. Polychaete populations are dominated by taxa associated with pollution and that have prolonged spawning seasons and mature rapidly. The sampling station farthest from the wastewater inflows harbored significantly higher densities of bivalves than did the other sites. The sampling station nearest the source of wastewater supported the fewest fish species.

At LPL, the channel assemblage is dominated by species that can survive salinity shock and very low levels of dissolved oxygen, are easily reintroduced during brief periods of mouth opening, or are introduced from freshwater inflows. Density and diversity of all species mirrors the changes in water chemistry; both decrease as water quality deteriorates and increase after water quality improves.

Neither of these coastal wetlands has a channel assemblage that is characteristic of pristine tidal ecosystems. Long histories of disturbance have shifted their composition to a small group of species that is tolerant of reduced salinity. Resilience in the short term is conferred by opportunistic life histories and quick reestablishment following the return of tidal influence. Recovery in the long term would require elimination of the hydrologic disturbances and time for native species to reinvade from refuges within the region's coastal water bodies.

Acknowledgments

We gratefully acknowledge R. Duggan, J. Covin, B. Dubinski, T. Griswold, K. Perry, S. Perry, B. Rees, S. Rutherford, and G. Vourlitis for field assistance; R. Duggan, E. White, and R. Martinez-Lara for invertebrate sorting and identification and additional field data. This research was funded by NOAA Office of Ocean and Coastal Resource Management, Marine and Estuarine Division, grant Nos. NA86AA-D-CZO16, NA87AA-D-CZO29, and NA88AA-D-CZ025, and a grant from the Los Peñasquitos Lagoon Foundation.

This manuscript is dedicated to Jordan Dale Covin, friend and colleague, who passed away during its preparation.

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Received for consideration, June 19, 1989
Accepted for publication, March 26, 1990