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Marsh Vertical Accretion in a Southern California Estuary, U.S.A.

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Vertical accretion was measured between October 1992 and March 1994 in low and high saltmarsh zones in the north arm of Tijuana estuary from feldspar market horizons and soil corings. Accretion in the *Spartina foliosa* low marsh (2–8·5 cm) was related almost entirely to episodic storm-induced river flows between January and March 1993, with daily tidal flooding contributing little or no sediment during the subsequent 12-month period of no river flow. Accretion in the *Salicornia subterminalis* high marsh was low (~ 1–2 mm) throughout the 17-month measuring period. High water levels in the salt marsh associated with the storm flows were enhanced in early January 1993 by the monthly extreme high sea level, when the low and high marshes were flooded about 0·5 m above normal high tide levels. Storm flows in January–March 1993 mobilized about 5 million tonnes of sediment, of which the low salt marsh trapped an estimated 31 941 tonnes, including 971 tonnes of carbon and 77 tonnes of nitrogen. Sediment trapping by the salt marsh during episodic winter floods plays an important role in the long-term maintenance of productivity of Tijuana estuary through nutrient retention and maintenance of marsh surface elevation. The potential exists, however, for predicted accelerated rates of sea-level rise to out-pace marsh surface elevation gain during extended periods of drought (i.e. low sediment inputs) which are not uncommon for this arid region.

Introduction

In the arid climate of southern California, rainfall and streamflow within coastal drainage basins are highly seasonal and may not occur at all for several years during periods of extended drought. The Tijuana river is a typical example of a coastal drainage basin from this region. Freshwater input, if any, occurs only during winter rains (approximately January–April), resulting in measurable streamflows during winter and early spring (Zedler & Onuf, 1984). During the rest of the year, flows are negligible. Streamflows are also influenced by three major dams in the upper reaches of the river which can both attenuate and prolong flows depending on their operation schedule. Hence, the coastal habitats of the lower Tijuana river are dominated by marine conditions during the dry season, while winter river flows result in seasonal or intermittent estuarine conditions

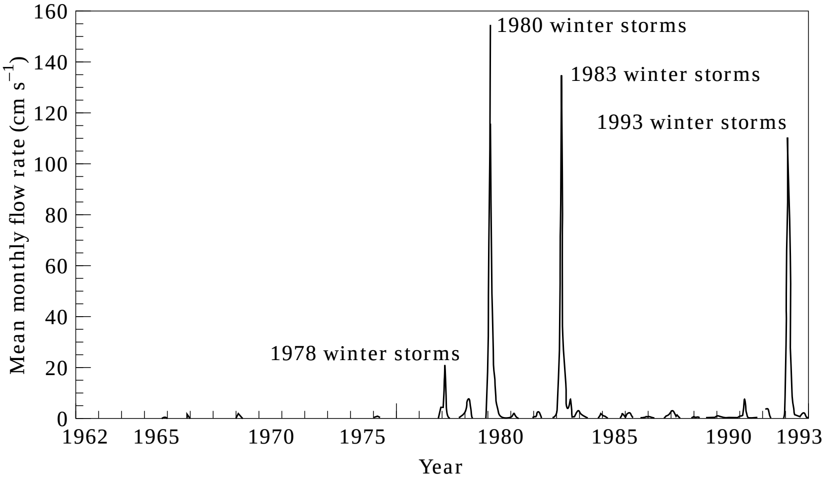

Figure 1. Mean monthly discharge of the Tijuana river, 1962–93, measured at the Nestor gauge. Data source: International Boundary and Water Commission. United States and Mexico, 1962–93. Flow data for 1993 are considered provisional.

during the wet season. Marine processes, such as tides and variations in sea level, influence water levels in the estuary throughout the year. The strong seasonal and annual variation in streamflows of the Tijuana river can be seen by reviewing International Boundary and Water Commission flow data from 1962 to 1993 (Figure 1). During this time interval, 15 consecutive years of negligible or no flow ended when three major storm years (1978, 1980 and 1983) occurred during a 6-year span. This period of storm activity was followed by 9 years of little or no flow which ended with the storm of 1993. The high flow rates occurred in the first half of each storm year.

The seasonal and annual shifts in hydrologic forces in the Tijuana watershed result in distinct temporal patterns of sedimentation and coastal geomorphologic change. Heavy winter storm rains, particularly those occurring after extended periods of drought, typically result in catastrophic erosion of desiccated upland soils and flash flooding of the river basin. Large quantities of water and sediment enter the drainage basin during and immediately after such storm events. For example, Tijuana estuary received 28 times the average freshwater input during 1980 (Zedler, 1983). Brownlie and Taylor (1981) estimated that the annual suspended sediment yield in the Tijuana river from 1937 to 1976 ranged from >3 million tonnes in the years of highest river flow (1941) to zero in years with no river flow. Actual sediment yields in the river, however, are only 30–49% of the natural sediment yields (Brownlie & Taylor, 1981; Simon, Li & Associates, Inc., 1988) because of the three dams in the upper watershed. Using the sediment rating curves generated by Brownlie and Taylor (1981), the authors estimated that the storm years 1980, 1983 and 1993 each generated a sediment load $\geq$5 million tonnes (Table 1).

This sediment load is mobilized and available for deposition primarily during a span of 1–3 months in the winter. Such acute, large depositional events can have catastrophic effects on basin morphology. Williams and Swanson (1987) reported sediment deposits up to 2 m thick during the 1980 storm at the foot of Goat Canyon, a steep canyon in the southern portion of the estuary [Figure 2(a)]. Between 1852 and 1986, there was an

TABLE 1. Total annual river discharge and estimated annual sediment yield for the Tijuana river, 1976–93

Date	Total river discharge[a] ($m^3 \times 10^6$)	Total sediment load[b] (tonnes)
1976	2·24	7796
1977	1·84	6371
1978	79·80	486 361
1979	52·76	302 210
1980	734·97	6 250 217
1981	13·07	60 751
1982	19·43	95 843
1983	603·68	4 984 413
1984	20·70	103 028
1985	16·43	79 002
1986	17·86	86 977
1987	18·79	92 217
1988	32·51	173 165
1989	14·02	65 861
1990	18·27	89 266
1991	36·36	196 960
1992	8·30	36 002
1993	605·66	5 003 266

[a]Data from the International Boundary and water Commission, United States and Mexico 1962–93.
[b]Total sediment load is estimated based on the sediment rating curve of Brownlie and Taylor (1981).

80% reduction in the tidal prism of the Tijuana river caused by sedimentation, landward migration of the beach, and human-fill activities (Williams & Swanson, 1987). Indeed, plans are underway to restore tidal flushing to portions of the estuary through dredging (Zedler *et al.*, 1992).

Such catastrophic changes in basin morphology are primary determining factors in wetland community development. Zedler *et al.* (1992) pointed out that the only sizeable area of low-marsh habitat dominated by *Spartina foliosa* in the Tijuana basin occurs in a drainage arm in the north-west quadrant [Figure 2(b)], because this is the only low, intertidal area not directly in the path of the river or the steep canyons that abut Mexico (e.g. Goat Canyon). Hence, this low marsh area has not been buried by catastrophic sedimentation events. Yet this area floods during catastrophic events and therefore the opportunity exists for suspended sediment to be deposited on its surface. Zedler (1983) estimated vertical accretion in this northernmost salt marsh between July 1979 and September 1980 to be 5 cm, based on comparisons of elevation surveys conducted throughout the marsh. Presumably, most of the elevation change was due to vertical accretion associated with increased river flows and suspended sediment loads which occurred during the winter storms of 1980, because sediment deposits were visible immediately after these storms (Zedler, 1983). Also, tides do not introduce much sediment to the estuary because longshore transport of sediment is away from the mouth of the river in both a northerly and southerly direction (Inman & Masters, 1991); however, the roles of daily tidal action in year-round sediment introduction and vertical accretion of this marsh have not been determined quantitatively. Consequently, the authors collected data on marsh vertical accretion in the northern arm of Tijuana estuary

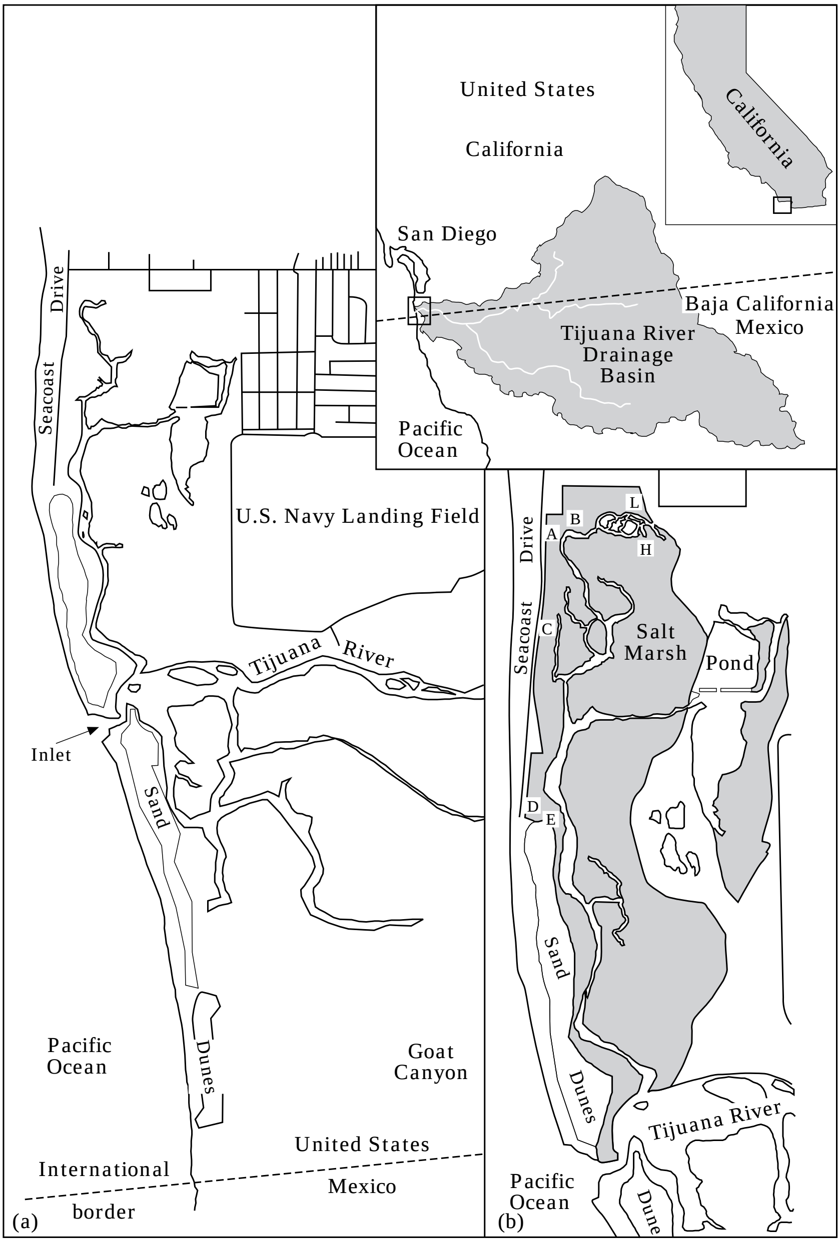

Figure 2. (a) Regional site map of the Tijuana river watershed and estuary. (b) Site map of the northern arm of the lower Tijuana river. Intertidal salt marsh is indicated by shading.

associated with the January–March 1993 winter storms determined from artificial soil horizons established in October 1992. Also, the amount of accretion during the winter floods was compared with the amount for the following 12 months when there was no significant river flow, in order to evaluate the relative contribution of episodic river floods *vs.* daily tidal flooding.

Study site

The total drainage area of the Tijuana river basin is 4483 km^2, approximately 27% of which lies in the United States (International Boundary and Water Commission, 1990) [Figure 2(a)]. The estuarine portion of the river is approximately 4·4 km^2 (Zedler & Onuf, 1984), or 0·1% of the total drainage area. The total area of the estuary is decreasing due to landward migration of the barrier beach during the current phase of sea-level rise and marine transgression (Florsheim *et al.*, 1991). The average rate of migration for the northern arm was 0·88 m $year^{-1}$ for 1852–1986. Storm activity accelerated the average migration rate to 5·79 m $year^{-1}$ for 1977–86. Hence, Tijuana estuary has a continuously diminishing tidal prism because of accumulation of sediments in the intertidal area and loss of area from the shoreline retreat.

The salt marsh in the northern arm of the estuary is connected with the lower Tijuana river by a drainage channel that extends northward parallel to the coast [Figure 2(b)]. This area comprises regularly flooded low marsh (160·2 ha, Pacific Estuarine Research Laboratory, unpubl. data) dominated by *Spartina foliosa*. High marsh, which is flooded only during higher tides, occurs mostly along the eastern edge and is dominated by glasswort, *Salicornia subterminalis*. Tides in the estuary are mixed and semi-diurnal (Flick & Cayan, 1984) with a mean daily range of approximately 1·1 m (Zedler, 1982). The salt marsh and tidal creeks of this northern arm make up only approximately one-third of the total saltmarsh area of Tijuana estuary, but 50% of the tidal prism (Zedler *et al.*, 1992). The northern arm of the estuary is included in the Tijuana Slough National Wildlife Refuge. The coast in the San Diego region is undergoing tectonic uplift at a rate of 0·16–0·20 mm $year^{-1}$ (Kern, 1977), while the rate of relative sea-level rise is estimated to be 1–3 mm $year^{-1}$ (Flick & Cayan, 1984; Roemmich, 1992).

Methods

Permanent sampling plots were located randomly in adjacent low (Site L) and high (Site H) marshes at the farthest reach of the tidal creek on 26–29 October 1992 [Figure 2(b)], north of the most northerly elevation transect surveyed by Zedler (1983). Small sampling platforms were constructed to minimize disturbance to the marsh surface and 21 0·25-m^2 feldspar marker horizons were established in each marsh. A single core was collected from a randomly selected location in each feldspar plot on 8–11 March 1993, 25–27 October 1993, and 15–17 March 1994 by using a cryogenic coring device (Knaus & Cahoon, 1990). The depth of the marker was measured to the nearest 1 mm at 1–4 locations on each core, and a mean datum was calculated. Additional soil cores were collected adjacent to each sampling platform by using a 10-cm diameter piston-corer with a razor blade cutting edge (Hargis & Twilley, 1994) and analysed for organic matter, carbon and nitrogen content, and dry bulk density. Organic matter content was determined by loss-on-ignition at 375 °C for 16 h (Hesse, 1971). Total carbon and nitrogen content were determined by using a Leeman Labs Elemental Analyzer.

In March 1993, the thickness of storm deposits at additional low marsh areas [A, B, C, D and E in Figure 2(b)] located downstream from Sites L and H were determined from visual interpretation of 10-cm diameter cores. The pre-storm marsh surface was readily identifiable by a sharp contact between a fibrous peat and a homogeneous, high density, organic-poor, silty clay (i.e. storm deposit). Dried, ash-free subsamples from all cores collected in March 1993 were analysed for grain size by using a Coulter counter.

In October 1993, additional feldspar plots were established in three areas corresponding with Core Locations A–E [Figure 2(b)]. In each area, two marker horizons were established; one inland near Seacoast Drive, the other near the tidal creek.

Water level was measured by a continuous-recording datalogger with pressure transducer located in the tidal creek about 300 m downstream from Sites L and H. The elevation of the pressure transducer and each sampling plot at Sites L and H were surveyed by using a laser level. These data were used to determine the number of flooding events and the mean flood depth per event for selected months in both dry and wet seasons.

Flows of the Tijuana river are monitored by the International Boundary and Water Commission at the Nestor gauge which is located 1·1 km downstream (north) of the international boundary, or about 10 km upstream from the mouth of the river; hence, Nestor gauge monitors 99·6% of the drainage basin. Flow data from this gauge were obtained for 1962–93.

Accretion data from the permanent plots were analysed statistically by using a repeated measures design under the split-plot framework (SAS Institute, Inc., 1991) and were tested at the $\alpha = 0{\cdot}05$ level. Soil profiles of organic matter and bulk density were analysed by one-way ANOVA and tested at the $\alpha = 0{\cdot}05$ level.

Results and discussion

Hydrology and sediment availability

Storm flows

Precipitation associated with the winter storms in January–March 1993 resulted in high rates of river flow (Figure 3) and higher than normal flood events in the salt marsh in the northern arm of the estuary. The high rate of flow on 7 January coincided with the occurrence of the predicted monthly extreme high tide (2·23 m MLLW) on 8 January (U.S. Army Corps of Engineers, 1991). It is likely that the extreme high sea level in early January retarded flow out of the mouth of the river forcing water levels even higher in the lower estuary, as apparently occurred at Mugu lagoon during the storms of 1978 and 1981. The water level gauge became submerged and ceased operating during the rising tide on 6 January 1993. A maximum high water level of 2·80 m MLLW was observed on 8 January at the north side of the pond [Figure 2(b), Zedler, 1993; Pacific Estuarine Research Laboratory (PERL), unpubl. data] which is 0·57 m higher than the predicted height of the extreme high tide on that day. The water level gauge was partly submerged again on 9 January 1993. Hence, it is likely that the marsh was inundated with extreme high water levels on 6–9 January at the very least. The extreme high water level during this 4-day period apparently was not continuous but was associated with the occurrence of daily high tides (P. Jorgensen, Tijuana River National Estuarine Reserve, pers. comm.). Based on watermarks inside the water level gauge, the authors estimated that the peak water level was 2·52 m MLLW. This meant that the plots at Site L were inundated to an average maximum depth of 0·86 m and the plots at Site H were inundated to an average maximum depth of 0·46 m. It is not known how many smaller storm-enhanced flood events may have occurred. Flick and Cayan (1984) noted that the extensive floods associated with the 1983 storms were also due, in part, to the coincidence of extreme sea levels in the San Diego area with storm-enhanced river flows.

The high flow rates on 16 January, 9 February and 20 February did not coincide with an extreme high sea level and apparently did not result in extreme marsh flooding based

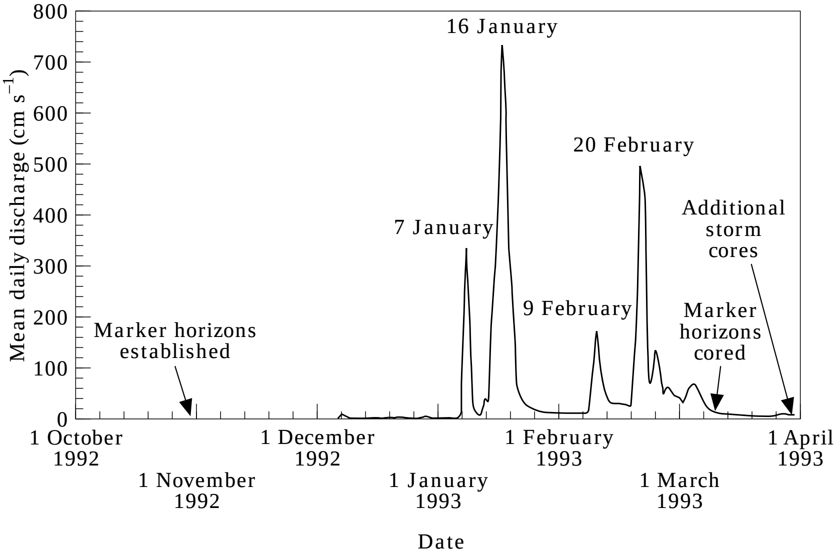

Figure 3. Mean daily discharge of the Tijuana river, 1 October 1992 to 1 April 1993, measured at the Nestor gauge. Data source: International Boundary and Water Commission. United States and Mexico, 1962–93. Flow data for 1993 are considered provisional.

on observations of refuge staff and researchers from PERL working in the marsh. Each flow event, however, likely carried a high suspended sediment load. Flow on 16 January was the second highest instantaneous discharge rate (923 cm s^{-1}) recorded since May 1947. The highest rate (937 cm s^{-1}) occurred on 21 February 1980. During this high-energy event, the river jumped its banks and scoured a new river channel. Scouring of the new channel mobilized a massive quantity of sediment which presumably was available for deposition on the marsh through normal tidal action, even if water levels were not enhanced by the high rate of flow. The same potential for sediment deposition would be true for the flows on 9 February and 20 February, although probably to a lesser degree. The total actual sediment load of the river during 1993 was estimated to be 5 003 266 tonnes based on sediment rating curves developed by Brownlie and Taylor (1981). In a separate analysis, Simon, Li & Associates (1988) generated a sediment rating curve for Tijuana river similar to that of Brownlie and Taylor (1981), indicating that an estimate of actual sediment yield of 4–5 million tonnes for 1993 is not unreasonable. Since most of the flow in 1993 occurred from January–March (Figure 1), most of the sediment yield would have occurred at this time as well.

Clearly, there was ample opportunity for sediment deposition on the marsh surface during the increased river flows and associated marsh flooding of January and February 1993. This opportunity, combined with high sediment loads in the river, indicated that a high potential existed for substantial amounts of sediment to be deposited on the surface of both the low and high salt marshes during January and February 1993.

Daily tides

The opportunity for sediment deposition by regular daily tidal flooding was high for the lower marsh, and moderate for the high marsh, throughout the calendar year (Table 2).

TABLE 2. Average flooding frequency, duration, and depth at Sites L and H for selected months, 1992–94[a]

Month	Site	Days	Flood events	Duration (h)	Depth (m)
December 1992	L	31	22	4·7 ± 0·3	0·17 ± 0·02
	H	31	5	1·6 ± 0·4	0·06 ± 0·01
January 1993[b]	L	6	6	4·2 ± 1·1	0·17 ± 0·06
	H	6	2	2·5 ± 1·5	0·17 ± 0·05
July 1993	L	31	29	4·5 ± 0·3	0·17 ± 0·02
	H	31	8	1·8 ± 0·2	0·06 ± 0·01
October 1993	L	31	30	3·8 ± 0·3	0·13 ± 0·02
	H	31	5	1·8 ± 0·4	0·09 ± 0·03
February/March 1994[c]	L	31	28	2·8 ± 0·2	0·07 ± 0·01
	H	31	0	0	0

[a]Calculations based on an average marsh surface elevation determined from 66 survey points in the high marsh and 64 survey points in the low marsh.
[b]Period of record is for 1–6 January.
[c]Period of record is for 10 February–13 March 1994.

The low marsh surface flooded, on average, once a day for 4 h to a depth of 13–17 cm for the months surveyed. The high marsh had fewer flooding events (25%) of shorter duration (50%) and shallower depth (33%) than low marsh, yet the opportunity for sediment deposition clearly existed year-round in the high marsh. What is not known is the amount of sediment from marine sources that entered the estuary during periods of no-flow in the river and was therefore available for deposition during daily tidal flooding events.

Marsh vertical accretion

Vertical accretion at Site L between October 1992 and March 1993 was 1·9 ± 0·18 cm (n=21) (Figure 4). During the subsequent 12 months, there was no significant change in the depth of the marker horizon. These data clearly indicate that vertical accretion at Site L was associated with flows in the Tijuana river and was influenced little by daily tidal flooding during periods of no river flow (Figure 4). The same temporal pattern occurred at Core Sites A–E farther downstream, where storm deposits ranged from 4·0 to 8·5 cm thick in April 1993 (Table 3), but negligible accretion occurred from October 1993 to March 1994 (Table 4). A similar pattern of storm-driven sedimentation, with little contribution by daily tidal flooding, was reported for a *Spartina alterniflora* salt marsh on the mid-Atlantic coast of the U.S. (Stumpf, 1983).

The thickness of storm deposits at Sites A–E were 3–4 times greater than at Site L, apparently because most sediment dropped out of the flood waters along the main axis of the drainage channel before the waters reached Site L located at a 90° angle to the head of the channel [Figure 2(b)]. A large area of the marsh around Sites A and B, where the channel turns 90° to the east, was covered with a thick storm deposit, as was the entire marsh area located west of the main channel as far south as Site E (Cahoon & Lynch, pers. obs.).

The pattern of accretion in the high marsh (Site H) differed from that in the low marsh. The rate of vertical accretion at Site H at the head of Oneonta Slough was low throughout the 17-month period of measurement (Figure 4). Site H apparently received little influx of mineral sediments during either the major flood events or daily tidal

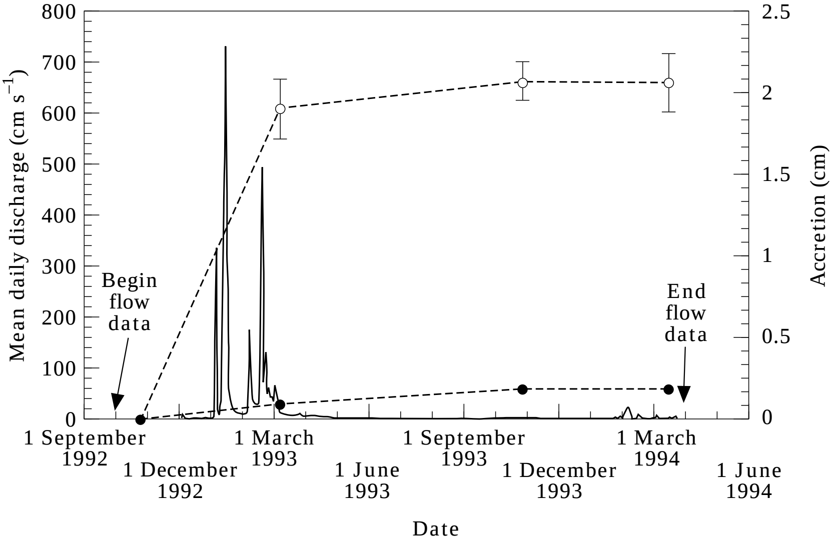

Figure 4. Mean daily discharge of the Tijuana river, 1 October 1992 to 1 April 1994, measured at Nestor gauge (——), and vertical accretion (– – –) in the low marsh (○) and high marsh (●). Flow data source: International Boundary and Water Commission. United States and Mexico, 1962–93. Flow data for 1993 are considered provisional. Accretion data are means ± 1 SE, $n=21$. Error bars for high marsh are smaller than the symbol.

TABLE 3. Depth of pre-storm marsh surface and grain size of storm deposits at selected locations in the low marsh on 1 April 1993

Core[a]	Depth (cm)	Grain size (phi)
A	4·0	6·39
B	8·5	6·26
C	8·0	7·19
D	6·5	6·28
E	6·5	6·27
Site L	1·9[b]	6·24
Mean	5·9	6·44

[a]See Figure 2(b) for location of cores.
[b]Depth datum was measured on 9 March 1993 (see Figure 4).

flooding. The substrate in the high marsh consisted primarily of coarse-grained sediments with only shallow peat development.

The storm deposits at Site L in March 1993 consisted primarily of a medium silt clay (6·2–6·3 phi) with a lower organic matter content (<10%) and a higher bulk density (0·4 g cm^{-3}) than pre-storm soils (Figure 5, Table 3). The coarser-grained soil horizon immediately below the top 2 cm surface layer (i.e. the storm deposit, Figure 5) was likely deposited by either January 1988 storm waves that overwashed the dunes and deposited sandy sediments in the marsh, or the winter storms of 1983. The total sediment accumulation at Site L between October 1992 and March 1993 of 7581 ± 874 g m^{-2} (Figure 6, based on 1·9 cm of vertical accretion) consisted primarily of mineral matter

TABLE 4. Depth of feldspar marker horizon at selected locations in the low marsh, October 1993–March 1994

Plot[a]	Location	Depth (cm)
1	Near road	0·18
2	Near creek	0·10
3	Near road	0·50
4	Near creek	0·18
5	Near road	0·05
6	Near creek	0·10
Mean (± 1 SD)		0·19 ± 0·16

[a]Plot locations, in relation to core locations in Figure 2(b), were as follows: 1 and 2 between Cores A/B and C; 3 and 4 in the vicinity of Core C; 5 and 6 in the vicinity of Cores D and E.

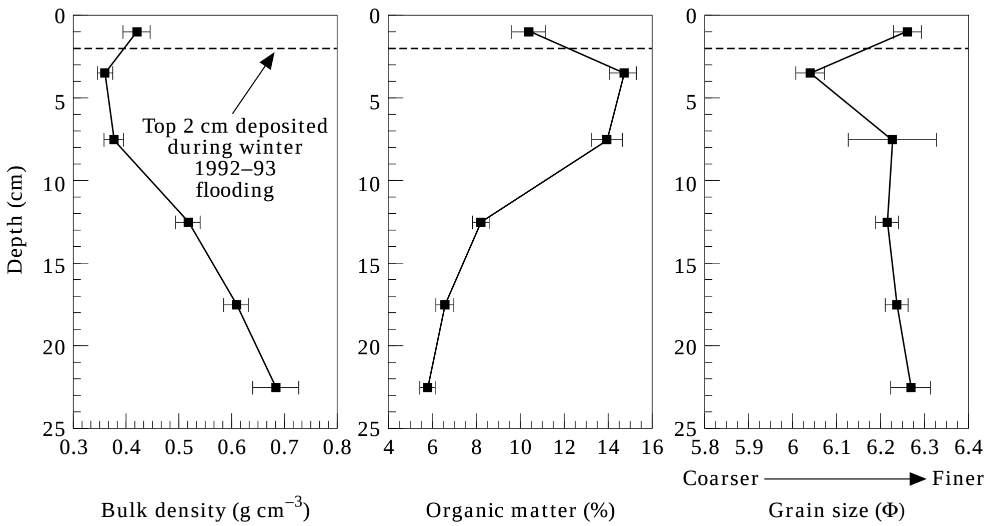

Figure 5. Depth profiles of bulk density, organic matter content and grain size for marsh soils at Site L, March 1993. Data are means ± 1 SE, n = 7. Cores were sliced at the following depth intervals (cm): 0–2, 2–5, 5–10, 10–15, 15–20, 20–25.

(6800 ± 787 g m^{-2}), with organic matter contributing only 10%. Total accumulation did not change significantly during the following 12 months.

The authors' direct measurements of storm deposits (1·9 cm average at the head of the channel and 4–8·5 cm west of the main channel) are comparable to the average elevation change (5 cm, range 0–10 cm) associated with the 1980 storm reported by Zedler (1983). The thickness of storm deposits measured at Site L was not typical of the thickness of measured and observed deposits in the rest of the northern arm, because Site L was located away from the main axis of water input at the head of the basin and behind a high marsh peninsula [Site H, Figure 2(b)]. Since the average measured depth of the storm deposits was 5·9 cm (Table 3), the authors estimated a conservative value for the average thickness of the storm deposits across the entire low marsh to be 5 cm. Using this estimate, the total amount of sediment trapped by the 160·2 ha of low

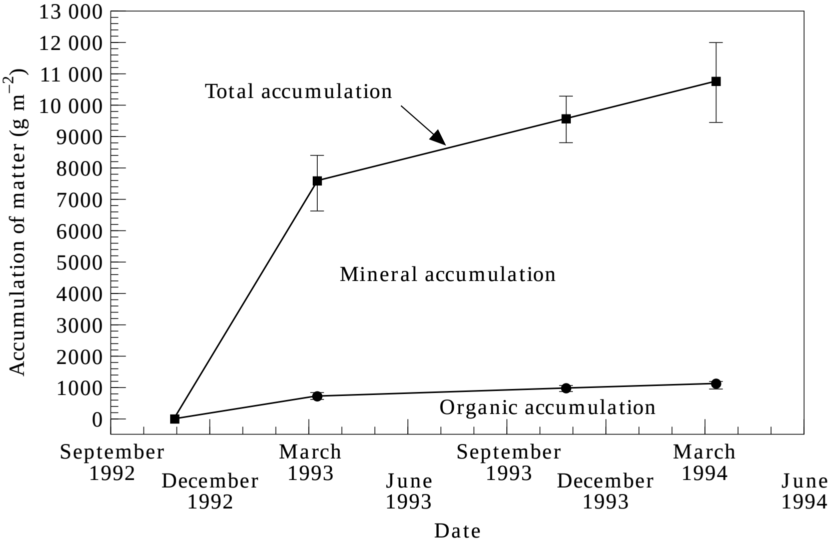

Figure 6. Accumulation of matter at Site L, October 1992–March 1994. Data are means ± 1 SE, $n=21$.

Spartina foliosa marsh during the winter of 1993 was calculated as 31 941 tonnes [assuming a total accumulation of 19 938 g m^{-2} (calculated as 2·63 × 7581 g m^{-2}, since 5 cm is 2·63 times greater than 1·9 cm)]. This amount of sediment represented 0·64% of the estimated sediment yield of the Tijuana river in 1993. Even the trapping of this small percentage of the sediment yield likely had important consequences for estuarine productivity as suggested by Zedler and Onuf (1984). The storm deposits from Sites L, H and A–E consisted of 3·04 ± 0·24% carbon and 0·24 ± 0·03% nitrogen (means, ± 1 SE; $n=21$), indicating that the *Spartina foliosa* marsh filtered approximately 971 and 77 tonnes of carbon and nitrogen, respectively, from the river. Given the episodic (i.e. rare) nature of these events and the lack of sediment introduction by tidal action, sediment trapping by marshes during winter storms apparently plays an important role in long-term productivity of Tijuana estuary. Catastrophic sedimentation, however, can bury marsh vegetation, so the position of marshes in the landscape relative to sediment sources is also a primary factor controlling long-term productivity (e.g. Mugu lagoon; Onuf, 1987).

Accretion and sea-level rise relationships

Sediment accumulation contributes to long-term vegetative vigour not only by providing nutrients to the marsh but also by counteracting the effects of a rising sea level. The vertical accretion rate for the past 1100 years in the marsh at Tijuana estuary is approximately 1 mm year^{-1} based on radiocarbon dates (Mudie & Byrne, 1980). This accretion rate is similar to the current rate of sea-level rise of 1–3 mm suggesting that accretion was in balance with sea-level rise during much of the last millenium but may have begun to lag behind since 1900. Subsidence related to near-surface compaction measured in this marsh over the 17-month period was zero (Cahoon & Lynch, unpubl. obs.), so the authors' measured accretion rates were equivalent to elevation increases. If the average amount of accretion was similar for the 1980, 1983 and 1993 winter storms

($\sim$50 mm each), and was somewhat lower for the 1978 storm based on flow data (Table 1), then the four storms resulted in 150–200 mm of vertical accretion in the low marsh in a 15-year period. Although this accretion rate is an order of magnitude more than the increase in sea level during that period (15–45 mm), this ‘ surplus ’ accretion may not always preclude increases in waterlogging stress to marsh vegetation related to sea-level rise. The timing of major sedimentation events (i.e. whether they are clustered or spread evenly over time) may play an increasingly important role in maintaining marsh vegetation vigour if the rate of sea-level rise accelerates as predicted. For example, 1947–77 was a period of low rainfall (Kuhn & Osborne, 1989), minimal river flow and presumably negligible marsh accretion. During this 30-year period, relative sea level probably rose 2·4–8·4 cm, even accounting for tectonic uplift. During such extended drought periods, the potential is great for increases in waterlogging stress on vegetation caused by increases in sea level with little or no concomitant sediment input and increase in marsh elevation. An increase in waterlogging stress could seriously decrease vegetative vigour (Mendelssohn & McKee, 1988), especially when added to the stress of hyper-salinity that occurs during periods of no river flow (Zedler *et al.*, 1986). The issue becomes whether or not an efficient sediment-trapping mechanism [i.e. vegetative canopy (Gleason *et al.*, 1979)] and soil organic structure can survive until the next major flood (i.e. sedimentation) event, although some sediment deposition would likely occur on barren mudflats.

The current rate of vertical accretion in the high marsh ($\sim$1 mm year^{-1}), combined with tectonic uplift, is apparently sufficient to maintain the high marsh surface elevation in balance with local sea-level increases. The lack of sediment input to this marsh zone even during winter floods, however, raises concern as to whether this accretionary balance can be maintained during predicted rapid increases in sea level. The higher rates of sediment accumulation in the low marsh in conjunction with sea-level rise will likely result in upward migration of low marsh communities with concomitant loss of high marsh habitat, especially if increases in sea level are coupled with increased storm activity (i.e. sediment delivery to the low marsh) as predicted by global climate change models.

Conclusions

Vertical accretion in the low salt marsh at Tijuana estuary measured between October 1992 and March 1994 was related almost entirely to episodic storm-induced river flows during January–March 1993, with daily tidal flooding during periods of no river flow contributing very little sediment. High water levels associated with high flow discharge during January–March 1993 were enhanced in early January by the coincident occurrence of the monthly extreme high tide. The storm flows mobilized an estimated 5 million tonnes of sediment during the 3-month period. Vertical accretion from storm deposits ranged up to 8·5 cm in the *Spartina foliosa* low marsh, where an estimated 31 941 tonnes of sediment were trapped, including 971 tonnes of carbon and 77 tonnes of nitrogen. Given the lack of sediment introduction by tidal action, sediment trapping by the salt marsh during episodic winter floods plays an important role in the long-term maintenance of productivity of Tijuana estuary through nutrient retention and maintenance of marsh surface elevation. These benefits to estuarine productivity derive from the unique position of the marsh in the estuary where it is protected from catastrophic sedimentation but still receives suspended sediment during major winter floods. It is possible, however, that predicted accelerated rates of sea-level rise will out-pace marsh surface elevation gain during extended periods of drought (i.e. low sediment inputs).

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