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SALINITY OF INTERSTITIAL WATER IN A SANDY BEACH

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ABSTRACT

The salinity in the upper 20 cm of intertidal sands was observed at two stations in Tomales Bay, California. In summer, there were no striking variations associated with elevation, except for the effect of evaporation. In winter, the influx of freshwater provides sufficient contrast between interstitial and open water to reveal features of circulation. High on the beach, the interstitial salinity at the 10- and 20-cm depth remains low through the tidal cycle. The salinity at 10 cm remains higher than at 20 cm. At an elevation of 1.0 m, the salinities at 10 and 20 cm converge. Below this elevation, interstitial salinity varies less than in the adjacent open waters of the bay. The environment of the infauna of the low intertidal zone is more stable than that of epifaunal or pelagic organisms in shallow water. The variations high in the intertidal zone must constitute a major obstacle to the spread of marine organisms into this area.

INTRODUCTION

As part of an investigation of the environment of infaunal animals (Johnson 1965), the salinity of interstitial water in the uppermost 20 cm of sand in the intertidal zone of two California beaches was observed. The observations were made because of the possible influence of variations in interstitial salinity upon the distribution of the infauna and because such variations might reflect the circulation of water within a sandy beach.

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AREA AND METHODS OF STUDY

Observations were made at two intertidal flats within Tomales Bay, California. The entrance to Tomales Bay is 64 km north of San Francisco at 39° 15′ N lat and 123° 00′ W long. The bay is 20.3 km long and from 0.7 to 2.7 km wide. The average annual rainfall is 102 cm. The drainage area of the streams emptying into the bay is about 500 km^2. Stream runoff is seasonal and erratic with most of the flow of freshwater occurring in the three winter months. The salinity of the bay near its mouth normally ranges from 30 to 35‰. Occasionally, torrential rains briefly depress the surface salinity near the entrance to as low as 14‰ (unpublished observations by staff of the Pacific Marine Station).

Most of the samples of interstitial water were collected on Lawson's Flat, a south-facing beach about 1.6 km east of the entrance to the bay. The slope of the intertidal zone at this locality is about 1° between 0 and 1.5 m above mean lower low water.[1] The substrate is a fine, well sorted

[1] All intertidal heights stated in this paper are relative to mean lower low water, the datum for the Pacific Coast of the United States.

sand, varying from 0.14 to 0.16 mm in median size. The sand is largely derived from a dune field north of the area.

The other study area is a north-facing tidal flat in White Gulch, a small embayment on the western shore of Tomales Bay, 4.8 km from the entrance. The slope of the intertidal zone varies from 1.8 to 3.5° between 0 and 1.1 m above sea level. The substrate varies from a fine sand to gravel and ranges from 0.19 to 2.5 mm in median size.

Both beaches are in sheltered locations and protected from strong wave action. The maximum change in sand level at Lawson's Flat during a two-year period was 20 cm at a height of 1.5 m. At other elevations, the change in sand level was negligible. The maximum change in sand level at White Gulch was 34 cm at 1.1 m during a three-year period. Elsewhere, the sand was nearly stable and there was no net accumulation or loss of sand over the area.

About 98 species of macroscopic invertebrates have been identified from samples taken in the Lawson's Flat area. A phoronid, *Phoronopsis harmeri,* is the most common species. The pelecypods, *Macoma nasuta, Transenella tantilla,* and *Schizothaerus nuttalli* are abundant. The rich polychaete fauna is dominated by *Boccardia proboscidea, Lumbrineris zonata, Notomastus tenuis,* and *Axiothella rubrocincta.* Some 190 species of invertebrates have been identified from the White Gulch study area. The fauna is dominated by the same species as on Lawson's Flat.

Samples were collected with a 5-cc syringe fitted with a special needle. Samples of interstitial water were obtained at depths of 10 and 20 cm below the surface of the sand. These depths were chosen because most of the animals live in the upper 20 cm. The needles were made in two lengths from stainless steel hypodermic needle stock having an internal diameter of 1.3 mm. The tips of the needles were sealed by a sharp solid point for ease of penetration. Near the point (10 or 20 cm from the hub) two sets of four holes were drilled. The holes were made 0.46 mm in diameter to minimize clogging by larger sand particles and organic debris. In practice, the needles seldom clogged and little or no sediment entered the syringe. The samples were collected by gently pushing the needle to the desired depth in the substrate and slowly withdrawing the water.

An experiment was performed to determine the depths sampled by the syringe method. After a 5-cc sample of interstitial water had been taken, the syringe barrel was detached and the needle left in place in the substrate. A 5-cc solution of fluorescein dye in seawater was injected into the substrate through the same needle and at the same rate as the sample had been withdrawn. The needle was left in place while the site was cored with a brass tube, 25 cm^2 in area and 25 cm long. The core was dug out of the flat so as not to displace the needle or disturb the dyed water enclosed in the sand. The core was sliced to reveal the distribution of the dyed sand about the needle point.

Repeated tests with the dye, using needles of several lengths at different sites on the sand flat, yielded the same result. The contact of the dyed and undyed sand was always sharp. The dyed sand body was egg shaped, with the needle point at the center. The vertical axis of the body was about 4 cm and the horizontal axis about 3 cm in length. These tests indicated that the needles sampled the sand within 2 cm of the needle holes. The 10-cm needle drew water from 8 to 12 cm below the surface. Occasionally, the needle would pierce an animal burrow or tube and might thereby draw water from greater distances. This circumstance could be detected by the comparative ease with which the sample could be withdrawn and from surface indications. Suspect samples were discarded.

The 5-cc samples were analyzed with a Cotlove chloridometer automatic titrator manufactured by the Buchler Instrument Company. Repeated trials on samples of known chlorinity were made to determine instrument and pipetting errors. This method of analysis allows the determination of salinity to within 1‰. Such accuracy is acceptable for the present study because intertidal animals are probably not sensitive to salinity changes of several parts per thousand. The automatic titrator makes possible the rapid analysis of a large number of small volume samples. Knudsen's tables were used to convert chlorinity to salinity. This conversion was meant for use with naturally buffered seawater and may not be reliable when applied to the interstitial waters of sandy beaches (Jansson 1962). No attempt was made to assess this source of error as attention here is focused upon variation and, particularly, upon variation in excess of one part per thousand.

A total of 924 samples of interstitial water was collected on six occasions (Table 1). The samples were taken at different depths in the substrate, at different elevations, and during sampling intervals varying from 3 to 72 hr. No samples were collected when a site was covered with more than 50 cm of water. Each site and depth in the substrate is represented by a mean of 3 samples taken about 20 cm apart. This procedure was based on the results of a field test in which a series of samples was taken 20 cm apart at the same site. The 95% confidence limits for nine such samples having a mean of 35‰ were found to be within the 1‰ accuracy of the analytical method.

Each elevation on the sand flat was represented by a single site. In a series of samples taken at the same elevation, at nearly the same time, 1.5, 3, 15.2, and 30.4 m apart, the range of interstitial salinity was only 1‰. Intertidal elevations were determined by reference to a Coast and Geodetic Survey tidal bench mark.

TABLE 1. *Schedule of salinity samples*

Date	Site	Observation period (hr)	Sampling interval (hr)	Sampling depth (cm)
22/7/64	Lawson's Flat	12	1	10
4–5/8/64	White Gulch	28	2	10, 20
10–11/8/64	White Gulch	26	2	10, 20
12/8/64	Lawson's Flat	3	1	10, 20
11–14/12/65	Lawson's Flat	72	6	10, 20

RESULTS

The range of summer and winter observations for a 10-cm depth on Lawson's Flat is shown in Table 2. Interstitial salinities were lower in February (the rainy season). The influx of greater amounts of freshwater in winter produced a greater contrast between interstitial and open bay salinities than was observed in summer. The range at 0-m height was less than that of the open bay on both occasions.

THE SUMMER OBSERVATIONS

The effect of evaporation during the exposure of the flat is evident in the summer data. On 22 July 1964, the sampling site at the 1.5-m height on Lawson's Flat was exposed for 11 hr (from 0100 to 1200 hours). During this period, the salinity at the 10-cm depth rose from 32 to 41‰. The effect of evaporation lower on the beach diminishes as the time of exposure decreases. During the same period on 22 July, the interstitial salinity at the 10-cm depth rose from 36 to 37‰ at the 1.3-m height. At elevations lower than 1.3 m, the surface of the flat remains wet throughout the period of exposure and no corresponding rise in salinity was detected. Similar circumstances were observed at the White Gulch sites.

The summer observations did not reveal any striking differences in interstitial salinity associated with elevation except for the effect of evaporation. Interstitial salinity at three elevations at White Gulch varied only 1 or 2‰ during the four-day period of observation. The differences between sites and between the 10- and 20-cm levels within the sand were also small—within or near the limit of the accuracy of the analysis. There is some variation in the summer data that is difficult to explain. For example, the rise in salinity on exposure (described above) was very irregular.

THE WINTER OBSERVATIONS

The winter observations yielded the most interesting results of this study. The influx of freshwater is enough to provide sufficient contrast between interstitial and open water to reveal some features of circulation. At elevations less than 1.3 m, interstitial salinity varied less than the salinity of the adjacent open waters of the bay. The observations are summarized in Table 3. Fig.

TABLE 2. *The range of summer and winter observations of interstitial salinity at 10 cm below the surface of Lawson's Flat*

Elevation	Range of salinity (‰)	
	22 July 1964	11–14 Feb 1965
1.5 m	32–41	24–30
1.3	35–37	29–36
1.0	35–36	30–33
0.7	34–36	33–34
0.0	32–33	33–35
Bay	34–36	30–35

1 shows typical variations occurring through one tidal cycle in February.

High on the beach, the interstitial salinity at the 10- and 20-cm depths remains low throughout the tidal cycle. The salinity at the 10-cm depth remains higher than at the 20-cm depth because of the periodic influx of saline waters at high tide. At a height of 1.0 m, the 10- and 20-cm salinities converge and the salinity at 20 cm is often slightly higher than at 10 cm. At this elevation, there is a sharp break in the slope of the beach, and the freshwater table probably intersects the beach surface at this point. Below this elevation, fresher waters are flowing across the surface at low tide than are found within the sand. At elevations less than 0.5 m, the sand remains completely saturated throughout the period of exposure on a low low tide. Water poured on the flat runs off at the surface without noticeable penetration into the sand.

DISCUSSION

The observations suggest that interstitial salinities remain fairly constant throughout the upper layers of the intertidal zone of Lawson's Flat and White Gulch during the summer. High on the beach, evaporation may increase interstitial salinity close to the surface during prolonged exposure. The winter observations indicate that the effect of the increased flow of freshwater is limited to elevations greater than 1.0 m on Lawson's Flat. Below this elevation, interstitial salinities are fairly constant. The beach below 1.0 m is almost completely saturated, so even after prolonged exposure,

TABLE 3. *The average and range of interstitial salinity at different elevations on Lawson's Flat, 12–14 February 1965. Samples taken at 6-hr intervals whenever depth of overlying water was less than 0.5 m. Each observation is the average of three samples*

Elevation (m)	No. of observations	Salinity ‰ 10 cm		20 cm	
		Avg	Range	Avg	Range
1.5	11	27	24–30	25	22–27
1.3	11	33	31–36	31	29–32
1.0	11	31	30–33	31	30–33
0.7	9	33	31–34	33	32–34
0.0	5	33	33–35	33	33–35
Bay	13	33		30–35	

it does not seem likely that interstitial salinities could be lowered by rain falling on the surface of the flat at low tide. The freshening of the bay water during rainy periods presumably would eventually affect interstitial salinities.

The stability of the salinity of interstitial water low in the intertidal zone of Lawson's Flat may reflect a low rate of flushing of interstitial water. The interstitial water at elevations below 0.5 m is low in oxygen, as evidenced by a black sulfide layer within 0.5 cm of the surface. The relationships between oxygen content, temperature, sediment size, and the depth to the black layer have been discussed by Bruce (1928), Perkins (1957), Brafield (1964), and others. Brafield stressed the relationship between depth to the black layer and sediment size. The unique feature of Lawson's Flat is that the sand is the same size throughout the area. Above 0.5-m elevation, the depth to the black layer is quite variable but tends to increase with elevation. High on the flat, the depth to the black layer ranges from 4 to 13 cm. The variation in depth appears to be strongly influenced by the recent history of the sand surface. Areas of deposition and scour were identified by the monthly measurement of the elevation of the sand surface. Where sand has been recently deposited, the layer is deeper than in places that were recently scoured.

The simplest explanation of the salinity variation observed on Lawson's Flat is that

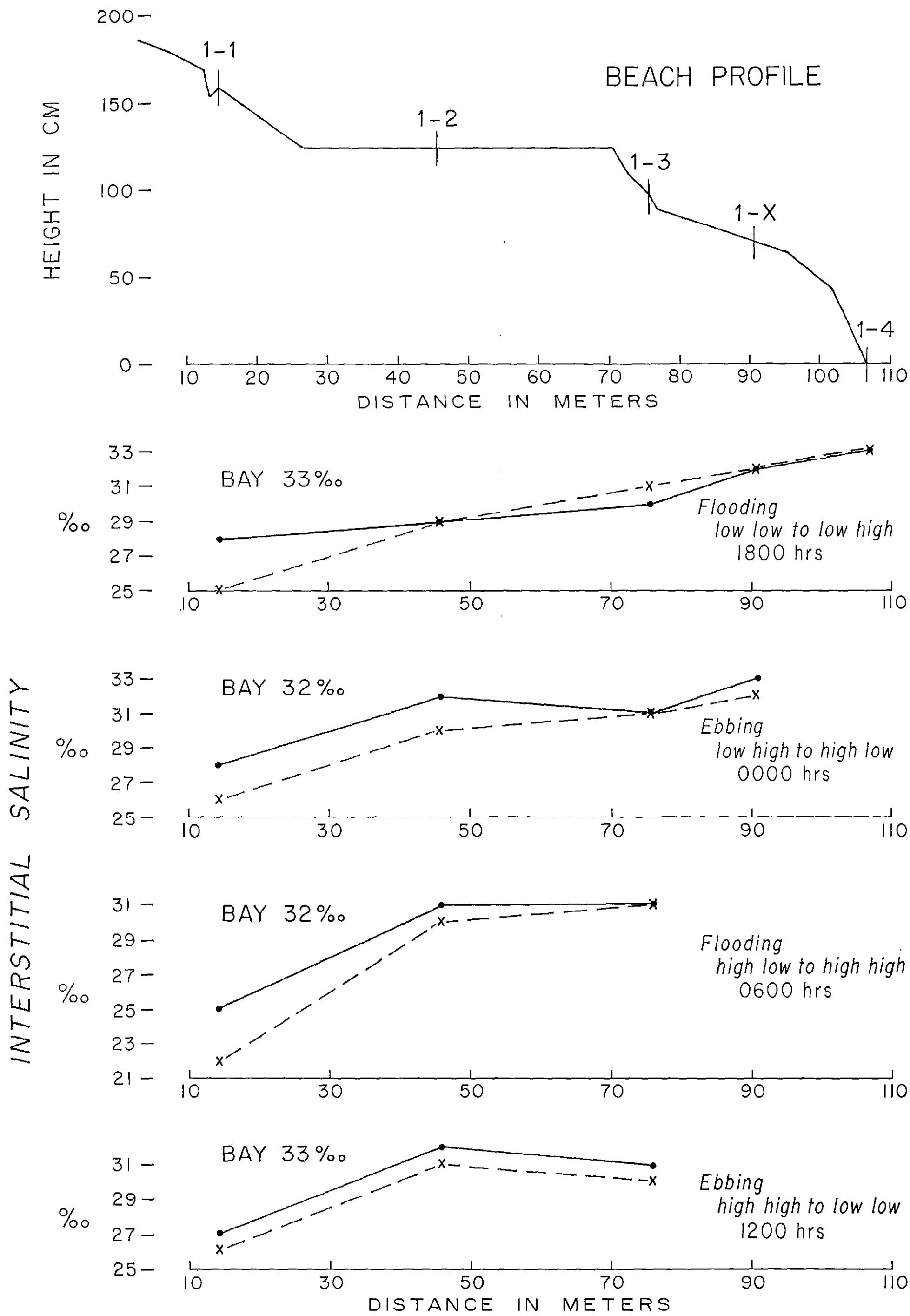

FIG. 1. The beach profile and variation in interstitial salinity at Lawson's Flat 13–14 February 1965. The sampling sites are shown on the beach profile as 1–1, 1–2, etc. Salinity at a depth of 10 cm in the sand is indicated by a solid line. Salinity at a depth of 20 cm is indicated by a dashed line.

the level of the water table below 0.5-m elevation remains at or near the surface. The interstitial water low on the beach is not rapidly exchanged and its salinity remains constant. If the water table below the 0.5-m elevation did fall on an ebb tide, the influx of freshwater should be evident. An alternative explanation is that some exchange does occur, but the magnitude of salinity differences is small and the short-period tidal fluctuation integrates the effect, buffering sediment salinities within a narrow range (*see* Sanders, Mangelsdorf, and Hampson 1965).

At intertidal heights greater than 0.5 m, the amplitude of the change in the water table increases with elevation. At low tide, the level of the water table would be expected to fall more than 20 cm below the surface of the flat at elevations greater than 1 m. Marine waters enter the high beach on flood. Landward of the high tide mark, the amplitude of the tidal fluctuation in the water table would be expected to decrease rapidly (Isaacs and Bascom 1949; Emery and Foster 1948).

It is difficult to generalize from these observations. Lawson's Flat is well protected from vigorous wave action; it is composed of a fine, clean sand of uniform size. In coarser sands and on steeper beaches, there should be a greater exchange of interstitial water with the exterior environment (Reid 1932). The depth to the black sulfide layer is probably a good clue to interstitial circulation.

The environment of the infauna of the low intertidal zone is quite stable, more so than the environment of epifaunal or pelagic organisms in shallow water. The observations are consistent with those obtained in muds (Sanders et al., 1965; Smith 1955, 1956). In gradient estuaries, the minimum number of species occurs in areas of the maximum salinity variation. Greater numbers occur where the rate of salinity change is small (Sanders et al., 1965). In the sandy intertidal areas of Tomales Bay (as at most places elsewhere), the maximum number of species and individuals is found low on the beach. This feature cannot, of course, be attributed to sediment salinity alone because the temperature, oxygen content, and other environmental factors also vary with intertidal height. Furthermore, the influence of the salinity of interstitial water on the larger infaunal organisms is not well understood. Most macroscopic animals maintain contact with the overlying water by tubes or burrows when the tide covers them. When the intertidal area is exposed at low tide, most of these animals are inactive. A few species may not maintain a connection with the surface of the flat. Smith (1955) cited an example of a brackish water polychaete that can live in a marine beach at a place where underground seepage of freshwater maintains low sediment salinities.

The variations in salinity and temperature high in the intertidal zone must constitute a major obstacle to the spread of marine organisms into this region. As Hedgpeth (1957) has suggested, the sand beach is a formidable barrier to most soft-bodied organisms and it is unlikely to have been an important avenue to freshwater or terrestrial habitats.

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