The Palmiet Estuary: A model for water circulation using salinity and temperature measurements over a tidal cycle

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Abstract

This paper deals with salinity and temperature measurements taken over a spring and a neap tidal cycle in mid-summer (February 1985) in the Palmiet Estuary. A conceptual model was compiled from this data, which showed the estuary as having two distinct layers, a fresher surface water layer overlying a saline bottom layer. The fresher surface layer flowed almost continuously seawards. During spring high tide, new saline water replaced the bottom water and the inflow energy determined how far this new water protruded into the estuary. During the subsequent neap tide the bottom water remained in the estuary, with a small amount of water exchanged at the shallower stations near the mouth. During each neap tidal cycle there was a net loss of bottom water, which was replaced during the next spring high tide or by a storm at sea.

Introduction

Many biological studies have been carried out in Cape estuaries, but to date no in-depth chemical investigations have been done on the "black water" systems in the South Western Cape (Scott *et al.*, 1952; Millard and Scott, 1954; Day, 1967; Harris, 1978; Noble and Hemens, 1978; Branch and Grindley, 1979; Heydorn and Grindley, 1981 - 1985; Heydorn and Tinley, 1980; Day, 1981; Roberts *et al.*, 1981; Whitfield *et al.*, 1981; Koop *et al.*, 1982; Marais, 1982; Taylor, 1983; Wallace *et al.*, 1984; Whitfield, 1983; Branch and Day, 1984; Eagle and Bartlett, 1984). It was therefore decided to initiate this investigation on the Palmiet River estuary.

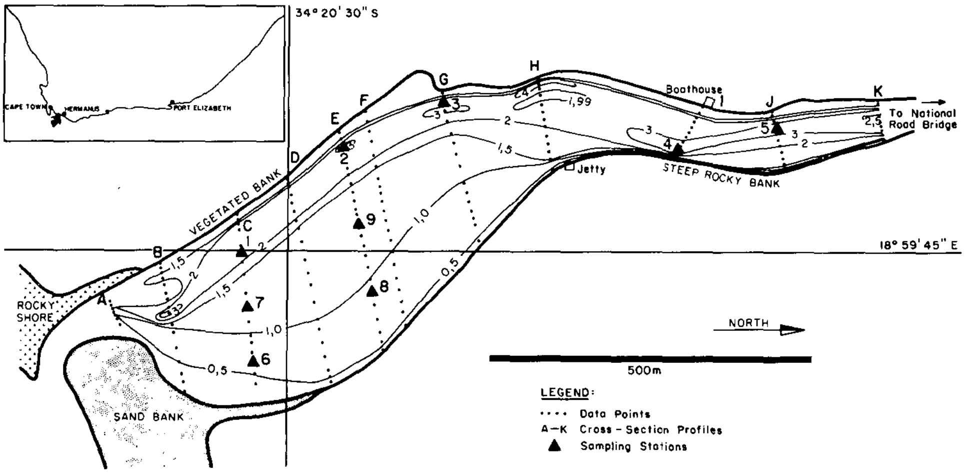

Figure 1
A map of the Palmiet Estuary.

A detailed description of the geographical and physical features of the Palmiet Estuary has been given by Branch and Day (1984). The Palmiet Estuary (34°20'S/18°59'E) is situated about 75 km south-east of Cape Town between the two coastal villages of Betty's Bay and Kleinmond. The Palmiet River and its tributaries flow in part through agricultural areas with emphasis on fruit growing, and in the lower mountain reaches through undisturbed mountain fynbos (*Macchia*). The river water is darkly coloured due to the presence of humic substances (King *et al.*, 1979). The latter feature is characteristic of the Cape southern coast rivers draining off sandstone of the Cape Fold Belt Mountains (Heydorn and Tinley, 1980). The river catchment lies in the Kogelberg, Paarde, Groenland and Hottentots Holland Ranges, covering an area of 539 km². The river rises in the Kogelberg Range and is 65 to 70 km long. On its way to the sea it is joined by two major tributaries and several minor feeder-streams, some of which are seasonal. The river bed is very steep and this results in a strong flow. Since the coastal plain is extremely narrow the Palmiet River changes from a mountain stream to an estuary with no intervening stretch, typical of a lower river. Such a system is classified as a "South Cape acid river" (Noble and Hemens, 1978). Between the Berg and Breede Rivers, a distance of about 350 km, the Palmiet River mouth is the only one which normally remains open to the sea and which receives a large, permanent inflow of fresh water.

The river is one of the least disturbed of its kind in the region and apart from apple orchards and plantations along the upper reaches, it has no industries in the catchment. Since some major state dams are being built upstream the system might not remain undisturbed for many more years. Phase 1 of this scheme is scheduled for completion in 1988, while Phase 2 will be completed between 1997 and 2007 (Roberts, 1985). Branch and Day (1984) presented data which gave a good overall view of the Palmiet Estuary, especially its biological features. This article is an extension of some of their findings. It discusses the physico-chemical data (salinity, temperature and pH) collected during a two-week period in mid-summer (February 1985), which included a spring and neap tidal cycle. A conceptual model was

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compiled from the data. Similar work has been done in larger estuaries and fjords overseas (Godfrey, 1980; Lara-Lara *et al.*, 1980; Heggie and Burrell, 1981; Matthews, 1981; Simpson and Nunes, 1981; Stigebrandt, 1981; Swenson and Chuang, 1983; Thomson and Godfrey, 1985). Largier (1985) discusses the mixing processes between the different layers in the estuary. Later papers will deal with distribution of dissolved nutrients such as organic nitrogen, ammonia, nitrate, nitrite, phosphate and organic carbon. The particulate matter in the water column, the movement of particulate matter and kelp at the mouth, meiofauna and nutrients in the sediments, macrophytes and other aspects will also be examined.

Materials and methods

Five sampling stations were set out in the water channel (1 to 5 in Figure 1), while four stations were marked out on the sand flats (6 to 9 in Figure 1). Ten cross sections of the depth were determined using an Atlas-Deso high-resolution echo sounder with frequency of 210 kHz (A to K in Figure 1). Five of these cross sections intersected with the five water channel stations. These depths are relative to a fixed point on the jetty between Stations 3 and 4. Water levels were measured from the same fixed point (Figure 2). The estuary's tidal area was estimated by means of a digitizing table. The depth contours were constructed using the cross-section depth data (Figure 1). On four occasions (spring high, average low, neap high and neap low tides) salinity and temperature measurements were taken with a salinity-temperature bridge at 0,5 to 0,1 m intervals from surface to bottom at the five water channel stations. During the spring and neap tidal cycle sampling, surface and bottom samples were collected hourly from the five water channel stations, over a period of 12 h. Similarly, surface samples were obtained from the stations on the sand flats.

At each sampling point salinity and temperature data were recorded and pH was measured on a pH meter (Model 29 Radiometer). Water samples for nutrient, particulate matter, dissolved oxygen and pH analyses were taken from a boat, using Niskin and Go-Flo sampling bottles. Dissolved oxygen was determined by the Winkler titration method (Watling, 1981), while nutrient samples were immediately filtered through 0,45 μm membranes and frozen.

Particulate matter samples were collected by filtering 0,5 dm³ of water through pre-weighed filters. Samples were rinsed to remove salt and the filters were then frozen immediately.

Sediment cores (0,3 m) were also collected from all nine stations for the determination of interstitial nutrient levels, sediment grain size analysis, meiofauna and algal determinations. Measurements on currents were also done over the two-week period.

Results

The tidal section of the Palmiet Estuary stretches 1,67 km from the mouth to the road bridge (Branch and Day, 1984). The whole estuary has a tidal area of 256 000 m². The contour map shows the main features at the time of the survey. The steep-sided channel in the upper part of the estuary can be seen meandering from the east bank at the head of the estuary across to the west bank nearer the mouth. Although the west bank remains rocky up to the mouth, the east bank opens out into a large sand flat. The main channel remains relatively shallow up to Station 3. Thereafter the channel depth increases quite significantly towards Station 5, with a distinct dip in the bottom profile at Station 4. The sand flat area with a depth of less than 1,5 m is estimated as 116 000 m². It is here where the estuary reaches its maximum width of about 280 m. Most of this sand flat is exposed during low tide and it is densely populated by the sand-prawn, *Callianassa kraussi*.

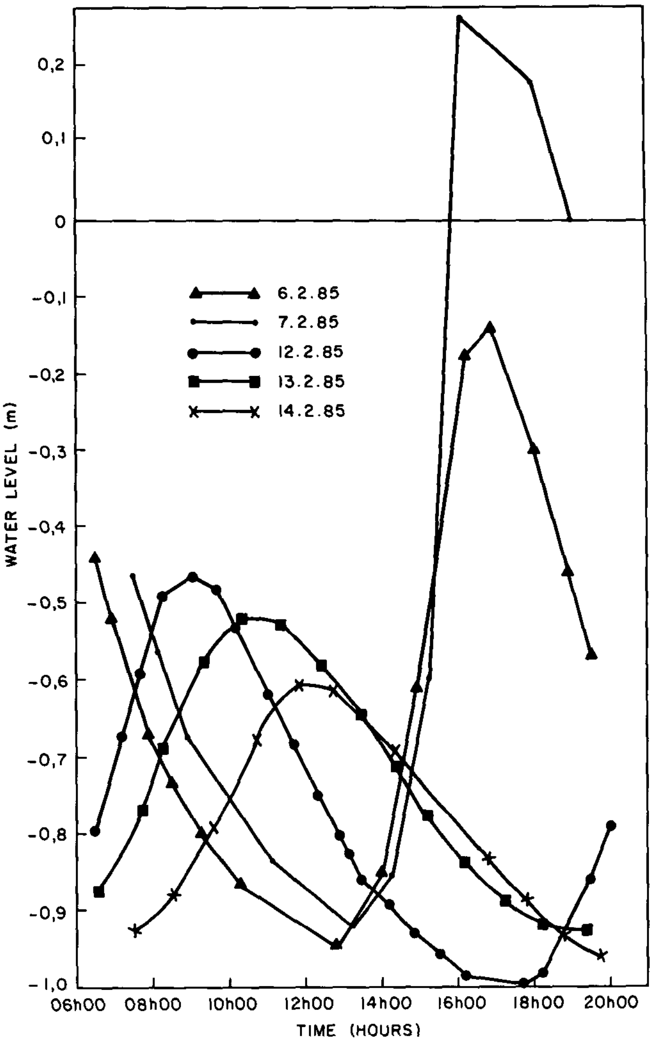

Figure 2
Water level profiles.

The profile of the mouth is extremely variable. To the west its position is fixed by a rocky bank, but it has an extensive, mobile sand spit to the east. The spit is built up by the prevailing westerly longshore currents together with the prevailing SSW to WSW swells and high-energy waves (Harris, 1978). Just inside the mouth there is a large fan-shaped bank formed by sand which is washed into the estuary from the spit. Immediately to the east of this there was, at the time of the survey, a fairly deep (3 m) hole which trapped a large amount of kelp washed in from the extensive kelp beds found just outside the mouth. Although the volume of the estuary varied to some extent due to wind and wave action, a normal spring high tide volume was estimated to be about 350 000 m³ (Largier, 1985).

The water level measurements obtained during the two weeks are summarized in Figure 2. Table 1 gives the sea tides on the days during which the water-level measurements were made. On 7 February overtopping of the sand spit from the sea occurred, resulting in the high water level during the spring high tide. The tidal difference in water level was about 0,8 m under calm, spring conditions, but it reached 1,25 m under stormy conditions. During neap tides the average difference was 0,5 m between high and low tides (Figure 2). The inflow period was shorter than the outflow, as was also observed by Branch and Day (1984). During spring tide, high water in the estuary corresponded with the sea high tide, while its low water lagged behind the sea low tide by about 3 h. A similar feature was observed during neap tide, except that the low water time lag was only about 1 h. Thus the inflow period varied between 3 and 5 h with a corresponding lengthening of the outflow period. During the sampling period the estuary was relatively shallow at the mouth compared to the rest of the water channel. This seemed to have a regulating effect on the outflow of water, thus the almost constant low-water levels in Figure 2.

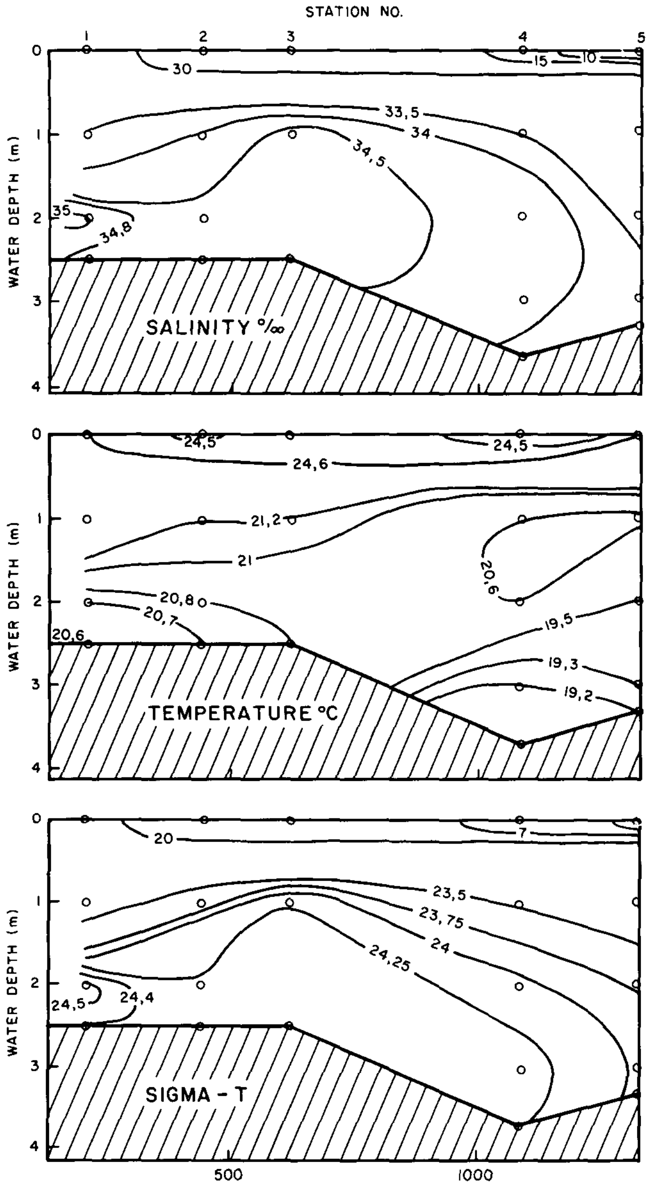

Figure 3
Salinity, temperature and sigma-T profiles 2 h after a spring tide.

The four salinity and temperature profiles which were taken at the water channel stations over the two-week period indicate the pattern of water movement during the different tides. The salinity and temperature values were used to compile the sigma-T profiles (Figures 3 to 6).

Trends in surface salinity and temperature measured during the spring tidal cycle in the water channel stations are shown in Figure 7A. The fresher surface water layer at that time was very thin (about 0,3 m) and the pycnocline was extremely sharp. Disturbances of the pycnocline by the boat or even the salinity probe were thus impossible to avoid, causing variability in the salinity and temperature readings. Any small disturbances in the pycnocline and differences in the depth at which the data were collected would have increased the variability. During the spring tidal cycle measurements of the water in the deepest channel indicated the inflow of the colder, more saline sea water during high tide (Figure 7B).

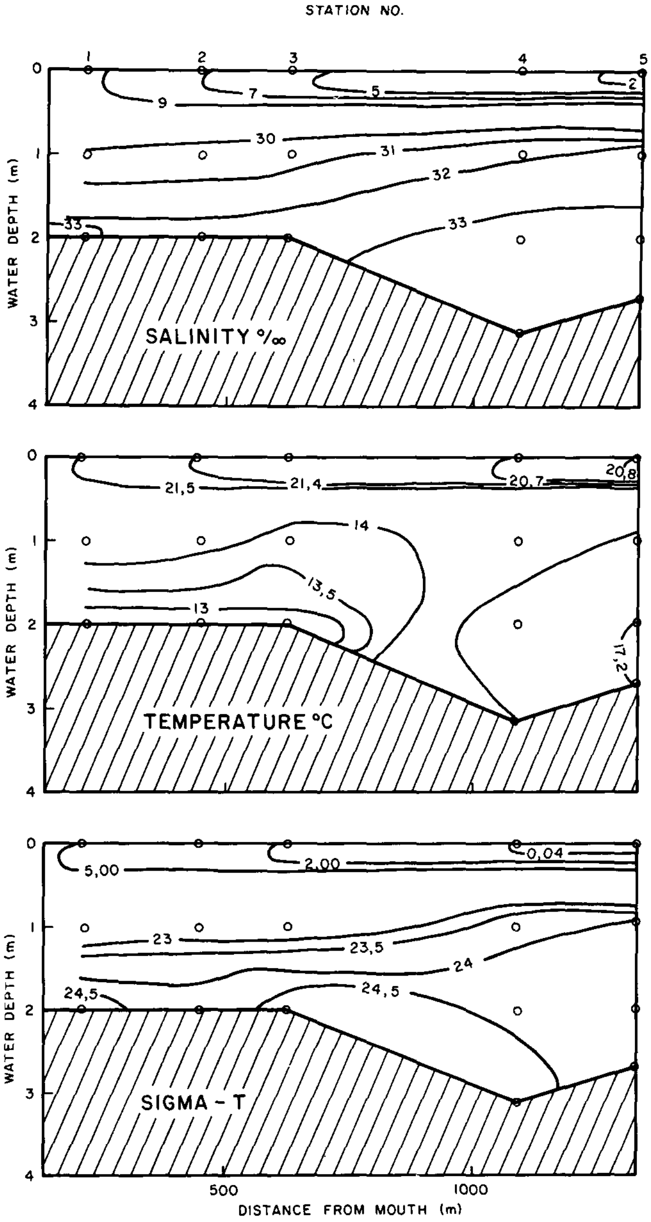

Figure 4
Salinity, temperature and sigma-T profiles 2 h before a low tide between spring and neap tides.

Between the spring and the neap tidal cycle measurements, heavy rains fell in the catchment (0,02 to 0,03 m), resulting in increased river flow. This caused the surface fresh-water layer (0,6 m) to be somewhat deeper during neap than during spring tides (Figures 8A). Although there were no significant fluctuations in the surface salinities at any specific water channel station during the neap tidal cycle, the overall salinity of this layer gradually decreased towards the head of the estuary. The surface temperature increased at each of the five stations during this tidal cycle due to diurnal heating. During neap tide the bottom water measurements showed no significant change in salinity at any of the five water channel stations (Figure 8B). Although the bottom temperature did not show any significant fluctuation at a specific station during the neap tidal cycle, it increased towards the head of the estuary (Figure 8B).

During the spring tidal cycle the salinity and temperature data from the stations on the sand flats were similar to those of the bottom channel water (Figure 9A). During neap tide, however, the water over the flats was similar to the surface water from the channel (Figure 9B).

TABLE 1
TIDE TABLES FOR THE DAYS ON WHICH SAMPLING WAS DONE

February 1985

Day	High Tide				Low Tide			
	h	min	h	min	h	min	h	min
6	–		16	09	09	59	22	14
7	–		26	49	10	41	22	51
12	08	18	20	59	14	59	–	
13	09	37	22	47	16	38	–	
14	11	19	–		18	16	–	

The river water entering the estuary had an average pH of 7,2 over the two-week period. During the spring tidal cycle the estuary had a pH of between 7,9 and 8,2 respectively at surface and bottom. During the neap cycle the surface pH was between 7,1 and 7,4 and that of the bottom water between 7,6 and 7,8.

Discussion

The estuary was very highly stratified. Apart from sharp changes in temperature and salinity, the fresh and salt water layers are easily seen, since the river water is dark brown. There was a sharp pycnocline, the depth of which was determined by the amount of fresh water that entered the estuary from the river. Changes in salinity from 3 to 28‰ over a depth of 0,25 m were recorded. During spring tide the pycnocline was at a depth of approximately 0,3 m. After rain in the catchment area just before the neap tidal cycle measurements, the depth of the pycnocline increased to 0,6 m.

Estuary area and volume data obtained during the February 1985 field trip differ from the values obtained by Branch and Day

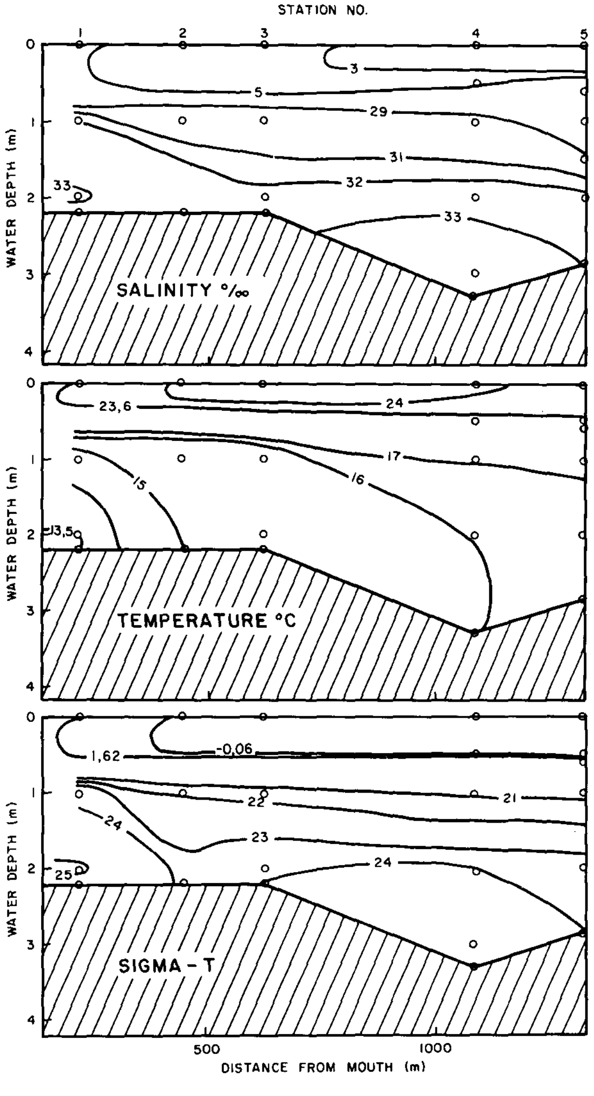

Figure 5
Salinity, temperature and sigma-T profiles during a neap high tide.

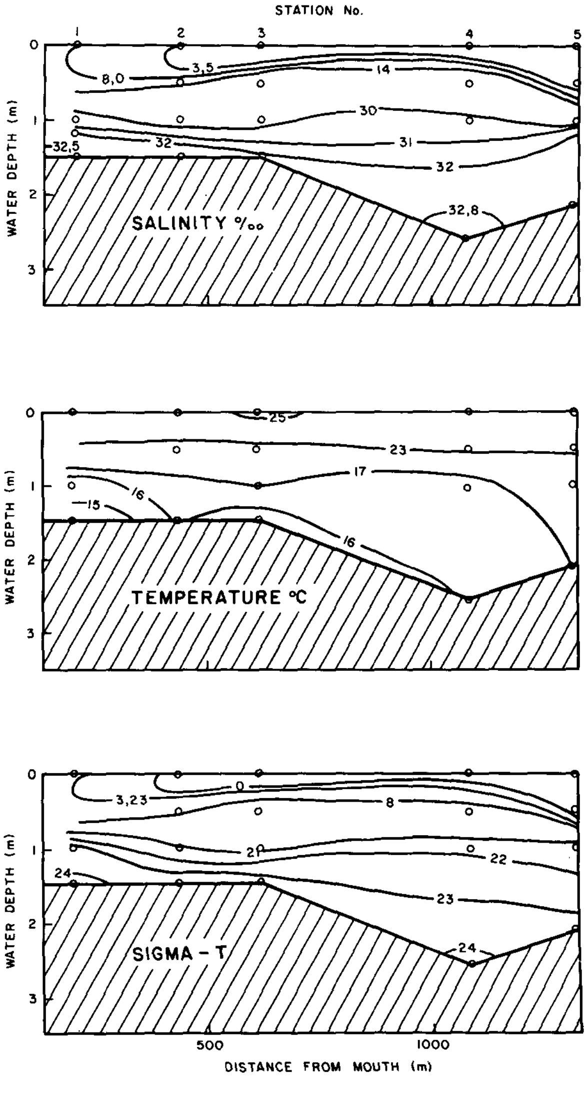

Figure 6
Salinity, temperature and sigma-T profiles 2 h before a neap low tide.

(1984). This might be due to a difference in the methods used to calculate these values or due to the dynamic nature of the bottom sediments and the non-rocky edges in the lower reaches of the estuary.

Examination of the salinity, temperature and sigma-T profiles (Figures 3 to 6) gives indications of the mechanism of sea water/fresh water exchange. These profiles have been drawn for spring tide to the following neap tide, thus giving a broad picture of the water movement during the two-week period. The sigma-T values are most strongly influenced by the salinities. The estuary can be divided into two separate layers, namely a thin, fresher water layer overlying a sea-water layer. The tides had very little influence on the surface fresh-water layer, but affected the sea-water layer much more strongly. During high-energy inflow from the sea, the bottom layer received new sea water (Figure 3). Under normal conditions this would happen during spring high tides; however, a storm at sea would also result in the renewal of the estuary's bottom water. This sea water reached as far as Station 5. However, the fact that high salinities have been detected as far up as the road bridge indicates that sea water can be pushed right up to the head of the estuary (Branch and Day, 1984). During the subsequent neap tide the sea water remained within the channel, moving back and forth depending on the tide (Figures 4 to 6). During neap low tide, bottom water from the shallower channel stations returned to the sea, some of which was partially replaced during the next high tide. Although the bottom layer of Stations 4 and 5 moved with the tide, it received no new water. The bottom water trapped in the dip at Station 4 seemed to remain stagnant over the neap cycle (Figures 5 and 6).

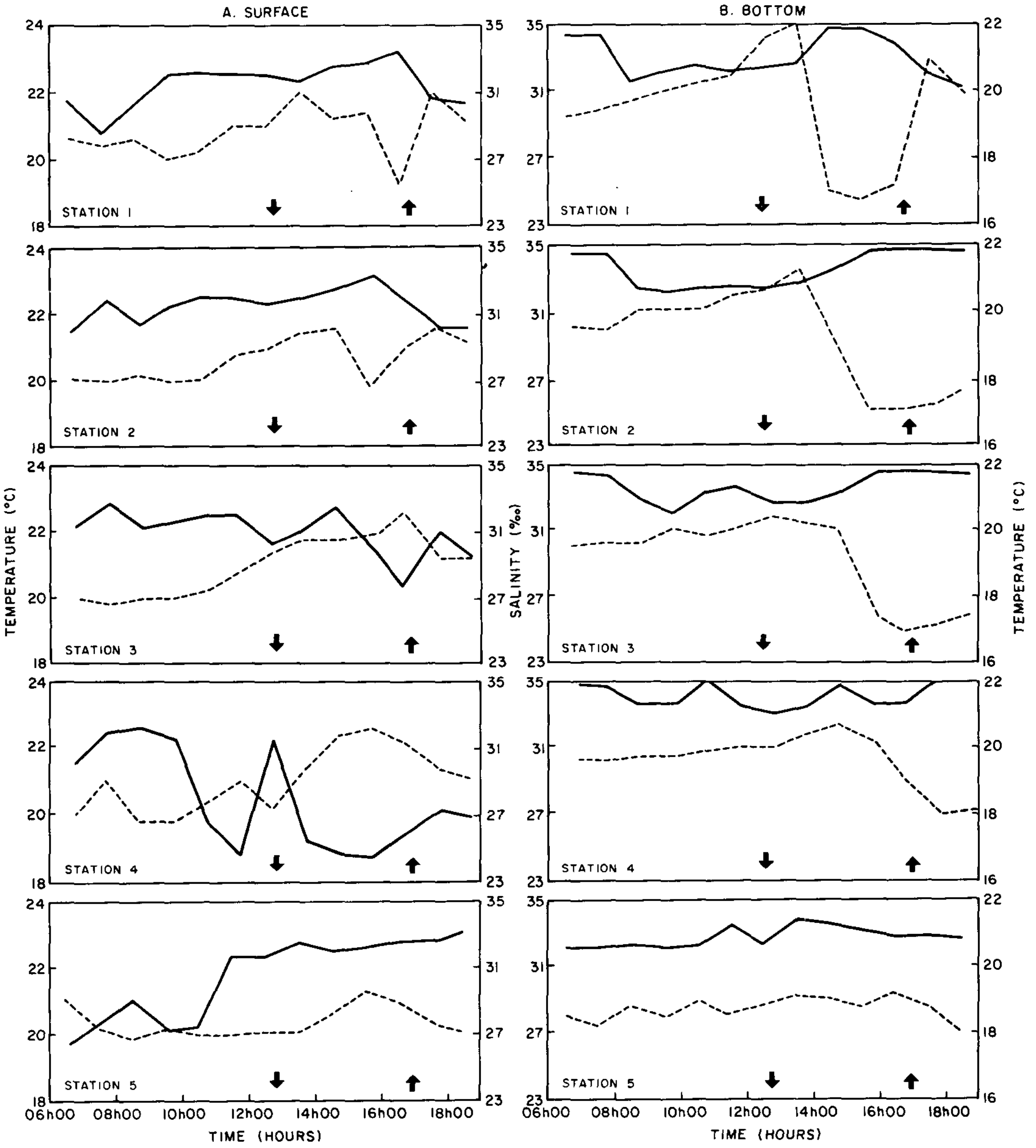

Figure 7A and B
Temperature [– – – – –] and salinity [————] changes during a spring tidal cycle in the surface and bottom water measured at stations 1 to 5 (∝ = high tide; ∞ = low tide).

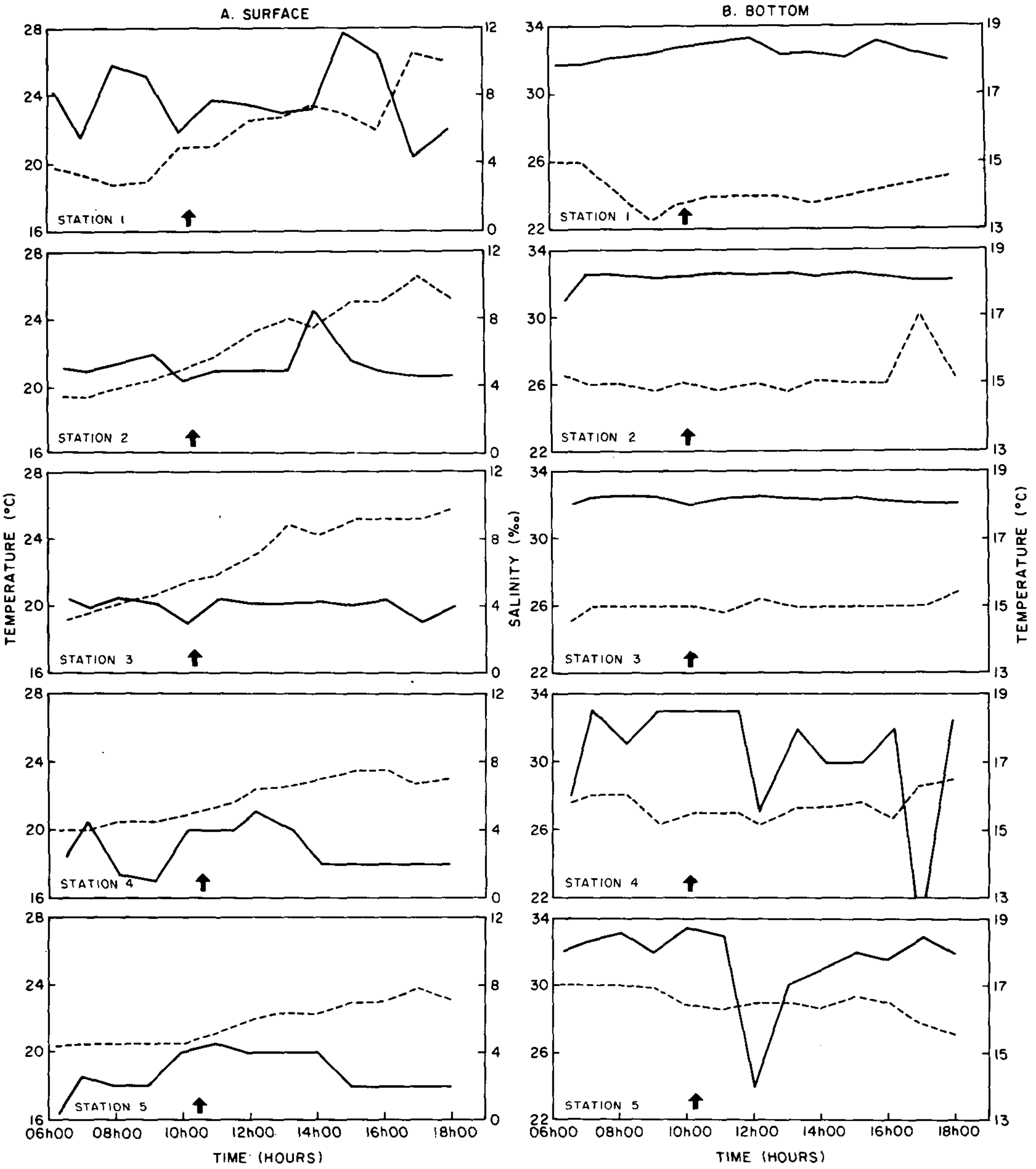

Figure 8A and B
Temperature [– – – – –] and salinity [————] changes during a neap tidal cycle in the surface and bottom water measured at stations 1 to 5 (∝ = high tide; ∞ = low tide).

Figures 7A and 8A showed that during both the spring and neap tidal cycle measurements the tide had no significant influence on the fresher surface water layer. The increase in surface salinity from the head to the mouth of the estuary was due to the entrainment of small amounts of sea water into the surface layer. This mixing increased towards the mouth because of the shallower channel depth and increased turbulence in the area. During neap tide the river water was warmer than it had been during the spring tidal cycle. This was due to natural fluctuation in air temperature.

During the spring tide the sea water was somewhat colder and more saline than the bottom water present in the estuary at the time. This colder water could be seen pushing up to Station 5 (Figure 7B). During the neap tide no drastic bottom water penetration occurred, except for a small amount at the shallower channel stations during the high tide. It is assumed that the increase in the temperature towards the head of the estuary emphasized the fact that very little or none of the colder, new sea water reached the upper, deeper parts of the estuary during neap tides in summer (Figure 8B). This confirms the conclusions made from the profile data (Figures 3 to 6).

The survey indicated that the water on the sand flats undergoes a weekly salinity cycle. Marine conditions dominated the system during spring tide, since its salinity and temperature was similar to that of the bottom channel water (Figures 7B and 9A). During neap tide, however, the water over the sand flat was similar to the fresh surface water layer, thus fresh water conditions dominated (Figure 8B and 9B).

The pH values obtained during this field excercise were significantly higher than those obtained by Branch and Day (1984) during their survey. The river water entering the estuary had an average pH of 7,2. During spring tide the estuary had a pH of between 7,9 and 8,2 while during neap tide these values decreased to between 7,1 and 7,8 due to the larger river water inflow.

The most important conclusions emerging from the experiment are summarized in a model represented in Figure 10. The

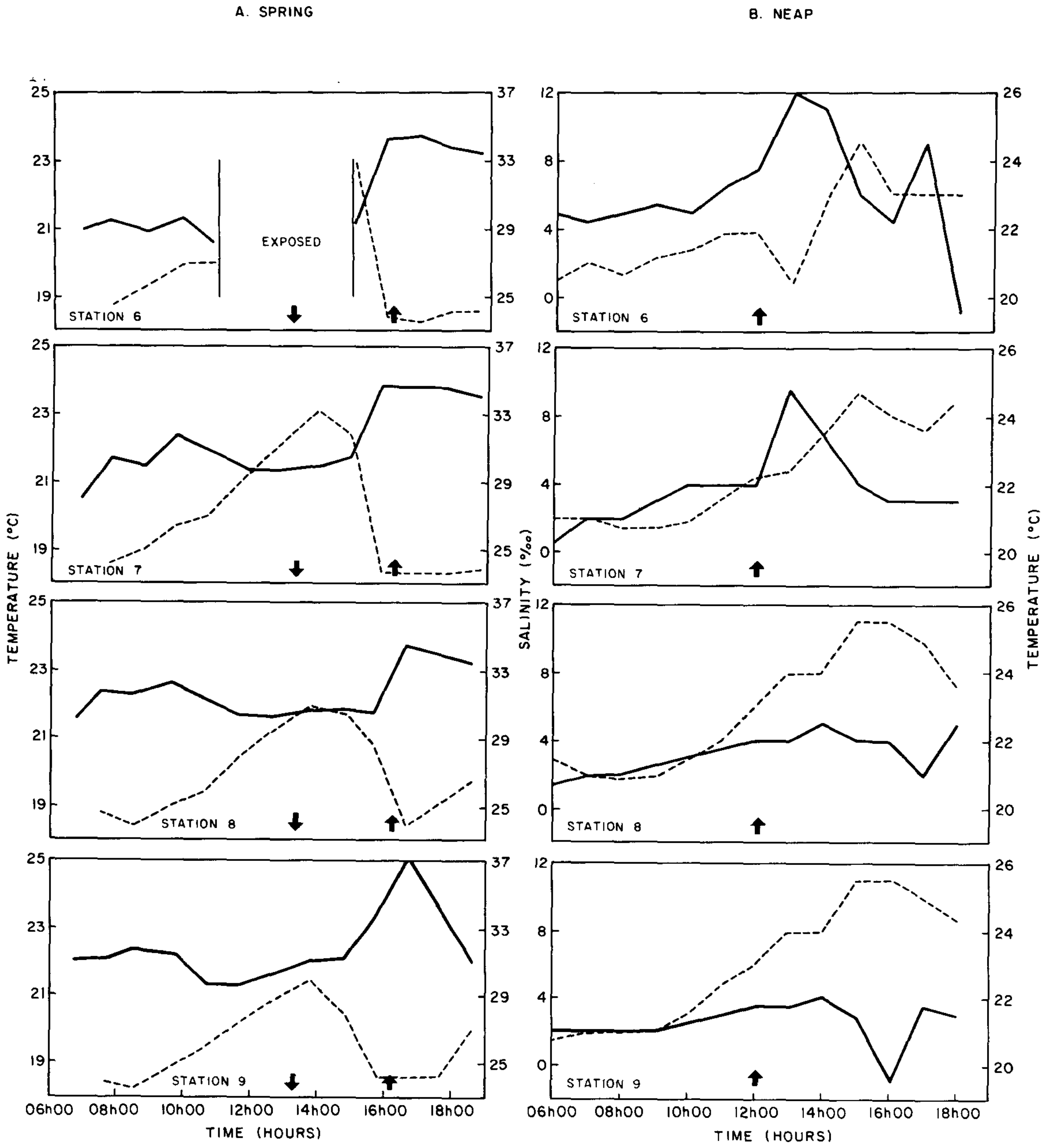

Figure 9A and B
Temperature [– – – – –] and salinity [————] changes measured during a spring and a neap tidal cycle at 4 sandflat stations (stations 6 to 9) (∝ = high tide; ∞ = low tide).

most striking feature of the estuary was its marked stratification. The top, fresh-water layer flowed, almost continuously, seawards. During spring high tide, new saline water replaced the estuary's bottom layer. The inflow energy determined how far the new water was being pushed up into the estuary and during this survey it reached Station 5. During the subsequent neap tide the bottom water remained in the estuary, moving back and forth with the tide. Some exchange occurred at the shallower channel stations near the mouth. There was a net loss of water during each neap tidal cycle, thus the system ran down partially until the next high-energy, saline water inflow. Under normal conditions this would happen at spring tide when the whole cycle is repeated.

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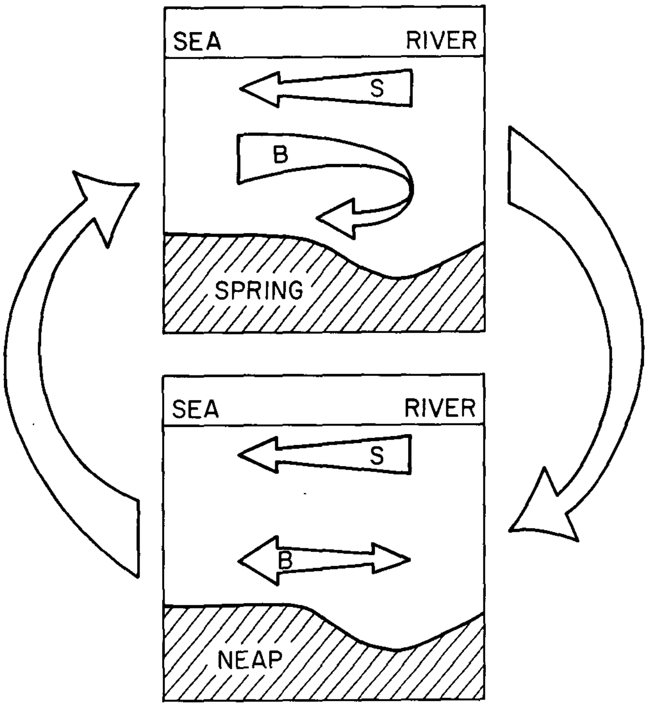

Figure 10
A conceptual model depicting the cyclic pattern of water movement from a spring to a neap tide. (S = surface water; B = bottom water).

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