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**WATER CIRCULATION AND NUTRIENT DISTRIBUTION  
PATTERNS IN THE PALMIET RIVER ESTUARY:  
A WINTER STUDY**

by  
S Taljaard and J L Largier

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## CONTENTS

	<u>Page</u>
ABSTRACT	
LIST OF TABLES	
LIST OF FIGURES	
1. INTRODUCTION	1
2. STUDY AREA	3
3. MATERIALS AND METHODS	5
4. WATER CIRCULATION PATTERNS	7
4.1 Results and Observations	7
4.2 Intrusion of Saline Water	9
4.3 Residence and Flushing	14
5. PH, DISSOLVED OXYGEN AND NUTRIENT DISTRIBUTION PATTERNS	18
5.1 Results and Observations	18
5.1.1 pH	18
5.1.2 Dissolved oxygen (DO)	19
5.1.3 Dissolved reactive phosphate	20
5.1.4 Dissolved nitrate	20
5.1.5 Dissolved nitrite	21
5.1.6 Dissolved ammonia	22
5.1.7 Dissolved organic nitrogen (DON)	22
5.1.8 Dissolved organic carbon (DOC)	23
5.1.9 Total organic matter	23
5.2 Discussion	23
6. COMPARISON WITH THE SUMMER SITUATION	28
7. SUMMARY AND CONCLUSIONS	33
ACKNOWLEDGEMENTS	34
REFERENCES	35
TABLES	
FIGURES	
APPENDIX I	

## ABSTRACT

As part of a physico-chemical investigation of the blackwater Palmiet River estuary, hydrographic and chemical data were collected in order to determine the typical winter circulation patterns. The supply of and interaction between the marine and riverine source waters is explained in terms of the successive tidal intrusion and fluvial-tidal flushing. The estuary is river-dominated in winter. Sea-water only enters the estuary on spring tides during moderate to weak river flow.

On entering, this dense saline water subducts below the estuarine water and forms a bottom density current which can propagate upstream even after the tide has turned. In general the internal Froude Number is subcritical and little mixing occurs beyond the initial subduction zone. This more saline water collects in the deeper sections of the estuary and is generally resident for more than one tidal cycle.

Flushing times, Richardson Numbers and entrainment velocities are calculated in order to characterize the ebb-tide removal of saline water. Patches of turbulent mixing are observed at the tidal intrusion front and near the head of the estuary. The bulk of the entrainment, however, is expected to be due to internal wave breaking on the halocline (larger Richardson Numbers).

The estuary, being river-dominated, has the chemical characteristics of a blackwater system, that is, low pH, low salinity and low light permeability (due to the high light absorbance of humic acids). However, unlike tropical blackwater systems, dissolved nutrients are not limited and show a strong correlation to water circulation patterns. Saline intrusion and fresh water flushing are clearly reflected in nutrient distribution patterns. Typical of blackwater influences the biological activity is greatly reduced during winter. This, in turn, acts as a natural control mechanism for algal growth which accumulates during summer.

This typical winter conditions is also compared with the typical summer situation (Largier, 1986; Taljaard, 1987).

LIST OF TABLES

- Table 1 Bulk Richardson Numbers. (station 4, 20 August 1986)
- 2 Tide tables for the days on which sampling was done
  - 3 Mean values ( $\bar{x}$ ) and ranges for pH, DO and dissolved nutrients measured on the sand flat and in sea- and river water on 20 August (spring tide) and 27 August (neap tide)
  - 4 Mean values ( $\bar{x}$ ) and ranges for pH, DO and dissolved nutrients measured in the channel over the spring tidal cycle (21 August)
  - 5 Mean values ( $\bar{x}$ ) and ranges for pH, DO and dissolved nutrients measured in the channel over the neap tidal cycle (28 August)
  - 6 pH, DO and dissolved nutrient levels measured in the sea and river on 21 August (spring tide) and 28 August (neap tide)
  - 7 Interstitial nutrient measurements

## LIST OF FIGURES

- Figure 1 The location and bathymetry of the Palmet River estuary during August 1986.
- 2 The record of river flow from 13 to 28 August 1986. Flow events on 14 and 26 August are noted.
- 3 The flood tide volumes (plotted as bars) during the two week field exercise. These volumes can be related to the overlaid plots of sea-level tidal range and river flow.
- 4 Longitudinal sections on 19 August 1986:  
a) Low tide b) Flood tide c) High tide  
d) Ebb-tide.
- 5 Longitudinal sections on 21 August 1986:  
a) Low tide b) Flood tide c) High tide  
d) Ebb-tide.
- 6 Longitudinal sections on 25 August 1986:  
a) Ebb-tide b) Low tide c) Flood tide  
d) High tide.
- 7 A time series of salinity structure at station 4; currents are indicated by arrows and turbulence by a collection of curved lines.
- 8 A temperature-salinity diagram of water at stations 4 and 5' on 20 August 1986. These water types are related to the three source waters.
- 9 Salinity changes over a spring tidal cycle in surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).
- 10 pH changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).
- 11 Dissolved oxygen changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).
- 12 Dissolved nitrate changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).
- 13 Dissolved nitrite changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).
- 14 Dissolved organic carbon changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5. ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

## 1. INTRODUCTION

The purpose of this study is to determine and explain the influence of a fresh, non-tropical blackwater river on the water circulation and nutrient distribution patterns of its stratified estuarine region. The Palmiet River estuary (South Africa), being a small, manageable system, was considered as the ideal study area. The aims were accomplished by monitoring the system over a complete spring and neap tidal cycle during August 1986. The intention is that this investigation complement the ecological study of Branch and Day (1984) and that it should be read together with the reports on the water and nutrient circulation patterns observed in the Palmiet estuary during summer (Taljaard *et al.*, 1986; Largier, 1986; Taljaard, 1987).

The effect of blackwater rivers on their estuarine environments is still relatively unknown, especially in the non-tropical regions of the world.

Janzen (1974) gave an informative review on the tropical black water rivers of the world; however, no mention was made of blackwater estuaries. Por *et al.* (1984) presented a preliminary hydrodynamic picture of the Rio Una estuary, a tropical blackwater system in Brazil. The estuary is strongly influenced by heavy rain in the catchment as well as the tides which penetrate far upstream. During the wet season and at neap tides the estuary exists as a blackwater system. During the dry season and at spring tides it changes to a more typical estuary as well-buffered sea-water moves in. The nutrient distribution showed good correlation with the water circulation, especially the phosphate enrichment which occurred after sea-water influx. Under fresh water conditions (blackwater presence) the estuary was extremely poor in both biomass and species in contrast to normal estuarine conditions. This is a typical feature of tropical blackwater rivers (Janzen, 1974). The low primary production and low species diversity in blackwater systems is usually related to low pH, low light penetration (high absorbance of humic acids present in blackwater) and low nutrient concentrations (Janzen 1974).

Other work done on non-tropical blackwater estuaries includes that by Sholkowitz (1976, 1978) in which the close association of some trace metals with both river-dissolved humic substances and the seawater-flocculated humates in four rivers (Stinchar River, Cree River, Water of Luce and Glen Burn) in Scotland was shown.

Nutrient distribution often strongly relates to water circulation patterns (d'Anglejan and Ingram, 1976; Lara Lara *et al.*, 1980; Loder and Gilbert, 1980; Webb and D'Elia, 1980; Millan-Nunez *et al.*, 1982; Morris *et al.*, 1982; Farfan and Alvarez-Borrego, 1983; Emmerson, 1985; Wilmot *et al.*, 1985). For a proper understanding of a system, it is therefore necessary to investigate both aspects in detail. Understanding the, as yet undisturbed, physical, chemical and biological features of the Palmiet estuary, especially in view of the construction of large dams upstream, will be necessary for effective management (Council for the Environment, Committee for Coastal and Marine Systems, 1986). This series of physico-chemical experiments on the Palmiet estuary will not only contribute to management, but can also provide a basis for comparison with similar systems elsewhere in the world.

## 2. STUDY AREA

The Palmiet estuary (34° 20'S, 18°59'E), a drowned river valley, is located on the narrow coastal plain to the west of the town of Kleinmond with a tidal area of about  $2,5 \times 10^5 \text{ m}^2$  and a tidal volume of about 256 000  $\text{m}^3$ . Although it is relatively undisturbed by development or pollution at present, the building of large dams upstream will certainly have a considerable effect on the ecology and the recreational carrying capacity of the estuary. The darkly coloured river water (due to the presence of humic acids) is characteristic of rivers draining off the sandstone of the Cape Fold Belt Mountains (King *et al.*, 1979; Heydorn and Tinley, 1980).

The estuarine hydrodynamics are controlled by an interaction between riverine and marine influences. As a result of the short length (about 1,7 km from the mouth to the road bridge) and the direct connection between the river and the sea, strong stratification and clear features are produced during each tidal cycle. The estuary is almost permanently open to the sea and the mouth is exposed to very energetic surf. The river enters the estuary as a fast flowing mountain stream. Intense rains may suddenly increase flow by two orders of magnitude to over  $100 \text{ m}^3 \cdot \text{s}^{-1}$ . The estuarine response is mostly confined to the single water channel and can therefore be analysed and discussed in a two-dimensional (that is, longitudinal and vertical) frame.

During summer (dry season) the estuary functions as a highly stratified marine-driven system. Chemical characteristics and nutrient levels in the estuary are strongly correlated to water movement and therefore are influenced mainly by the sea (Taljaard, 1987). The river water (blackwater) in the estuary only exists as a thin surface layer which flows seaward almost continuously (Largier, 1986; Taljaard *et al.*, 1986). The highly stratified nature of the system during summer allows no significant chemical influence of the blackwater on the main saline water body, not even under conditions of higher river flow (Taljaard, 1987). The large biomass in the form of the algae *Cladophora* and the sand prawn *Callinassa kraussii* emphasizes the latter, since the chemical influence of blackwater is usually

associated with poor biological activity (Janzen, 1974; Por *et al.*, 1984).

Although the blackwater has no significant influence on the nutrient status of the estuary during summer, the river water as such is of physical importance since it keeps the mouth of the estuary open to the major nutrient source, namely the sea. During high tides the incoming sea-water, in addition to importing nutrients, also transports sand into the estuary, which results in the formation of a delta just inside the mouth (Taljaard *et al.*, 1986). This delta formation is counteracted by sufficient freshwater supplies (CSIR, 1980; Largier, 1986), but without proper management the upstream dams will certainly generate problems in this respect.

### 3. MATERIALS AND METHODS

Data were collected during August 1986 (mid-winter).

Six sampling stations were set out in the channel (stations 0 to 5 in Figure 1), while four stations were marked out on the sand flat (stations 6 to 9 in Figure 1). Depth profiles were determined at ten cross-sections (Lines A-K in Figure 1) using an Atlas-Deso high resolution echo sounder with frequency of 210 kHz. Water levels in the estuary were recorded over the sampling period using a Vertical Ott Waterlevel Recorder (Huizinga and Smith, 1987). All depth and water level measurements were taken relative to mean sea level (MSL). Sea levels were extracted from the SA tide tables published by the SAN Hydrographer. River flow data were obtained from the Department of Water Affairs from the weir just upstream of the estuary. Sea tides on the sampling days are given in Table 2.

Discretely-sampled salinity and temperature profiles (0,25 to 0.50 m intervals) were taken hourly at each channel station over complete tidal cycles using a Kent salinity-temperature bridge and a YSI S-C-T Meter. This was done on four days: a post-neap/pre-spring tide (19 August), a spring tide (21 August), a post-spring/pre-neap tide (25 August) and a neap tide (28 August). The salinity data are used to describe water circulation patterns since, in this case, it is the determining factor for density and provides the clearest tracer of water type and flow. On 20 August similar (but less regular) temperature and salinity profiles were combined with current-meter and drogue measurements in order to investigate the intrusion and flushing processes. Stations 0 to 4 were located the same as for the other sampling days, but instead of station 5 an adjacent but deeper position (referred to as 5') was chosen. Current speeds were measured with an in-house built current-meter which uses a Savonius rotor with a stalling speed of  $0,02 \text{ m}\cdot\text{s}^{-1}$ .

Chemical samples (pH, dissolved oxygen (DO) and dissolved nutrients) were collected three hourly at stations 1-9 (Figure 1). Samples were collected over a spring tidal cycle during relatively low river flow (stations 1-5 on 20 August and

stations 6-9 on 21 August) and over a neap tidal cycle during higher river flow (stations 6-9 on 27 August and stations 1-5 on 28 August). Surface and bottom samples were collected in the channel, while only surface samples were collected from the shallow sand flat area. Sea-water samples were collected at a point where no detectable effect of the river water was evident. River water samples were collected at the weir just above the head of the estuary.

DO measurements were done in the field using the Winkler titration method (Watling, 1981). Nutrient samples were filtered through 0,45  $\mu\text{m}$  Millipore filters and immediately frozen for later analysis in the laboratory. Dissolved reactive phosphate ( $\text{PO}_4$ ), nitrate ( $\text{NO}_3$ ), nitrite ( $\text{NO}_2$ ), ammonia ( $\text{NH}_3$ ) and dissolved organic carbon (DOC) were analysed on a Technicon Auto Analyzer using a modification (Windt, *in prep.*) of the methods described by Mostert (1983a, 1983b). Dissolved organic nitrogen (DON) were analysed using a modification of the manual method (Taljaard, 1987) described by Koroleff (1983).

Sediment cores were obtained from stations 1 to 9. Interstitial water was extracted from these cores to determine  $\text{PO}_4$ ,  $\text{NO}_3$ ,  $\text{NO}_2$  and  $\text{NH}_3$ , while the percentage total organic matter (TOM) in the sediments was determined by loss on ignition (Bligh *et al.*, 1984).

Scatter in the results was not due to analytical errors, but due to real differences among the samples. The Palmiet estuary is a highly variable system and considering sampling procedures and sampling periods, short term variations, such as isolated peaks, should not always be considered as significant. Consistent, longer term trends will, however, be highlighted in this paper.

#### 4. WATER CIRCULATION PATTERNS

The general observations derived from the results will be discussed in Section 4.1. However, the dynamics controlling the observed circulation, namely the alternating introduction and removal of salinity, will be investigated in more detail in Sections 4.2 and 4.3, respectively.

##### 4.1 Results and Observations

A contour map of the estuary (based on depth profiles measured) at the time of the winter study is given in Figure 1. The estuarine bed morphology was similar to that observed during summer (Taljaard *et al.*, 1986), except that the fan-shaped flood-tide delta, which is characteristic of the marine-dominated summer situation, had been removed by strong riverine outflow and scouring (Figure 1). Situated in a Mediterranean climate (35°S), the mountainous Palmiet catchment receives heavy rainfall during the passage of mid-latitude cold fronts. This water collects rapidly and rushes down to the estuary as a fast-flowing mountain stream capable of both mouth and channel scouring. Two distinct regions were identified in the estuary, namely the channel (stations 0 to 5) and the shallow sand flat (stations 6 to 9).

The hydrograph of river flow over this two-week period (Figure 2) displays a sudden and large increase in flow (14 August) from 15 to 80 m<sup>3</sup>.s<sup>-1</sup> in 8 hours following one of several major rainstorms which occur in winter. A similar event occurred on 5 August. A later rainstorm on the 26 August, which increased flow from 10 to 40 m<sup>3</sup>.s<sup>-1</sup>, is mild in comparison but, nevertheless, has a significant effect on the estuarine hydrodynamics (Section 4.3). Water-level measurements which were obtained during the sampling period were used by Huizinga and Smith (1987) to calculate the volume of the flood tide inflows (Figure 3). The tidal range of estuarine water levels varied from 1,2 m during spring tide (21 August) to 0,2 m during neap tide (28 August). The corresponding sea level ranges are plotted in Figure 3 alongside the river flow for 18 to 29 August.

To represent the water circulation observed in the estuary, four longitudinal salinity sections of the channel (low, flood, high and ebb tides) were selected from the data of each sampling day. Over the sand flat, the water column remained fresh over the entire two-week period and therefore it is not addressed in this paper. At low tide on 19 August, two days before spring tide, there was no saline water in the estuary (Figure 4a). Following the strong river flow ( $80 \text{ m}^3 \cdot \text{s}^{-1}$ ) during neap tide (14 August), the weaker flow of  $20 \text{ m}^3 \cdot \text{s}^{-1}$  on 18 August was sufficient to exclude saline water from the estuary. On 19 August the flow dropped below  $20 \text{ m}^3 \cdot \text{s}^{-1}$  and the tidal range increased (Figure 3) such that an intrusion of sea-water, possibly the first since the previous spring tide, invaded the estuary as a bottom density current on the flood tide (Figure 4b). This saline water collected in the deeper pools near station 4 (Figure 4c) and appeared to survive the subsequent ebb-tide flushing (Figure 4d). Three further intrusions between 19 and 21 August enhanced the salinity of the deep pools (Figure 5a). The  $7 \times 10^4 \text{ m}^3$  influx of sea-water on 21 August pushed the freshwater back to station 3 (Figure 5b) before subducting and continuing to the head as an underflow (Figure 5c). Not only was there a greater volume of diluted sea-water, but the riverflow ( $\sim 15 \text{ m}^3 \cdot \text{s}^{-1}$ ) and associated flushing also decreased. A larger saline pool remained during ebb-tide (Figure 5d). Even as the successive intrusions of saline water were reduced (Figure 3), this basal layer remained and was still evident at ebb and low tide on 25 August (Figure 6a+b). A small amount of sea-water ( $4 \times 10^3 \text{ m}^3$ ) was introduced on the late flood tide (Figure 6c+d). Although this saline layer survived the subsequent ebb-tide, there was a net loss in salinity since the previous tide. With the considerable increase in river flow on 26 August (to  $40 \text{ m}^3 \cdot \text{s}^{-1}$ ) and the absence of tidal inflow, the old basal layer disappeared and did not return until the next spring tide. The salinity sections for the neap tide on 28 August were all homogeneously fresh.

These four days of data provide a good description of how the tidal succession of intrusion and flushing is modulated by river flow and the spring-neap cycle. This strong residual vertical circulation - basal intrusions and surface layer flushing - is

the dominant circulation feature. On 20 August process-oriented data were collected to understand this feature. These specific data, together with the general background data, are used in the investigations of these processes.

#### 4.2 Intrusion of Saline Water

The tidal volume of the sea-water drawn into the estuary is determined by the shortfall between the requirement imposed by the tidal rise in sea level and the supply provided by the river flow (*cf.* Huizinga and Smith, 1987). Therefore the tidal prism in the Palmet estuary is typically smaller during the winter rainfall season but varies as a result of the spring-neap tidal cycle and the eventful nature of winter rains. Such variation is evident in Figure 3 where the volume of the tidal intrusion is plotted alongside the sea level tidal range and river flow for the period from 18 to 29 August. Prior to 19 August and after 25 August no sea-water entered the estuary because the river flow was sufficient to maintain a water level gradient and net flow towards the sea throughout the tidal cycle.

Fortunately a homogenous freshwater structure was recorded at the low tide on 19 August (Figure 4a). This allowed clear observation of the intrusion of a new saline basal layer (Figure 4b) following an increase in tidal range and a simultaneous decrease in river flow. This intrusion takes the form of a gravity-driven bottom flow. In Figure 7 a similar intrusion of saline water is seen to arrive at station 4 after 14h00 on the 20 August with a peak influx at about 15h00. Although the tide turned at the mouth at about 14h30, the intrusion continued to grow until 16h00. There is a lag of about 1,5 to 2,0 hours between saline inflow through the mouth (~12h45) and its arrival at station 4 (~14h15); this corresponds to an average intrusion speed (celerity) of about  $0,15 \pm 0,05 \text{ m.s}^{-1}$ . Associated basal current speeds ( $u$ ) from 0,2 to 0,3  $\text{m.s}^{-1}$  were recorded in this intruding layer. Using the empirical result of Simpson and Britter (1979) that the mean overtaking speed ( $u-c$ ) is  $0,15c$ , or  $u \sim 1,15c$ , these water velocities correspond to celerities between 0,17 and 0,26  $\text{m.s}^{-1}$  or a mean of 0,22  $\text{m.s}^{-1}$ . A further field estimate of the celerity of the current head is

obtained from surface foam lines which, in the absence of wind forcing, mark weak surface convergence. These weak surface convergences are located above the strong subsurface convergence at the head of the bottom flow. Curved foam lines indicate smaller  $c \sim 0,15 \text{ m.s}^{-1}$  between stations 0 and 1 and between 1 and 3 than between 3 and the pool at 4 ( $c \sim 0,20 \text{ m.s}^{-1}$ ). Bearing in mind the large uncertainty in these values, they are accountable for in terms of a narrower channel (greater  $h$ ) and possible downhill slope between stations 3 and 4.

By equating the flow force at sections upstream and downstream of the head Benjamin (1968) obtained a general expression for the celerity of the front of a buoyant or dense horizontal gravity current:

$$c = \left( \frac{g'h (1-\delta) (2-\delta)}{(1+\delta)} \right)^{0,5} \quad (1)$$

where

$g'$  = the reduced gravity

$h$  = the layer depth

$\delta$  = the fractional layer depth  $h/H$

This equation predicts a speed of  $0,27 \text{ m.s}^{-1}$  as the  $0,5 \text{ m}$  thick saline layer, with  $\Delta\rho \sim 14 \text{ kg.m}^{-3}$ , intrudes below a homogeneous freshwater layer. The presence of some residual salinity from the previous high tide would reduce this celerity as a result of smaller  $g'$ . This effect is probably only significant in the deeper water at station 4 - at the same time however the sloping approach to this deeper pool will increase  $c$  above that predicted by Equation (1). Alternatively, any sediment load could increase  $g'$  and  $c$ . In any case, a steady, uniform flow of a density current over a horizontal surface cannot be realized in a viscous fluid. An empirical plot of normalized celerity versus fractional depth (Wilkinson, 1983) approximates the simple theoretical result of Benjamin (1968) but suggests that as  $\delta > 0$  Equation (1) overestimates  $c$  as a result of neglecting viscosity. Extracting a value from these empirical results predicts a celerity of  $0,22 \text{ m.s}^{-1}$ . It is expected that the frictional drag of a rough sandy bottom would be even greater in a field situation. Simpson (1982) suggests that a density current

intruding below an opposing headwind will be retarded by about 0,6 of the headwind speed. For a headwind of about  $0.06 \text{ m.s}^{-1}$  the front of the current would only progress at  $0,17 \text{ m.s}^{-1}$ . The blunt shape of the front of this current suggests that it is a density current (as opposed to a density wedge), that is, the bouyancy forces driving the current are balanced by bottom friction (Jirka and Arita, 1987).

The sea-water intrusion is diluted through turbulent mixing with the fresh estuarine surface layer at a tidal intrusion front. During spring flood tides the pressure-driven inflow of sea-water is sufficient to exceed  $c$  of the freshwater plume front over the shallow sill at the mouth (Equation 1). Consequently, the freshwater outflow although propagating against the tidal inflow, is pushed back into the estuary. A V-shaped front develops (similar to that described by Simpson and Nunes, 1981) and is pushed back into deeper water until an increase in  $H$  results in a decrease in the mean flood tide velocity  $U$  and a simultaneous increase in the celerity of a surface freshwater current (Equation 1). The plunge line, or intrusion front, will be located where  $U=c$ , that is, where the internal Froude number takes a critical value of order unity (Imberger and Hamblin, 1982). This double-sided surface convergence is marked by a clear foam-line. Along this line the sea-water plunges below the less saline estuarine water. Subcritical bulk Richardson numbers (between 0,4 and 0,8 on 20 August) indicate strong turbulent mixing. The effect of this mixing appears to be greater during the initial stages and to decrease once the intrusion front has established itself in a position partially removed from the sandbank across the mouth. On 20 August at about 12h30 the flood tide water of  $27^0/_{00}$  (already diluted by the outflow of water on the previous ebb-tide) was diluted to  $21^0/_{00}$  in this turbulent front; corresponding to a 30 per cent entrainment of the surface layer. Later on the flood tide, at about 14h00, water of  $31^0/_{00}$  was diluted to  $27^0/_{00}$ ; corresponding to a 14 per cent entrainment of surface water.

On propagating as a density current further into the estuary, water is lost through entrainment to the overlying ambient fluid. Turbulent entrainment, characterized by subcritical Richardson numbers and vortex-engulfing at the interface, is mostly confined to the head of this intrusive current. Mixing in the wake is characterized by supercritical Richardson numbers and internal wave breaking (cf. Pedersen, 1986). Nevertheless the homogeneous basal layer, below the stratified shear layer, is negligibly diluted by downward entrainment. Water of  $26^0_{\text{‰}}$  intrudes to station 4. Input of saltier water later on the flood tide is prevented from reaching station 4 by the strong currents and flushing action of the ebb-tide. At about 15h00 the water velocity at station 4 was about  $0,1 \text{ m.s}^{-1}$  immediately below the halocline and increased to  $0,2 \text{ m.s}^{-1}$  nearer the bottom. At the same time an ebb current of  $0,1$  to  $0,2 \text{ m.s}^{-1}$  was found above the halocline (Figure 7). The bulk Richardson number  $Ri$  can be evaluated with  $\Delta\rho \sim 9 \text{ kg.m}^{-3}$ ,  $\Delta z \sim 1 \text{ m}$  and  $\Delta u \sim 0,25 \text{ m.s}^{-1}$ . The calculated value  $Ri \sim 1,4$  is marginal and thus indicates that some significant exchange may occur across the halocline as the intrusion approaches the head of the estuary. The bulk Richardson number is found to be more stable at station 1 at about 13h10 ( $Ri \sim 5$ ) and at station 3 at about 13h40 ( $Ri \sim 2$ ) which is immediately (about 5 min) after the arrival of the density current. As the front arrives at station 3, a marginal value of  $Ri \sim 1$  indicates the possibility of turbulent exchange at the head. Subcritical values of  $Ri \sim 0,6$  and  $Ri \sim 0,9$  are obtained in the intrusion front at the mouth and over the shallow areas between stations 4 and 5. This indicates the turbulent mixing and partial breakdown of the density current that occurs in patches at the mouth and in the upper portion of the estuary.

The saline intrusion during the daylight hours of 20 August was repeatedly sampled for temperature and salinity *in situ*. A diagram of temperature versus salinity displays a number of interesting features (Figure 8). Fresh surface water entered the estuary at  $12,5^{\circ}\text{C}$  in the early morning. During the calm, warm and sunny day the temperature of this river water increased to about  $14^{\circ}\text{C}$ . The estuarine surface water was heated further to

over 15°C at the mouth. This diurnal heating affected the whole surface layer (that is, to a depth of about 1 to 1,5 m).

All the water types found in the estuary can be obtained from the linear combination of the three source water types (Figure 8): river input (zero salinity; temperature between 12,5°C and 15°C), marine input (salinity 35,5<sup>0</sup>/<sub>00</sub>; temperature decreased from 16,5°C to 16°C during the day) and the old deep water which had intruded on the previous flood tides (salinity 21<sup>0</sup>/<sub>00</sub>; temperature about 14,2°C). The influx of sea-water occurs immediately after noon as a density current with a character of salinity 26<sup>0</sup>/<sub>00</sub> and temperature 15,8°C, once established. The dilution of 3 parts sea-water to 1 part river water is achieved mostly through turbulent mixing (subcritical Ri) in the ebb-tide plume outside of the estuary and at the tidal intrusion front near the mouth. On approaching the pools of residual saline water at stations 4 and 5', this new intrusion ( $\sigma_t \sim 18,9$ ) dives below the older water ( $\sigma_t \sim 15,4$ ). In order to result in shear instabilities, this new water would have to intrude with a relative speed of about 0,2 m.s<sup>-1</sup> (given a pycnocline of the order of 1 m thick) relative to the older water. It appears that this does not occur and the new saline layer (of final character salinity 25<sup>0</sup>/<sub>00</sub>, temperature 15,5°C and  $\sigma_t \sim 18,2$ ) is only fractionally diluted by the older water (4:1). The final mixture is then roughly 60 per cent sea-water, 20 per cent freshwater and 20 per cent old saline layer.

In a pool near station 5' at about 15h30, the recorded temperature and salinity clearly shows the new saline water pushing in slowly under the older resident saline water (Figure 8). In addition to being entrained into the new basal layer this older water is also raised towards, and entrained into, the relatively fast flowing (0,1 to 0,2 m.s<sup>-1</sup>) surface layer. A consequent increase in salinity in the surface layer from 0,5 to 1,5<sup>0</sup>/<sub>00</sub> is apparent at stations 4 and 5' after 15h30 (Figure 8).

The flood tide prism on 21 August was more than double the size of that on 20 August. A large saline intrusion is obvious in Figure 5b and results in a halocline existing at a depth of about 1 m shallower than on 19 August (Figure 4). After 21 August the

decreasing tidal range led to smaller and ultimately no intrusions of new salinity until subsequent spring tides (Figure 3).

#### 4.3 Residence and Flushing

Flushing times, which can be calculated for both the freshwater and sea-water fractions of the estuary, characterize the mean integrated effect of mixing and interaction between these source waters. This time scale is also ecologically relevant as the residence time of biota and nutrients which are transiently introduced to the estuarine system.

Following Largier (1986), one can calculate flushing times  $Tf_s$  for sea-water and  $Tf_o$  for freshwater in a two-layer system. Simple ratio formulas compare the resident volumes of water to inflow rates. Flushing, however, refers to removal of water and flushing times should rather be calculated from outflow rates. This can be done irrespective of the thermohaline structure provided that the outflow is well mixed. Dronkers and Zimmerman (1982) consider various time scales and dispersion coefficients which can be used to estimate residence and to determine the dominant mixing processes.

Although instantaneous rates  $Tf_s(t)$  and  $Tf_o(t)$  can be calculated, it is only really meaningful to calculate mean values  $Tf_s$  and  $Tf_o$  over a tidal cycle. Given a mixed estuarine outflow  $Q$  of given salinity  $S$ , the time-dependent and tidal-mean flushing times are:

$$Tf_s(t) = \frac{V_s(t)}{Q_m(t) \cdot S(t)/S_s(t)}$$

$$Tf_o(t) = \frac{V_o(t)}{Q_m(t) \cdot (S_s - S(t))/S_s}$$

$$Tf_s = \frac{1}{\tau} \int_0^{\tau} Tf_s(t) \cdot dt \quad (2)$$

$$Tf_o = \frac{1}{\tau} \int_0^{\tau} Tf_o(t) \cdot dt \quad (3)$$

where

- $V_s(t)$  = the time-dependent volume of the sea-water fraction in the estuary  
 $S_s(t)$  = the salinity of the source sea-water  
 $V_o(t)$  = the time-dependent volume of the freshwater fraction in the estuary  
 $r$  = is the tidal period

For the purpose of calculation Equations (2) and (3) are simplified to:

$$Tf_s = \frac{Vh_s \cdot S_s}{Q \cdot S} \quad (4)$$

$$Tf_o = \frac{Vh_o \cdot S_s}{Q \cdot (S_s - S)} \quad (5)$$

where

$Vh_s$  and  $Vh_o$  are the high-tide volumes of the sea-water and freshwater fractions in the estuary.

The formulae for  $Tf_s$  used by Largier (1986) yield values of zero during the first intrusion of saline water on 19 August and infinity after the tidal intrusion has ceased to exist (26 August). This approach only accounts for the removal of resident saline water as a result of new saline water pushing into the estuary and under the old saline layer. The older water is lifted and rapidly incorporated into an enlarged surface layer effluent. The background entrainment in the absence of basal sea-water intrusions is not accounted for in this approach. As evidenced by the absence of saline water on 28 August,  $Tf_s$  is finite in spite of zero intrusion after 25 August. Equation (4) accounts for both processes by considering the net effect rather than an individual cause. A more fundamental expression, similar to Equation (4), can be obtained by replacing  $Q$  and  $S$  by the entrainment flux  $Q_e$  and salinity  $S_e$ ; Equations (4) and (5) are based on the understanding that

$$\overline{Q \cdot S} = \overline{Q_e \cdot S_e}$$

On 20 August the weighted average saline outflow  $\overline{Q \cdot S}$  was  $190/_{00} \cdot m^3 \cdot s^{-1}$  and the high tide volume was  $3,3 \times 10^5 m^3$  of which 12 per cent was sea-water. Equations (4) and (5) give a sea-water

flushing time of 1,6 tidal cycles and a freshwater flushing time of 0,4 tidal cycles (5 hrs 22 min). On 21 August, the day on which the largest saline intrusion was recorded (Figure 3),  $\overline{Q.S} = 35^0/_{00} \cdot \text{m}^3 \cdot \text{s}^{-1}$  and 20 per cent of the high tide volume ( $3,9 \times 10^5 \text{ m}^3$ ) was sea-water. The sea-water flushing time was 1,8 tidal cycles and the freshwater flushing time was 0,5 tidal cycles (6 hrs 40 min). Insufficient data is available to calculate these time scales during the demise of the saline layer but  $Tf_s$  is clearly finite.

Entrainment into the fast-flowing surface layer appears to be most active at stations 4 and 5 nearer the head of the estuary. The river water (zero salinity) flows turbulently into the narrow upper section of the estuary. The salinity of this surface layer typically increases to about  $1,5^0/_{00}$  at station 4 (Figure 8) and then entrains more slowly between station 4 and the mouth where outflow salinity of  $2,0^0/_{00}$  is typical. Some insight into this entrainment can be gained from reviewing the time series at station 4 (Figure 7). A period of strong erosion of the halocline precedes the intrusion of new saline water which occurs between 14h00 and 16h00. After 16h00 the halocline is eroded again. Through rough calculation of the bulk Richardson number (Table 1) periods of enhanced entrainment can be identified. Low but supercritical values are obtained during peak ebb flow before 11h00 and after 17h30. The lowest value, however, is at 14h45 during the intrusion of new saline water. It is only during this brief period that turbulent exchange may occur. The majority of the exchange, however, is expected during the extended ebb flow periods when the surface layer speeds up to  $0,3 \text{ m} \cdot \text{s}^{-1}$ . This entrainment would be upward into the fast-flowing turbulent surface water. Closer to high or low tide the interfacial shear and associated entrainment decreases substantially at station 4 (Table 1).

These periods of low Richardson Number correspond well to severe deepening of the halocline. The local entrainment velocity  $w_e$  at station 4 is  $4,2 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$  between 09h30 and 13h30 with a peak of  $8,2 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$ . This decreases to  $2,3 \times 10^{-5} \text{ m} \cdot \text{s}^{-1}$  immediately preceding the intrusion. On the new ebb flow (between 17h00 and

19h00) local entrainment velocity of  $3,5 \times 10^{-5} \text{ m.s}^{-1}$  is attained. The instantaneous flushing time varies inversely proportional to the entrainment flux  $Q_e = w_e \cdot A_i$ , where  $A_i$  is the area of the interface. These local entrainment velocities can be compared to the overall mean entrainment velocity of the estuary calculated from the relative salinities of the outflow and the entrained water. A tidal average  $Q_e$  is about  $1 \text{ m}^3.\text{s}^{-1}$  which corresponds to an average  $w_e \sim 3,0 \times 10^{-5} \text{ m.s}^{-1}$ . This indicates that entrainment is above average at station 4; and presumably even greater towards the head of the estuary. Also of interest is the double peak in entrainment flux which corresponds to the double trough in Richardson number (Table 1). Surface salinity values near the mouth exhibit a similar double peak due to this double peak in entrainment of saline water.

## 5. pH, DISSOLVED OXYGEN AND NUTRIENT DISTRIBUTION PATTERNS

### 5.1 Results

As stated before, the water column of the estuary can be divided into two main regions, namely the channel and the sand flat (Figure 1). During the entire two-week experiment the water column over the sand flat remained homogeneously fresh. As expected the pH, DO and dissolved nutrient data resembled that of the river water at the time. Thus, during winter the chemical characteristics of this very shallow area are mainly determined by the blackwater river. Although these results will not be addressed in this paper, a summary of the data is presented in Table 3. Discussion will be based mainly on the channel data (stations 1-5).

Chemical changes and distribution patterns are often correlated to physical water movement. Since water movement was best described by salinity measurements, surface and bottom water values were extracted from the profile data of 21 August (spring tide and relatively lower river flow) in order to compare findings with corresponding chemical measurements. Results are presented in Figure 9. On the 28 August (neap tide and relatively higher river flow) the estuary remained homogeneously fresh over the complete tidal cycle.

Mean values and ranges of pH, DO and dissolved nutrients measured in the water column at stations 1-5 on 21 August and 28 August are presented in Table 2 and 3, respectively. Levels measured in the sea- and river water at the time are presented in Table 4.

#### 5.1.1 pH

On 21 August (spring tide) low pH levels were measured for the fresh surface layer throughout the tidal cycle (mean = 6,8; range = 6,6-6,9) (Table 4), showing strong, acidic blackwater influence (pH = 6,8) (Table 6).

During late ebb-tide and at low tide pH levels (~6,9) in the bottom water of stations 1-3 were low (Figure 10) corresponding to the fresh blackwater conditions which existed at the

shallower stations at the time. However, on the flood tide pH levels increased to about 8,0 (Figure 10) as a result of sea-water intrusion (pH = 8,1) (Table 6). Although saline intrusion is usually diluted with fresh surface water at the intrusion front through turbulent mixing, the amount and buffering capacity of the sea-water was large enough to have the major influence in shallow bottom water during flood tide.

Due to insufficient flushing of resident saline water from the deeper pools at station 4 during ebb and low tide, pH values remained high (mean = 7,9; range = 7,7-8,0) throughout the experiment and resembled that of the sea-water (8,1) (Tables 4 and 6) (Figure 10).

Station 5, again being shallower than station 4, showed a similar pattern in bottom water pH levels to that of stations 1-3 (Figure 10) over the tidal cycle, except for a time lag of about two hours. The same trend was observed in water circulation measurements discussed in a previous section (Section 4).

On 28 August (neap tide) pH levels in the surface and bottom channel water remained low (mean = 6,5; range = 6,2-6,6), similar to the levels measured in the river water (pH = 6,5) (Tables 5 and 6).

#### 5.1.2 Dissolved oxygen (DO)

Surface DO levels remained relatively high and constant over the spring tidal cycle experiment (mean = 10,6 mg.l<sup>-1</sup>; range = 9,9-11,2 mg.l<sup>-1</sup>), similar to that of the river (10,7 mg.l<sup>-1</sup>) (Table 4 and 6).

On the ebb and low tide the DO levels in the bottom water of stations 1-3 (~10,6 mg.l<sup>-1</sup>) also resembled that of the fresh river water (Figure 11). However, during the flood tide saline intrusion, DO levels dropped to about 9,8 mg.l<sup>-1</sup> as a result of marine input. Oxygen is less soluble (Bell, 1973) in more saline and warmer sea-water (8,1 mg.l<sup>-1</sup> versus 10,7 mg.l<sup>-1</sup> in the fresh river water) (Table 6).

DO levels showed no marked change over the tidal cycle in the bottom water of station 4 (mean = 8,4 mg.l<sup>-1</sup>; range = 7,7-8,8 mg.l<sup>-1</sup>) (Table 4). Levels compared favourably to that measured in the sea-water (8,1 mg.l<sup>-1</sup>) (Table 6) (Figure 11).

Bottom water DO levels at station 5 again showed a similar pattern to stations 1-3, except for the two-hour lag (Figure 11).

During the neap tide DO levels throughout the channel remained constant and relatively high (mean = 10,5 mg.l<sup>-1</sup>; range = 10,1-10,7 mg.l<sup>-1</sup>) (Table 5), suggesting well-flushed homogenous fresh water conditions (Table 6).

#### 5.1.3 Dissolved reactive phosphate

During the spring tide no marked changes in the PO<sub>4</sub> levels over the tidal cycle could be detected. The channel showed an average PO<sub>4</sub> concentration of 0,60 μmol P.l<sup>-1</sup> (range = 0,27-1,46 μmol P.l<sup>-1</sup>) similar to levels measured both in the marine and river source (0,79 μmol P.l<sup>-1</sup> and 0,61 μmol P.l<sup>-1</sup> respectively) (Tables 4 and 6).

During the neap tide experiment PO<sub>4</sub> levels measured in the water column also showed no marked changes over the tidal cycle (mean = 1,13 μmol P.l<sup>-1</sup>; range = 0,65-2,27 μmol P.l<sup>-1</sup>) (Table 5). Sea and river water levels were 1,16 μmol P.l<sup>-1</sup> and 1,01 μmol P.l<sup>-1</sup> respectively (Table 6).

High dissolved reactive phosphate levels were measured in the interstitial water (Table 7).

#### 5.1.4 Dissolved nitrate

Surface water NO<sub>3</sub> levels during the spring tide were high (mean = 89,2 μmol N.l<sup>-1</sup>; range = 55,5-204,9 μmol N.l<sup>-1</sup>), similar to levels measured in the river (67,9 μmol N.l<sup>-1</sup>) (Table 4 and 6).

During ebb and low tide NO<sub>3</sub> levels in the bottom water of stations 1-3 were similar to surface water measurements (~65 μmol N.l<sup>-1</sup>) (Figure 12). However, during flood tide intrusion, the NO<sub>3</sub> levels showed a decreasing tendency

( $\sim 47 \mu\text{mol N.l}^{-1}$ ) as the influence of lower  $\text{NO}_3$  sea-water increased ( $13,4 \mu\text{mol N.l}^{-1}$ ) (Table 6).

In the deeper pools at station 4  $\text{NO}_3$  levels remained constant and relatively low (mean =  $34,6 \mu\text{mol N.l}^{-1}$ ; range =  $12,3-83,4 \mu\text{mol N.l}^{-1}$ ) throughout the tidal cycle, comparing favourably with the lower levels measured in the sea-water (Tables 4 and 6) (Figure 12).

Bottom water trends at station 5 were similar to those observed at stations 1-3, except for a two-hour time lag (Figure 12).

No marked change occurred in  $\text{NO}_3$  levels measured in the channel during neap tide (mean =  $63,1 \mu\text{mol N.l}^{-1}$ ; range =  $35,1-140,9 \mu\text{mol N.l}^{-1}$ ), indicating strong river water influence ( $52,2 \mu\text{mol N.l}^{-1}$ ) (Tables 5 and 6).

Interstitial water dissolved nitrate levels were similar to that measured in the river water ( $\sim 64,3 \mu\text{mol N.l}^{-1}$ ) at the time (Table 7).

#### 5.1.5 Dissolved nitrite

Dissolved nitrite levels remained low in the surface layer of the channel throughout the spring tidal experiment (mean =  $2,3 \mu\text{mol N.l}^{-1}$ ; range =  $0,3-9,1 \mu\text{mol N.l}^{-1}$ ), similar to levels in the river water ( $0,8 \mu\text{mol N.l}^{-1}$ ) (Tables 4 and 6). The latter is characteristic of well-oxygenated waters.

During ebb and low tide nitrite concentrations in the bottom waters of stations 1-3 were also low ( $\sim 4 \mu\text{mol N.l}^{-1}$ ), characteristic of the fresher waters at the time. However these values showed a marked increase during the flood tide intrusion ( $\sim 50 \mu\text{mol.l}^{-1}$ ) (Figure 13). At the time sea-water nitrite concentrations were exceptionally high ( $45,7 \mu\text{mol.l}^{-1}$ ) (Table 6).

Nitrite levels in the bottom water of station 4 remained high throughout the tidal cycle (mean =  $56,8 \mu\text{mol N.l}^{-1}$ ; range =  $36,2-83,4 \mu\text{mol N.l}^{-1}$ ), showing strong marine influences (Tables 4 and 6) (Figure 13).

Bottom water at station 5 also showed a marked increase in nitrite values, corresponding to an increase in salinity at the station, two hours after the effect occurred at the shallower stations near the mouth (Figure 13).

During the neap tide the entire channel showed low nitrite values (mean =  $0,7 \mu\text{mol N.l}^{-1}$ ; range =  $0,1-1,8 \mu\text{mol N.l}^{-1}$ ), similar to that of the river ( $0,8 \mu\text{mol N.l}^{-1}$ ) (Tables 5 and 6).

Dissolved nitrite levels in the sediments were slightly higher than values obtained for the river water ( $\sim 0,6 \mu\text{mol N.l}^{-1}$ ), but significantly lower than that of the sea-water ( $\sim 44,9 \mu\text{mol N.l}^{-1}$ ) (Table 7).

#### 5.1.6 Dissolved ammonia

Ammonia levels remained low throughout the two-week experiment compared to other nitrogen nutrients (mean =  $1,4 \mu\text{mol N.l}^{-1}$ ; range =  $0,8-3,4 \mu\text{mol N.l}^{-1}$ ) (Tables 4 and 5). This is usually the case in well-oxygenated systems like the Palmiet estuary (Eagle and Bartlett, 1984). In contrast to nitrite, ammonia levels were very low in the sea-water (Table 6).

High ammonia levels were measured in the interstitial water of the estuary (Table 7).

#### 5.1.7 Dissolved organic nitrogen (DON)

Although no specific trend was observed in the DON levels of the channel during the spring tidal cycle experiment, the surface water DON levels (mean =  $23,4 \mu\text{mol N.l}^{-1}$ ; range =  $12,8-50,4 \mu\text{mol N.l}^{-1}$ ) showed a tendency to be slightly higher than that of the bottom water (mean =  $11,8 \mu\text{mol N.l}^{-1}$ ; range =  $2,0-23,2 \mu\text{mol N.l}^{-1}$ ) (Table 4). Sea-water levels were also lower ( $10,3 \mu\text{mol N.l}^{-1}$ ) compared to that measured in the river water ( $26,4 \mu\text{mol N.l}^{-1}$ ) (Table 6). The latter suggested a different distribution characteristic for DON compared to the strong correlation to water circulation as was the case with other dissolved nutrient forms.

During the neap tide DON levels remained relatively high throughout the water column (mean = 29,1  $\mu\text{mol N.l}^{-1}$ ; range = 15,7-49,9  $\mu\text{mol N.l}^{-1}$ ), similar to levels measured in river water (39,9  $\mu\text{mol N.l}^{-1}$ ) (Tables 5 and 6).

#### 5.1.8 Dissolved organic carbon (DOC)

The relatively high DOC levels, measured in the surface channel water during the spring tidal cycle (mean = 620  $\mu\text{mol C.l}^{-1}$ ; range = 310-1130  $\mu\text{mol C.l}^{-1}$ ) were similar to river water levels (730  $\mu\text{mol C.l}^{-1}$ ) (Tables 4 and 6).

DOC levels markedly decreased at the shallower stations (stations 1-3) during flood tide intrusion (from ~530 to 210  $\mu\text{mol C.l}^{-1}$ ) (Figure 14), indicating the introduction of lower DOC sea-water.

The DOC concentration in the bottom water of station 4 remained relatively low throughout the tidal cycle (mean = 190  $\mu\text{mol C.l}^{-1}$ ; range 180-310  $\mu\text{mol C.l}^{-1}$ ), showing permanent, lower DOC, saline water (140  $\mu\text{mol C.l}^{-1}$ ) presence (Tables 4 and 6).

Bottom water at station 5, was influenced similarly to that of station 1-3 during flood tide intrusion, except for the time lag (Figure 14).

DOC levels remained constant and relatively high during the neap tide (mean = 900  $\mu\text{mol C.l}^{-1}$ ; range = 640-1580  $\mu\text{mol C.l}^{-1}$ ), indicating permanent river water influence (980  $\mu\text{mol C.l}^{-1}$ ) in the water column over the neap tide experiment (Tables 5 and 6).

#### 5.1.9 Total organic matter

The organic matter in the sediments was very low and never exceeded 0,4 per cent of the total sediment of coarser sediments (Branch and Grindley, 1979).

### 5.2 Discussion

The pH levels measured in the estuary over both the spring and neap tidal cycles correlate well with salinity changes, that is, water movement. During spring tide the surface layer, dominated by acidic blackwater, has correspondingly low pH values. Low pH

values obtained for the shallower stations 1-3, near the mouth of the estuary during ebb and low tide, also indicated the presence of acidic river water. The increase in pH during flood tide is the result of higher pH sea-water being pushed in along the bottom as an intrusion front. River flow is therefore strong enough to flush these shallower stations sufficiently during ebb/low tide. However, it is not strong enough to keep the higher pH sea-water from entering the estuary during spring high tide. Insufficient flushing of resident saline water from the deeper pools at station 4 during ebb/low tide, is the reason for permanently higher pH conditions existing in that region. Although new saline water enters those pools during flood tide (Section 4), water characteristics remain the same and can only be detected by very detailed measurements e.g. using salinity and temperature (Section 4). Bottom water pH measurements at station 5 show changes over the tidal cycle similar to those observed at stations 1-3, despite being near the head of the estuary. Since station 5 is also a shallower station, ebb/low tide flushing is efficient enough to remove saline water which enters the system during spring flood tides. However, pH changes at station 5, near the head, show a time lag of about 2 hours compared with changes at stations 1-3, near the mouth. Water circulation patterns show the same phenomenon, related to the speed with which the intrusion front progresses into the bottom waters of the estuary. Increased river flow during the neap tide prevents any saline intrusion. The estuary then exists as a homogeneously fresh, blackwater system with low pH (acidic) levels.

Changes in DO levels over the spring and neap tidal cycles have similar trends to that of pH, also showing strong correlation with water circulation patterns. Solubility of oxygen increases in fresh, colder waters, therefore higher levels are measured under conditions of river water dominance, that is, in the surface waters, as well as bottom waters of the shallower stations (stations 1-3 and 5) on ebb/low tide during the spring tidal cycle and in the entire water column during neap tide.

Although  $\text{PO}_4$  results show no tidal cycle pattern during the spring tide due to sea-water and river water levels being similar, it can be assumed that any marked increase or decrease in sea-water  $\text{PO}_4$  concentrations, will influence bottom water levels in the estuary especially during flood tide intrusions. Likewise, any changes in river water  $\text{PO}_4$  will affect the levels in areas which are dominated by fresh water conditions over the tidal cycle. Reactive  $\text{PO}_4$  concentrations were slightly higher during conditions of increased river flow during the second week. The latter could be attribute to  $\text{PO}_4$  (derived from fertilizers) being washed from the agricultural areas in the catchment.

Dissolved nitrate and nitrite changes in the estuary are also well correlated with water circulation patterns. Nitrate levels were relatively high in the river water, as well as the sea-water at the time. High levels in the river water can be ascribed to agricultural run-off or to run-off from the dam construction in operation at the time (some explosives contain  $\text{NO}_3$ ). Boyd *et al.* (1985) suggested that increases in nitrate concentrations in the waters along the south-western Cape coast could be ascribed to limited uptake as a result of lower light levels and plankton being removed from the euphotic zone by turbulent vertical mixing. It could also be the result of upwelling along the coast. However, the latter is usually associated with strong south-easterly winds during the summer months and is therefore not very likely (Schumann *et al.*, 1982). Under fresh water conditions nitrite levels remain low, typical of well-oxygenated systems. However, despite well-oxygenated water, nitrite levels in the saline waters were exceptionally high. Although Webb (1981) observed nitrite peaks in autumn and late winter, the levels were much lower than those measured during this survey. Webb (1981) suggested that nitrite oxidation might be greatly reduced compared to ammonia oxidation at the extremes of the biological temperature range, since the peaks mentioned occurred just after the hottest and coldest parts of the year. The present survey took place in late Winter. No further explanation could however be found for the very high levels measured in the sea-water entering the Palmiet estuary.

Typical of well-oxygenated systems, the ammonia levels remained low throughout the two-week experiment (Eagle and Bartlett, 1984). In contrast to nitrite, ammonia levels were very low in the sea-water. The latter strengthens the suggestion made by Webb (1981) that ammonia oxidation is not reduced during temperature extremes as might be the case with nitrite.

DON results do not show strong correlation with water circulation patterns although river water and sea-water concentrations differed, which suggests some other influences. Results obtained during the summer experiment showed a marked removal of DON from river water once it entered the more saline conditions in the estuary (Taljaard, 1987). Removal was evident at a salinity as low as 1 per cent. Sea-water is more alkaline than blackwater and because of the relatively weak buffer capacity of the latter, the presence of small quantities of saline water can have a marked effect on pH, which in turn is probably the direct cause of DON removal. Humic acids, present in blackwater rivers, are known to form insoluble complexes with proteins (which forms part of the DON pool) (Janzen, 1974). The latter can be stimulated by the small salinity changes. Although flushing is considered effective with respect to pH, etc. small traces of saline water can create an unstable environment for river water DON. The latter could therefore be the reason for the non-conservative relationship of DON to salinity, that is, water circulation, in contrast to the more conservative behaviour of the other nutrients. During the neap tide when strong river flow allowed no trace of saline water into the estuary, no DON removal occurred from the humic acid-rich blackwaters present in the system at the time.

DOC changes over the spring and neap tidal cycles are again well correlated with water movement, with saline conditions showing lower DOC levels compared with times of fresh water dominance.

No evidence can be found for high-nutrient interstitial water leaching into the water column from the sediments. The latter is usually related to processes occurring in the surface sediment and at the sediment-water interface, since normal diffusion rates of nutrients present in such small quantities are low.

Biological activity in the surface sediment usually favours transfer of nutrients (Callander and Hammond, 1982). Considering the low biological activity indicated by meiofauna numbers (Fricke, *in prep.*) the latter can also be ruled out as a possible mechanism for sediment-water nutrient fluxes in the Palmiet estuary. The low organic content of the sediments further emphasizes the low biological activity.

Considering the above discussion, the major part of the water column in the Palmiet estuary receives its chemical characteristic from the fresh, blackwater source. During spring tide the sea has a temporary effect on the characteristics of a small bottom water layer, as a result of flood tide intrusion. For the major part, low pH, low salinity and low light permeability exist in the estuary (typical of blackwater systems) except in the case of non-limited nutrient concentrations. As is the case in other blackwater environments, biological productivity is greatly reduced. The algae, *Chladophora*, completely disappears from the estuary, while it occurs in abundance during summer. A decrease in the numbers of sand prawn, *Callinassa kraussi*, was also observed. The reduction in biological productivity can however be considered as a "cleansing mechanism" for the estuary in that it is a natural process for controlling excess algal growth which accumulates during summer. In a recreational area such as the Palmiet estuary, where the aesthetic value of the environment is of utmost importance, these natural processes are essential. Consequently, unless seasonal water releases from upstream dams are well managed and controlled, serious environmental and economical problems could develop.

## 6. COMPARISON WITH THE SUMMER SITUATION

It was fortunate that the summer field survey in February 1985 (Largier, 1986; Taljaard, 1987) and the winter field survey in August 1986 (this paper) were executed in conditions which were seasonally typical (refer also to Branch and Day, 1984). Summer is typically dry (low river flow  $<10 \text{ m}^3 \cdot \text{s}^{-1}$ ) and warm (high river and estuary surface temperature). Episodic south-east winds often provide nutrient-rich, cold upwelled sea-water. Winter is typically wet (high river flow  $>10 \text{ m}^3 \cdot \text{s}^{-1}$ ) and cool (lower river and estuary temperature). Episodic north-west frontal winds often provide pulses of enhanced river flow. It is obviously quite possible that typical winter conditions may occur in summer and *vice versa*.

Four primary effects are responsible for the key seasonal changes. In winter:

- (1) Thermal stratification is less important;
- (2) The estuarine mouth region is scoured more deeply;
- (3) The tidal prism is much smaller or non-existent;
- (4) Surface layer velocities are faster.

The most significant morphological change is the deepening of the mouth passage. The shallowest constriction, at MSL in February 1985, was at about 1m below MSL in August 1986. This was due to extreme outflow rates such as  $80 \text{ m}^3 \cdot \text{s}^{-1}$  on 14 August. Simultaneously the flood tide delta, which was found in summer, was removed completely although the sandbar remained. As a result of a deeper mouth channel (below MSL) sea-water could enter the estuary from a lower sea level and was subject to less mixing. In August 1986, saline water was observed entering the mouth simultaneously with a weak ebb in the surface layer. Unlike summer, the strong mixing at the tidal intrusion front did not dilute the inflow to the extent of forming an intermediate saline layer into which the later flood water intrudes as a separate bottom density current. In August, the full tidal prism was included in a single coherent density current of about  $26^0/_{00}$ . This density current served to replenish the deep saline layer. In addition, the deeper mouth channel in August allowed the

estuarine water level to drop much lower (greater estuarine tidal range) and resulted in the sandflats being completely exposed each low tide. However, as a result of increased river flow the total winter spring tidal prism ( $\sim 7 \times 10^4 \text{ m}^3$ ) was significantly smaller than the corresponding summer tidal prism ( $\sim 2 \times 10^5 \text{ m}^3$ ). In August the saline layer was continually confined to the water channel and the sandflats were tidally inundated with fresh water only. Whereas in February 1985 fresh water was limited to a shallower layer ( $\leq 0,5\text{m}$  deep), the surface layer in August 1986 was never less than 1 m.

Apart from comparing volumes and shapes of the water masses, it is interesting to compare temperature-salinity diagrams (e.g. Figure 8 of Largier, 1986, with Figure 8 of this paper). The surface estuarine water cooled from about  $24^\circ\text{C}$  to  $14^\circ\text{C}$  and was less salty ( $5\text{‰}$  and  $2,5\text{‰}$  at stations 1 and 4 to about  $1,5\text{‰}$  and  $1,8\text{‰}$ ). The winter bottom water was also less salty (between  $30\text{‰}$  and  $35\text{‰}$  in summer to about  $25\text{‰}$  in winter).

Flushing times and entrainment velocities are taken as indices of the rate of removal of saline (or fresh) water from the estuary. Flushing times are an index of the rate relative to the resident volume of water in the estuary. Although improved expressions for  $Tf_s$  and  $Tf_o$  were developed for this winter case (Equations 4 and 5), the expressions used by Largier (1986) are comparable for larger finite values of the tidal prism and high tide saline volumes, as found in summer. The spring tide flushing times of 1,6 tidal cycles for 7 February and 20 August as well as 1,8 tidal cycles for 6 February and 21 August are remarkably similar. This is particularly interesting because summer flushing is mostly marine-forced as a result of the new sea-water pushing in and forcing old saline water out, whereas winter flushing is largely riverine-forced through the current shear imposed by the fast-flowing surface layer (Section 4.3). The deep saline layer found in summer is analogous to the winter situation. Entraining velocities in the summertime intermediate saline layer, however, are slower (particularly during the neap tides) and protect the deep saline layer which, therefore, may have a flushing time of many tidal cycles. This difference in flushing mechanism is

symptomatic of the fundamental change from marine-driven tidal dynamics (and predominance of saline water) in summer to river-driven dynamics (and predominance of fresh water) in winter.

Entrainment velocities calculated for 20 August are between  $2 \times 10^{-5}$  and  $4 \times 10^{-5}$  m.s<sup>-1</sup> whereas those for 12 February are between  $0,5 \times 10^{-5}$  and  $1 \times 10^{-5}$  m.s<sup>-1</sup>. The summer example is taken from the neap tide when the tidal prism (the driving force of entrainment) is small. It is anticipated that an entrainment velocity calculated for spring tide on 7 February would be significantly greater than that of 20 August. Given that the salinity *S* of the outflow is significantly greater on 7 February, this result can be expected from Section 5 (Equation 4). What is clear, however, is that either of these two competing salinity removal mechanisms may dominate.

Referring to the extrapolation of Largier (1986) into a five state scheme, this winter study has provided new information. The essential assumption of this extrapolation was that the sill at the mouth is not deepened. Given the deepening as observed in August 1986, states (iv) and (v) become one and the same only a few days after the tidal inflow stops and this probably occurs in most winter seasons. State (i) seems unlikely since summer river flow usually decreases asymptotically to between 0,5 and 1 m<sup>3</sup>.s<sup>-1</sup>. States (ii) and (iii) were observed in February 1985. States (iii), (iv) and (v) were observed in August 1986, but the saline layer mentioned in states (iii) and (iv) is only resident for a few tidal cycles owing to the deepened mouth sill.

A strong correlation exists between water circulation patterns and chemical features of the estuary during both the summer (February 1986) and winter (August 1986) field survey. Considering the marked changes in the physical water circulation patterns mentioned above, changes in the chemical characteristics of the system were also expected.

Blackwater rivers have certain chemical characteristics that differ from that of clear water rivers (Janzen, 1974). Due to large humic acid concentrations these waters are quite acidic. The dark colour of the water (due to high light absorbance of

humic acids) also limits light penetration. Tropical blackwater rivers are also known to have low nutrient concentrations. As a result of these characteristics blackwaters usually have low biological activity and low species diversity (Janzen, 1974; Por *et al.*, 1984).

During summer the chemical characteristics (Taljaard, 1987) of the water column mainly resemble that of the sea, showing a high salinity, a relatively high pH and dissolved nutrient concentrations typical of coastal waters. The only effect blackwater has on the water column is during neap tide/rainy conditions when a weak tidal prism and higher river flow allow for blackwater being pushed in over the shallow sand flat area, resulting in a drop in salinity and pH and a decrease in light availability. Dissolved nutrient levels are however not drastically affected, since the Palmiet River, in contrast to tropical blackwater systems, is not nutrient poor. Although the algae, *Chladophora* and the sand prawn, *Callianassa kraussi* are able to tolerate these sporadic blackwater influences, low species diversity confirms the observations made by Janzen (1974).

During winter a marked increase in river flow results in the water column chemical characteristics being dominated by fresh, blackwater. This long term exposure to blackwater characteristics results in a reduction in biological activity in that the algae, *Chladophora*, were observed to disappear from the system, while the numbers of the sand prawn, *Callianassa kraussi*, also decreased. Considering the relatively high nutrient levels measured in the Palmiet River at the time, nutrient limitations could not be responsible for the reduction in biological activity. It should rather be attributed to the drastic changes in salinity, pH and light permeability.

While the sediment-water interface is permanently subjected to saline, relatively higher pH conditions during summer, winter conditions change drastically. Typical spring tide conditions, result in the sediment-water interface being exposed to relatively high salinity and pH (high tide) as well as fresh, more acidic (low tide) conditions during a single tidal cycle. Although the sediment-water interface is usually considered as a

Although the sediment-water interface is usually considered as a biologically active environment, these continuous changes in chemical properties are probably one of the major reasons for the lack of sediment-water interface activity in the Palmett estuary.

## 7. SUMMARY AND CONCLUSIONS

Two basic situations occur in winter. Either the tidal rise in sea level is sufficiently rapid for saline water to enter the estuary on the flood tide or, alternatively, it is insufficient and it only serves to retard the freshwater outflow. The former was observed at the Palmet estuary during the spring phase (19 to 25 August) and the latter during the neap phase (prior to 19 and after 25 August). Discussion is focussed on the real estuarine case (that is, when sea-water enters the estuary).

On the flood tide the flow of sea-water over the shallow sill at the mouth contains the freshwater outflow and pushes it back to a position where the internal Froude number is unity (Section 4). At this plunge line the saline water is subducted below the surface estuarine water; forming a convergent tidal intrusion front which is marked by a surface foam line. Shear instabilities and the resultant turbulent mixing dilute the inflowing saline water. This diluted saline water propagates up the estuary as a bottom density current. On reaching the deeper pools near stations 4 and 5, the new saline water replenishes or replaces the older resident saline water. The surface slope and the depth-integrated tide turn before the interfacial slope flattens and the density intrusion stops. During the subsequent ebb phase the fast-flowing turbulent surface layer entrains this residual saline water. The nature and rate of entrainment is a function of position in the estuary and time (Section 4). The possibility of this deep saline water surviving the extended ebb-tide (about 9 hours) until the subsequent flood tide is dependent on the flow rates and the volume of the saline layer. Calculation of flushing times  $T_f$ , provide an indication of the persistence of this saline water and its contents (e.g. biota, nutrients, pollutants). Some of the estuarine effluent, which forms a buoyant plume in the coastal water, may be returned on the subsequent flood tide. The presence of significant long-shore currents (e.g. 20 August), which are common off the south coast, prevent or reduce this effect.

Nutrient distribution patterns are strongly correlated with physical water circulation, in that the nutrient characteristics of the estuary are similar to those of the water source at the time, that is, the sea or the river. Unlike tropical blackwater systems the river water was not nutrient poor. Strong blackwater influences on the other chemical properties of the estuary, that is, low salinity, low pH and low light permeability, were probably the causes of drastic reductions in biological productivity. Since the algae, *Chladophora*, accumulates in the estuary during summer, this reduction in productivity actually acts as a "cleansing mechanism" for the system in that it is a natural process for controlling the excess algal growth. In a recreational area such as the Palmiet estuary this process is of the utmost importance. Consequently, unless water releases from the upstream dams are controlled, through proper management, serious environmental problems could develop in the estuary.

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TABLE 1: BULK RICHARDSON NUMBERS : (STATION 4, 20 AUGUST 1986)

Time	Tide phase	Richardson Number
08h45	Ebb	3,0
10h00	Ebb	2,3
11h10	Ebb	3,9
13h50	Late ebb	14,6
14h45	Intrusion	1,8
15h45	Local high	8,7
17h30	Ebb	2,9
18h00	Ebb	2,7
18,50	Ebb	2,7

TABLE 2: TIDE TABLES FOR THE DAYS ON WHICH SAMPLING WAS DONE

Days	August 1986							
	High tide				Low tide			
	hrs	min.	hrs	min.	hrs	min.	hrs	min.
20	3	35	15	56	9	40	22	04
21	4	12	16	32	10	12	22	40
27	7	42	20	13	1	41	13	32
28	9	21	22	11	2	57	15	53

TABLE 3: MEAN VALUES ( $\bar{x}$ ) AND RANGES FOR pH, DO AND DISSOLVED NUTRIENTS MEASURED ON THE SAND FLAT AND IN SEA- AND RIVER WATER ON 20 AUGUST (SPRING TIDE) AND 27 AUGUST (NEAP TIDE)

Tide	pH		DO (mg.l <sup>-1</sup> )		PO <sub>4</sub> (μmol P.l <sup>-1</sup> )		NO <sub>3</sub> (μmol N.l <sup>-1</sup> )		NO <sub>2</sub> (μmol N.l <sup>-1</sup> )		NH <sub>3</sub> (μmol N.l <sup>-1</sup> )		DON (μmol N.l <sup>-1</sup> )		DOC (μmol C.l <sup>-1</sup> )	
	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range
6 : Spring	6	6,8 6,5-7,4	6	10,2 9,6-10,7	6	0,49 0,38-0,67	6	78,2 60,1-117,4	6	2,6 0,8-8,6	6	1,1 0,9-1,1	4	11,0 6,2-16,9	6	570 380-670
: Neap	10	6,2 5,7-7,0	10	9,8 8,6-10,5	10	1,05 0,88-1,48	10	50,0 22,3-112,6	10	0,6 0,5-1,2	9	1,9 1,2-2,4	4	13,4 7,5-18,2	9	950 750-1 030
7 : Spring	6	6,7 6,6-7,0	6	10,5 10,3-10,8	6	0,51 0,40-0,63	6	76,1 60,6-105,6	6	1,5 0,4-3,2	6	1,5 0,9-2,3	6	8,3 4,3-15,2	6	640 540-710
: Neap	10	5,9 5,6-6,4	10	10,0 8,6-10,5	10	0,96 0,92-1,04	10	42,3 22,3-77,7	10	0,5 0,5-0,6	10	1,8 1,4-2,3	6	15,1 6,9-24,8	10	1060 790-1 750
8 : Spring	6	6,7 6,6-6,8	6	10,7 10,5-10,9	6	0,59 0,40-0,75	6	72,6 60,4-93,8	6	1,2 0,4-2,0	6	1,1 1,0-1,3	4	19,6 6,0-46,3	6	600 500-830
: Neap	10	5,8 5,5-6,2	10	10,3 9,5-11,3	10	0,94 0,92-1,13	10	40,4 22,4-77,9	10	0,5 0,4-0,5	10	1,8 1,4-2,4	6	16,4 10,8-23,5	8	950 750-1 350
9 : Spring	6	6,7 6,6-6,8	6	10,4 10,1-10,9	6	0,59 0,40-0,92	6	76,3 52,3-87,2	6	0,8 0,5-1,3	6	1,2 0,9-1,6	4	20,5 9,7-37,7	6	590 460-670
: Neap	10	5,8 5,5-6,2	10	10,3 9,9-10,7	10	1,00 0,68-1,29	10	42,7 22,3-64,4	10	0,5 0,5-0,6	10	1,7 1,3-2,1	3	12,6 8,0-15,4	9	980 720-1 710
Sea :																
Spring	8,1		8,5		0,63		13,4		19,4		2,5		13,4		170	
Neap	8,1		7,4		0,98		31,6		58,6		2,1		18,8		160	
River :																
Spring	6,7		11,0		0,61		87,4		0,4		1,5		26,4		730	
Neap	6,1		10,4		0,86		49,5		0,5		1,5		39,9		870	

TABLE 4: MEAN VALUES ( $\bar{x}$ ) AND RANGES FOR pH, DO AND DISSOLVED NUTRIENTS MEASURED IN THE CHANNEL OVER THE SPRING TIDAL CYCLE (21 AUGUST)

Station	pH		DO (mg.l <sup>-1</sup> )		PO <sub>4</sub> (μmol P.l <sup>-1</sup> )		NO <sub>3</sub> (μmol N.l <sup>-1</sup> )		NO <sub>2</sub> (μmol N.l <sup>-1</sup> )		NH <sub>3</sub> (μmol N.l <sup>-1</sup> )		DON (μmol N.l <sup>-1</sup> )		DOC (μmol C.l <sup>-1</sup> )	
	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range
1 : Surface	10	6,7 6,7-6,8	10	10,6 10,1-11,1	10	0,61 0,47-0,75	10	98,9 67,5-204,9	9	2,5 0,4-9,1	10	1,4 0,8-3,0	4	27,4 12,8-50,4	10	600 400-830
: Bottom	9	7,5 6,7-8,0	10	10,0 9,4-10,5	10	0,62 0,38-1,21	10	58,4 27,2-81,7	10	23,6 0,3-56,6	10	1,3 0,9-1,9	10	11,1 2,0-15,8	10	300 90-570
2 : Surface	10	6,8 6,7-6,9	10	10,6 10,4-11,0	9	0,52 0,40-0,73	9	97,8 56,6-116,1	9	2,7 0,9-7,5	10	1,0 0,9-1,5	5	16,8 14,0-23,2	10	530 310-880
: Bottom	10	7,3 6,8-8,0	10	10,3 9,9-10,8	10	0,71 0,42-1,46	7	58,2 21,2-86,1	8	18,2 1,6-59,0	10	1,2 0,9-2,0	8	12,7 4,2-23,9	10	400 160-610
3 : Surface	10	6,8 6,7-6,9	8	10,5 9,9-11,0	10	0,50 0,40-0,58	10	72,8 55,5-93,7	10	2,8 0,6-8,1	10	1,4 0,7-2,9	5	23,3 14,8-39,9	10	630 440-830
: Bottom	10	7,5 6,9-8,1	10	10,1 9,4-10,7	10	0,66 0,27-0,92	10	67,7 41,6-135,1	10	22,7 0,9-93,7	10	1,4 1,0-1,9	10	13,7 4,3-20,0	10	340 160-610
4 : Surface	10	6,8 6,7-6,9	10	10,7 10,5-10,9	9	0,56 0,36-1,04	10	86,4 56,6-167,5	9	2,7 0,6-7,6	9	1,3 0,8-1,6	4	20,4 17,7-23,4	9	640 420-1 130
: Bottom	9	7,9 7,7-8,0	10	8,4 7,7-8,8	10	0,75 0,58-0,96	10	34,6 12,3-83,4	10	56,8 36,2-89,5	10	2,4 1,1-3,4	10	11,8 3,5-18,5	10	190 180-310
5 : Surface	10	6,7 6,6-6,9	10	10,9 10,8-11,2	9	0,57 0,40-0,92	9	90,0 67,5-148,0	10	0,7 0,3-1,7	10	1,3 1,0-2,0	6	28,9 17,5-38,0	10	720 530-950
: Bottom	10	7,6 6,7-8,0	7	9,7 8,9-10,9	10	0,69 0,52-0,88	8	44,2 13,4-86,4	9	34,4 1,3-72,4	10	1,3 0,8-2,1	9	9,7 2,1-18,6	9	350 160-750

TABLE 5: MEAN VALUES ( $\bar{x}$ ) AND RANGES FOR pH, DO AND DISSOLVED NUTRIENTS MEASURED IN THE CHANNEL OVER THE NEAP TIDAL CYCLE (28 AUGUST)

Station	pH		DO (mg.l <sup>-1</sup> )		PO <sub>4</sub> (μmol P.l <sup>-1</sup> )		NO <sub>3</sub> (μmol N.l <sup>-1</sup> )		NO <sub>2</sub> (μmol N.l <sup>-1</sup> )		NH <sub>3</sub> (μmol N.l <sup>-1</sup> )		DON (μmol N.l <sup>-1</sup> )		DOC (μmol C.l <sup>-1</sup> )	
	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range	n	Range
1 : Surface	8	6,5 6,4-6,5	8	10,4 10,3-10,6	8	1,17 0,68-2,65	8	69,7 46,8-140,9	8	0,6 0,3-0,9	8	1,6 1,3-2,2	4	29,0 18,4-35,9	8	870 770-1 170
: Bottom	8	6,5 6,3-6,6	8	10,5 10,4-10,6	8	1,09 0,68-1,39	7	59,1 45,0-81,1	8	0,9 0,2-2,0	8	1,4 1,1-1,7	4	21,4 16,6-27,9	8	970 750-1 580
2 : Surface	8	6,5 6,4-6,5	8	10,5 10,3-10,6	8	1,23 0,84-2,58	8	62,6 35,1-86,1	8	0,8 0,5-1,8	8	1,5 1,0-2,5	3	29,1 23,7-34,3	8	960 770-1 580
: Bottom	8	6,5 6,4-6,6	8	10,5 10,3-10,7	7	1,06 0,65-1,42	8	65,3 52,8-109,4	8	0,7 0,5-1,2	8	1,4 1,1-1,5	4	29,2 26,5-33,7	8	870 750-1 310
3 : Surface	8	6,5 6,4-6,5	8	10,5 10,3-10,6	8	1,21 0,65-1,74	8	51,4 38,8-68,6	8	0,6 0,4-1,0	8	1,6 1,1-2,3	2	38,2 28,9-47,5	8	880 770-990
: Bottom	8	6,4 6,2-6,5	8	10,5 10,4-10,6	8	1,22 0,66-2,74	8	58,0 48,6-68,5	8	0,6 0,3-0,9	8	1,4 1,1-1,9	2	34,1 21,1-47,1	8	870 770-1 080
4 : Surface	8	6,5 6,4-6,5	7	10,4 10,1-10,7	7	1,03 0,68-1,39	8	71,4 42,3-102,8	8	0,6 0,3-1,3	8	1,4 1,1-1,8	3	23,8 15,7-28,8	8	860 750-950
: Bottom	8	6,5 6,4-6,5	8	10,5 10,3-10,6	7	1,09 0,68-1,48	7	81,0 44,9-122,9	8	0,5 0,3-0,8	8	1,5 1,0-2,1	3	28,5 18,4-36,9	8	950 680-1 310
5 : Surface	8	6,5 6,4-6,5	8	10,5 10,3-10,6	8	1,08 0,65-1,48	8	54,9 46,5-61,5	8	0,7 0,5-1,3	8	1,5 1,2-1,7	4	35,1 21,4-49,9	8	930 810-1 200
: Bottom	8	6,5 6,5	8	10,5 10,4-10,6	8	1,10 0,77-2,26	6	57,6 47,7-79,7	8	0,6 0,1-1,2	8	1,2 1,0-2,1	4	22,9 17,6-30,9	8	850 640-1 080

**TABLE 6: pH, DO AND DISSOLVED NUTRIENT LEVELS MEASURED IN THE SEA AND RIVER ON 21 AUGUST (SPRING TIDE) AND 28 AUGUST (NEAP TIDE)**

Tide	pH	DO mg.l <sup>-1</sup>	PO <sub>4</sub> μmol P.l <sup>-1</sup>	NO <sub>3</sub> μmol N.l <sup>-1</sup>	NO <sub>2</sub> μmol N.l <sup>-1</sup>	NH <sub>3</sub> μmol N.l <sup>-1</sup>	DON μmol N.l <sup>-1</sup>	DOC μmol C.l <sup>-1</sup>
Spring Sea	8,1	8,1	0,79	13,4	45,7	2,9	10,3	140
River	6,8	10,7	0,61	67,9	0,8	1,1	26,4	730
Neap Sea	8,1	8,6	1,16	27,8	56,0	1,6	17,4	130
River	6,5	10,4	1,01	52,2	0,8	1,1	39,9	980

**TABLE 7: INTERSTITIAL NUTRIENT MEASUREMENTS**

Station No.	Depth (m)	PO <sub>4</sub> μmol P.l <sup>-1</sup>	NO <sub>3</sub> μmol N.l <sup>-1</sup>	NO <sub>2</sub> μmol N.l <sup>-1</sup>	NH <sub>3</sub> μmol N.l <sup>-1</sup>	TOM %
1	0,0-0,1	111	86	4,4	161	0,2
	0,1-0,2	98	66	3,7	109	0,1
	0,2-0,3	86	80	4,1	70	0,2
2	0,0-0,1	80	71	3,1	70	0,1
	0,1-0,2	64	82	4,1	52	0,1
	0,2-0,3	96	74	3,2	83	0,1
3	0,0-0,1	45	103	5,3	92	0,1
	0,1-0,2	60	75	3,3	104	0,2
	0,2-0,3	46	59	3,1	84	0,1
4	0,0-0,1	22	90	5,0	68	0,1
	0,1-0,2	28	189	8,2	78	0,1
	0,2-0,3	35	154	6,2	85	0,1
5	0,0-0,1	68	181	9,9	454	0,1
	0,1-0,2	60	269	14,8	448	
	0,2-0,3	72	934	8,1	414	
6	0,0-0,1	42	86	7,3	288	0,3
	0,1-0,2	26	77	4,8	171	0,4
	0,2-0,3	19	51	5,2	174	0,4
7	0,0-0,1	51	187	4,4	131	0,3
	0,1-0,2	38	92	7,6	176	0,4
	0,2-0,3	49	213	7,8	140	0,4
8	0,0-0,1	74	107	14,1	121	0,4
	0,1-0,2	24	79	4,2	155	0,4
	0,2-0,3	15	85	4,6	79	0,4
9	0,0-0,1	100	123	6,0	346	0,3
	0,1-0,2	36	89	5,8	117	0,4
	0,2-0,3	29	58	8,2	141	0,3

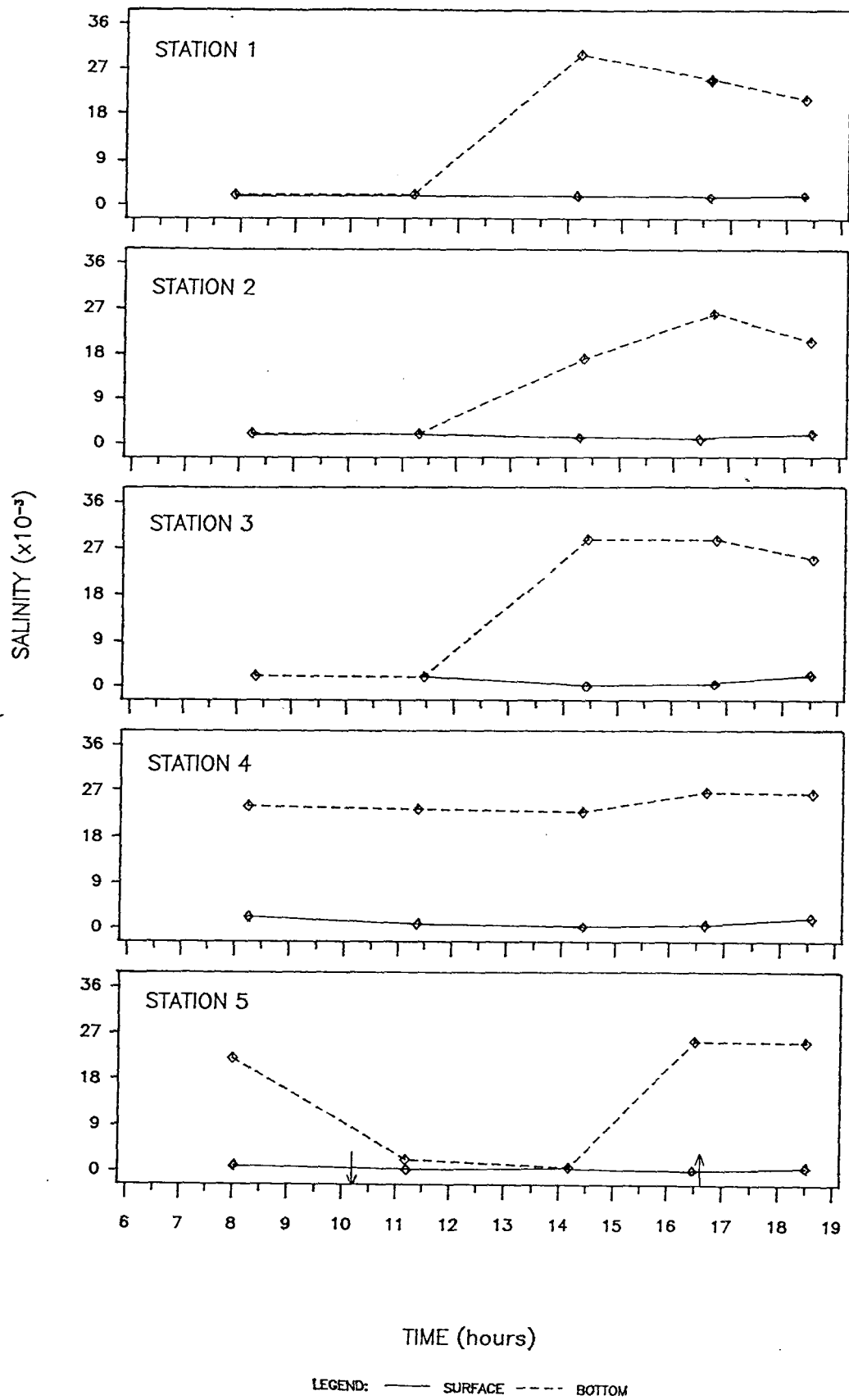


Figure 9 Salinity changes over a spring tidal cycle in surface and bottom water measured at stations 1-5 ( $\uparrow$ = high tide;  $\downarrow$ = low tide).

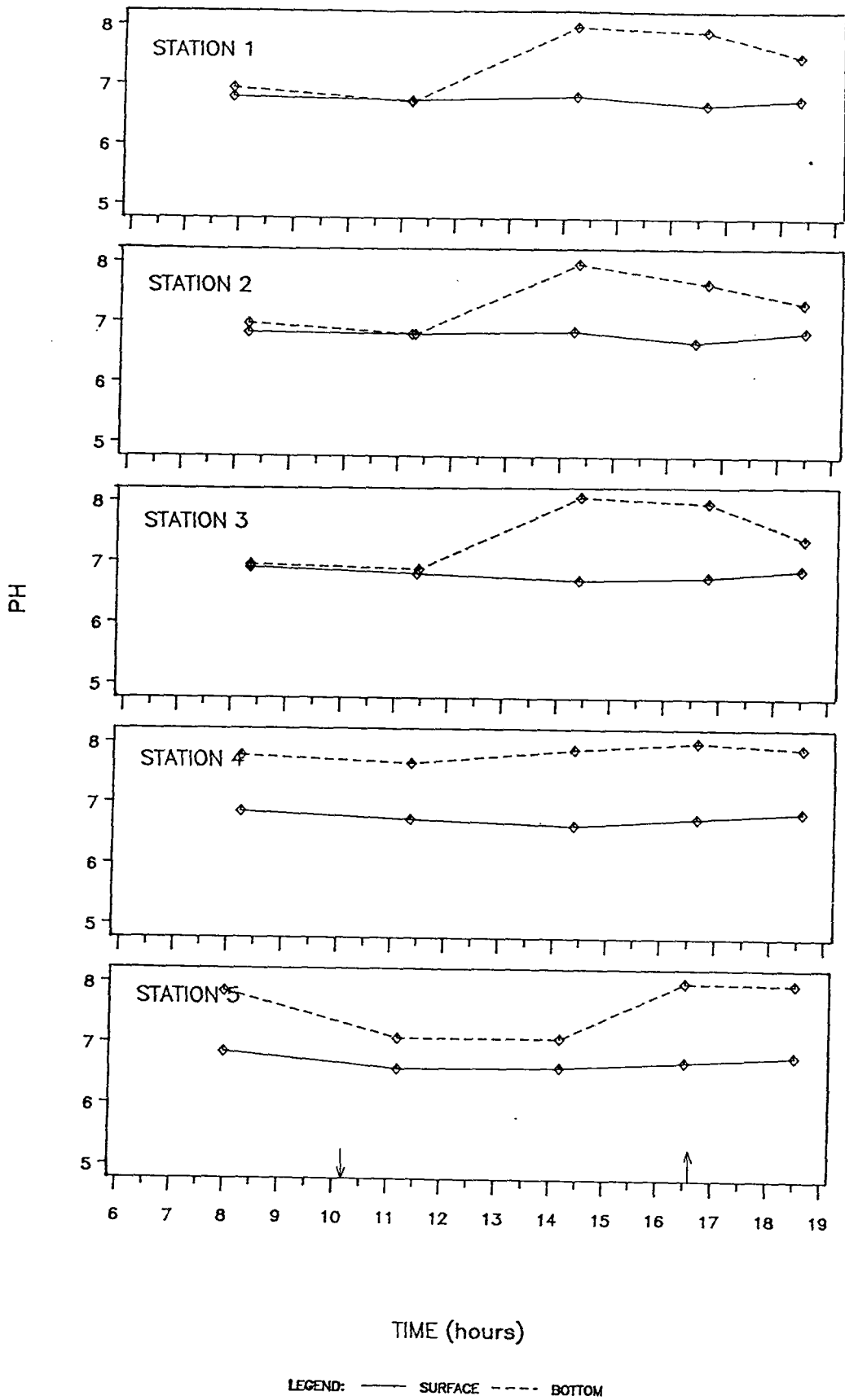


Figure 10 pH changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

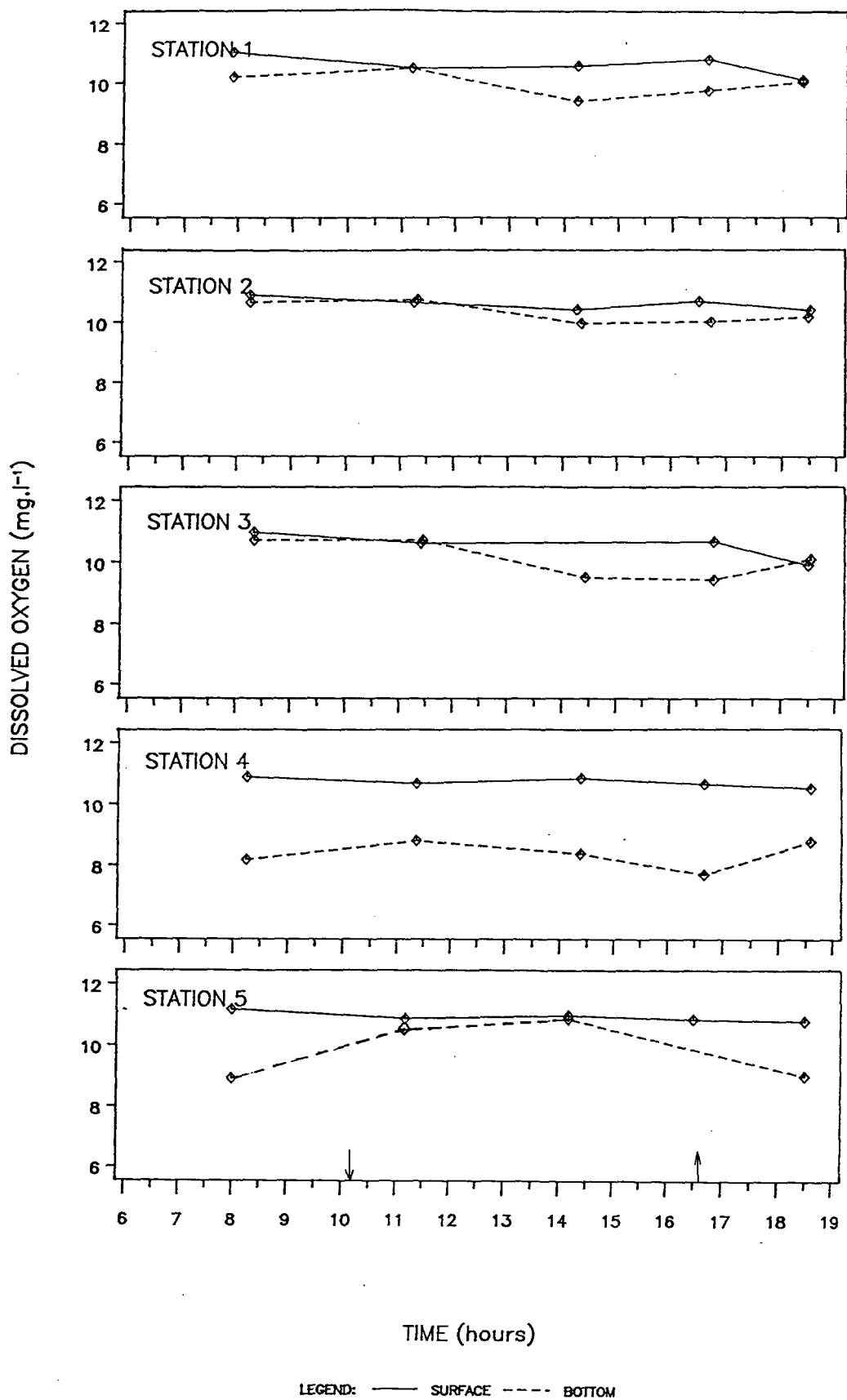


Figure 11 Dissolved oxygen changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

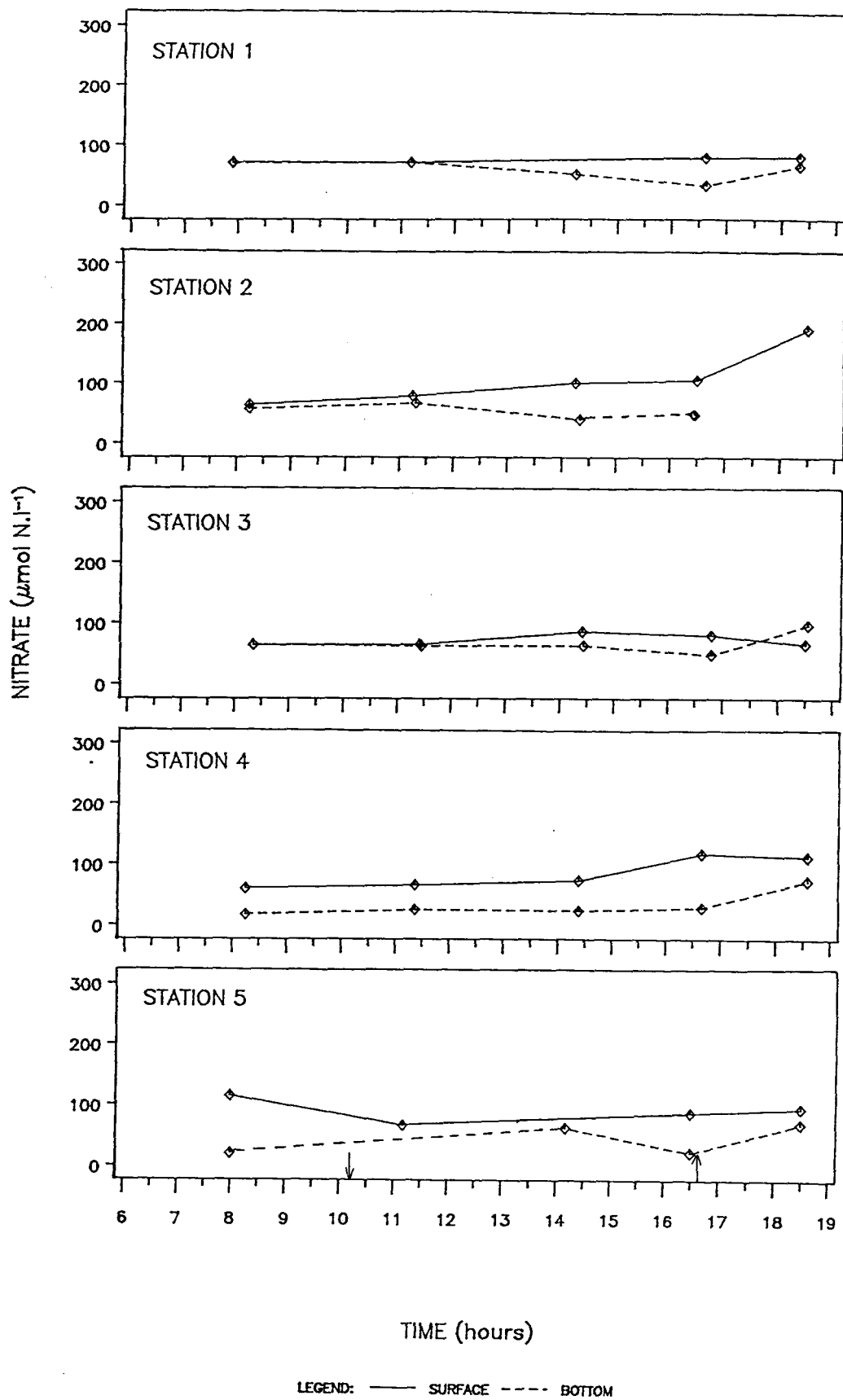


Figure 12 Dissolved nitrate changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

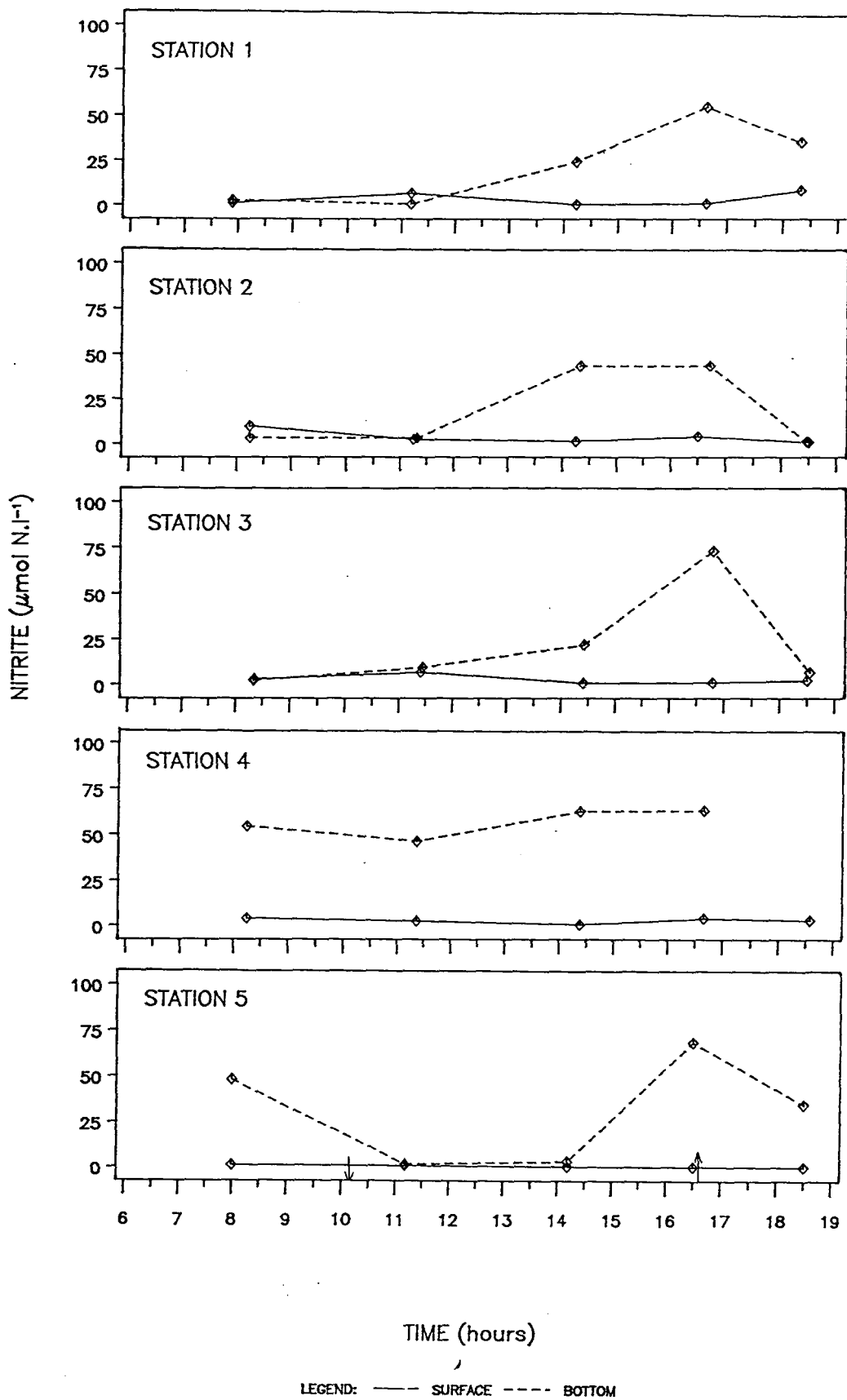


Figure 13 Dissolved nitrite changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5 ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

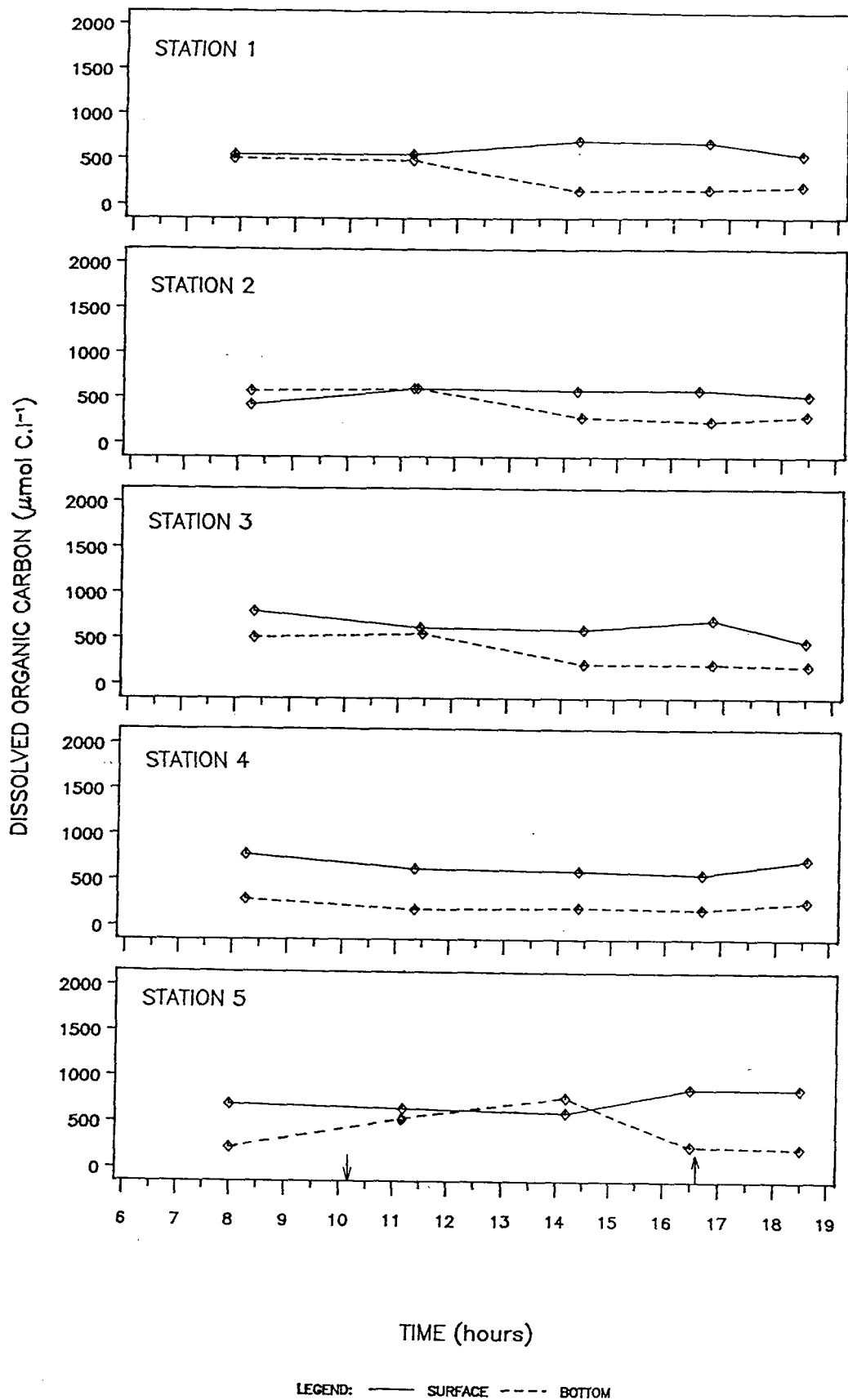


Figure 14 Dissolved organic carbon changes over a spring tidal cycle in the surface and bottom water measured at stations 1-5. ( $\uparrow$  = high tide;  $\downarrow$  = low tide).

LIST OF ABBREVIATIONS

(/1 and /2 denote the duplicate values)

D

DO dissolved oxygen ( $\text{mg.l}^{-1}$ )  
DOC dissolved organic carbon ( $\mu\text{mol C.l}^{-1}$ )  
DON dissolved organic nitrogen ( $\mu\text{mol N.l}^{-1}$ )

N

NH3 ammonia ( $\mu\text{mol N.l}^{-1}$ )  
NO2 nitrite ( $\mu\text{mol N.l}^{-1}$ )  
NO3 nitrate ( $\mu\text{mol N.l}^{-1}$ )  
NP neap tide

P

PH pH  
PO4 phosphate ( $\mu\text{mol P.l}^{-1}$ )  
POM suspended particulate organic matter ( $\text{mg.l}^{-1}$ )  
%POM percentage suspended particulate organic matter

S

SAL salinity ( $\times 10^{-3}$ )  
SP spring tide

T

TEMP temperature ( $^{\circ}\text{C}$ )  
TIME time (hours)

PALMIET WINTER DATA  
 SPRING AND NEAP RIVER DATA

	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
SP(20/8)	0.00	13.90	6.65	6.65	11.07	11.05		0.61		87.38		0.39	1.52	1.46
SP(21/8)	0.00	13.90	6.80	6.80	10.72	10.70	0.56	0.66	68.15	67.71	0.54	0.98	0.89	1.37
NP(27/8)	0.00	14.00	6.10	6.10	10.31	10.47	0.83	0.88		49.54	0.44	0.46	1.30	1.62
NP(28/8)	0.00	14.00	6.50	6.50	10.38	10.33	1.03	1.00	51.36	53.09	0.86	0.76	1.12	1.12

	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	%POM/1	%POM/2
SP(20/8)	24.33	28.54	833.00	625.00	1.00	2.00	29.41	58.82
SP(21/8)	26.40		714.00	754.00	1.40	1.40	46.67	46.67
NP(27/8)	39.90		873.00		1.00	1.40	100.00	100.00
NP(28/8)	36.93	42.78	983.00	983.00	1.40	1.80	40.70	64.29

PALMIET WINTER DATA  
 SPRING AND NEAP SEA DATA

	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
SP(20/8)	35.00	16.50	8.10	8.10	8.52	8.48		0.63				19.43	2.52	
SP(21/8)	35.00	15.00	8.10	8.10	8.09	8.06		0.79	16.57	10.32	63.56	27.84	3.21	2.62
NP(27/8)	35.00	16.50	8.05	8.05	7.45	7.37	1.00	0.94	43.89	19.33	61.47	55.67	1.82	2.47
NP(28/8)	35.00	16.50	8.10	8.10	8.56	8.61	1.03	1.29	27.83		43.97	68.02	1.65	1.65

	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	%POM/1	%POM/2
SP(20/8)	17.48	9.29	167.00	167.00	1.80	2.00	100.00	100.00
SP(21/8)	15.08	5.43	200.00	80.00	1.60	2.00	80.00	66.67
NP(27/8)	21.59	16.07	135.00	180.00	4.20	4.00	58.33	51.28
NP(28/8)	18.59	16.15	86.00	171.00	4.40	6.80	36.67	55.74

PALMIET WINTER DATA  
 STATION 1 SPRING SURFACE DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.54	2.40	13.90	6.75	6.80	10.98	11.05	0.69	0.75	74.67	67.61	1.65	1.08	2.99	1.11
11.11	2.00	14.30	6.70	6.75	10.52	10.49	0.65	0.50	71.06	71.58	9.07	4.74	0.82	1.24
14.14	1.60	15.00	6.80	6.80	10.55	10.62	0.75	0.60			0.80	0.41	1.06	0.89
16.38	1.60	15.60	6.65	6.65	10.84	10.80	0.63	0.54	67.48	90.39	1.21	1.19	1.55	2.80
18.20	1.90	15.50	6.75	6.75	10.13	10.22	0.56	0.47	85.45	76.73	2.32		1.01	1.01

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	%POM/1	%POM/2
7.54	50.42	12.79	458.00	625.00	1.60	1.60	47.06	47.06
11.11			614.00	483.00	1.20	1.60	35.29	50.00
14.14			833.00	570.00	1.20	1.00	40.00	38.46
16.38	21.10	25.14	833.00	516.00	1.40	1.00	50.00	38.46
18.20			675.00	400.00	1.80	2.20	64.29	57.89

## PALMIET WINTER DATA

## STATION 2 SPRING SURFACE DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.15	3.00	13.70	6.80	6.85	10.88	10.96	0.44		56.58	68.85		7.47	0.88	1.11
11.15	1.90	14.10	6.80	6.80	10.63	10.70	0.46	0.54	65.06	90.73	3.63	0.85	0.94	1.48
14.15	1.00	15.20	6.85	6.85	10.45	10.41	0.54	0.73	109.53	89.98	1.13	1.60	1.36	1.24
16.30	1.00	15.20	6.65	6.70	10.71	10.71	0.40	0.47	93.51	116.13	5.70	2.16	0.89	0.89
18.30	2.10	15.00	6.85	6.85	10.46	10.40	0.51	0.56	189.95		0.85	0.52	0.77	0.71

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.15	13.96	14.80	375.00	458.00	2.40	1.60	57.14	44.44
11.15	17.35	23.15	877.00	307.00	1.40	1.80	38.89	47.37
14.15			570.00	570.00	1.20	1.00	40.00	29.41
16.30		14.83	600.00	556.00	1.00	1.40	29.41	35.00
18.30			516.00	516.00		1.20		35.29

## PALMIET WINTER DATA

## STATION 3 SPRING SURFACE DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.21	2.10	13.80	6.90	6.90	10.94	11.00	0.50	0.54	72.09	55.54	4.23	1.70	1.00	2.87
11.25	1.70	14.10	6.80	6.80	10.64	10.60	0.46	0.40	67.09	64.36	5.41	8.14	0.89	0.94
14.25	0.00	15.00	6.70	6.70			0.58	0.46	90.94	83.02	0.64	0.93	2.56	2.02
16.48	0.25	15.40	6.75	6.75	10.74	10.61	0.46	0.54	93.65	68.20	1.75	0.49	1.01	1.01
18.30	2.00	15.00	6.90	6.85	9.85	9.98	0.56	0.49	66.47	66.32	2.22	2.37	0.71	0.71

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.21	19.70	25.29	750.00	833.00	2.00	1.60	50.00	47.06
11.25			614.00	614.00	1.80	1.60	36.00	44.44
14.25	39.88	16.76	526.00	658.00	1.40	0.80	38.89	30.77
16.48		14.76	714.00	675.00	1.20	1.60	37.50	47.06
18.30			476.00	437.00	1.40		43.75	

## PALMIET WINTER DATA

## STATION 4 SPRING SURFACE DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.15	2.20	13.20	6.8	6.90	10.92	10.86	0.71	1.04	56.58	64.62		4.07	1.58	1.29
11.22	1.00	14.00	6.70	6.75	10.71	10.66		0.46	69.25	63.01	3.25	1.86	1.36	1.30
14.23	0.00	14.80	6.65	6.60	10.85	10.85	0.50	0.65	79.51	68.07	0.62	0.62	1.31	
16.40	0.50	14.90	6.75	6.75	10.68	10.66	0.36	0.37	83.95	152.12	7.63	0.52	1.07	1.49
18.35	1.80	13.80	6.90	6.80	10.62	10.45	0.49	0.46	167.54	59.10	0.36	5.77	1.13	0.83

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.15	19.70	17.72	417.00	1125.00	1.80	1.80	60.00	47.37
11.22		23.39	526.00	702.00	1.00	1.40	29.41	46.67
14.23			570.00	614.00	1.20	0.80	40.00	25.00
16.40	20.64		476.00	635.00	1.40	1.00	46.67	29.41
18.35			714.00		1.40	1.40	43.75	46.67

## PALMIET WINTER DATA

## STATION 5 SPRING SURFACE DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.00	1.00	13.20	6.90	6.80	11.20	11.15	0.54	0.92	148.02	82.22	0.80	1.73	1.29	1.99
11.11	0.00	15.00	6.55	6.60	10.88	10.89	0.46	0.40	68.17	67.50	0.52	1.19	1.48	1.36
14.11	0.00	15.00	6.60	6.60	10.95	11.01	0.73		79.51		0.62	0.34	1.31	1.07
16.30	0.00	14.90	6.70	6.70	10.92	10.80	0.45	0.28	106.46	68.17	0.39	0.52	1.31	1.01
18.30	0.80	13.90	6.90	6.70	10.82	10.79	0.71	0.63	114.22	76.04	0.26	0.28	1.19	1.31

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
8.00	27.21	32.71	583.00	791.00	1.60	1.60	61.54	47.06
11.11			644.00	658.00	1.20		35.26	
14.11		17.47	526.00	658.00	1.20	1.40	40.00	50.00
16.30	28.55		754.00	952.00	1.00	1.20	35.71	42.86
18.30	29.54	37.96	913.00	794.00	1.40	1.60	50.00	53.33

## PALMIET WINTER DATA

## STATION 6 SPRING SURFACE DATA (20/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
14.07	0.50	17.00	7.40	7.20	10.71	10.66	0.67	0.52	117.39	89.54	0.90	2.04	1.11	1.11
16.17	0.50	15.00	6.50	6.55	10.42	10.45	0.38	0.46	60.12	60.28	0.93	0.77	1.05	1.05
18.15	1.00	15.10	6.60	6.60	9.63	9.59	0.40	0.53	62.45	79.16	2.42	8.61	1.11	0.88

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
14.07	10.84	16.94	542.00	666.00	1.20	2.20	40.00	55.00
16.17			542.00	666.00	2.20	1.40	55.00	50.00
18.15	6.21	10.12	375.00	625.00	1.60	1.20	44.44	42.86

## PALMIET WINTER DATA

## STATION 7 SPRING SURFACE DATA (20/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
14.03	1.00	15.00	7.00	6.75	10.78	10.75	0.46	0.54	65.52	94.06	3.17	1.34	2.28	1.17
16.12	1.00	14.00	6.60	6.60	10.27	10.36	0.50	0.50	60.64	105.56	0.41	1.29	2.34	0.88
18.12	1.50	14.50	6.70	6.70	10.32	10.36	0.63	0.40	64.00	66.94	0.88	1.75	1.00	1.00

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
14.03	10.35	15.24	708.00	583.00	1.20	2.00	40.00	55.56
16.12	4.34	9.39	750.00	625.00	2.20	1.20	73.33	40.00
18.12	4.54	5.85	542.00	625.00	1.00	2.40	45.45	75.00

## PALMIET WINTER DATA

## STATION 8 SPRING SURFACE DATA (20/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
13.43	0.50	16.50	6.70	6.75	10.79	10.88	0.75	0.67	90.55	60.61	1.03	0.44	1.11	1.00
16.03	1.00	16.00	6.60	6.65	10.72	10.78	0.65	0.48	93.78	60.38	1.62	0.67	1.11	1.11
18.18	1.50	15.00	6.65	6.65	10.49	10.45	0.58	0.40	66.73	63.43	1.96	1.44	1.00	1.29

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
13.43	9.69	5.98	625.00	833.00	2.00	2.00	45.45	55.56
16.03			542.00	500.00	1.80	1.40	50.00	43.75
18.18	16.56	46.27	583.00	500.00	1.60	1.40	44.44	50.00

## PALMIET WINTER DATA

## STATION 9 SPRING SURFACE DATA (20/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
13.51	0.50	15.00	6.75	6.80	10.88	10.83	0.58	0.56	52.34	83.49	1.08	0.46	1.64	0.94
15.53	1.00	15.00	6.60	6.70	10.14	10.19	0.40	0.50	75.86	87.20	0.46	0.57	0.88	1.52
18.21	1.60	14.00	6.70	6.80	10.23	10.31	0.92			82.66	0.98	1.29	1.23	1.05

TIME	DDN/1	DDN/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
13.51	23.16	37.73	625.00	625.00	1.80	2.20	47.37	45.38
15.53			666.00	625.00	1.80	1.40	52.94	41.18
18.21	11.48	9.71	542.00	458.00	1.60	1.60	38.10	57.14

## PALMIET WINTER DATA

## STATION 1 SPRING BOTTOM DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.54	2.00	13.80	6.90	6.95	10.20	10.20	0.75	0.79	57.26	81.68	3.79	2.27	1.93	1.17
11.11	2.00	14.10	6.70		10.52	10.47	0.42	0.44	67.25	76.04	1.44	0.28	1.42	1.18
14.14	25.00	16.30	7.95	8.00	9.45	9.41	1.21	0.83	68.07	35.87	12.06	36.63	1.43	1.01
16.38	25.00	16.10	7.80	8.00	9.72	9.85	0.38	0.55	27.24	38.80	52.89	56.60	1.13	1.13
18.20	21.00	16.20	7.40	7.55	10.00	10.19	0.42	0.38	58.52	73.22	36.88	33.63	0.89	1.73

TIME	DDN/1	DDN/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.54	14.66	17.12	500.00	500.00	1.80	2.00	56.25	52.63
11.11	11.64	15.78	570.00	395.00	2.00	1.80	55.56	52.94
14.14	10.86	8.68	88.00	219.00	1.80	2.20	56.25	52.38
16.38	17.41	8.63	119.00	198.00	2.40	2.60	50.00	59.09
18.20	2.04	4.20	159.00	238.00	2.00	2.20	38.46	45.83

## PALMIET WINTER DATA

## STATION 2 SPRING BOTTOM DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.15	2.00	13.70	7.00	6.95	10.69	10.67	0.58	0.67	52.24	59.45	5.00	1.60	1.95	0.94
11.19	1.90	14.10	6.75	6.85	10.79	10.75	0.42	0.75	67.09	64.26	1.60	4.43	0.94	0.94
14.20	17.00	15.90	8.00	7.95	10.01	9.94	0.63	0.67	21.18	57.04	58.95	26.91	1.55	1.67
16.43	26.00	16.20	7.65	7.65	10.06	10.02	0.64	0.44		42.00	43.00		0.95	1.07
18.28	20.50	16.00	7.35	7.30	10.20	10.21	1.46	0.81					0.77	1.31

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.15	23.90	22.23	526.00	614.00	2.00	1.60	50.00	42.11
11.19			614.00	570.00	1.40	1.40	41.18	46.67
14.20	11.23	11.74	238.00	318.00	2.60	2.80	48.15	46.67
16.43	9.78	8.93	318.00	159.00	2.20	2.80	42.31	50.00
18.28	4.16	9.47	318.00	278.00	1.80	1.80	37.50	42.86

## PALMIET WINTER DATA

## STATION 3 SPRING BOTTOM DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.21	2.00	14.10	6.95	6.95	10.72	10.71	0.75	0.63	65.08	63.99	3.61	0.88	1.42	1.77
11.27	1.75	14.10	6.85	6.90	10.72	10.73	0.81	0.58	60.75	65.13	7.94	11.19	1.00	1.36
14.26	28.80	16.00	8.10	8.05	9.52	9.50	0.71	0.92	41.67	85.97	23.20	20.88	1.61	1.55
16.48	28.70	16.10	7.95	8.00	9.42	9.46	0.69	0.54	46.79	51.30	52.43	93.71	1.19	1.90
18.33	20.00	16.40	7.30	7.45	10.11	10.13	0.69	0.27	135.05	61.68	2.32	10.82	1.37	1.19

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.21	20.04	17.50	526.00	483.00	1.80		50.00	
11.27	14.91	18.31	614.00	483.00	1.60	2.20	47.06	55.00
14.26	8.80	4.30	278.00	159.00	1.60	2.40	53.33	63.16
16.48	15.15	15.90	159.00	278.00	2.40		52.17	
18.33	11.07	11.18	159.00	238.00	1.60	2.00	36.36	47.62

## PALMIET WINTER DATA

## STATION 4 SPRING BOTTOM DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.15	24.10	14.90	7.75	7.80	8.15	8.22	0.67	0.67	21.26	14.25	43.61	65.88	3.42	2.48
11.22	23.50	14.80	7.65		8.80	8.82	0.63	0.71	25.52	26.71	50.80	41.98	3.07	3.01
14.23	23.00	14.50	7.85	7.90	8.39	8.37	0.87	0.71	32.50	17.31	36.19	89.54	2.56	1.43
16.40	26.80	16.00	8.00	8.00	7.67	7.72	0.96	0.88	12.34	47.99	48.71	77.94	1.96	1.73
18.35	26.50	15.30	7.90	7.90	8.79	8.78	0.58	0.77	83.44	64.36			1.13	2.80

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.15	12.68	18.01	307.00	263.00	2.00	2.00	62.50	62.50
11.22	15.67	16.73	175.00	175.00	1.40	1.60	53.85	53.33
14.23	3.54	8.13	198.00	198.00	1.40	1.60	87.50	88.89
16.40	18.53	11.20	198.00	159.00		1.80		100.00
18.35	7.07	6.27	238.00	278.00	1.60	1.60	34.12	100.00

## PALMIET PALMIET WINTER DATA

## STATION STATION 5 SPRING BOTTOM DATA (21/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
8.00	22.10	14.20	7.85	7.85	8.93	8.91	0.54	0.54	19.21	21.67	72.37	24.12	1.59	1.53
11.11	2.00	13.70	6.70	7.45	10.02		0.71	0.88			2.19	1.34	0.83	2.13
14.11	0.70	14.00	7.20	6.95	10.85	10.89	0.72	0.72	76.83	49.21	3.30		1.25	0.71
16.30	25.50	15.50	8.00	8.00			0.81	0.76	32.64	13.43	66.57	70.52	1.85	0.95
18.30	25.30	15.10	7.95	8.00	9.03	8.99	0.71	0.52	86.39	53.90	35.72	33.87	1.25	1.01

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
8.00	8.90	9.69	219.00	219.00		1.20		46.15
11.11	7.22	10.31	600.00		2.40	2.60	46.15	48.15
14.11		2.07	754.00	754.00	1.40	1.40	43.75	46.67
16.30	15.95	18.56	278.00	198.00	2.20	1.40	84.62	70.00
18.30	6.97	7.19	278.00	159.00	1.60	1.80	57.14	81.82

## PALMIET WINTER DATA

## STATION 1 NEAP SURFACE DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.38	0.00	12.20	6.40	6.40	10.64	10.64	0.90	0.71	60.97	96.07	0.62	0.48	2.21	1.88
10.15	0.00	12.90	6.40	6.40	10.54	10.49	0.68	0.84	56.04	140.94	0.56	0.43	1.59	1.72
13.23	0.00	13.50	6.50	6.50	10.28	10.30	1.26	1.61	55.14	46.89	0.34	0.43	1.32	1.65
16.07	0.00	13.50	6.50	6.50	10.33	10.29	2.65	1.13	51.48	49.94	0.90	0.90	1.39	1.26

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.38	25.84	18.36	901.00	1036.00	1.40	2.20	100.00	73.33
10.15			1171.00	1036.00	1.80	1.80	60.00	56.25
13.23	35.81	35.92	897.00	940.00	2.00	1.80	66.67	69.23
16.07			1068.00	769.00	2.20	1.80	55.00	52.94

## PALMIET WINTER DATA

## STATION 2 NEAP SURFACE DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.50	0.00	12.00	6.40	6.40	10.63	10.59	0.87	0.84	86.08	69.46	0.48	0.46	1.75	1.75
10.26	0.00	12.70	6.40	6.40	10.60	10.63	1.13	1.16	86.08	79.28	0.48	0.62	1.39	2.51
13.31	0.00	13.20	6.50	6.50	10.39	10.32	1.42	2.58	40.32	60.08	0.49	0.29	1.32	1.39
16.16	0.00	13.60	6.50	6.50	10.44	10.48	0.90	0.97	35.14	44.48	1.83	1.74	0.99	1.06

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.50			1441.00	766.00		2.40		66.67
10.26	23.73	34.32	991.00	991.00	1.60	4.00	61.54	100.00
13.31	29.16		855.00	812.00	2.20	1.80	64.71	56.25
16.16			812.00	983.00	2.80	1.60	43.75	38.10

## PALMIET WINTER DATA

## STATION 3 NEAP SURFACE DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.59	0.00	12.10	6.40	6.40	10.59	10.56	0.65	0.65	49.46	49.43	0.48	0.51	2.34	1.62
10.35	0.00	12.50	6.45	6.45	10.53	10.55	1.74	1.35	54.96	51.73	0.52	0.49	1.26	1.52
13.37	0.00	13.60	6.50	6.50	10.29	10.35	1.29	1.48	38.76	39.82	0.40	0.98	1.32	1.79
16.21	0.00	13.80	6.50	6.50	10.43	10.31	1.23	1.26	58.09	68.60	0.45	0.73	1.12	1.85

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.59			811.00	991.00	1.20	2.40	75.00	66.67
10.35	47.52		856.00	856.00	1.60	2.00	57.14	66.67
13.37		28.94	940.00	897.00	2.00	1.60	58.82	72.73
16.21			769.00	897.00	1.80	1.20	52.94	35.29

## PALMIET WINTER DATA

## STATION 4 NEAP SURFACE DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.40	0.00	12.80	6.40	6.40		10.71	0.68	0.84	102.81	97.76	0.40	0.46	1.17	1.30
10.27	0.00	12.60	6.45	6.45	10.56	10.55	1.29	1.35	71.37	84.42	0.43	0.43	1.26	1.32
13.35	0.00	13.20	6.50	6.50	10.16	10.08		1.39	61.75	59.95	0.26	0.43	1.39	1.79
16.15	0.00	13.40	6.50	6.50	10.47	10.39	0.97	0.71	42.30	51.09	0.84	1.29	1.12	1.72

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.40			901.00	856.00	1.40	2.40	70.00	75.00
10.27			901.00	946.00	1.20	1.80	42.86	69.23
13.35		28.83	812.00	940.00	2.20	1.40	68.75	53.85
16.15	15.71	26.82	812.00	727.00	2.00	1.60	55.56	57.14

## PALMIET WINTER DATA

## STATION 5 NEAP SURFACE DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.30	0.00	12.90	6.40	6.40	10.63	10.57	0.65	0.65	56.06	52.71	0.54	0.56	1.26	1.59
10.15	0.00	12.70	6.45	6.45	10.59	10.61	1.48	1.42	61.52	61.41	0.49	0.60	1.39	1.19
13.25	0.00	13.20	6.50	6.50	10.34	10.26	1.35	0.84	54.73	51.62	0.75	0.60	1.72	1.39
16.10	0.00	13.40	6.50	6.50	10.39	10.47	1.16	1.10	54.72	46.47	0.74	1.29	1.52	1.79

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.30	21.42	35.00	856.00	946.00	2.00	2.00	90.91	66.67
10.15			856.00	1200.00	1.80	2.20	75.00	61.11
13.25	49.88	34.23	1026.00	812.00	1.80	1.80	52.94	69.23
16.10			812.00	940.00	1.80	1.40	56.25	46.67

## PALMIET WINTER DATA

## STATION 6 NEAP SURFACE DATA (27/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PD4/1	PD4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
6.43	0.00	12.10	6.35	6.35	9.87	9.91	0.90	0.88	29.99	22.33	0.54	0.57		2.08
8.15	0.00	12.10	6.00	5.90	10.40	10.48	1.00	0.92	22.33	22.33	0.57	0.57	2.38	1.90
11.08	0.00	12.00	5.75	5.70	10.15	10.07	0.94	0.94	22.33	22.33	0.57	0.57	2.27	1.69
14.04	0.00	13.50	6.00	6.00	10.24	10.16	1.23	1.10	83.41	56.70	0.54	0.54	2.01	1.69
17.00	1.00	13.00	6.95	6.95	8.64	8.56	1.48	1.10	105.36	112.64	1.18	0.56	1.23	1.49

TIME	DDN/1	DDN/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
6.43	13.26	14.75		754.00	2.00	1.60	100.00	100.00
8.15			1032.00	952.00	1.60	1.40	46.67	100.00
11.08			1032.00	992.00	1.40	1.60	46.67	100.00
14.04	18.16	7.51	913.00	1032.00	1.60	1.60	100.00	72.73
17.00			901.00	901.00	1.40	1.60	46.67	53.67

## PALMIET WINTER DATA

## STATION 7 NEAP SURFACE DATA (27/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PD4/1	PD4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
6.39	0.00	12.10	5.95	5.85	10.43	8.61	0.92	0.96	26.14	33.85	0.57	0.49	1.90	2.32
8.12	0.00	12.00	5.70	5.70	10.32	10.40	0.92	0.92	22.33	22.33	0.57	0.57	1.90	2.08
11.06	0.00	12.00	5.70	5.60	9.98	9.94	0.96	0.96	29.99	29.99	0.54	0.54	1.56	1.95
13.52	0.00	13.20	5.90	5.90	10.50	10.43	1.04	0.98	60.56	60.56	0.49	0.49	1.56	1.56
17.00	0.00	12.50	6.35	6.20	9.58	9.51	0.98	0.98	77.70	59.39	0.54	0.54	1.43	1.88

TIME	DDN/1	DDN/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
6.39	12.10	24.85	1429.00	1746.00	1.80	1.60	81.82	100.00
8.12	16.88	17.92	952.00	873.00	1.20	1.20	100.00	75.00
11.06			913.00	794.00	1.00	1.40	62.50	77.78
13.52	6.93	12.17	873.00	873.00	1.40	1.20	100.00	100.00
17.00			1216.00	946.00	1.40	1.40	63.64	100.00

## PALMIET WINTER DATA

## STATION 8 NEAP SURFACE DATA (27/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PD4/1	PD4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
6.31	0.00	12.00	5.75	5.60	11.31	10.38	0.96	1.13	22.38	30.01	0.52	0.52	1.90	2.44
8.05	0.00	12.10	5.60	5.55	10.43	10.51	0.92	0.92	22.36	22.36	0.54	0.54	1.82	1.69
10.58	0.00	12.00	5.60	5.50	10.48	10.40	0.96	0.96	26.19	29.99	0.52	0.54	1.49	1.36
14.00	0.00	13.00	5.80	5.80	10.35	10.35	0.96	0.92	62.06	54.90	0.44	0.46	1.62	1.69
17.00	0.00	12.00	6.20	6.15	9.62	9.54	0.81	0.90	56.12	77.78	0.48	0.46	2.08	1.56

TIME	DDN/1	DDN/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
6.31	17.54	15.19			1.80	1.60	100.00	100.00
8.05			833.00	913.00	1.20	1.20	75.00	66.67
10.58			873.00	1349.00	0.80	1.40	40.00	63.64
14.00	23.45	18.94	754.00	873.00	1.40	1.40	100.00	87.50
17.00	12.28	10.75	1036.00	991.00	1.40	1.40	60.87	77.78

## PALMIET WINTER DATA

## STATION 9 NEAP SURFACE DATA (27/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
6.30	0.00	12.10	5.60	6.15	10.47	10.39	1.00	0.96	22.36	22.33	0.54	0.57	2.08	1.85
8.08	0.00	12.00	5.55	5.55	10.72	10.68	1.08	1.00	41.44	22.33	0.54	0.57	1.69	1.56
11.02	0.00	12.00	5.50	5.50	10.40	10.48	1.29	1.08	56.72	64.35	0.52	0.52	1.56	1.75
13.52	0.00	12.90	5.80	5.80	9.91	9.99	1.04	1.02	63.83		0.46	0.46	1.95	1.49
17.00	0.00	12.50	6.15	6.15	10.23	9.94	0.87	0.68	51.12	39.47	0.48	0.48	1.23	1.56

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
6.30	15.41	14.27	1706.00		1.40	1.80	100.00	100.00
8.08			873.00	952.00	1.20	1.20	100.00	100.00
11.02			1032.00	913.00	1.20	1.40	54.55	87.50
13.52	8.04		833.00	794.00	1.40	1.40	100.00	87.50
17.00			991.00	721.00	1.40	1.60	100.00	50.00

## PALMIET WINTER DATA

## STATION 1 NEAP BOTTOM DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.38	0.00	12.80	6.45	6.50	10.57	10.57	0.68	0.71	62.88	81.09	2.04	0.48	1.72	1.32
10.15	0.00	13.00	6.25	6.40	10.59	10.62	1.39	1.35	53.42	72.91	0.43	0.52	1.46	1.06
13.23	0.00	13.10	6.55	6.55	10.40	10.41	0.77	1.35	45.03		0.66	0.17	1.32	1.39
16.07	0.00	13.50	6.50	6.50	10.44	10.44	1.16	1.29	47.61	50.98	1.69	1.40	1.32	1.32

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.38	16.57	18.92	1577.00	1036.00	2.00		83.33	
10.15			727.00	940.00	2.60	3.00	100.00	68.18
13.23	27.86	22.28	855.00	897.00	1.20	1.40	42.86	77.78
16.07			855.00	855.00	1.60	1.80	50.00	50.00

## PALMIET WINTER DATA

## STATION 2 NEAP BOTTOM DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DD/1	DD/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.50	0.00	12.50	6.50	6.50	10.60	10.64	0.87	0.65	109.41	52.76	0.46	0.51	1.19	1.46
10.26	0.00	12.80	6.40	6.45	10.64	10.67		1.42	64.78	58.29	0.49	0.46	1.46	1.26
13.31	0.00	13.20	6.55	6.55	10.39	10.43	0.97	0.97	61.12	54.27	0.89	1.21	1.39	1.12
16.16	0.00	13.90	6.50	6.50	10.32	10.28	1.35	1.16	60.55	61.00	1.07	0.62	1.46	1.46

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	XPOM/1	XPOM/2
7.50			1306.00	901.00	2.00	1.60	55.56	61.54
10.26			727.00	727.00	2.20	1.80	68.75	64.29
13.31	27.96	26.50	727.00	855.00	2.00	1.80	66.67	81.82
16.16	28.78	33.66	897.00	855.00	2.00	2.00	50.00	52.63

## PALMIET WINTER DATA

## STATION 3 NEAP BOTTOM DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.59	0.00	12.50	6.50	6.50	10.63	10.63	0.66	0.77	55.90	66.11	0.70	0.48	1.59	1.85
10.35	0.00	12.80	6.15	6.45	10.56	10.56	2.74	1.42	56.68	51.70	0.43	0.52	1.39	1.46
13.37	0.00	13.10	6.45	6.45	10.38	10.42	0.97	0.97	48.61	61.61	0.34	0.40	1.39	1.12
16.21	0.00	13.80	6.50	6.50	10.43	10.35	1.16	1.03	68.46	54.76	0.87	0.70	1.19	1.32

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
7.59			1081.00	991.00	1.80	1.80	69.23	52.94
10.35	47.10		769.00	855.00	1.80	2.20	52.94	68.75
13.37		21.08	855.00	769.00	2.00	1.60	58.82	66.67
16.21			769.00	855.00	1.80	2.00	56.25	58.82

## PALMIET WINTER DATA

## STATION 4 NEAP BOTTOM DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.40	0.00	12.80	6.40	6.45	10.55	10.60	0.84	0.68		82.75	0.40	0.48	1.46	1.06
10.27	0.00	12.60	6.45	6.45	10.57	10.61		1.29	104.01	61.55	0.43	0.46	1.52	2.12
13.35	0.00	13.20	6.50	6.50	10.43	10.47	0.94	0.90	46.15	44.93	0.46	0.76	1.32	0.99
16.15	0.00	13.40	6.50	6.50	10.32	10.32	1.48	1.48	104.45	122.94	0.31	0.31	1.72	1.46

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
7.40			1036.00	1306.00	2.00	1.80	83.33	50.00
10.27		30.32	1111.00	983.00	1.80	2.00	52.94	71.43
13.35	36.94	18.36	897.00	684.00	1.40	1.60	63.64	66.67
16.15			897.00	684.00	1.80	1.40	50.00	38.89

## PALMIET WINTER DATA

## STATION 5 NEAP BOTTOM DATA (28/08/86)

TIME	SAL	TEMP	pH/1	pH/2	DO/1	DO/2	PO4/1	PO4/2	NO3/1	NO3/2	NO2/1	NO2/2	NH3/1	NH3/2
7.30	0.00	12.80	6.45	6.45	10.62	10.61	0.77	0.77	56.12	62.78	0.48	0.48	1.26	1.32
10.15	0.00	12.70	6.45	6.45	10.62	10.62	2.26	0.77		51.21	0.14	1.01	2.06	0.99
13.25	0.00	13.20	6.50	6.50	10.48	10.48	0.77	0.97	48.06	47.71	0.89	1.24	1.06	1.06
16.10	0.00	13.40	6.50	6.50	10.43	10.48	1.16	1.35		79.72	0.22	0.39	1.32	1.79

TIME	DON/1	DON/2	DOC/1	DOC/2	POM/1	POM/2	ZPOM/1	ZPOM/2
7.30	30.94	18.92	901.00	1081.00	2.20	1.80	78.57	56.25
10.15			897.00	855.00	2.60	2.00	72.22	76.92
13.25	17.68	24.20	855.00	812.00	1.40	1.40	63.64	53.85
16.10			641.00	769.00	1.60	0.80	53.33	23.53

**ADDENDUM**

to

**CSIR RESEARCH REPORT 680**

**WATER CIRCULATION AND NUTRIENT DISTRIBUTION PATTERNS IN  
THE PALMIET RIVER ESTUARY: A WINTER STUDY**

by

**S Taljaard and J L Largier**

**(June 1989)**

(Please staple onto the back page of the report)

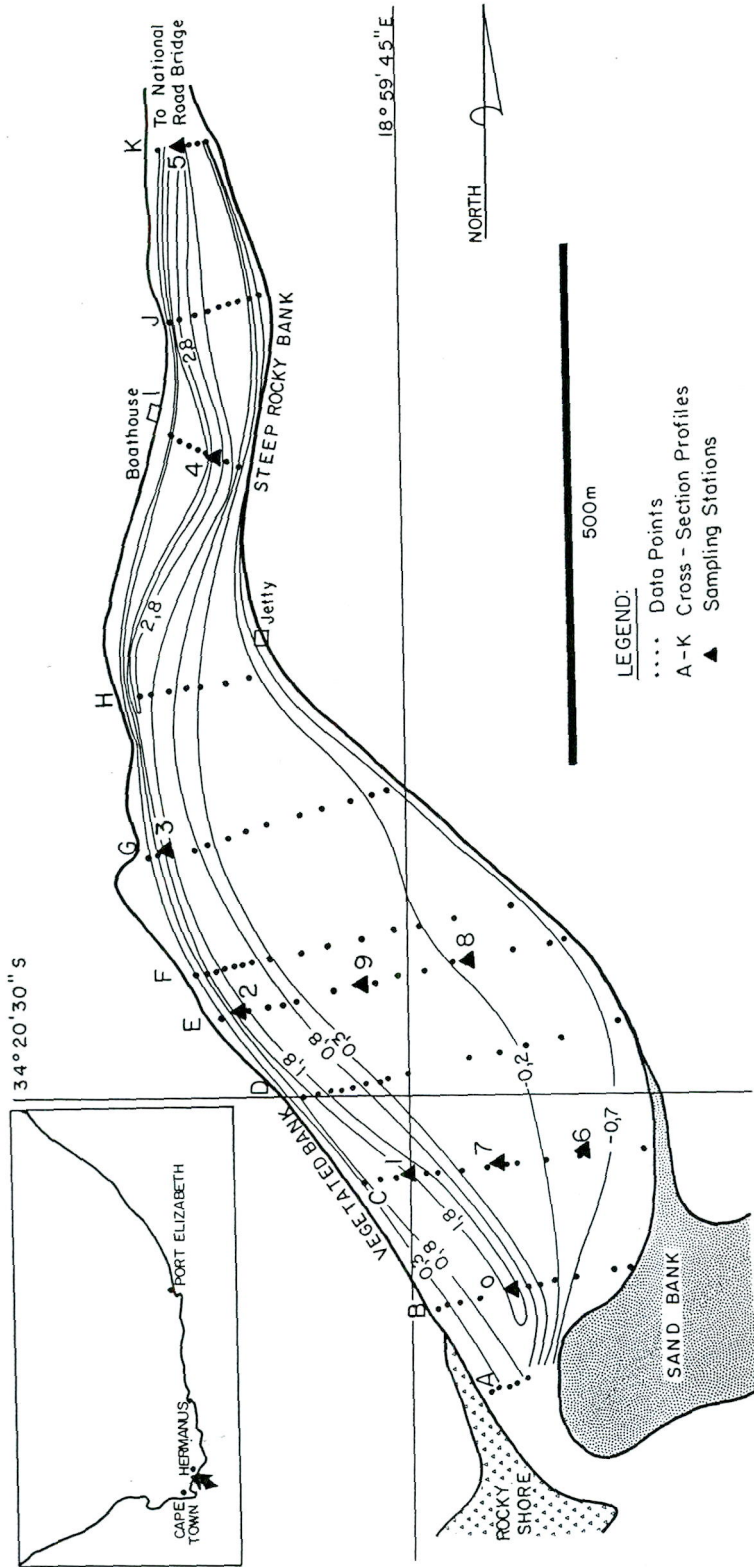


Figure 1 The location and bathymetry of the Palmetto River estuary during August 1986.

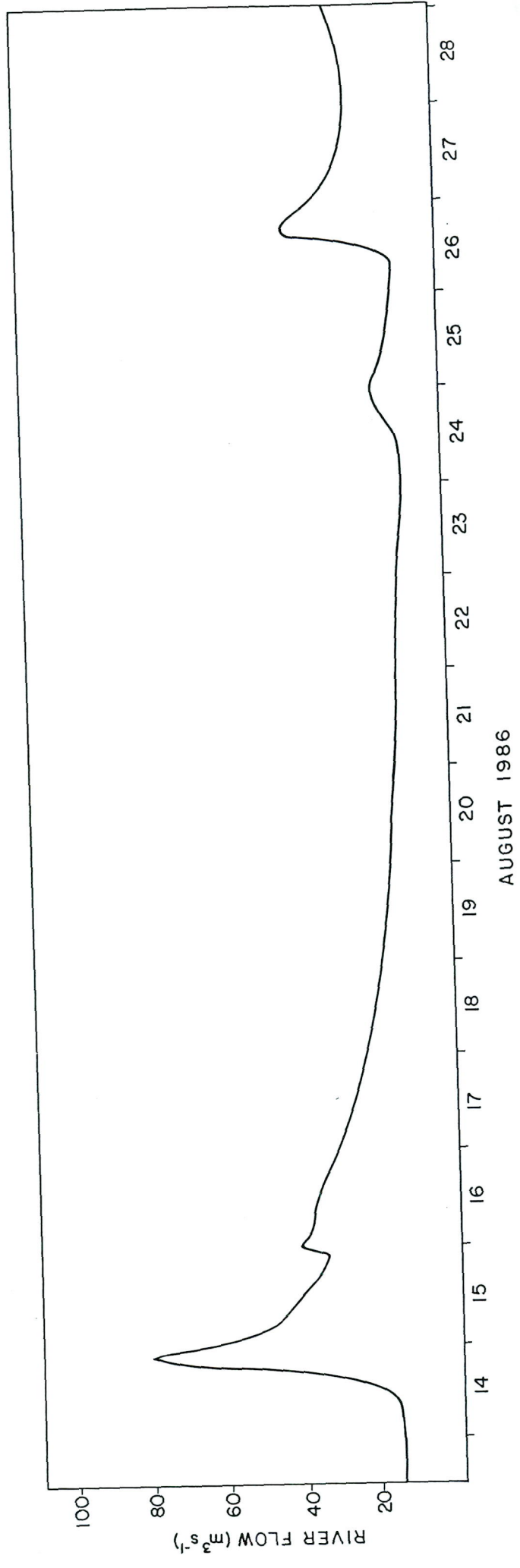
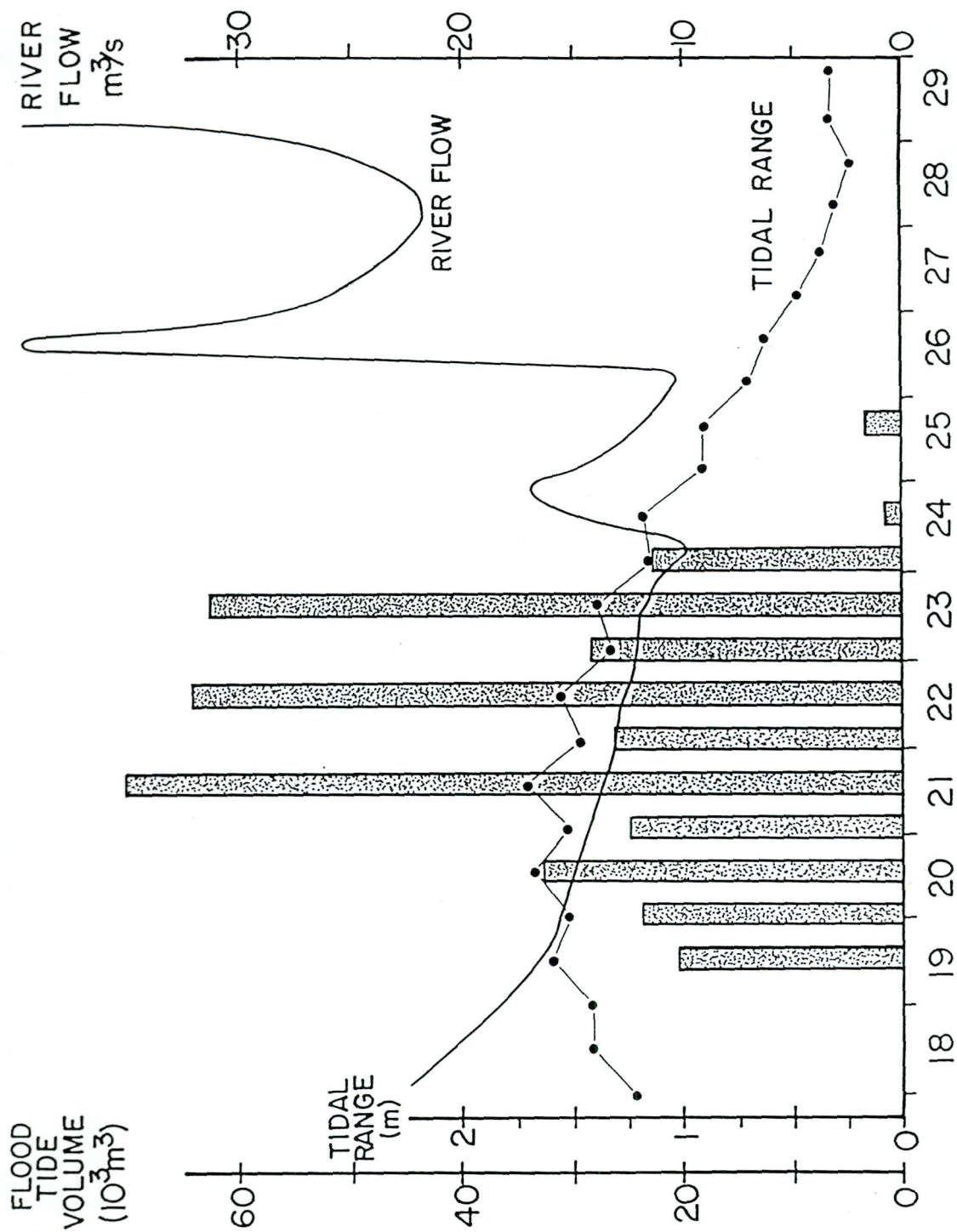


Figure 2 The record of river flow from 13 to 28 August 1986. Flow events on 14 and 26 August are noted.



AUGUST 1986

Figure 3 The flood tide volumes (plotted as bars) during the two week field exercise. These volumes can be related to the overlaid plots of sea-level tidal range and river flow.

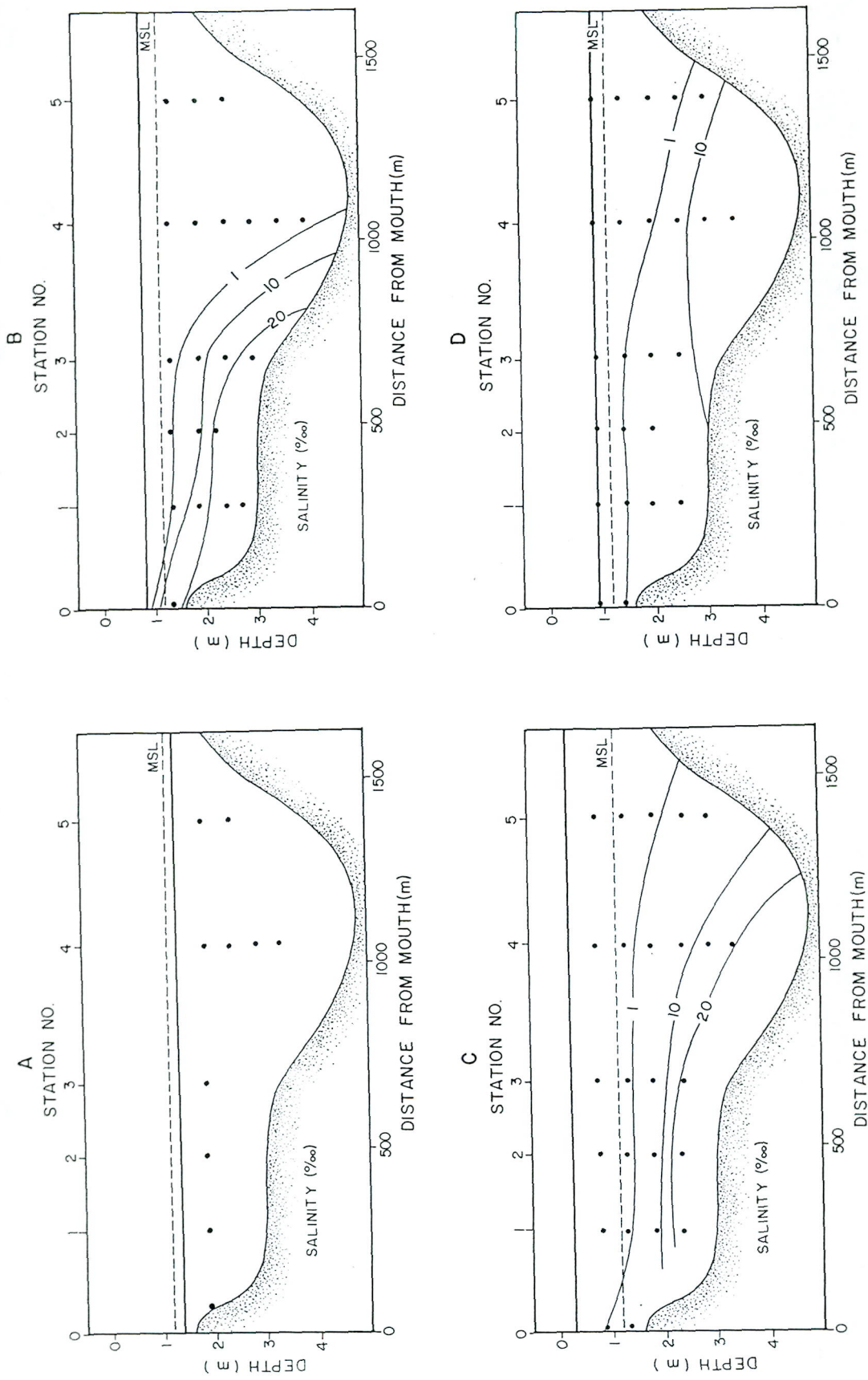


Figure 4 Longitudinal sections on 19 August 1986:  
 a) Low tide b) Flood tide c) High tide d) Ebb-tide.

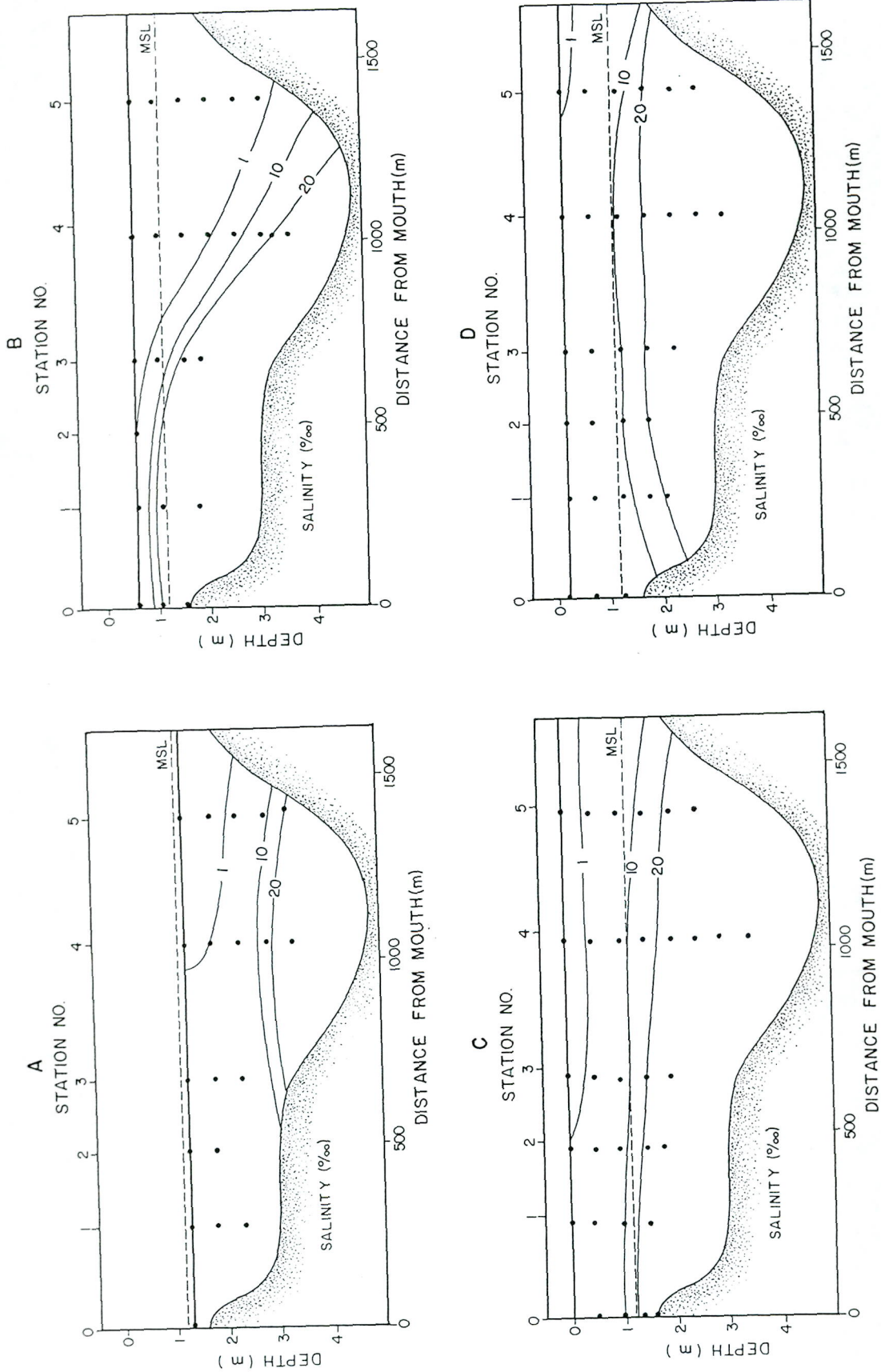


Figure 5 Longitudinal sections on 21 August 1986:  
a) Low tide b) Flood tide c) High tide d) Ebb-tide.

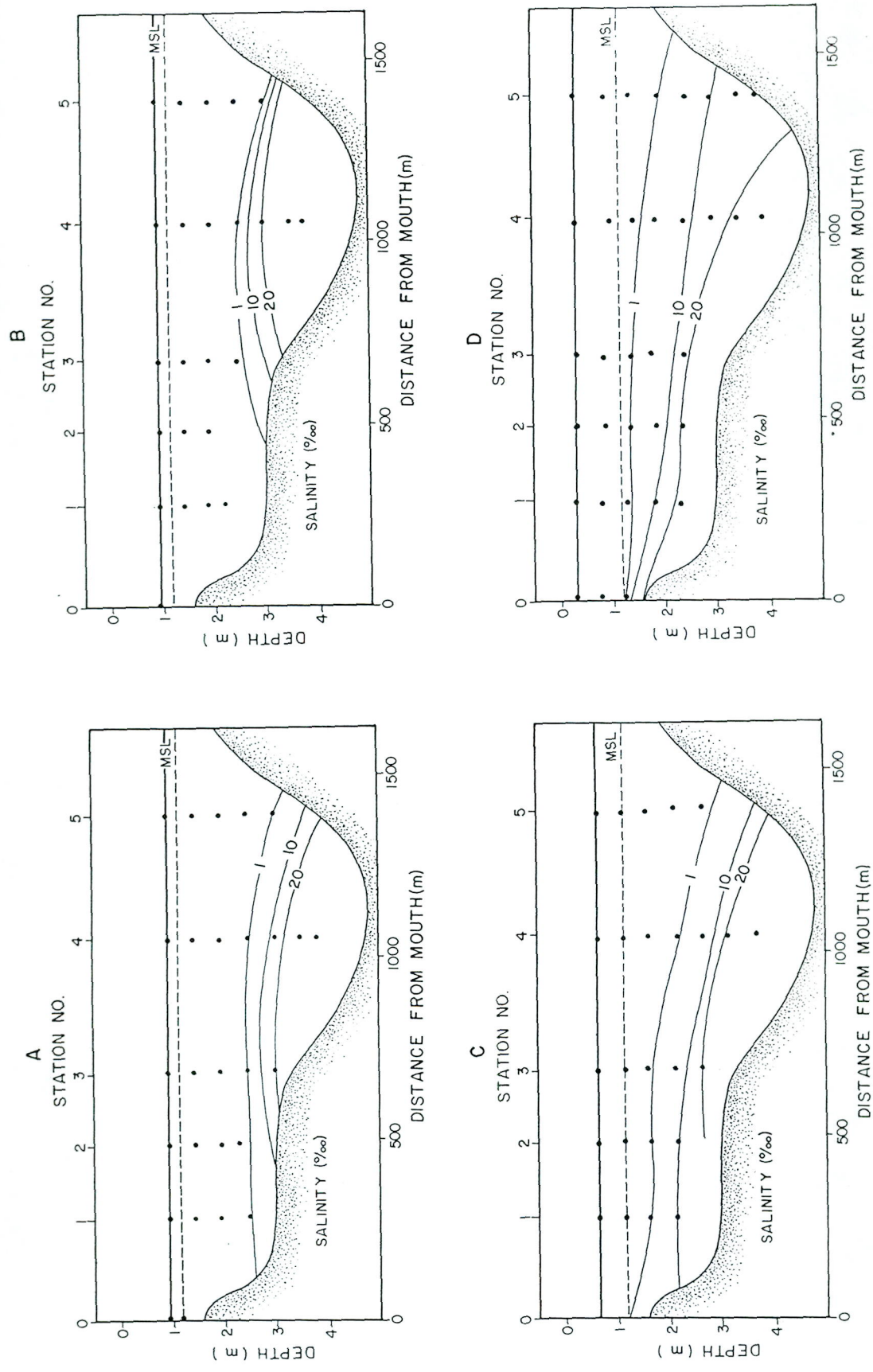
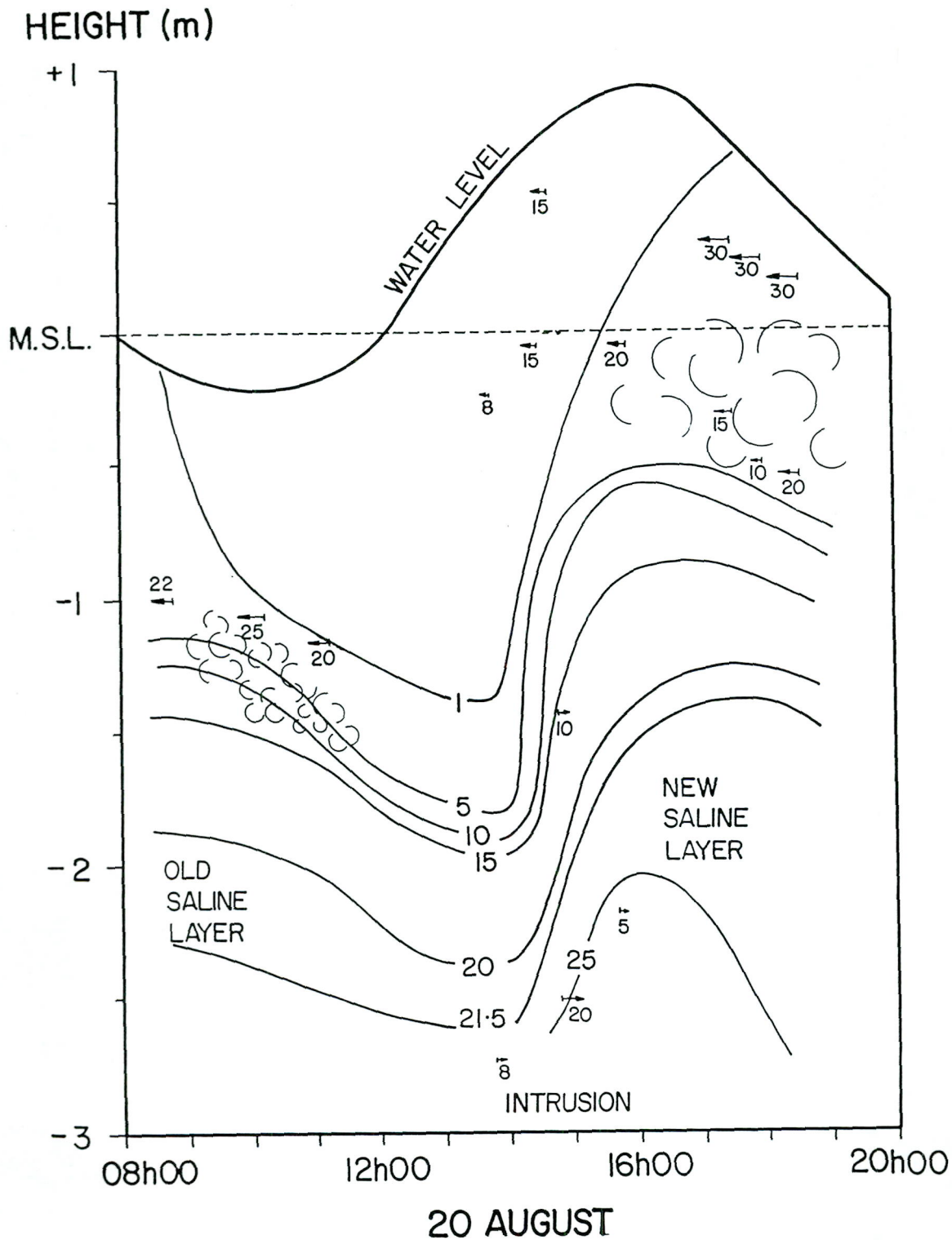


Figure 6 Longitudinal sections on 25 August 1986: a) Ebb-tide b) Low tide c) Flood tide d) High tide.



(Currents in cm/s are superimposed; sea to the left)

### SALINITY AT STATION 4

Figure 7 A time series of salinity structure at station 4; currents are indicated by arrows and turbulence by a collection of curved lines.

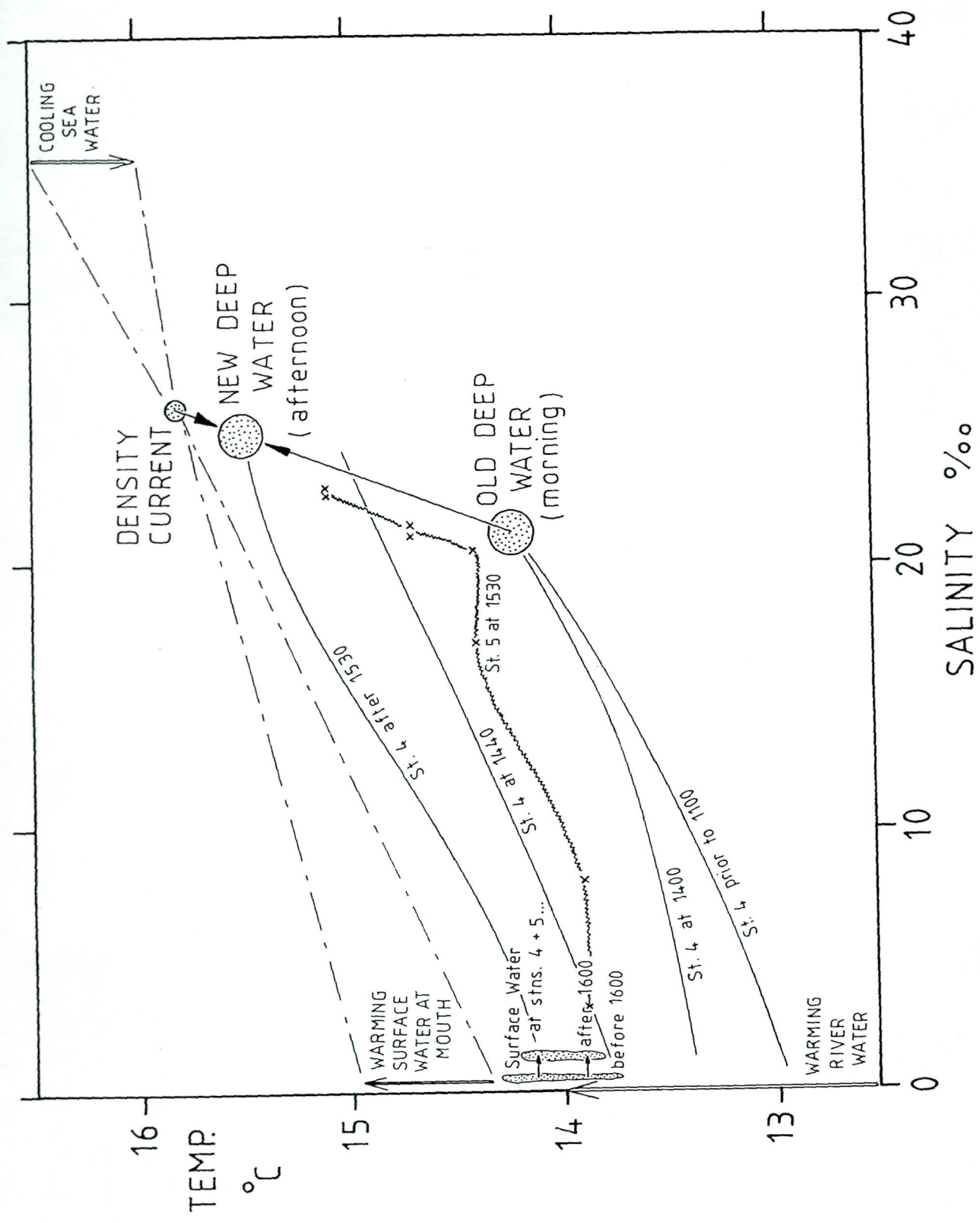


Figure 8 A temperature-salinity diagram of water at stations 4 and 5' on 20 August 1986. These water types are related to the three source waters.