Preliminary investigation of seasonality in the Great Berg Estuary

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Abstract

The hydrodynamics and water quality of the Great Berg Estuary were studied under river flow conditions typical of the winter and summer seasons. Results reflect a strongly seasonal regime with the estuary exhibiting fluvial dominance during winter and marine dominance under the low-flow conditions of summer. Limited renewal of estuarine water occurs over the summer period with the result that a plug of characteristically estuarine water is formed. Tidal influence extends 69 km upstream of the mouth in summer, while salinities in excess of 5×10^{-3} occur 37 km from the mouth. The role of river flow in counterbalancing the upstream dispersion of salt during the summer season is highlighted. The relevance of these findings in the preliminary assessment of the freshwater requirements of the Great Berg Estuary is addressed.

Introduction

Published information on the hydrodynamics and water quality of the Great Berg Estuary is limited to salinity records (FISCOR, 1973), preliminary observations of water chemistry (Cloete and Oliff, 1976), a summary by Day (1981), chemical studies undertaken in 1975 and 1976 by Eagle and Bartlett (1984) and preliminary results of this study and a concurrent modelling investigation (Taljaard and Slinger, 1992; Huizinga et al., 1993; CSIR, 1993). Supplementary hydrodynamic and water quality information is obtainable from ecological and biomonitoring investigations undertaken on the estuary (Gaigher, 1979; Kalejta and Hockey, 1991; Ninham Shand Inc., 1993; Adams and Bate, 1994; CSIR, 1994).

Large seasonal variations in salinities, temperatures and water chemistry were observed in the earlier studies (FISCOR, 1973; Eagle and Bartlett, 1984). The penetration of seawater into the estuary was limited during the wet season (April 1976), but by early summer (October 1976) saline water extended more than 6 km upstream. A salinity of 9×10^{-3} was recorded at Kersefontein, 45 km from the mouth, in February 1979 (Day, 1981).

The need for more detailed information on the hydrodynamics and water quality characteristics of the Great Berg Estuary, particularly with regard to seasonal variation, was evident, especially as further exploitation of the water resources of the upper and middle catchment is proposed (Ninham Shand Inc., 1993). The investigation subsequently described was launched in an effort to meet this need.

Study area

The Great Berg River flows northward from its source in the Great Drakenstein Mountains near the town of Franschoek, draining a catchment of approximately 7 715 km^2 (CSIR, 1988) before entering the sea at St Helena Bay (34°46'S, 18°09'E) on the west coast of South Africa (Fig. 1). Streamflow in the 294 km long river is seasonal with high flows occurring in winter (May to August) and low flows in summer (November to February). Two major impoundments are located on the river, the Voëlvlei Dam and the Wemmershoek Dam with storage capacities of 164.1×10^6 m^3 and 58.5×10^6 m^3, respectively. The present mean annual runoff is 693×10^6 m^3 (Berg, 1993).

In 1966, entrainment of the mouth of the Great Berg Estuary occurred, owing to problems encountered by fishing vessels attempting to enter the sheltered harbour at Laaiplek (US, 1963). A new mouth was cut through the sand dunes and fixed in position about 1 km north of the original mouth position. The original mouth has since silted up completely and now forms a blind side-arm or lagoon running parallel to the coast (Eagle and Bartlett, 1984). The main channel of the estuary is about 250 m wide and 5 m deep in the vicinity of the mouth, generally becoming narrower and shallower with distance upstream. The average width and depth of the estuary are 150 m and 3 m, respectively. The estuary meanders through flat terrain, rising only 1 m in the first 50 km. Extensive floodplains, which are seasonally inundated, lie adjacent to the channel and support a rich bird population.

Material and methods

Field expeditions were undertaken from 17 to 20 September 1989, 29 January to 1 February 1990 and on 20 March 1990. Salinities, temperatures and current velocities were measured at hydrographic stations located along the length of the estuary (Fig. 1), providing quasi-synoptic pictures of the thermohaline structure and circulation on flood- and ebb-tides. Salinity and temperature were measured at 0.25 m depth intervals using a Valeport Series 600 MK II CTDS Meter (accuracy 0.2×10^{-3}, 0.2°C, 0.1 m), while current velocities were measured at 0.5 m depth intervals with an NBA DNC-1 MK III Current Meter (accuracy 0.02 m·s^{-1}).

On 4 occasions, namely the flood-tides of 18 September 1989 and 29 January 1990 and the ebb-tides of 19 September 1989 and 30 January 1990, surface and bottom water samples were collected at hydrographic stations in the lower and middle reaches of the estuary. These were analysed for pH, dissolved nutrients (nitrite, nitrate, total ammonia, reactive phosphate, reactive silicate), dissolved oxygen, chlorophyll *a*, trace metals and faecal bacterial numbers. Whereas pH was measured in the field using a Radiometer Model 29, the dissolved nutrient samples were filtered through 0.45 µm Millipore filters, frozen in 4 m*ℓ* vials, and later analysed on a Technicon Auto Analyser using a modified version of the methods described by Mostert (1983). Dissolved oxygen levels were obtained by the method of Winkler (Watling, 1981).

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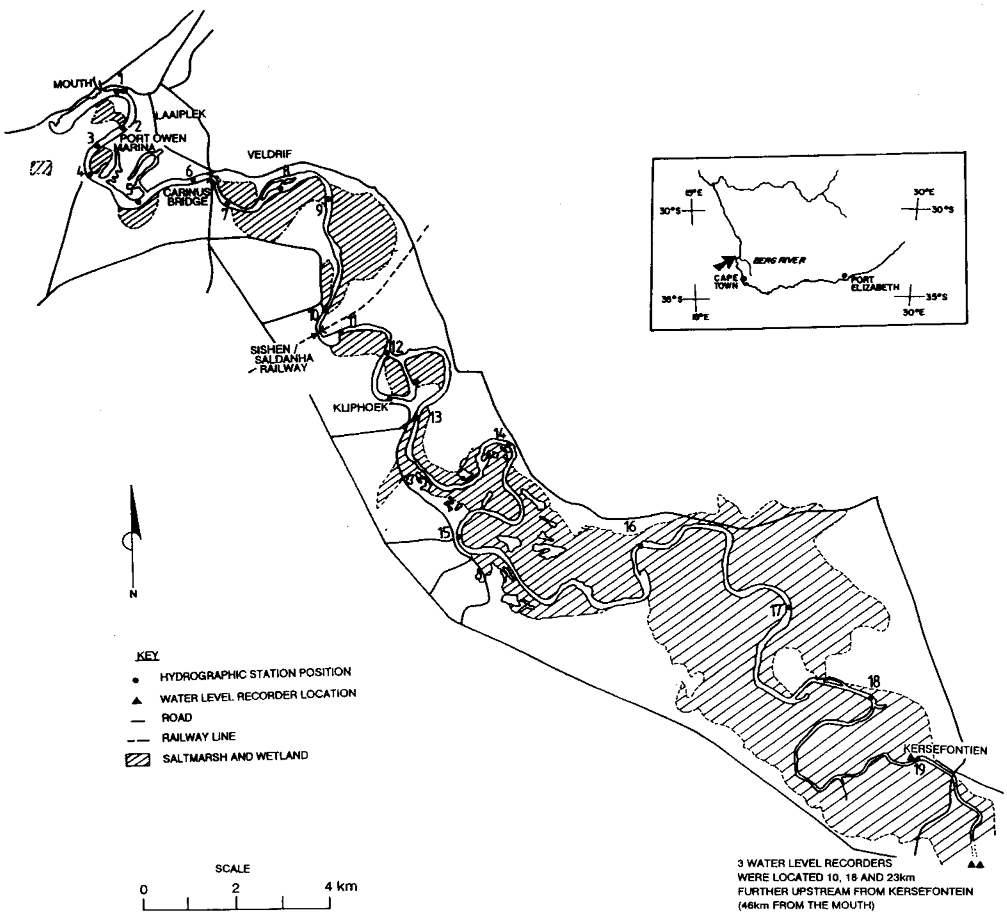

Figure 1

Map of the Great Berg Estuary. The lower estuary is considered to extend from the mouth to the Sishen/Saldanha Bridge, while the stretch from the bridge to Kersefontein, 46 km from the mouth, is termed the middle reaches. Hydrodynamic station positions and the location of water level recorders are indicated.

Chlorophyll *a* concentrations were determined fluorometrically according to the method of Parsons et al. (1984). Water column trace metal samples were pre-treated, extracted and then analysed on a Varian AA-1475 Spectrophotometer according to the methods of Watling (1981). Faecal bacterial levels were established by testing for 2 indicator organisms: faecal coliform and faecal streptococci. A modified form of the membrane filter method (Windle Taylor and Burman, 1964) was used to obtain the bacterial counts. Results represent means of duplicates per 100 mℓ.

Tidal variations were recorded from 6 to 20 March 1990, to an accuracy of 1 mm, using MC-systems float-type, digital datalogger water level recorders installed at 6 positions along the length of the estuary from the mouth to Steenboksfontein (69 km upstream of the mouth). Although difficulties were experienced with data retrieval, some data were also available from 3 water level recorders which had been installed at the mouth, Kliphoek and Kersefontein from 17 September to 25 October 1989.

A survey of the Great Berg Estuary, comprising 38 cross-sectional profiles, was undertaken during September 1989. These bathymetric data were used in conjunction with the depths measured at the hydrographic stations on flood- and ebb-tidal sampling runs to derive an average water level and so compensate to some extent for the temporal distortion introduced into the measured longitudinal profiles by the logistical constraint of using one boat on a long estuary. The time required to complete the September 1989 and the January/February/March 1990 sampling runs was about 1.5 h and 5 h, respectively.

River flow data from the gauging station G1H031 (Misverstand/Die Brug) located at 32°59'36"S, 18°46'27"E were obtained from the Department of Water Affairs and Forestry for the period May 1974 to April 1990.

Results

During July, August and September 1989 the Berg River flowed strongly (Fig. 2). The maximum average daily flow rate for the 1988/89 hydrological year (398 $m^3 \cdot s^{-1}$) occurred on 5 September 1989. The summer which followed was substantially drier and the total inflowing volume for the period May 1989 to April 1990 was only 86% of the mean annual runoff. The lowest flow rate of 0.5

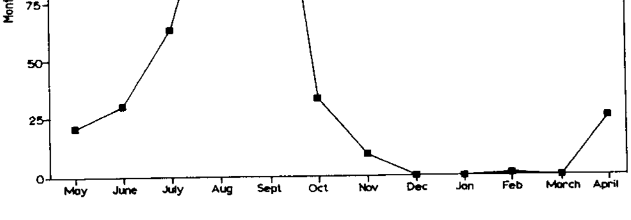

Figure 2

Monthly flow data for the period May 1989 to April 1990 from the gauging station G1H031, upstream of the Great Berg Estuary.

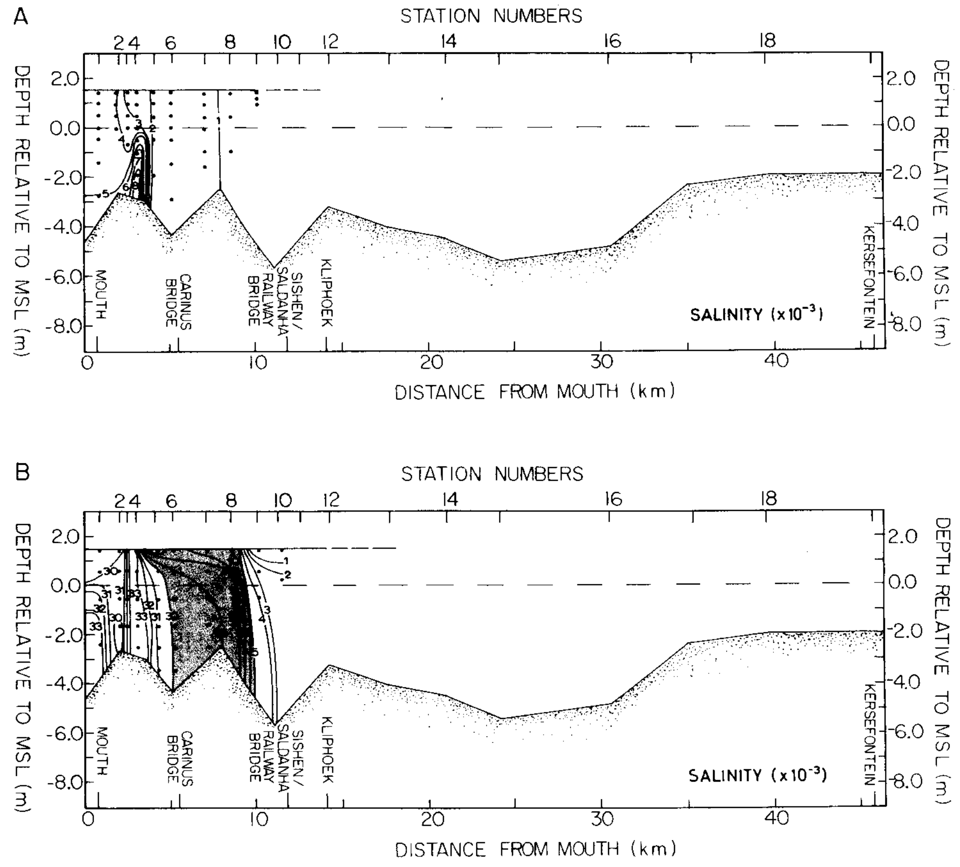

Figure 3
Longitudinal salinity sections at ebb-tide (A) and at flood-tide (B) on 18 September 1989

$m^3 \cdot s^{-1}$ occurred on 31 January 1990. Flow rates remained at this low level during February and March 1990. Thus, the summer 1990 field trip was conducted during low-flow conditions, while the September 1989 field trip occurred during the high-flow conditions typical of the winter season (Fig.2).

No effluents were discharged into the water by the fish factories located in the lower reaches of the estuary during any of the field surveys.

High-flow conditions

On the morning of 18 September 1989, during late ebb-tide, the waters of the Great Berg Estuary were fresh (salinities $< 2 \times 10^{-3}$) to within 4 km of the mouth (Fig. 3A). On the subsequent spring-flood-tide, seawater with salinity 33.07×10^{-3} and temperature 15.09°C intruded into the Great Berg Estuary. By 18:00 (about 6 h after low tide) water of salinity 20×10^{-3} extended 9 km upstream of the mouth (Fig. 3B). An intense longitudinal gradient in salinity (15×10^{-3} km^{-1}) occurred over the next kilometre as the intruding seawater encountered riverine water. Upstream of the Sishen/Saldanha railway bridge, the water in the estuary was of riverine character (salinity $< 2 \times 10^{-3}$).

The upstream extent of saline intrusion on the flood-tides of 17 and 19 September 1989 was similar to that measured on 18 September 1989. This strong intrusion of saline water to between 8 and 10 km upstream of the mouth appears to be characteristic of flood-tides under high-flow conditions.

During the ebb-tides of 18 and 20 September 1989, the water in the estuary was fresh, apart from lenses of saline water (salinity $> 4 \times 10^{-3}$), located on the bottom about 3 km upstream of the mouth. Such a feature was not detected on 17 September as flood-tidal intrusion had already commenced at the mouth when measurements were taken. The saline lenses form as a result of the slow drainage of water from the canals of the Port Owen Marina. This dense water is trapped on the bottom and prevented from flowing seaward on the ebb-tide due to the presence of a slight sill about 2 km upstream of the mouth. Such topographic trapping occurs in other southern African estuaries (Largier and Slinger, 1991; Largier et al., 1992), where the saline water is usually expelled by upward entrainment into the outflowing, buoyant surface layers. However, the high riverine flow rates prevailing at the time in the Great Berg Estuary, were of insufficient magnitude to ensure the removal of the saline lenses and the complete flushing of the estuary with freshwater.

Measurements of pH in the estuary lay within the limits of the seawater and riverine water (Table 1), ranging from 7.4 to 7.8. On both flood- and ebb-tides the average saturation levels of dissolved oxygen exceeded 70%, even in the bottom waters (Table 2). Dissolved nitrite levels generally were low (Table 2). However, there were marked differences in the concentrations of dissolved nitrate measured on the ebb- and the flood-tides. During the ebb-tide, relatively high levels characteristic of the river water were measured throughout the estuary (Fig. 4A). Nitrate levels in the estuary were lower on the flood-tide with a minimum at the mouth, and increased with increasing distance upstream (Fig. 4A). Lower nitrate levels also were measured in the more saline bottom water. Dissolved reactive silicate concentrations were higher on the ebb-tide than on the flood-tide and higher in the surface waters than the bottom waters (Fig. 4C). In contrast, concentrations of dissolved total ammonia and dissolved reactive phosphate measured on the ebb-tide were markedly lower than on the flood-tide, except in the immediate vicinity of the mouth where flood-tidal intrusion had commenced (Fig. 4E and G). Total ammonia and dissolved reactive phosphate levels were higher in the bottom waters (greater marine influence) than in the surface waters (greater riverine

TABLE 1
WATER QUALITY CHARACTERISTICS OF THE SEA AND THE RIVER MEASURED DURING THE SEPTEMBER 1989 AND JANUARY/FEBRUARY 1990 SURVEYS OF THE GREAT BERG ESTUARY

Water quality parameters		**September 1989**		**January/February 1990**	
		Sea	**River**	**Sea**	**River**
Temperature (°C)		14.94	16.83	16.89	26.19
Salinity (x 10^{-3})		33.55	0.15	34.47	0.20
pH		7.9	7.4	8.1	7.3
Dissolved nutrients ($\mu g \cdot \ell^{-1}$)	NO_2-N	22	4	4	1
	NO_3-N	230	536	118	12
	NH_3-N	197	47	64	57
	PO_4-P	82	29	110	41
	Si	1 162	2 014	722	1 503
Chl *a* ($\mu g \cdot \ell^{-1}$)		1.6	2.0	0.2	2.7
Trace metals ($\mu g \cdot \ell^{-1}$)	Cr	0.7	1.7	0.7	3.7
	Cu	0.8	2.0	0.8	2.5
	Fe	96	1 177	142	1 354
	Mn	4.4	36.9	4.1	83.7
	Ni	0.4	1.9	0.4	2.9
	Zn	2.3	2.9	3.8	7.4

TABLE 2
AVERAGE WATER QUALITY MEASUREMENTS FROM THE SEPTEMBER 1989 AND JANUARY/FEBRUARY 1990 SURVEYS OF THE GREAT BERG ESTUARY

Water quality parameters		**September 1989**		**January/February 1990**	
		Ebb	**Flood**	**Ebb**	**Flood**
pH		7.5	7.7	7.8	7.6
DO ($mg \cdot \ell^{-1}$)		7.4	6.3	5.8	7.4
DO saturation (%)		78	73	79	98
NO_2-N ($\mu g \cdot \ell^{-1}$)		7	15	4	4
Chl *a* ($\mu g \cdot \ell^{-1}$)		1.8	1.5	0.2	0.2
Bacterial counts $\cdot 100\ m\ell^{-1}$	Faecal coliform	92	-	-	106
	Faecal streptococci	46	-	-	113
Trace metals ($\mu g \cdot \ell^{-1}$)	Cr	2.6	2.9	0.9	0.7
	Cu	2.2	1.9	0.8	0.7
	Fe	1 273	1 170	154	158
	Mn	35.7	27.5	52.2	27.8
	Ni	2.0	2.4	0.6	0.6
	Zn	4.5	5.5	2.6	3.5

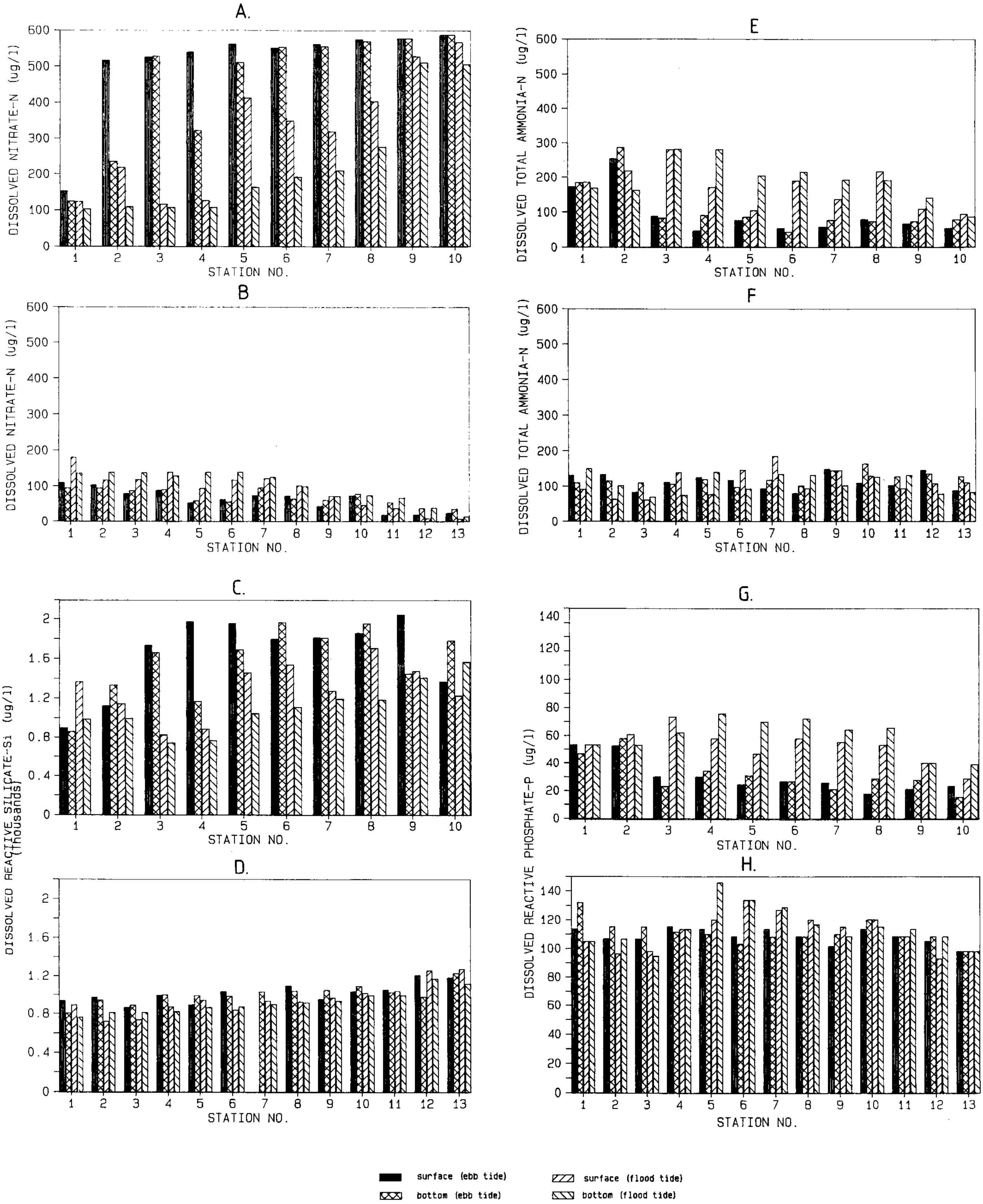

Figure 4

Dissolved nutrient concentrations (nitrate, reactive silicate, total ammonia and reactive phosphate) measured in surface and bottom waters during ebb- and flood-tides under high-flow (A, C, E, G) and low-flow (B, D, F, H) conditions

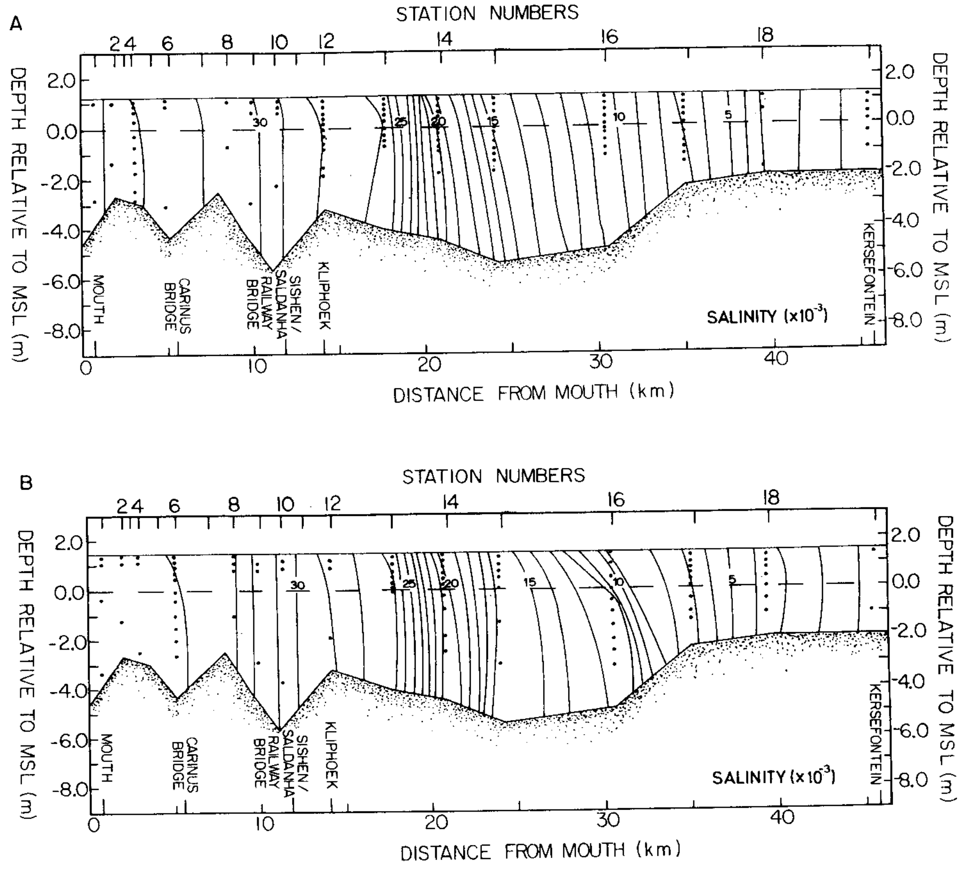

Figure 5

Longitudinal salinity sections at ebb-tide (A) on 31 January 1990 and at flood-tide (B) on 1 February 1990

influence).

The faecal coliform and faecal streptococci bacterial counts indicated that there was little evidence of sewage contamination in the estuary in September 1989 (Table 2).

Trace metal concentrations in the surface water were characteristic of riverine water, particularly the iron concentrations (Tables 1 and 2). Cadmium, copper and lead were not detected. Little change in trace metal concentrations occurred between ebb- and flood-tides.

Chlorophyll *a* levels were low, with a mean concentration of 1.8 $\mu g \cdot \ell^{-1}$ on the ebb-tide and 1.5 $\mu g \cdot \ell^{-1}$ on the flood-tide. This indicates that phototrophic activity in the Great Berg Estuary under high-flow conditions was poor (Janus and Vollenweider, 1981).

Low-flow conditions

During the flood-tide of 1 February 1990 (3 d after spring-tide), water temperatures in the Berg Estuary ranged from 13.73°C at the mouth to 25.01°C at Kersefontein, 46 km upstream. The corresponding salinities varied between 34.24 x 10^{-3} and 0.20 x 10^{-3} (Fig. 5). Water of salinity greater than 5 x 10^{-3} extended 37 km upstream of the mouth, while salinities exceeded 10 x 10^{-3} for 30 km from the mouth on the flood-tide. The water column was generally vertically mixed, although slight haline stratification was recorded at Station 16, 30 km upstream of the mouth, where salinities 4 x 10^{-3} greater than surface salinities were recorded at the base of the 6.5 m water column. The greatest longitudinal gradient in salinity (2.12 x 10^{-3} km^{-1}) was measured between Stations 13 and 14 where salinities decreased by 7 x 10^{-3} over 3.3 km. Comparison of salinities measured on the ebb- and flood-tides (Fig. 5) indicates that there were no distinctive differences upstream of the 25 x 10^{-3} isohaline, located about 4.8 km upstream of Kliphoek. Thus the direct influence of the tidal intrusion of seawater extended throughout the lower and lower middle reaches of the estuary under the low-flow conditions of summer 1989/90. In contrast to the high-flow situation, only limited excursion of estuarine water occurred during ebb-tides. Instead, the marine influence predominated and from 18.8 km upstream of the mouth water remained resident in the estuary.

By mid-neap-tide on 20 March 1990, temperatures within the estuary varied from 16.68°C at the mouth to 23.86°C at Kersefontein and the corresponding salinities varied from 34.34 x 10^{-3} to 1.00 x 10^{-3} (Fig. 6). Water of salinity greater than 5 x 10^{-3} extended 35 km upstream of the mouth, while water exceeding 10 x 10^{-3} extended to 25 km. Vertical stratification in salinity was evident with a maximum gradient of 1.25 x 10^{-3} m^{-1} (surface to bottom salinity difference of 7.5 x 10^{-3} over 6 m) measured at Station 15 in the middle reaches. The maximum longitudinal gradient in salinity, 1.8 x 10^{-3} km^{-1}, occurred about 20 km upstream of the mouth.

As the sampling runs of 1 February and 20 March 1990 were conducted at different stages of the spring-neap-tidal cycle, it is unclear whether the profile of 20 March 1990, which exhibits increased stratification in the middle reaches, reflects a situation of increasing riverine dominance or is merely indicative of the weaker marine influence over neap-tide. Thus it is difficult to determine

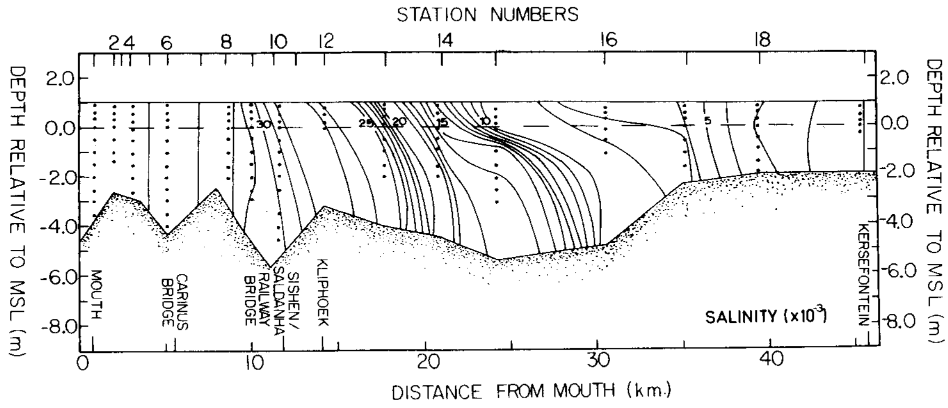

Figure 6

Longitudinal salinity section at mid-tide on 20 March 1990

whether a nett upstream or downstream movement of salt occurred from 1 February to 20 March 1990. However, it is clear that river inflow during summer and early autumn acts to counterbalance the tidally-driven upstream dispersion of salt.

Measurements of pH ranged from 7.7 to 8.1, falling within the limits of the measured values for the sea and river (Table 1). Average saturation levels for dissolved oxygen were higher during the summer (January/February 1990) flood-tide than during the ebb-tide. Although less well oxygenated on the ebb-tide, average saturation levels still exceeded 70% (Table 2). No marked variation in dissolved oxygen concentrations was observed with depth. Concentrations of dissolved nitrite in the estuary water were low (Table 2), as expected in a well-oxygenated system (Eagle and Bartlett, 1984). Dissolved nitrate concentrations in the lower reaches increased on the flood-tide as sea-water intrusion occurred. Generally, concentrations were low, possibly depleted in the middle reaches, in comparison with those measured under high-flow conditions (Figs. 4A and B). Dissolved total ammonia levels ranged from 62 to 186 $\mu g.\ell^{-1}$ with no obvious variation on flood- and ebb-tides (Fig. 4F). Although the concentrations of dissolved reactive phosphate did not vary significantly on flood- and ebb-tides, the average levels were high compared with those measured during the September 1989 survey (Fig. 4G and H). Concentrations of dissolved reactive silicate increased with distance upstream, but also exhibited little variation on flood- and ebb-tides (Fig. 4D). Average levels were lower under low-flow conditions than under high-flow conditions, reflecting the increased influence of saline water (generally concentrations are lower in sea-water than in river water). Unlike patterns observed for dissolved nitrate and dissolved reactive phosphate concentrations, there was no apparent depletion or accumulation of dissolved reactive silicate.

The faecal coliform and faecal streptococci bacterial counts indicated that there was little evidence of sewage contamination in the estuary in January/February 1990.

Trace metal concentrations in the surface water were similar to those measured in earlier studies (Van Wyk, 1983; Hennig, 1985) with no marked differences between ebb- and flood-tides. Cadmium, copper and lead were not detected.

Chlorophyll *a* levels were low, with mean concentrations of 0.2 $\mu g{\cdot}\ell^{-1}$ on both the ebb- and the flood-tides. This indicates that phototrophic activity in the Great Berg Estuary under the low-flow conditions of the summer season was poor (Janus and Vollenweider, 1981).

Current velocities

Of the current measurements conducted on a flood-tide under high-flow conditions, the maximum depth-averaged reading of 0.72 $m{\cdot}s^{-1}$ was recorded about 1 km from the mouth on 17 September 1989. The maximum depth-averaged current measured on an ebb-tide under high-flow conditions was 0.6 $m{\cdot}s^{-1}$, recorded 5 km upstream of the mouth on 18 September 1989. Current velocities varied with depth, exhibiting higher current speeds in the bottom 2 m of the water column on the flood-tides (intruding saline water) and in the surface layers (upper 2 m) on the ebb-tides. These velocity measurements accord well with the stratified circulation patterns deduced from the concurrently measured temperatures and salinities. Under low-flow conditions, the maximum flood-tidal, depth-averaged current velocity measured was 0.55 $m{\cdot}s^{-1}$, recorded 10 km upstream of the mouth on 1 February 1990. The maximum depth-averaged current measured on an ebb-tide under low-flow conditions was 0.46 $m{\cdot}s^{-1}$, recorded at the same position on 31 January 1990. Current velocities differed little with depth in the water column. The uni-directional, depth-independent flow observed during both ebb- and flood-tides indicates that the water column is vertically mixed, a deduction in agreement with thermohaline measurements. Clearly, the circulation was not as vigorous under low freshwater inflows as under high fresh-water inflows (lower current velocities), despite the fact that the summer survey was conducted over spring-tide while the September 1989 survey occurred at a stage intermediate between spring- and neap-tides.

Tidal variations

On 12 March 1990, between low tide at about 10:00 and high tide at 16:00, the water level at the mouth of the Great Berg Estuary varied 1.43 m, the same as the predicted sea-tidal variation for Saldanha Bay (Fig. 7). This indicates that the present mouth has little damping effect on vertical tidal variation. An oscillation with an amplitude of 0.10 m and a period of about 70 min (i.e. a frequency higher than the semi-diurnal tides) contributes to the wavy appearance of the recording at the mouth. This feature, known as an overtide, is most clearly discernible at low tide (about 10:00) and at high tide (about 04:00 and 16:00) and is characteristic of tidal recordings along the West Coast (CSIR, 1980). Overtides originate when the tide propagates from the deep ocean into coastal waters and estuaries and complex distortion

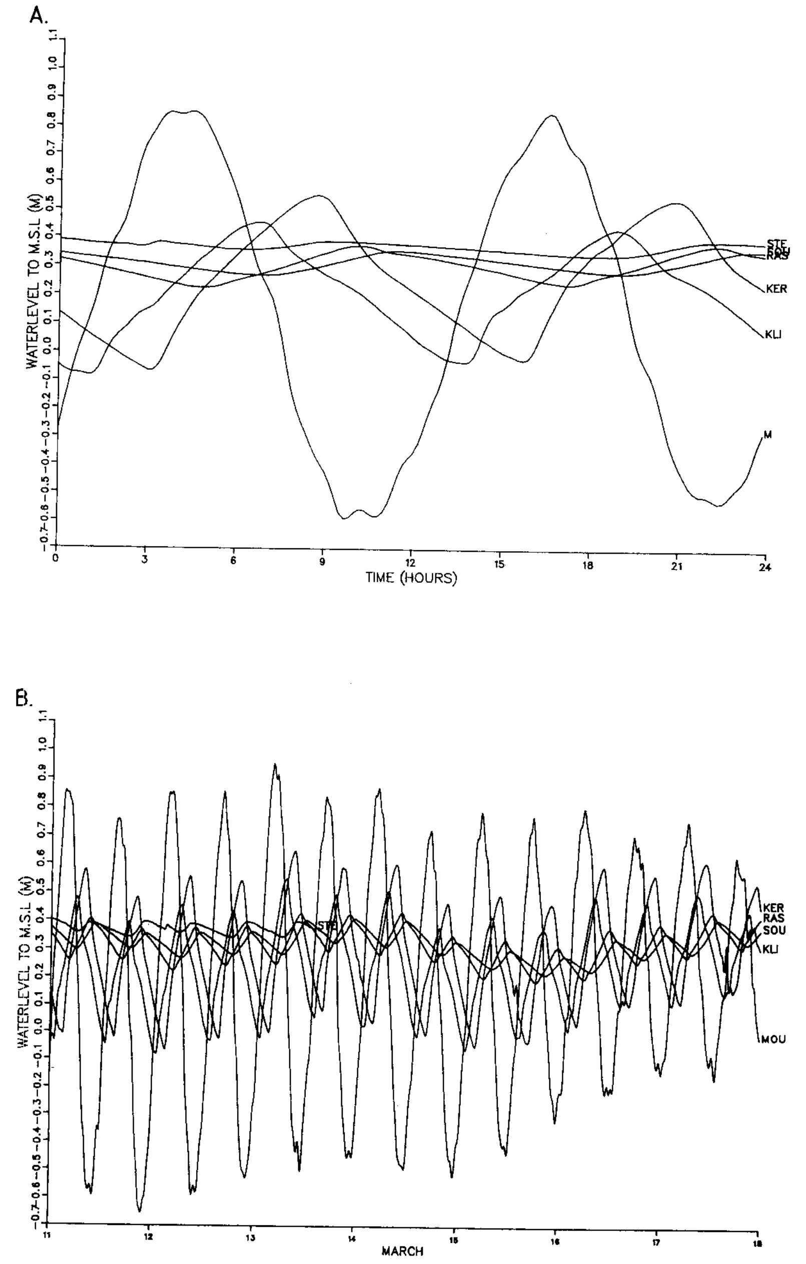

Figure 7
Water level variations measured on 12 March 1990 (A) and from 11 to 17 March 1990 (B) at the mouth (MOU), Kliphoek (KLI), Kersefontein (KER), Rasgat (RAS), Soutkloof (SOU) and Steenboksfontein (STE) in the Great Berg Estuary.

occurs as the trough of the tidal wave is retarded more than the crest of the tidal wave (Dronkers, 1964).

The tidal amplitude of water level variation is reduced by approximately 67% at Kliphoek, 14 km upstream of the mouth (Fig. 7), and the higher frequency oscillation is barely evident. Low tide at Kliphoek (at 14:00) lagged that at the mouth by 4 h, while high tide (at 18:20) was delayed by 2.3 h. The difference in phase shift between high and low tide is occasioned primarily by the dependence of the propagation speed of the tidal wave on the depth of the water. However, the reduction in tidal amplitude and the phase shifts are a composite response to factors such as the topography of the estuary (the variation in depth and cross-sectional area with distance upstream), friction effects and fresh-water inflow (Wicker, 1965). In the lower estuary, where there is a wide tidal plain, friction predominates and the tidal amplitude is reduced.

At Kersefontein, 46 km upstream of the mouth, the tidal variation is 0.57 m, moderately amplified compared with Kliphoek (0.47 m). This amplification occurs consistently between Kliphoek and Kersefontein as can be seen in the water level recordings for the week 11 to 17 March 1990 (Fig. 7B). Although the tidal amplitude at Kersefontein is only 40% of that at the mouth, it is 21% greater than that at Kliphoek. In the stretch between Kliphoek and Kersefontein, therefore, the convergence of the cross-sectional area of the estuary (topographic funnelling) more than counterbalances frictional effects. The phase shifts in low and high tide at Kersefontein are 5.5 and 5.0 h compared with the mouth.

At Rasgat, 56 km from the mouth, the tidal variation in water level is only 26% of that at Kersefontein, that is 10% of the variation at the mouth (Figs. 7A and B). The phase shifts for low and high tide are 7 h and 6.7 h, respectively. Thus when the tide is flooding at the mouth, it is ebbing between Kersefontein and Rasgat and vice versa.

Variations in water level of approximately 0.09 and 0.05 m were recorded at Soutkloof (64 km from the mouth) and Steenboksfontein (69 km from the mouth), respectively, in response to tidal forcing. The amplitudes of variation were 6% and 3.5%, respectively, of that at the mouth. The shift in phase was similar at both positions, increasing to 9.3 h at low tide and 7 h at high water.

Over the spring-tide of 17 to 19 September 1989 (high-flow conditions in the estuary), the maximum tidal variation recorded at the mouth was 1.79 m, slightly less than the predicted tidal variation in the sea. On 19 September 1989, the amplitudes of tidal variation at Kliphoek and Kersefontein were 0.52 m and 0.33 m, approximately 33 % and 21 %, respectively, of the amplitude of variation at the mouth. Thus tidal variation in the Great Berg Estuary is substantially reduced within 14 km of the mouth under the high-flow conditions typical of the winter season. High-flow conditions also exert a strong retarding influence on the propagation of the tidal wave, particularly in the middle reaches of the estuary. For instance, high and low tides at Kliphoek lag those at the mouth by 2.2 h and 3.4 h, respectively (very similar to the summer phase shifts), but high and low tides at Kersefontein lag those at the mouth by 5.3 h and 6.2 h, respectively (delayed relative to the summer phase shifts).

Discussion

The measured hydrodynamic and water quality parameters reflect a strongly seasonal regime. During winter the estuary is fluvially dominated and flood-tidal intrusion of seawater is limited to the lower reaches of the estuary (that is, to within about 10 km of the mouth). During summer the low-flow volume entering the estuary appears to be critical in limiting the upstream extent of saline influence. Whereas the seaward advection of salt depends primarily on riverine flow, the landward propagation or dispersion of salt occurs through the mechanisms of shape-induced transverse velocity shear, the trapping and release of water from embayments during different stages of the tidal cycle, vertical velocity shear, wind- and density-driven currents and nett differences in the advection of salinity on flood- and ebb-tides (Fischer, 1979). As the relative magnitude of these terms can only be determined from detailed cross-sectional velocity measurements, the efficacy of the different mechanisms in causing the landward transport of salt in the Great Berg Estuary is difficult to establish. However, it is likely that the dominant mechanisms are transverse velocity shear induced by the meandering channel, vertical velocity shear owing to bottom friction and tidal trapping by embayments or side channels. Additionally, the density-induced currents which occur under the stratified conditions of winter and the persistent high winds blowing along the West Coast during summer contribute to upstream salt transport. However, as the influence of river flow decreases over the summer season, the effects of tidally-induced dispersion increase, resulting in the formation of a characteristically estuarine water mass and increased upstream salinities. This water mass is warmer in temperature than the colder seawater, cooler than the river water and has salinities between those of seawater and freshwater. The slow upstream progression of salt is constrained by low freshwater inflows during summer, but is only reversed following the onset of the winter rains. As the rainy season proceeds, the fluvial dominance of the estuary increases and by the start of the next summer the system is predominantly fresh.

The water column appears to be well oxygenated under both high- and low-flow conditions. This is ascribed to vigorous circulation in winter and active vertical mixing in the water column during summer. Whereas under high flows, concentrations of dissolved nutrients characteristic of riverine water predominate during ebb-tides and those associated with seawater are evident during flood-tides, low dissolved nitrate concentrations and relatively high dissolved reactive phosphate concentrations were measured in the middle reaches of the estuary on both flood- and ebb-tides during summer. As the nutrient-limiting factor in marine systems is usually nitrogen (Sharp, 1983), rather than phosphate which may accumulate owing to regeneration, this confirms that water is resident in these reaches of the estuary over the summer months and that flood-tidal intrusion only results in limited renewal of the water in the estuary (up to 18.8 km upstream of the mouth in February 1990). Phototrophic activity in the water column is poor, owing primarily to short residence times of the water under high-flow conditions and to the limited availability of nutrients (especially nitrate) during low-flow conditions.

The extreme seasonality exhibited by the Great Berg Estuary is atypical of the majority of South African estuaries. Many Natal/ KwaZulu and northern Transkeian rivers in the subtropical biogeographical region (Whitfield, 1993) experience seasonality in river flow with high flows in summer and low flows in winter. However, they are also characterised by steep gradients from source to mouth and elevated inlet channels (Reddering and Rust, 1990), while many systems exhibit intermittent closure of the mouth (Begg, 1978; Whitfield, 1992). So, although the variability in discharge may be as extreme as that of the Great Berg Estuary, similar differences in the axial extents of tidal and saline influences between the winter and summer seasons are not exhibited. The estuaries of the warm temperate biogeographical zone, which extends from south of the Mbashe Estuary in the Transkei to the Buffels (West) Estuary in False Bay (Whitfield, 1993), generally do not experience such highly seasonal riverine discharge (Heydorn and Tinley, 1980). However, many estuaries exhibit temporary mouth closure or constriction and this varies in frequency and duration with the seasons. Consequently, many systems display distinct seasonal changes in hydrodynamic and water quality parameters, but do not exhibit large axial variations in salinity and tidal variation (Estuaries of the Cape: Part II, 1981-1993). In the cool temperate biogeographical zone, which extends from the Cape Peninsula to the Orange River mouth (Whitfield, 1993), highly seasonal or erratic river discharge is common (Heydorn and Tinley, 1980). However, the low gradient of the Great Berg Estuary (rising only 1 m in the first 50 km) is a distinctive feature. The other large permanently open estuary in this biogeographical region, the Olifants Estuary, is also strongly seasonal, but the extent of tidal variation is limited by a causeway 32 km upstream of the mouth and the influence of saline intrusion has been observed to extend only to about 16.5 km inland (Slinger, 1990). Thus, extreme seasonality in the form of axial variations in the extent of tidal and saline influences is a unique feature of the Great Berg Estuary at present.

It must be borne in mind, however, that anthropogenic perturbation of the depth and position of the mouth of the Great Berg Estuary occurred when the mouth was fixed in position in 1966. Prior to this perturbation, the mouth of the estuary was known to be shallow during low-flow periods, owing to the deposition of marine sand (US, 1963). Such shoaling of the entrance channel would have reduced the tidal influence and limited the penetration of seawater into the estuary (Huizinga et al., 1993). During summer, the combined influence of low riverine flows and the shoaling of the mouth, possibly would have constrained the axial extents of tidal and saline influences more effectively than at present. However, verification of this supposition cannot be undertaken directly from the limited available data (Huizinga et al., 1993).

Further anthropogenic perturbation of the Great Berg Estuary and floodplain is likely as extensive development of the water resources of the catchment is proposed (Ninham Shand Inc., 1993). The information gathered in this investigation has been used to assist in the decision process surrounding the proposed water resource developments. The water level recordings and the current velocity and salinity measurements were used to calibrate a one-dimensional hydrodynamic and transport-dispersion model (CSIR, 1993) and the model was used to simulate the hydrodynamic state of the estuary under various freshwater inflow scenarios corresponding to different impoundment options. These predictions, in turn, provided a basis for the assessment by ecologists of the consequences of the different development scenarios for the estuarine biota (Ninham Shand Inc., 1993). Thus the hydrodynamic and water quality information yielded by this investigation, proved essential in the preliminary assessment of the freshwater requirements of the Great Berg Estuary. However, it is evident that the available data, which do not address inter-annual variability in seasonality, nor episodic events such as the intrusion of low oxygen water from St Helena Bay into the estuary in March 1994, are an insufficient basis for effective decision-making. Further investigation/monitoring of the hydrodynamics and water quality of the Great Berg Estuary for the purposes of addressing these deficiencies and providing a comprehensive basis against which future changes can be assessed, is essential.

Concluding remarks

Limited historical data indicated that the flow regime of the Great Berg Estuary was strongly seasonal. This study, aimed at quantifying the seasonal influence in a preliminary fashion, has determined that the extent of saline influence in the estuary under a high-flow condition is limited to within 10 km of the mouth, whereas salinities in excess of 5×10^{-3} were measured 37 km upstream of the mouth under a low-flow condition. In contrast to earlier studies, which concentrated on the lower estuary, this investigation has highlighted the role of fluvial input in the determination of the seasonal character of the system. In particular, the low river flows of summer appear to be critical in limiting the upstream extent of saline influence. Amongst South African estuaries, the extreme seasonality exhibited in the axial extent of saline water in the Great Berg Estuary is distinctive.

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