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DISSOLVED OXYGEN CHARACTERISTICS OF THE GAMTOOS ESTUARY, SOUTH AFRICA

M. W. PEARCE and E. H. SCHUMANN†*

The fall and recovery of dissolved oxygen (DO) is documented throughout the Gamtoos Estuary, South Africa during dry conditions and following light and heavy rainfall over a 13-month period from November 1992 to November 1993. Hypoxic conditions generally occurred in the near-bottom waters of the upper estuary. Localized fluctuations in DO levels are related to the natural diurnal fluctuation associated with photosynthesis of aquatic flora. The drop in DO levels following light rainfall is associated with the volume of oxygen-consuming compounds entering the estuary via runoff from adjacent agricultural fields. This hypoxia was short-lived. Following an extreme rainfall event, however, almost immediate hypoxia was recorded throughout the estuary, and DO levels deteriorated for some time thereafter as a result of the substantial input of organic matter into the estuary. The area of hypoxia and recovery was governed by the freshwater input at the tidal head, estuarine hydrometry and hydrodynamics. Tidal processes were identified as a source of replenishment of oxygen when, during high tide, seawater with a higher DO content penetrated the estuary.

Key words: dissolved oxygen, estuary, hypoxia, oxygen replenishment, rainfall

Dissolved oxygen (DO) is essential for respiration in aquatic fauna and therefore impacts on the biotic functioning of an estuary. The DO concentration in estuarine waters will drop when oxygen consumption exceeds replenishment. The main factors causing depletion of DO include benthic community oxygen demand (Dortch *et al.* 1994), decomposition of organic matter (Zagorc-Koncan *et al*. 1991, Greb and Graczyk 1993), resuspension of oxygen-consuming compounds, and the input of large volumes of low DO runoff into the water body (Graczyk and Sonzogni 1991). Furthermore, thermal and salinity stratification inhibits exchange of oxygen between surface and bottom strata, resulting in low DO conditions in the bottom strata (Kuo and Nielson 1987).

DO is indirectly influenced by turbidity (or depth of light penetration). Introduction of suspended matter via surface runoff during rainfall and resuspension of river bed and bank sediments during turbulent flow are the main natural causes of an increase in turbidity and a corresponding drop in light penetration. A drop in light penetration may hinder photosynthesis, so reducing oxygen replenishment. Furthermore, increased turbidity causes an increase in the rate of drift and smothering of benthic organisms (Ratcliffe 1991, as cited by Dallas and Day 1993), impaired gill function in fish (Bruton 1985), reduced juvenile recruitment (Rowe *et al*. 2000) and larval densities (Harris and Cyrus 1999), fish mortality (Whitfield and Paterson 1995) and impaired growth and survival of aquatic flora (Adams and Talbot 1992, Czerny and Dunton 1995).

This paper examines the fall and recovery of DO levels in the Gamtoos Estuary during dry and wet conditions over a 13-month period from November 1992 to November 1993. The Gamtoos Estuary has a limited freshwater input as a result of the upstream impoundment of the Kouga River, and a low annual rainfall (<600 mm), which restricts the freshwater input at the upper tidal limit (Boschhoek – Fig. 1) to an average flow of 1 $m^3 s^{-1}$. At the time of the present study, the recommended minimum DO concentration for the protection of aquatic life was 4 mg ℓ^{-1} (Dallas and Day 1993), whereas the revised criteria for coastal marine waters (Department of Water Affairs and Forestry 1995) specify that DO should not fall below 5 mg ℓ^{-1} 99% of the time and below 6 mg ℓ^{-1} 95% of the time. The results presented in this paper will therefore focus on these recommended levels of DO.

STUDY AREA

The Gamtoos Estuary, which is approximately 20 km long, is narrow (50–200 m) and shallow, with depths generally between 2.5 and 3.5 m in the lower reaches, and an aggraded stretch in the upper estuary (averaging between 0.5 and 1.5 m deep), which restricts the penetration of tidal water upstream, except during spring

* School of Geography, Population and Environmental Management, Flinders University, GPO Box 2100, Adelaide 5001, South Australia, Australia. E-mail: meryl.pearce@flinders.edu.au
† University of Port Elizabeth, P. O. Box 1600, Port Elizabeth 6000, South Africa

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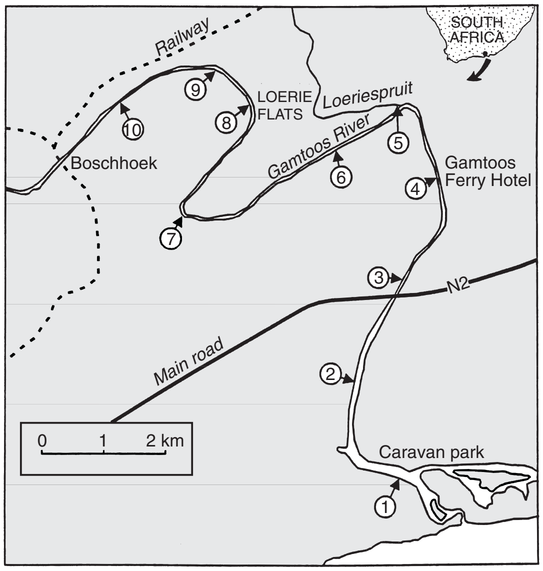

Fig. 1: Map of the Gamtoos Estuary and the Loeriespruit tributary. The positions of the 10 measurement stations are shown. The railway crossing at Boschhoek marks the upper tidal limit of the estuary

high tide. There are localized areas of scour throughout the estuary (Reddering and Scarr 1990). The tides in the ocean adjacent to the estuary are semi-diurnal, with neap tidal amplitudes within the estuary around 0.5 m, varying up to 2 m at spring tide, with tidal exchanges being the main mixing agent (Schumann and Pearce 1997).

During the study period, the average freshwater input at the upper tidal limit was 1 $m^3 s^{-1}$, although flow ranged from 0.5 $m^3 s^{-1}$, following two weeks without rainfall, to around 100 $m^3 s^{-1}$ after three days of exceptionally heavy rainfall. The Loeriespruit, a minor tributary, provides an additional small freshwater input (<0.5 $m^3 s^{-1}$) at its confluence with the estuary 8.5 km from the mouth.

MATERIAL AND METHODS

Measurements were undertaken between neap and spring tides during four intensive periods from November 1992 to November 1993. Measurements were taken at the judged centre of flow from an anchored boat, at 10 stations extending over an 18-km stretch of the estuary (Fig. 1); one station (Station 5) was situated at the confluence of the Loeriespruit and Gamtoos Estuary. Constriction at the estuary mouth has resulted in a time delay of about 1 hour to the peak of the tide in the estuary. Measurements were taken twice a day at low and high tides (South African Navy 1992, 1993), commencing at Station 1 at the predicted high and low water times within the estuary (Schumann and Pearce 1997), and proceeding upstream with the tide to obtain readings at near slack water over the whole estuary. At each station, a vertical profile of salinity, temperature, dissolved oxygen (DO) and Secchi disc depth was taken. A Secchi disc gives an indication of the approximate depth to which 5% of sunlight penetrates, and provides an indication of turbidity, or of suspended organic and inorganic matter in the water body. On many occasions the entire water column being measured was clear, and in such cases the Secchi disc reading given is the depth to the sediment.

The salinity and temperature readings were made using a Valeport series 600 MkII CTD meter with an accuracy of 0.3 and 0.1°C. Two instruments were used to measure DO: a microprocessor-based, auto-calibration DO meter (Hanna HI 914, with 1% accuracy over the scale of 0–19.99 ppm [mg ℓ^{-1}]), with a built-in thermistor for temperature compensation and auto-correction for salinity levels; and a YSI Model 57 Oxygen Meter that required manual calibration for salinity. To establish a vertical profile, readings were taken at 0.5-m intervals from the sediment to the surface, and

Table I: Proportion of dry days, single rainfall days, light and heavy rainfall periods between November 1992 and the end of November 1993

Rainfall conditions	Number of days or periods (consecutive days)	Proportion of the 13-month period (%)
No rainfall	351 days	88.9
Single days with <20 mm rainfall	20 days	4.5
Light rainfall: 1–3 consecutive days of rainfall between 20 and 45 mm	9 separate periods	4.3
Heavy rainfall: 87 mm over 4 days and 133 mm over 5 days	2 separate periods	2.3

where a marked change in a parameter was detected, readings were then taken at 0.1 or 0.2-m intervals to provide details of the gradient.

Because there are no gauging stations along the Gamtoos River, an indication of the freshwater inflow into the estuary at the tidal head was obtained by applying the velocity-area method (Shaw 1988).

Rainfall data, collected from a weather station established at the Gamtoos Ferry Hotel near Station 4, are incomplete on account of equipment problems. However, long-term rainfall records (102 years) are available (Weather Bureau 1994) for the nearby town of Hankey, and such data are used where the Gamtoos data are incomplete. Rainfall conditions during the 13-month monitoring period were divided into four categories: dry days (on which no rainfall was recorded); single rain days when the amount of rain recorded was <20 mm; light rainfall; and heavy rainfall. For the purpose of this paper, light rainfall is defined as 1–3 consecutive rainfall days totalling between 20 and 45 mm. Heavy rainfall occurred during two periods, from 10 to 13 June and from 21 to 24 September 1993, with 87.2 and 133.2 mm recorded respectively. From the data gathered, only one or two examples typical of each "rainfall situation" are highlighted in this paper.

RESULTS

The DO characteristics of the Gamtoos Estuary are appraised in relation to rainfall. Table I summarizes the proportion of dry days (88.9%), single rainfall days (4.5%), light and heavy rainfall (4.3 and 2.3% respectively) during the study period. Measurements did not coincide with any of the single rainfall days nor with the second of the two heavy rainfall periods, so they are not discussed here.

The study was preceded by a drier-than-average year (314 mm in 1992, compared with the 102-year average annual rainfall of 423 mm), whereas 1993 was a wetter-than-average year (642 mm). Although the 1993 high annual rainfall seems to indicate unusually wet conditions, Table I shows that dry and low-rainfall periods predominated during that year, with two short periods of high-intensity rainfall (87.2 and 133.2 mm over four and five consecutive days respectively).

DO levels throughout the estuary typical of non-rainfall periods

Of the 351 dry days (Table I), the conditions on 10 December 1992 and 6 April 1993 (after 14 and 13 consecutive dry days respectively) are presented as the DO conditions typical of non-rainfall periods.

At low tide on 10 December 1992, only Station 5 at the confluence of the estuary and the Loeriespruit had a DO concentration <3 mg ℓ^{-1} (Fig. 2a). During that time, the DO levels at the other stations ranged from <6 mg ℓ^{-1} (in the bottom strata of Station 6) to >12 mg ℓ^{-1} at Station 5. Conditions during spring high tide (later that day) show that the pocket of low DO rose to around 11 mg ℓ^{-1} (at Station 5). This rise in DO corresponds with the influx of seawater, with vertically homogenous salinity throughout the middle and lower estuary. The area of 6 mg ℓ^{-1} DO appears to have shifted upstream during spring high tide to the sediment-water interface at Station 7. Surface waters with a DO >11 mg ℓ^{-1} extended from Stations 3 to 10, where a maximum of >13 mg ℓ^{-1} was recorded.

The hypoxic conditions at Station 5 can be attributed to the localized activities of cattle, which were frequently observed wading into the river at this station, thus stirring up bottom sediments and so accounting for the low oxygen. Such hypoxic conditions generally did not persist for longer than a tidal cycle (approximately 6 h); during high tide, saltwater with a higher DO content would penetrate into the tributary.

Figure 2b illustrates the DO conditions on 1 April. During low tide (at dawn), DO levels of <5 mg ℓ^{-1} occurred in the near-bottom strata at Station 7, and the lower 0.8 m of the water column at Station 8 had a DO of 3 mg ℓ^{-1}. Station 10 could not be reached then, because of the shallowness of the water at the sand banks. However, by noon on the same day, at high tide, the DO content at Station 8 had increased to 6 mg ℓ^{-1}, and it was greater than this value at the other stations.

DO levels within the estuary typical of post light-rainfall periods

There were nine periods of light rainfall (between 20 and 45 mm over 1–3 consecutive days), with on average rainfall of 33.2 mm. This paper examines two typical periods, namely conditions following the 35 mm of rainfall that fell over two days on 2 and 3 April 1993 (8 mm, followed by 27 mm), and the conditions following the light rainfall (28 mm) on 3 June 1993.

Unlike the immediate rainfall-salinity response within the estuary (Schumann and Pearce 1997), the drop in DO within the estuary was delayed. While the rain was recorded on 2 and 3 April, the DO levels in the estuary ranged from 4 to 10 mg ℓ^{-1}, with the higher levels of DO mostly in the lower estuary and surface strata. The lowest DO levels (associated with this rainfall-runoff) were recorded some three days later on 6 April. Figure 3a shows that, by spring low tide on 6 April, hypoxic conditions were measured in the

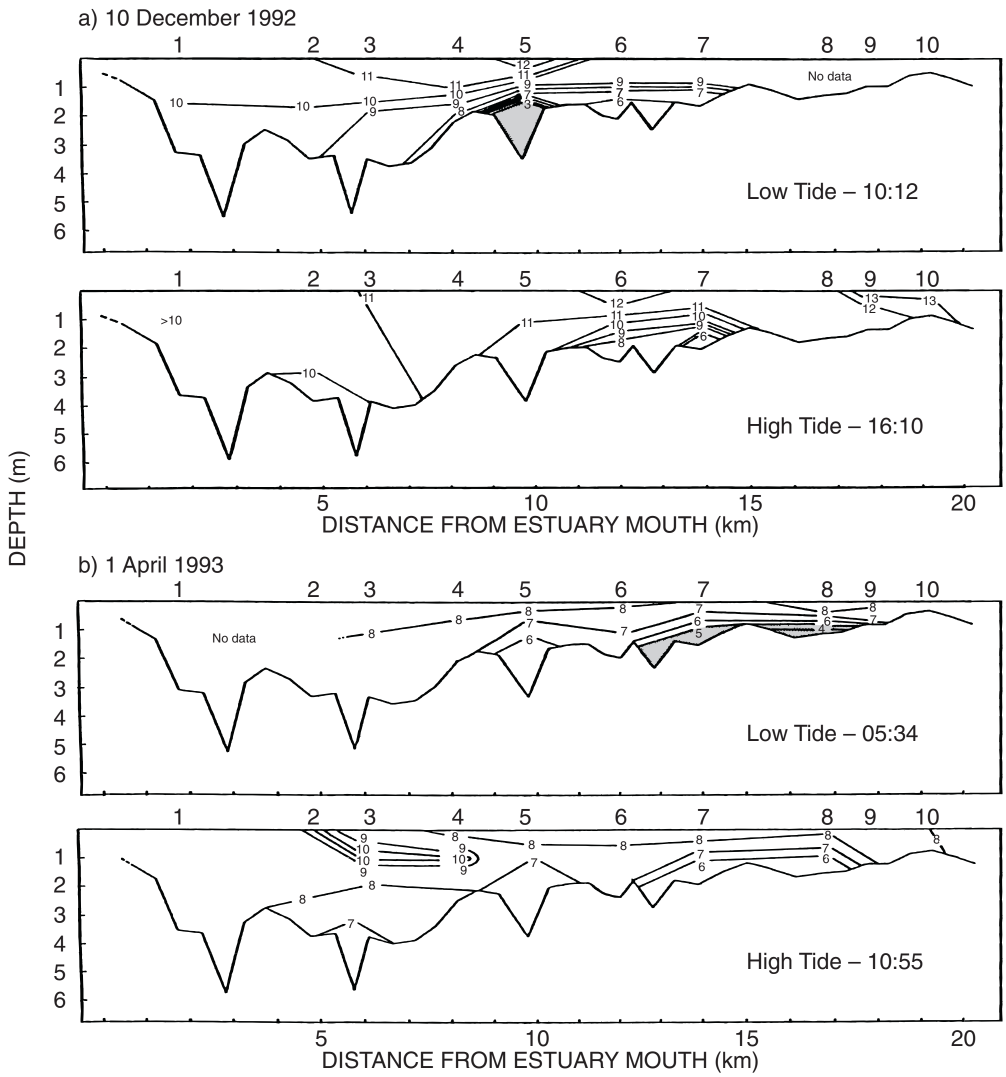

Fig. 2: Dissolved oxygen (mg ℓ^{-1}) profiles of the Gamtoos Estuary typical of non-rainfall conditions at high and low tide on (a) 10 December 1992 and (b) 1 April 1993

near-bottom strata from Station 7, upstream to Station 9. However, recovery of DO levels was within the tidal cycle, when during spring high tide that afternoon, saline water (Fig. 3b), with a core DO content of 10 mg ℓ^{-1}, penetrated upstream, mixing and replenishing DO levels. The replenishing effects were evident as far as Station 7, where DO was >6 mg ℓ^{-1}. The shallow sand banks beyond Station 7 hinder penetration of seawater beyond that point, except at spring high tide, and the freshwater input was much reduced by high tide on 6 April, extending just downstream of Station 9.

A delayed response to the drop in DO was again observed three days after a small rainfall event (28 mm) in early June 1993. During high tide on 7 June, DO ranged from >10 mg ℓ^{-1} in the surface water of the

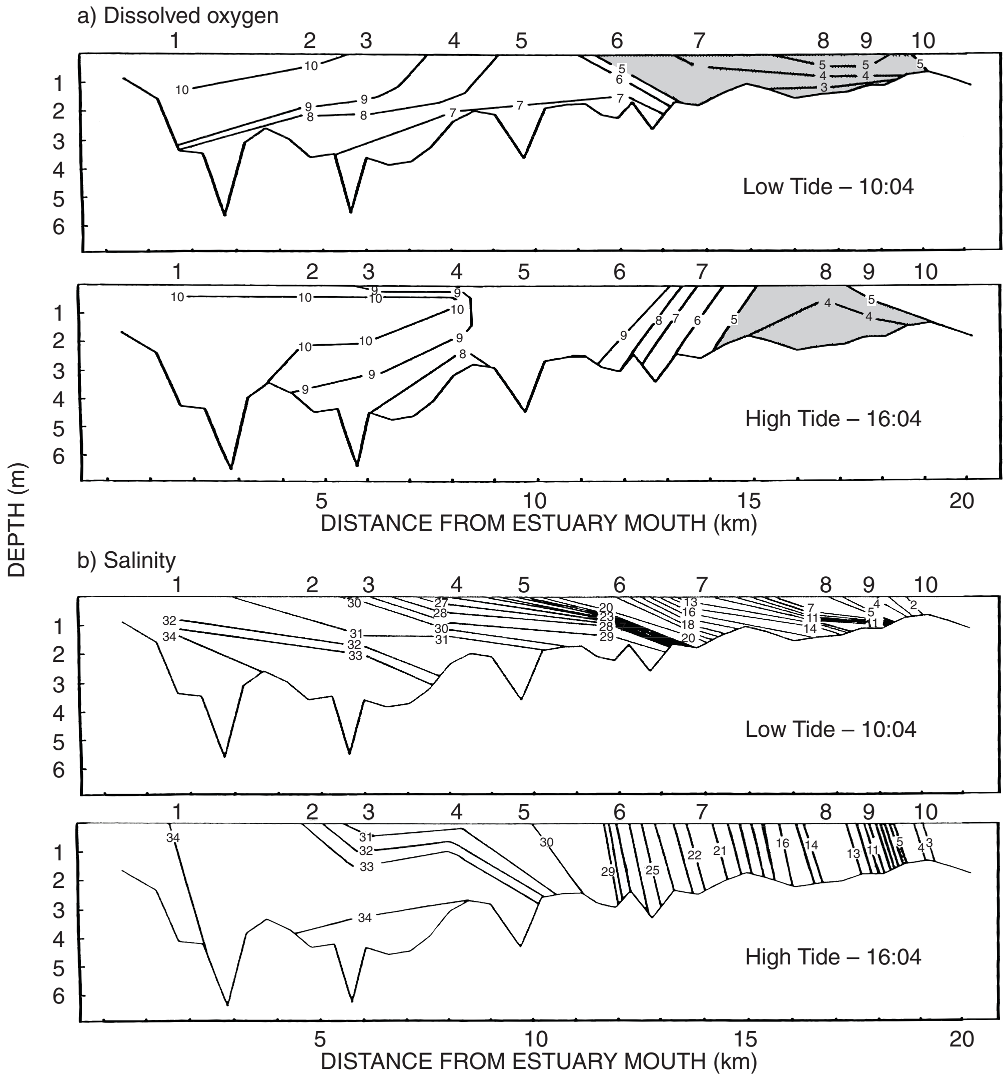

Fig. 3: (a) Dissolved oxygen (mg ℓ^{-1}) and (b) salinity profiles of the Gamtoos Estuary typical of post light-rainfall conditions at high and low tide on 6 April 1993

lower estuary (Stations 1, 2, 3 and 4) to <5 mg ℓ^{-1} in the bottom water of Station 7 and <3 mg ℓ^{-1} in the bottom water of Station 8 (Fig. 4a). Later that day, when measurements were made at low tide, and with not much change to the salinity stratification (Fig. 4b), the DO had risen to levels recommended as suitable for the health of aquatic organisms (i.e. the DO was around 6 mg ℓ^{-1} at Stations 6 and 7).

DO levels within the estuary typical of a heavy rainfall event

Between 10 and 13 June 1993, more than 87 mm of rain was recorded, with the rainfall on 12 June being the most to fall within a 24-h period over the 102 years of data collection at Hankey (Weather Bureau 1994). Flow increased from around 1 m^3 s^{-1} to an estimated

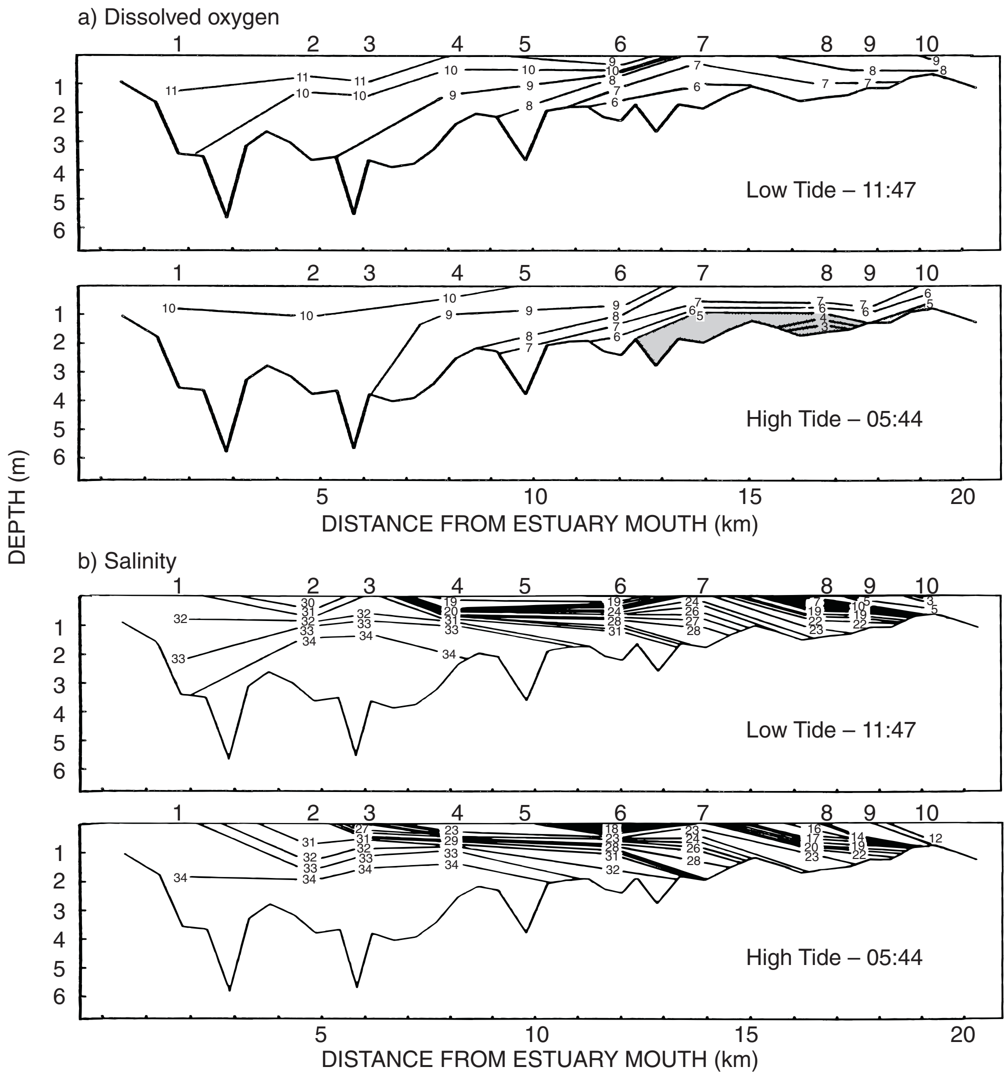

Fig. 4: (a) Dissolved oxygen (mg ℓ^{-1}) and (b) salinity profiles of the Gamtoos Estuary typical of post light-rainfall conditions at high and low tide on 7 June 1993

flow >100 $m^3 s^{-1}$ (automated measuring equipment had to be removed from the estuary, and some instrumentation was lost during the high flows). Figure 5a shows the drop in DO following this sizeable rainfall event when hypoxic conditions were recorded throughout the estuary during low tide. The influx of marine water with a DO content of 10 mg ℓ^{-1} at high tide allowed some replenishment of oxygen in the lower and middle estuary, penetrating upstream to the aggraded section near Station 7. However, hypoxic conditions persisted in the bottom strata of Stations 2 and 3, as well as from Stations 6–10. The DO at the confluence with the Loeriespruit (Station 5) did not show the same range of DO as the rest of the estuary;

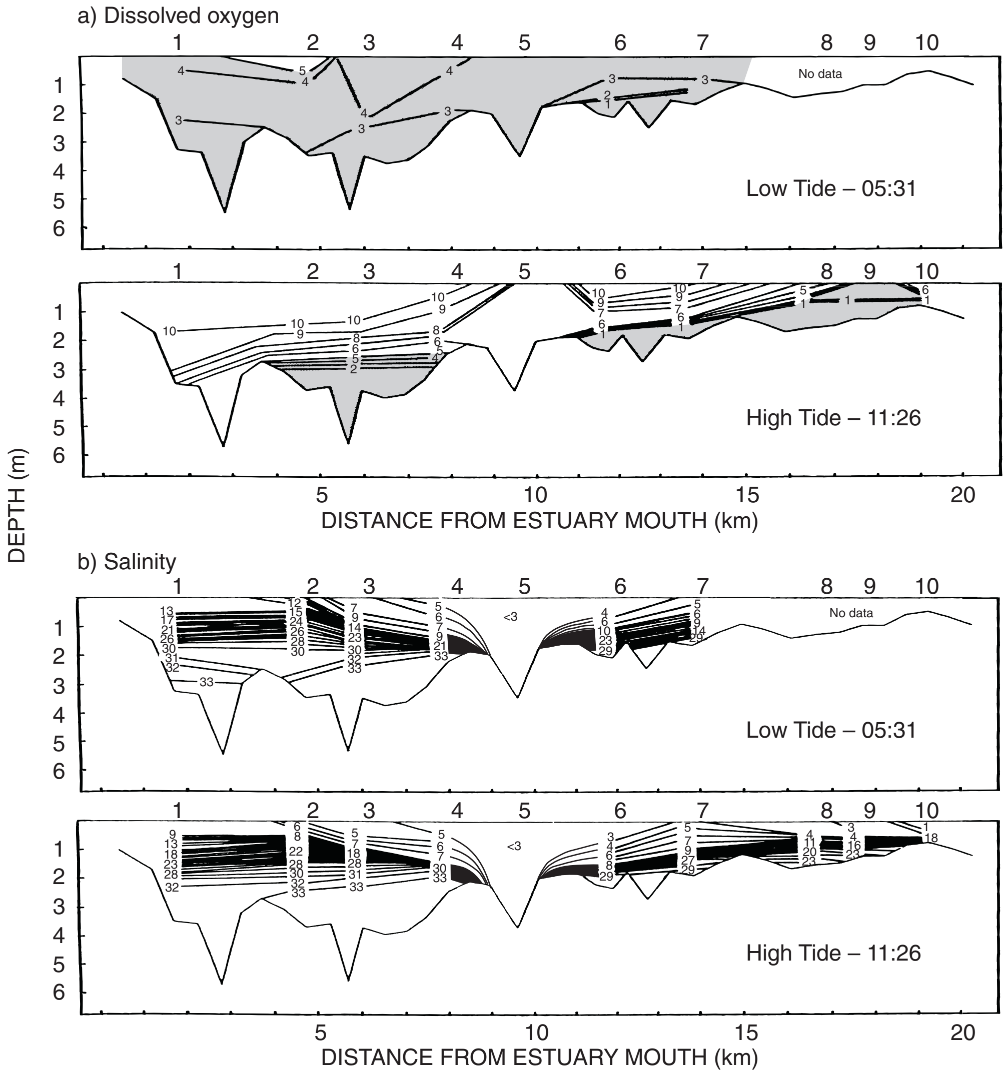

Fig. 5: (a) Dissolved oxygen (mg ℓ^{-1}) and (b) salinity profiles of the Gamtoos Estuary showing conditions following heavy rainfall at high and low tide on 14 June 1993

DO values were between 6 and 7 mgℓ^{-1} throughout the water column, whereas at adjacent stations values ranged from <5 to 11 mg ℓ^{-1} (Station 4) and <1 to 10 mg ℓ^{-1} (Station 6). This may be partly attributable to the strong freshwater discharge from the Loeriespruit with a uniform salinity <3 (Fig. 5b), compared with the conditions at the adjacent stations where there was salinity stratification, as well as the lack of penetration of seawater (with its higher DO) into the tributary. The Loeriespruit is bounded by a smaller and less intensively farmed area than that of the Gamtoos catchment area, which may also account for the higher minima at this station. At Station 9, there were hypoxic conditions throughout the water column, with a narrow layer at the surface where DO was >2 mg ℓ^{-1}. The hypoxic conditions at Station 9 may have been exacerbated by the discharge of low-oxygen runoff from an agricultural drain outlet pipe just upstream of the station. The outlet pipe is the discharge point for a surface drainage system that collects runoff and soil-water throughflow from an adjacent 0.5 km^2 area of agricultural fields (Pearce and Schumann 1999).

Prior to the 10–13 June rainfall there was a high degree of clarity throughout the estuary at both high and low tides, all stations exhibiting a 5% light penetration >0.9 m. The Secchi disc readings dropped to <0.1 m following the heavy rainfall, when sediment-charged surface runoff entered the estuary and turbulent flow caused the disturbance of estuarine sediments.

The freshwater input into the estuary increased further, and by 16 June the entire upper estuary upstream of Station 7 had a salinity of <1 (Fig. 6b), the surface stratum (to about 1 m deep) of freshwater extended to the ocean. With the freshwater outflow dominating, Figure 6a shows that the DO content of the entire estuary remained below the recommended aquatic limit with a value of <3 mg ℓ^{-1}.

DISCUSSION

Ballester *et al.* (1999) and Ansa-Asare *et al*. (2000) found that the areal extent of hypoxia, and the time delay to hypoxia (Clark *et al*. 1995), were related to the quantity of biodegradable organic matter entering the aquatic environments. Inputs of organic matter into the Gamtoos Estuary during rainfall occur as diffuse surface runoff and point source inputs, as well as through delayed diffuse inputs of irrigation return flow (subsurface) from adjacent agricultural fields (Pearce and Schumann 2001). The extensive hypoxic conditions following the extreme rainfall of June 1993 were almost immediate throughout the estuary and deteriorated for some time thereafter, which indicates a substantial input of organic matter into the estuary.

Hypoxia generally occurred in the near-bottom waters of the upper estuary. The localized nature of the hypoxia can be related to a number of factors: localized point source inputs (at the agricultural drain upstream of Station 9 – see Pearce and Schumann 1999); the zone of settling of decaying organic matter at the sediment-water interface (which is in turn determined by the position of the freshwater-saltwater interface); estuarine hydrodynamics (low flow rates will hinder surface aeration); the rate of mixing of estuarine water with oxygen-rich marine waters; the rate of flushing through the mouth; and estuary hydrometry (localized areas of scour; estuarine-marine exchanges as determined by mouth configuration). Whereas there are localized areas of scour throughout the estuary, the deep scour holes in the upper estuary (particularly in the vicinity of Station 8) acted as a sink for the accumulation of organic debris. The subsequent decomposition of the organic matter would therefore lead to localized areas of hypoxia in the bottom strata. Hypoxic conditions in the bottom strata could adversely affect benthic communities. Over the inner shelf off Cameron, Louisiana, hypoxic conditions in the bottom strata led to reduced numbers of macrobenthic species, with high mortalities during anoxia (Gaston 1985). Macrobenthic species are further reduced through increased predation while attempting to move from hypoxic areas (Dauer *et al*. 1992).

Pronounced salinity stratification, as takes place during higher freshwater inflow, inhibits the exchange of oxygen between surface and bottom strata (Kuo and Nielson 1987). Where such stratification exists, the less dense surface water will flow as a coherent layer, exhibiting little mixing with the denser bottom water. DO in surface strata will therefore remain within the surface layers, with little mixing with underlying strata. The stratified conditions during low tide on 6 April (Fig. 3b) may have influenced the upper estuary hypoxia. However, during high tide, vertically homogeneous salinity was measured in the middle and upper estuary, but despite the lack of estuarine stratification, there were hypoxic conditions in the near-bottom strata of Stations 8 and 9. Therefore, factors other than stratification alone were controlling DO levels. Conversely, during the afternoon of 7 June, salinity stratification was more pronounced than in the morning (Fig. 4b), which should have hindered a rise in DO, yet this was contrary to observations, again indicating that variables other than stratification were controlling DO dynamics. Similarly, on 14 June, although there was salinity stratification throughout the estuary (Fig. 5b), low DO values were not confined to the lower strata, but extended throughout the estuary during low tide.

One of the factors controlling the depletion and replenishment of DO (regardless of stratification) is the natural diurnal fluctuation in DO corresponding with respiration and photosynthesis of aquatic organisms. During the day as photosynthesis increases, so too does DO, provided there is adequate light penetration, whereas at night DO drops because of respiration. The rise in DO levels on 7 June (following light rainfall) may be partly attributable to localized photosynthesis activity. The water clarity then (and during the non-rainfall periods monitored) was sufficient to permit 5% light penetration to a depth of at least 1 m throughout the estuary. Given the thick aquatic plant growth in the upper estuary, the change in DO exhibited on 7 June (Fig. 4a) could be a result of natural diurnal fluc-

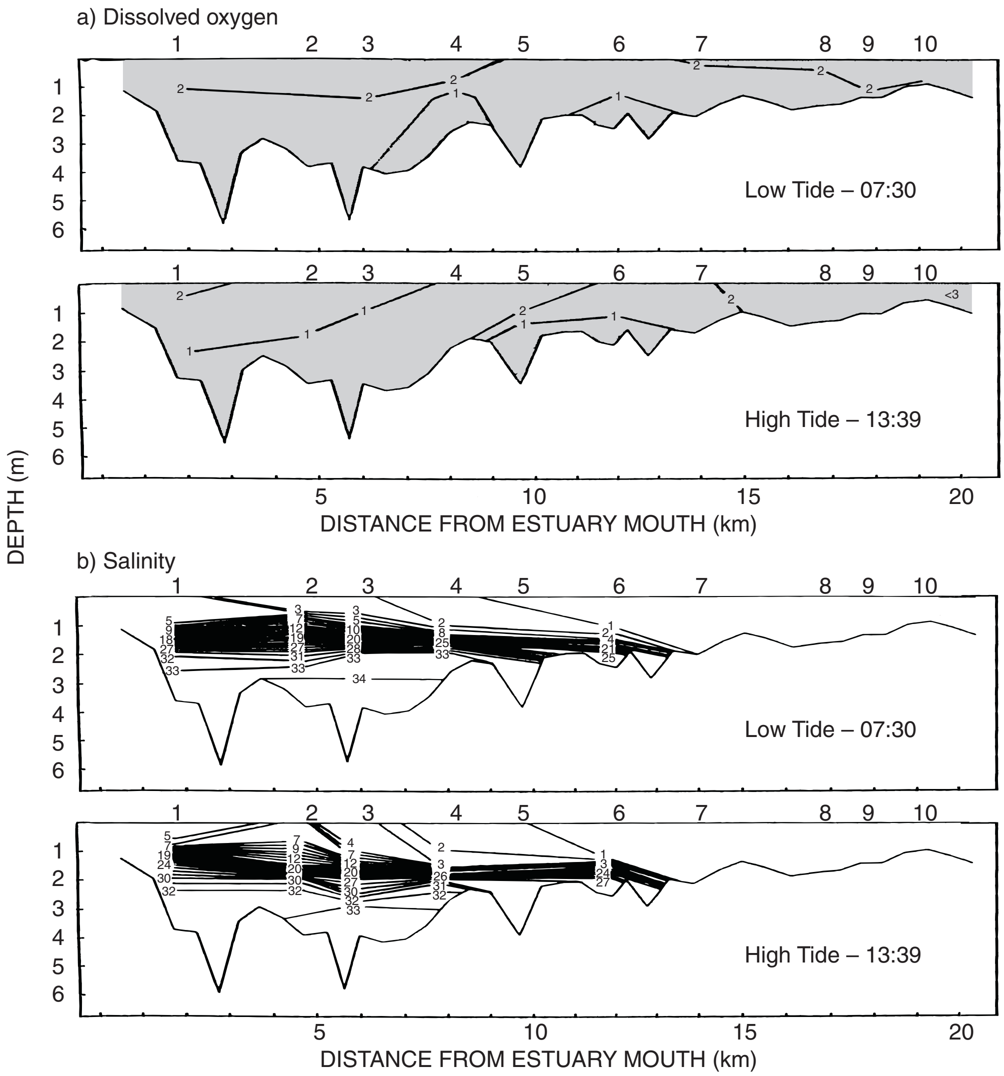

Fig. 6: (a) Dissolved oxygen (mg ℓ^{-1}) and (b) salinity profiles of the Gamtoos Estuary showing conditions following heavy rainfall at high and low tide on 16 June 1993

tuations associated with the photosynthesis of aquatic flora. Similarly, the drop in DO and recovery exhibited in the upper estuary on 1 April (non-rainfall period) may be partly on account of natural diurnal fluctuations. After the heavy rainfall, however, the high sediment load would hinder DO replenishment, because of the subdued photosynthesis of aquatic flora as a consequence of poor light penetration during this period. Even after three days, although the depth of 5% light penetration had increased to 0.5 m, this is still deemed insufficient to permit photosynthesis. Furthermore, any photosynthesis would be masked by the dominating influence of the freshwater input at the tidal head.

Other factors (besides photosynthesizing aquatic flora) responsible for the replenishment of DO include the aeration of surface waters through turbulence during high flows (Atkinson *et al.* 1995, Guasch *et al.* 1998) or wind-generated aeration (Pearce and Schumann in prep.), and the input of more-oxygenated water into the estuary. Contrary to the findings of Atkinson (1995), but in keeping with those of Graczyk and Sonzogni (1991) and Reyes and Merino (1991), it appears in the Gamtoos Estuary as if the resuspension of sediment during turbulent flow led to the release of stored organic matter, which retarded photosynthesis and led to an increase in oxygen consumption (resulting in hypoxia).

Following the light rainfall in April, there was substantial replenishment of DO during high tide, when seawater with a DO concentration of around 10 mg ℓ^{-1} penetrated the estuary. After the light rains in early June, however, oxygen replenishment was during low tide; this may be attributed to both localized photosynthetic activity as well as the input of freshening waters with a DO of 9 mg ℓ^{-1} at the tidal head. Similarly, during dry periods, the role of freshwater and saltwater inputs in replenishing DO levels is demonstrated, although to a lesser extent.

Although tidal processes have been identified as an important source of replenishment of oxygen in the Gamtoos Estuary, following the extreme rainfall of mid June there was no quick replenishment of DO, and the extensive nature of the hypoxia would have severe implications for estuarine biota. The loss of estuarine biota could happen in a number of ways – when species are unable to move to higher oxygenated waters (Nebeker *et al*. 1992), through the synergistic toxicity of compounds in the presence of low DO (Hagerman and Vismann 1995), or when juvenile populations are flushed from the estuary during high flows (Gupta *et al*. 1994). Furthermore, the period of exposure to hypoxia may impact biota; Allan and Maguire (1991) reported mass mortalities of the prawn *Penaeus monodan* after 72 h of hypoxia. In South Africa, Whitfield and Paterson (1995) reported mass fish mortalities during flood events in the Sundays and Great Fish estuaries as a result of the combined effect of clogging of the gill filaments and respiratory stress (due to low DO levels). Webb *et al*. (1997) report the flushing of mysid populations (*Mysidopsis wooldridgei, Rhopalophthalmus terranatalis, Gastrosaccus brevissura*) from the Gamtoos Estuary during floods.

Although a number of reports on South African estuaries mention the relationship between DO levels and estuarine biota (Whitfield 1996), and the drop in DO following flooding (Liptrot and Allanson 1978) or dam releases (Scharler and Baird 2000), Whitfield and Paterson (1995) emphasize the need for further research on the tolerance limits of estuarine fish to suspensoid and DO levels during floods. The research reported here, while lacking a biological component, nonetheless presents useful data on the fall and recovery of DO levels in the Gamtoos Estuary following rainfall. Furthermore, although the study was conducted in a wetter-than-average year, given the temporal distribution of rainfall, it is deemed that the results presented are characteristic of the response of the estuary during a range of rainfall conditions. Also, the findings may have value for studies of similar open, low-flow estuaries that experience periodic floods, such as the Sundays and Swartkops systems. The DO dynamics in permanently or temporarily closed systems (such as the Great Brak and Kromme estuaries) may differ considerably, although Baird and Pereyra-Lago (1992) report that the slow current velocities, thermal and saline stratification of the water column, inefficient mixing and water exchange and decaying plant material in the Marina Glades system of the Kromme Estuary were responsible for localized hypoxia in bottom waters in the system. In the Gamtoos Estuary, if estuarine morphology (e.g. constriction at the estuary mouth because of sedimentation) or upstream controls (such as overtopping or releases from the Kouga Dam, which did not occur during the present study period) were to change, the response and recovery of DO levels may differ from those presented here.

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