The effects of a single freshwater release into the Kromme Estuary. 1: General description of the study area and physico-chemical responses

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Abstract

The natural runoff from the Kromme River catchment area has been severely restricted by impoundments with storage capacities exceeding the mean annual runoff (MAR). As a consequence, freshwater input into the Kromme Estuary has been drastically reduced and the estuary itself has been labelled as 'freshwater-starved'. The annual allocation of storage water to the estuary (2 x 10^6 m^3) has been released from the Mpofu Dam as a single release. The impact on various physico-chemical parameters as well as inorganic dissolved nutrients (phosphate, nitrate, nitrite, ammonia) in the estuary has been investigated with regards to the magnitude, persistence and management of future releases. The impact on dissolved nutrient concentrations was short-lived (less than 7 d), and pre-release concentrations were quickly re-established. The release raised especially nitrate and nitrite concentrations temporarily because of elevated concentrations in the storage water, but slightly diluted phosphate concentrations in the estuary. N:P ratios indicated phosphate limitation, while ammonia showed no direct response to the release. This experiment showed no long-lasting effect on the estuary in terms of inorganic dissolved nutrients, and it is apparent that the nutrient status can only be enhanced under a continuous release strategy. Natural runoff reaching the estuary appears to be more beneficial, especially in terms of phosphate.

Introduction

The high productivity in estuaries is a result of riverine and oceanic input into these systems. Nutrients in estuaries are derived from various sources, which include *inter alia* terrigenous runoff, the sea, the atmosphere and internal nutrient (re)cycling (Webb, 1981). The riverine input is in general the most important contributor to its estuary (e.g. Aston, 1980; Funicelli, 1984), which emphasises the consequences of excessive freshwater abstraction in the catchment area. Nutrients in the estuary are exposed to biological, chemical and physical interactions (Aston, 1980; Webb, 1981; Smith et al., 1985; Eyre, 1994; 1997), including the ad-/desorption by sediments and particulate material, the utilisation by plants, and export to the sea. Estuaries can act as either a source or a sink for nutrients, depending on the amount received and the extent of internal processes (Biggs and Cronin, 1981; Pritchard and Schubel, 1981; Chapman and Thornton, 1986; Baird and Winter, 1990; Falcao and Vale, 1990; De la Lanza-Espino and Rodriguez-Medina, 1993; Eyre, 1994).

The aims of this study were to investigate the impact of a freshwater pulse on the nutrient status of the otherwise freshwater-starved Kromme Estuary with regard to the magnitude and persistence of change brought about by the release, and to comment on the feasibility of freshwater release strategies from upstream impoundments. The freshwater pulse comprised a release of 2 x 10^6 m^3 from the Mpofu Dam, which is equal to the annual allocation of water to the estuary to compensate for evaporation (Jezewski and Roberts, 1986).

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Study area

The Kromme River, which is approximately 95 km long, originates in the Tsitsikamma mountains and drains a catchment area of approximately 936 km^2 (Reddering and Esterhuysen, 1983). The catchment is partly vegetated by fynbos and natural forest. The remaining area is utilised as farmland for stockraising and grain cultivation (Baird et al., 1992). Rainfall peaks in spring and autumn, but is low during January and February (Bickerton and Pierce, 1988). The mean annual precipitation ranges between 700 and 1 200 mm. The high mean annual runoff of approximately 105.5 x 10^6 m^3 is a consequence of the geomorphologic catchment characteristics, i.e. high relief, rocky slopes and sparsely vegetated areas (Reddering and Esterhuysen, 1983) (see Fig. 1).

Alterations to the river flow in the Kromme catchment are a result of two major obstructions that have severely reduced freshwater input into the estuary. The Kromrivier Dam (built in 1943) is situated approximately 35 km from the tidal head of the estuary and has a storage capacity of 33.3 x 10^6 m^3. The Mpofu Dam, situated only 4 km from the tidal head of the estuary, with a storage capacity of 107 x 10^6 m^3, was completed in 1982 (Bickerton and Pierce, 1988). Both dams have the combined capacity of storing ca 133% of the mean annual runoff of the Kromme River catchment.

The Kromme Estuary opens into St. Francis Bay and stretches inland for about 14 km from the mouth to the tidal head. The Geelhoutboom is a major tributary, which enters the estuary 7 km from the mouth. There are also numerous small tributaries along the entire length of the Kromme Estuary. The most prominent of these, the Sand River, drains part of a by-pass dunefield and joins the estuary 1.3 km of the mouth (Bickerton and Pierce, 1988). The estuary is a popular recreation area. A marina is situated near the mouth and numerous holiday shacks have been built further upstream. The land adjoining the estuary is used for farming to a limited extent (Reddering and Esterhuysen, 1983; Bickerton and

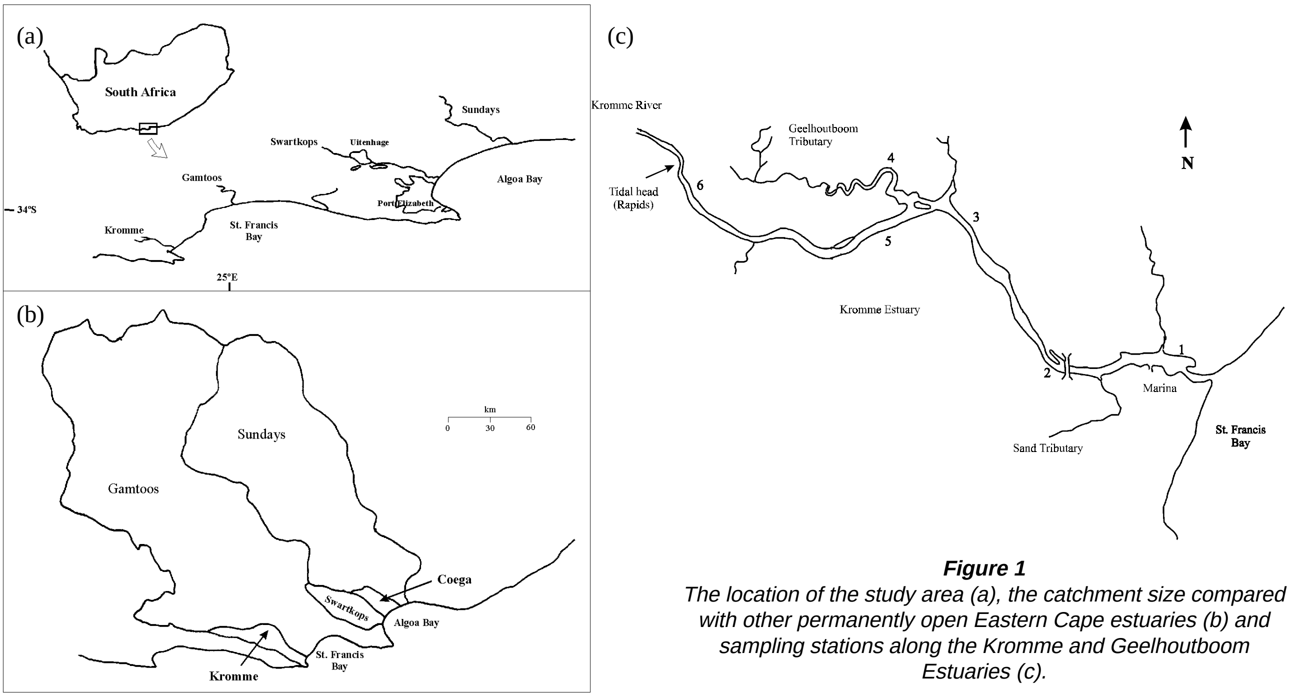

Figure 1
The location of the study area (a), the catchment size compared with other permanently open Eastern Cape estuaries (b) and sampling stations along the Kromme and Geelhoutboom Estuaries (c).

Pierce, 1988). Natural vegetation occurs alongside the middle and upper reaches of the estuary, as well as along the banks of the Geelhoutboom tributary.

A direct effect of the extensive water abstractions in the catchment is the high salinity in the estuary throughout the year and the occasional occurrence of hypersaline conditions in the upper reaches. Various studies often characterised the Kromme Estuary as freshwater starved (e.g. Marais 1983; Hanekom and Baird, 1984; Emmerson and Erasmus, 1987; Adams et al., 1992; Newman, 1993; Jerling and Wooldridge, 1994). Data collected during the past 25 years show that both the Sand River and Geelhoutboom tributary, the biggest tributaries to the Kromme system, are not significant freshwater contributors to the system (Scharler et al., 1997). These data also show that salinities above 25 ‰ predominate at the tidal head of the estuary, whereas lower salinity values (< 25 ‰) were only measured on occasion near the surface in the upper reaches of the estuary (Scharler et al., 1997).

Transparency in general increases towards the head of the Kromme Estuary (Hecht, 1973; Marais, 1984; Cloete, 1990; Scharler et al., 1997), but can change rapidly during freshets (equivalent to a one in two years flood (Huizinga, 1999)) or floods. Due to erosion of the unvegetated areas in the Geelhoutboom catchment, episodic freshwater inflows can result in high loads of silt to the Geelhoutboom and Kromme Estuaries.

Materials and methods

Physico-chemical measurements and water samples were taken at low water slack tides at six stations in the Kromme and Geelhoutboom estuaries (Fig. 1). Salinity (‰) and temperature (°C) were measured at depths of 0.5 m intervals with a CTDS Valeport Ser. 600. Secchi depth (cm) measurements gave an indication of transparency. Dissolved oxygen concentrations ($mg \cdot l^{-1}$) and percentage saturation (using a Jenway 7091 meter) and pH (using a Jenway 3100 meter) measurements were taken at the surface, 0.5 m, 1 m and 1 m intervals thereafter.

At the same six stations, inorganic dissolved nutrient concentrations were measured at three occasions before (6, 13 and 16/11/1998), two during (18/11/1998 and 20/11/1998) and three occasions after the release (23/11/1998, 3/12/1998 and 14/11/1998). Duplicate water samples were taken at the surface, 0.5 m and 1 m, and at 1 m depth intervals from thereon. Samples were filtered the same day and analysed the following day. Methods for analysing the selected nutrients followed those given by Strickland and Parsons (1972) for phosphate, Solórzano (1969) for ammonia, and Bate and Heelas (1975) for nitrate and nitrite (as modified from Strickland and Parsons (1972)). Concentrations of nutrients expressed in text and on figures in micromoles (μM) per litre.

Results

Physico-chemical parameters

On 16 November at approximately 18:00 the sluice gates of the Mpofu Dam were opened to release 2×10^6 m^3 of surface water at a rate of 15 $m^3 \cdot s^{-1}$. The released water reached the head of the estuary approximately 6 to 7 h later, with inflow being supplemented by natural runoff following heavy rains. The Geelhoutboom River and a small tributary about 2 km downstream of the tidal head of the Kromme Estuary also started flowing on 20/11/98 in response to these rains. Seven days after the start of the release (23/11/1998) freshwater inflow from all sources had ceased.

Before the release, salinity measurements ranged from 34.0 to 35.0‰ throughout the Kromme Estuary (Fig. 2). One day after the start of the release (17/11/1998), depth-averaged salinities decreased to 17.9‰ in the upper reaches and to 27.3‰ in the middle reaches, measured upstream of the Geelhoutboom confluence. The lowest salinity values were measured two days after the start of the release (on 18/11/1998), and measured 7.0‰ in the upper reaches and 26.0‰ in the middle and lower reaches. In the Geelhoutboom tributary and downstream of the confluence with the Kromme Estuary main channel, salinity values were 22.0‰ as a result of rain induced runoff. Shortly after the release, salinity gradually increased. Seven days after the release (on 23/11/1998), a longitudinal salinity gradient ranging from 28.3‰ in the upper reaches to 34.2‰ at the mouth was established which was similar to the gradient measured before the experimental release.

Water temperature in the estuary did not change much follow-

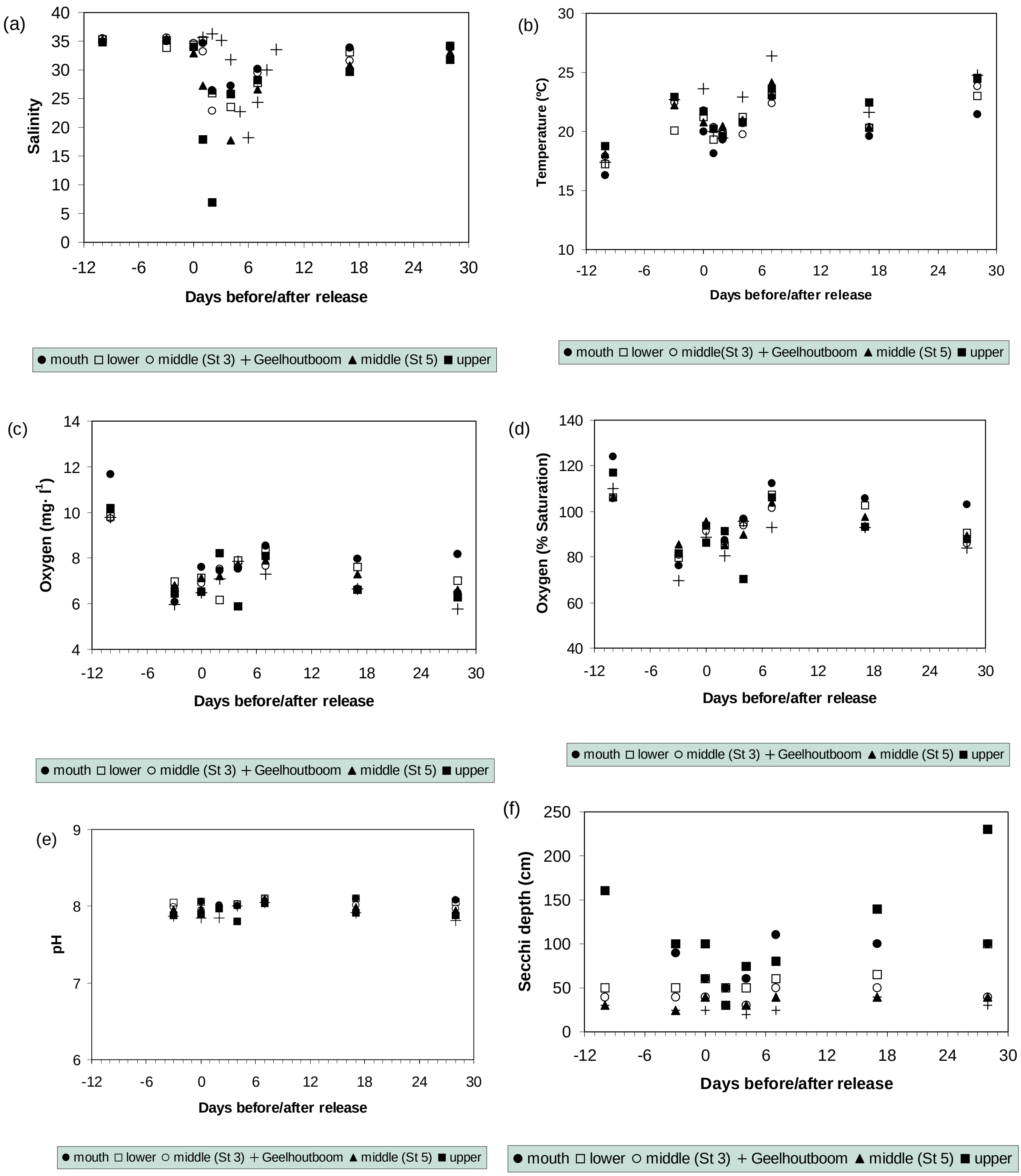

Figure 2
Salinity (a), Temperature (b), dissolved oxygen (c), % oxygen saturation (d), pH (e) and Secchi depth (f) measured in the Kromme Estuary before, during and after the release from the Mpofu Dam. On the evening of the16 November (day 0 in the graphs) the sluice gates were opened.

ing the freshwater release and pH values were virtually the same throughout the study period (Fig. 2). Dissolved oxygen concentrations and percentage saturation also did not deviate from their normal range as measured before and after the release (Fig. 2). Water transparency changed in the upper reaches as well as near the mouth and in the lower reaches. In the upper reaches, Secchi depths decreased from 100 cm (measured before the release) to 30 cm two days after the release, but subsequently rose to 80 cm seven days after the release, 140 cm 17 days after and > 200 cm four weeks later. In the lower reaches of the estuary, Secchi depths increased from 50 cm measured two days after the release to 100 cm four weeks later (Fig. 2).

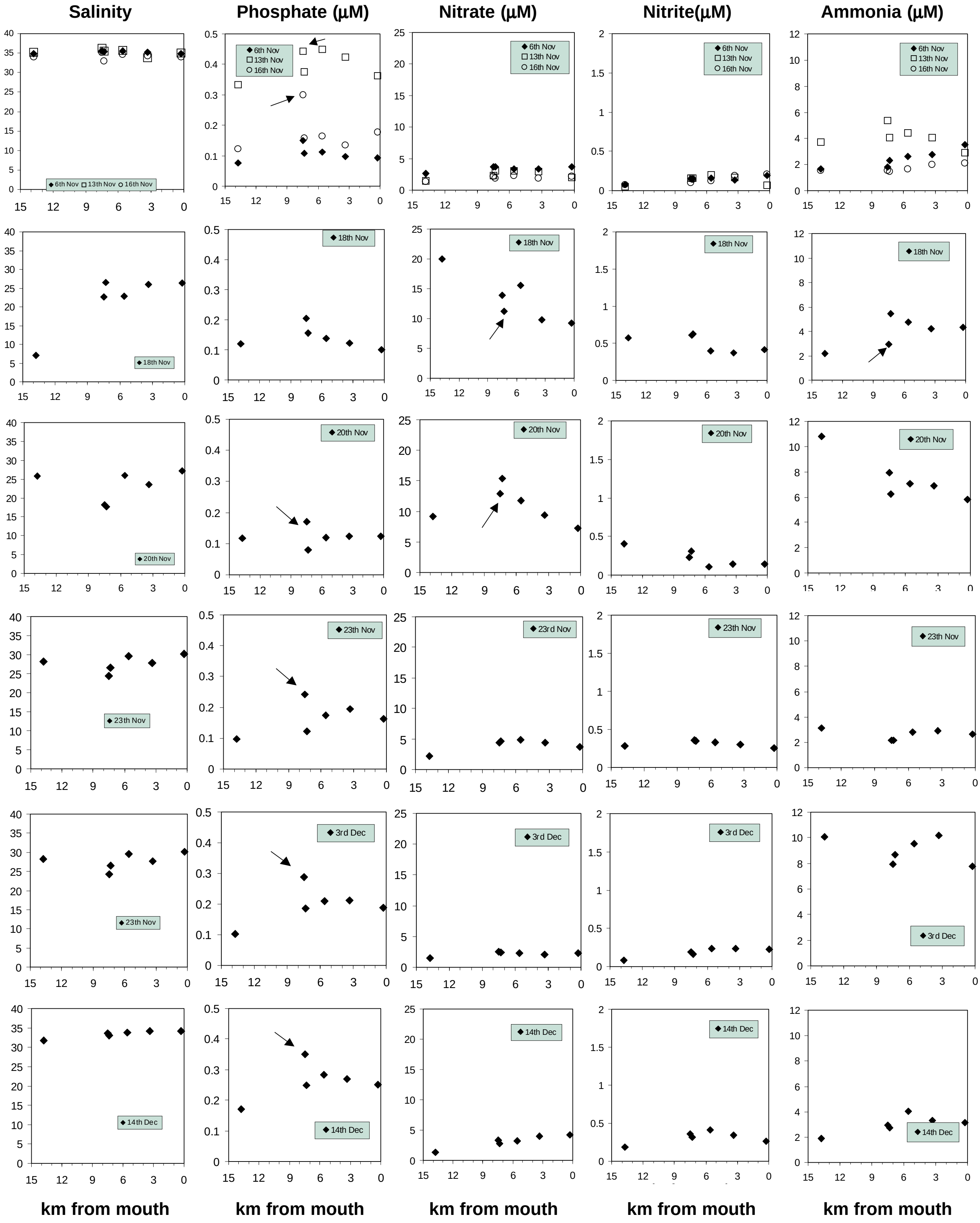

Figure 3

Salinity and inorganic dissolved nutrient concentrations measured in the estuary before, during and after the release. (a) before release (6, 13 and 16/11/1998), (b) 18/11/1998, (c) 20/11/1998, (d) 23/11/1998, (e) 3/12/1998, (f) 14/11/1998. Arrows indicate concentrations measured in the Geelhoutboom tributary.

Inorganic dissolved nutrients

The freshwater input into the estuary resulted in a stratified water column in terms of nitrate, nitrite and phosphate concentrations. Phosphate concentrations were low throughout the study (< 0.5 µM) and were reduced further during the release (18/11/1998 and 20/11/1998) throughout the estuary to < 2 µM. They then increased steadily until 7 d after the start of the release (23/11/1998) when they were once again back to former levels (Fig. 3).

Nitrite concentrations were below 0.5 µM throughout the estuary, both before and after the release, but were elevated slightly above 0.5 µM (depth-averaged value) during the release. The greatest change in inorganic nutrients was in nitrate concentration which increased from < 5.0 µ M before the release to between 9.0 and 21.0 µM (depth-averaged values) during the release (18 and 20/11/1998). Pre-release concentrations were re-established by 23/11/1998 (7 d after the start of the release). Nitrate concentrations in the water flowing in at the tidal head ranged from 17.5 to 26.0 µM and this input was responsible for the elevated nitrate levels in the estuary. Ammonia concentrations in the inflowing water at the tidal head (ranging from 1.1 to 2.9 µM) were generally lower than the levels measured in the upper reaches of the estuary (depth-averaged values ranging from 2.2 to 10.8 µM).

The data from the Geelhoutboom tributary showed slightly higher phosphate concentrations compared with the middle reaches of the Kromme Estuary main channel before, during and after the release, and could therefore be a source of small amounts of phosphate. Nitrate and ammonia concentrations, however, were lower in the Geelhoutboom during the release (18 and 20/11/1998), but similar to those in the Kromme Estuary main channel before (6, 13 and 16/11/1998) and after (23/11/1998, 3 and 14/12/1998) the release (Fig. 3).

Highly significant relationships ($p < 0.001$) were found between salinity and phosphate, nitrite and nitrate (Table 1). Phosphate showed a positive correlation with salinity ($r = 0.41$), whereas nitrite ($r = -0.39$) and nitrate ($r = -0.92$) were negatively correlated. Ammonia ($r = -0.05$), however, was not significantly correlated to salinity (Table 1). These results once again emphasise the strong influence freshwater pulses may have on nitrate, nitrite and phosphate levels in estuaries.

Results from multiple comparison tests for differences in salinity and dissolved inorganic nutrient species before, during and after the release are summarised in Table 2. The results indicated statistically significant differences in salinity between each of the three time periods. Concentrations of phosphate, nitrate and ammonia were not significantly different before and after the release. Only nitrite maintained significantly higher concentrations after the release, although overall concentrations measured in all three time periods were low (see Fig. 3). During the release (18 and 20/11/1998), all dissolved inorganic nutrients measured underwent significant changes in concentrations when compared with measurements taken before and after the release. In the case of phosphate and nitrite, statistically significant differences were detected, but differences in actual concentrations were small.

Throughout this study, N:P (DIN:PO_4) ratios in the estuary were higher than the Redfield ratio (16:1) (Fig. 4). The ratios ranged from approximately 13 (measured only once) to 80 before and after the release. The water in the Geelhoutboom tributary often had a slightly lower N:P ratio than the middle reaches of the Kromme Estuary. There was no apparent pattern of N:P ratios along the longitudinal axis of the estuary. During the release, N:P ratios changed considerably, and mean values were between 130 and 160 (Fig. 4). The high ratios were mainly caused by the high nitrate input. On 18/11/1998 (2 d after the start of the release) the highest ratio values were measured at the tidal head, which ranged from 261 at the surface to 57 at the bottom. On 20/11/1998, however, highest N:P ratios (ranging from 332 at the surface to 180 at the bottom) were measured in the middle reaches. The Geelhoutboom showed comparatively low N:P ratios (around 85 to 123) during the release.

TABLE 1
Linear Correlation/Regression Statistics of Salinity vs. Inorganic Dissolved Nutrients for the Entire Estuary (NS: Not Significant, S*: P < 0.001, α = 0.05)

	r	r^2	t	p	n	Significance
Phosphate	0.41	0.17	6.18	< 0.001	190	S*
Nitrate	-0.92	0.83	-30.71	< 0.001	183	S*
Nitrite	-0.39	0.15	-5.84	< 0.001	191	S*
Ammonia	-0.05	0.003	-0.69	0.49	191	NS

TABLE 2
Multiple Comparison of Salinity and Inorganic Dissolved Nutrient Measurements Taken Before, During and after the Release (α = 0.05)

ANOVA	F	p	Tukey	p
Salinity	48.13	< 0.001	before ≠ after during ≠ after during≠ before	0.003 < 0.001 < 0.001
Phosphate	3.92	0.03	before = after during ≠ after during ≠ before	0.84 0.045 0.045
Nitrate	100.14	< 0.001	before = after during ≠ after during ≠ before	0.74 < 0.001 < 0.001
Nitrite	15.78	< 0.001	before ≠ after before ≠ during during = after	< 0.001 < 0.001 0.13
Ammonia	6.68	0.003	before = after during ≠ before during ≠ after	0.67 0.02 0.02

Discussion

The Kromme Estuary is, in general, characterised by low nutrient levels and low water column productivity, which is a result of low freshwater input (Scharler et al., 1997). The aim of this study was to assess the influence of a freshwater pulse to an otherwise freshwater-starved system. The amount of water released in this experiment from the Mpofu Dam was $2 \times 10^6\ m^3$, which is equivalent to the total volume of water allocated to the estuary to account for the annual evaporative losses from the estuary (Jezewski and Roberts, 1986). Since little or no freshwater reaches the estuary

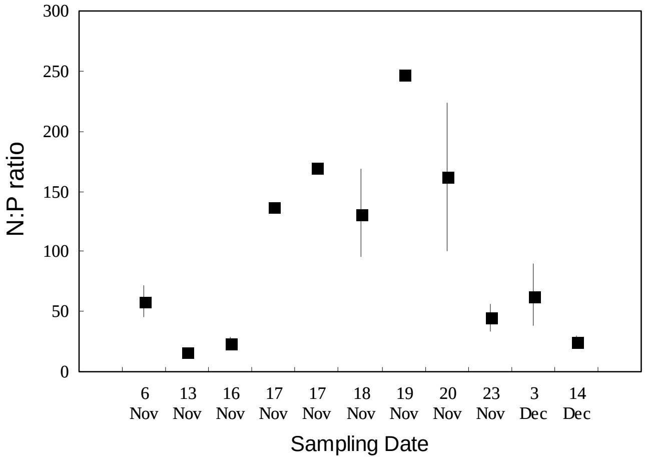

Figure 4
Dissolved inorganic N:P ratios measured before, during and after the release. Data are mean estuarine values SD. Points without SD bars on 17 and 19/11/1998 denote N:P ratios in the upper reaches of the estuary only.

via natural runoff unless the Mpofu Dam overtops after heavy rains, the nutrient levels in the estuary are very low compared to other Eastern Cape estuaries which receive constant freshwater inputs. In a previous study, the effect of natural runoff events on the Kromme Estuary was tested, and results showed an elevation of inorganic dissolved nutrients (phosphate, nitrate, nitrite, ammonia) throughout the estuary during such events (Scharler et al., 1997). It was anticipated that a release of storage water from the Mpofu Dam would have a similar beneficial effect on the estuary.

The extent of nutrient input to the estuary during this release experiment was essentially a reflection of the concentrations of nutrients in the storage water of the Mpofu Dam. The concentration levels changed little from the dam to the estuary. The variations in nutrient concentrations of the inflowing water did not follow a distinct pattern and there was no evidence of an initial flushing and leaching effect on the riverbed downstream of the Mpofu Dam. During the 4 d (17 to 20/11/1998) of freshwater inflow at the tidal head following the release, variations of 1.0 to 2.0 µM in the case of ammonia and up to 5.0 µM in the case of nitrate were measured in the inflowing freshwater. Very high nitrite concentrations (11.0 µM) were measured in the inflowing water on the first day after the sluice gates were opened on the 17/11/1998, but dropped to 0.7 µM on the following day.

The total nutrient load received by the estuary cannot be accurately estimated since the inflow rate at the tidal head could not be quantified. It is also not clear whether the release rate of 15 $m^3 \cdot s^{-1}$ at the Mpofu Dam was an accurate estimate of the amount of water reaching the estuary for two reasons: firstly, a proportion of the released water was absorbed by the dry riverbed downstream of the Mpofu Dam, and secondly, and perhaps more importantly, heavy rains occurred during the time of the release experiment, adding water to the amount released from the dam. It was estimated that approximately 98 % of the released storage water reached the estuary (Huizinga, 1999).

Nutrient removal by sediments

The freshwater pulse has had a very short-lived effect on the nutrient status of the Kromme Estuary. Essentially, on Day 7 after the start of the release (i.e. on the evening of the 16/11/1998), nutrient concentrations in the upper and middle reaches had reverted to pre-release levels. Nutrients, particularly nitrate and the slightly elevated nitrite, were quickly absorbed (in a matter of 4 to 5 d). One usually very important and effective sink for estuarine nutrients, namely the subtidal sediments, did not play any role in nutrient absorption during this study, since stratification occurred at all times and bottom salinities remained constant at approximately 35‰ during the release, which indicates virtually no mixing between the inflowing freshwater and bottom waters. It is therefore unlikely that the nutrient concentrations of bottom waters and sediments could have been affected by this release. However, the inflowing freshwater affected intertidal sediments, and a response was measured in the form of increased benthic microalgal biomass in the intertidal areas (Snow et al., 2000).

Biological nutrient removal

Pelagic biota in the estuary, which act as sinks for nutrients include *inter alia* bacteria and phytoplankton. Snow et al. (2000) did not record a significant increase in phytoplankton biomass (chlorophyll *a*) in response to the freshwater pulse, despite the rapid depletion of introduced nitrate within only a few days. Nutrient starvation of algae might be responsible for nutrient removal without showing any growth (Borchardt, 1996). Since very low nutrient concentrations persist in the Kromme Estuary over long periods, it is possible that the already low standing stock of phytoplankton in the estuary might be nutrient starved. The slight increase in phytoplankton biomass possibly accounts for further nitrate removal. The freshwater pulse failed to introduce an adequate amount of phosphate and N:P ratios were persistently higher than the Redfield ratio. This suggests phosphate limitation of some biota in addition to general nutrient starvation of primary producers. We assume therefore that some biota in the Kromme Estuary could be P limited. A study on the Sundays and Gamtoos Estuaries revealed similarly high N:P ratios, although a permanent freshwater input and high standing stocks of phytoplankton are characteristic of these two systems (Hilmer, 1990; Scharler et al., 1997; Snow, 1999). Overall nutrient concentrations in these two estuaries are, however, higher compared with those of the Kromme system, and their pelagic production is orders of magnitude higher than in the Kromme Estuary (Scharler et al., 1997). Due to the high standing stocks of living biota, the ability to recycle nutrients is a very important feature of the Sundays and Gamtoos systems. Although phosphate concentrations are low, they do not seem to be limiting, as reflected in the high productivity of these systems. In the Kromme Estuary, pelagic productivity and standing stocks are comparatively low (Baird and Heymans, 1996; Scharler et al., 1997).

Phytoplankton stochiometry depends on the ambient environment, and will impact on the productivity of its consumer communities (De Mott et al., 1998). In addition, the recycling efficiency by e.g. phytoplankton consumers is reduced in case of limiting nutrients, and phytoplankton in turn will not be able to use recycled nutrients for further production (Sterner, 1990; Kraft, 1992). Estuaries depend largely on the renewal of their nutrient pool via river flow (e.g. Capone, 1991). During periods of low or absent flows these systems rely heavily on nutrients recycled within the estuary (see Baird et al., 1995). The excessive freshwater abstraction in the Kromme catchment has reduced input of ‘new’ nutrients to the Kromme Estuary, which led to increasingly diminished standing stocks in the estuary and therefore a lower nutrient recycling efficiency. In fact, Baird and Ulanowicz (1993) showed that the amount of recycled material in the Kromme Estuary is indeed much lower in comparison with other tidal estuaries they examined.

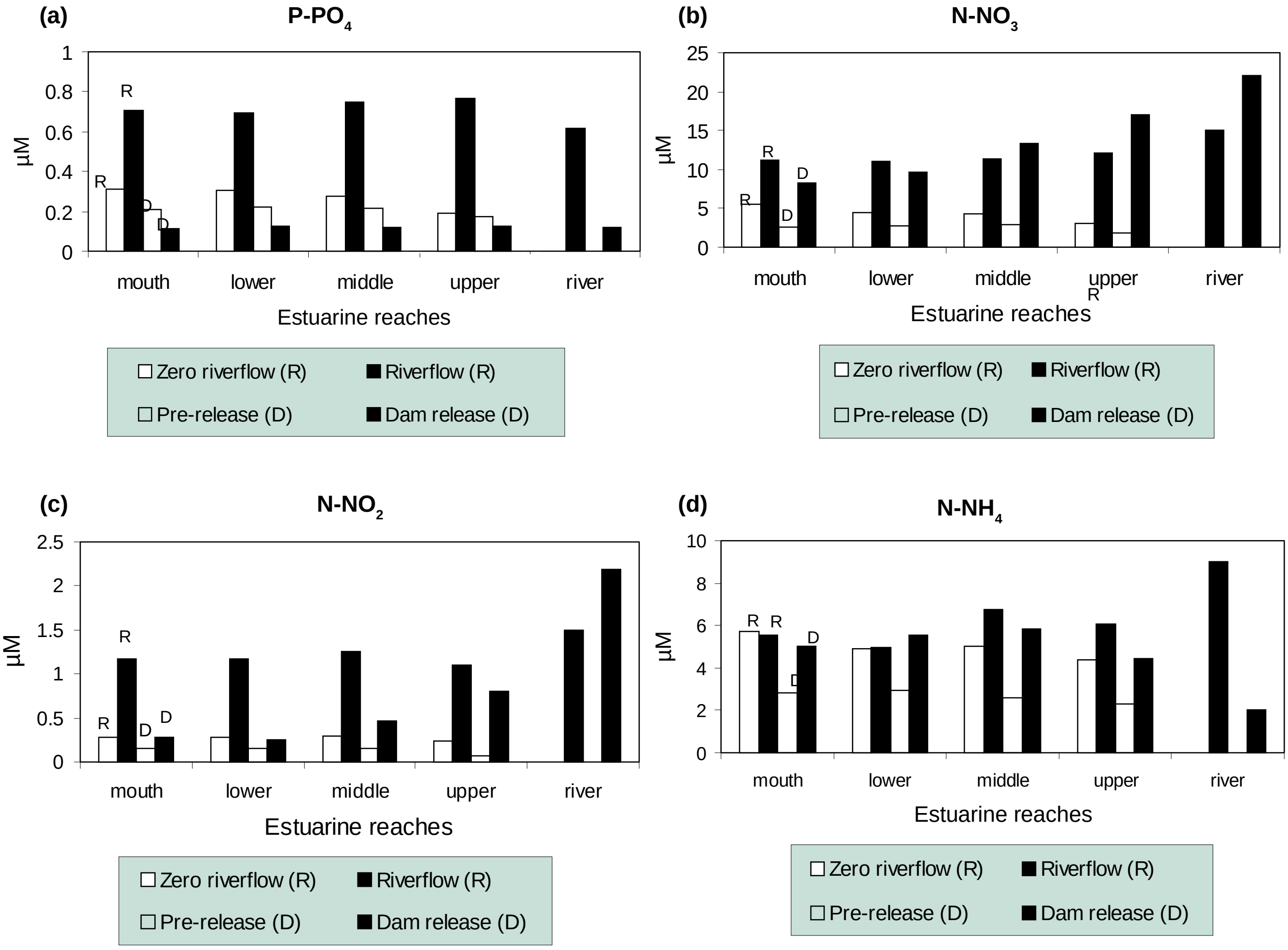

Figure 5

Inorganic dissolved nutrient concentrations (a) P-PO_4, (b) N-NO_3, (c) N-NO_2, (d) N-NH_4 measured during zero riverflow and present riverflow during 1993/94as well as pre-and post- dam release during this study

During periods of zero freshwater input into the estuary, which prevails most of the time, water column productivity in the Kromme Estuary relies virtually entirely on internal nutrient recycling.

In addition to phytoplankton, bacteria are consumers of inorganic dissolved nutrients. Several studies have shown that bacteria can account for a substantial proportion of nutrient uptake and may compete with phytoplankton for these resources (e.g. Caron et al., 1988; Lebo, 1990). Heterotrophic microflagellates can in turn recycle a large proportion of ingested N and P in their inorganic form, again making nutrients available for bacteria and phytoplankton (Andersson et al., 1985; Caron et al., 1988; Ulanowicz and Baird, 1999). In the Kromme Estuary, standing stocks of bacteria and microzooplankton are too low to account for any efficient recycling in the system.

Physical processes

The physical processes resulting from a freshwater pulse to an estuary are typically stratification of the upper deeper reaches, since buoyant freshwater flows over denser saline water. In the shallower mouth area, tidal forces are causes of less pronounced stratification. As the freshwater body moves over the saline layer it entrains the saline estuarine water at a rate which is dependent on the rate and duration of the freshwater inflow. Tidal mixing furthermore causes mixing of freshwater and estuarine water, and wind-induced mixing can aid in the breakdown of the stratified water column. In the case of the Kromme Estuary, the upper and deeper 8 km were characterised by strong stratification, whereas the lower reaches are characterised by shallow areas, intertidal sandbanks and stronger tidal currents and the water column was thus more readily mixed. After the freshwater release from the Mpofu Dam, the freshwater layer moved rapidly downstream over the bottom layers in the upper reaches of the estuary and strong mixing occurred in the lower reaches. Most of the released water reached the estuarine mouth within a few days through advection and dispersion (CSIR, 1999).

During this experiment the inflowing freshwater displaced the upper layers of the estuarine waterbody downstream as far as the middle reaches. This low salinity water was gradually mixed with more saline water during the following four to five days. Bottom water was not removed by the flushing event and on 18 and 20/11/1998 bottom salinities remained at approximately 35 ‰. It was also noted that wind-induced mixing did not affect bottom waters.

A quick return of a temporarily reduced salinity regime to a pre-release structure indicates rapid flushing of the system and suggests

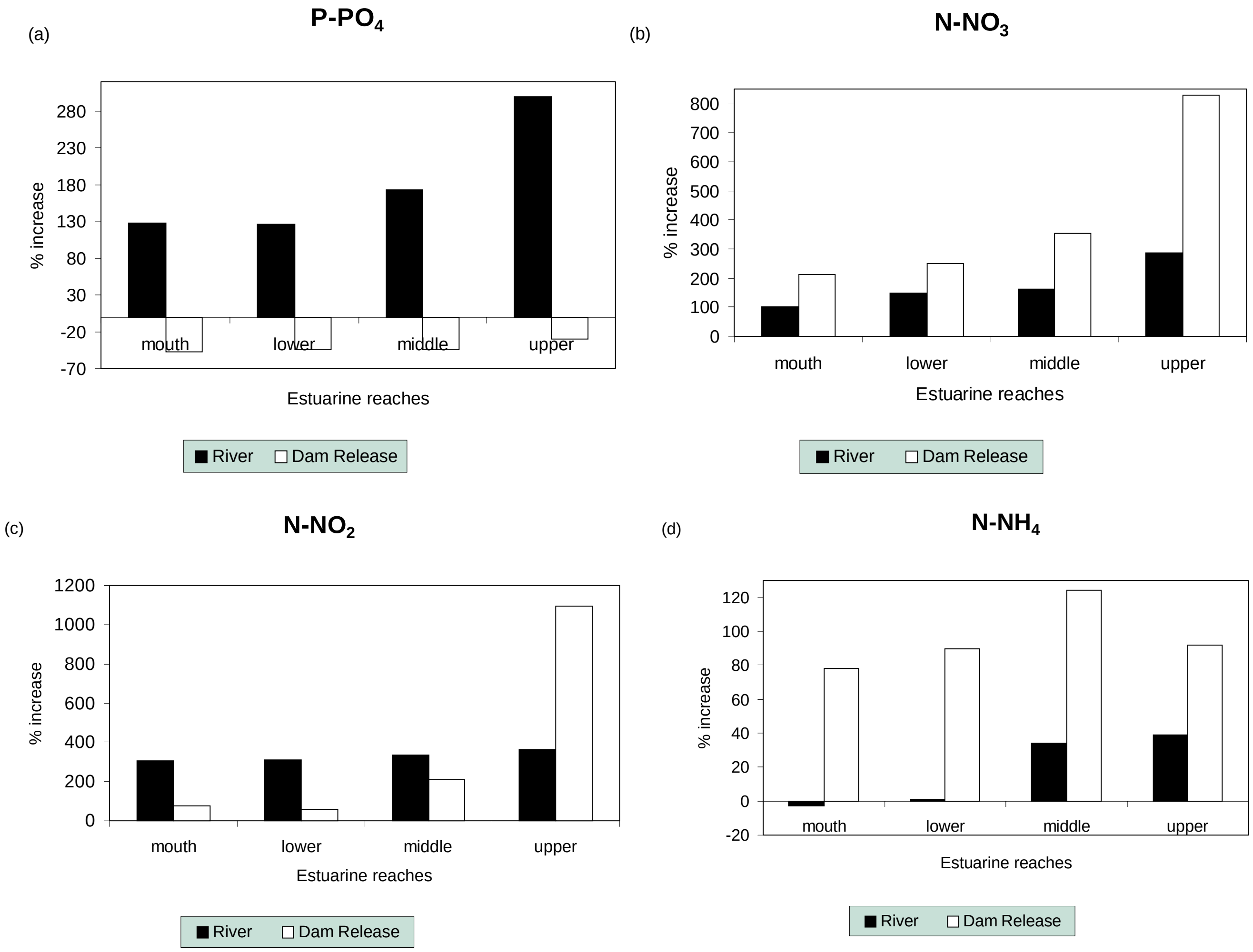

Figure 6
Percent increase in inorganic dissolved nutrient concentrations (a) P-PO_4, (b) N-NO_3, (c) N-NO_2, (d) N-NH_4 during natural runoff conditions in 1993/94 and during the dam release.

that dilution by intruding seawater was largely responsible for the rapid reduction in nitrate concentrations. In addition, the negative correlation between salinity and nitrate was very strong (Table 1), and a rapid dilution would also suggest minimal phytoplankton activity. Scharler et al. (1997) measured only a small increase in phytoplankton biomass during short periods of freshwater input. Snow et al. (2000) observed a similar phenomenon during this study. Top-down grazing pressure of starved zooplankton might also be partly responsible for the minimal increase in phytoplankton biomass.

It is apparent that the estuarine flora only plays a partial role in nutrient removal from these systems. The low phytoplankton response to the freshwater pulse in this study shows clearly that factors other than simple assimilation of nutrients play a role in phytoplankton productivity. Boyer et al. (1994) pointed out that the exclusion of heterotrophic and nitrogen demands from other organisms from estimates for the Neuse Estuary may result in a serious underestimation of the nitrogen demand for the whole system. Results from this study and other studies on Eastern Cape estuaries show that a simple application of Redfield ratios to the whole estuarine system equally do not reflect the overall estuarine nutrient demand (e.g. Scharler et al., 1997).

The above considerations highlight various factors which influence the physico-chemical response of an estuary to a single and short-lived freshwater pulse. These include the duration and flow rate of the release, the physico-chemical properties of the released freshwater and the estuarine water at the time of the release, and that of the sea at and immediately after the release. Although the sea gains in importance as a nutrient source in case freshwater inflow into an estuary is restricted (Allanson and Read, 1995; Grange and Allanson, 1995), especially during upwelling, such events have never been investigated for the Kromme Estuary. Due to the low productivity of especially the water column biota in the Kromme Estuary (Scharler et al., 1997) we believe that nutrient inputs from the sea are not able to sustain viable plankton populations.

Natural runoff vs. storage water

Oligotrophic conditions can be created in storage water as a result of nutrient assimilation in the euphotic zone of impoundments. In the presence of a thermocline, mixing is prevented and water below the euphotic zone will remain richer in nutrients, although it may become low in oxygen content due to bacterial decomposition of organic material.

Natural runoff from the catchment (i.e. nutrient-rich freshwater) might therefore be more beneficial to the estuary than possibly oligotrophic storage water released from impoundments. In this study, there was no stratification in terms of nutrients in the storage water of the Mpofu Dam, although it was possibly oligotrophic compared with river water entering the Mpofu Dam. Natural runoff conditions were measured in 1993/94, when the Kromme River was flowing strongly and the Mpofu Dam overtopped after heavy rains. This natural runoff had a beneficial effect for the estuary in that the inorganic dissolved nutrient concentrations were raised throughout the estuary (Scharler et al., 1997).

During this study, the short-lived response of dissolved inorganic nutrients in the Kromme Estuary was a direct reflection of the nutrient concentrations in the Mpofu Dam. Compared with natural runoff conditions, the released storage water was poorer in phosphate and ammonia, but richer in nitrate and nitrite (Fig. 5). Nutrient concentrations measured in the estuary preceding riverine input in 1993/94 were slightly higher than pre-release concentrations during this study (Fig. 5). For this reason, the measured concentrations in the estuary during natural runoff conditions in 1993/94 and during the release in this study might not reflect the 'real' increase in nutrient concentrations in the estuary. Hence, in order to be able to compare effects of natural runoff and the release from the Mpofu Dam, the changes in nutrient concentrations in the estuary have been expressed as percent increase (Fig. 6). These data showed that the net increase in nitrate and ammonia in the estuary was higher during the dam release than during natural runoff conditions. However, in the case of nitrite and especially phosphate, natural runoff resulted in higher concentrations in the estuary (Fig. 6) (Table 2).

The most striking difference between the 1993/94 study of nutrient concentrations in natural riverflow and the present study lay in the phosphate concentrations. Contrary to this study, where water was released in one short pulse, riverflows during runoff events in 1993/94 were not single flushing events. When measurements were taken, the river had already been flowing for several days, and peak flows of about 10 to 13 $m^3 \cdot s^{-1}$ had been recorded before the sampling date. Under these conditions, phosphate concentrations were found to be higher than those measured during this single experimental release. The leaching and desorption of phosphate from soil particles takes longer than DIN flux from the substrate and a continuous flow might therefore enhance phosphate concentrations in the inflowing water and consequently in the estuary. The importance of the duration of the freshwater inflow to the estuary is here highlighted, and natural runoff therefore seem more beneficial to the estuary than single flushing events such as planned releases from storage facilities.

Conclusions

The response of nutrient concentrations in the Kromme Estuary to a once-off release of storage water from the Mpofu Dam was beneficial, but very short-lived. Elevated nutrient concentrations in the estuary did not persist for any length of time after freshwater input into the system ceased. Only a continuous base flow into the estuary is likely to ensure a constant addition to and renewal of the nutrient pool. Increased standing stocks and pelagic productivity of phyto- and zooplankton as well as their consumers will benefit from a continuous nutrient supply. In this way the increased capacity of nutrient recycling will benefit subtidal benthic productivity. Increased standing stocks of benthic biota will in turn enhance benthic nutrient (re)cycling.

The quality of the storage water in the Mpofu Dam in terms of dissolved inorganic nutrients is not static, but influenced by the residence time of the water as well as the quality of the inflowing river water. An approximation of natural runoff conditions (in terms of water quality) could be achieved by allowing river water to reach the estuary when runoff is high. The subsequent planning of releases from the Mpofu Dam must include an investigation of the state of its water quality, to ensure any beneficial effects to the dynamics of the Kromme Estuary.

Nutrient dynamics in estuaries is a complex issue and the identification of nutrients as limiting factors and limiting concentrations need careful consideration. Different communities may be impacted in different ways by different nutrients, as is illustrated by Ulanowicz and Baird (1999) for the mesohaline Chesapeake Bay ecosystem. They have shown, for example, that N may be limited for some planktonic communities, but nekton may be P limited. No doubt, the limited input of 'new' nutrients from the catchment to the Kromme Estuary has affected the productivity of the system, which is also reflected in the overall ecosystem properties (Baird and Heymans, 1996).

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