

EXTENSION OF A QUALITATIVE MODEL ON NUTRIENT CYCLING AND TRANSFORMATION TO INCLUDE MICROTIDAL ESTUARIES ON WAVE-DOMINATED COASTS: SOUTHERN HEMISPHERE PERSPECTIVE

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Abstract

Estuaries are dynamic transition zones acting as filters and transformers of nutrients passing from catchments to the sea. We propose an extension to an existing southern hemisphere model on nutrient dynamics in estuaries to include the relatively constricted, microtidal estuaries located along wave-dominated coasts in the region, specifically focusing on the limiting macronutrients nitrogen (N) and phosphorus (P) and on key processes, including physical (e.g. flushing, mixing and sedimentation), geochemical (e.g. flocculation), biochemical (e.g. remineralisation) and biological (e.g. primary production) processes. A simplified model of the physical states (primarily controlled by hydrological characteristics) is used as the basis for the qualitative model, where these are defined in terms of characteristic salinity-induced stratification of the water column, flushing time and the mouth condition. Four physical states are identified: a freshwater-dominated state, freshwater pulsed/recovery state, marine-dominated state and the closed mouth state. The states and their physical characteristics largely resemble that of the earlier model, except that the extended model reflects the dynamics of restricted inlets and introduces the closed mouth state. This model specifically explores the variation within southern African estuarine systems to better inform research and management programmes on the appropriate trophic, temporal and spatial scales at which uncertainties in ecosystem functioning need resolving. It can also be applied to other regions in the southern hemisphere, and even the northern hemisphere, with similar hydrological and estuarine geomorphological characteristics (e.g. the Mediterranean coast, the west coasts of North and South America, and the south-west and south-eastern coasts of Australia).

Key words: microtidal estuaries, macronutrient cycling, wave-dominated, restricted inlet, qualitative model, southern hemisphere

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1. Introduction

Estuaries are important geochemical (e.g. flocculation), biochemical (e.g. remineralisation) and biological (e.g. primary production) ‘reactors’, filtering and transforming nutrients passing from the catchment (river) to coastal shelf waters (Church, 1986). In their reviews on the nutrient characteristics of South African estuaries, Allanson and Winter (1999) and Allanson (2001) concluded that, with the diversity of estuary types and individual responses to physical and chemical determinants within highly dynamic environments, the need for techniques with which to integrate these features into qualitative and numerical models was becoming essential.

Major distinguishing factors influencing nutrient cycling patterns and storage in estuaries across climatic regions are the timing and magnitude of hydrologic inputs and the ability to trap nutrient loads (Eyre, 2000). In the temperate northern hemisphere (e.g. North America and Western Europe) annual runoff is much less variable than, for example, in subtropical and temperate regions of the southern hemisphere, as illustrated by the coefficient of variation of annual flow (C_v) for western European (0.29), North American (0.35), Australian (0.7) and South African (0.7) systems (Braune, 1985; Eyre, 1998). Typically the larger estuaries in the temperate northern hemisphere vary from well-mixed to partially stratified, two-layered systems (usually in spring when runoff increases) (Fisher et al., 1988). These systems receive regular nutrient loading from the catchment (e.g. during spring) and have a high nutrient-retention efficiency (i.e. a significant proportion of the nutrient load is trapped and recycled to fuel subsequent production) (Eyre, 2000). In contrast, smaller systems in the southern hemisphere (e.g. Australia and South Africa) can vary from completely flushed freshwater-dominated systems during periods of high runoff to completely marine-dominated systems during periods of low or no river inflow (Largier and Taljaard, 1991; Eyre, 2000; Taljaard et al., 2009). In these systems nutrient loading can be highly variable, while nutrient-retention efficiency is low (Eyre, 2000).

Models describing nutrient dynamics in estuaries have been developed for larger systems in the temperate regions of the northern hemisphere (e.g. North America and Western Europe) (Fisher et al., 1988; Eyre, 1998). However, these models are not necessarily applicable to southern hemisphere systems of South Africa and Australia, primarily due to variability in

runoff (climatology and hydrology of the southern hemisphere force greater variability in runoff) and geomorphology (catchment and marine sediment availability and geological processes lead to a large number of small, shallow systems compared with the temperate northern hemisphere systems) (Eyre, 1998; Cooper, 2001; Peel et al., 2004).

Although conceptual (or qualitative) models of nutrient dynamics have been proposed for the smaller temporarily open/closed estuaries of South Africa (Snow and Taljaard, 2007; Snow and Adams, 2007; Taljaard et al., 2009), such models have not been developed for the wider spectrum of estuarine types in the region (based on the classification of Whitfield, 1992). Nutrient dynamic models for Australian systems mainly focused on the wet and dry subtropical/tropical estuaries found in northern New South Wales, Queensland, the Northern Territory and northern Western Australia (Eyre and Twigg, 1997; Eyre, 1998; Eyre, 2000; Eyre and Ferguson, 2006). These systems are largely tide-dominated and have less restricted inlets compared with, for example, estuaries along a wave-dominated coast (Turner et al., 2004). Despite the complexity of nutrient processes in estuaries, Eyre (1998, 2000) was able to develop a simplified model, primarily linked to different phases of the southern hemisphere region's hydrological regime.

An extension of the above model is presented here to include the relatively sediment-rich, microtidal estuaries that occur along the wave-dominated coast of South Africa. In particular, the model recognises the occurrence of restricted inlets and includes a closed state, i.e. when estuaries are isolated from the sea by the formation of a sand bar across the mouth (Whitfield, 1992; Cooper, 2001). The model identifies the dominant nutrient cycling and transformation processes under different physical states, focusing mainly on the limiting macronutrients N and P and key processes, such as physical (e.g. flushing, mixing and sedimentation), geochemical (e.g. flocculation), biochemical (e.g. remineralisation) and biological (e.g. primary production) processes.

Like the original model developed by Eyre (1998, 2000), the extended model can be applied to other regions of the world with similar hydrological and geomorphological characteristics, such as the Mediterranean coast (e.g. Palmones, Modego and Tagus estuaries), west coast of north and south America (e.g. Pozuelos–Murillo lagoon system and Elkhorn Slough) and south-west and south-eastern Australia (e.g. Swan and Hopkins river estuaries) (Sharples et

al., 2003; Hernández-Romero et al., 2004; Avilés and Neill, 2005; Brearly, 2005; Caffrey et al., 2007; Libellø, et al., 2007; Simas and Ferreira, 2007; Robson et al., 2008).

2. Study Area

According to Brown and Jarman (1978) the South African coast spans three biogeographical regions (or climatic zones), namely the cool temperate west coast, warm temperate south coast and subtropical east coast (Figure 1). Rainfall patterns in the different regions vary greatly as a result of South Africa's highly variable climate. In the cool temperate region, the climate ranges from semi-arid (extended periods of low to no rainfall interspersed with short flash rain events) along the west coast to Mediterranean (dominated by seasonal winter rainfall) along most of the south-western coast. In the warm temperate region along the south coast, rainfall is largely bi-modal, with peaks in spring and autumn, while the subtropical region along the east coast is dominated by seasonal summer rainfall (Davies and Day, 1998). River inflow to the estuaries is determined by these climatic conditions, as well as the size and shape of the catchment, the latter controlling the magnitude and flow distribution of runoff (Reddering and Rust, 1990). Catchment size varies significantly, ranging from very small (less than 1 km²) to very large (greater than 10 000 km²), with those in the cool temperate region tending to be larger than those in the warm temperate and subtropical regions (Jezewski et al., 1984; Reddering and Rust, 1990).

South Africa's coast is generally characterised by low tidal ranges and high wave energy, making it a wave-dominated coast (Cooper, 2001). The approximately 250 functional estuaries (Whitfield, 1992) are predominantly microtidal systems that are highly dynamic and shallow (~ 2-3 m). Owing to strong wave action and high sediment availability, more than 90% of the estuaries have restricted inlets, with more than 75% closing for varying periods of time when a sand bar forms across the mouth (Whitfield, 1992). Using a variety of criteria such as catchment size, mouth characteristics and tidal prism, Whitfield (1992) categorised South Africa's estuaries into five types: temporarily open/closed, permanently open, river mouths, estuarine bays and estuarine lakes. Most of these types occur in all three biogeographical regions, apart from estuarine bays and lakes, which are absent from the cool temperate region (Whitfield, 1992).

Numerous definitions for estuaries have been published (Elliot and McLusky, 2002). The estuary study boundaries in this paper are based on a combination of the definitions proposed by Fairbridge (1980), setting the extent of an estuary as the limit of tidal rise, and Day (1981), recognising that estuaries may not necessarily have a 'free connection with the sea' but are 'either permanently or periodically open to the sea'. The most appropriate definition in this context is as follows: "An estuary is a partially enclosed water body, either permanently or periodically open to the sea, extending as far as the upper limit of tidal rise and usually being divisible into three sectors: (a) a marine or lower estuary; (b) a middle estuary subject to strong salt and freshwater mixing; and (c) an upper or fluvial estuary, characterized by freshwater but subject to strong tidal action. The limits between these sectors are variable and subject to constant changes in the river discharges."

3. Methods

Both existing and new empirical data were used to develop the extended model. Existing empirical data (salinity and inorganic nutrients data) include that from the Knysna (an estuarine bay situated in the warm temperate region) (Switzer, 2003) and Kromme (a permanently open system in the warm temperate region) (Scharler and Baird, 2000) estuaries (Figure 1). New data were collected from five systems, namely the Keurbooms (a permanently open system in the warm temperate region), the Great Berg (a permanently open system in the cool temperate region), the Breede estuary (a permanently open system in the warm temperate region), the Olifants (a permanently open system in the cool temperate region) and the Great Brak (a temporarily open/closed system in the warm temperate region) estuaries (Figure 1). Sampling took place during 16-19 March 1987 in the Keurbooms estuary (6 stations, Figure 2a), on 19 September 1989 in the Great Berg estuary (10 stations, see Figure 1, Slinger and Taljaard, 1990), on 23 August 2000 in the Breede estuary (12 stations, Figure 2b), on 2 March 2004 in the Olifants estuary (13 stations, Figure 2c) and on 28 July 2007 in the Great Brak estuary (18 stations, see Figure 1, Slinger et al., 1990). Details on key physical characteristics of the above-mentioned estuaries are provided in Table 1, while Table 2 summarises the type of data (salinity and inorganic nutrients) used from the different systems to develop the model.

Salinity and temperature measurements were taken in situ at 0.25 to 0.5 m depth intervals along the estuaries using a Valeport MKII CTDS meter (accuracy: salinity 0.2; temperature

0.2°C; depth 0.1 m). Salinity was measured on the Practical Salinity Scale. South African estuaries receive relatively limited freshwater inflow, with the result that salinity within systems varies over the entire range from 0 to 35, whereas temperature seldom varies through a range of more than 10°C at any one time. Consequently, salinity is generally the dominant factor in determining stratification (density variations), and is frequently used to describe water circulation patterns (Schumann et al., 1999). Samples for macronutrient analyses, in this case total inorganic nitrogen [dissolved nitrate, nitrite, total ammonia] (DIN) and dissolved reactive phosphate (DRP), were collected from surface and bottom waters in the five systems at the selected stations. Samples were filtered in the field through 0.45-µm Millipore filters, stored in polyethylene sampling bottles and frozen until further analyses. A Technicon Auto-analyser II (Seal Analytical, West Sussex, England) (detection limits for dissolved nitrate, nitrite, total ammonium and reactive phosphate: 10 µg l⁻¹) was used for the analyses according to the methods described in CSIR (2002).

Longitudinal salinity contour plots are used to demonstrate salinity distribution patterns, while mixing diagrams (or property-salinity plots) - widely used to assess water column nutrient dynamics in estuaries (Church, 1986; Eyre, 2000; Eyre and Balls, 1999; Ferguson et al., 2004) - are used to describe inorganic nutrient distribution patterns. Nutrient concentrations are plotted against salinity along the estuarine gradient, providing a convenient method for displaying the net effect of nutrient processes within estuaries. For example, a linear relationship in the mixing diagram typically reflects straight mixing of the two water sources (i.e. the river and the sea), while downward curvature implies in situ nutrient uptake and upward curvature in situ nutrient release (Eyre, 2000; Ferguson et al., 2004). Conservative behaviour tends to occur during high river inflow, when estuaries are rapidly flushed. High nutrient input from the catchment (relative to input from the sea) reveals a negative linear correlation, whereas high input from the sea shows a positive linear correlation. Deviation from the conservative mixing line tends to occur during periods of low or no river inflow, when long flushing times allow in situ processes to have a more significant influence on nutrient dynamics (e.g. remineralisation releasing nutrients into the water column or primary production taking up nutrients from the water column) (Eyre, 2000).

Published literature on salinity and inorganic nutrient distribution patterns on several other systems was also sourced to validate the model design and include the East Kleinemonde (Taljaard et al., 2009), Gamtoos (Snow et al., 2000a), Great Fish (Allanson and Winter, 1991;

Jennings, 2005), Groen (Bickerton, 1981a), Kariega (Allanson and Winter, 1991; Taylor, 1992; Allanson and Read, 1995), Kromme (Baird and Heymans, 1996; Snow et al., 2000b; van Ballegooyen et al., 2004; Snow and Adams, 2006), Langebaan (Mazure and Branch, 1979; Tibbles et al., 1994), Mdloti (Perissinotto et al., 2004), Palmiet (Largier and Taljaard, 1991), Spoeg (Bickerton, 1981b), Swartkops (Baird and Winter, 1992), Swartvlei (Howard-Williams and Allanson, 1981) and Van Stadens (Gama et al., 2005) estuaries (Figure 1). Key physical characteristics of these estuaries are provided in Table 1.

4. Assessment of Empirical Data

The array of salinity and nutrient distribution patterns that occur under different river inflow regimes in microtidal estuaries along a wave-dominated coast (Table 2) is illustrated using results from the Keurbooms, Great Berg, Breede, Olifants, Great Brak, Knysna and Kromme estuaries.

Strong marine influence was evident in the Keurbooms estuary during 16-19 March 1987, when river inflow was low (Figure 3a). Similarly, salinity profiles measured in the Great Berg and Olifants estuaries during dry seasons in January 1990 (Figure 3b, after Slinger and Taljaard, 1994) and March 2004 (Figure 3c), respectively, showed strong marine influence with a gradual horizontal salinity gradient extending along the entire length of the systems. Salinity profiles measured in the Great Berg estuary on 19 September 1989, towards the end of the rainy season, showed strong freshwater influence (Figure 3d). The system was fresh throughout, except in the lower reaches near the mouth, where limited intrusion of seawater occurred during high tides, creating a small but strong horizontal salinity gradient in this area. Salinity profiles collected in the Breede estuary on 23 August 2000 (Figure 3e) reflected a significant pulse of freshwater present in the system, well beyond the head of the estuary. Pronounced stratification occurred towards the middle reaches, with significant seawater influence in the lower reaches. This phenomenon was also evident in the Knysna estuary on 13/14 November 2000 during a small flood (Switzer, 2003). Similarly, a strong freshwater front was created in the Kromme estuary during a water release from a dam (simulating a freshwater pulse) situated just upstream of the estuary in November 1998 (Scharler and Baird, 2000). Salinities in the Great Brak estuary measured on 28 July 2008 (Figure 3f), during a low-flow period and after the system had been closed for 80 days, revealed relatively well-mixed conditions with only a weak salinity gradient along the estuary (salinity 30 – 25).

During a low-flow period and strong marine influence in the Keurbooms estuary (16-19 March 1987), $\text{NO}_x\text{-N}$ (nitrate + nitrite, a component of DIN) concentrations in the water column did not show any clear relationship with salinity (Figure 4a). However, mean $\text{NO}_x\text{-N}$ concentrations measured in a shallow ‘blind arm’ near the mouth (Figures 2a) were significantly higher ($241 \mu\text{g l}^{-1}$) than those measured in the rest of the estuary ($86 \mu\text{g l}^{-1}$) ($t = -3.5$; $P < 0.001$; d.f. = 35), suggesting that the “blind” arm (with extensive intertidal and subtidal cover of the macrophyte *Zostera* sp.) was a significant in situ source of $\text{NO}_x\text{-N}$. This trend, however, was not apparent in the DRP data, which remained low throughout the estuary (mean = $13 \mu\text{g l}^{-1}$; range: $5\text{-}32 \mu\text{g l}^{-1}$; $n = 66$) (Figure 5a). Under low flows and strong marine influence, mixing diagrams for DIN in both the Great Berg (31 January 1990) and Olifants (4 March 2004) estuaries indicated downward curvature, suggesting removal of inorganic nitrogen from the water column (Figures 4b and 4c, respectively) (Great Berg: exponential; $r^2 = 0.6$; $n = 51$; Olifants: 2nd order polynomial; $r^2 = 0.7$; $n = 25$). The mixing diagram for DRP in the Great Berg estuary also showed downward curvature, suggesting removal of this nutrient from the water column (Figure 5b) (exponential; $r^2 = 0.7$; $n = 51$). Mixing diagrams for DRP in the Olifants estuary, however, showed upward curvature, suggesting in situ release of DRP into the water column (Figure 5c) (2nd order polynomial; $r^2 = 0.8$; $n = 25$). At the time, dense submerged macrophyte beds (e.g. *Potamogeton* sp.) were observed in the fresher upper reaches of the Olifants estuary. Towards the end of the rainy season, under freshwater-dominated conditions (19 September 1989), the mixing diagram for DIN in the Great Berg estuary followed the conservative mixing line ($r^2 = 0.8$; $n = 38$) (Figure 5d), with river inflow introducing the highest concentrations. DRP also displayed strong linear correlation with salinity ($r^2 = 0.8$; $n = 38$), except that highest concentrations were introduced from the sea (Figure 5d). In the Breede estuary, when elevated river inflow created a significant freshwater front well beyond the head of the estuary (23 August 2000), DIN concentrations showed a strong linear correlation with salinity ($r^2 = 0.95$; $n = 23$) (Figure 4e). DRP concentrations were low, revealing no particular relationship with salinity (mean = $20 \mu\text{g l}^{-1}$; range: $15 - 28 \mu\text{g l}^{-1}$; $n = 23$) (Figure 5e). Likewise, DIN concentrations in the Knysna estuary showed strong linear correlation with salinity ($r^2 = 0.8$; $n = 44$) during a small flood on 13/14 November 2000 (Figure 4f, after Switzer, 2003). DRP concentrations were generally low with no clear relationship to salinity (median = $25 \mu\text{g l}^{-1}$; range: $9 - 186 \mu\text{g l}^{-1}$; $n = 44$) (Figure 5f, after Switzer, 2003). Immediately after a water release (simulating a freshwater pulse) in the Kromme estuary (18 November 1998), the mixing diagram for DIN tended to followed a conservative mixing line ($r^2 = 0.6$; $n = 43$) (Figure 4g, after Scharler and

Baird, 2000). Again, DRP concentrations were low and did not display any clear relationship with salinity ($< 10 \mu\text{g l}^{-1}$) (Figure 5g, after Scharler and Baird, 2000). A few days after the release (23 November 1998), the mixing diagram for DIN showed downward curvature (2nd order polynomial; $r^2 = 0.9$; $n = 22$) (Figure 5h, constructed from data presented in Scharler and Baird, 2000), suggesting some removal of DIN from the water column of the estuary. DRP concentrations in the estuary remained low with no particular relationship to salinity ($< 10 \mu\text{g l}^{-1}$) (Figure 5h, constructed from data presented in Scharler and Baird, 2000). DIN and DRP concentrations measured in the Great Brak estuary on 28 July 2007, during a low-flow period when the system had been closed for about 80 days, were near depleted, with concentrations of both nutrients mostly below the detection limit ($< 10 \mu\text{g l}^{-1}$) (Figures 4i and 5i).

5. Development of Extended Qualitative Model

The assessment of empirical data, as well as other previous assessments of South African systems (e.g. Schumann et al., 1999; Adams et al., 2002; Van Ballegooyen et al., 2004), revealed four characteristic physical states for relatively sediment-rich, wave-dominated, microtidal systems, namely a freshwater-dominated state, freshwater pulsed/recovery state, marine-dominated state and the closed mouth state (Figure 6). These states and their physical characteristics largely resemble those presented in Eyre's model (1998, 2000), except that the extended model now reflects the dynamics of restricted inlets and introduces the closed mouth state. Focusing on specific climatic regions (e.g. wet and dry subtropical/tropical), Eyre (1998, 2000) was able to provide 'unique' hydrological descriptors for the different states, namely 'flood phase' (freshwater-dominated state), 'recovery or small flood phase' (freshwater pulsed/recovery state) and 'dry season' (marine-dominated state). With the large variability in climatic conditions (influencing rainfall) and catchment sizes (controlling the magnitude and flow distribution of runoff), such hydrological descriptors are no longer considered appropriate within the South African context. For example, a freshwater-dominated state can occur as a result of a flood (e.g. in estuaries receiving runoff from smaller catchments), as in Eyre's model, but also as a result of extended periods of elevated seasonal high flows (e.g. in estuaries receiving runoff from larger catchments in the seasonal winter rainfall region). Furthermore, in microtidal systems with restricted inlets, a 'dry season' can result in a marine-dominated state as in Eyre's model, but also in a closed mouth state. It was considered more appropriate to use the description of the physical condition in the estuary as

state descriptors in the extended model. Therefore, although a different naming convention is used, Eyre's (1998, 2000) general approach is still applied. Using a simplified model of the *physical states* (primarily controlled by hydrological characteristics) as the basis for the nutrient cycling and transformation model, states are defined in terms of the characteristic salinity distribution (e.g. position of the freshwater front), water column stratification (e.g. stratified or well-mixed), flushing time and, in this case, the mouth condition (e.g. open or closed).

5.1 Freshwater-dominated state

The freshwater-dominated state (Figure 6a) occurs during periods of high river inflow when an estuary is either completely flushed by freshwater (e.g. during floods) or becomes freshwater-dominated on the weaker tides (e.g. seasonal high flows), as observed in the Great Berg estuary during September 1989. This state has also been observed in the Palmiet estuary (a small temporarily open/closed system situated in the cool temperate region) during periods of high (winter) rainfall (Largier and Taljaard, 1991). During this state a pronounced freshwater front is present outside the estuary in the nearshore coastal shelf, occasionally moving into the lower estuary (e.g. during spring flood tides). The location of the front is a function of the size of the estuary, since smaller estuaries are completely flushed more readily than large systems, as well as the volume of river inflow. Flushing times are short, typically ranging from hours to days.

During the freshwater-dominated state, mixing diagrams for water column nutrients (DIN and DRP) typically followed a conservative mixing line, as was observed in the Great Berg estuary (September 1989). This indicates that concentrations are largely determined by the extent of mixing between river (fresh) water (salinity 0) and seawater (salinity ~ 35), and are hence primarily influenced by physical processes. Nutrients entering the estuary from the catchment are flushed out onto the nearshore coastal shelf without any significant transformation happening in the estuary (Figure 7a). As a result of this rapid flushing, biochemical and biological (e.g. phytoplankton production) processes usually have little influence on nutrient transformation in the water column, as was illustrated by the low water column chlorophyll *a* concentrations measured in the Great Berg estuary at the time (below 3 $\mu\text{g l}^{-1}$) (Slinger and Taljaard, 1990). In addition, the low light availability associated with high turbidity inhibits primary production by both phytoplankton and benthic microalgae and

submerged macrophytes. Nutrient fluxes across the intertidal-open water boundary are usually insignificant compared with those being introduced from the catchment. During floods, it can also be expected that sediments and benthic particulate organic matter (and associated nutrients) will be re-suspended in the estuary through scouring, and subsequently transported onto the nearshore coastal shelf (Figure 7a).

5.2 Freshwater pulsed/Recovery

This state, as observed in the Breede (23 August 2000), Knysna (13/14 November 2000) and Kromme (November 1998) estuaries, is typical of periods when river inflow is sufficiently elevated to create a pronounced freshwater front well downstream from the estuary head, but with tidal intrusion preventing it from moving outside the system onto the nearshore coastal shelf (Figure 6b). In their study on the Gamtoos estuary (a permanently open system in the warm temperate region), Schumann and Pierce (1997) also observed the formation of this pronounced freshwater front after a freshwater pulse. Density differences at the freshwater front result in marked stratification (longitudinal and/or vertical) and most likely a decrease in turbulence (Eyre, 2000).

Flushing times in the freshwater pulsed/recovery state can range from days to weeks depending on the size and shape of the estuary. Water exchange across the intertidal-open water boundary can be significant depending on the extent of tidal exchange, although exchange may be restricted for short periods as the freshwater pulse enters the estuary. This state typically occurs for relatively short periods ('pulse' effect), either as a transition period between the marine-dominated and freshwater-dominated states or when a small flood or freshette introduces a pulse of freshwater into an estuary. However, in the Great Fish estuary (a permanently open system situated in the warm temperate region) the freshwater pulsed state is artificially maintained through an inter-basin transfer supplying additional water to its catchment, perpetuating a pronounced freshwater front and strong stratification for extended periods (Jennings, 2005). This state also occurred in the Thukela estuary (a river mouth situated in the subtropical region) during periods of relatively low river inflow (RSA DWAF, 2004), illustrating that this state can occur during low flows in estuaries with volumes that are small compared to the volume of runoff received from the catchments.

Conservative mixing lines for DIN measured in the Breede (23 August 2000) and Knysna (13/14 November 2000) estuaries during the onset of the freshwater pulsed/recovery state indicate that water column nutrient concentrations were largely determined by the extent of mixing between river (fresh) water (salinity 0) and seawater (salinity ~ 35). Conservative behaviour was also evident in the mixing diagrams constructed for nitrate-N for both the Kariega and Fish estuaries (see Allanson and Winter, 1999) at the onset of freshwater pulsed/recovery states. Therefore, as the freshwater pulse is introduced, water column nutrient distribution patterns typically display conservative behaviour, largely influenced by physical processes (e.g. flushing and mixing). However, as this state prevails and the flushing time increases, processes other than flushing and mixing become more significant, for example biological processes (e.g. phytoplankton production), with the result that nutrient distribution patterns become non-conservative (Figure 7b). Many of South African estuaries rely on catchment-derived nutrients to stimulate water column primary production (Snow et al., 2000a; Gama et al., 2005), so when a pronounced freshwater front is introduced to these systems it creates a plug of lingering higher nutrient waters that promote water column primary production. For example, in the Kromme estuary DIN concentrations initially had a strong linear relationship with salinity at the onset of a freshwater pulsed/recovery state (18 November 1998) (i.e. strong conservative behaviour). However, the downward curvature in the DIN mixing diagram from a few days later (23 November 1998) suggests in situ removal of this limiting nutrient by phytoplankton production (Snow et al., 2000b). The increase in water column primary production was short-lived as a result of the rapid depletion of the 'new' nutrient introduced by the freshwater pulse, and low in situ estuarine nutrient supplies (Scharler and Baird, 2000). Interestingly, subtidal benthic primary production did not increase significantly, attributed to pronounced stratification that prevented the nutrient-rich surface waters introduced by river inflow from reaching the sediments (Snow et al., 2000b; Snow and Adams, 2006).

During this state, strong salinity, pH and other physico-chemical gradients near the freshwater front increase the potential effects of geochemical processes such as adsorption/desorption and flocculation, contributing to the removal of sediment, organic matter and associated inorganic nutrients (Eyre and Twigg, 1997; Nielsen et al, 2001). The lower turbulence in the vicinity of the freshwater front allows catchment-derived sediment and organic matter to settle from the water column, the extent of deposition depending on factors such as land-use and catchment geology, the timing and size of the flow event, particle size, current velocities,

and the position of the freshwater front, which is primarily influenced by river inflow and the tidal phase. This state is therefore important in supplying potential nutrients, or 'food stores', to the estuary to be utilised in subsequent states, e.g. a marine-dominated state (Eyre and Twigg, 1997). Allanson and Read (1995) proposed that the salinity gradient at freshwater fronts, coupled with the phenomenon of hydrodynamic trapping, the flocculation of suspended matter and the availability of nutrients, provides the stimulus for water column production and, ultimately, defines the richness of the phytoplankton and zooplankton stocks in microtidal estuaries. For example, during a freshwater pulsed state in the Thukela estuary phytoplankton concentrations peaked in the middle reaches, coinciding with the position of the freshwater front, with highest concentrations at water depths between 0.5 and 2 m (chlorophyll a $\sim 120 \mu\text{g l}^{-1}$) (RSA DWAF, 2004). Although benthic biogeochemical and biological processes may well be significant in terms of nutrient cycling and transformation in sediments, these processes are not considered to have a marked affect on water column nutrients during the freshwater pulsed/recovery state because flushing times remain relatively short. During this state the role of intertidal areas in nutrient dynamics may become significant where extended tidal inundation of such areas occurs. However, it is expected that the effect of fluxes across the intertidal-open water boundary may still be masked by the (stronger) catchment fluxes, particularly towards the fresher middle and upper reaches of the estuary. This cannot be confirmed for microtidal estuaries in the region due to the lack of data, and needs further investigation

5.3 Marine-dominated state

The marine-dominated state typically occurs during periods of low or no freshwater inflow and where the estuary mouth remains open (due to limited sediment input and sufficient tidal exchange), allowing seawater to penetrate upstream as observed in the Keurbooms (March 1989), Great Berg (31 January 1990) and Olifants (4 March 2004) estuaries. Large estuarine bays such as the Knysna estuary predominantly function as marine-dominated systems, with a small freshwater front present only in the extreme upper reaches (Largier et al., 2000). A horizontal salinity gradient is usually present in the estuary with a weak freshwater front situated towards the upper reaches, depending on the extent of river inflow (Figure 6c). Limited vertical stratification may exist in the vicinity of the front. In the larger systems flushing times in the middle and upper reaches may be long (weeks to months), whereas stronger tidal exchange results in much shorter flushing times in the lower reaches (hours to

days). In the smaller systems tidal exchange may even be able to maintain short flushing times for the entire estuary depending, on the state of the mouth and tide.

In extreme cases of the marine-dominated state, estuaries can become completely saline or even hypersaline (salinity greater than 35). This is typical of estuaries where sediment input is limited and the tidal exchange is strong enough to maintain an open mouth even when there is no river inflow, as in the Kromme estuary (van Ballegooyen et al., 2004). Here hypersaline conditions developed as a result of extended periods of no freshwater inflow combined with high evaporation rates. The extreme marine-dominated state has also been observed in the Kariega estuary (a permanently open system in the warm temperate region), where Jennings (2005) showed that the system became hypersaline in the upper reaches during a dry period (June). Tidal exchange, which is largely a function of the state of the tide and mouth dimensions (width and depth), plays a major role in the extent of water exchange across the intertidal-open water boundary within an estuary during the marine-dominated state.

Mixing diagrams for DIN measured in the both the Olifants (4 March 2004) and Great Berg (31 January 1990) estuaries showed downward curvature during marine-dominated states, suggesting in situ removal of water column nutrients with only limited renewal from the catchment in the upper reaches (salinity less than 5) and tidal intrusion near the mouth (salinity greater than 30). In the Kromme estuary, water column DIN and DRP concentrations also became near depleted (less than $50 \mu\text{g l}^{-1}$ and less than $10 \mu\text{g l}^{-1}$, respectively) during this state (Scharler and Baird, 2000). Here the standing stock of bacteria and microzooplankton, and possibly also organic matter, was considered too low to provide sufficient quantities of recycled nutrients to the water column in the absence of nutrient supplied through river inflow. This was supported by the low phytoplankton productivity measured in the estuary during marine-dominated states on other occasions (Baird and Heymans, 1996; Snow et al., 2000b). In the Kariega estuary, Allanson and Winter (1999) also observed that the sea became the only potential source of new nitrate-N to the system during periods of low or no river inflow. Therefore, when river inflow decreases and the external nutrient supplies are limited, these shallow microtidal systems are unable to support significant water column primary production once nutrient stocks in the water column have been depleted. Primary productivity by benthic microalgae and rooted macrophytes then becomes dominant, as was observed in the Kariega (Allanson and Read, 1995) and Knysna (Switzer, 2003) estuaries. Switzer (2003) argued that such benthic processing zones play an

important role as nutrient sinks in enriched systems, and the destruction of such zones (e.g. as a result of coastal development) will result in an increased nutrient load to the water column, and hence eutrophication. However, excessive enrichment of systems can also deviate from this expected regime of dominant benthic primary productivity with low river inflow, as in the case of the Gamtoos estuary, where agricultural return flow introduces persistently high nutrient loads, maintaining high water column phytoplankton production even during periods of low river inflow (Snow et al., 2000a).

In larger systems, long flushing times and low current velocities characteristic of the fresher upper reaches during the marine-dominated state can favour the development of large beds of submerged macrophytes (e.g. *Potamogeton* sp.) that influence nutrient cycling, as was observed in the Olifants estuary (January 1990). Upward curvature in the DRP mixing diagram suggested an in situ source of this nutrient, attributed to foliar release by the *Potamogeton* sp. known to supply DRP to estuarine waters (McRoy et al., 1972; Adams et al., 1999). This is contrary to Howard-Williams and Allanson's (1981) findings in the Swartvlei (a coastal lake in the warm temperate region), where the exchange of DRP between *Potamogeton* sp. beds located in the littoral zone and the open waters of the estuary was low, which they attributed to rapid nutrient recycling within the littoral zone. However, the *Potamogeton* sp. beds in the Olifants estuary were exceptionally dense as a result of artificial nutrient enrichment (N) from fertiliser introduced in the catchment. These dense beds probably generated DRP through foliar release at faster rates than could be assimilated by new growth, as was the case in a more natural situation (e.g. Swartvlei).

Where tidal exchange is significant, the sea becomes an important source of new nutrients to estuaries (especially DIN) during the marine-dominated state, particularly in systems adjacent to coastal upwelling cells. However, rapid water exchange (short flushing times) in the lower reaches probably prevents this nutrient source from being utilised effectively by water column primary producers (e.g. phytoplankton), and it is largely submerged macrophytes and intertidal communities (e.g. salt marsh) that benefit (Taylor, 1992; Scharler and Baird, 2000). In the Kariega estuary tidal nutrient inputs associated with upwelling were significant, having a marked impact on the flux of DIN to intertidal saltmarsh areas (*Sarcocornia perennis* and *Chenolea diffusa*), even increasing biological uptake rates in the marsh (Taylor, 1992).

During this state, tidal exchange can influence nutrient exchange across the intertidal-open water boundary within the estuary, depending on factors such as the size of the intertidal area and the extent and energy of tidal intrusion (Figure 7c), as observed in the Keurbooms estuary (16-19 March 1987). Here, remineralisation/nitrification associated with macrophyte litter in the extensive *Zostera* beds within a shallow blind arm provided a significant source of $\text{NO}_x\text{-N}$ for the open waters of the lower reaches. Hence, the large variety of vegetation types in southern African estuaries, including macroalgae, submerged macrophytes, reeds and sedges, saltmarsh and mangroves (Adams et al., 1999, Steinke, 1999; Adams et al., 2004), also play an important role in nutrient cycling and transformation (Valiela et al., 1978; Lee, 1995). Studies in the Langebaan Lagoon (a estuarine bay in the cool temperate region receiving mostly groundwater input) showed that colonisation of macrophyte (*Zostera capensis*) litter by N-fixing bacteria increased the N content of this litter, which was an important source of new N to the system (Tibbles et al., 1994; Mazure and Branch, 1979). However, in the Swartkops estuary (a permanently open system in the warm temperate region), nutrient fluxes between an intertidal marsh (*Spartina maritima*) and the open waters of the estuary were small, since the marsh retained and utilised most of its own production, virtually functioning as an independent ecosystem (Baird and Winter, 1992). Therefore, depending on the dominant vegetation, intertidal areas can act either as sinks or sources of nutrients.

Although river inflow and the sea can still influence the nutrient characteristics within an estuary during the marine-dominated state, longer flushing times and more stable sediments generally create conditions favourable for biochemical and biological processes to contribute significantly to nutrient cycling and transformation, particularly in the middle and upper reaches (although wind-mixing may reduce sediment stability in shallower areas) (Figure 7c). However, during this state the importance of different nutrient cycling and transformation processes is strongly linked to site-specific conditions that should be considered when assessing the extent of the different processes for a particular estuary. For example, in smaller systems effective tidal exchange is able to maintain short flushing times throughout the estuary, and processes requiring longer flushing times may not be as relevant.

5.4 Closed mouth state

During periods of little or no river inflow, relatively sediment-rich and wave-dominated microtidal estuaries can become isolated from the sea by the formation of a sand bar across

the mouth, as observed in the Great Brak estuary (28 July 2007). Flushing times (or lack thereof) depend on the duration of closure, which can range from days to years. In small, shallow systems the closed mouth state eventually reverts to a well-mixed (due to wind turbulence) brackish system, with no distinct salinity gradient or stratification (Figure 6d). If the low-flow periods coincide with periods of high evaporation, estuaries can become more saline, or even hypersaline, a condition observed in systems receiving runoff from catchments in the semi-arid areas in the cool temperate region, e.g. the Groen and Spoeg estuaries (Bickerton, 1981a & 1981b). Alternately, systems where river inflow is balanced by seepage to the sea through the sand bar can become increasingly fresh, which is typical of estuaries along the east coast of South Africa with lower evaporation rates during the low-flow periods (Perissinotto et al., 2004; Snow and Taljaard, 2007). For example, the Mdloti estuary (a small temporarily open-closed estuary in the subtropical region and typical of many small systems in this region) is generally closed during low-flow periods (winter) (Perissinotto et al., 2004), but seldom becomes marine-dominated because the mouth is perched (limiting tidal exchange) and the wave action and sediment supply along the adjacent coast is high (requiring significant river inflow to maintain an open mouth) (Perissinotto et al., 2004). For the same reason, such estuaries can close while still in the freshwater pulsed/recovery state, i.e. with a pronounced freshwater front still present in the estuary (Perissinotto et al., 2004). In estuaries that do not have perched mouths, or where the mouth areas are not subject to continuous high wave action (e.g. in the cool and warm temperate regions), the closed mouth state is normally preceded by the marine-dominated state (e.g. Great Brak estuary) (CSIR, 1998). A number of small perched estuaries along the South African coast also display variations of the closed mouth state, namely the 'semi-closed state' and 'over-wash of seawater' (Van Niekerk et al., 2002). These variations on the closed mouth state are discussed in greater detail in Snow and Taljaard (2007). With no tidal exchange during the closed mouth state, water exchange across the intertidal-open water boundary within the estuary is limited.

Nutrient cycling and transformation processes during a closed mouth state can vary considerably depending on the period of closure. Limited water exchange, together with stable sediments, creates favourable conditions for biochemical and biological processes to have a potentially significant influence on nutrient cycling and transformation throughout the estuary (Figure 5d). For example, in the Great Brak estuary DIN and DRP concentrations were near-depleted after 80 days of closure (28 July 2007), indicating significant removal of

water column nutrients. Although benthic-pelagic coupling (e.g. sediment remineralisation providing nutrients for water column primary production) cannot be excluded, it is argued that most South African systems lack sufficient sediment organic matter stocks to support large-scale water column primary productivity through benthic-pelagic coupling, except perhaps in anthropogenically enriched estuaries (Taljaard et al., 2009). The rationale here is that the smaller, shallow systems (e.g. the East Kleinemonde estuary, a small temporarily open/closed system in the warm temperate region) can be effectively flushed (or re-set) of accumulated organic matter during seasonal high flows, in contrast with larger, deeper and wider estuaries that will require much higher river inflows for effective flushing, resulting in a build-up of benthic organic matter (benthic total organic matter recorded in the East Kleinemonde estuary was 0.7 mg.g^{-1} [Taljaard et al., 2008]). During the closed mouth state, benthic biochemical processes (e.g. remineralisation and N-fixation) are, however, still important in terms of supporting benthic biological processes (e.g. benthic microalgal production and macrophyte growth). Where closure occurs soon after a freshwater pulse, dominant nutrient cycling and transformation processes may show stronger resemblance to those occurring in the freshwater pulsed/recovery state at the onset. For example, the Mdloti estuary often closes while the influence of a strong freshwater pulse is still evident in the system, so the nutrients introduced from the catchment are retained for a sufficiently long time to stimulate significant water column primary production (Perissinotto et al., 2004). However, low DIN and DRP concentrations measured in the water column on occasions when the mouth had been closed for some time also suggest that these small and shallow microtidal systems are unable to support significant water column primary production once nutrient stocks in the water column have been depleted, although benthic production may be significant. The latter is reflected in higher DIN and DRP concentrations measured in the interstitial water of the sediments of the Mdloti estuary at the time (compared with a freshwater-dominated state), which was attributed to benthic remineralisation becoming more dominant after closure (Perissinotto et al., 2004). Benthic microalgal production was also greater during the closed mouth state, owing to stable sediments and greater benthic nutrient availability.

In the semi-closed state (i.e. when there is an outflow, but no tidal exchange), estuaries receive a continuous, low supply of (river-derived) nutrients that may be retained sufficiently long to stimulate water column production (Snow and Taljaard, 2007). Therefore, in the semi-closed state, water column productivity can sustain a marked influence on nutrient cycling and transformation, as long as the system remains in the semi-closed state. During the

closed state, 'overwash' can also introduce nutrient-rich coastal waters (e.g. the result of upwelling), albeit limited to the lower reaches near the mouth. Here higher nutrient availability, together with sufficient residence time, can stimulate water column primary production in the form of phytoplankton or macroalgal blooms in the lower reaches, as observed in the Van Stadens estuary (a small temporarily open/closed system in the warm temperate region), where a peak in phytoplankton production occurred after an overwash event (Gama et al., 2005).

Although nutrient exchange across the intertidal-open water boundary is expected to be low, extended periods of inundation (caused by raised water levels during the closed state as a result of limited freshwater inflow or seawater overwash) can result in die-back of the intertidal vegetation. This may subsequently become a significant source of organic matter to the estuary and adjacent coastal ecosystems when tidal exchange is re-established, or when the system is flushed (Adams and Bate, 1994; Adams et al., 1999).

6. Concluding Remarks

An extension to an existing southern hemisphere model on nutrient dynamics in estuarine systems (Eyre, 1998 and 2000) was presented here so as to include the relatively constricted, microtidal estuaries located along wave-dominated coasts in the region, largely based on the knowledge and understanding of the temperate and subtropical systems in South Africa. Similar to Eyre's (1998, 2000) general approach, a simplified model of the *physical states* (primarily controlled by hydrological characteristics) was used as the basis for the qualitative model on nutrient cycling and transformation, where the states were defined in terms of characteristic salinity distribution (e.g. position of the freshwater front), water column stratification (e.g. stratified or well-mixed), flushing time and the mouth condition (e.g. open or closed). The model specifically focused on the limiting macronutrients nitrogen (N) and phosphorus (P) and on key processes, including physical (e.g. flushing, mixing and sedimentation), geochemical (e.g. flocculation), biochemical (e.g. remineralisation) and biological (e.g. primary production) processes.

Although the different states can potentially occur in all wave-dominated, microtidal estuaries (depending on the river inflow regime), current understanding suggests that some states tend to occur more frequently in specific estuarine types (based on Whitfield's classification,

1992). The estimated frequency of occurrence and distribution of the various states for specific estuarine types are shown in Table 3. The range of river inflow volumes corresponding to each of the states is site-specific and will depend on characteristics such as the size and shape (bathymetry) of the estuary, tidal exchange, and other physical factors controlling the dimensions (depth and width) of the mouth. Therefore, to establish the typical seasonal frequency distributions of states within a particular system it is necessary to define the relationship between the river inflow and individual states, taking into account the site-specific physical characteristics of the estuary in question. Further refinements to the model include the possibility of differentiating between models for estuaries dominated by different vegetation types, e.g. the salt marsh-dominated systems of the temperate regions versus the mangrove-dominated systems of the subtropical regions.

The model explores the variation within southern African systems to better inform research and management programmes on the appropriate trophic, temporal and spatial scales at which uncertainties in ecosystem functioning need resolving. As with the original model (Eyre, 1998 and 2000), this extended model can be applied to other regions in the southern hemisphere - and even the northern hemisphere - with similar hydrological and geomorphological characteristics, such as the Mediterranean coast (e.g. Palmones, Modego and Tagus estuaries), west coast of north and south America (e.g. Pozuelos–Murillo lagoon system and Elkhorn Slough) and south-west and south-eastern Australia (e.g. Swan and Hopkins river estuaries) (Sharples et al., 2003 ; Hernández-Romero et al., 2004; Avilés and Neill, 2005; Brearly, 2005; Caffrey et al., 2007; Libellø et al., 2007; Simas and Ferreira, 2007; Robson et al., 2008).

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Figure Captions

Figure 1: Distribution of biogeographical regions along the South African coast as well as locations of estuaries discussed

Figure 2: Sampling stations in the a) Keurbooms, b) Breede and c) Olifants estuaries

Figure 3: Salinity distribution patterns measured in the a) Berg Estuary (19 September 1989), b) Breede Estuary (23 August 2000), c) Berg Estuary (31 January 1990), d) Olifants Estuary (2 March 2004), e) Keurbooms Estuary 16-19 March 1987) and f) Great Brak Estuary (28 July 2008)

Figure 4: Mixing diagrams for DIN (unless otherwise indicated) for a) Great Berg Estuary (19 September 1989), b) Breede Estuary (23 August 2000), c) Knysna Estuary (13/14 November 2000, d) Kromme Estuary (18 November 1998), e) Kromme Estuary (23 November 1998), f) Great Berg Estuary (31 January 1990), g) Olifants Estuary (4 March 2004), h) Keurbooms Estuary (16-19 March 1987) and i) Great Brak Estuary (28 July 2008)

Figure 5: Mixing diagrams for DRP (unless otherwise indicated) for a) Great Berg Estuary (19 September 1989), b) Breede Estuary (23 August 2000), c) Knysna Estuary (13/14 November 2000, d) Kromme Estuary (18 November 1998), e) Kromme Estuary (23 November 1998), f) Great Berg Estuary (31 January 1990), g) Olifants Estuary (4 March 2004), h) Keurbooms Estuary (16-19 March 1987) and i) Great Brak Estuary (28 July 2008)

Figure 6: Qualitative model of the different physical states common to South African estuaries a) freshwater-dominated, b) freshwater pulsed/recovery, c) marine-dominated and d) closed mouth (modified from Eyre, 1998 and 2000)

Figure 7: Qualitative model of dominant nutrient cycling and transformation processes during a) a freshwater-dominated state, b) freshwater pulsed/recovery state, c) marine-dominated state and d) closed mouth state (modified from Eyre, 1998 and 2000)

Table Captions

TABLE 1: Specific details on estuaries used as case studies (Bickerton, 1981; Heinecken, 1981; Jezewski et al., 1984; Allanson and Read, 1995; Cowan, 1995; Whitfield and Wood, 2003; Turpie, 2004; Whitfield et al., 2008)

TABLE 2: Summary of empirical data and information used in the development of the model from the different estuaries

TABLE 3: Apparent distribution of the occurrence of various physical state in each of the five estuarine types within the cool temperate, warm temperate and subtropical regions (as classified by Whitfield, 1992)