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19/G10/00/2413/2

Department of Water Affairs
Directorate: Options Analysis

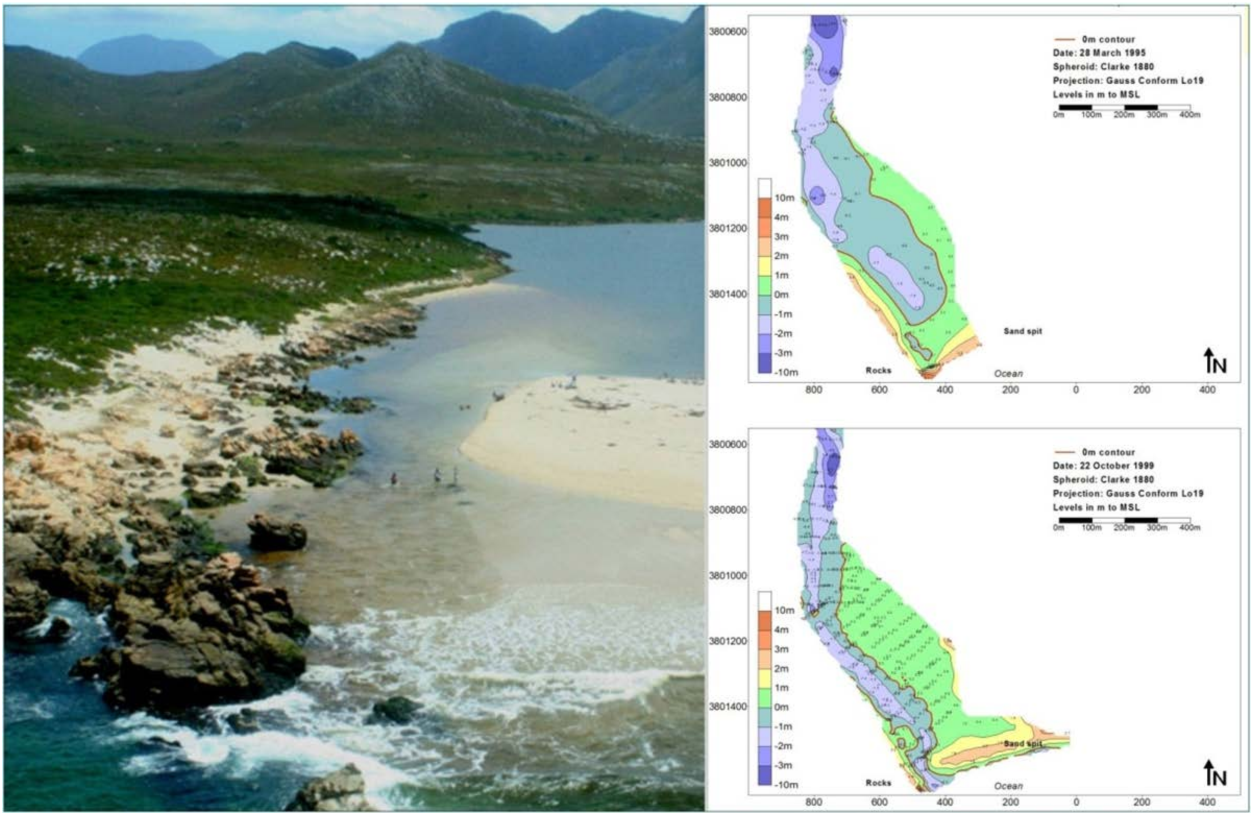
PRE-FEASIBILITY AND FEASIBILITY STUDIES FOR AUGMENTATION OF THE WESTERN CAPE WATER SUPPLY SYSTEM BY MEANS OF FURTHER SURFACE WATER DEVELOPMENTS

REPORT No.1 – VOLUME 2

Rapid Determination of the Environmental Water Requirements of the Palmiet River Estuary

APPENDIX No.C

Abiotic Specialist Report



June 2012

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RECORD OF IMPLEMENTATION DECISIONS

PWMA19 G10/00/2413/7

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1 INTRODUCTION

1.1 BACKGROUND

The Western Cape Water Supply System (WCWSS) serves the City of Cape Town (CCT), other urban users and irrigators. It comprises infrastructure owned and operated by both the CCT and the Department of Water Affairs (DWA).

The Western Cape Reconciliation Strategy Study reviewed the future water requirement scenarios of greater Cape Town and the reconciliation options for meeting these water requirements within a planning horizon to 2030. It identified potential suites of options for meeting future water demand from the WCWSS. It also identified various alternative implementation options, which offered flexibility in planning, such that possible changes in the projected water requirements could be accommodated. One set of implementation options is to further develop the surface water resources of the Berg and Breede Water Management Areas (WMAs).

In July 2008, the then Department of Water Affairs and Forestry (now DWA) appointed the Western Cape Water Consultants Joint Venture to undertake Pre-feasibility and Feasibility level investigations of the potential development of six surface water options, namely:
- the Michell's Pass Diversion Scheme;
- the First Phase Augmentation of Voëlvlei Dam;
- Further Phases of Voëlvlei Dam Augmentation;
- the Molenaars River Diversion;
- the Upper Wit River River Diversion;
- further Phases of the Palmiet Transfer Scheme.

This entailed investigations in three major catchments, *viz*. Breede, Palmiet and Berg Catchments.

Southern Waters sub-consulted CSIR, on behalf of the JV, to undertake a rapid Ecological Water Requirement (EWR) determination for the Palmiet River Estuary.

1.2 OBJECTIVES OF THE REPORT

This report is the Abiotic Specialist Report for the EWR study. The study was done at a **RAPID** level.

2 THE STUDY AREA

The Palmiet Estuary, located 75 km south east of Cape Town, is a small system, 1.67 km in length and some 300 m at its widest extent (Figure 2.1). The head of the estuary is marked by a series of rocky sills. The channel meanders between steep rocky banks in the upper reaches of the estuary, and scour holes (4-5 m) are located on the outer bends of these meanders. From about 700 m upstream of the mouth, the channel hugs the west bank and there are broad, shallow tidal flats on the eastern side (CSIR, 1992).

The mouth is located close to a rocky bank on the western side. Prevailing westward longshore currents and the SSW and WSW high-energy waves result in an extensive mobile sand spit on th eastern side of the mouth.

The estuary is in a good condition. However, based on the simulated run-off data provided for this project, it is estimated that the mean annual run-off has been reduced by 36.1%, from 256.3 x 10^6 m^3a^{-1} under natural conditions to 163.7 x 10^6 m^3a^{-1} in 2009. The runoff from the catchment shows strong seasonal variations with high flows and major floods during the winter months, and low flows during the summer months.

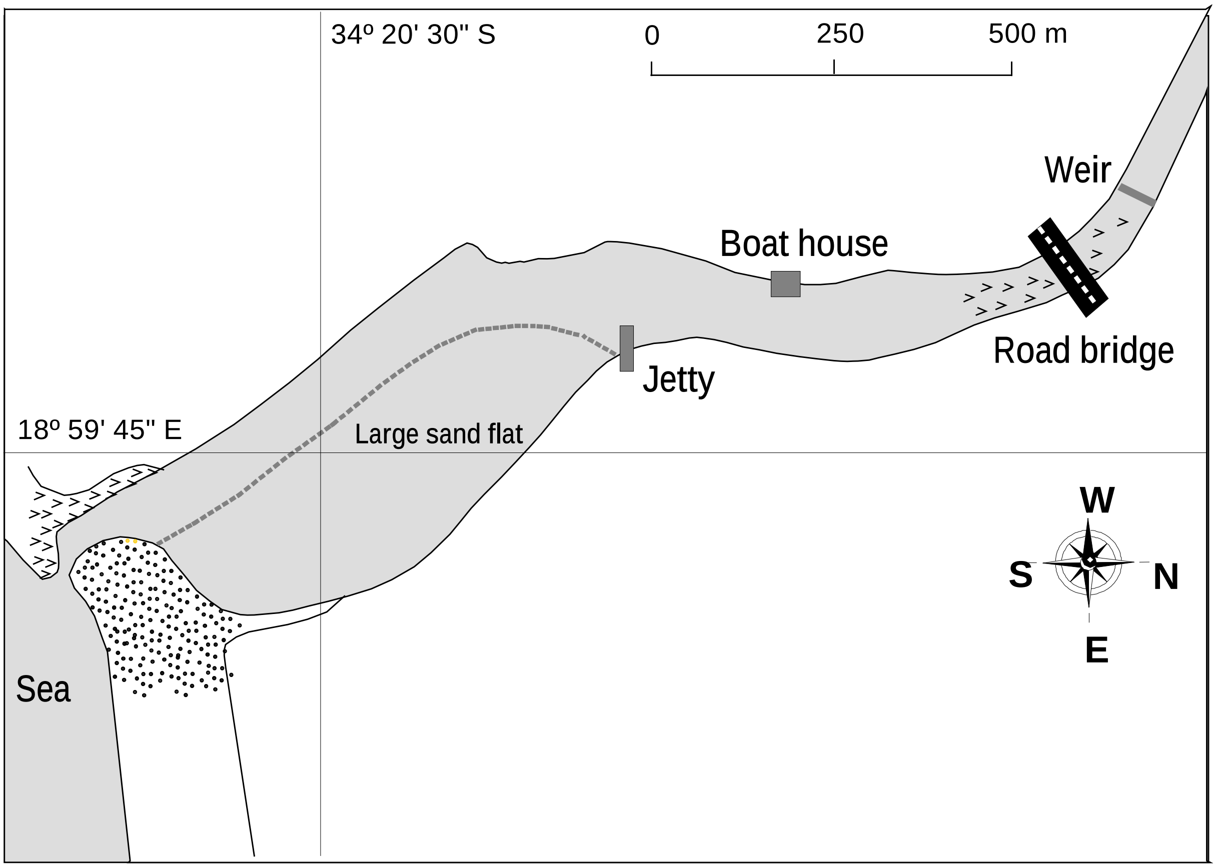

Figure 2.1 Map of the Palmiet River Estuary

3 TYPICAL ABIOTIC STATES OF THE PALMIET ESTUARY

Based on available literature, five characteristic abiotic states can be identified for the Palmiet Estuary (Table 3.1). These are related to tidal exchange, salinity distribution and water quality, and are primarily determined by *river inflow patterns, state of the tide* and *wave conditions*.

Table 3.1 Typical abiotic states in the Palmiet Estuary

State 1	Closed mouth: No exchange through the mouth (usually during the dry season)
State 2	Semi-open mouth: No seawater intrusion, but with water flowing out to sea (usually during the dry season)
State 3	Highly stratified, with significant marine influence: Open mouth with extensive seawater intrusion (usually during the dry season);
State 4	Highly stratified, with significant freshwater influence: Open mouth with limited seawater intrusion and strong river influence (usually during the wet season)
State 5	Freshwater dominated: Open mouth with no seawater intrusion and very strong river influence (i.e. river or fluvially dominated) (usually during the wet season)

The physical and water quality characteristics associated with each of the abiotic states is discussed in greater detail in the following chapters.

River inflow patterns are one of the key controlling parameters in determining the 'state' of the estuary and are also the primary parameter influenced by dam development. Simulated run-off data were used to estimate typical variation and duration of 'states' (and the associated physical and water quality characteristics) for each of a series of scenarios. This provided a framework within which changes in physical dynamics and water quality that may occur as a result of the proposed dam development scenarios relative to natural and present conditions could be assessed.

Using the above approach to estimate the degree to which the hydrodynamics and water quality may be altered from the present and natural situation provides a platform from which to assess ecological impacts.

4 PHYSICAL CHARACTERISTICS

Changes in run-off can have direct effects on the physical condition of an estuary, which can indirectly affect other environmental components.

The main concern at the Palmiet Estuary is the effect that changes in run-off could have on the dynamics of the mouth of the estuary, and in particular, the occurrence of closed or semi-closed mouth conditions (i.e. States 1 and 2). Open mouth conditions at nearby estuaries are also discussed.

Water level variations in the estuary under different flow conditions, as well as sediment and erosion processes in the estuary, are also discussed briefly.

4.1 MOUTH DYNAMICS

The most important physical aspect of the estuary related to changes in runoff is probably the condition of the mouth in the berm. A reduction in runoff could increase closed-mouth conditions. Premature closure of an estuary mouth can have dire consequences for its physical (e.g. no flushing of sediments) and ecological (e.g. spawning of juvenile fish, benefits of influx of fresh sea water) functioning. Recreational use of an estuary can also be affected through, for example, aesthetics problems (bad smells as algae builds up).

An investigation was therefore undertaken on the dynamics of the estuary mouth, based on available information. The understanding that was acquired was used to predict conditions under the different runoff scenarios that were provided for this investigation.

Physical dynamics, which are associated with the different ‘states’ described in Table 1, are discussed and analysed below.

4.1.1 State 1: Closed mouth

This state, i.e. closed mouth with no exchange, could occur in the Palmiet Estuary when the mouth is closed and river flow ceases, or if river flow is lower than the losses through evaporation and seepage. Reliable data on this situation are not available but, based on observations, it is estimated that this ‘state’ could occur at river flows of less than 0.05 m^3s^{-1}. The present base flows are, according to the available data never lower than 0.2 m^3s^{-1}.

State 1 has been observed in the Palmiet Estuary, but available data indicate that only persisted for a few days. This happened when the berm built up at high wave conditions to a level above the water level in the estuary. Inflows then resulted in a slow increase in water levels until the berm started overflowing again.

4.1.2 State 2: Semi-closed mouth

State 2, i.e. the semi-closed mouth, occurs as a result of an interesting process in the Palmiet Estuary. During low flow, usually in the summer, the mouth often shifts on to the rocks at the south-western end of the berm. An almost continuous outflow then occurs, but the rocky sill in the mouth is too high to allow influx of seawater, even during spring tides. The normal functioning of the mouth involving tidal exchange between the estuary and the sea is then interrupted. While it is physically open in terms of river outflow, it is effectively closed in terms of tidal exchange, which is the basis of estuarine functioning.

This state is considered to be critical to the EWR evaluations as it is likely to be enhanced by dam development. When an estuary mouth closes, it has major effects on the water dynamics and therefore also water chemistry of the estuary. If these conditions persist for long periods, the biota is also usually affected. It was therefore important to establish the conditions under which this situation develops and is maintained, and under which conditions the mouth is breached again.

Fortunately, excellent data have been collected in recent years, allowing a proper analysis of the correlation between river flow and the occurrence of the semi-closed mouth condition. There is a river flow gauging station (G4H007) *c*. 500 m upstream of the head of the estuary and a water level recorder (G4R009) that was installed in the estuary in January 1992 on recommendations from the CSIR. Department of Water Affairs (DWA) operates both of these.

Analysis of water level recording data is an accurate and effective method to establish when and how mouth closure/semi closure (State 2) occurred, and can be linked to inflow patterns measured at the flow gauging station.

Table 4.1 provides the dates when State 2 occurred, the number of days before (-) or after (+) neap tide that this occurred, the river flow at the time, as well as some additional comments.

Ten of the 17 mouth closures/semi-closures on record occurred at neap tide or within two days after neap tide. This indicates that tidal flows at spring tides play a significant role in keeping the mouth open, and that the critical period for closure is during neap tide when tidal flows through the mouth are not strong enough to keep it open. This also suggests that less river flow may be needed to maintain an open mouth conditions at spring tide than at neap tide.

The river flows at which mouth closure/semi-closure occurred ranged from 0.23 to 1.01 m^3s^{-1}. The large range is an indication of the influence that high waves and tidal exchange have on such occurrences. This information was used in further analysis of simulated runoff data.

Table 4.1 Dates on which semi-closure of the mouth occurred, including stage of the tide and river inflow

DATE	PERIOD RELATIVE TO NEAP TIDE (days)	RIVER FLOW (m^3s^{-1})	MOUTH STATE
14 Feb 1992	+1	0.49	Closed (State 1)
1 Feb 1993	0	0.61	Almost Closed (State 2)
1 Apr 1993	+1	0.33	Closed (State 1)
21 Jan 1994	+3	0.33	Almost Closed (State 2)
2 to 7 Feb 1994	-2 to +3	0.23 to 2.1	Almost Closed (State 2)
08 Feb 1994	+4	0.74	Closed (State 1)
22 Feb 1994	+2	0.49	Closed (State 1)
11 Jan 1995	+1	0.33	Closed (State 1)
30 Jan 1995	+5	0.10	Closed (State 1)
7 Apr 1995	-2	0.38	Closed (not on rocks) (State 1)
12 Apr 1995	+2	0.49	Closed (State 1)
2 Feb 1996	0	0.43	Almost Closed (State 2)
26 Feb 1996	-1	0,74	Closed – High Waves (State 1)
21 Apr 1996	-5	1,01	Closed – High Waves (State 1)
4 Mar 1997	+1	0,38	Closed (State 1)
23 Jan 1998	+1	0,67	Almost Closed (State 2)

DATE	PERIOD RELATIVE TO NEAP TIDE (days)	RIVER FLOW (m^3s^{-1})	MOUTH STATE
27 Jan 1998	+5	0,61	Closed (State 1)

Because dam development is likely to increase the occurrence of State 2, conditions at which the mouth was breached after closure/semi-closure (i.e. river flow that would take the estuary from State 2 to State 3) were also accessed as these are the condition that could affect the duration of State 2. The dates at which breaching occurred, together with corresponding river flows and the number of days for which the mouth had been closed, are listed in Table 4.2. Unfortunately the dates of mouth breachings could not be accurately identified because the water level recorder data were unreliable at times.

The lowest river flow at which breaching occurred was 0.28 m^3s^{-1} and the highest 11.16 m^3s^{-1}. The mouth was breached six times at inflows lower than 1.0 m^3s^{-1}.

The longest duration of mouth closure was 94 days during 1994, while on six occasions the mouth remained in the semi-closed state (i.e. State 2) for five days or less.

Table 4.2 Dates on which mouth breach occurred, and the preceding period of semi-closure and river inflow

DATE	RIVER FLOW (m^3s^{-1})	PERIOD BEING SEMI-CLOSED (days)
12 Feb 1992	3.80	2
10 Apr 1992	10.68	39
9 Apr 1993	8.42	8
13 Feb 1994	0.49	5
27 May 1994	11.16	94
15 Jan 1995	0.28	4
19 Mrch 1995	0.94	48
9 Apr 1995	0.87	2
17 Apr 1995	0.61	5
8 Mrch 1996	0.38	12
27 Apr 1996	1.93	2
6 Apr 1997	3.52	33
19 May 1997	1.01	30

Occurrences of higher flow during which the mouth remained semi-closed are listed in Table 3.3

Table 4.3 Occurrences of higher flows while the mouth remained semi-closed

DATE	FLOW (m^3s^{-1})
1 Apr 1992	1.31
6 Apr 1993	1.39
8 Feb 1994	0.74
28 Apr 1994	1.93
2 Feb 1995	0.55
27 Feb 1996	0.74
11 Mar 1997	0.74
6 May 1997	1.72
18 May 1998	1.39

The highest flow under semi-closed conditions that failed to breach the mouth was 1.93 m^3s^{-1}, but on five occasions flows > 1.0 m^3s^{-1} occurred that did breach the mouth.

Thus, flows of 3 $m^3.s^{-1}$ or more for a period of 12 hours will probably be sufficient to flush the mouth open when it is semi-closed. This equates to a volume of approximately 130 000 m^3 and, at an estimated surface area of 250 000 m^2 (Huizinga, 1987), which would result in an increase in water level of *c*. 0.5 m while the mouth stayed closed.

Occurrences where the mouth remained open under low flow conditions (i.e. State 3) are listed in Table 4.4

Table 4.4 Occurrences of low flows while the mouth remained open

DATE	FLOW (m^3s^{-1})
28 Dec 1992	0.61
18 Jan 1993	0.28
1 Mrch 1992	0.38
22 Nov 1993	0.49
10 Jan 1994	0.28
12 Dec 1994	0.23
19 Jan 1995	0.49
12 Feb 1996	0.33
18 Feb 1997	0.55
5 Jan 1998	0.61

On several occasions the river flow dropped below 0.5 m^3s^{-1} while the mouth was open, but this did not result in closures or semi-closures.

The information presented in Table 4.1 to Table 4.3 gives an indication of the wide range of river flows that could cause State 2 and of the variability in flows that could subsequently breach the mouth. This indicates both the vulnerability of the mouth under low flow conditions and the influence of wave conditions and tides.

This information was translated into general assumptions about the relationship between open/closed mouth conditions in the Palmiet Estuary and river inflow, which we used in the assessment of the scenarios (Table 4.5).

Table 4.5 Assumptions about the relationship between State 2 and river inflow

RIVER FLOW ($m^3 s^{-1}$)	MOUTH CONDITION
0	The mouth will be closed without any over flow at the berm (i.e. representative of State 1)
< 0.3	The mouth will normally be closed or semi-closed without tidal exchange taking place, while overflow of the berm takes place. Under prolonged conditions of low waves the mouth will stay open especially at spring tide (i.e. representative of State 2)
between 0.3 and 0.7	The mouth will be semi-closed for approximately 50 per cent of the time. Closure is more likely to occur at neap tides.
between 0.7 and 1.5	The mouth will normally be open (i.e. representative of State 3), but can occasionally close or semi-close during high wave conditions, especially at neap tides.
3 or more for a period of 12 hrs	Probably be sufficient to flush the mouth open after it had been semi-closed (i.e. taking it from State 2 to State 3)

4.1.3 State 3: Highly stratified with strong marine influence

State 3 exists when the mouth is open, and when the river flow is significantly lower than the tidal flows through the mouth. These indicate that this state will exist when river flow is between 5 and 10 $m^3 s^{-1}$.

4.1.4 State 4: Highly stratified with strong freshwater influence

State 4 usually occurs during the wet season with limited seawater intrusion and strong river influence (i.e. river or fluvially dominated). It occurs at river flows between approximately 10 m^3s^{-1} and 20 m^3s^{-1}. However, there are probably overlaps between State 3 and State 4 at lower flows, and between State 4 and State 5 at higher flows.

River flow dominates during this state and only a limited influx of saline water from the sea takes place at high tides, as is described in Section 5. This state has been referred to as a ‘cleansing mechanism’ for the estuary because it is largely responsible for flushing algae and other accumulated organic matter from the system (Taljaard and Largier, 1989).

4.1.5 State 5: Freshwater dominated

State 5 occurs at river flows > 20 m^3s^{-1}. As mentioned before, there is probably an overlap State 4.

The estuary will become totally fresh within a day or three of flows reaching 20 m^3s^{-1}, and will stay fresh until the river flow drops below 20 m^3s^{-1} and State 4 re-occurs.

4.2 MOUTH CONDITIONS AT NEARBY ESTUARIES

Estuaries are extensively used as nurseries for juvenile fish and other organisms, particularly during spring/summer, thus, it is critical to ensure at least some estuaries remain open to sea within a coastal region. In the south-western Cape, the Palmiet Estuary is often the only open system during these critical times (ANNEXURE IV). The importance of the Palmiet Estuary, in this regard, is highlighted in the brief summary given below on open mouth conditions at neighbouring estuaries, based on existing understanding.

4.2.1 Bot and Kleinmond river system

The Bot River is only occasionally directly open to the sea. Sometimes it is closed for two to three years in a row, resulting in a freshening of the system. When the mouth is breached, a great deal of sediment is flushed out, and mouth only closes again after three to five months. The mouth would probably be open more often and for much longer, if it was not drained through the shallow channel connecting it with the mouth of the Kleinmond River.

The Kleinmond River mouth is open more frequently and longer (six to eight months per year) than is the Bot River mouth. It is maintained by the flow from the Klienmond and from the Bot River vlei. The Kleinmond River Estuary is small, with little tidal exchange through the mouth.

4.2.2 Onrus River mouth

The Onrus River Estuary is very small, and the mouth, when open (three to five months per year), is normally in a perched (i.e. pushed above MSL) position, only allowing limited tidal exchange at high spring tides.

4.2.3 Klein River mouth near Hermanus

The Klein River mouth is normally open for four to six months per year. Breaching occurs during winter, and the mouth normally closes during spring or early summer.

4.2.4 Uilkraals River mouth

The Uilkraals River mouth, approximately 50 km east of the mouth of the Palmiet River, is always open, because of the perennial river flow, but the estuary is small and tidal exchange is limited. At low tide it often runs dry.

4.3 WATER LEVEL VARIATIONS

Water levels in an estuary give an good indication of the state of the estuary mouth, e.g. when the mouth has been extensively scoured/eroded, by a freshet or a flood, water levels in the estuary drop, because there is less restriction on the outflow of water through the mouth, thus allowing more water to drain from the estuary over the tidal cycle. Although the correction factor of the gauge plate at the recorder in the estuary is not available, a relative comparison shows that, during low tides, water levels may drop up to 0.5 m lower shortly after strong river inflow, compared to low tide water levels just prior to semi-closure of the mouth. However, this normally only occurs on a few consecutive low tides after floods or freshets. The occurrence of very low water levels will be therefore be reduced if river flow is reduced. A map of the bathymetry of the estuary, based on a surveys undertaken by the CSIR in 1995 and 1999 (Figure 3.1) also indicates that only a small additional band of the flood plain will become exposed at these lower water levels.

Normally water levels at low tide vary within a relatively narrow band of approximately 0.3 m.

4.4 SEDIMENTATION AND EROSION INSIDE THE ESTUARY

The sediment dynamics inside the estuary are not well understood because of lack of information. The major processes are:

- Influx of marine sediments because of tides and waves.
- Flushing of sediments (marine and fluvial) during major floods.
- Limited supply of sediment from the catchment, although this may be somewhat offset by erosion in catchment because of agriculture.

Dam developments on the river can affects the sediment dynamics of the Palmiet Estuary in two opposing ways:

- A reduction in the occurrence of floods can result in sedimentation.
- Dam in the lower catchment will act as a sediment trap and could reduce sediment supply to the estuary. This could result in a deepening of the estuary.

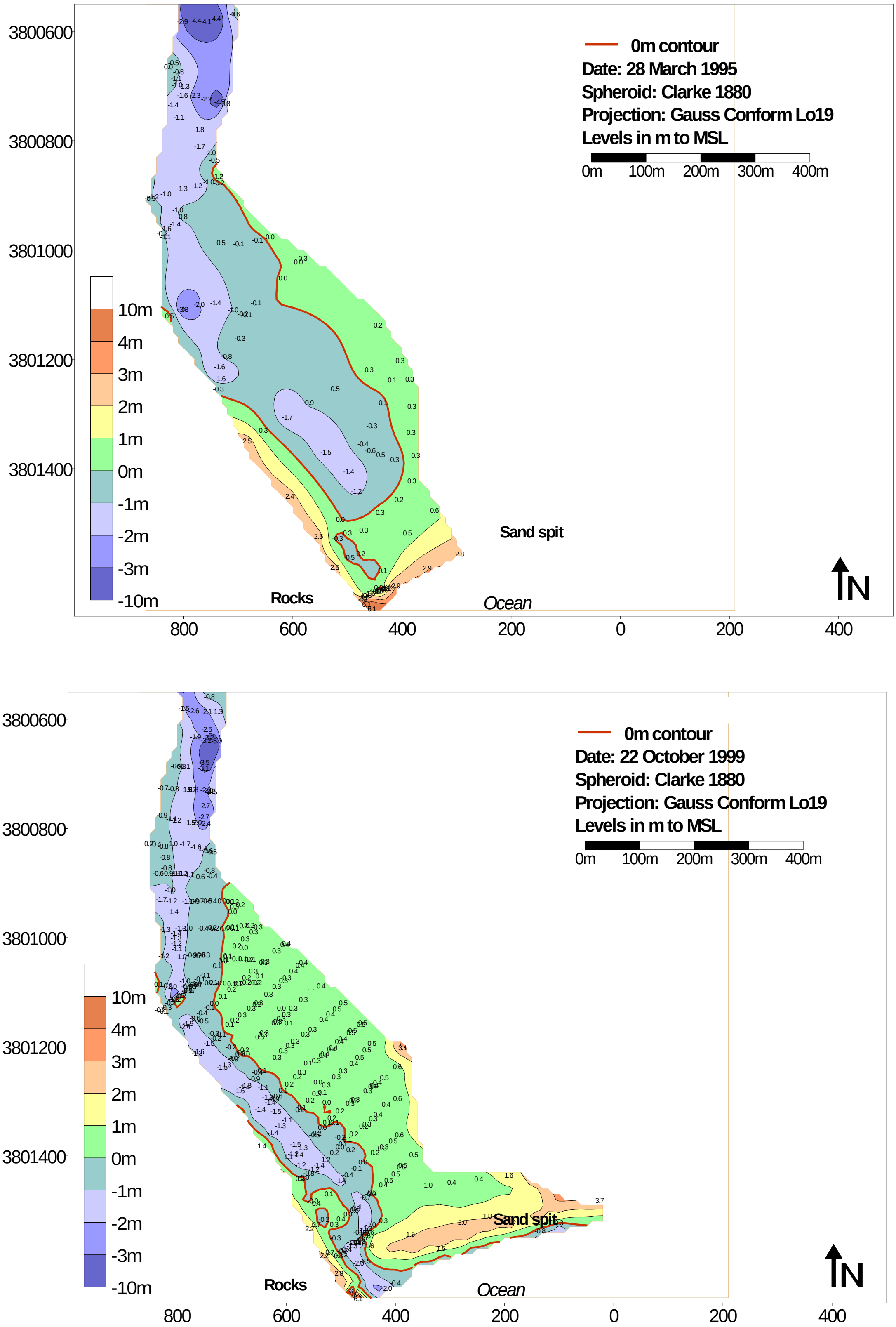

Figure 4.1 Bathymetry maps of the Palmiet Estuary for 1995 and 1999

5 WATER QUALITY CHARACTERISTICS

To assess change in water quality, typical water quality characteristics associated with each of the predefined abiotic states were determined, based on available data and expert opinion. In providing such ‘generic’ characterisation of an estuary’s water quality, event specific details, discussed in the literature, might have been excluded. For this reason a comprehensive reference list is also provided. The key water quality characteristics described here are considered to be appropriate for the purposes of this study. The water quality characteristics of the system are described in terms of the following parameters:

- Salinity
- Temperature
- pH
- Dissolved oxygen
- Dissolved inorganic nutrients (dissolved inorganic nitrogen [DIN], dissolved inorganic phosphate [DIP] and reactive silicate).

(Limited data on dissolved organic carbon available on the system is also provided.)

No data were available on toxic substances. The system is not considered to be subject to gross pollution typically associated with large urban development (e.g. trace metals, hydrocarbons). However, agricultural activities in the catchment may have introduced pesticides/herbicides to the system (DIN data suggest significant nutrient inputs during freshettes of which such agricultural activities [fertilizers] are most likely the source).

Available water quality data on river inflow to the Palmiet Estuary (from DWAF gauging station G4H007) are presented Figure 5.1.

The data show a marked increase in pH of river inflow in the early 1990 when average pH levels appeared to increase from ~5 to ~ 7. DIN concentrations show a distinct seasonal signal, with distinct peaks during winter. Winter peaks appeared to have dropped markedly since 2002 from ~1000 μg.l^{-1} to ~500 μg.l^{-1}. A black water system like the Palmiet River is expected to be oligotrophic in its Reference Condition. These exceptionally high winter DIN peaks are therefore most likely associated anthropogenic inputs from agricultural activities in the catchment (although this needs to be confirmed). DIP concentration in river inflow remained low over the years with no distinct seasonal signal. Concentrations showed a slight increase from ~20 μg.l^{-1} to 30 μg.l^{-1} in the past 8 years. Dissolved reactive silicate-Si (DRS) also did not show any distinct seasonal pattern, averaging 1500 μg.l^{-1}.

Available data and information on water quality characteristics of the Palmiet Estuary for the different abiotic states, described in terms of the above parameters, are discussed below.

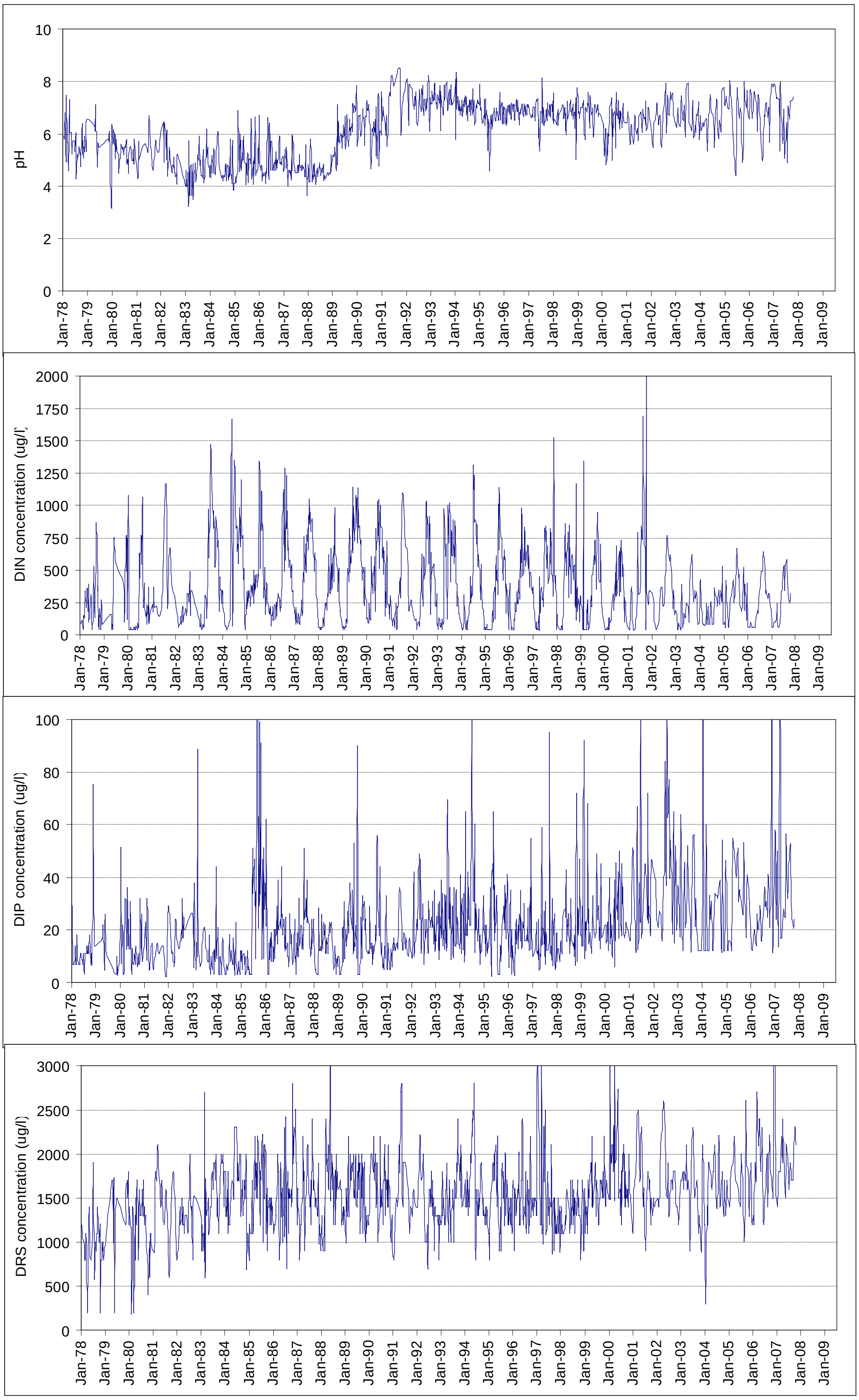

Figure 5.1 **Data on river inflow to the Palmiet Estuary 1978-2007 (DWAF Station G4H007)**

5.1 STATE 1: CLOSED MOUTH

The closed state does not occur for extensive periods (a few days to a week) and usually only during relatively dry *summer seasons*. As a result, literature on the water quality characteristics during this state is not widely available. Slinger and Largier (1990) did, however, take salinity and temperature profiles in the estuary in February 1988 when this state existed for a few days. The salinity profile measured in the estuary at the time is given in Figure 5.2.

Salinity measurements during the closed state (1988) showed strong vertical stratification, ranging from 34 ppt in the deeper areas to 5 ppt in the surface waters near the head of the estuary, with a strong halocline between 1 to 2 m water depth. Given the high bottom water salinities measured at the time, the system probably closed whilst in State 3 (open with strong marine influence), e.g. as a result of a storm at sea that increased berm height abruptly. Although no data were available, it is anticipated that as long as the mouth remains closed, this strong stratification will persist for an extended period, mainly because the estuary is protected from wind (wind mixing can affect stratification) and turbulence associated with river inflow is small. However, the mouth could also close after the system had been in State 2: Semi-closed mouth for a period of time. In such instances it is expected that the estuary will be much less stratified and more brackish (5-15 ppt) during the closed mouth state.

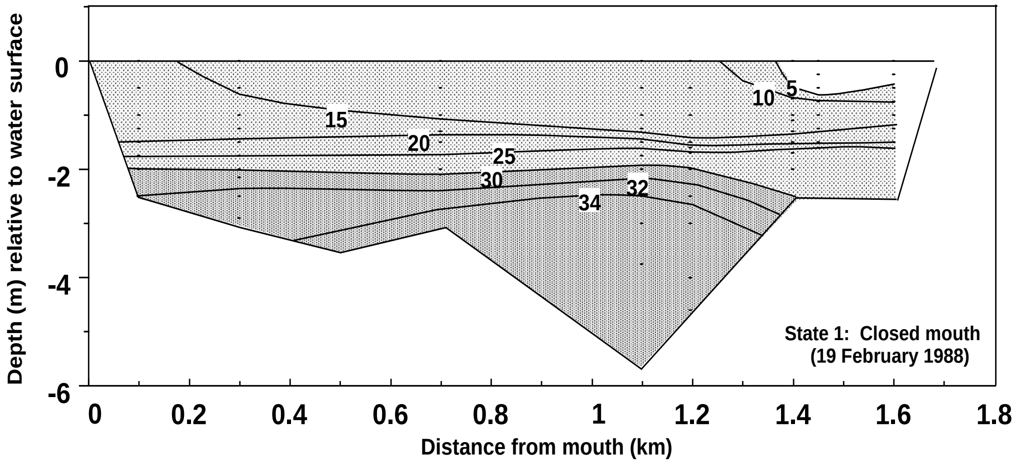

Figure 5.2 Salinity (in ppt) distribution measured during State 1: Closed mouth (February 1988)

During the 1988 survey, ***temperatures*** in the estuary decreased with depths ranging from 26.0 ^{o}C in the surface layers to about 22.5 ^{o}C in the deep scour holes about 1 km upstream of the mouth. However, the temperature in an estuary is a non-conservative parameter that, at any point in time, is largely a function of the temperature of the seawater that originally entered the estuary, the temperature of the inflowing river water and the atmospheric temperature (Slinger and Largier, 1992).

Although no measurements were taken, ***pH*** levels in the water column would typically range between 7 and 8 under strong marine influence. Even though the Palmiet River is a blackwater system with characteristic low pH levels (levels as low as 4 have been measured), it is unlikely that this will have a major influence once it enters the estuary, owing to the strong buffering capacity of seawater (Branch and Day, 1984).

Dissolved oxygen (DO) measurements for State 1 were not available. However, it is expected that a large proportion of the bottom layer, below the halocline, may become hypoxic and even anoxic. The extent to which oxygen will be reduced in the bottom layer during this state is probably dependent on benthic organic matter loads (e.g. kelp and macrophyte derbis) in the estuary prior to closure. Where the biomass is high, marked reductions in DO of the bottom water can be expected below the halocline.

No data on water transparency was available for State 1: Closed mouth.

Also, no data on ***dissolved inorganic nutrients*** were available for State 1: Closed mouth. It, however, is anticipated that DIN and DIP concentrations will be relatively low, although strong marine influence (and associated with upwelling) may result in elevated concentrations at the onset of the closed state becoming depleted with time. If the state persists for extended periods, nutrient concentrations in anoxic bottom water trapped below the halocline, can be elevated significantly (see State 2: Semi-closed mouth).

5.2 STATE 2: SEMI-CLOSED MOUTH

The semi-closed mouth state, i.e. when there is no seawater intrusion into the estuary, but where water still flows out to sea, typically occurs during the late summer months (dry season). This state has been monitored previously (Slinger and Largier, 1990; CSIR, 1992), focusing mainly on salinity and temperature distributions and not providing sufficient information on changes in important water quality parameters, such as dissolved oxygen and nutrients.

Studies specifically aimed at monitoring water quality characteristics during the semi-closed state were undertaken in 1998 (CSIR, 2000; Van Ballegooyen et al., 2004). Changes in water quality were measured in terms of salinity, temperature, dissolved oxygen and dissolved inorganic nutrients. The experiments extended over a period of about 3 months.

Salinity profiles measured over the sampling period are presented in Figure 5.3. Seawater intrusion was cut off just prior to the first field exercise (28 January 1998) when high waves at sea deposited sediment in the mouth area. At the time the estuary was highly stratified with a strong halocline at about 1 m water depth. Over the following 3 months the halocline gradually moved deeper, mainly as result of the turbulence caused the inflowing river water. At the end of the sampling period (i.e. after about 3 months), the water in the estuary was almost completely fresh, except in the deeper scour holes, where a very strong halocline (at about 4 m water depth), still trapped old seawater (salinity of 32 ppt). The rate at which this process occurs is obviously largely dependent on the river flow rate. It is anticipated that if State 2 persists for a long enough period (about 5 months), the entire estuary could become fresh. The detailed physical dynamics of this particular process were discussed in Slinger and Largier (1990) for a similar event in 1988.

As mentioned before, the ***temperature*** is a non-conservative parameter that, at any point in time, is largely a function of the temperature of the seawater that originally entered the estuary, the temperature of the inflowing river water and the atmospheric temperature (Slinger and Largier, 1992). Recent surveys showed that during the initial stages of State 2, i.e. up to about 2 weeks after seawater intrusion was cut off, the temperature levels in the estuary were generally fluctuating between 26°C and 18°C, decreasing with depth. Although in the following months the temperature range remained more or less the same, temperature structure in the water column become more complex, e.g. when colder river water started moving into the surface layer. The detailed temperature profiles and physical dynamics of this process were also been discussed in Slinger and Largier (1990).

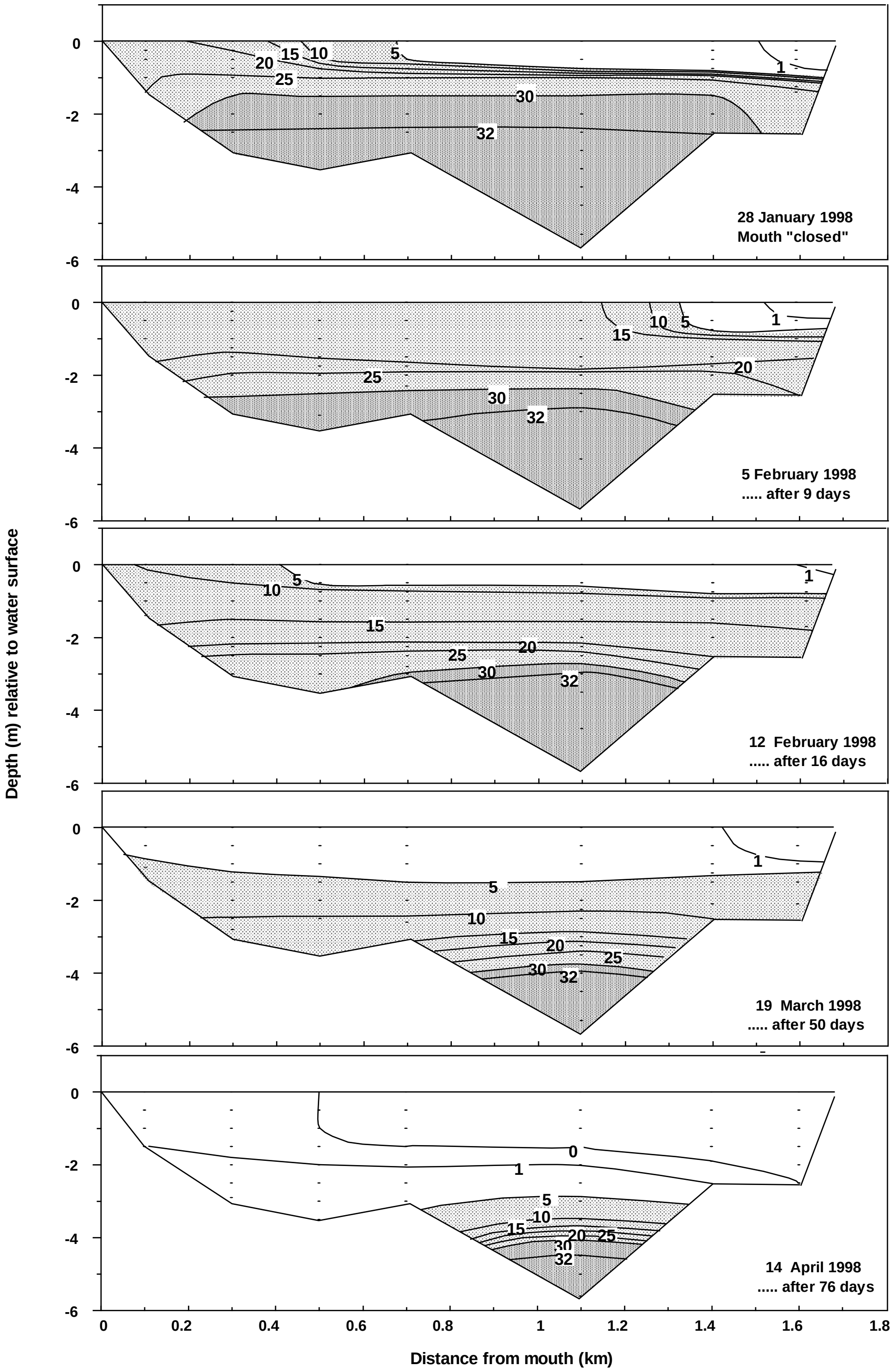

Figure 5.3 Changes in salinity (in ppt) distributions over time measured during State 2: Semi-closed mouth (summer/autumn 1998)

Although no measurements were taken, it is anticipated that ***pH*** values will initially range between 7 and 8, owing to the strong buffering capacity of seawater.

Changes in DO distribution patterns during a semi-closed state are provided in Figure 5.4.

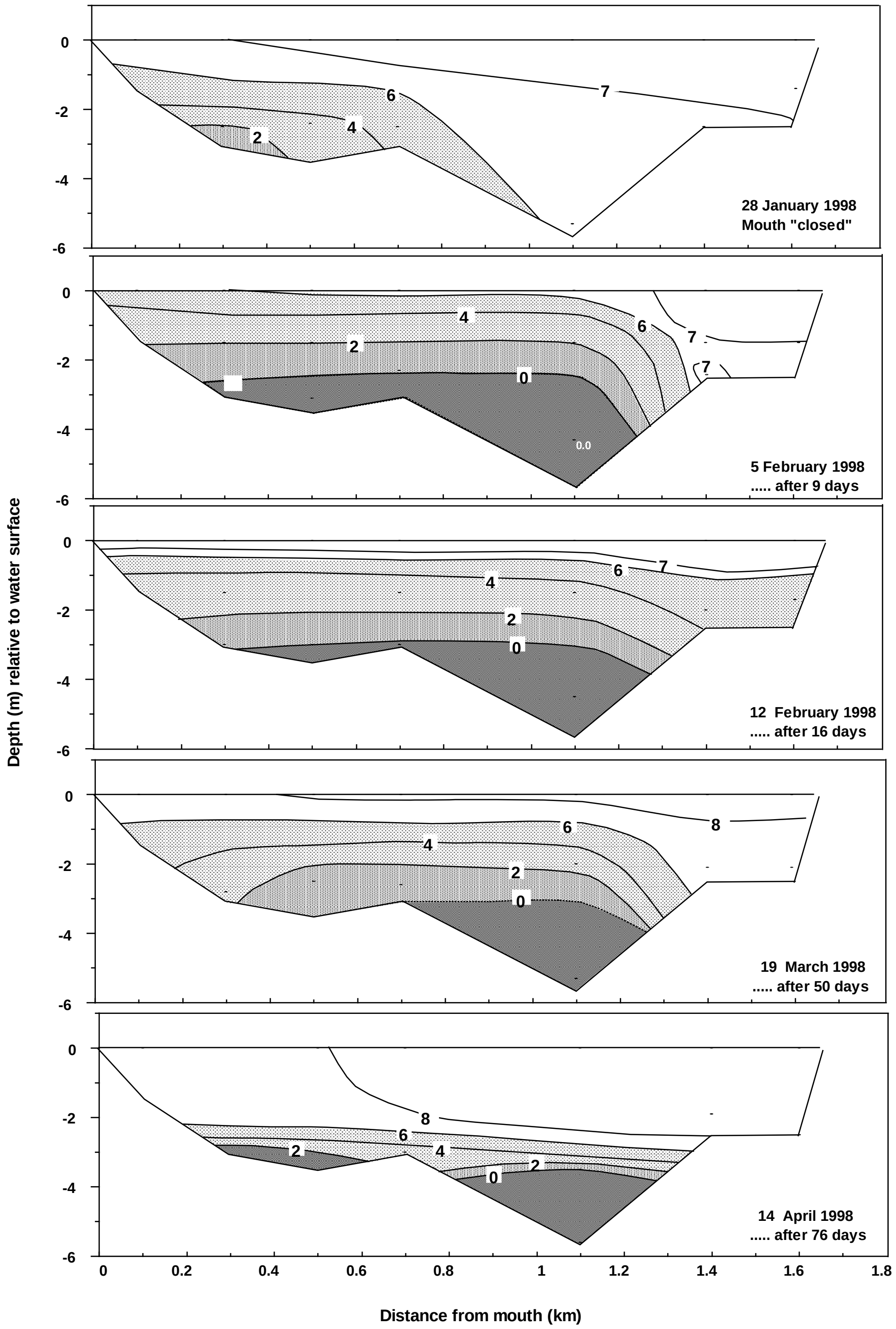

Figure 5.4 Changes in DO (in mg. l^{-1}) distributions measured over time during State 2: Semi-closed mouth (summer/autumn 1998)

Almost immediately after the seawater exchange was cut off, thereby cutting off the main flushing mechanisms of bottom waters during the dry season, oxygen levels in the bottom layers started decreasing. This was attributed to high oxygen demand of decaying organic material (e.g kelp and *Chladophora*). This trend rapidly increased, so that within a week after seawater intrusion was cut off, a large section of the estuarine water column below the halocline became hypoxic (oxygen levels below about 4 mg.l^{-1}) and even anoxic (dissolved oxygen down to zero). However, as turbulent mixing, caused by river inflow increased, low oxygen water was gradually replaced by more oxygenated fresh water. Eventually, after about 3 months, a large portion of the estuary was again well-oxygenated, with hypoxic and anoxic conditions only occurring below the strong halocline at about 4 m water depth. It is anticipated that if State 2 persists for a long enough period (about 5 months), the entire estuary could become oxygenated again. Similar to salinity, the rate at which this process will occur is largely dependent on the river flow rate (i.e. the source of turbulence). Note that the extent to which oxygen will be reduced in the bottom layer during State 2 is probably dependent on benthic organic matter load (e.g. kelp and macrophyte derbis) in the estuary prior to closure. In this instance, the biomass was extensive hence, the marked reduction in DO in bottom waters below the halocline.

Water ***transparency*** in the Palmiet Estuary (measured as Secchi disc depth in m) remained at about 2 m along the length of the estuary during State 2 for the entire sampling period.

Inorganic nutrient distribution patterns measurements in the Palmiet Estuary over a period of about 3 month during State 2 are presented in Table 5.1 and Table 5.2.

Table 5.1 Changes in surface water (i.e. above halocline) nutrient concentrations measured over time during State 2: Semi-closed mouth (1998)

NUTRIENT	TIME AFTER SEAWATER INTRUSION WAS CUT OFF (28 JAN 1998)				
	At cut off	9 days	16 days	50 days	76 days
Nitrite-N (µg.l^{-1})	< 5	< 5	< 5	< 5	< 5
Nitrate-N (µg.l^{-1})	10	15	6	<5	28 -265*
Total ammonia-N (µg.l^{-1})	22	15	14	17	22
DIN (µg.l^{-1})**	32	30	20	17	50-287*
DIP (µg.l^{-1})	65	9	< 5	< 5	< 5
Reactive silicate-Si (DRS) (µg.l^{-1})	370	430	480	470	230 - 1110*

* *The higher concentration were measured in the upper reaches owing to an increase in river water concentrations after a freshet*

** *Nitrite-N + Nitrate-N + Total ammonia-N*

Table 5.2 Changes in bottom water (i.e. below the halocline) nutrient concentrations measured during State 2: Semi-closed mouth (1998)

NUTRIENT	TIME AFTER SEAWATER INTRUSION WAS CUT OFF (28 JAN 1998)				
	At cut off	9 days	16 days	50 days	76 days
Nitrite-N (µg.l^{-1})	< 5	< 5	< 5	< 5	< 5
Nitrate-N (µg.l^{-1})	10	< 5	< 5	< 5	< 5
Total ammonia-N (µg.l^{-1})	34	30	16	2 273	4 132
DIN (µg.l^{-1})*	44	30	16	2 273	4 132
DIP (µg.l^{-1})	29	49	32	32	310
Reactive silicate-Si (DRS) (µg.l^{-1})	340	436	487	1 192	1 507

* *Nitrite-N + Nitrate-N + Total ammonia-N*

Results indicate that in surface waters there was not a marked change in nutrient concentrations over time, except when rain in the catchment increased nitrate-N and reactive silicate concentration, particularly in the upper reaches. In general, concentrations of nitrite, nitrate and reactive phosphate remained very low and even became depleted.

Bottom waters below the halocline (of which the salinity was generally above 25 ppt), remained low in nitrite and became depleted of nitrate soon after seawater intrusion, considered to be the main nutrient source during summer, was cut-off. Drastic changes were observed in the concentrations of total ammonia and reactive silicate, and to a lesser extent, in reactive phosphate. Over the first weeks, concentration remained more or less similar to those measured at the cut-off. However, after 50 days (possibly earlier), concentrations of total ammonia and reactive silicate increased dramatically, probably as a result of nutrient regeneration from sediments. Although not as dramatic, reactive phosphate concentrations also started to increase between 50 and 76 days after cut off. A point of concern is the very high concentrations of total ammonia. For the marine environment, concentrations above 600 µg.l^{-1} (DWAF, 1995) may start to have toxic effects on biota. In this instance, these high concentrations were limited to a relatively small section of the estuary (Figure 5.3). However, under lower flow conditions, when the entrainment of resident water may be less efficient (i.e. the deepening of halocline will be a slower process), the situation may become more serious.

5.3 STATE 3: HIGHLY STRATIFIED WITH STRONG MARINE INFLUENCE

State 3 typically occurs during summer (dry season). This state has been studied on a number of occasions, including studies by Branch and Day (1984), Largier (1986), Taljaard *et al*. (1986), Taljaard (1987) and Largier *et al.* (1992).

Salinity distributions measured during this state are provided in Figure 5.5 (Taljaard *et al.*, 1986). During this state, the estuary is generally very stratified with strong marine influence (salinities mostly above 30 ppt). A strong halocline usually occurs at about 0.5 m water depth, the exact position being largely dependent on the river flow rate. Flushing of the system is mainly achieved through extensive tidal intrusion through the open mouth, particularly during spring flood tides when most of the bottom water in the estuary is replenished. Salinities on the large shallow tidal sand flat along the eastern bank (Figure 1.1) may alternate from a tide-dominated saline state (e.g. during spring tides) to a river-dominated fresh state (e.g. during neap tides) (Largier, 1986; Taljaard, 1987). The physical dynamics of the above are discussed in greater detail in Largier (1986) and Largier *et al.* (1992).

Because the estuary is largely marine dominated during State 3, ***temperature*** characteristics are strongly influenced by the sea (Largier, 1986; Taljaard et al., 1986; Taljaard, 1987), particularly in the bottom layers. During summer, seawater temperature can vary between 13 ^{o}C and 17 ^{o}C (Taljaard, 1987). The low temperature, i.e. 13 ^{o}C, coincided with an upwelling event at sea. Upwelling of colder, nutrient rich bottom waters along the south-west coast of South Africa is caused by strong south easterly winds which frequently occur during summer (Schumann, et al., 1982). River water temperature during summer may vary between 20 ^{o}C and 25 ^{o}C (Taljaard, 1987 and current monitoring programme, refer to Appendix A). Its influence is usually limited to the surface waters. Atmospheric temperature changes (e.g. diurnal cycles) obviously also play a role in determining the temperature characteristics of the surface waters during State 3.

Because of the strong marine influence during this state, ***pH*** values generally ranged between 7 and 8 (Taljaard, 1987). Lower pH values were measured in surface waters near the head of the estuary, but owing to the weak buffering capacity of the river water, pH rapidly increased once this flowed into the estuary (Branch and Day, 1984).

Owing to regular flushing and water exchange, the estuary is typically oxygenated (concentrations above 6 mg.l^{-1}), because of regular flushing and replenishment of bottom waters (Branch and Day, 1984; Taljaard, 1987). Surface waters are generally slightly more oxygenated than bottom water. Owing to regular flushing of the system, these differences could probably largely be attributed to oxygen being less soluble in the bottom saline water

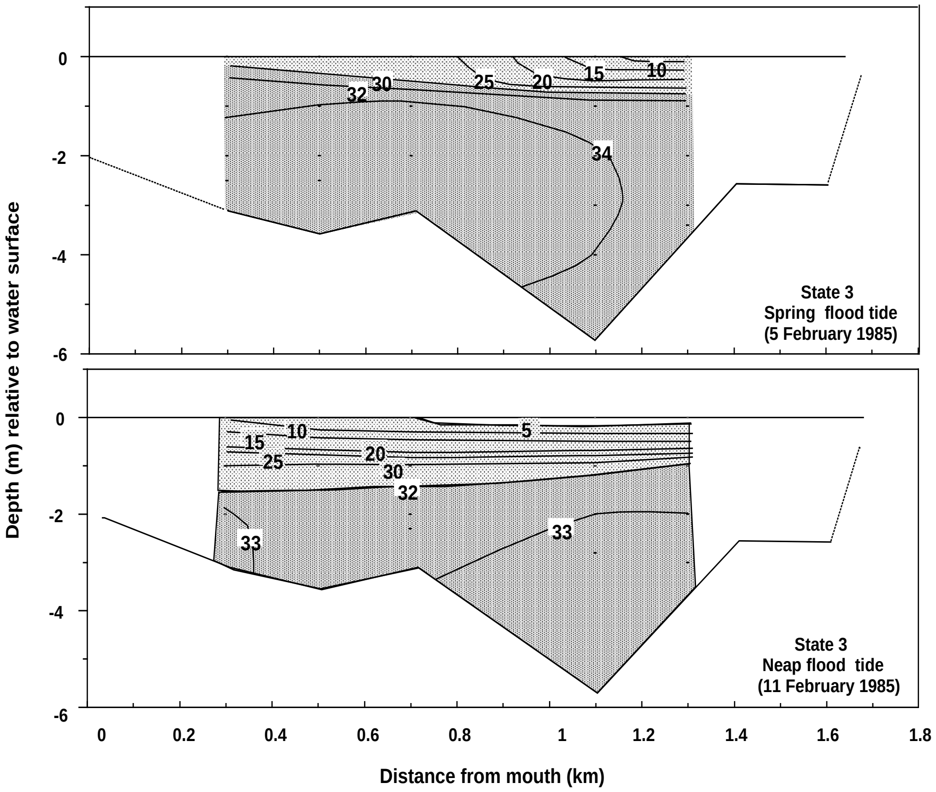

Figure 5.5 Salinity (in ppt) distributions measured during State 3: Highly stratified with strong marine influence during a spring and neap flood tide (February 1985)

than in the surface fresh water (Grasshoff *et al.*, 1983). During neap tides when the replenishment of bottom waters in the deeper area are less effective, biochemical processes may also play a role.

No data on ***water transparency*** could be obtained for State 3.

Nutrient concentrations in the estuary showed a strong correlation with the water circulation patterns as reflected in salinity distributions (Branch and Day, 1984; Taljaard, 1987). Thus, nutrient concentrations were mainly influenced by the two water sources, namely the sea and the river. The contribution of nutrients to the system from internal sources such as sediments and remineralisation appeared to be relatively unimportant compared to the above. Upwelling at sea usually results in an increase in dissolved nutrients (e.g. DIN, DIP and DRS) and depending whether such events coincide with a neap or spring tide, they have marked effects on nutrient levels in the estuary. Nutrient concentrations, measured in the Palmiet Estuary during State 3 are provided in Table 5.3.

Table 5.3 Dissolved nutrient concentrations measured in the water column during State 3: Highly stratified with strong marine influence (December 1979 and February 1985)

NUTRIENT	CONCENTRATION
Nitrite-N (µg.l^{-1})	6
Nitrate-N (µg.l^{-1})	40 – 190*
Total ammonia-N (µg.l^{-1})	12
DIN (µg.l^{-1})**	58 – 208*
DIP (µg.l^{-1})	12 – 30**
Reactive silicate-Si (DRS) (µg.l^{-1})	20 – 730***
Dissolved organic Carbon (DOC) (mg.l^{-1})	3 – 9****

* *Higher concentrations were as a result of upwelling at sea (as reflected in the bottom waters) and rain in the catchment (as reflected in the surface waters)*
** *Higher concentrations result of upwelling at sea*
*** *Higher concentrations result of stronger river influence (reflected in surface waters)*
**** *Higher concentrations result of rain in catchment (reflected in surface waters)*

5.4 STATE 4: HIGHLY STRATIFIED WITH STRONG FRESHWATER INFLUENCE

State 4 typically occurs during winter (wet season) when the mouth is open with strong fluvial or river influence, with some seawater intrusion resulting in the presence of a strong halocline. This state has been studied on a number of occasions, including studies by Largier (1986), Taljaard and Largier (1989), Largier and Taljaard (1991) and Largier *et al.* (1992).

Salinity distributions observed in the estuary during State 4 (a flood and ebb tide) are given in Figure 4.6 (Taljaard and Largier, 1989), showing the strong fluvial (or river) influence compared to State 3.

The extent of seawater intrusion along the bottom during the flood tide, and subsequently, the extent of removal of salt during the ebb tide, is mainly a function of river flow and the state of the tide (i.e. spring or neap). Salinities on the sand flats along the eastern bank (Figure 2.1) remained low (less than 1.5 ppt) throughout the flood and ebb tide. The physical dynamics of these processes are discussed in detail in Taljaard and Largier (1989), Largier and Taljaard (1991) and Largier *et al.* (1992).

Temperatures in the estuary ranged between 12.0 °C and 16.5 °C, with slightly higher temperatures associated with intruding seawater along the bottom layer (Taljaard and Largier, 1989).

The ***pH*** in the estuary ranged between 7 and 8, with the higher values limited to occasions were seawater intruded along the bottom (Taljaard and Largier 1989).

Dissolved oxygen measured during State 4 (Taljaard and Largier, 1989) showed the system to be well-oxygenated, with concentrations ranging between 7.7 and 11 mg.l^{-1}. The lower ranges were representative of saline waters which intruded along the bottom during flood tide. This would be expected since oxygen is less soluble in saline than in fresh water.

No data on ***water transparency*** could be obtained for State 4.

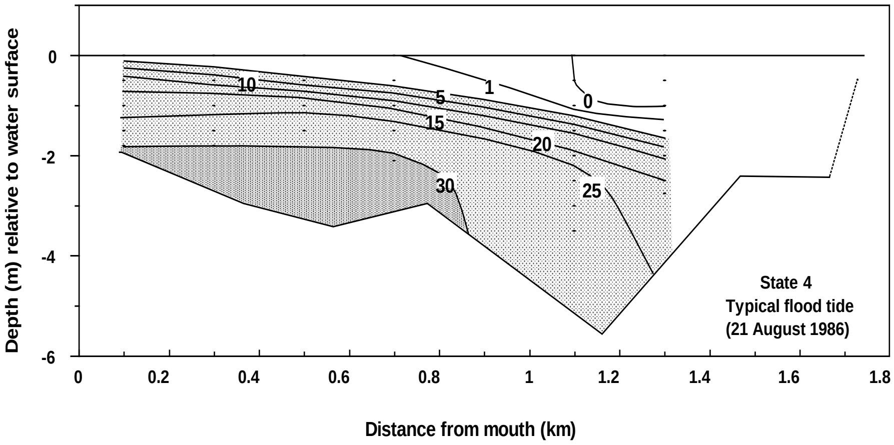

Figure 5.6 Salinity (in ppt) distributions measured during State 4: Highly stratified with strong freshwater influence (August 1986)

Dissolved nutrient concentrations in the estuary were strongly correlated to water circulation patterns, as reflected in the salinity distribution during State 4 (Taljaard and Largier 1989). Thus, nutrient concentrations were strongly influenced by the two water sources, namely the sea and the river, while other internal sources such as sediments and bio-conversion appeared to be relatively unimportant. Because the system is fluvially-dominated during this state, nutrient concentrations typical of the river, were usually dominating, although influence from the sea was detected along the bottom layer during flood tides. Nutrient concentration ranges measured in the Palmiet Estuary during State 4 are provided in Table 5.4 (Taljaard and Largier, 1989).

Table 5.4 Dissolved nutrient concentrations measured in the water column of the Palmiet Estuary during State 4: Highly stratified with strong freshwater influence (August 1986)

NUTRIENT	CONCENTRATION
Nitrite-N (μg.l^{-1})	5 – 700*
Nitrate-N (μg.l^{-1})	190 – 1 300**
Total ammonia-N (μg.l^{-1})	20
DIN (μg.l^{-1})**	215 – 2 020**
DIP (μg.l^{-1})	20
Reactive silicate-Si (DRS) (μg.l^{-1})	-
Dissolved organic Carbon (DOC) (mg.l $^{-1}$)	2.3 – 13.6***

* *The exceptionally high concentrations were limited to the bottom layer as a result of seawater intrusion (the high concentrations in seawater could not be explained)*

** *Lower concentration were limited to bottom layer coinciding with seawater intrusion. Agricultural run-off could have caused the higher concentrations which dominated the estuary and were representative of the river water*

*** *The higher ranges, originating from river, dominated the estuary, while the lower ranges were limited to periods of seawater intrusion*

5.5 STATE 5: FRESHWATER DOMINATED

State 5 occurs occasionally during the winter (wet season) when very strong river inflow flushes the estuary completely. Such conditions are discussed in Largier (1986), Taljaard and Largier (1989), Largier and Taljaard (1991) and Largier *et al.* (1992).

Salinities throughout the estuary remain fresh, as was observed in the system during August 1986, even during spring flood tides owing to strong river inflow (Taljaard and Largier, 1989).

As expected, water ***temperatures*** in the estuary are largely influenced by that of the inflowing river water, averaging about 13 ^{o}C during the 1986 study (Taljaard and Largier, 1989).

Similarly, ***pH*** values are strongly influenced by that of the river water, being around 6.5 during 1986 study (Taljaard and Largier, 1989).

The estuary is also well-oxygenated, with average ***dissolved oxygen*** concentrations 10.5 mg.l^{-1} (Taljaard and Largier, 1989).

No data on ***water transparency*** was available for State 5.

Dissolved nutrients, representative of the inflowing river water at the time are provided in Table 5.5 (Taljaard and Largier, 1989).

Table 5.5 Dissolved nutrient concentrations measured in the water column during State 5: Freshwater dominated (August 1986)

NUTRIENT	CONCENTRATION
Nitrite-N (µg.l^{-1})	10
Nitrate-N (µg.l^{-1})	880
Total ammonia-N (µg.l^{-1})	20
DIN (µg.l^{-1})	1010
DIP (µg.l^{-1})	35
Reactive silicate-Si (DRS) (µg.l^{-1})	-
Dissolved organic Carbon (DOC) (mg.l $^{-1}$)	10.8

6 SUMMARY

Five characteristic abiotic states were identified for the Palmiet Estuary, related to tidal exchange, salinity distribution and water quality. A schematic representation of the circulation features of each of the states is provided in Figure 6.1.

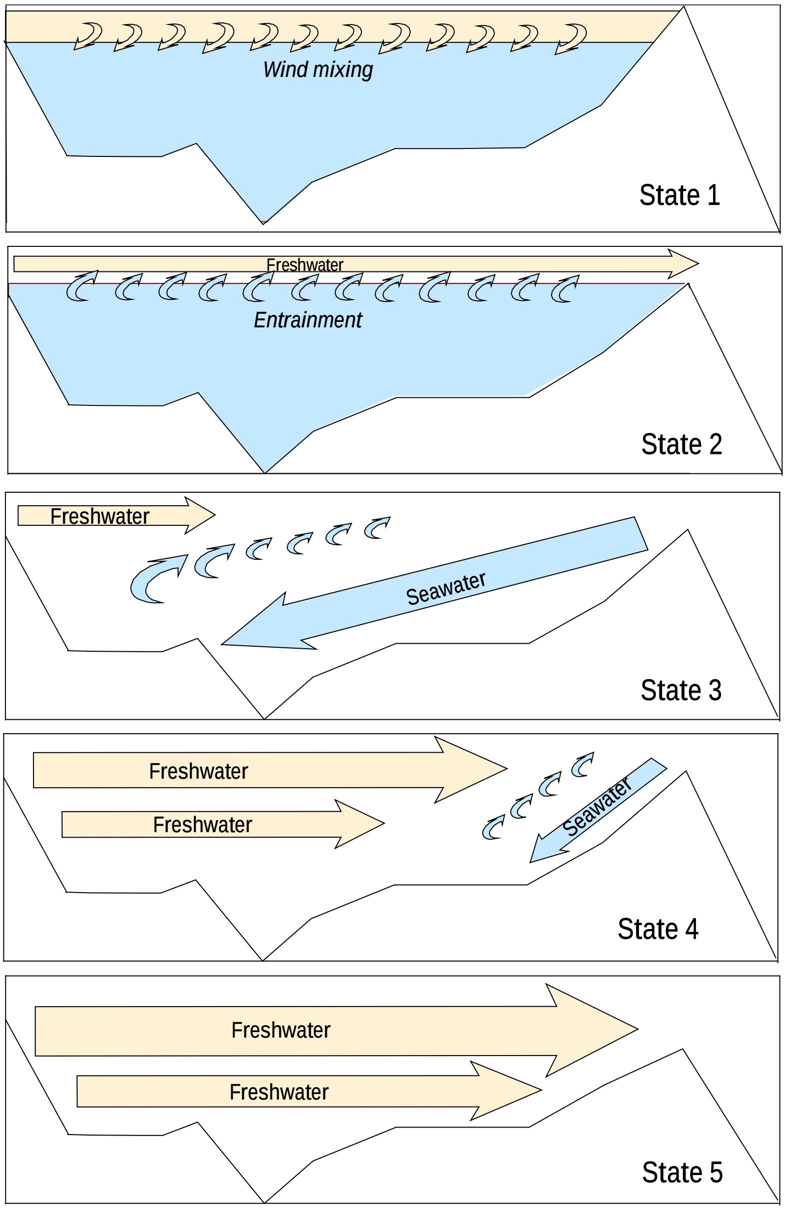

Figure 6.1 Schematic representation of the key circulation features of the five abiotic states of the Palmiet Estuary (after Van Ballegooyen et al. 2004)

Based on an interpretation of the available data discussed in the previous chapters, typical physical and water quality characteristics for each of the five abiotic states are summarised in Table 6.1.

Note; For the purposes of summarising typical salinity distributions, the system was sub-divided into 4 sections representing the lower (0-800 m) and upper (800 – 1 800 m) estuary (moving upstream from the mouth left to right) and into surface (water depth < 1.5 m) and bottom (water depth > 1.5 m) waters (top, left also represents the intertidal area – sand flats).

Table 6.1 Summary of typical physical and water quality characteristics of different abiotic States in the Palmiet Estuary

PARAMETER	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5
River flow (m^3s^{-1})	**< 0.15**	**0.15- 1** (refer to **Table 3.5**)	**1 - 10**	**10 - 20**	**> 20**
Mouth condition	**Closed**	**Semi-closed**	**Open** (with extensive sea water intrusion)	**Open** (with limited seawater intrusion on the flood tide and strong river influence)	**Open** (with no seawater intrusion and very strong river influence)
Water level variation	**None**	**None**	**0.3** m (could drop up to 0,5 m lower during low tide after freshet)	**0.3** m (could drop up to 0,5 m lower during low tide after freshet)	**Backing up effect**
Inundation	**Limited inundated**	**Intertidal area inundated**	**None**	**None**	**Intertidal & Floodplain inundated during peak flows**
Circulation	**Wind mixing**	**Entrainment**	**Tidal**	**Freshwater flushing and Tidal**	**Freshwater flushing**
Retention	**> month** **> month** **> month** **> month**	**5-7 days** **3-5 days** **> month** **> month**	**1-3 days** **<1 days** **1-3 days** **1-2 weeks**	**< 1 days** **<1 days** **1-2 days** **< 1 week**	**< 1 days** **<1 days** **< 1 days** **< 1 days**
*Salinity (ppt)**	15 15 30 30 Storm event or 5 5 5 10 Following State 2	15 15 20 25 < 1 months or 5 5 5 15 > 1 months	20 15 35 30	0 0 25 10	0 0 0 0
Temperature (°C)	**18 – 26** (usually summer)	**18 – 26** (usually summer)	**12 – 26** (usually summer, lower range saline waters during occasional upwelling)	**12 -17** (usually winter)	**13 – 15** (usually winter)
pH	**7 - 8**	**7 – 8**	**7 - 8**	**<6 – 8**	**< 6**
DO ($mg.l^{-1}$)	**Oxygenated** (if stratification persist saline bottom waters **hypoxic/anoxic** depending on benthic organic matter load)	**Oxygenated** (is stratification persists saline bottom waters **hypoxic/anoxic** depending on benthic organic matter load)	**Oxygenated** (> 6)	**Well-oxygenated** (>8)	**Well-oxygenated** (>8)
*Transparency** (Sechhi depth in m)*	**~2**	**~2**	**> 2** (strong marine influence)	**~ 2**	**~ 2**
DIN ($\mu g.l^{-1}$)	**Low** (<20), may be higher in fresher water under Present State - some agriculture inputs (high NH_4-N in bottom water pockets if “trapped” longer than 1 month)	**Low** (<20), may be higher in fresher water under Present State - some agriculture inputs (high NH_4-N in bottom water pockets if “trapped” longer than >2 months)	**Low to ~ 200** (upper range in saline waters during occasional upwelling)	**Low** (<20) (natural) **Low to ~500** (present) (upper range in freshwater)	**Low** (<20) (natural) **~500** (present)
DIP ($\mu g.l^{-1}$)	**Low** (~5) (higher conc’s in bottom water pockets if “trapped” longer than 1 month)	**Low** (~5) (higher conc’s in bottom water pockets if “trapped” longer than 1 month)	**Low to ~30** (upper range in saline waters during occasional upwelling)	**Low to ~ 30** (upper range in freshwater)	**30**
DRS ($\mu g.l^{-1}$)	**~ 500** (higher conc’s in bottom water pockets if “trapped” longer than 1 month)	**~800** (higher conc’s in bottom water pockets if “trapped” longer than 1 month)	**200 – 1000** (upper range in fresher waters)	**200 - ~1500** (upper range in freshwater)	**~1500**

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