Tide-induced pulsing of nutrient discharge from an unconfined aquifer into an *Anaulus australis*-dominated surf-zone

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Abstract

Groundwater levels in the slacks of the Alexandria dune field were monitored over a 14 d spring-to-neap tidal cycle. During this period water level at the seaward end of the slacks rose and fell in relation to the spring-to-neap tidal heights. The levels at the back of the slack fluctuated much less than in the front. This resulted in a change in the slope of the water table between spring and neap tides. During neap tide, the difference in water table height was 133 mm between the seaward and landward ends of the slack (a distance of 110 m), while just after spring tide the difference was only 54 mm. This means that groundwater is discharged in a pulsing fashion from the aquifer into the surf-zone, releasing nutrient-rich water at a rate of 0.157 $m^3·d^{-1}·m^{-1}$ (spring tide) and 0.328 $m^3·d^{-1}·m^{-1}$ (neap tide). The daily tidal cycle influences the groundwater mainly around spring tide and mostly at the seaward side of the slack. The influence extends for a distance of 325 m from the mean shoreline. A 20% change in flow was calculated between low and high spring tides and only a 6% change between low and high neap tides. Groundwater provides 2.6 g $N·d^{-1}$ at spring tide and 5.6 g $N·d^{-1}$ at neap tide for every running metre of beach on average. This gives rise to a pulsing of nitrogen availability with twice as much nitrogen entering the surf-zone at neap tide compared to that at spring tide. This nitrogen is an important source of this element to the surf diatom *Anaulus australis* Drebes *et* Schulz.

Introduction

The Alexandria dune field is still relatively unaffected by interference from man. Studies have been published that refer to the nature of dune plant and animal communities (e.g. Van der Laan, 1979; McLachlan et al., 1982; Sykes and Wilson, 1987). Dune groundwater has been recognised as being important for these communities, but has also been identified as a potential source of nutrients for adjacent marine ecosystems (Johannes, 1980; McLachlan and Illenberger, 1985). Submarine groundwater discharge occurs wherever an aquifer is open to the sea. Such conditions occur in many places (Johannes, 1980), particularly where the shore is backed by sand deposits.

Typically, submarine groundwater discharge into the sea is a source of nitrogen to the coastal marine environment (Capone and Bautista, 1985). The magnitude of this contribution depends on the concentration of nitrogen in the aquifer water as well as on the rate of discharge.

The need to quantify nutrient loading by submarine groundwater discharge has arisen from the construction of nutrient models and budgets (Capone and Slater, 1990; Oberdorfer et al., 1990). Most studies have addressed this problem on a long time scale (Capone and Slater, 1990), studies having been conducted mostly on a quarterly, biannual or annual basis.

In attempts to describe the food web of a surf-zone dominated by the diatom, *Anaulus australis* Drebes *et* Schulz, it became necessary to develop a model to describe nutrient dynamics. The Alexandria dune-beach system supports a high biomass of the surf diatom, *A. australis*. Talbot and Bate (1987) indicated that there is little seaward loss of cells from the surf-zone. A surf water half-residence time of approximately 3.6 h was calculated. Groundwater entering the surf-zone contributes sufficient nutrient to balance the losses of nutrient in the form of cells lost from the ends of the surf-zone (estimated at 15% of the standing stock), thus maintaining the high rates of phytoplankton productivity that have been measured (Campbell and Bate, 1988a; 1991a). This contribution of nitrogen to the surf-zone was calculated based on a published study on groundwater discharge from the Alexandria dune field (McLachlan and Illenberger, 1985). These authors list a discharge rate of about 1 m^3 of groundwater per running metre of beach per day, but no temporal variance of flow is indicated.

During studies to determine the rate of groundwater discharge to the beach, it was observed that water levels in experimental wells rose and fell in a fashion not entirely linked to the daily tidal cycle. It has been suggested that the groundwater level in dune sands follows the daily tide curve directly (Dominick and Wilkins, 1971), i.e. the levels in wells would follow the tidal cycle of the adjacent sea. We have no knowledge of any work that has investigated the influence of spring or neap tidal cycles on dune groundwater level. The purpose of this study was to investigate changing water levels over both a 12 h (low-high-low) tidal cycle, as well as on a 14 d (spring-neap-spring) tidal cycle in order to describe the fluctuation of groundwater discharge over both these time scales. This description would enable us in turn to describe the fluctuation of nutrient loading to the surf-zone associated with this groundwater.

Materials and methods

Study area

The Alexandria dune field (Fig. 1) adjoins a 40 km stretch of coastline and covers an area of approximately 120 km^2. The annual rainfall is between 400 and 600 $mm·a^{-1}$ from west to east (Illenberger and Rust, 1988).

A series of 40 moist inter-dune depressions, known as dune slacks, occurs along the western seaward section of the dune field

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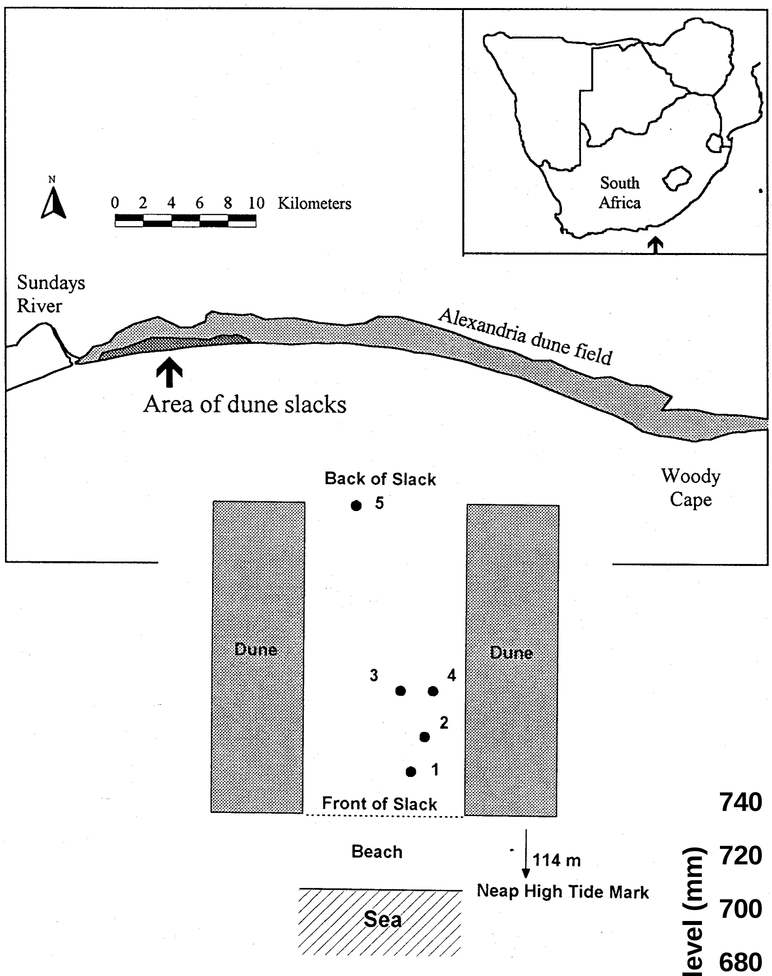


Figure 1
A map of the study area showing the section of the dune field where dune slacks occur and a diagram (not to scale) of the position of the sampling wells in one of the slacks

(Fig. 1). These slacks form as inter-dune valleys between parallel dune crests (Tinley, 1985) oriented roughly perpendicular to the coast for a distance of about 200 m (McLachlan et al., 1982), before giving way to wind-blown dunes.

Each slack is about 50 m wide and 200 m long, altogether covering less than 1% of the total dune field (Ascaray, 1982). The salinity in the groundwater decreases over a 100 m on-offshore distance from 35 ‰ at the swash line to almost 0 ‰.

Sampling wells

Five sampling wells were installed to a depth of 500 mm below the water table in one of the slacks (Slack A): one just behind the berm separating the dune slack from the beach, one at the back of the slack and the remainder in between (Fig. 1). Two wells were installed in each of two other slacks (Slacks B and C): one at the seaward and another at the landward end of each slack. The wells were lined with unperforated plastic pipe 110 mm dia., allowing groundwater entry from the base of the hole only. The pipes were kept covered to prevent sand from blowing in.

The heights of the top of each pipe were surveyed relative to a mean sea level datum post installed during the survey by McLachlan and Illenberger (1985).

Groundwater levels

Water levels were measured in wells in Slack A at hourly intervals for 14 d. Measurements were also taken hourly in all the

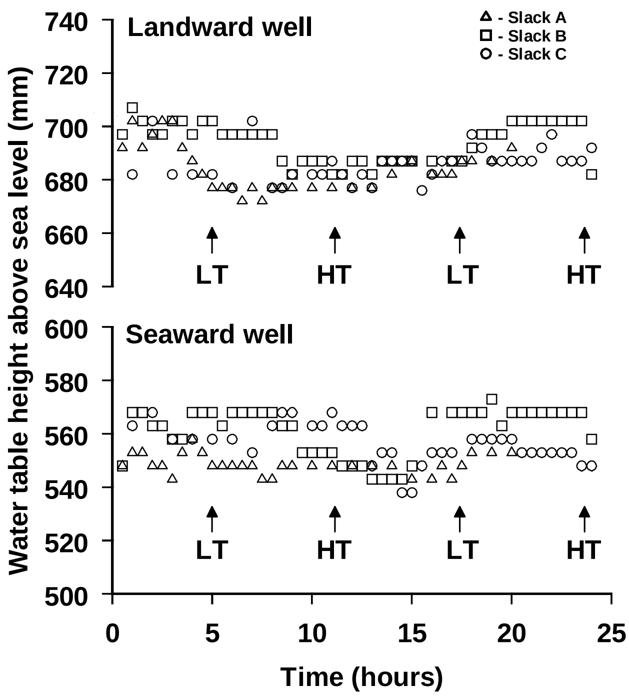


Figure 2
The water table height above sea level measured over a day at neap tide in the seaward and landward wells of three dune slacks (A, B and C).
LT - low tide; HT - high tide

wells (Slacks A, B and C) over a 24 h period firstly at neap tide and then at spring tide. No rain fell during this time.

The flow rate of water discharged from the aquifer to the sea was calculated using Darcy's Law and the Ghyben-Herzberg relation (Freeze and Cherry, 1979; Raghunath, 1982) as follows:

$$Q = \frac{K.S.(h_1^2 - h_2^2)}{2(d_1 - d_2)}$$

where:

- Q = flow rate ($\ell \cdot d^{-1} \cdot m^{-1}$)
- K = hydraulic conductivity ($\ell \cdot d^{-1} \cdot m^{-2}$)
- S = difference in relative density of fresh and salt water
- h_1 = height of water table above sea level in landward well (m)
- h_2 = height of water table above sea level in seaward well (m)
- d_1 = distance of landward well from the swash line (m)
- d_2 = distance of seaward well from the swash line (m)

Hydraulic conductivity was taken to be 8 636 $\ell \cdot d^{-1} \cdot m^{-2}$ after Jolly (1983) in keeping with McLachlan and Illenberger (1985). The difference in relative density between freshwater and sea-water is 0.034 (Raghunath, 1982).

Results

Low tide-high tide changes

At neap tide the fluctuation in height of the water table in both landward and seaward wells showed a maximum difference of 35 mm (Fig. 2). The changes did not follow the tidal pattern directly and the variation in water levels observed could not be ascribed to tidal movement. However, during spring tide, water levels varied in a pattern that followed the tidal fluctuation (Fig. 3). At spring tide, the change in water levels could be ascribed to tidal influence. The water level in the seaward well fluctuated by 45 mm while that in the landward well only fluctuated by 15 mm (Fig. 3).

The water level in the landward well rose by 65 mm from neap to spring tide (difference between mean values of the data in Figs. 2 and 3) while in the seaward well the water level rose by 137 mm over the same period.

At spring low tide the difference in water levels corresponds to a calculated freshwater flow rate to the sea of 0.0059 $m^3 \cdot h^{-1} \cdot m^{-1}$. At spring high tide the difference represents a freshwater flow rate of 0.0049 $m^3 \cdot h^{-1} \cdot m^{-1}$. This represents an increase of 20% flow at low tide compared to high tide. At neap low tide the difference in water levels corresponds to a calculated freshwater flow rate of 0.0094 $m^3 \cdot h^{-1} \cdot m^{-1}$. At neap high tide the difference represents a freshwater flow rate of 0.0089 $m^3 \cdot h^{-1} \cdot m^{-1}$. This represents an increase of only 6% flow at low tide compared to high tide.

The difference in the water table level between the seaward and landward wells is shown in Fig. 4. At spring tide the difference ranged from 30 mm to 80 mm with a mean of 60 mm with an influence of the tidal fluctuations evident. At neap tide the difference increased to a mean of 132 mm (a range of 19 mm to 159 mm) but no tidal pattern was evident.

Spring-neap tide changes

The water table height above mean sea level was also measured over a neap-spring tidal cycle. The water levels in the wells decreased slowly at the beginning of the monitoring period in both landward and seaward wells (Figs. 5 and 6). The decrease in the seaward well was greater than at the landward well, the seaward well decreasing at a rate of 0.26 $mm \cdot h^{-1}$, and only 0.14 $mm \cdot h^{-1}$ (Figs. 5 and 6) in the landward well.

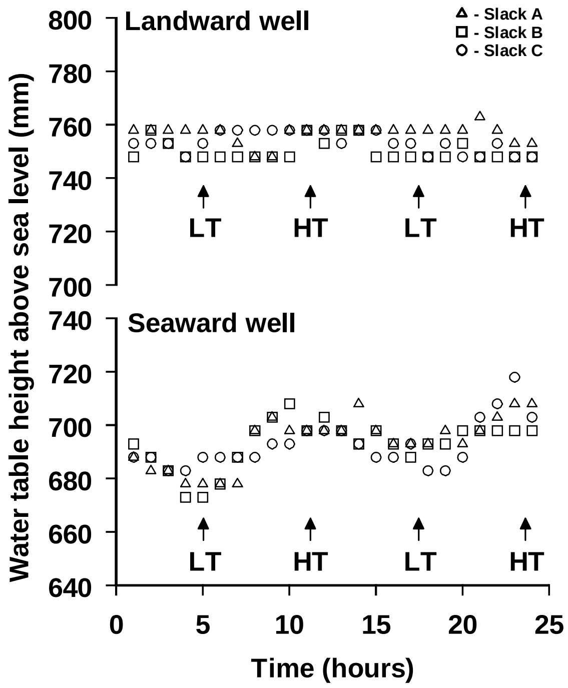


Figure 3
The water table height above sea level measured over a day at spring tide in the seaward and landward wells of three dune slacks (A, B and C).
LT - low tide; HT - high tide

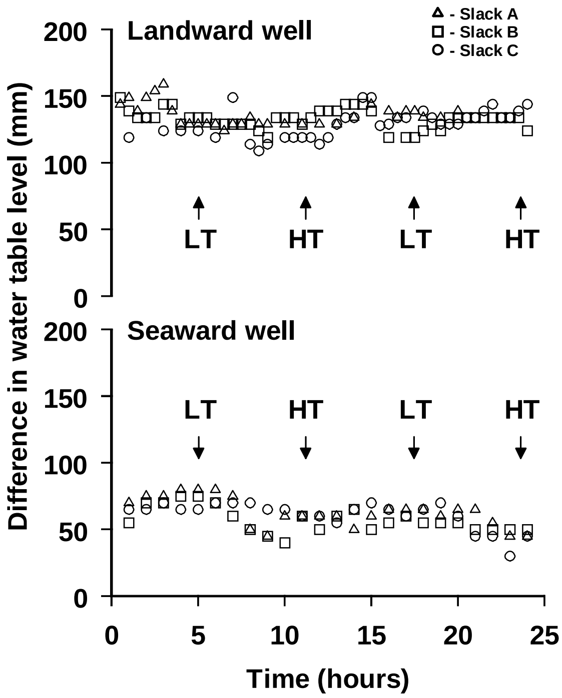


Figure 4
The difference in water table height between the seaward and landward wells of three dune slacks (A, B and C).
LT - low tide; HT - high tide

Four and a half days before spring tide (Fig. 5) the water levels in the seaward well began to rise. This increase in water level occurred 40 h later in the landward well (Fig. 6). There was a correlation between the rate of increase in water level and distance from the sea (r^2 = 0.943; n = 5; Fig. 7). Large changes were recorded in the seaward well and smaller changes in the landward well.

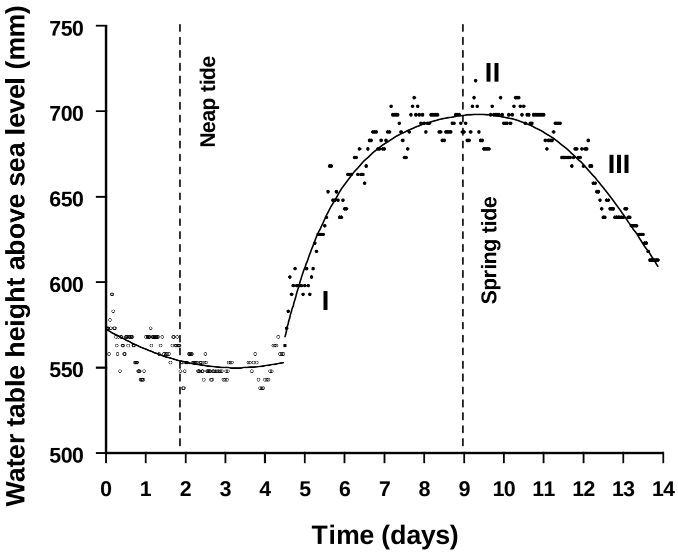
The water level in the wells reached a maximum at spring tide in the seaward and landward wells (Fig. 5 and 6). The water level then began to decline in the seaward well (Fig. 5) but remained relatively unchanged for 3 d in the landward well (Fig. 6) after which it also began to decline. The rate of decline was correlated to the distance from the sea (r^2 = 0.922; n = 5; Fig. 7).

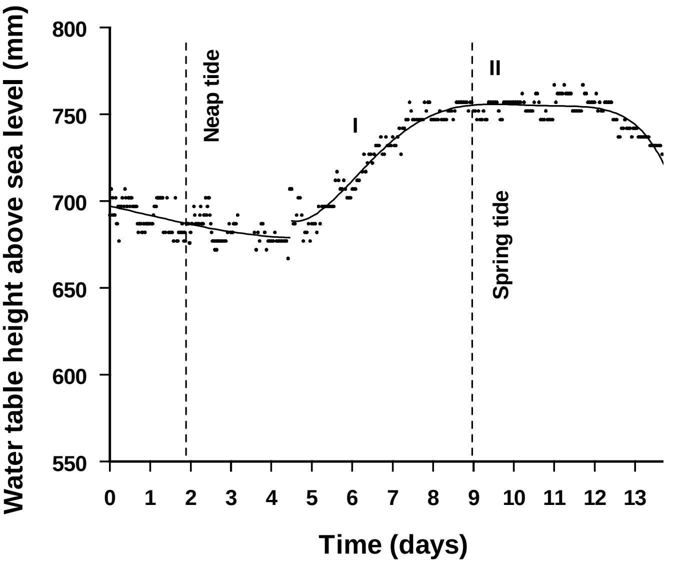
The difference in water table height above sea swash level between Wells 3 and 5 of Slack A (Fig. 8) showed an initial increase from 127 mm to 133 mm at neap tide. The difference decreased sharply to only 54 mm and remained low for 3 d before spring tide. The difference then increased, after which the next tidal cycle began (Fig. 8).

The rate of freshwater flow into the adjacent surf-zone was calculated from the data collected from Wells 3 and 5 of Slack A (Figs. 5 and 6). The flow rate around spring tide was 0.157 $m^3 \cdot d^{-1}$ per running metre of beach (Fig. 9). The flow rate nearly doubled at neap tide to 0.328 $m^3 \cdot d^{-1}$ per running metre of beach (Fig. 9). The cumulative flow over a spring-neap tidal cycle (14 d) was calculated to be 3.3 m^3 of groundwater entering a running metre of beach and an annual flow of 86 m^3 per running metre.

Discussion

The tide influences the water table level in the seaward part of the dune field on two time scales. The first of these is the 12 h low-high tide cycle. This tidal pattern influences the water levels mostly at the seaward end of the slack at spring tides (Figs. 2 and 3). The change resulted in an increase of 0.0010 $m^3 \cdot h^{-1} \cdot m^{-1}$ flow representing a 20% increase at low tide. Changes in neap low tides only accounted for a 6% increase of flow compared to the neap high-tide flow rate. The changes at spring tides follow the ocean tide directly (Dominick and Wilkins, 1971).





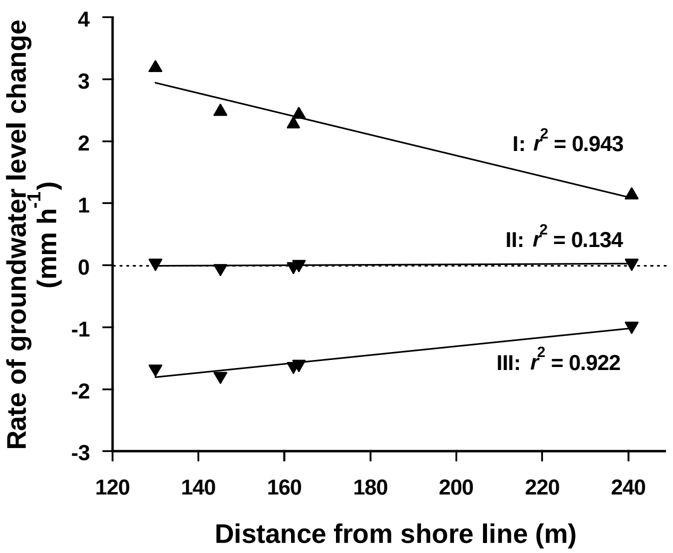


Figure 5 (top)
The water table height above sea level measured over two weeks in the seaward well (Well 1) of Slack A. I, II and III indicate the times at which the rate of water level change is presented in Fig. 7

Figure 6 (middle)
The water table height above sea level measured over two weeks in the landward well (Well 5) of Slack A. I, II and III indicate the times at which the rate of water level change is presented in Fig. 7

Figure 7 (bottom)
The difference in rate of water level change with distance from the shore line before spring tide (I, Figs. 5 and 6); at spring tide (II, Figs. 5 and 6); and after spring tide (III, Figs. 5 and 6)

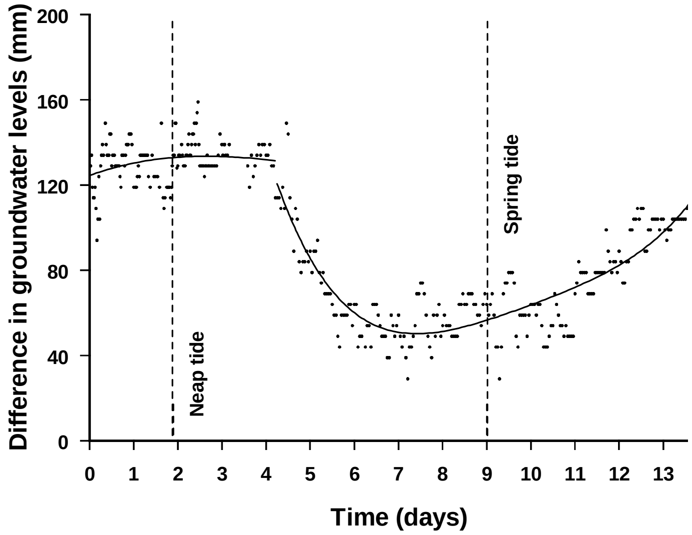


Figure 8
The difference in water table levels measured over a 14 d period between the seaward (Well 3, Slack A) and landward (Well 5, Slack A) wells

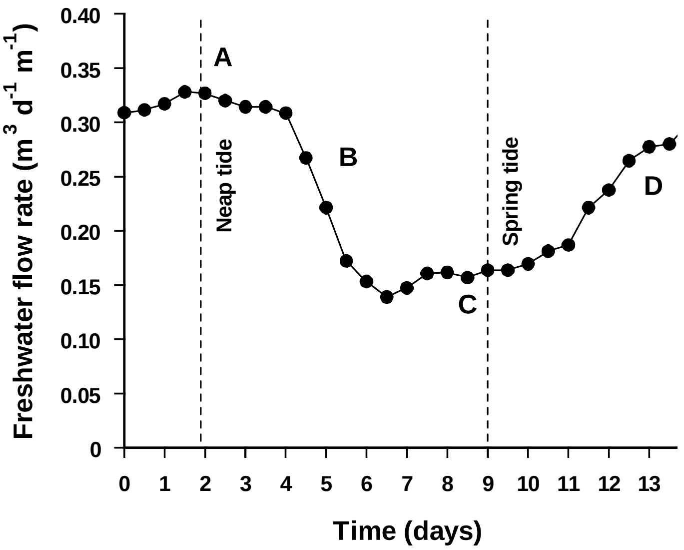


Figure 9
The flow rate of groundwater from the Alexandria dune field into the surf-zone calculated from the data presented in Fig. 8

Larger changes in groundwater levels occur as a result of the spring-neap tidal cycle (Figs. 5 and 6). These changes are marked at the seaward side of the slacks but become less marked with distance from the sea. Tidal fluctuations in the groundwater persist for between 310 and 370 m from the sea calculated from the data presented in Fig. 7.

The average rate at which the aquifer water discharges into the surf-zone over the whole Alexandria dune field has been estimated at 1 $m^3 \cdot m^{-1} \cdot d^{-1}$ providing 1 050 g $N \cdot m^{-1} \cdot a^{-1}$ to the surf-zone (McLachlan and Illenberger, 1985). In our study, only a portion of the coastline was investigated: the section 3 to 7 km east of the Sundays River mouth. In this same section McLachlan and Illenberger (1985) calculated an average flow of 0.16 $m^3 \cdot d^{-1} \cdot m^{-1}$, whereas we estimate 0.24 $m^3 \cdot d^{-1} \cdot m^{-1}$ as a mean flow rate over the spring-neap tidal cycle. McLachlan and Illenberger (1985) do not relate their calculations to the state of the tide or tidal cycle, nor do they refer to any major change in the water level in the aquifer. Adjusting the data obtained for the slack area in this study in proportion to the data presented by McLachlan and Illenberger (1985) gives an estimated mean flow of 1.5 $m^3 \cdot d^{-1} \cdot m^{-1}$ for the whole Alexandria dune field. This represents a spring flow of 0.981 $m^3 \cdot d^{-1} \cdot m^{-1}$ and a neap flow of 2.050 $m^3 \cdot d^{-1} \cdot m^{-1}$.

At an inorganic nitrogen concentration of 2.7 g $N \cdot m^{-3}$ (Campbell and Bate, 1991a) the flow rates reported in this study represent a nitrogen input to the surf-zone of 2.6 g $N \cdot d^{-1} \cdot m^{-1}$ during the spring tides and 5.6 g $N \cdot d^{-1} \cdot m^{-1}$ at neap tides. This converts to a total of 1 500 g $N \cdot m^{-1} \cdot a^{-1}$ that enters the surf-zone from groundwater discharge.

The primary production of the surf ecosystem has been estimated at 120 kg C per running meter of beach per year (Campbell and Bate, 1988a). Using the estimates calculated by Campbell (1987), the nitrogen requirements of the surf phytoplankton would be 10 100 g $N \cdot m^{-1} \cdot a^{-1}$. The surf ecosystem is a closed system on the seaward side (Talbot and Bate, 1987), and an estimated 11% of the primary producers are lost from the end of the ecosystem (Campbell and Bate, 1988b), therefore the estimated loss of nitrogen from the surf-zone is 1 100 g $N \cdot m^{-1}$. This means that enough nitrogen enters the ecosystem from the dunes (1.5 kg $N \cdot m^{-1}$) to replace that lost in the form of diatom cells. This is supported by the results of Du Preez (1996) who found that *A. australis* in the Sundays River surf-zone were not limited with respect to N. Elemental composition of the diatoms suggested that they have a surfeit of P and a sufficiency of N (Du Preez, 1996).

The pulsing of the freshwater flow from the dunes into the surf-zone results in a pulsing of inorganic nitrogen into the surf water. There has been no evidence of any accumulation of nutrients in the surf water (Campbell and Bate, 1991a) implying that all the nutrients are utilised by surf diatoms. Standing stocks of surf diatoms have been found to be proportional to the amount of nutrient entering the surf from the adjacent dune field (Campbell and Bate, 1991b). Considering that Du Preez (1996) reports that N is the most likely limiting nutrient, this suggests that there should be a 14 d cycle in the phytoplankton biomass in response to the pulsing of the nitrogen input. At neap tides the biomass should be about double that at spring tides if this theory holds.

While the link between biomass and nutrient input remains to be confirmed, this study has shown that tide-induced pulsing of freshwater from dune aquifers may vary the nutrient loading from this source by twofold.

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