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Tidal Fluctuations in Biological Oxygen Demand in Exposed Sandy Beaches

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Tide-induced fluctuations in biological oxygen demand (BOD) on two medium to fine sandy beaches were recorded over two separate 24-h periods in February (summer) 1979. Fluctuations in BOD of over two orders of magnitude were found with the highest occurring at or just after high tide and the lowest at low tide. Greatest fluctuations occurred at the higher tidal levels as well as near the surface of the substratum. Significant correlations between BOD and the degree of water saturation of the sand were found, although no such correlations with either bacterial or protozoan numbers or temperature occurred. It appears that in areas of the beach where the water content decreases to 30% or less, BOD is greatly reduced and increases again only upon re-wetting by the incoming tide. Measurements of BOD made during low tide in such areas may underestimate oxygen consumption by as much as 300%. Conversely, measurements made on saturated sediments only may be overestimates of a similar magnitude.

Introduction

Much interest has been shown in the study of benthic metabolism in recent years. Measurements are made primarily in terms of oxygen consumption either *in situ* (Odum, 1957; Teal, 1957; Pomeroy, 1959; Pamatmat, 1968; Hargrave, 1969; Biggs & Flemmer, 1972; Smith *et al.*, 1973) or on intact cores in the laboratory (Hayes & MacAulay, 1959; Teal & Kanwisher, 1961; Knowles *et al*, 1962; Duff & Teal, 1965; Edwards & Rolley, 1965; Carey, 1967; Pamatmat, 1971; Gallagher & Daiber, 1974). Although other approaches have been used, e.g. carbon dioxide liberation (Pamatmat, 1968), radioactive tracers (Meyer-Reil, 1978) and direct calorimetry (Pamatmat & Bhagwat, 1973), oxygen consumption remains the most practical approach in areas where the community is predominantly aerobic. This approach is particularly suited to the study of well-drained sandy beaches. It is interesting, therefore, to note the paucity of information on benthic oxygen consumption in such areas. In an excellent review of the subject Pamatmat (1977) makes no mention of such studies. The most comparable work is that of Pamatmat (1968) on a sand flat. Even in this case the substratum was anoxic below 2 cm. According to Pamatmat (1977) rates of oxygen consumption have been related *inter alia* to pH, temperature, tidal cycle, diel cycle, season, bacterial count and primary production. In an ongoing study of benthic metabolism in two sandy beaches

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near Port Elizabeth (33°55′S; 25°55′E) factors such as tidal level and depth, season, temperature, oxygen content of the substratum, bacterial and protozoan density and meiofaunal numbers are being studied in relation to biological oxygen demand (BOD). This paper presents the results of a study of the effect of tide, or more specifically desiccation, on biological oxygen demand.

Methods

The study areas were a fine sandy beach (214 µm Mdφ) in the city of Port Elizabeth and a somewhat coarser beach (313 µm Mdφ) some 40 km to the west. The particle analyses are according to Morgans (1956). Both beaches experience semi-diurnal tides but the latter is more exposed, receiving heavy wave action throughout the year. Both beaches have porosities between 23 and 26% and are very permeable. Consequently, the upper tidal levels, particularly near the surface of the substratum, experience considerable desiccation during low tides. Oxygenated conditions therefore prevail to depths in excess of 1 m at the high tide level (McLachlan *et al.*, 1979). The finer, less exposed beach has a mean slope of 1 : 28 while the coarser beach has a slope of 1 : 17. The finer beach is relatively poor in macrofauna and the dominant species is the plough shell *Bullia rhodostoma* Reeve at the lower tidal levels. The exposed beach, however, supports a large macrofaunal population. Here the bivalves *Donax serra* Röding and *D. sordidus* Hanley are dominant, although the gastropod *B. rhodostoma* is well represented.

On both beaches meiofaunal densities are typically less than 50 animals per 100 cm^3.

Two tidal levels were chosen for study, i.e. high water of neaps (HWNT), a vertical height of 1·65 m above mean spring low tide level, and mid water (MW), 1·3 m above mean spring low tide level. At HWNT total oxygen demand (TOD) was measured on duplicate cores taken horizontally from the walls of a hole, at intervals of 20 cm from just below the surface (2 cm) to a depth of 60 cm. At MW the cores were taken from the surface layer and at 20 cm. In this way measurements of TOD could be made on sand with a range of water content from permanently saturated to almost permanently dry. The cores were taken in opaque 10 cm PVC tubes of 4·6 cm internal diameter which were sealed with vented rubber bungs. The measurements were carried out every 3 h over two 24-h periods in February 1979. TOD was measured in the laboratory by incubating the intact cores in the dark at constant temperature (22 °C) for 3·0 h. The partial pressure of oxygen in the interstitial water of the cores which were 40% water saturated or greater was measured on 1 ml samples withdrawn by syringe from the centre of the core. The water was injected into an airtight chamber fitted with a Clark-type oxygen electrode (E5046) connected to a Radiometer Acid-Base Analyser (PHM 71). The formula used to convert the partial pressure changes to volumes of oxygen was as follows (Dye, 1979*a*):

$$V_{O_2} = \frac{6{\cdot}45 \times 10^{-3}\, C\, \Delta P_{O_2}\, P_s}{t}$$

where V_{O_2} is the volume of oxygen used (µl cm^{-3} h^{-1}); $6{\cdot}45 \times 10^{-3}\, C$ is the solubility coefficient of oxygen (C) in water of given temperature and salinity, as a fraction of the atmospheric partial pressure of oxygen (155 mmHg) (Weiss, 1970); ΔP_{O_2} is the change in partial pressure of oxygen (mmHg); t is the duration of the incubation (3 h); P_s is the porosity of the sand.

The standard deviation of the results obtained with the equipment was determined by repeatedly injecting a sample of aerated seawater into the chamber. It was found that the readings obtained after 10 injections varied by only 0·20 mmHg (S.D.). With the present experimental procedure this gives a sensitivity of $5{\cdot}6 \times 10^{-4}$ µl O_2 cm^{-3} h^{-1} at 22 °C.

Cores 30% water saturated or less have too little water for oxygen analysis and the interstitial air is withdrawn instead. However, since air contains approximately 41 times more oxygen per unit volume than water at the same temperature, the above formula must be modified to contain a term which will correct for this. This formula is

$$V_{O_2} = \frac{2{\cdot}64 \times 10^{-1}\, C\, \Delta P_{O_2} P_s,}{t}$$

where the terms are as described above.

In view of this, the same oxygen consumption in air will be reflected in a much smaller partial pressure change and ΔP_{O2} is in the order of 1–2 mmHg only, over the 3 h incubation period. Such changes are, however, well within the capability of the equipment. In the case of air measurements the sensitivity is $5{\cdot}4 \times 10^{-3}$ µl O_2 cm^{-3} h^{-1} at 22 °C.

Although between 30 and 100% water saturation some contamination of the oxygen in the water with that in the air will occur, the effect is not reflected in the results until 30% water saturation is reached.

The effect of photosynthesizing organisms on oxygen measurements is considered to be negligible since South African beaches are characterized by low primary productivity with few algal cells present (Brown, 1961). This seems fairly typical of warm temperate beaches (Ansell, personal communication).

Total oxygen consumption was converted to biological oxygen consumption by subtracting 10·44% for chemical oxygen demand. This figure is based on a 2-year study of oxygen consumption on sandy beaches which indicated that there is no significant correlation between water content of the sand and chemical oxidation (Dye, 1980).

In addition to the 3-hourly measurements of TOD, sand samples were brought back to the laboratory at the same time for enumeration of bacteria and protozoa. The bacteria were extracted from 1 g sand by sonication (23 kHz; 8 µm peak to peak) for five 60-s periods in 50 ml of 0·45 µm filtered seawater. This procedure was found to be 85% efficient for extractable bacteria and to have no deleterious effects on the cells (Dye, 1979*a*).

Counting was done by means of an epi-fluorescence microscope after staining in Acridine Orange. Protozoa were extracted from 50 g sand by hand-shaking in 100 ml of 0·45 µm filtered seawater for three 60-s periods. This procedure is 93% efficient (Dye, 1979*b*). Counting was done as for bacteria.

The water content of the sand was measured every 3 h in the field by means of a 'Speedy Moisture Tester' (Thomas Ashworth: England). Temperature was measured by a mercury-in-glass thermometer. Note was also kept of sunrise and sunset times as well as inundation periods.

Results and conclusions

Figures 1 and 2 show the fluctuations in BOD at various depths in the substratum of the sheltered beach (A) and the exposed beach (B), respectively. A tidal fluctuation characterized by high BOD during or slightly after high tide and low BOD at low tide is evident. The fluctuations are greatest near the surface of the substratum and at the higher tidal levels. Statistical analysis of the data revealed that on beach A the fluctuations were significant at HWNT at the surface and at 20 and 40 cm depth, but not at 60 cm or at MW (analysis of

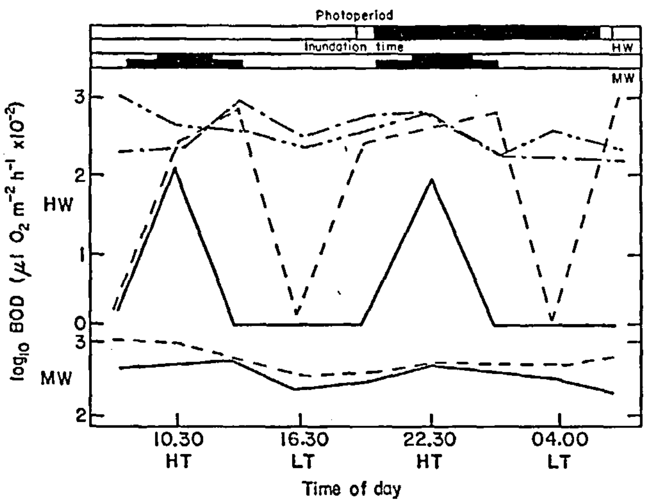

Figure 1. Fluctuations in BOD over a 24-h period at two tidal levels and various depths in the substratum of a medium to fine sandy beach (A). HT, high tide; LT, low tide; ———, 0–3 cm; – – – –, 20 cm; – · – · –, 40 cm; – · · – · · –, 60 cm.

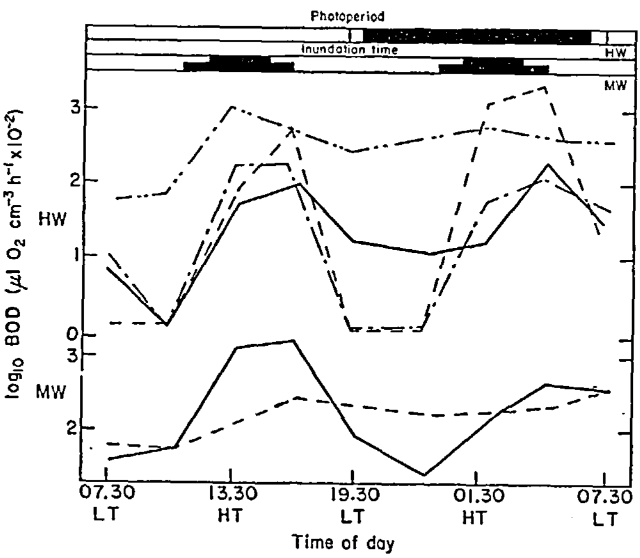

Figure 2. Fluctuations in BOD over a 24-h period at two tidal levels and various depths in the substratum of a medium sandy beach (B). Key as in Figure 1.

variance; $P=0{\cdot}001$). On beach B the fluctuations were significant at HWNT at the surface and at 20 cm depth but not at 40 cm or at any depth at MW (analysis of variance; $P=0{\cdot}001$). In some cases the fluctuations represent an order of magnitude change of two between high and low tides.

Figures 3 and 4 show the fluctuations in percentage water saturation and temperature on the two beaches. Water content varies tidally, with the greatest values occurring during high tide and the lowest at low tide. However, even when inundated, the higher tidal levels were not always saturated due to the trapping of air by swash running over the surface. Thus, while MW is always saturated, the mean saturation at HWNT is below 50%.

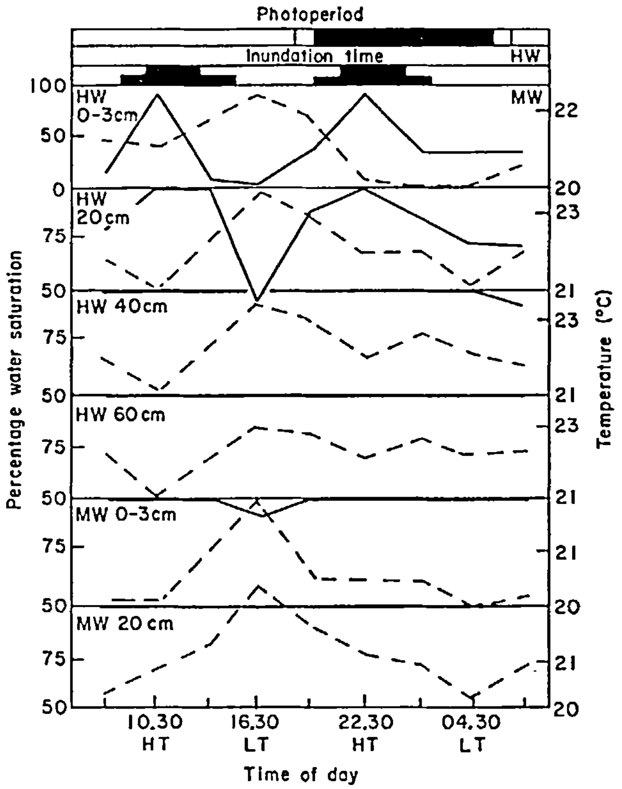

Figure 3. Fluctuations in water content and temperature over a 24-h period at two tidal levels and various depths in the substratum of a medium to fine sandy beach (A). HT, high tide; LT, low tide; ———, percentage saturation; – – – – –, temperature (°C).

Temperature varies diurnally, reaching a maximum at mid-afternoon and a minimum just before dawn. The degree of fluctuation decreases with depth and with proximity to the sea.

No clear fluctuation was found in the case of bacteria and protozoa. The number of bacterial cells remained at approximately 5×10^8 cells g^{-1} throughout the 24-h period. Similarly, the protozoan numbers varied slightly around a mean of 2×10^3 cells g^{-1} on both beaches.

Statistical analysis revealed no relationship between temperature and BOD or between the number of microorganisms and BOD. A significant relationship was found between water content and oxygen consumption on both beaches. These relationships are

$$\log_{10}V_{O_2}=0{\cdot}46-0{\cdot}31\log_{10}(\%H_2O),$$
$$r^2=0{\cdot}71,\ n=18,\ P=0{\cdot}005$$

for beach A and

$$\log_{10}V_{O_2}=0{\cdot}20-0{\cdot}02\log_{10}(\%H_2O),$$
$$r^2=0{\cdot}72,\ n=36,\ P=0{\cdot}005$$

for beach B, where V_{O_2} is the volume of oxygen consumed (µl cm^{-3} h^{-1}).

The method used to measure TOD was developed for use in well drained sandy beaches characterized by aerobic community metabolism (Dye, 1979*a*). The method enables measurements to be made at various depths and for the results to be expressed in terms of sand volume rather than area. This is of importance in a three-dimensional system such as a beach.

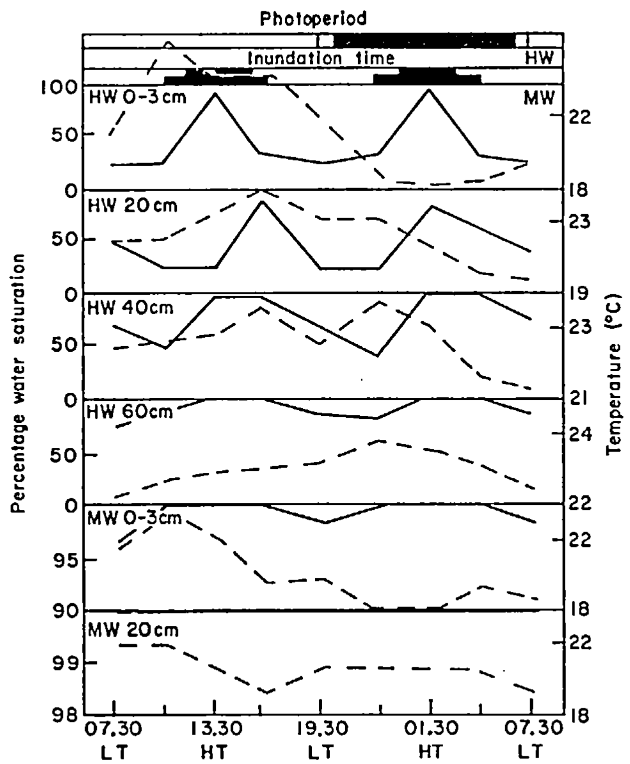

Figure 4. Fluctuations in water content and temperature over a 24-h period at two tidal levels and various depths in the substratum of a medium sandy beach (B). Key as in Figure 3.

Because of the lack of information regarding community metabolism on sandy beaches, comparison of the rates of oxygen consumption found in the present study is difficult. A range of oxygen consumptions of 1·0–125·0 ml m^{-2} h^{-1} has been published for a sand flat (Pamatmat, 1968). However, the area was characterized by a redox potential discontinuity zone within 2 cm of the surface. The present values for beach A of $10{\cdot}45\pm3{\cdot}5$ and $7{\cdot}1\pm1{\cdot}67$ ml O_2 m^{-2} h^{-1} at HWNT and MW, respectively, and for beach B of $10{\cdot}65\pm2{\cdot}94$ and $7{\cdot}96\pm1{\cdot}04$ ml O_2 m^{-2} h^{-1} at these tidal levels, respectively, are well within such a range. Such figures are also in agreement with data published from other sandy areas (Smith, 1973; Smith *et al.*, 1973), although these were subtidal.

Turning to the microorganisms, Meyer-Reil (1978) gives bacterial densities of 10^5–10^9 cells g^{-1} for a sandy substratum, densities of 10^7–$1{\cdot}5\times10^7$ cells g^{-1} were found by Rheinheimer (1977) and Westheide (1968) gives a value of $1{\cdot}5\times10^6$ cells g^{-1}.

It appears that the driving force behind the fluctuations in BOD is water content, in as much as it may affect food supply and exchange of materials with the environment. In areas where little or no desiccation occurs, i.e. deep down in the substratum or at lower tidal levels, BOD exhibits random, low amplitude fluctuations characteristic of steady state conditions. As fluctuations in water content increase, the changes in BOD become greater and more regular. During times of low tide, BOD may drop to unmeasurably low levels despite the fact that the substratum still contains large numbers of microorganisms. What appears to happen is a process of metabolic inhibition or dormancy induced in the microorganisms by a decrease in sand moisture. Such a phenomenon has been recently suggested by Stevenson (1978). It is not necessary for the sand to dry out completely; all that is needed is for the water content of the sand to drop to a level where the microlayer of water around the sand grains becomes too small to support the previous level of metabolism. At this point ($\simeq 30\%$ saturation) nutrients become limiting and waste products as well as mutual inhibitors build up and conditions become unfavourable for bacterial activity (Burkholder, 1963). Thus, although oxygen is abundant, the microorganisms cannot use it since the aqueous medium necessary for their metabolism is critically reduced. Such a situation should prevail whatever the mode of metabolism, aerobic or anaerobic. The high metabolic rate of the organisms would preclude the storage of metabolic by-products such as CO_2 or lactate for lengthy periods.

Although many physical factors have been shown to relate to BOD, few of the studies from which the data come have been concerned with the effects of fluctuating moisture. This is because most such studies have been on subtidal sediments or in areas experiencing virtually no desiccation. In well drained beaches the effect of varying sand moisture may be so strong that it overshadows more subtle effects such as temperature and light. The fluctuations in BOD reported here are of such a nature that, at the higher tidal levels, variations of two or three orders of magnitude may be expected between high and low tides. This is clearly of importance when attempting to assess mean oxygen consumption from measurements made at specific stages of the tide. For instance, if measurements are made only during low tide an underestimate of up to 300% may result at the upper tidal levels.

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