J. exp. mar. Biol. Ecol., 1976, Vol. 22, pp. 179–192; © North-Holland Publishing Company

AN ANNUAL CYCLE, AT CONSTANT TEMPERATURE, IN A MODEL SANDY BEACH. I. NUTRIENT CHEMISTRY

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Abstract: A model sandy beach, successfully mimicking the natural environment has been operated under controlled conditions at a constant temperature (5 °C, representative of British winter coastal sea-water temperatures) for a year. The nutrient chemistry (nitrate, nitrite, ammonium, phosphate) and dissolved oxygen concentration of the beach ground water and its inundating sea water has been monitored over that period. The nitrifying activity of the sand profile and the associated oxygen status of the beach appear to be the dominant characteristics of the system. The rôle of the beach sand as self-regulating, self-purifying, and thus a cleansing filter of sea water is considered.

INTRODUCTION

Sandy beaches and their interstitial (ground) water have received very little systematic chemical study *per se*. Much of the information that can be extracted from the literature is only subsidiary to the biological data, and as such is usually incidental and fragmentary. Perhaps the most notable exceptions to this are the work on some beaches of South Africa (Oliff *et al.*, 1967, 1970), and of Anglesey, North Wales (Pugh *et al.*, 1974).

There are difficulties associated with any study of natural marine beaches since they are a complex inter-relationship of continually varying factors, none of which can be controlled, and none of which can be varied independently of the others. A model successfully mimicking the natural environment offers the ability to observe many facets of the marine beach environment, *e.g.*, its chemistry under controlled, constant conditions. The construction and operation of such a model sandy beach has been described and its ability to mimic the natural environment in general terms established (Pugh, 1975). This model has now been in operation, under constant, controlled conditions for an annual cycle and the nutrient chemistry of the sandy beach and the water feeding the model has been determined. The results are described herein.

METHODS

The model sandy beach, comprising a wedge of fine sand continually inundated under conditions of constant tide and wave action, with non-cycled sea water, and having ground water and sea water sampling facilities, was operated under the conditions already described (Pugh, 1975). A water temperature of 5 °C (±1 °C) was maintained throughout the year. This selection was considered representative of British coastal winter conditions, and held constant to eliminate another experimental variable. Air temperature ranged between 3° and 28 °C.

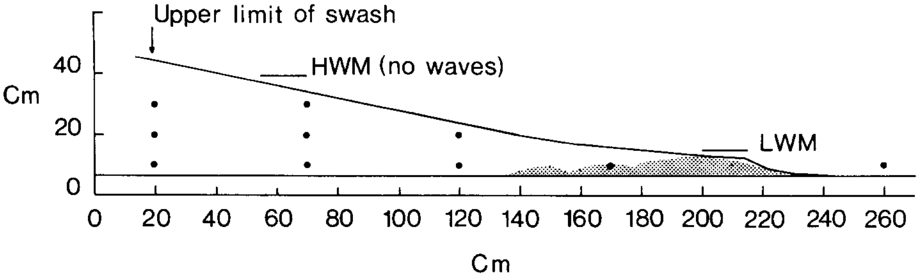

Fig. 1. Diagram of the model beach, showing the sampling points (●) and the sulphide system (stippled).

During the annual cycle, water samples, taken within an hour before or after low water, were drawn from sampling needles 1/20/10, 1/120/10 and 1/SW (which define model number/horizontal position/vertical position of sampling needle, see Fig. 1; nb. 1/SW = 1/260/10) and stored at −20 °C until analysed. The samples were taken weekly, except during the first few months. The dissolved nutrient (nitrate, nitrite, ammonium, phosphate) concentrations were determined as described by Pugh & Chubb (1974) and Pugh & Gibbs (1974). The dissolved oxygen concentration of the water samples was determined by allowing water to drain directly from the appropriate sampling needle into a flow-through oxygen electrode (see Pugh, 1975). A series of such measurements was usually made at about the middle of an ebbing tide.

RESULTS AND DISCUSSION

THE ANNUAL CYCLE

Nitrate nitrogen

It is apparent that when the survey commenced in March 1974 the nitrate concentration (Fig. 2) of the sea water was already decreasing from its previous winter maximum, and by May it was depleted, with less than 0.5 μg-at.NO_3-N/l present. A small increase in June to 2.5 μg-at.NO_3-N/l gradually declined so that during August less than 1.0 μg-at.NO_3-N/l was present. From the beginning of September there was a steady increase to an autumn maximum of 11 μg-at.NO_3-N/l at the beginning of November. This had declined to 7 μg-at.NO_3-N/l by the end of that month, before the onset of another gradual increase to the (expected) winter maximum of 16 μg-at.NO_3-N/l in late February. The cycle then began to repeat itself, but was unexpectedly interrupted by a further nitrate input giving a maximum (indicated by subsequent measurements) of almost 20 μg-at.NO_3-N/l early in April.

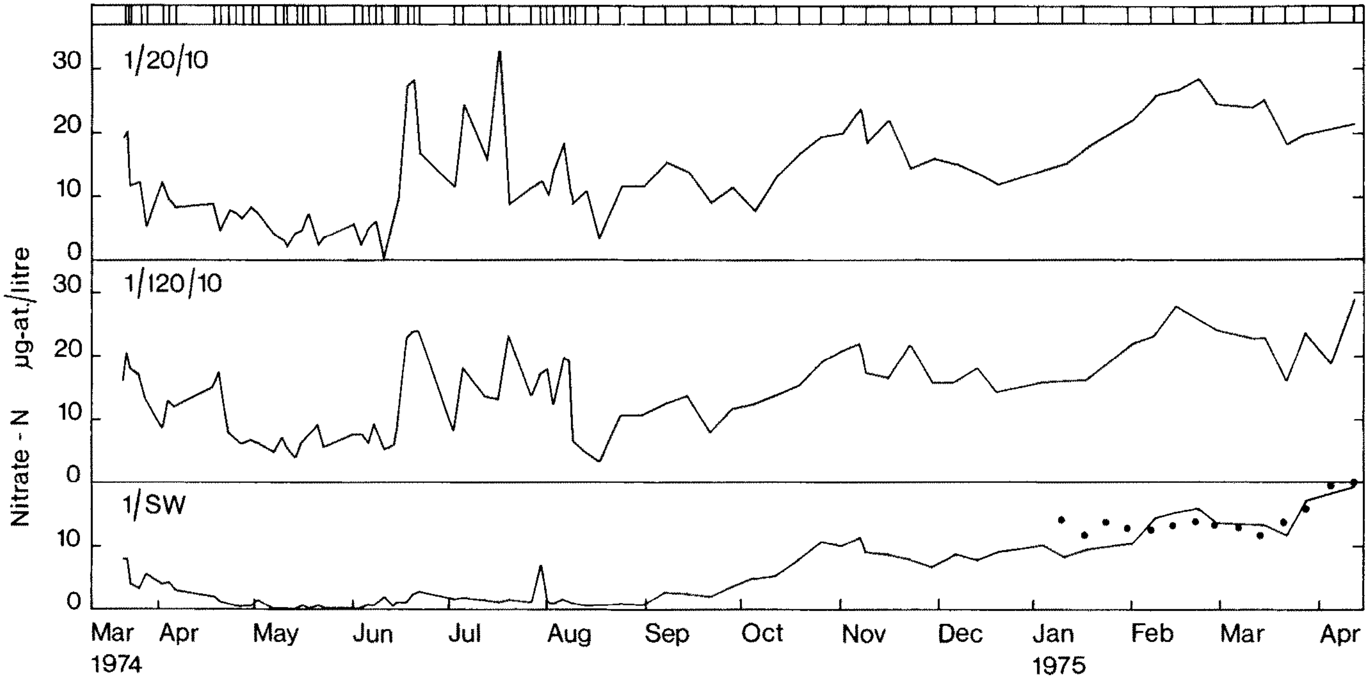

Fig. 2. The annual cycle of nitrate-nitrogen concentration of the ground and sea water: ●, weekly means for sea water sampled from Menai Bridge pier: frequency of sampling shown along the top of this and other figures.

Ewins & Spencer (1967) monitored the nutrient conditions of the water of the Menai Straits (the source of the water to the model beach) for an annual cycle in 1963/4. Their observations of nitrate–nitrogen concentrations were almost identical to those for 1974/5 given above, the major difference being in the time and 'bifurcation' of the 'winter' maximum, a single maximum in late March in 1964, but maxima in late February and early April in 1975.

The beach ground water sampled from Stations 1/20/10 and 1/120/10 was approximately twice as concentrated as the inundating sea water with respect to nitrate-nitrogen throughout much of the year. The trends, whether increasing or decreasing, were for the most part gradual, indicating a dynamic equilibrium between input and utilization. During the summer months, the ground water was, however, relatively very rich in nitrate-nitrogen, whilst the sea water concentration did not exceed 2.5 μg-at.NO_3-N/l. Within a week, 10–17th June, the concentration increased from less than 1 to more than 28 μg-at.NO_3-N/l at Station 1/20/10 and from 5 to 24 μg-at.NO_3-N/l at Station 1/120/10. Between early June and mid-August, the pattern of nitrate concentration observed was very erratic, suggesting a lack of balance between input and utilization. By mid-August the concentration at both stations had decreased to 3–4 μg-at.NO_3-N/l. There was an increase to 14-15 μg-at.NO_3-N/l by early September, a slight reduction towards the end of that month, and subsequently a pattern analogous to that for sea water, except that the February/April double maxima was not so well reflected in the ground water, particularly at Station 1/20/10.

Nitrate depletion of the source sea water and so of that in the model during spring and early summer has been attributed to phytoplankton growth and activity, and particularly to the *Phaeocystis* bloom (Ewins & Spencer, 1967). During this time nitrification may occur, but if it does the rate of nitrate production is exceeded by its rate of uptake, so giving rise to the depletion. The autumn and winter nitrate repletion is thought to result from degradative processes within the water column, enhanced by inputs from terrestrial drainage and fluvial discharge which are substantial during these seasons.

The relationship between the nitrate concentration of the model beach ground water and the inundating sea water is not clear. Fig. 3 shows the increase in nitrate concentration of the ground water samples relative to the sea water, and emphasizes particularly the midsummer burst of nitrifying activity in the sand profile. This increase has been attributed to nitrification of the degradative products of the spring *Phaeocystis* bloom which enter the sand profile in the inundating sea water (Pugh, 1975). That the primary substrate for this activity must be dissolved, nitrogen-rich organic material is suggested by the very low concentrations of ammonium- and nitrite–nitrogen. Furthermore, there appears to be a potential for nitrification in the sand profile throughout the year. The temperature of the source water, over which there was no control, may determine the rate and extent of the spring and autumn degradative processes in the water column and in turn affect the rate and extent of nitrification in the sand profile of the model. The rapid and extensive nitrate produc-

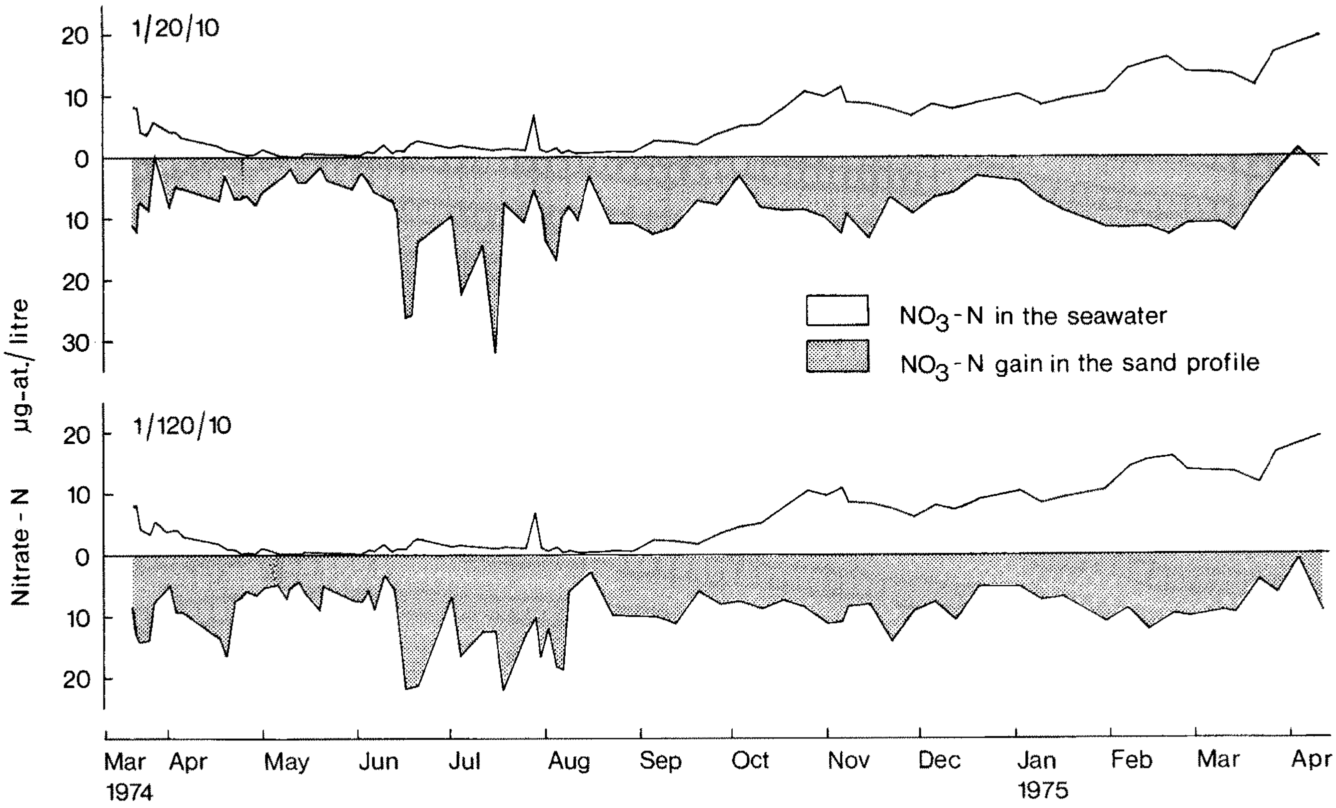

Fig. 3. The gain in nitrate-nitrogen concentration of the ground water at two sampling points relative to the concentration of the inundating sea water.

tion with a lack of balance between production and utilization rates in early summer, and a dynamic equilibrium in the autumn may thus be explained.

That nitrification is enhanced in the sand/ground-water system relative to the sea-water system (as indicated by the amount of nitrate present) is possible evidence for the requirement of surfaces by nitrifying organisms at which the oxidation of ammonia to nitrite can take place, a requirement well known for terrigenous organisms (see *e.g.*, Burges, 1958), but debated for their marine counterparts (see *e.g.*, Spencer, 1956).

Ammonium-nitrogen

Unlike the pattern of nitrate concentration, that of ammonium (Fig. 4) was very similar at both of the ground-water stations to that of the inundating sea water. At the beginning of the survey, ammonium concentrations were decreasing from their winter values and from April until mid-June, ammonium was not detected in any of the water samples, with the exception of very occasional, unexplained occurrences of a high concentration. As soon as the intensive nitrification had raised the nitrate-nitrogen concentration (19th June), ammonium-nitrogen was detected at all stations. The concentration of ammonium-nitrogen in all the water samples was of the order of 2.5 μg-at.NH_4-N/l with increases to 7.5 μg-at.NH_4-N/l to correspond with the mid-August low nitrate concentrations. There was another increase to 7.5 μg-at.NH_4-N/l in the sea water to correspond with the autumn nitrate maximum, but this was not evident in the ground-water samples. An exceptionally high concentration of ammonium in the sea water in mid-December was not reflected in the ground-water samples from the beach stations. Likewise, in January an exceptionally high concentration was measured in the ground water at Station 1/20/10 which was not found elsewhere.

Nitrite-nitrogen

Nitrite-nitrogen concentrations in the beach ground water rarely exceeded 0.2 μg-at. NO_2-N/l and were usually lower than those of the inundating sea water. In the sea water the concentration only occasionally exceeded 0.2 μg-at.NO_2-N/l until October but then there was an increase to 1.0 μg-at.NO_2-N/l by November followed by a gradual decrease during the remainder of the winter.

Dissolved inorganic phosphate

The sea water inundating the model beach was gradually depleted of phosphate during the spring of 1974 so that by early summer only about 0.2 μg-at. PO_4-P/l was measured (Fig. 5). Indeed, except for some higher concentrations late in July and again late in August the amounts were almost identical to those of Ewins & Spencer (1967) for 1964, in that phosphate concentration remained low. During the autumn and winter months there was a continual increase of phosphate up to a maximum in

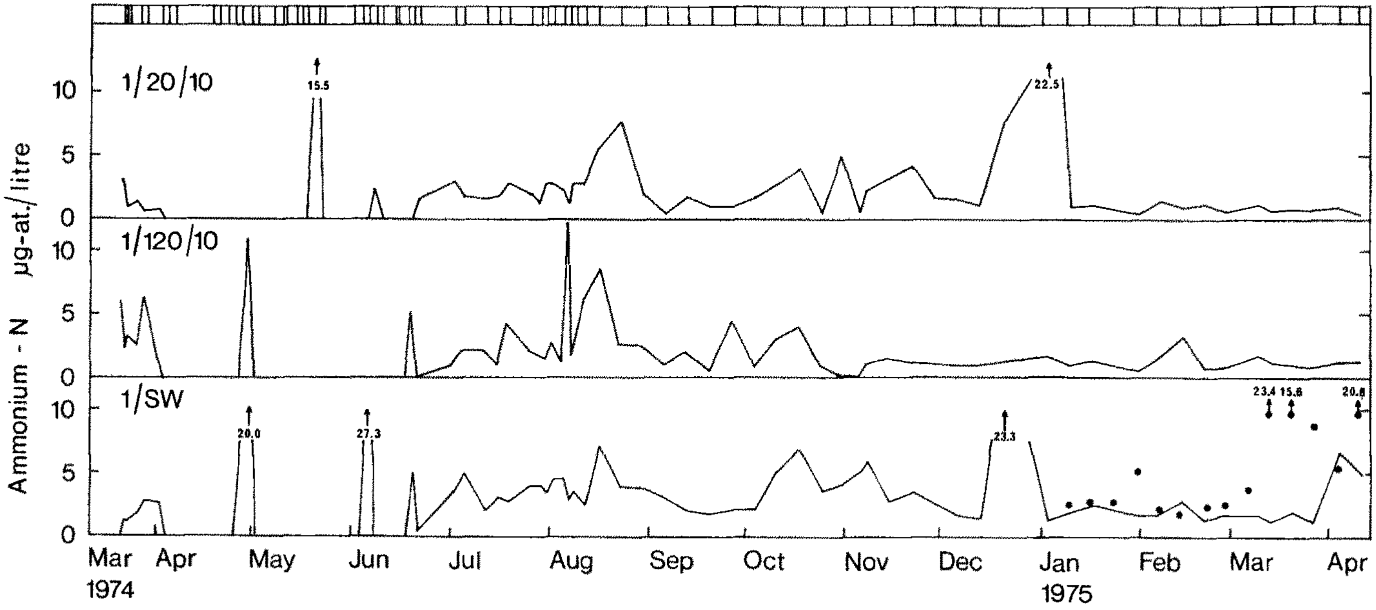

Fig. 4. The annual cycle of ammonium-nitrogen concentration of the ground and sea water: ●, weekly means for sea water sampled from Menai Bridge pier.

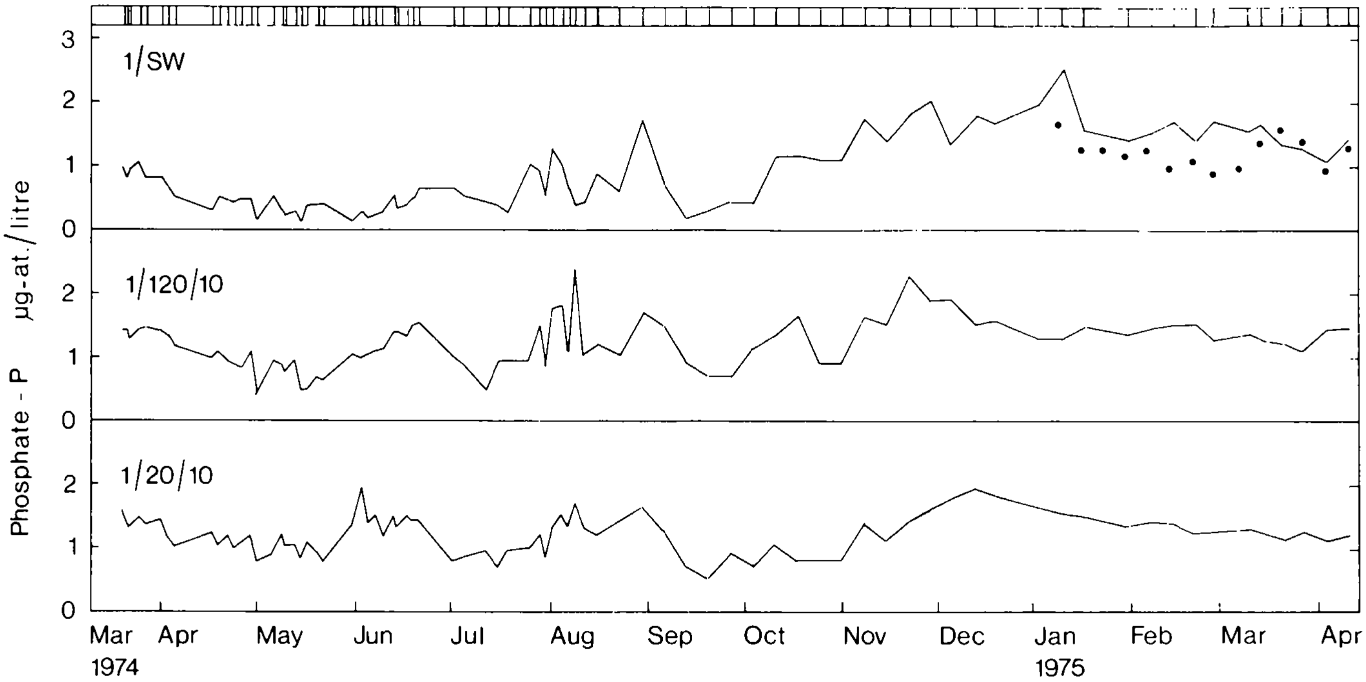

Fig. 5. The annual cycle of inorganic phosphate concentration of the ground and sea water ●, weekly means for sea water sampled from Menai Bridge pier.

January, 1975 of 2.5μg-at.PO_4-P/l, *i.e.*, three times the maximum measured in December 1963 and March 1964. A notably high concentration (double that of spring 1974) was then maintained well into the spring of 1975.

From the beginning of the survey until the middle of July 1974 the concentration of phosphate in the beach ground waters was very approximately double that of the sea water and subsequently very similar to it. Throughout the survey all water samples, ground and sea, had the same pattern of variation of concentration with time.

Dissolved oxygen

Since the model beach was operated with its sea-water temperature controlled at 5 °C ($\pm$ 1 °C), the amount of dissolved oxygen in the sea water remained, as expected, nearly constant at its saturation value of $\approx$ 10 mg/l (Fig. 6). Late in November and through December the sea water in the model was supersaturated (11 mg/l).

The beach ground water from both stations was not saturated with respect to oxygen. Initially ground water from Station 1/20/10 in the upper beach was more concentrated with respect to oxygen than that at the station (1/120/10) nearer low water with 7 and 6 mg/l, respectively, but this difference diminished during the survey. Furthermore, the concentrations decreased during the early summer months but gradually increased during the autumn to a higher value ($\approx$ 8 mg/l) which, except for a small decrease in February 1975, was maintained throughout the rest of the experimental period. The reason for this summer decrease is not clear though several factors may have contributed to it. The measurements were made at the base of the sand profile so that the conditions observed should be considered as the resultant of all the processes occurring above it during the tidal cycle. Though the temperature of the sea water in the model was controlled that of the air was not, and occasionally reached 28 °C, so that microbial activity at the surface of the sand may have been enhanced with a consequent higher oxygen demand and hence a lower oxygen concentration. This effect was considered of minimal importance being confined to the upper part of the profile. Of more importance is the chemical evidence of active nitrification during this time, nitrification being an oxygen requiring process, and hence the cause of the observed low oxygen concentrations.

Pugh (1975) found that a grey/black sulphide system gradually developed in the sublittoral area of the model where fine grained material (organic and inorganic) had been allowed to sediment from the overlying water (unfiltered Menai Straits water) because of the diminished turbulence and wave action at low water. The rest of the beach remained aerobic. That condition, as observed at the inspection window (Fig. 7b, c, in Pugh, 1975) prevailed unchanged from August onwards and its extent is represented in Fig. 1.

Attention is now drawn to the observation that of the two ground-water samples investigated, that from the greatest depth (point 1/20/10) was the more concentrated in oxygen, but comment will be reserved until more data has been presented (see below).

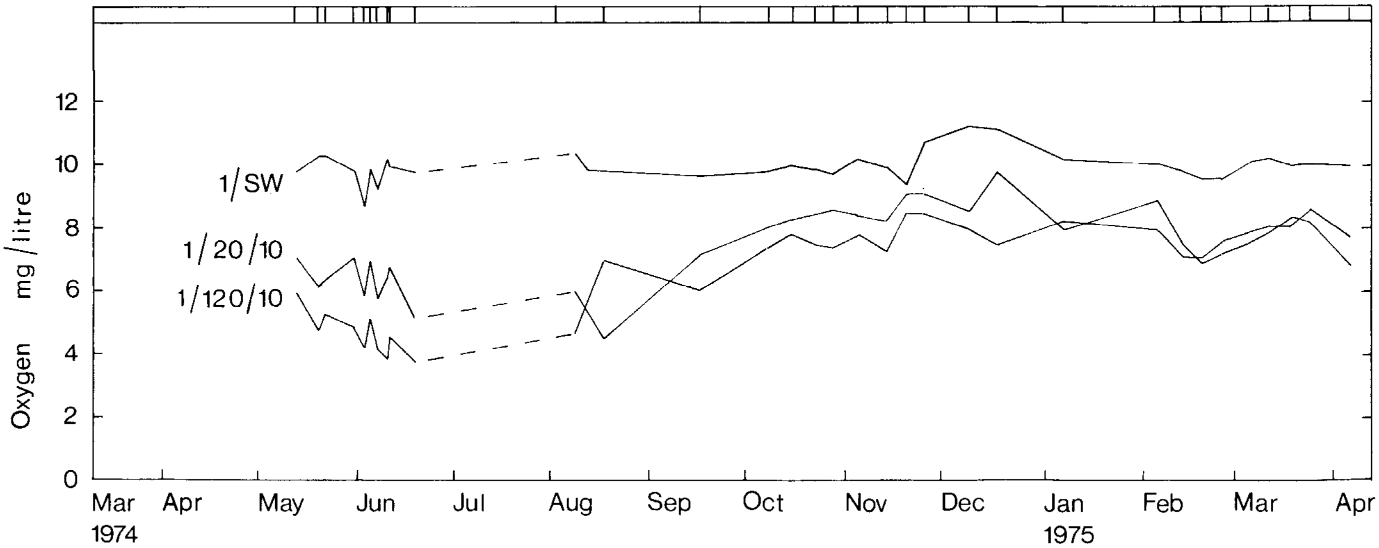

Fig. 6. The annual cycle of dissolved oxygen concentration of the ground and sea water.

Brafield (1964) has published extensive studies of the oxygen status of marine sandy beaches and the temptation to compare his results with those obtained in this study is great. There is, however, a fundamental difference; his samples were truly of interstitial water whereas these are of ground water, *i.e.*, samples drawn from below the water table.

SHORT TERM INVESTIGATIONS

The question arises as to what effect the pumping and storage of the sea water in the header tanks (see Pugh, 1975), albeit for a very short time, might have on the chemistry of the sea water feeding the model. Sea water sampled daily (or more frequently) from Menai Bridge pier in connection with another study (Spencer, Hunt and Pugh, unpubl.) was analysed for nitrogen species as in the present study, and for phosphate by the method of Chan & Riley (1966). The weekly means are plotted as solid circles in Figs 2, 4 and 5. The results indicate that there was little, if any, change in the chemistry of the water, particularly with respect to nitrate, nitrite, and phosphate (there were slight differences in the method of determination of this latter nutrient). The results for the ammonium concentrations were generally very similar during January and February, but erratic during March and April. This is explained by reference to the data from the monitoring programme at Menai Bridge pier since, during this latter period, very high ammonium concentrations, very localized in time, were observed and such gave high weighting to the weekly means, *e.g.*, samples taken at 09.30 h and 15.30 h on 4th April, 1975 contained, respectively, 32.9 and 8.8 μg-at.NH_4-N/l, and to illustrate even greater variability in the source water, six consecutive hourly samples collected on the 29th January, 1975 contained, respectively, 3.6, 2.9, 26.6, 22.6, 1.5 and 1.8 μg-at.NH_4-N/l. Such variability in the source water to the model would tend to be smoothed on its passage to and through the model, so that samples collected from the model (Station 1/SW) would not be expected to have such high ammonium concentrations.

Water samples were usually collected from the model beach at or near low water and always from within the water table. On one occasion (6th November, 1974) a group of samples were taken from the model at high water from sampling points both along the transect and in the profiles. Table I summarizes the results of nitrogen analyses. From a consideration of any of the nitrogen species it is clear that nitrification within the sand profile is a rapid process. Sampling points 1/20/30 and 1/70/30 had been inundated with sea water containing 11.2 μg-at.NO_3-N/l for only a little longer than 3 h but ground water sampled from those points then had nearly twice that concentration. Furthermore, by reference to the results for Station 1/70 that part of the profile submerged for the longest period (1/70/10) experienced nitrifying activity for the longest time and thus had the highest nitrate concentration. The higher value at point 1/170/10 is probably explained by the increased input of nitrogen-rich material to that area by sedimentation under quiescent conditions at low water.

It is seen (Table I) that the intermediate chemical species of the nitrification process – nitrite and ammonium – are rapidly oxidized; while 1.0 μg-at.NO_2-N/l was found in the sea water, no more than one fifth of that was present in the ground water from the sand profiles. A similar situation existed for the ammonium-nitrogen.

TABLE I

A nitrogen survey of the model beach at high water on 6th November, 1974: sampling points given in Fig. 1.

(cm)	Nitrate-N, μg-at./l					Nitrite-N, μg-at./l					Ammonium-N, μg-at./l				
(cm)	20	70	120	170	260(SW)	20	70	120	170	260(SW)	20	70	120	170	260(SW)
30	21.1	17.7				0.2	0.2				3.9	0.9			
20	19.9	19.7	19.0			0.1	0.1	0.1			0.8	1.1	5.5		
10	23.7	21.9	21.8	26.3	11.2	0.2	0.1	0.0	0.1	1.0	0.6	1.6	0.4	0.4	5.3

Occasionally a more extensive oxygen survey was made by including more sampling stations (Table II). Almost invariably it was found that increasing distance away from the low water mark, *i.e.*, increasing depth to the water table since the latter follows the tidal height very closely (Pugh, 1975), was accompanied by increased dissolved oxygen concentration (as noted earlier). As the tide recedes and the sand profile drains, oxygen enters the profile with subsequent re-aeration of the capillary water as it passes through the funicular and pendular stages to the ground water. The trend of dissolved oxygen concentrations observed may, therefore, be explained in terms of the relative exposure time of each profile to the atmosphere as the tide ebbs.

TABLE II

A more detailed survey of the dissolved oxygen concentration (mg/l) of the ground water of the model beach.

Date	Sampling station				
	1/20/10	1/70/10	1/120/10	1/170/10	1/SW
7.vi.74	5.74	5.23	4.21	1.57	9.25
19.vi.74	5.19	4.67	3.79	0.82	9.76
16. x.74	7.13	6.56	6.05	1.23	9.65
7. x.74	7.99	7.89	7.38	5.02	9.75
28. x.74	8.58	8.35	7.39	5.35	9.69
13.ii .75	7.44	7.50	7.07	6.04	9.78
19.iii.75	8.32	9.01	8.08	6.59	9.93

The data also confirm the early summer decrease in ground-water oxygen concentration with a subsequent autumn and winter restoration to higher values for all stations. It is particularly marked in the profile at Station 1/170. The sampling point 1/170/10 is interesting in that, quite by chance, it is situated in that part of the transect which apparently fluctuates between anaerobic and aerobic conditions (Fig. 1). The sulphide system at the inspection window remained unchanged, but the sampling needles extend to the centre of the beach transect and the results relate to that point. From time to time faunal activity was considerable in this area of the transect and casts of sulphide blackened sand frequently caused upheavals in the otherwise uniform topography. Clearly the samples were drawn from an area which was anaerobic in June, 1974, but had become aerobic in the autumn and winter. The reason for this transformation remains unclear, but one must look for some change in the nature of the sea water, either chemical or biological, since the sand and its physical environment (temperature, waves, tides, etc.) remained constant.

TABLE III

A survey of the oxygen (mg/l) dissolved in the ground water of the model beach one hour after high water (11th June, 1974): sampling points given in Fig. 1.

(cm)					
30	7.70	7.49			
20	7.39	6.26	5.49		
10	6.77	6.20	4.51	1.54	9.95
(cm)	20	70	120	170	260(SW)

A more complete oxygen survey of the ground water of the model on one occasion (Table III) involving several sampling points in the profiles along the transect gave the anticipated result. The ground water residing in the beach for the longest time, *i.e.*, that at stations low in the profiles and nearest the low water mark, were the least concentrated with respect to oxygen. Sea water initially containing 9.95 mg/l of dissolved oxygen, and residing in the sand system for only a few hours (samples 1/20/30 and 1/70/30) had a 22–25 % reduction in oxygen concentration.

CONCLUSIONS

This is the first chemical study of a marine sandy beach held under controlled conditions of temperature, waves and tides. The model system has already been established as a satisfactory mimic of the natural environment (Pugh, 1975) by reference to earlier work (Pugh *et al.*, 1974). The initial question posed, *i.e.*, what is the annual cycle of nutrients in such a beach? has been answered. Oliff *et al.* (1970) consider beach sediments to be self-purifying and self-regulating mechanisms on the shores. The beaches which they investigated were thought to be in an equilibrium state with the nutrient supply from the ocean. The present work illustrates their emphasis on the fact that increased input of organic material (*e.g.*, degradative products of *Phaeocystis*) gives a new equilibrium with higher levels of nutrients (*e.g.*, nitrate-nitrogen). The trend towards anaerobiosis was also observed, but was less pronounced in our case, either on account of a non-excessive loading, or the low temperature under which the model was operated.

The control in the model is limited in that the source water from the Menai Straits cannot be chemically controlled, but is subject to its own natural fluctuations (illustrated, especially with respect to ammonium-nitrogen, by the monitoring programme. It would be a useful to assess the effect of controlled additions of organic material (of known composition), at 5 °C and a higher temperature (say 15 °C, representative of British summer coastal sea-water temperatures), in order to substantiate the claim of Oliff *et al.* (1970) that beaches filter the sea water on their margins, and the sands may be acting as self-purifying and self-regulating units. The present study confirms that, with respect to their nutrient chemistry, this is so under conditions of low loading and low temperature. The timing of any increased loading of organic (*e.g.*, polluting) material in the year may be a critical factor. It might be anticipated that an increased input during the early summer when nitrification is apparently most active would have a far more deleterious effect on the beach because of oxygen limitation than were it to occur in the autumn or winter months when the oxygen status appears more favourable.

ACKNOWLEDGEMENTS

I am indebted to my colleagues of the Oil Biodegradation Unit, Drs C. F. Gibbs, G. D. Floodgate, Messrs A. R. Andrews and S. J. Davis, who have ensured the continuous operation of the model during my occasional absence. The work was performed under contract to the Natural Environment Research Council.

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