Estuarine, Coastal and Shelf Science (1985) **21**, 91–104

Water Filtration through Reflective Microtidal Beaches and Shallow Sublittoral Sands and its implications for an Inshore Ecosystem in Western Australia

Anton McLachlan[a,d], Ian G. Eliot[b] and Des J. Clarke[c]
[a]*CSIRO Marine Laboratories, P.O. Box 20, North Beach, Western Australia 6020,* [b]*Geography Department, University of Western Australia, Perth, and* [c]*Mathematics Department, University of Woolongong, P.O. Box 1144, Woolongong, N.S.W., Australia*

Received 29 November 1983 and in revised form 16 August 1984

Keywords: sand beaches; groundwater; waves; filtration; nutrients

Volumes of seawater filtered through the intertidal zone were measured on three modally reflective microtidal beaches in Western Australia. The filtered volumes were large, 19 $m^3 m^{-1} day^{-1}$ and 73 $m^3 m^{-1} day^{-1}$ on two ‘clean’ beaches but only 0·4 $m^3 m^{-1}$ per tidal cycle on a beach covered in kelp and seagrass wrack. The mean residence times of this water in the interstitial system and its percolation paths were both short, 1–7 h and 2–5 m respectively. Water input was greater across a beach cusp horn than across a cusp embayment. Most input occurred in the upper swash zone where the water table was less than 20 cm deep. Tidal variations in input volumes were evident even with tide ranges of only 20 cm. The inshore zone off these beaches filters on average 0·07 $m^3 m^{-2} day^{-1}$ at an average depth of 5·5 m under 0·4 m waves of 6·5 s duration. The importance of these procedures in the mineralization of organic materials and the regeneration of nutrients for an inshore ‘lagoon ecosystem’ is estimated and discussed.

Introduction

Large volumes of seawater are filtered through the porous sand bodies of exposed beaches as well as through the bed in their surf zones. In the intertidal zone this percolation is driven by tides and waves flushing water into unsaturated sand in the beach face to displace the air (Riedl, 1971; Riedl & Machan, 1972), while in the subtidal this is driven by hydrostatic pressure changes as a result of waves (Riedl *et al.*, 1972; Swart & Crowley, 1983). This water filtration is of physical importance in affecting swash/backwash processes coupled to accretion/erosion on the beach face and in affecting the attenuation of wave energy passing over a sandy bottom. It is also of biological

---

[d]Present Address: Zoology Department, University of Port Elizabeth, P.O. Box 1600, Port Elizabeth 6000, South Africa.

0272–7714/85/070091 + 14 $03.00/0

importance in providing oxygen and dissolved and particulate organic materials to the interstitial fauna of marine sands.

Waves, and to a lesser extent tides, thus provide the basic physical energy at the beach face to drive the interstitial ecosystem of marine sands. Landward of the berm crest, groundwater fluctuations are determined by tidal forcing (Dominick *et al.*, 1971; Chappel *et al.*, 1979; Lanyon *et al.*, 1982) except under higher wave conditions when swashes overrun the berm. This process on beaches can also be of profound significance to adjacent marine environments. Inorganic materials may be released in sufficient quantities from marine sands to add significantly to inshore marine nutrient pools (McLachlan, 1979, 1980; McLachlan *et al.*, 1981).

A model of swash water filtration and nutrient regeneration by exposed sandy beaches (McLachlan, 1982) predicted that maximum water percolation through the beach face should occur under conditions of small tide range, steep beach face slope and coarse sand, i.e. under microtidal conditions on reflective beaches. As virtually all the sandy beaches along the coastline near Perth, Western Australia, are of this type, they afford the opportunity to test this prediction. Further, studies on the inshore ecosystem in this area by the CSIRO require estimates of the extent of nutrient regeneration by these processes. This study was therefore planned to estimate filtered volumes for microtidal reflective beaches under a range of conditions and to assess the importance of this, as well as subtidal pumping, in nutrient regeneration in the inshore zone.

Study area

Most of the coastline north of Perth has discontinuous barrier reefs 1–5 km offshore. The reefs break the incoming wave energy so that a sheltered lagoonal basin lies on the inner continental shelf between the reefs and the shore (Figure 1). The floor of the lagoon is complicated with reef outcrops in many areas. Most of the sandy beaches are modally reflective (following terminology used by Wright *et al.*, 1979), with well developed cusps and distinct berms. Sediments of the lagoon bottom consists of well sorted sands of 300 μm mean particle diameter (Kirkman, personal communication), while beach material ranges from coarse to fine sand with high calcium carbonate contents. Many of the sheltered beaches accumulate large amounts of seagrass and kelp wrack, derived from the reefs and seagrass banks within the vicinity of the lagoon.

Three sites were studied, at Scarborough, Sorrento and Quinns Rocks (Figure 1). Scarborough is the least sheltered of the three beaches. A reflective beach mode with wide berm, cusps, steep beachface (slope 1 in 5) and deep inshore zone is common during summer, while complex arrangements of transverse and alongshore bar patterns occur more frequently in winter. Beach sediments comprise medium to coarse grained sands with a mean grain size of 610 μm and 13% $CaCO_3$.

Sorrento Beach is the southernmost part of a sandy, cuspate foreland with its apex at Mullaloo Point. The beach is sheltered from the direct impact of open-ocean storm and swell. It is narrow, has a face slope of 1 in 11 and is backed by a berm and an escarpment cut into the frontal dunes. Swash cusps are present on the upper beach face at most times. The beach consists of medium grained sands, with a mean particle diameter of 310 μm and including 30% $CaCO_3$.

Quinns Rocks beach is well sheltered behind the offshore reefs and is usually covered with piles of wrack. Below the wrack, the beach has a slope of 1 in 7 and the sands have a mean particle diameter of 370 μm and are comprised of 58% $CaCO_3$. The wrack

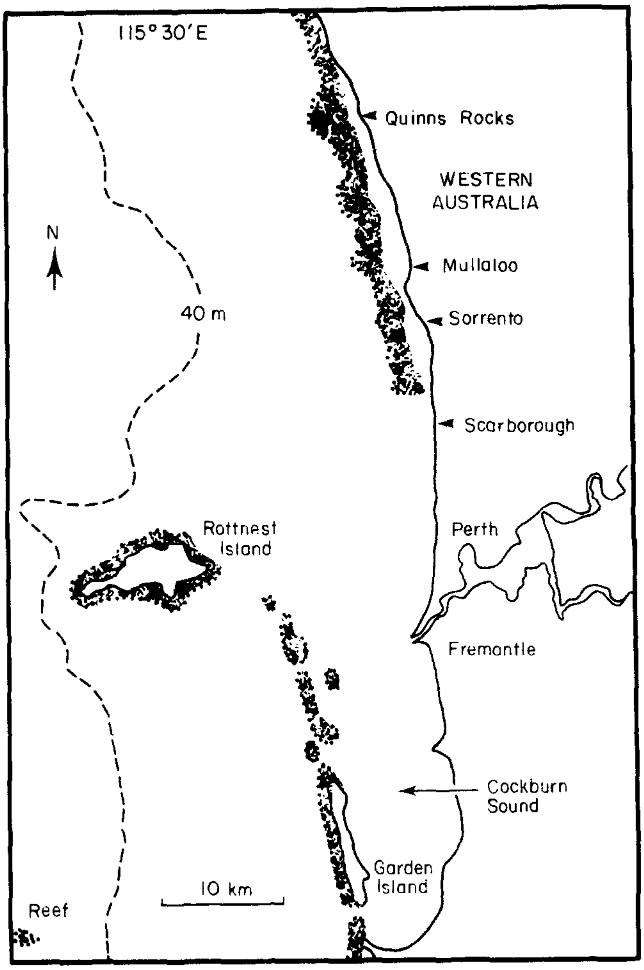

Figure 1. The study area.

effectively filters high frequency wave action so that only tidal effects on the beach water table are apparent. The beaches at Quinns Rocks and Sorrento are presently undergoing secular shoreline retreat.

The study area is in a microtidal environment where the coast experiences a mixed but predominantly diurnal tidal regime with an astronomical tide range of 0·9 m. Semidiurnal constituents prevail during the neap-tide phase and diurnal constituents during the springs. The small tides of the region are frequently overridden by barometric pressure effects on sea level, by low frequency shelf-wave activity and by storm surge.

The Perth metropolitan coast north of Fremantle is dominated by a low to moderate energy deepwater wave regime characterized by persistent south to southwest swell (Silvester, 1976). Waves measured in deep water off Garden island (Riedel & Trajer, 1978; Steedman *et al.*, 1977) and inside the reefs at 10 m depth off Mullaloo Point had median significant heights of 1·4 m and 0·4 m respectively, modal maximum heights of 2·0–2·5 m and 1·0–1·5 m respectively, and modal periods of 6–7 s in both instances. There is little variation in the low wave energy from year to year for the summer to autumn period (December through May). However, the wave climate is more severe during the winter to spring period, with large variations possible between successive years. Wave heights observed at Scarborough during the storm of July 1983 would have been close to the maximum wave heights observed on this part of the coast since 1974.

Methods

Water table movements and the swash input zone were monitored over a tidal cycle on Scarborough beach. Methods used to measure water table oscillations generally follow those described by Lanyon *et al.* (1982). Water table levels were monitored mechanically, using floats within well tubes. Half-hourly readings of the water table levels were obtained from each well.

The method used to measure water filtration through the beach face is that devised by Riedl (1971) and adapted by McLachlan (1979) with some further modifications. This essentially involves measuring the volume of water flushed into unsaturated sand by an individual swash and summation of this for a series of swashes over a particular interval. This is done by recording the dimensions of each swash reaching unsaturated sand over a 15-min period. Where there is a large tide range a series of such measurements is taken over a tidal cycle and integrated to give the total volume filtered over a tidal cycle. To calculate the water input for each swash a relationship must be obtained between height in the sand above the water table and air space (saturation gap) in the sand. Saturation gap was measured *in situ* on the three beaches as described by McLachlan (1979) for heights of 5–30 cm above the water table and linear regression fitted to the data.

During each series of swash records, lasting 15 min, the following measurements were taken [see Figure 2(b)]: (1) the length of the wedge of unsaturated sand overrun by each swash, i.e. the distance from the water table outcrop (effluent line or glassy layer) prior to the swash to the upper limit of the swash; and (2) the depth of the water table at the upper limit of the swash prior to the swash reaching it. These two measurements define a wedge of sand that receives water. Computation of the volume of this wedge for a strip of beach 1 m wide, integrated with the saturation gap equation, yields the input volume. However, where the water table is more than about 20 cm below the sand surface the whole wedge is not saturated by the overrunning swash. In this case only the surface layers are wetted above the wedge terminating where the water table reaches 20 cm. On fairly flat, fine sand beaches this effect is sufficiently small to be ignored (McLachlan, 1979). On the beaches in this study area, however, a large proportion of swashes exceeded the point where the water table was 20 cm deep, a result of the relatively steep slopes, coarse sands and deep water tables. Some correction was therefore needed and when swash lengths were measured *in situ* two components were recorded separately: (1) the length from the water table outcrop to where the water table was 20 cm, and (2) the length from there to the limit of the swash. Observations suggested that the value of 20 cm used for South African beaches (McLachlan, 1979) was a good approximation for these beaches.

To estimate the volume of input in this layer above the wedge, observations were made on the periods of swashes, the times they overlay the sand and their thicknesses. The volumes of water seeping into the sand under such conditions were measured as hydraulic conductivity under different heads. A PVC tube 10-cm diameter was pushed 5 cm into the sand and the sand surface protected by two layers of 1-mm mesh gauze. Various volumes of water were then poured into the tube to give different heads and the

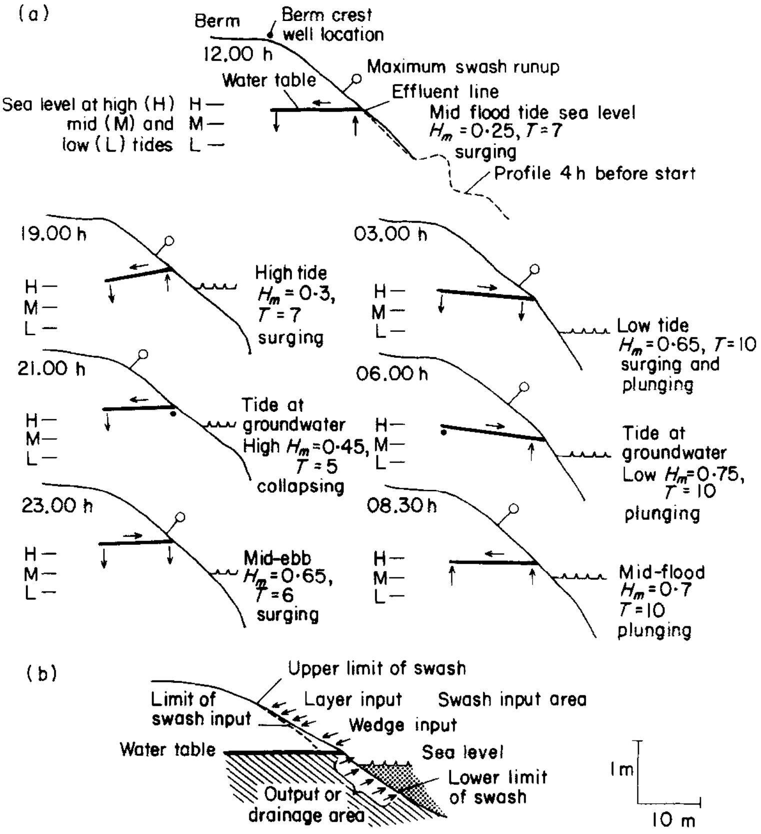

Figure 2. (a) Variations in beach face profile and relative locations of the water table, sea level, effluent line and upper limit of swash run-up over a tidal cycle at Scarborough beach. Time, maximum breaker height (H_m in m), breaker type and wave period (T in s) are also listed. Arrows indicate direction of water movement. (b) Diagrammatic representation of swash input and gravity drainage output zones on the beach face.

seepage rates were measured by stopwatch. Knowing the volume of water seeping into the sand under a particular head within a specified time, the volumes of water input in layers could thus be estimated from swash characteristics.

Because of the small tides, swash infiltration readings were not taken over whole tidal cycles but rather during specific parts of the tidal cycle. Each set of readings was taken for 15 min except one set of 30 min during a storm at Scarborough. All measurements were done half way between a cusp horn and an embayment except for a comparative series at Sorrento done simultaneously along a horn and an embayment. Beach surface and water table profiles were measured at all sites. Further, water table fluctuations over 7 h at Sorrento were followed along a cusp horn using a series of wells. Measurements of water table profiles allowed estimates of the total water volume held in the sand affected by wave flushing and thereby calculations of residence times based on filtration rates.

Volumes of water pumped through the sandy bed of the lagoon were calculated from the methods of Swart and Crowley (1983) for vocoidal wave theory and Riedl *et al.* (1972) for linear wave theory using the wave data of Steedman *et al.* (1977).

Interstitial water was collected at a number of sites and analysed for NO_3, NO_2, NH_4 and PO_4, following the modification of Strickland and Parsons (1972).

Results

The swash infiltration zone and tidal water table excursions

Variations in swash run-up and water table slope over a tidal cycle are illustrated for Scarborough Beach [Figure 2(a)] from observations made over 26 h on 25–26 March 1983. The survey was made under very low energy conditions in a cusp embayment. Wave heights ranged from 0·25 to 0·75 m, and the tidal range was 0·6 m. The water table ranged 0·2 m in a well positioned on the berm slope break, away from the immediate effects of high frequency groundwater oscillations. Swash ranging was estimated as the vertical differences between the lowest level of the effluent line and the uppermost limit of swash run-up recorded over 10 min every 30 min during the survey. Maximum ranging occurred at high and low groundwater levels when the swash ranged over 0·6 m and 0·7 m respectively. Minimum ranging occurred when the groundwater level was rapidly changing, particularly during the mid-ebb tide conditions when the sea level was well below the effluent line. The swash run-up ranged over 0·1 m only at this time.

Although the sequence of events in Figure 2(a) was specific to the particular conditions at that time, a number of points can be made from those observations. Maximum swash run-up above the groundwater effluent level (i.e. swash water input to the beach face) occurred throughout the tidal cycle. This differs from observations on beaches with a larger tide range (Lanyon *et al.*, 1982). The water table surface beneath the berm crest was above the average tide level for this study. The sand wedge saturated by swash resurgence was located below the berm water table level for one third of the tidal cycle. It was below the berm water table from just after mid-ebb to just before mid-flood tides, this spanning the period when the water table had a marked seaward slope below the beach face. Maximum swash infiltration, indicated by the period in which the water table sloped landward beneath the beach face, began before mid-flood tide and continued through high tide conditions. It lasted until the falling tide was sufficient to overcome swash recharge effects, 1–2 h after high tide. At high tide the groundwater table at the berm crest was approximately 15 cm above the high tide water level. By the time of the water table peak, the tide had fallen by 10 cm while the berm crest water table had risen a further 5 cm, the difference between the two thus being about 30 cm. As the tide fell to the mid-ebb level the swash input continued, but at a much diminished rate, indicated by a reduction in the maximum swash excursion. Below the mid-ebb level swash infiltration was elutriated by the groundwater outflow.

Figure 2(b) is a diagrammatic representation of the beach face showing input and output (drainage) areas. The input area lies between the effluent line and the limit of swash run-up. The output area is from the effluent line down to the lower limit of the swash. Gravity drainage occurs throughout this area. The input is divided into wedge and layer inputs. These are discussed later.

Swash infiltration on the beach face

Saturation gaps for the three beaches are shown in Figure 3. There were highly significant differences between the slopes of the lines for Sorrento and Scarborough ($F = 17{\cdot}9$, $P < 0{\cdot}001$) and Scarborough and Quinns Rocks ($F = 15{\cdot}1$, $P < 0{\cdot}001$) but not between the lines for Sorrento and Quinns Rocks ($F = 0{\cdot}7$, $P > 0{\cdot}1$). In all three cases maximum saturation gap, 30 cm above the water table, was about 35% of sand volume. However, the saturation gap increased much more rapidly in the first few centimetres above the water table in the coarse sands at Scarborough than on the other two beaches. This

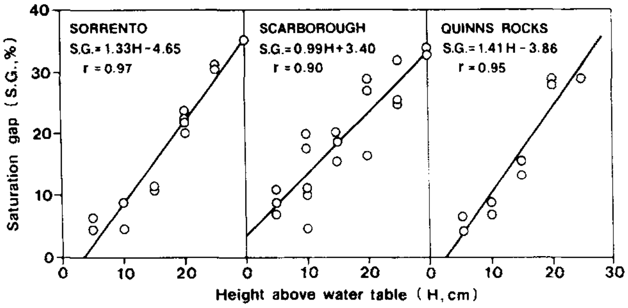

Figure 3. Saturation gaps (% air space) in the sands of three beaches as a function of height above the water table. Least squares regression equations are given.

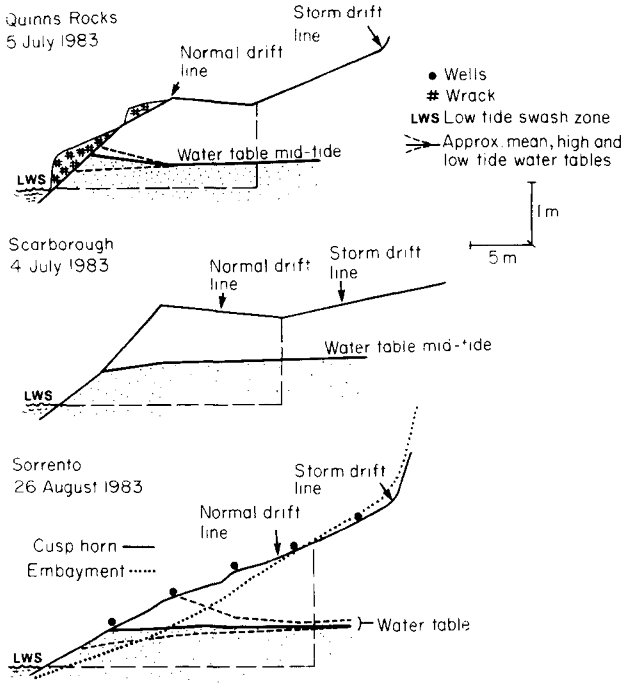

Figure 4. Profiles of the three study beaches showing water table positions. Broken lines demarcate the approximate boundary of the area where groundwater is circulating as a result of swash inputs.

is exaggerated slightly by the regression line which does not take into account the sigmoidal nature of the relationship (Riedl, 1971). Nevertheless, the regression lines give reasonable approximations of the data as indicated by the correlation coefficients.

Profiles of the beach (Figure 4) show the large accumulation of wrack at Quinns Rocks. This wrack completely filtered out wave action and the water line rose and fell on the beach with the tides. The extent to which the tide may have been filtered was not determined. The broken lines, showing the theoretical positions of the water table during a high and low tide of range 0·38 m, illustrate the small size of the input area relative to the total area of groundwater affected by water filtration through the beach face (enclosed in broken lines). This includes the input (swash influent) area from the water table outcrop (effluent line) to above the normal drift line and the output area below the

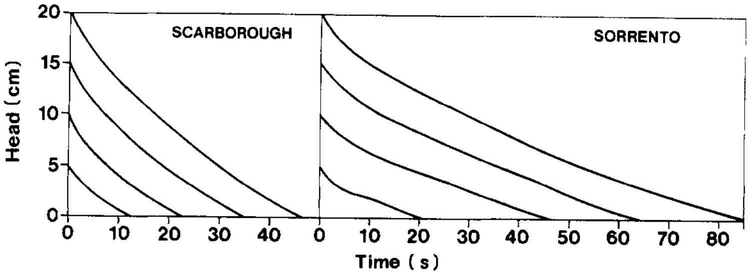

Figure 5. Hydraulic conductivity measured in the swash zone on two beaches as the time taken for water to seep through the sand under different starting heads.

water table outcrop where water seeps back to the sea. The input area is considered to extend a little way landwards of the normal drift line because some of the input moves back with decreasing amplitude and increasing lag and gradually decays. The lower boundary of this system corresponds with the low tide swash zone. The approximate volume of water enclosed within these boundaries can be calculated for a 1 - m wide strip of beach assuming 35% porosity by volume. This gives a total circulating groundwater volume of 3·0 $m^3 m^{-1}$ at Quinns Rocks. The mean circulating groundwater volume is approximately 4·1 $m^3 m^{-1}$ at Scarborough using this method.

Cusp horn and embayment showed markedly different profiles at Sorrento (Figure 4). The high and low tide positions of the groundwater table as well as the approximate mean condition are for the cusp horn profile only. This gives a mean circulating groundwater volume of about 4·5 $m^3 m^{-1}$ along the horn and (assuming the same boundaries) about 3·6 $m^3 m^{-1}$ along the embayment. On average the vertical swash range was about 2 m at Scarborough and 1 m at Sorrento, so tidal effects with a predicted mean range of 0·38 m would be expected to be small.

Figure 5 shows the empirical results of the hydraulic conductivity measurements at Scarborough and Sorrento. This shows the drop in head of water from different starting heights. Observation of swashes filling wedges and layers on these two beaches indicated that swash thickness in the input zone ranged from 1 to 20 cm and covered the input zone for periods of 1–8 s under normal conditions. Approximate means for swashes running far enough up the beach to saturate only the surface layers were 3 s coverage and 5 cm head (6 s with 10 cm head at seaward and 1 s with 1 cm head at landward end). From Figure 4 this gives an average input of 1·8 cm of water or 18 $l\,m^{-2}$ at Scarborough and 1·5 cm or 15 $l\,m^{-2}$ at Sorrento. These values were therefore used to calculate layer inputs. During the storm at Scarborough, when winds were gale force, swashes were, however, much larger and values of 4 s and 20 cm were used to obtain an input value of 3·5 cm or 35 $l\,m^{-2}$.

Based on the foregoing, the results of 12 series of measurements of input volumes are summarized in Table 1. During the storm at Scarborough, input was dominated by low frequency large swashes which overtopped the berm so that more swash water was input by layers (infiltration from the berm surface) than wedges. On this occasion the vertical swash range was 3 m. An input volume of 3·83 $m^3 m^{-1} h^{-1}$ gives a total input of 92 $m^3 m^{-1} day^{-1}$, nearly an order of magnitude above the previous highest recorded value (McLachlan, 1979). During all other recordings much more input occurred in wedges than layers. During calm conditions with a near maximum tide (0·7 m) there was a large difference between input volumes during the high (3·68 $m^3 m^{-1} h^{-1}$) and low (1·82 $m^3 m^{-1} h^{-1}$) tide at Scarborough. Swash frequencies were much higher during

TABLE 1. Summary of measurements of water inputs. Period refers to input swashes only

Beach	Tide types and predicted tide range		State of tide	Conditions	Position	Swash period (s)	Mean swash length (m)	Volume input by wedges ($m^3 m^{-1} h^{-1}$)	Volume input by layers ($m^3 m^{-1} h^{-1}$)	Total input ($m^3 m^{-1} h^{-1}$)
Scarborough	diu.	0·4 m	high	storm	intermed.	46	4·5 m	1·73	2·10	3·83
Scarborough	diu.	0·4 m	midoutgoing	f. calm	intermed.	21	2·1 m	2·77	0·09	2·86
Scarborough	diu.	0·7 m	high	f. calm	intermed.	21	2·6 m	3·59	0·09	3·68
Scarborough	diu.	0·7 m	low	f. calm	intermed.	19	1·6 m	1·82	0·00	1·82
Sorrento	semi	0·5 m	midoutgoing	f. calm	intermed.	29	2·8 m	0·74	0·11	0·85
Sorrento	semi	0·2 m	high	f. calm	cusp horn	24	2·6 m	0·93	0·27	1·20
Sorrento	semi	0·2 m	midoutgoing	f. calm	cusp horn	27	2·7 m	1·00	0·06	1·06
Sorrento	semi	0·2 m	low	f. calm	cusp horn	27	2·3 m	0·77	0·14	0·91
Sorrento	semi	0·2 m	high	f. calm	cusp bay	40	2·5 m	0·55	0·05	0·60
Sorrento	semi	0·2 m	midoutgoing	f. calm	cusp bay	46	2·6 m	0·34	0·07	0·41
Sorrento	semi	0·2 m	low	f. calm	cusp bay	40	2·5 m	0·51	0·05	0·56
Quinns Rocks		0·38 m	whole cycle	—	—	—	—	0·4	—	0·4 $m^3 m^{-1}$ tide^{-1}

normal conditions than during the storm at Scarborough. Because of this the input volume during the high tide was similar to that during the storm when much wave energy was consumed in the expanded surf zone. Although input volumes were measured under a limited range of conditions, they fell in a sufficiently narrow range to suggest the use of an overall mean value. The overall mean input volume for Scarborough was 3·05 $m^3\,m^{-1}\,h^{-1}$ or 73 $m^3\,m^{-1}\,day^{-1}$.

At Sorrento swash frequency was lower than at Scarborough and was much higher on the cusp horn than in the cusp embayment. Swash lengths were, however, similar in both places. Average input on the cusp horn was 1·06 $m^3\,m^{-1}\,h^{-1}$ with 85% of input as wedges and only 15% as layers. Input decreased from high to low tide. For the embayment there was no clear change with the tides and input averaged 0·52 $m^3\,m^{-1}\,h^{-1}$ with 89% as wedges and 11% as layers. This is a result of the flatter slope and shallower water table in the embayment. Overall mean input at Sorrento was 0·8 $m^3\,m^{-1}\,h^{-1}$ or 19 $m^3\,m^{-1}\,day^{-1}$.

At Quinns Rocks the input resulting from just the rise and fall of a 38-cm tide was estimated to be approximately 0·4 $m^3\,m^{-1}\,tide^{-1}$ based on Figure 4. Clearly, the tides alone account for a very small proportion of total water input under such circumstances. During storms, however, wrack is removed from this beach and the normal wave swash input mechanism should rise to the same level as Sorrento. On average these beaches are covered in wrack for about 70% of the time (A.I. Robertson, personal communication). Based on this proportionality Quinns Rocks should have an overall average input volume of about 6 $m^3\,m^{-1}\,day^{-1}$.

The approximate mean residence time of filtered water in the interstitial system of the beach can be obtained by dividing the approximate mean circulating groundwater volume by the mean hourly input. At Scarborough this is 4·1 m^{-3} divided by 3·05 $m^3\,m^{-1}\,h^{-1}$, giving a mean residence or percolation time of approximately 1·3 h. At Sorrento this is 4·5 m^3 across a cusp horn divided by 1·06 $m^3\,m^{-1}\,h^{-1}$ giving 4·2 h, while across an embayment it is 3·6 m^3 divided by 0·52 $m^3\,m^{-1}\,h^{-1}$ giving 6·9 h. The average condition at Sorrento may be intermediate between these values as there may be some net longshore movement from cusp horn to embayment (Lanyon *et al.*, 1982). At Quinns Rocks the residence or percolation time in the presence of wrack filtering out wave effects would be 90 h for a semidiurnal tide and 180 h for a diurnal tide of 0·38 m. These are all mean values and actual times will vary from seconds (small wedges on ebb tide) to days (long layers overtopping the berm).

Subtidal pumping

Volumes of seawater pumped through the lagoon bed at a mean depth of 5·5 m under a 0·4-m swell of period 6·5 s are estimated to be 0·04 $m^3\,m^{-1}\,day^{-1}$ based on the method of Swart and Crowley (1983) and 0·103 $m^3\,m^{-1}\,day^{-1}$ based on the method of Riedl *et al.* (1972) for bottom sediments with a permeability of 61 Darcys. This gives a mean value of 0·07 $m^3\,m^{-2}\,day^{-1}$.

Nutrients

Nutrient values in interstitial, surf and lagoon water are summarized in Table 2. Only mean values are given for lagoon water and surf water off wrack banks, based on studies done in the CSIRO Marine Laboratory, Perth. For interstitial water samples the range is given for a series of samples taken from the swash zone to the backshore on each beach. On Scarborough and Sorrento beaches interstitial nutrient concentrations increased

TABLE 2. Nutrient concentrations in interstitial and lagoon water. Values for interstitial water are from this study, those for lagoon water are from J. Hansen and C. Manning, CSIRO Laboratory (personal communication). NO_3-N includes NO_2-N

	Concentration ($\mu g\ l^{-1}$)				
Locality	NO_3-N	NH_4-N	PO_4-P	DON	DOP
Scarborough interstitial water	56–448	112–368	28–84	—	—
Sorrento interstitial water	27–336	46–1078	37–87	—	—
Quinns Rocks interstitial water	196–381	155–536	50–158	—	—
Lagoon water	14	<1	14	140	31
Surf water near wrack bank	14	4	14	—	31

from the swash zone to the backshore. This is a result of longer residence time and increased input from drift line wrack leachates towards the backshore. At Quinns Rocks, however, highest concentrations were recorded in the midshore region, near and just above the big wrack banks. Nutrient levels in surf and lagoon water are much lower than in interstitial water.

Discussion

The infiltration zone

Interaction between the tide and swash are important for groundwater filtration through sandy beaches in two respects. First, water filtration from waves crossing the water table effluent line will locally raise the water table as the swash runs up the beach (Grant, 1948; Emery & Foster, 1948; Riedl & Machan, 1972; Waddell, 1973). Essentially this is a high frequency response. The effluent line retreats back down the beachface as the backwash run out is completed. It returns to its previous condition of slow change with the tide unless interrupted by subsequent swash uprush or some other event involving beachface water table change. The second set of interactions include tide and water table effects on swash run-up. Infiltration is favoured when the water table is low, relative to swash run-up, and during rising water table conditions when the water table slopes landward beneath the beachface (Grant, 1948; Duncan, 1964; Ericksen, 1970; Chappell *et al.*, 1979).

The filtration process

Very high volumes of seawater are filtered through the faces of these reflective microtidal beaches. A model derived for intermediate high energy beaches of fine to medium sand and 0·5–2 m tide range (McLachlan, 1982) predicts a filtered volume of $19\ m^3\ m^{-1}\ day^{-1}$ for Scarborough and $11\ m^3\ m^{-1}\ day^{-1}$ for Sorrento under average conditions, while measured volumes were $73\ m^3\ m^{-1}\ day^{-1}$ and $19\ m^3\ m^{-1}\ day^{-1}$. One reason for these volumes being above the predictions is the higher swash frequency. In this area wave period is 6·5 s and input swash frequency about 30 s, whereas in South Africa, where the model was obtained, wave period is 10–14 s and input swash period about 100 s (McLachlan & Young, 1982). Thus, on these beaches one swash in four or five produces an input while in South Africa it is only one in seven to 10. This is because broad intermediate surf zones in the latter case reduce much of the wave energy to infragravity bores while the reflective beaches studied here, with their very narrow surf zones, generally have every wave reaching the beach as a swash. The very high filtered volume at Scarborough is also a result of the very coarse sand, as permeability is related to the square of the radius of pore diameter which is directly related to particle size (Leyton, 1975; Crisp & Williams, 1971). The filtered volumes obtained here are thus close to the maximum possible values, although Riedl & Machan (1972) predict that maximum values may be as high as 200 $m^3 m^{-1} day^{-1}$.

Because of the steep slopes and small tide range, these beaches have small circulating groundwater volumes and thus the residence times of the filtered seawater in the beach-face sand are very short (ca. 1–7 h). On North Carolina beaches with 1-m semidiurnal tides and 200 μm sands, Riedl and Machan (1972) estimated a mean residence time of 22·2 h where the slope was 1 in 20 and the input volume 6 $m^3 m^{-1} day^{-1}$. In South Africa, on high energy beaches with mean slope 1 in 25, 250-μm mean particle size and a semidiurnal mean tide range of 1·1 m, residence time is about 24 h for an input volume of 10 $m^3 m^{-1} day^{-1}$ (McLachlan, 1979, 1982). The mean drainage distance or percolation path of filtered water is about 35% of the intertidal distance (Riedl & Machan, 1972). This is about 2·5 m at Scarborough, 5 m at Sorrento and 17 m on the South Africa beaches. Thus, although these reflective microtidal beaches filter larger volumes of water than more dissipative, higher energy beaches, they do so less effectively, the average water particle percolating 15–29% of the distance and having 5–30% of the residence time that it would have on a South African beach.

The effect of cusps was pronounced on Sorrento beach and the results suggest a net input across the cusp horn and a net output across the cusp embayment. Hence the cusp should be accreting and the embayment eroding (Lanyon *et al.*, 1982). This in fact did occur, and the cusp accreted by about 4 cm while the embayment eroded by about 2 cm over the 7-h study at Sorrento. This differential input and output, as well as possible lateral flow and differences in saturation, should have pronounced effects on the interstitial fauna.

From the foregoing it may be concluded that input volume will decrease, while percolation distance and residence time will increase as beaches become flatter with finer sand and larger tides.

Subtidal pumping

The volumes of water being pumped through the lagoon bottom are comparable to those obtained for the inner shelf off North Carolina by Riedl *et al.* (1972). These are conservative estimates as the wave data on which their calculation was based came from the most sheltered part of the 'lagoon' and patches of coarse sand which occur on the lagoon bottom (H. Kirkman, personal communication) and have high permeability, were ignored. However, possible damping of wave pumping by beds of seagrass have also been ignored.

Nutrients

The high concentrations of nutrients in interstitial waters are indicative of the large amounts of organic materials mineralized in these beaches. Comparatively high PO_4-P values suggest that interstitial water may be an important source of phosphate to the lagoon, although Johannes and Hearn (in prep.) show discharging groundwater to be deficient in phosphate due to removal by carbonate sands.

Implications for the lagoon ecosystems

The Marmion Lagoon study site of the CSIRO, between the barrier reefs and the dunes, is oval-shaped and approximately 7·5 × 4·3 km with a mean depth of 5·5 m (Johannes & Hearn, in prep.). Of the 7·5-km shoreline, 5·5 km is an open beach including Sorrento, 0·2 km is wrack covered beach like Quinns Rocks and the rest is rocky shore. Of the total lagoon bottom of $2{\cdot}5 \times 10^7\ m^2$, 82% is sand (Johannes & Hearn, in prep.; Kirkman, 1981). Based on the foregoing results the total filtered volumes would be $0{\cdot}11 \times 10^6\ m^3\ day^{-1}$ for the beaches and $1{\cdot}44 \times 10^6\ m^3\ day^{-1}$ for the lagoon bottom. This means that the equivalent total water volume of the lagoon ($138 \times 10^6\ m^3$) could be filtered through sand every 89 days.

Lagoon macrophytes contain about 13×10^4 kg of fixed nitrogen above ground in kelps (80·5%) and seagrasses (19·5%). Since kelps turnover 1·5 times and seagrasses three times per annum (Kirkman, 1981), Johannes and Hearn (in prep.) estimated that annual nitrogen requirements of the macrophytes are approximately 24×10^4 kg. Submarine groundwater discharge supplies about 294 kg N day^{-1} or 107310 kg N $year^{-1}$, 45% of the nitrogen requirements of these plants. As about 17% of macrophyte biomass ends up on the beaches where the nutrients are recycled by grazing and microbial decomposition (Robertson & Hansen, 1982; Hansen, personal communication) enough nitrogen to meet 17% of macrophyte requirements must be recycled in this way.

Nutrient regeneration by the sublittoral bed and intertidal zone can be estimated from input volumes and mineralization estimates. Experimental sand columns have recorded mineralization of 70–100% of the organic nitrogen percolating through the sand (Pugh, 1976; Boucher & Chamroux, 1976; Munro *et al.*, 1978; Wormald & Stirling, 1979) although figures as low as 18–45% have been measured in a beach simulation (McLachlan *et al.*, 1981). Fifty per cent mineralization is therefore considered a conservative estimate. Average levels of DON in the lagoon are 140 μg N l^{-1} (Table 2). Levels of fine PON are not known, but, if assumed to be half those for DON (i.e. 70 μg N l^{-1}), this would mean that the sediments of the lagoon have 13×10^4 kg organic nitrogen passing through them each year in a filtered volume of $6 \times 10^8\ m^3$. At 50% mineralization this could regenerate $6{\cdot}3 \times 10^4$ kg inorganic nitrogen each year, enough to meet 26% of macrophyte requirements.

Acknowledgements

We thank Alistar Robertson, Hester McLachlan, Bob Johannes, Graeme Major, Jack Harding, Alan Pearce, Harry Swart, Hugh Kirkman, Judi Hansen, Craig Manning and Patrick Hesp for advice and assistance. Financial support came from the CSIRO, the South African CSIR and the University of Port Elizabeth.

References

Boucher, G. & Chamroux, S. 1976 Bacteria and meiofauna in an experimental and sand ecosystem. I. materials and preliminary results. *Journal of Experimental Marine Biology & Ecolgy*, **24**, 229–237.

Chappell, J., Eliot, I. G., Bradshaw, M. P. & Londsdale, E. 1979 Experimental control of beachface dynamics by water table pumping. *Engineering Geology*, **14**, 29–41.

Crisp, D. J. & Williams, R. 1971 Direct measurement of pore size distribution on artificial and natural deposits and prediction of pore space accessible to interstitial organisms. *Marine Biology, Berlin,* **10,** 214–226.

Dominick, T. F., Wilkins, B. & Roberts, H. 1971 Mathematical model for beach groundwater fluctuations. *Water Resources Research,* **7,** 1626–1635.

Duncan, J. R. 1964 The effects of water table and tidal cycle on swash-backwash sediment distribution and beach profile development. *Marine Geology,* **2,** 186–197.

Emery, K. O. & Foster, J. F. 1948 Water tables in marine beaches. *Journal of Marine Research,* **7,** 644–654.

Ericksen, N. J. 1970 Measurement of tide induced changes to water table profiles in coarse and fine sand beaches along Pegasus Bay, Canterbury. *Earth Science Journal,* **4,** 24–31.

Grant, U.S. 1948 Influence of the water table on beach aggradation and degradation. *Journal of Marine Research,* **7,** 655–660.

Kirkman, H. 1981 *The biology of* Ecklonia radiata *and other macrophytes of the sublittoral of southwestern Western Australia.* Ph.D. Thesis, University of Western Australia. 167 pp.

Lanyon, J. A., Eliot, I. G. & Clarke, D. J. 1982 Groundwater level variation during semidiurnal spring tidal cycles on a sandy beach. *Australian Journal of Marine and Freshwater Research,* **33,** 377–400.

Leyton, L. 1975 *Fluid Behaviour in Biological Systems.* Clarendon Press, Oxford. 235 pp.

McLachlan, A. 1979 Volumes of sea water filtered through eastern Cape sandy beaches. *South African Journal of Science,* **75,** 75–79.

McLachlan, A. 1980 Exposed sandy beaches as semi-closed ecosystems. *Marine Environmental Research,* **4,** 59–63.

McLachlan, A. 1982 A model for the estimation of water filtration and nutrient regeneration by exposed sandy beaches. *Marine Environmental Research,* **6,** 37, 47.

McLachlan, A. & Young, N. 1982 Effects of low temperature on the burrowing rates of four sandy beach molluscs. *Journal of Experimental Marine Biology and Ecology,* **65,** 275–284.

McLachlan, A., Dye, A. & Harty, B. 1981 Simulation of the interstitial system of exposed sandy beaches. *Estuarine, Coastal and Shelf Science,* **12,** 267–278.

Munro, A. L. S., Wells, J. B. J. & McIntyre, A. D. 1978 Energy flow in the flora and meiofauna of sandy beaches. *Proceedings of the Royal Society of Edinburgh,* **76,** 297–315.

Pugh, K. B. 1976 An annual cycle, at constant temperature, in a model sandy beach. I. Nutrient chemistry. *Journal of Experimental Marine Biology & Ecology,* **22,** 179–192.

Riedel, H. P. & Trajer, F. L. 1978 Analysis of five years of wave data, Cockburn Sound. *Proceedings of the Fourth Australian Conference on Coastal Ocean Engineering,* Adelaide. pp. 143–167.

Riedl, R. 1971 How much seawater passes through sandy beaches? *International Revue der gesamten Hydrobiologie,* **56,** 923–946.

Riedl, R. J. & Machan, R. 1972 Hydrodynamic patterns in lotic intertidal sands and their bioclimatological implications. *Marine Biology, Berlin,* **13,** 179–209.

Riedl, R. J., Huang, N. & Machan, R. 1972 The subtidal pump: a mechanism of interstitial water exchange by wave action. *Marine Biology, Berlin,* **13,** 210–221.

Robertson, A. I. & Hansen, J. A. 1982 Decomposing seaweed: a nuisance or a vital link in coastal food chains. *CSIRO Marine Laboratories Research Report 1362,* 75–83.

Silvester, R. A. 1976 Wanneroo coastline. Report for the Shire of Wanneroo, Western Australia. 85 pp.

Steedman, R. K. & Associates. 1977 Mullaloo marina environmental investigations. Part 1. Physical oceanographic studies. *Report to Wanneroo Shire Council,* 210 pp.

Strickland, J. D. H. & Parsons, T. R. 1972 A practical handbook of seawater analysis. 2nd edition. *Fisheries Research Board of Canada, Bulletin,* **167,** 310 pp.

Swart, D. H. & Crowley, J. 1983 Wave-generated water flow through a porous sea bed. In *Sandy Beaches as Ecosystems* (McLachlan, A. & Erasmus, T., eds). Junk, The Hague. pp. 177–189.

Waddell, E. 1973 Dynamics of swash and implications to beach response. *Coastal Studies Institute, Louisiana State University, Technical Report,* **139,** 35 pp.

Wright, L. D., Chappell, J., Thorn, B. G., Bradshaw, M. P. & Cowell, P. 1979 Morphodynamics of reflective and dissipative beach and inshore systems: south-eastern Australia. *Marine Geology,* **32,** 105–140.

Wormald, A. P. & Stirling, H. P. 1979 A preliminary investigation of nutrient enrichment in experimental sand columns and its effect on tropical intertidal bacteria and meiofauna. *Estuarine and Coastal Marine Science,* **8,** 441–453.