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The Interstitial Environment of Sandy Beaches

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With 19 figures and 1 table

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Abstract. The interstitial system of sandy beaches is lacunar and has its dimensions defined by the sand granulometry. It can be described by features such as pore size, porosity, permeability, and water content. The most important process occurring in this system, water filtration, is driven by inputs of freshwater from groundwater discharge, and inputs of seawater by tides, wave run-up, and subtidal wave pumping. Reflective beaches have seawater input effected mainly by waves; they filter large water volumes with short residence times. Dissipative beaches display the opposite patterns, slowly filtering small volumes input by tides. Flow patterns and their effects on interstitial climate are described. The water table of the beach moves in response to groundwater discharge, tides, and waves and influences erosion/accretion processes on the beach face: a high water table promotes erosion. A series of moisture zones can be recognised from the dry surface sand at upper tide levels, to permanently saturated sand below the low tide water table, namely: a stratum of dry sand, a stratum of retention, a stratum of resurgence, and stratum of saturation. Interstitial chemistry is briefly described in terms of salinity changes, organic loads, oxygen content, and nutrient cycling. It is concluded that the interstitial environment of sandy beaches spans a continuum between physically and chemically controlled extremes: the former condition occurs on coarse sand reflective beaches, which experience low organic inputs and high filtration rates of large water volumes — resulting in powerful hydrodynamic forces; the latter occurs on dissipative beaches of fine sand, which are subject to high organic inputs and low filtration volumes — resulting in stagnation and steep vertical chemical gradients. Many intermediate situations occur and these are more favourable to interstitial life than either of the extremes.

Problem

Sandy beaches dominate the open coasts of tropical and temperate regions (DAVIES, 1972), where they play a significant role as 'great digestive and incubating systems' (PEARSE *et al.*, 1942). They process organic materials through their interstices and return the 'purified' water and nutrients to the sea. These important functions are driven by the physical process of water filtration through the porous sand body of the beach and are accomplished by the activities of the interstitial fauna. To properly understand interstitial fauna and its capacity for mineralization in coastal systems, an appreciation of the interstitial environment, its physical and chemical

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climate, and controlling factors is essential. Recent studies on the key process of water circulation through beaches make such a review possible and timely.

Exposed sandy beaches are amongst the simplest, most dynamic, and least hospitable of all marine environments. They require only sand and wave energy for their formation and can be fully defined in terms of particle size characteristics, wave climate, and tide range. A beach ecosystem thus consists of two major components, a sand body stretching from the backshore to beyond the breakers and, overlying it, a moving water envelope driven by waves and tides (McLachlan, 1983). The sand body in turn consists of two components, the sand grains themselves and the porous system between them. It is this lacunar system that is the focus of our review.

Following a brief overview of beach morphodynamics we examine the interstitial systems of intertidal sandy beaches as they occur around the open coasts of the world. We cover their physical dimensions and characteristics, the flows of water through them, the physical gradients created by this water circulation, as well as the chemical cycles and chemical gradients developing in response to these physical processes. Finally, we attempt to synthesise this information into a conceptual model of the physical and chemical driving forces and gradients defining the spectrum of interstitial systems in ocean sandy beaches. Sand flats in waveless environments are not covered.

An overview of sandy beach systems

Ocean beaches can be broadly defined as either reflective, intermediate, or dissipative (Fig. 1) on the basis of interactions between sand particle size and wave height and period (Short & Wright, 1983; Wright & Short, 1984). Reflective

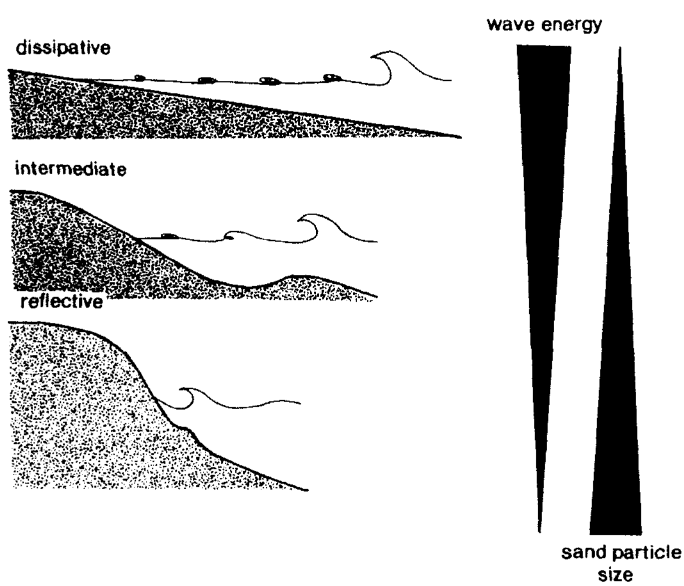

Fig. 1. Beach types. (After Short & Wright, 1983.)

beaches occur in conditions of persistently low wave energy (small, long period waves) and coarse sediments. These beaches are characterised by steep, well-drained intertidal zones with no true surf zone; instead, plunging waves break directly on the beach face. Much of this wave energy is reflected back to sea.

At the other end of the spectrum, conditions of persistenly high wave energy combined with fine-grained sediments result in the formation of dissipative beaches. These beaches are wide, low gradient and are fronted by extensive surf zones where spilling waves dissipate most of their energy before reaching the shoreline.

Although reflective and dissipative beaches exhibit markedly differing morphology and surf zone dynamics, both states are characterised by low mobility. In contrast, the intermediate beach states between these two extremes exhibit much greater variability due to their being associated with intermediate but variable wave energy and medium-grained sediment. A variety of intermediate beaches can be distinguished. Characterised by both reflective and dissipative elements, they have surf zones with bars and rip channels and beach faces of intermediate slope.

Any beach will have a modal state determined by the regional wave climate and local sediment characteristics, but all beaches will change in response to variations in incident wave energy and (less common) long-term changes in sediment characteristics. During calm conditions a beach will shift towards a more reflective state as sand is moved onshore and the beach steepens, whereas during storms or other high wave energy events a beach will become increasingly dissipative as its sand is moved offshore and the gradient flattens. An appreciation of these fundamental differences between beach states is essential to further discussion of their interstitial systems.

Characteristics of the system

The sand body of a beach consists of both sediment grains and the pore spaces between them. Occasionally coastal sediments can be identified as originating from a specific source, but more often sediments are mixtures from several sources, often having been reworked and previously incorporated through geological time in a number of coastal environments. Beach sediments may be divided on the basis of their origin or source: primary sources include wave-eroded cliffs, rock platforms, and biogenic production; secondary sources include sediment delivered to the coast by rivers, glaciers, and aeolian action (CARTER, 1988). Sediment properties and sand grain arrangement control the dimensions of the interstitial spaces. Properties of the sediment and resulting sand bodies important to defining the interstitial environment include: size, sorting, shape, porosity, pore size, permeability, and thixotropy/dilatancy. These are discussed in turn below.

Grain size

Sand grain size is most commonly described by the Wentworth scale (Table 1), in which grain diameter is divided into grades where the base is 1 mm size and other grades follow by dividing or multiplying by two. Grain diameter may be expressed either in millimetres or phi (Φ) units, where

Table 1. The Wentworth scale for classifying sand-sized grains

grade	phi range	mm range	μm range
very coarse sand	−1–0	1–2	1000–2000
coarse sand	0–1	0.5–1	500–1000
medium sand	1–2	0.25–0.5	250–500
fine sand	2–3	0.125–0.25	125–250
very fine sand	3–4	0.0625–0.125	62.5–125

$$\Phi = -\log_2 (\text{diameter (mm)}).$$

This logarithmic phi scale is preferred by sedimentologists and geologists because of the ease with which most common sediment sizes less than 1 mm can be referred to. The linear millimetre scale is more appropriate for engineers and other fields where quantitative physical processes are the focus. Biologists have generally used both scales interchangeably. On most ocean beaches the majority of particles fall in the range 0.125–1 mm, *i.e.*, fine to coarse sand.

Mineralogy

Most sand grains on ocean beaches fall into two categories: quartz along with other particles originating from the weathering of rocks, and calcium carbonate fragments of biogenic origin, the proportion of the latter generally increasing towards the equator. Quartz is common in granites and other igneous rocks and, on weathering, forms grains generally <1 mm in diameter. Calcium carbonate grains tend to be larger and more angular than quartz particles. Most other sedimentary particles are, like quartz, derived from the silica tetrahedron with various additions and modifications, *e.g.*, feldspars, clays (Dyer, 1986). Beach sands are usually mixtures of grains of more than one mineral type.

Sorting

A sandy beach will never be composed of uniform sediment of a single size; thus, a measure of sorting provides insight into the distribution of grain sizes present within a sample. Sediment sorting is defined as the standard deviation of grain sizes about the mean (calculated as the second moment about the mean). Hence, a small value for sorting indicates relative uniformity of sediment, whereas a large value for sorting indicates that a wide range of grain sizes is present. Other statistical measures of sand samples include skewness (the third moment of the size distribution) and kurtosis (the fourth moment); which, respectively, are measures of the asymmetry and abundance of extreme particle sizes within a sediment distribution. Beach sands, because of the strong sorting action of waves, tend to be well sorted with limited skewness or kurtosis.

Grain shape

Sand grains are rarely spherical, due to their origin as fragments of crystals which in turn are chips of amorphous material of geological or biogenic origin. There is at present little agreement as to an appropriate nomenclature to describe the diverse range of grain shapes found on sandy beaches, both sphericity and roundness being useful measures. Sphericity is a measure of how closely the volume of a particle compares to the volume of a circumscribing sphere. Roundness refers to the outline of the grain and compares the average radius of corners to the radius of the maximum inscribed circle. These two measures are often described jointly, since sphericity is unlikely to change greatly by abrasion during transport and is therefore a fairly fundamental property of the grain, whereas roundness can be altered significantly during transport (DYER, 1986). The quantitative analysis of grain shape involves a tedious measurement of individual grain dimensions. As a result, visual comparison to standard charts (*e.g.*, KRUMBEIN & SLOSS, 1963) is often more practical. In general, quartz sands are more spherical and rounded than carbonate sands, and roundness tends to increase landwards across the beach and towards finer grades.

Porosity

An accumulation of sand comprises discontinuous particles — the grains — which may touch at points, and continuous channels and lacunae — the interstitial system — the subject of this review. The ratio of total void volume to the total volume of both grains and voids defines sediment porosity. The porosity of a sediment depends on the arrangement of individual grains, in other words sediment packing. The packing of a sediment in turn is related to both the sorting and shape of sand grains, and also to the manner of sediment deposition. For the simple case of uniform spheres there are basically four ways of packing grains, the densest having a porosity of 26 % and the most loosely packed a porosity of 48 % (GRATON & FRAZER, 1935). Close packing can take the form of 4 or 6 spheres enclosing curvilinear voids which will be tetrahedrons or cubes with radii 0.225 or 0.414 of the radii of the spheres, respectively. For an infinite lattice of spheres there will be twice as many voids as spheres and half will be tetrahedrons and half cubes. If smaller spheres are added they can fill the voids and reduce them or push the spheres further apart, depending on their size and packing. All this applies to the ideal situation of perfect spheres. Natural sands are neither uniform nor are they arranged in this manner.

For natural sands, depending on size, sorting, and packing, porosity may range 20–50 % by volume, with a mean around 37 % for well sorted beach sands (BRUCE, 1928; GAITHER, 1953; WEBB, 1958; CRISP & WILLIAMS, 1971). This porosity can be measured in thin sections (CRISP & WILLIAMS, 1971) or as the amount of water needed to saturate the sand (WEBB, 1958; HULINGS & GRAY, 1971; SAKAMOTO, 1990). The latter in turn can be on a mass or volume basis. When measured on a mass basis, porosity generally falls in the range 15–25 % and must be converted to volume using the densities of water and sand (*e.g.*, quartz = 2.65) at the required temperature. For graded sands, porosity is 16–25% by mass and 30–40% by volume (WEBB, 1958).

Maximum porosity of natural sands is obtained with well rounded grains and very well sorted (nearly uniform) sand. Porosity decreases as grains become more angular and varied in size and lowest porosity occurs where very coarse and fine sand mix, resulting in the most efficient packing when fine particles fill the voids between the large ones. As the size range of particles becomes less extreme and more uniform, porosity increases. Porosity is thus determined by the size and shape of the dominant size fraction and the sizes and proportions of other fractions mixed with it. There also tends to be an increase in porosity with a decrease in the mean grain size of the dominant fraction (WEBB, 1958), since the finer the sand the less the chance of still finer particles filling the voids.

Pore size

The minimum number of pores leading to a dilation or cavity is four for tetrahedral packing, but much higher numbers can be obtained and six may be a good average (CRISP & WILLIAMS, 1971). Pore size is related to particle size for uniform sands (ORR & DALLAVALLE, 1959) as follows:

$$d/D = 2/3 \cdot e/1 - e$$

where e = porosity and d and D are the pore and particle diameters, respectively. Thus for e = 0.375, d/D = 0.4. Measuring this in thin sections, CRISP & WILLIAMS (1971) obtained values of 0.15–0.20 for poorly sorted natural shell gravels and 0.3–0.4 for nearly monometric uniform spheres (Fig. 2). Hence for natural beach sands, mean pore size may be 0.2–0.4 mean particle size. It follows that for fine to medium beach sands most pores will be in the range 10–200 μm.

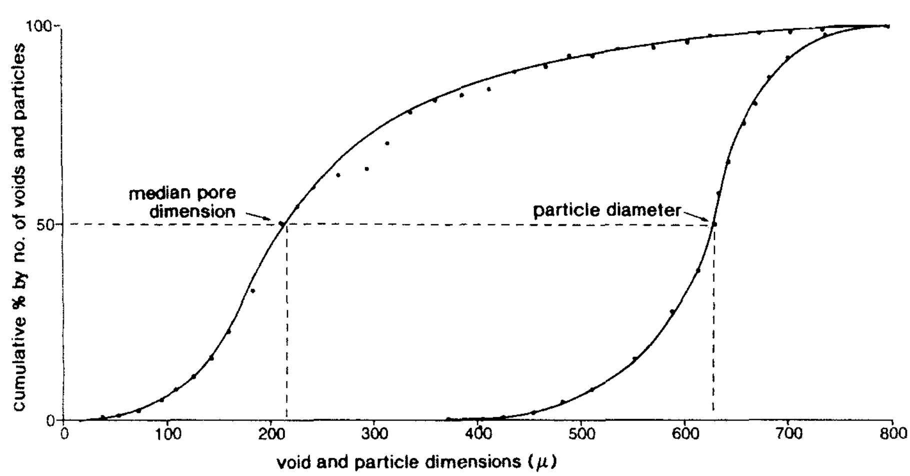

Fig. 2. Frequency histograms of void and particle dimensions for artificial, nearly uniform sands. (After CRISP & WILLIAMS, 1971.)

Permeability (hydraulic conductivity)

Not only the porosity or total void volume, but also the rate at which water can flow through a sandy beach is an important characteristic of the interstitial environment. The discharge rate of a liquid through a body of sand depends on grain and liquid properties as well as on the pressure head producing the flow. The expression (known as DARCY's Law) for the discharge of water (Q) moving a distance (L) through a cross-sectional area (A) in time t due to a hydrostatic head (h) is given by:

$$Q = KAht/L \ (m^3 \cdot s^{-1}) \text{ or}$$
$$K = QL/Aht \ (m \cdot s^{-1})$$

where K is the permeability (or hydraulic conductivity) of the sediment with units of metres per second. It is worth noting that there is often confusion between hydraulic conductivity and specific permeability (k), whose dimensions are length squared and often given in DARCY's (1 Darcy = 0.987 × 10–12 m^2). Specific permeability is a property of porous media only, and related to hydraulic conductivity by:

$$K = kgP/v$$

where v and P are the kinematic viscosity and density of the fluid and g is acceleration due to gravity.

The permeability of sands typically ranges from 10^{-2} to 10^{-6} $m \cdot s^{-1}$. Well sorted coarse sands have the highest permeabilities and poorly sorted fine sands the lowest. Permeability decreases dramatically with the addition of very fine sand, or especially silt, because of its effect in filling and blocking the voids. Permeability also depends on fluid viscosity, which in turn is influenced by temperature. Water, for example, is twice as viscous at 5°C as at 30°C. This can cause large seasonal changes in the permeability of fine sands in temperate climates (WEBB, 1991).

The porous system of the sand includes both capillary space and cavity space, the ratio between the two defining the previously discussed specific permeability. Water flows through pores and is stored in cavities; thus this ratio gives an idea of movement relative to stagnant water in the interstitial system and is particularly relevant to the study of interstitial fauna (WEBB, 1991). This index is specific for a particular lattice, irrespective of the degree of compaction, and is therefore constant for any sand unless the geometry of the lattice is changed by reorientation of the grains.

Moisture content

Pore spaces within a sandy beach may be entirely filled with water, contain a combination of air and water, or moisture may be totally absent. Capillary forces (the mutual attraction of water molecules and the attraction of water molecules to sand grains) can draw water 4–50 cm up a column of sand depending on particle size and sorting, typical values for natural beach sands being 20–30 cm. Capillarity increases with decreasing grain size (Fig. 3). Capillary forces can supersaturate sand, pushing the grains apart and increasing porosity.

When water leaves the sand it is replaced by air. Air bubbles in the cavities can remain behind after the sand is inundated again, thereby reducing the permeability, although not changing capillary lift. Generally on a beach about 85 % of the air in the intertidal sand body may be displaced from the sand when the tide comes in.

In moist sand, surface tension holds grains together with pendular rings of moisture at their points of contact, forming a firm lattice (Harris & Morrow, 1964). This pendular water occupies about 20 % of void space and gives moist sand the cohesion needed for making sand castles!

Capillary rise fills about 95 % of void space just above a water table, but only 25 % of void space where capillary rise stops and there are more air bubbles in the sand (Webb, 1991). In a cross section from the sand surface to the water table, the following can be recognised in terms of moisture: dry sand, moist sand retaining pendular moisture, sand wetted by capillary lift, and finally saturated sand at the water table (Webb, 1991).

A volume of beach sand may thus contain sand particles (about 60–65 % of volume), captured water (*e.g.*, 10–20 %), air bubbles (*e.g.*, 15–20 %) alternately filled with water and air (Sakamoto, 1990). A relation between porosity and mean particle size, obtained for Japanese beaches and showing both captured (capillary and/or pendular) water and 'shift' porosity or space available for new water, is given in Fig. 3.

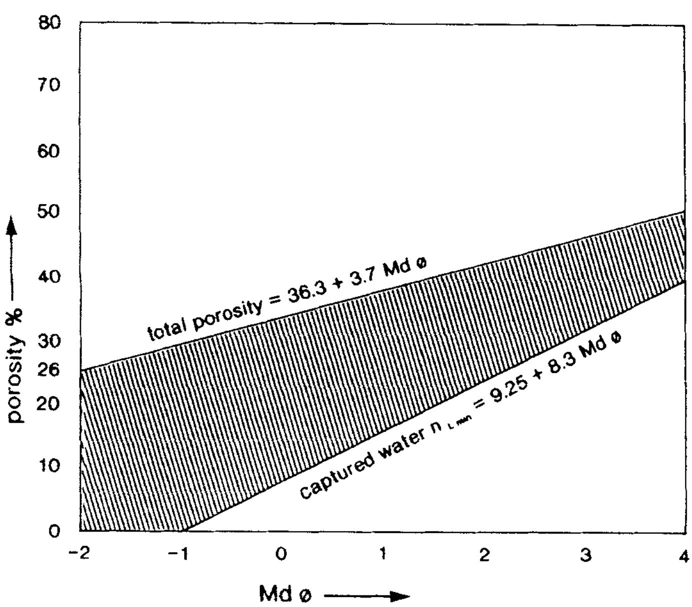

Fig. 3. Porosity and capillarity as a function of sand grain size. Shift porosity (shaded) is the proportion of total porosity that can gain and lose water. (After Sakamoto, 1990.)

Thixotropy and dilatancy

Thixotropy is the term given to the reduction in resistance of a sand with increased rate of shear, as opposed to dilatancy, where increasing shear force causes increased resistance (CHAPMAN, 1949). This is of especial significance for animals which must burrow in sand, since dilatancy makes burrowing impossible. Thixotropy is primarily dependent on the water content of a sand, although the fluidity of the sand is also a function of the viscosity and density of the liquid filling the interstices. Saturated fine sand exhibits maximum thixotropy. In extreme cases this takes the form of a tendency to liquify like quicksand, where the sand is supersaturated due to expansion of the lattice by capillarity, thereby reducing the contact points between grains and increasing the number of floating grains (WEBB, 1958).

Processes of water input

In the preceding section we have seen that the interstices of sandy beaches vary in size and shape due to grain characteristics and the arrangement of the sand matrix and that the moisture content within this environment will range from dry to saturated conditions. The input of water to the system is via a combination of terrestrial, marine, atmospheric, and biological processes. These processes include: precipitation, ground water discharge, tides, wave run-up, sub-tidal wave pumping, and bioturbation.

The activities of animals burrowing in sand can irrigate the sediment. This is important in deep fine sediments where other input mechanisms are absent or in dense beds of thalassinid prawns on sand flats, but relatively insignificant on ocean beaches. Rain also represents a small and sporadic input of freshwater, but this is very limited in comparison to the other inputs. We shall therefore not discuss precipitation or bioturbation further.

Groundwater discharge

Sandy coasts act generally as unconfined aquifers connected hydraulically to the sea through permeable beach sediments. Their hydraulic heads are above the sea and they are thus characterised by groundwater discharge to varying extents (JOHANNES, 1980). The groundwater discharge rate can be described by the GHYBEN–HERZBERG model (RAGHUNATH, 1982) and depends on the hydraulic head (height of the water table or aquifer above sea level) and the permeability (hydraulic conductivity) of the sand.

This water may discharge on the beach or in the subtidal, since it typically flows out between the fresh/seawater interface and the water table outcrop on the beach. At the seaward end the discharge will be brackish because of mixing with salt water in the zone of diffusion. The width of the discharge zone is proportional to the volume of freshwater flow (HUBERT, 1940; GLOVER, 1959; COOPER, 1959). A salt wedge typically underlies the aquifer along the coast, impeding the downward mixing of less dense freshwater and forcing the aquifer to discharge close to shore (Fig. 4).

The discharge zone may be in the intertidal during low tide and inundated during high tide. Rarely, a perched water table can result in the entire beach being the zone of discharge. Whereas water in the main aquifers typically moves seawards at 1–1 000 $m \cdot a^{-1}$, discharge at the beach is faster (typically 0.1–1 $m \cdot h^{-1}$) because it is focussed through a narrow zone (JOHANNES, 1980).

On the global scale, groundwater discharge to the sea is much less important than river discharge but nevertheless significant as a supplier of nutrients to coastal waters (JOHANNES, 1980) and for its role in water filtration, its influence on interstitial salinities, and its enhancement of beach face erosion (DUNCAN, 1964).

Tides

The tidal rise and fall across the intertidal region of a sandy beach produces an alternately landward-directed then seaward-directed hydraulic gradient at the frequency of the local tides. From DARCY's Law this necessitates the flow of water into and out of the beach. Due to the ability of water on the rising tide to infiltrate vertically into a beach much more rapidly than it can drain nearer horizontally on the falling tide (NIELSEN, 1990), there is the tendency for the super-elevation of the beach water table above the mean sea level. Water input therefore only occurs when the elevation of the tide exceeds the elevation of the beach water table, hence input occurs on the rising tide and discharge mainly on the outgoing tide. This can be discerned as a rising and falling water table including a tidal 'wave' which decays back into the beach (EMERY & FOSTER, 1948; McLACHLAN, 1989; SAKAMOTO, 1990). Output may occur all the time, whereas input only occurs when the tide rises above the water table outcrop.

Simple patterns would result from tidal inputs alone: the sand would fill with

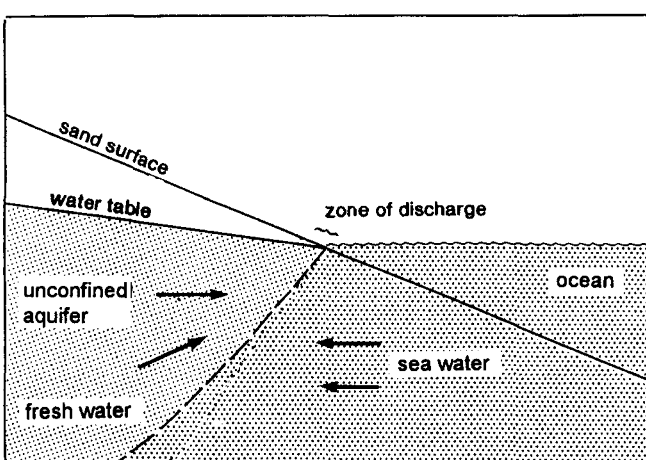

Fig. 4. Diagrammatic representation of an unconfined aquifer discharging through a beach system. (After JOHANNES, 1980.)

water up to the high tide mark on the rising tide, resulting in a water table sloping off landwards, followed by drainage on the falling tide, initially both landwards and seawards and then only seawards (EMERY & FOSTER, 1948; RIEDL, 1971). The rates of these processes would depend on slope, permeability, and tide range.

Beach face wave run-up

Ocean beaches are subject to wave effects in addition to tides; water inputs to the intertidal occur when swashes run-up the beach face, cross the water table outcrop, and infiltrate water into unsaturated sand. Wave run-up on the beach face induces a setup of the local mean water level, which in itself produces a hydraulic gradient that drives both flow into the beach and an offshore bottom current (undertow) in the surfzone (LONGUET-HIGGINS, 1983).

Since the frequency of waves and swashes on ocean beaches is nearly 10^3 times that of the tides, they represent a considerable amount of hydrodynamic energy and can be more important than the tides as an input mechanism, especially on coarse sand beaches that drain rapidly. RIEDL (1971) was the first to quantify swash infiltration, and it has subsequently been examined in several regions (RIEDL & MACHAN, 1972; MCLACHLAN, 1979, 1982, 1989; MCLACHLAN *et al.*, 1985).

RIEDL (1971) described the mechanism of seawater input by swash action in terms of filling wedges (Fig. 5). The beach surface below the drift line shows two boundaries, (1) the water table outcrop, below which the surface sand is saturated

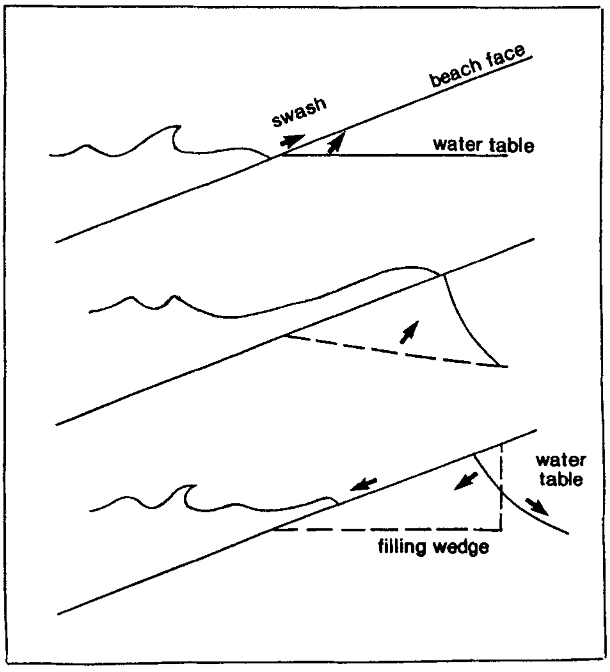

Fig. 5. Representation of a filling wedge. Arrows indicate direction of water table movement. (After RIEDL, 1971 and MCLACHLAN, 1979.)

and glassy in appearance, and (2) the waters' edge, or swash line, which pulses up and down the beach as swash and backwash. Above the water table outcrop the water table slopes into the sand landwards, drawing air into the capillary network. Thus, a slice cut through the beach perpendicular to the shoreline will show a wedge-shaped body of unsaturated sand between the water table and the surface above the outcrop. Close to the water table in the area of capillary rise, the air space in the sand will be small (or negligible, TURNER, 1993a), but above this there will be appreciable air space. The sharp or seaward edge of this wedge will migrate seawards as water seeps out of the beach, surface drainage reducing pore pressure and causing a loss of the glassy appearance, even though sand just above the water table may remain saturated. Whenever a swash overruns the water table outcrop and the top of the saturated capillary fringe (generally 5–20 cm above the outcrop depending on particle size), it will fill this wedge as far up as it reaches, this input water displacing a corresponding volume of air. As soon as the backwash retreats, the outcrop will again migrate seawards as water drains out of the sand. This cycle will be repeated for every wedge-filling swash.

The extent of a filling wedge will depend on the slope of the beach and depth of the water table, the length of the swash above the outcrop, and the amount of air space in the sand (the saturation gap). Because of capillary forces, saturation gaps will generally be zero just above the water table, but increase to as much as 30 % 20–30 cm above the water table (Fig. 6). (Recently, however, using neutron probe techniques, TURNER (1993a) has indicated that saturation gaps may be lower than estimated by other techniques and that the saturated zone may extend 10's of cm above the water table.) The wedge is filled not only from the surface, but also by capillary rise and lateral seepage. This especially occurs when the beach is flat and the water table rises ahead of the advancing swash. Conversely, on steep, coarser-grained beaches the water table may be left behind and air may be trapped between water infiltration from above and the water table rising from below. The wedge in fact is not flat; its bottom is sine-shaped and not sharply defined (RIEDL, 1971).

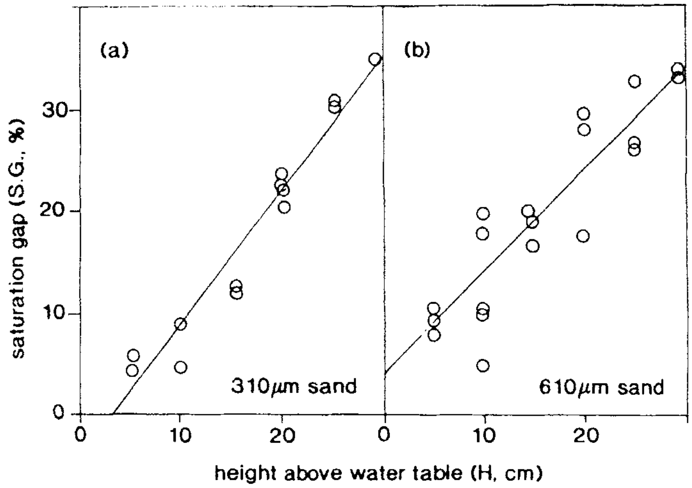

Fig. 6. Saturation gaps for different sands. (After McLACHLAN *et al.*, 1985).

The slope of the filling wedge (h/l) can range from 1/10 to 1/80, being steepest towards high tide.

Subtidal wave pumping

Water input through the bed in the subtidal occurs as a result of wave pumping, *i.e.*, it is driven by the pressure differences between wave crests and troughs passing overhead. This inflow and outflow can operate over much of the beach during high tide and in the subtidal at all states of the tide. In the intertidal, wave pumping will often be working against water draining out of the sand due to the water table head. However, pumping currents may have twice the amplitude of the gravity drainage currents (Riedl & Machan, 1972).

The fluid dynamic effects of waves passing over a porous bed have been examined by a number of researchers including Putnam (1949), Reid & Kajiura (1957), Hunt (1959), Murray (1965), Webb & Theodor (1968), Steele *et al.* (1972), Madsen (1978), and Swart & Crowley (1983). Percolation into and out of the bed results in wave energy attenuating as waves propagate in towards the shore (Sleath, 1970). Unlike the intertidal swash filtration process, this is essentially oscillatory flow, with input and output approximately balanced.

Water filtration through beach systems

As outlined above, the driving forces for water filtration through beach sands are hydraulic gradients resulting from tides, waves, and aquifer recharge. We have also demonstrated that the moisture content of beaches varies both spatially within a beach and temporally through the tidal cycle. Having introduced the mechanisms responsible for water input to the interstitial system of sandy beaches and the distribution of this water within the beach sand matrix, we now examine the filtration process and quantities of water filtered.

Volumes and residence times of tide and wave-driven inputs

The inputs of seawater through intertidal sandy beaches were first estimated by Riedl (1971), who measured the dimensions of filling wedges, and later by Riedl & Machan (1972) using hot thermistor probes to monitor interstitial flows. Subsequently, using the former technique, McLachlan (1979, 1982, 1989) and McLachlan *et al.* (1983) measured filtered volumes on a variety of beaches in different regions. Sakamoto (1990) estimated tidal input through a Japanese beach in a similar fashion.

On an intermediate beach in North Carolina (mean wave height of 1 m and tide range of just over 1 m, slopes 1/15–1/25, and mean grain size 250 μm), Riedl (1971) estimated an average filtered volume of 20 $m^3 \cdot m^{-1} \cdot d^{-1}$, which he later modified to 6 $m^3 \cdot m^{-1} \cdot d^{-1}$ (Riedl & Machan, 1972). The latter ranged from 0.09 to 0.7 $m^3 \cdot m^{-1} \cdot h^{-1}$ over the tidal cycle, lowest values being just after low tide. Riedl (1971) indicated that tides alone could account for about 25% of the filtered volumes. Riedl & Machan (1972) estimated mean percolation paths at 24 m or 35% of the intertidal and mean percolation time at 22.2 h. They expected flatter beaches with larger tide ranges to filter greater volumes.

McLachlan (1979) subsequently examined this process on three South African beaches over spring and neap tides using Riedl's (1971) filling wedge technique. These were high energy intermediate beaches with a maximum tide range of 2 m and sands of 200–300 μm mean particle diameter. Filtered volumes ranged from 4 to 15 $m^3 \cdot m^{-1} \cdot d^{-1}$ for two semidiurnal tides. McLachlan (1979) suggested that maximum inputs would occur with steepest beach face slopes, large tides, high waves of short period, and coarse sands (to increase saturation gaps and hasten drainage). He later (1982) expanded on this in the same area, measuring filtered volumes on an exposed intermediate to dissipative beach over 14 tidal cycles and modelling responses. Filtered volumes ranged from 1 to 12 $m^3 \cdot m^{-1} \cdot d^{-1}$, being highest towards steepest slopes and small to moderate tides. There was a clear cycle with greatest inputs on the late incoming tide (Fig. 7).

The prediction (McLachlan, 1982) of greatest filtered volumes on steep, coarse-grained beaches with small tides was tested on microtidal reflective beaches near Perth, Australia (McLachlan *et al.*, 1985). Three beaches in this area had medium to coarse sand, modal wave heights of 0.4 m, and a maximum tide range of 0.9 m for mixed, predominantly diurnal tides. Filtered volumes ranged from 19–92 $m^3 \cdot m^{-1} \cdot d^{-1}$ on two wave-exposed beaches, confirming the prediction of high input volumes on beaches with steep slopes, coarse sand, and small tides. A third beach, covered in algal wrack which filtered out swash effects, received <1 $m^3 \cdot m^{-1} \cdot d^{-1}$. Residence times for this water in the beaches were estimated at 1–7 h and >90 h on the wrack-covered beach. These are matched by mean percolation

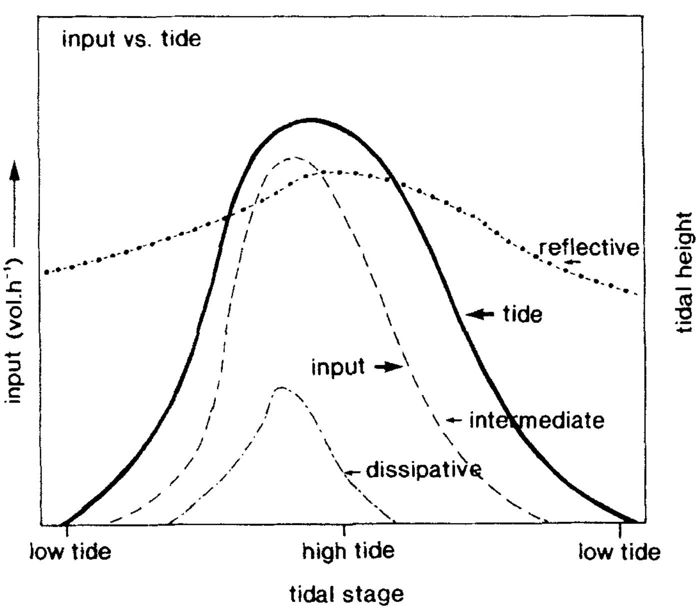

Fig. 7. Relative change in water input to reflective intermediate and dissipative beaches (by swash and tide action over a tidal cycle). (After McLachlan, 1982.)

paths of 2–5 m. These beaches clearly have water input driven mainly by waves (>90 %), with tides playing a small role.

More recently, McLachlan (1989) tested the prediction of low inputs on flat beaches by examining two dissipative meso/macrotidal beaches in Oregon, USA. These beaches had fine to medium sands, flat slopes, mixed tides up to 3.6 m, and were subject to large waves, the modal breaker height being 1–2 m in summer and 3–4 in winter. Filtered volumes were low, 0.1 to 7 $m^3 \cdot m^{-1} \cdot d^{-1}$, and residence times long, 15 to 400 d. During a major storm with 7 m waves, one beach filtered 31 $m^3 \cdot m^{-1} \cdot d^{-1}$. These inputs were calculated to be almost entirely accounted for by tidal effects, most wave energy being filtered out by the dissipative surf zones, except during storms. However, because of the extensive saturated sand body typically associated with dissipative beaches, they would be expected to filter significant volumes by wave pumping during the high tide. Sakamoto (1990) estimated water input to a Japanese beach by tides alone at 6 $m^3 \cdot m^{-1} \cdot d^{-1}$ during a 1.95 m spring tide and 0.7 $m^3 \cdot m^{-1} \cdot d^{-1}$ during a neap tide with a range of 0.31 m.

A plot of filtered volume, residence time, and relative importance of waves vs. tides is shown in Fig. 8. In reflective beaches large volumes of water are filtered rapidly and input is driven mainly by waves. On dissipative beaches smaller volumes are filtered slowly and input is driven primarily by tides. Intermediate beaches are intermediate in all these parameters, and both waves and tides play a role. It is

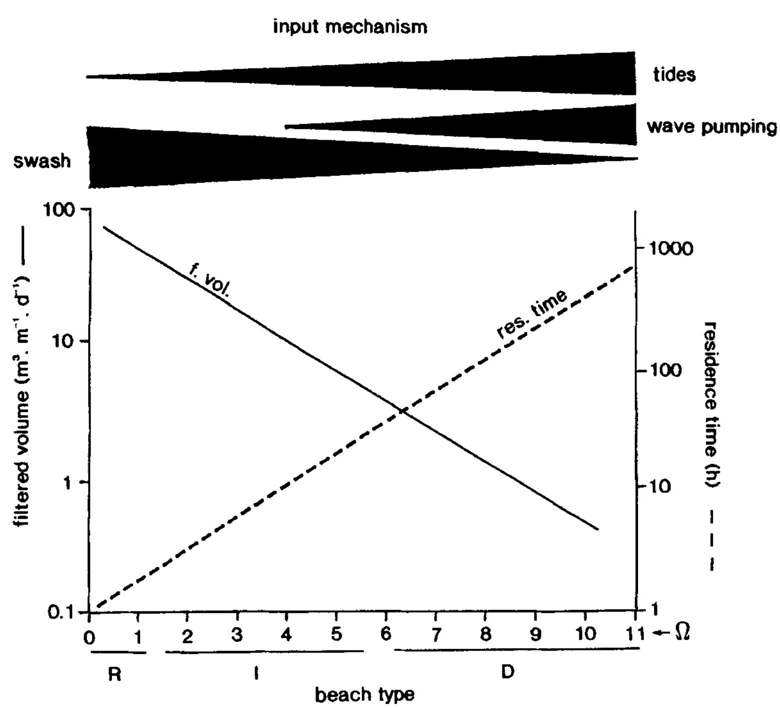

Fig. 8. Graphic model of the volume of water filtered and its mean residence time as a function of beach type. The relative importance of tides vs. waves (including wave pumping over saturated sand) in driving input is indicated.

thus clear that, where they have direct access to the beach face and are not too dissipated in wide surf zones, waves, via swash action on the beach face, greatly increase input volume above that accounted for by tides alone. It should be noted that recent work by TURNER (1993a) suggests that saturation gaps might be overestimated (*i.e.*, by the presence of the saturated capillary fringe) by the methods employed and consequently that filtered volumes may be more conservative than indicated in Fig. 8.

Flow patterns and interstitial climate

Seawater infiltration into and through sandy beaches is concentrated towards the late incoming tide (Fig. 7) when the swash zone is over the upper shore and the water table is rising rapidly. It is a complex process driven by tidal and swash effects, neglecting for the moment wave pumping below the swash zone. This input by filling wedges consists of two types of flow: 1) slow, smooth gravity flows, which may drain landwards at and above the input zone on the incoming tide, and seawards below this and throughout the beach on the outgoing tide; 2) more complex pulsing flows resulting directly from the swash inputs (RIEDL & MACHAN, 1972). The frequency of the latter is 2–4 orders of magnitude higher than that of the gravity flows, which are primarily tidal. Tidally-driven gravity flows, which obey the previously defined DARCY'S Law, occur throughout the sand body, whereas swash-driven pulsing flows only occur near the surf and swash, *i.e.*, the input zone.

In the absence of waves, only gravity flows will occur. Seaward gravity flows dominate at all times except on the mid to late incoming tides, when landward flows are important, especially at and above the input zone. A point on the midshore will thus experience a sequence of gravity currents over a tidal cycle as illustrated in Fig. 9.

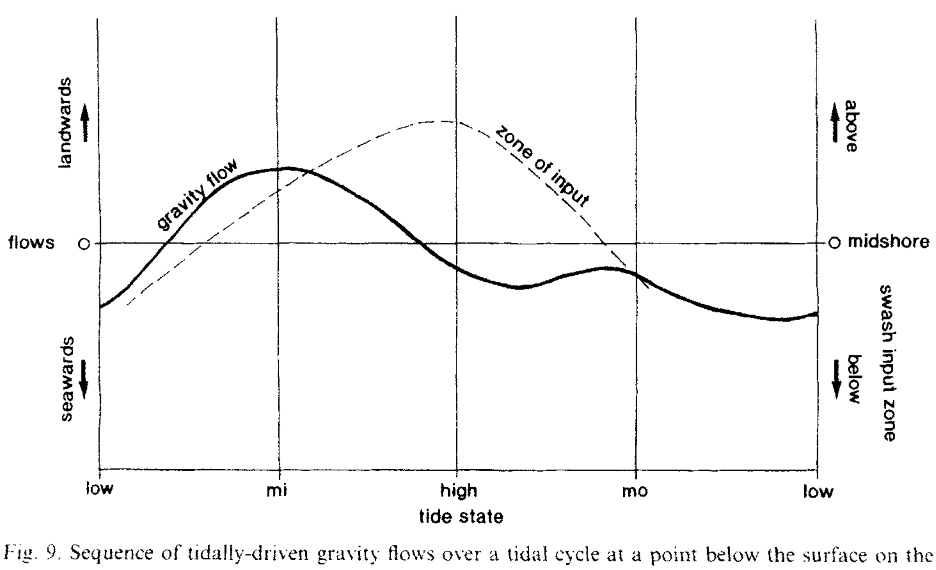

Fig. 9. Sequence of tidally-driven gravity flows over a tidal cycle at a point below the surface on the midshore. (Based on information in RIEDL & MACHAN, 1972.)

Swash pulsing is caused by swashes filling wedges above the water table outcrop, this input extending downwards and sideways from the wedge and spreading predominantly in the cross-shore direction. Because swash pulsing is superimposed on the more constant gravity flows, the pulsing flows will be retarded on one side of the swash zone (*e.g.*, landwards if water is flowing seawards) and boosted on the other (*e.g.*, seawards), where they run against and with the gravity currents, respectively. Current speeds in the interstices can be up to 370 $\mu m \cdot s^{-1}$ and can even reach 2 $mm \cdot s^{-1}$ in the filling wedge—high speeds for interstitial animals.

Rhythmic discharge of the head of water in the wedges influences flow in a bag-shaped region extending far down into the interstices. Riedl & Machan (1972) called this the filling bag and defined it as the area where pulsing currents exceed 10 $\mu m \cdot s^{-1}$ (Fig. 10). Greatest velocities and velocity changes are encountered at the wedge/bag boundary and these drop off deeper into the bag, as much as 1 m into the sediment. Input thus goes from the filling wedge to the bag and then drains into the rest of the porous system. This input zone migrates over the shore with the tides, whereas the output area, extending seawards from the bag, expands when the tide rises and shrinks as the tide falls. From this, Riedl & Machan (1972) estimated the mean length of the percolation pathway at about 35 % of the intertidal width: paths would be shorter in reflective beaches and longer in dissipative beaches.

Surf pulsing occurs in the sand below waves and is caused by pressure and motion fields generated by the waves penetrating into the sediment. It is thus strong in the submerged part of the intertidal (Riedl & Machan, 1972). On the beach this is superimposed on a seaward gravity current whose speed is just more than half the amplitude of the surf pulsing current; thus the gravity current is continuous, but varies with the amplitude of the surf pulsing current.

The above flows occur in various combinations and will vary in proportions and timing between beach types. Movement of the velocity field for interstitial currents

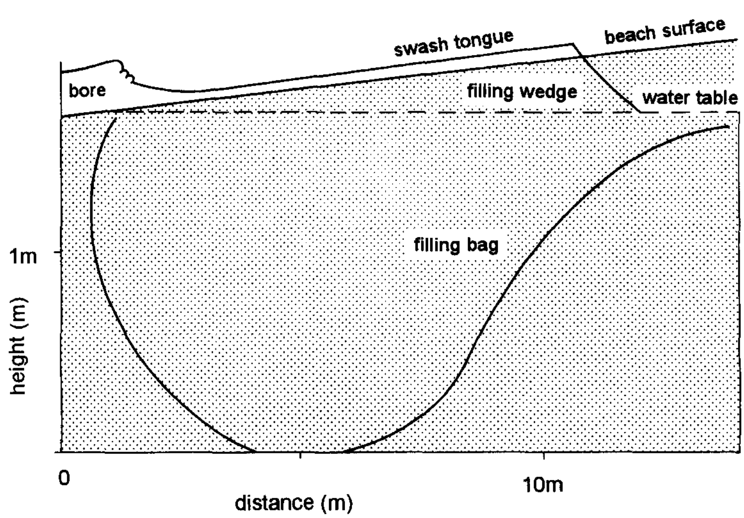

Fig. 10. Diagrammatic representation of the filling bag below the filling wedge input area on an incoming tide. (After Riedl & Machan, 1972.)

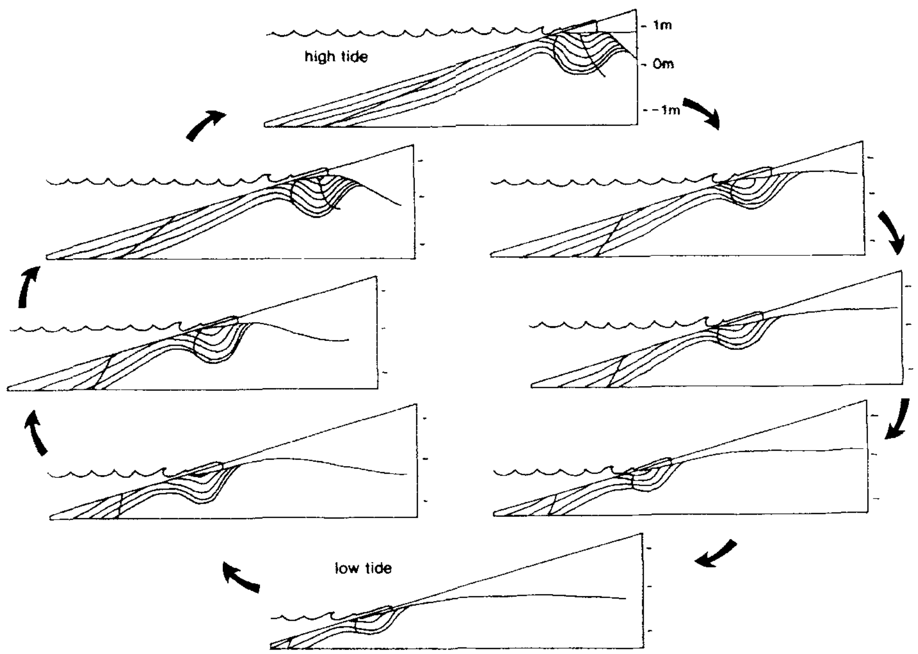

Fig. 11. Velocity field of pulsing (swash) flows over a tidal cycle. Contours represent flows of 10–1000 $m \cdot s^{-1}$. (After RIEDL & MACHAN, 1972.)

driven by swash and surf pulsing is shown for a tidal cycle in Fig. 11 and that for gravity flows in Fig. 12.

Interstitial climatic parameters were reconstructed by RIEDL & MACHAN (1972) from a synthesis of the above processes and currents (Fig. 13). These show for a typical beach that vigorous input occurs on the upper shore where aeration and infiltration are strong to some depth in the sand. Just below this and extending downshore is a stratum characterised by substantial water input and circulation but low pulsing disturbance. The area of maximum percolation but minimum disturbance occurs below the surface on the lower shore, whereas maximum input, aeration, and disturbance occur near the surface at mid to upper tide levels. Thus, for interstitial fauna requiring inputs of water, oxygen, and food materials, optimum conditions may occur in a layer extending from just below the surface near MTL to well below the surface towards HTL. Above this, disturbance and aeration may become extreme and below this conditions will tend towards stagnation because of restricted flow and net output.

Subtidal wave pumping: input volumes and flow patterns

Although confined mainly to the subtidal, wave pumping will occur during the high tide over much of the intertidal, especially on dissipative beaches. Currents in this situation have two components (RIEDL *et al.*, 1972): gravity currents draining water from the intertidal seawards and, superimposed on these currents, regular variation at wave frequency and amplitude dependent on wave energy. Flow

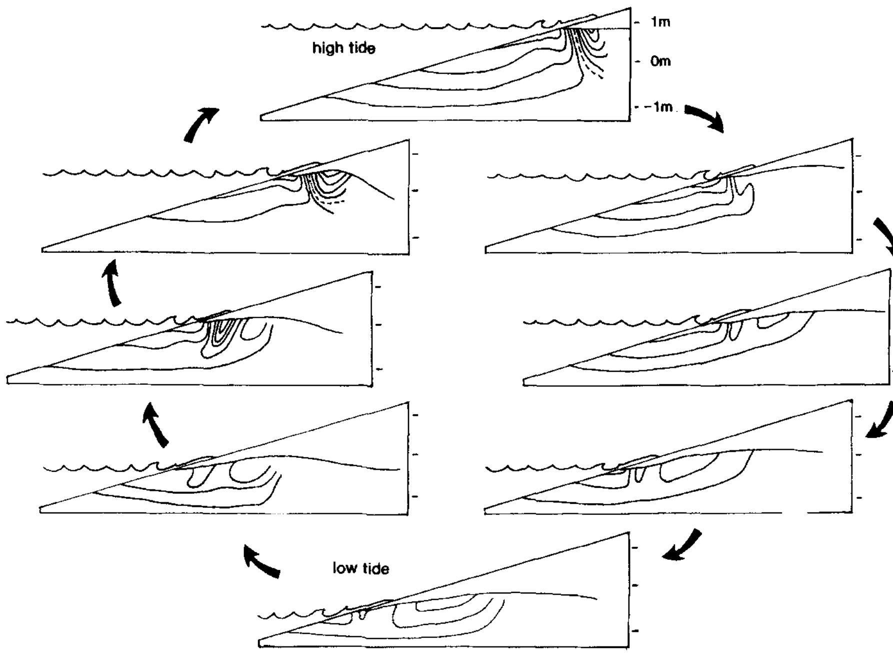

Fig. 12. Velocity field of tidally-driven gravity flows over a tidal cycle. Contours represent flows of 10–500 $\mu m \cdot s^{-1}$. (After RIEDL & MACHAN, 1972.)

speeds measured through the interstices by RIEDL *et al.* (1972) were typically 0–200 $\mu m \cdot s^{-1}$. The more efficient this pump, the greater will be the irrigation and oxygenation of submerged sands and the deeper the reduced layers will be pushed. In the shallow subtidal of exposed beaches this process may account for filtered volumes of 0.01–1.0 $m^3 \cdot m^{-2} \cdot d^{-1}$ (RIEDL *et al.*, 1972; SWART & CROWLEY, 1983; MCLACHLAN *et al.*, 1985).

Water table fluctuations

The dynamics of water tables within sandy beaches warrant particular discussion since they are critical in distinguishing zones of contrasting interstitial moisture content, potential regions of inflow and outflow of water to the interstitial environment, and hence flow patterns of water through the beach. Beach water tables are far from static and respond to, and modify, wave and tide action. But first, to avoid ambiguities that have found their way into the coastal literature, it is useful to provide a physical definition of beach water tables.

Definition

The water table defines the upper boundary of the groundwater zone. More precisely, the water table is the surface where pore water pressure equals atmospheric pressure. Below the water table, pore pressure is greater than atmospheric

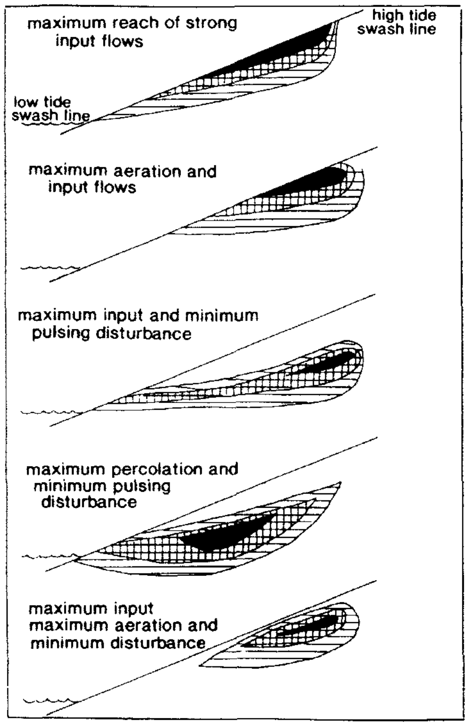

Fig. 13. Diagrammatic representation of some interstitial climatic parameters on an intermediate beach. (From McLACHLAN, 1983, after RIEDL & MACHAN, 1972.)

pressure, and above the water table, pore water pressure is less than atmospheric (TURNER, 1989, 1993a). This definition based on pore water pressure is important as it allows the clear distinction of the water table from the capillary fringe, that region above the water table that is also saturated due to capillary rise. The only distinction between these two zones is indeed pore pressure.

This is particularly significant when the capillary fringe extends to the beach face. With the water table tens of centimetres below the sand surface, the addition of a thin film of water (of the order of one grain diameter) can result in a rapid rise of the water table tens of centimetres through the capillary fringe to the sand surface (Fig. 14). This process of rapid rise, termed the reverse Wieringermeer effect, was demonstrated by GILLHAM (1984), and the contrasting process of a rapid fall of the water table was demonstrated in the laboratory by NIELSEN *et al.* (1988). This phenomenon is important to remember since significant and rapid fluctuations of the water table in the vicinity of the sand surface do not necessarily always result from significant inflow or outflow to and from the beach.

Tidal effects

It has long been known that water tables in marine sandy beaches fluctuate in response to the tides. EMERY & FOSTER (1948) first monitored the movement of a

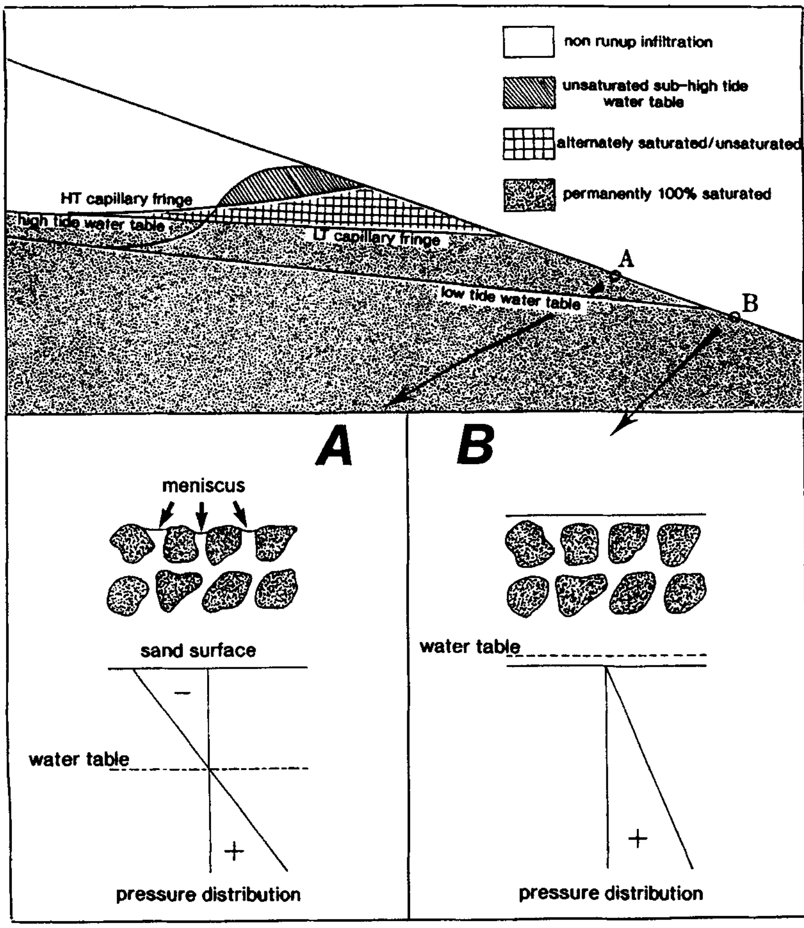

Fig. 14. The relation between pore pressure and saturation zones in a sandy beach, including the Wieringermeer Effect. (After TURNER, 1993a.)

water table in an intermediate beach and showed it to respond to the tide with a landward–moving pulse which decayed back into the beach with a lag of 1–3 h over a distance of 13 m landwards of the water line (Fig. 15). During the flooding tide the water table was landward sloping, in contrast to a seaward slope on the ebbing tide. This resulted in water exchange between the sea and the interstitial system. They recorded significant capillary rise and salt formation in the upper sand due to evaporation and elutriation of silt from the beach by discharging water during low tide. A number of researchers have substantiated and extended these observations (ERICKSEN, 1970; POLLOCK & HUMMON, 1971; LANYON *et al.*, 1982).

Other workers have mathematically modelled the propagation of the tidal wave as it passes into sandy beaches. DOMINICK & WILKINS (1971) modelled tidal fluctuations in the water table in a tropical carbonate beach and used it to predict inflow and outflow through the beach interface. A similar analysis using the finite element method was carried out by HARRISON *et al.* (1971) based on 31 days of observations of water table fluctuations in response to tides in Virginia. The

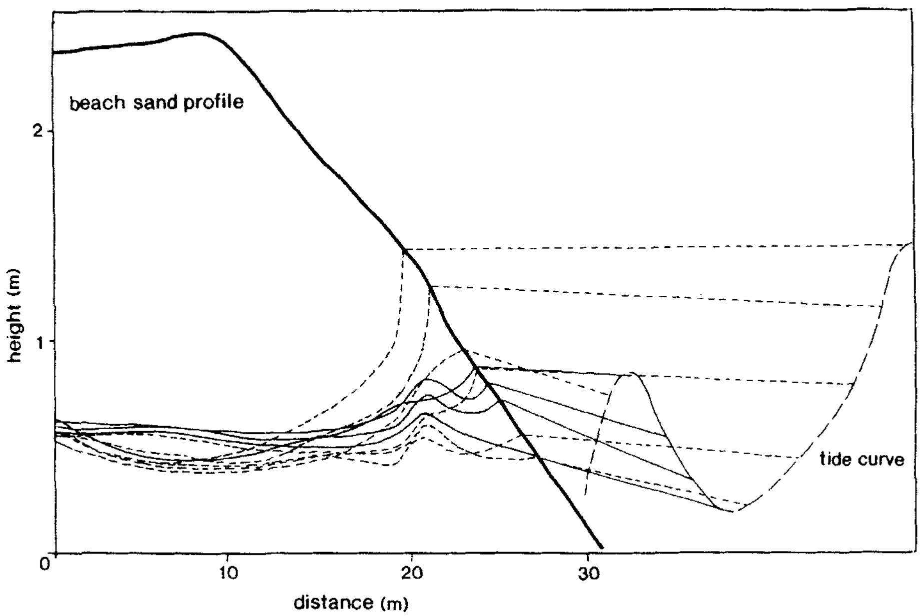

Fig. 15. Fluctuations of the water table in a sandy beach over a tidal cycle. (After Emery & Foster, 1948.)

influence of the tides on such fluctuations has also been modelled by Fang *et al.* (1972), Philip (1973), Knight (1981), and Nielsen (1990).

In summary, the beach acts as a highly non-linear tidal filter, with water table fluctuations both diminishing and changing phase in the landward direction. The water table slopes landwards during the rising tide and seawards on the falling tide. Lag time increases towards the backshore, with fluctuations at any point being far from sinusoidal. Lag times are greatest on the falling tide due to drainage rates significantly slower than rates of rising tide infiltration. Because of this asymmetry the mean water table surface within a beach (averaged over an entire tidal cycle) will stand above the mean ocean level.

Groundwater effects

There have been several reports of fresh groundwater discharge through sandy beaches and its effects on water tables (Glover, 1959; McLachlan *et al.*, 1992). Lanyon *et al.* (1982) showed that tidally induced fluctuations in the beach water table were superimposed on a three-dimensional water table affected by both beach morphology and groundwater recharge from the backshore.

Wave/swash effects and the capillary fringe

Studies of the response of beach water tables to swash motion are limited. High frequency water table oscillations have been measured by Bradshaw (1974), WADDELL (1976), and HEGGE & MASSELINK (1991). Of these authors, only HEGGE & MASSELINK (1991) recognised the importance of pore pressure distribution in the capillary fringe in promoting the rapid water table fluctuations (Fig. 14), in contrast to previous hypotheses of significant mass flux through the beach with each wave. Common to all these studies is the observation that the water table near the swash zone responds to individual waves. However, the beach face and sediment matrix effectively act as a filter to these higher frequency fluctuations.

Influence on beach face erosion/accretion

The elevation of the beach water table is critical in influencing the onshore/offshore movement of sand on the beach face. GRANT (1948) first studied this influence and suggested that a dry beach facilitates accretion by run-up infiltration and hence a reduction in backwash, whereas, on a saturated beach, outflow supplements backwash, dilates the sand, and encourages erosion.

DUNCAN (1964) applied GRANT's (1948) concept to elucidate beach face erosion and accretion through a tidal cycle. On the rising tide, run-up advances above the water table and onshore transport is promoted due to reduced backwash. In contrast, during the falling tide the water table lags behind the tide and hence backwash is enhanced by water table outflow, resulting in offshore transport (Fig. 16).

The importance of water table elevation in promoting beach erosion and/or accretion has been substantiated by a number of studies including MACHEMEHL *et al.* (1975), CHAPPELL *et al.* (1979), and ELIOT & CLARKE (1986, 1988). It is noteworthy that the artificial lowering of beach water tables by pumping is currently being commercially exploited as a means of beach stabilisation (TERCHUNIAN, 1990).

On beaches exposed to large tide ranges the significance of this process may become accentuated since the intertidal outcrop of the water table around low tide distinguishes an upper region of the beach that is unsaturated during the rising tide (and hence promotes onshore sand transport and profile steepening), from a lower region that is permanently in a saturated state (enhancing offshore transport and profile lowering). Both DYER (1986) and TURNER (1993b) suggest that the distinct intertidal break in slope often observed on macro-tidal beaches marks the time-averaged position of this point of divergent sediment transport.

Zones of interstitial moisture

WEBB (1991) described the moisture zones from the surface downwards as: dry sand, moist sand retaining pendular moisture, sand near the water table wetted by capillary rise, and saturated sand at and below the water table. Much earlier, however, SALVAT (1964) had recognised similar zones and used them to describe animal zonation (SALVAT, 1966). His scheme was expanded and verified by POLLOCK & HUMMON (1971) and MCLACHLAN (1980). It was initially defined for the surface of sandy beaches but has been expanded to describe strata encompassing the sand body.

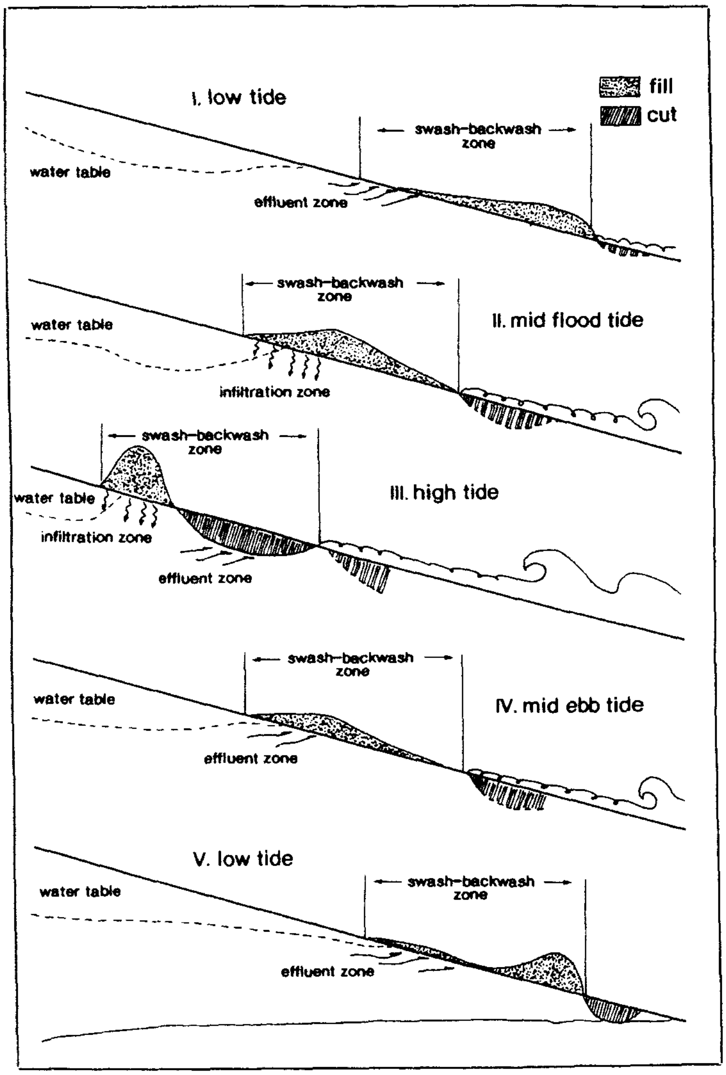

Fig. 16. Sediment distribution and swash-backwash cut and fill on the beach face over a tidal cycle. (After DUNCAN, 1964.)

Combining the schemes of SALVAT (1964), POLLOCK & HUMMON (1971), McLACHLAN (1980) and the information in the foregoing sections, the following zones or strata in terms of water content can be described from the top of the shore downwards (Fig. 17): — a stratum of dry sand above neap high tides which loses capillary and pendular moisture during the low tide and at neap tides. It undergoes strong thermal fluctuations and is immersed irregularly. It supports a sparse interstitial meiofauna, typically small nematodes, but dependent on granulometry; — a stratum of retention underlying the former zone, where the sand remains moist during low tide. It is wetted by all tides, but loses capillary water and retains only pendular moisture during low tide. Loose packing and high

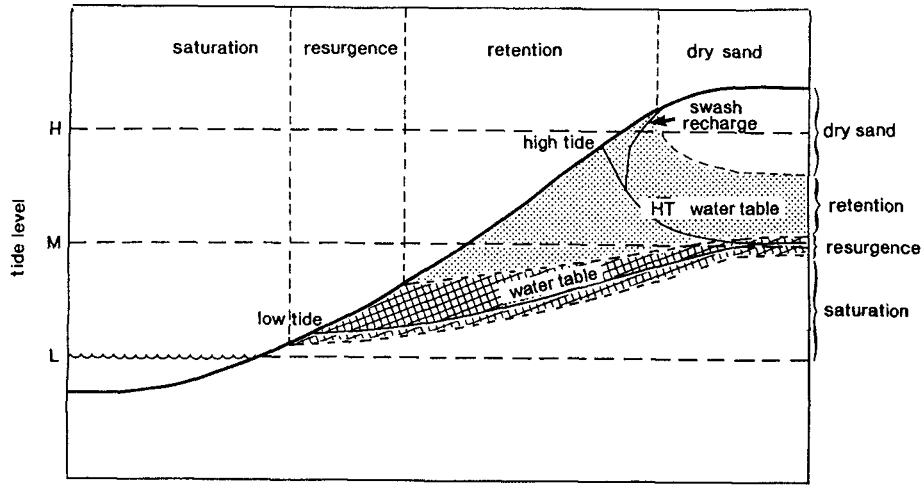

Fig. 17. Interstitial moisture strata on an intermediate sandy beach. Derived from models in SALVAT (1964), POLLOCK & HUMMON (1971), and MCLACHLAN (1980). (Note: this is expanded to include reflective and dissipative types in Fig. 19.)

porosity and permeability allow extensive percolation and circulation of interstitial water. On the surface, most water input here occurs on the mid and later part of the incoming tide (Fig. 7). Since it does not retain capillary moisture, its lower limit is defined by the upper limit of capillary rise above the water table during low tide, *i.e.*, 20–30 cm above the low tide water table. It is often the most extensive zone, especially on well drained beaches. This zone supports the richest interstitial fauna, with harpacticoids and nematodes usually the dominant groups, dependent on granulometry. Temperature variations may be moderate in the upper layers; — a stratum of resurgence consists of wet sand including capillary moisture and marked by intense circulation of interstitial water. Much gravitational water drains out through this zone on the ebb tide, this resurgence continuing through till the low tide. This discharge consists of water that was input to the retention zone and has circulated through it: oxygen tensions here are thus slightly lower than in the above zone. The sand is more compact in this zone, which is underlain by the water table. In steep reflective beaches it will be narrow, but will widen considerably in flat dissipative beaches. On steep, coarse-grained, reflective beaches it may tend to extend seawards over the next zone as a thin veneer reaching to the low water mark. It supports a moderate interstitial fauna of nematodes, harpacticoid copepods, and other groups, depending on granulometry. Temperature variations are small; — a stratum of saturation at and below the permanent water table, where percolation is slow and marked by groundwater discharge. The sand is generally compact and circulation slow.

POLLOCK & HUMMON (1971) and MCLACHLAN (1980) described this as being overlain by the resurgence stratum even on the lower shore, whereas SALVAT (1964) envisaged it as reaching the surface on the lower shore. On fine sand beaches it will be a surface zone, but on very coarse-grained beaches it may not surface in the intertidal. Where this stratum extends out seawards beyond the resurgence zone its surface is subject to wave pumping described earlier, and may thus be well oxygenated. Other than this, however, there may be a tendency for stagnation with low interstitial oxygen tensions since water circulating through this zone generally comes via the retention and resurgence strata, where interstitial fauna utilise much of the oxygen and organic materials. The interstitial fauna in this stratum is poor to moderate and nematodes are generally dominant, depending on granulometry. Temperature variations are minimal.

These strata appear as surface zones during low tide, and all except the dry sand stratum become saturated by tides. Although POLLOCK & HUMMON (1971) subdivided the top zone of drying, this suggestion has not been adopted by other workers. In terms of water filtration, the retention stratum is the main receiver of wave- and tide-driven inputs, and the resurgence and saturation zones are the main discharge sites. The dry sand stratum only receives water inputs on spring high tides. Coupled to changes in water flow through these strata are variations in oxygen tensions, interstitial chemistry, and interstitial fauna. If these strata are defined by oxygen and water circulation alone, the resurgence stratum would always overlie the saturation stratum, but if defined by moisture, as above, the saturation stratum will emerge on the lower shore in most cases. The subsurface parts of the retention stratum correspond to the area with optimal conditions for interstitial life according to RIEDL & MACHAN's (1972) description of interstitial climate (Fig. 12).

Temperature and interstitial chemistry

Temperature

Temperature variations in intertidal sandy beaches have been recorded in several cases (SALVAT 1964; JANSSON, 1967b; POLLOCK & HUMMON, 1971; McLACHLAN, 1977). Maximum variation occurs on the surface at upper tide levels and temperatures become more stable towards the sea and into the sediment. Extreme temperatures are generally only encountered in the upper few cm at mid to high tide levels during the low tide. Otherwise, most of the interstitial system takes on temperatures close to those of the adjacent sea. Temperature changes will affect the viscosity of pore water and thus flow rates and capillary forces.

Groundwater inputs

Fresh groundwater discharging from land carries elevated levels of inorganic nutrients, especially nitrate (JOHANNES, 1980). This results both in inputs to the adjacent sea and elevated nutrient levels in the interstitial system (McLACHLAN & ILLENBERGER, 1986; MAIER & PREGNALL, 1990). Groundwater discharge can also influence oxygen levels here (JANSSON, 1967a). Interstitial nutrient levels are usually well above those of the sea, depending on organic load and water circulation time in the interstitial system, highest levels occurring with high loads and long residence times.

Salinity

The salinity of interstitial water is determined primarily by the salinity of seawater and the extent and distribution of fresh groundwater seepage. Since most beaches experience some fresh groundwater output, and this groundwater usually underlies the intertidal sand wedge, salinities will decrease from seawater values in the input zone both landwards and possibly deeper into the sediment.

Organic inputs

Organic inputs to beaches occur as dissolved organic matter (DOM) or particulate organic matter (POM). DOM inputs depend on primary production levels in the adjacent seawater and usually exceed POM. This DOM is carried into the interstitial system by water filtration and is capable of supporting interstitial fauna (McIntyre *et al.*, 1970; Boucher & Chamroux, 1976; McLachlan *et al.*, 1981).

POM inputs include larger debris cast ashore and fine particulate matter which may be carried directly into the interstices. The former will enter the interstitial system after breakdown and consumption by the macrofauna (Koop & Lucas, 1983). On beaches adjacent to kelp beds, seagrass meadows, or other sources of macrophytes this input can be substantial.

Benthic microflora constitutes a resident source of organic input via primary production in the interstices. This is generally insignificant in the intertidal of exposed beaches, but becomes increasingly important with shelter and distance seawards (Steele & Baird, 1968).

Oxygen concentrations

Exposed sandy beaches have been termed 'high-energy windows' because strong hydrodynamic forces keep them oxygenated in contrast to most other sediments which are anoxic below the surface (Fenchel & Riedl, 1970). Oxygen availability generally decreases into the sand, yet oxygen can be absent a few cm below the surface in low energy, fine sand beaches (Fenchel & Riedl, 1970) but near saturation more than 1 m below the surface in well drained, coarse-grained beaches (McLachlan *et al.*, 1979). The availability of oxygen in the interstitial system is crucial in determining the redox status of nutrients, the vertical zonation of redox conditions, and levels of microbiological activity.

The low permeability associated with fine sand beaches, the low filtered volumes associated with dissipative beaches, and the large microbiological oxygen demand in fine sands (with greater surface area for bacterial attachment) all contribute to low oxygen availability (Eagle, 1983). Every m^3 sand of 250 μm and 38 % porosity provides 1.5 ha for bacterial colonisation (Pugh, 1983). The finer the sand the greater the surface area and the greater the microbial populations (Dale, 1974). Thus, fine sands tend to develop higher oxygen demands than coarse sands.

When such beaches receive high organic loads, reducing conditions occur (Bruce, 1928). The three redox zones defined by Fenchel & Riedl (1970) will

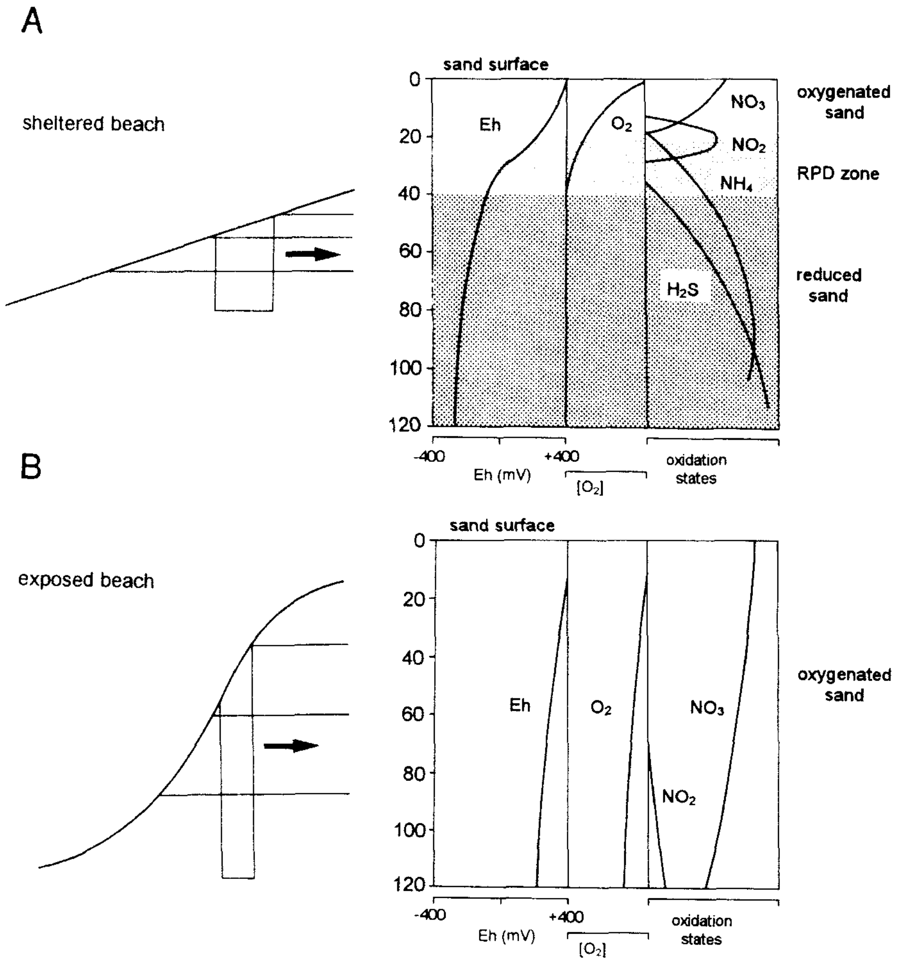

Fig. 18. Chemical gradients in contrasting beach types: (A) reduced layers in a fine sand beach of low wave energy — the low energy, low oxygen dissipative type and (B) the fully oxygenated case in a well drained beach of the high energy intermediate or reflective type.

then be evident (Fig. 18): (1) an upper oxygenated layer with 'yellow' sand, (2) a grey transition zone or redox potential discontinuity (RPD) where oxygen becomes limiting and a switch occurs from oxidising to reducing conditions, and (3) a reduced or black layer discoloured by iron sulphides and distinguished by toxic reduced compounds such as H_2S and NH_4. The reduced layer is not black in carbonate sands because of the absence of iron sulphides.

The amount of oxygenation of the interstitial water, and consequently the depth of reduced layers, depends primarily on the balance between organic and oxygen inputs (RUTTNER-KOLLISKO, 1956; JANSSON, 1967a; FENCHEL & RIEDL, 1970). The depth of the black layer shows a good inverse correlation with sand permeability (WEBB, 1958). Low permeability decreases oxygen inputs by diffusion or flushing and brings reduced layers towards the surface. These layers migrate and may move down when storms stir the sediment and introduce extra oxygen; or they may move up when higher summer temperatures raise benthic metabolism and cause more rapid oxygen depletion (McLachlan, 1978).

In contrast, high energy, coarse sand beaches, especially in reflective situations, tend to be well flushed with seawater, and oxygen may be supplied in excess of the beaches' digestive requirements. Here, aerobic conditions will occur to great depth. The contrasting vertical oxygen and nutrient gradients associated with these different beach types can be referred to as the low oxygen dissipative and well flushed reflective extremes (Fig. 18).

It has been said that beaches are in equilibrium with organic inputs from the ocean (Oliff *et al.*, 1970). Increasing organic inputs increase the equilibrium levels of nutrients, and above a certain point overloading begins and anaerobic conditions will occur (Pugh, 1983). Thus, increasing organic loads can push interstitial systems towards the low oxygen dissipative type.

Temperature changes and primary producers can also affect interstitial climate, pH, and Eh levels (Gnaiger *et al.*, 1978). Swash and tide effects moving water and oxygen through the sand cause vertical movements of redox boundaries, as do groundwater discharge and gravity currents (Jansson, 1967a; Ott & Machan, 1971). Swash input of oxygenated water pushes the reduced layers deeper, whereas gravity drainage of filtered water with lower oxygen tensions raises them. Vertical migration of reduced layers can thus be caused by (1) increasing or reducing wave energy, (2) daily or seasonal temperature changes modifying respiration rates, (3) varying levels of organic input, (4) sunlight causing photosynthesis at the surface, and (5) changing rates of groundwater discharge.

Nutrients

The interstitial systems of sandy beaches have been described as 'great digestive and incubating systems' (Pearse *et al.*, 1942) because of their role in mineralising organic materials and recycling nutrients, especially nitrogen as nitrate or ammonia and phosphorus as phosphate. Much release may be regular and governed by water output and diffusion, but storms reworking the sediment are also important forces releasing stored nutrients. Most mineralisation of organic matter occurs in the first part of the filtration process (McIntyre *et al.*, 1970; McLachlan *et al.*, 1981), and the more refractory components are broken down more slowly. Thus, microbial activity is concentrated near the input zone and the start of interstitial percolation paths, *i.e.*, the retention stratum in most cases.

It has been suggested that beaches act as nutrient sinks (Koop & Lucas, 1983; Hennig *et al.*, 1983) by storing — in microbial biomass or adsorbed to the sand — nutrients derived from mineralisation. However, this has been shown to be unlikely except in the case of prograding beaches (McLachlan & McGwynne, 1986). In the long-term, beaches must be in equilibrium and return to the sea all nutrients they receive (Oliff *et al.*, 1970). Changing inputs can change the equilibrium, but self regulation is the rule unless assimilation capacities are exceeded by very high loads. High energy beaches will have highest capacities and, since interstitial BOD is usually proportional to flow (Jansson, 1968; McLachlan *et al.*, 1981), reflective beaches with high flow rates will generally be able to process DOM and fine POM fastest. Phosphate, may, however, be adsorbed on carbonate sands, depending on redox state (JOHANNES, 1980).

Nutrient concentrations in interstitial waters are generally several times higher than in overlying waters and can be exceptionally high in some cases: NO_3 can exceed 5 mg·l^{-1} in areas of groundwater discharge (JOHANNES, 1980; McLACHLAN & ILLENBERGER, 1986). NH_4 has been recorded at concentrations exceeding 0.5 mg·l^{-1} (MAIER & PREGNALL, 1990), and H_2S up to 700 mg·l^{-1} in reduced zones (FENCHEL & RIEDL, 1970). The greater the interstitial water circulation and the more rapid the flushing rate, the lower nutrient concentrations will be; sheltered situations will exhibit the highest concentrations. In low energy beaches, nutrient concentrations and distribution may be controlled by wave action in the top 10 cm, by waves and diffusion at 10–30 cm, and by diffusion alone below 30 cm (LIEBEZEIT & VELIMIROV, 1984). In high energy situations, water filtration paths will be more important and distribution patterns more complex.

Information on the role of the interstitial system in nutrient cycling in different beach types is limited (PUGH, 1976). STEELE (1976) compared the interstitial processes of temperate Scottish (dissipative?) and tropical Indian (reflective?) beaches and suggested much higher rates of microbial activity in the latter with higher water circulation rates. In South African high energy intermediate beaches characterised by surf phytoplankton blooms, COCKCROFT & McLACHLAN (1993) estimated 30 % of nitrogen recycling to occur in the interstitial system, 80 % of this in the subtidal (450 m) as opposed to the intertidal (50 m), with the surf zone microbial loop accounting for 55 % and the macrofauna for 15 %.

BROWN & McLACHLAN (1990) suggested an overriding importance of the intertidal interstitial system in reflective situations because of the virtual absence of surf zones or macrofauna and the large volumes of water filtered; however, the microbial loop in the surf water and the macrofauna become more important towards dissipative conditions in conjunction with increased surf zone primary production. Certainly all open sandy beaches have well developed interstitial systems which play a significant role in nutrient cycling.

Conclusion — The interstitial environment over a range of beach types

The interstitial environment of sandy beaches may be envisaged as spanning a continuum (Fig. 19). At one extreme is the coarse-grained, reflective beach state which filters large water volumes. Water circulation is rapid and pulsing currents dominate. Filtered water has a low residence time in the interstices, which are well flushed, mainly by wave action, well drained during low tide, and highly oxygenated. This is a physically controlled system dominated by vigorous interstitial circulation and thus has limited chemical gradients. It supports a deep-dwelling, impoverished interstitial fauna adapted to powerful hydrodynamic forces and large pore sizes. This fauna has a vertical distribution with recognisable strata penetrating several metres into the sand.

At the other extreme the fine-grained, ultra-dissipative beach filters small volumes of seawater. Because wave effects are largely filtered out in the surf zone, this

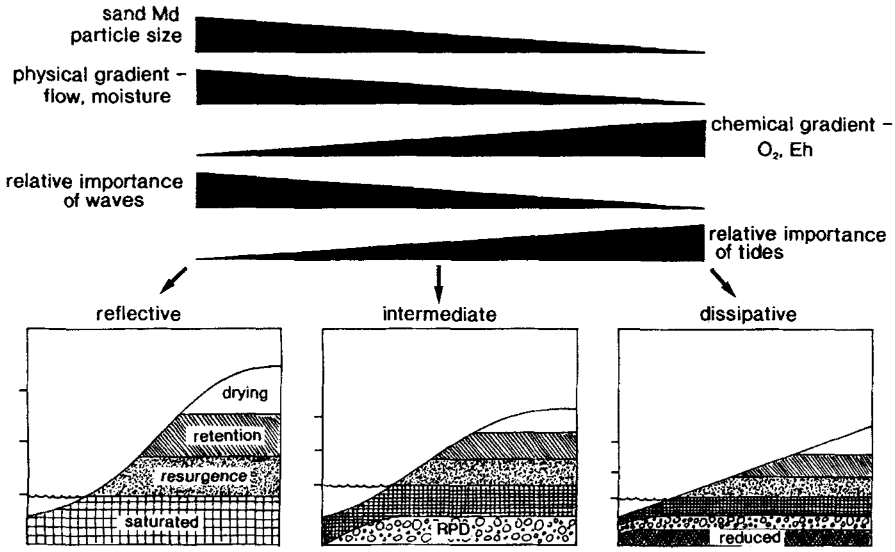

Fig. 19. Conceptual model of main gradients defining the interstitial system in different beach types.

is driven mainly by tidal action, and slow gravity currents dominate. Long residence or turnover times of interstitial water and stagnant interstitial conditions result in low oxygen tensions and steep vertical chemical gradients. This is principally a chemically controlled system with most interstitial life confined to the oxygenated upper few cm; black reduced layers may occur deeper. The distribution patterns of such a concentrated fauna are thus mainly horizontal across the beach in shallow zones.

Intermediate situations bearing some elements of both these extremes will be common. In general, upper shores will tend to have more physical control by flushing (since most beaches tend to be more reflective towards high tide and this is the area where inputs occur), whereas lower shores will be more chemically controlled. Truly reducing conditions will only occur in the most sheltered and organically loaded situations. Nevertheless, low oxygen tensions will occur in the deeper sediment.

Across the entire continuum, groundwater seepage also has an influence in raising water tables and thus causing beaches to become flatter, filter less water, and tend more towards stagnation. This groundwater will also lower salinities and elutriate the fauna. Thus, while discharge of groundwater high in nutrients may contribute to elevated surf zone productivity, its direct effects in the intertidal interstitial system are less likely to be beneficial to the fauna.

Between the physical and chemical extremes on the above continuum lies the ideal situation for interstitial life in terms of taxonomic diversity and abundance. We envisage the optimum being an intermediate beach of fine to medium sand (200–400μm) where the role of tides is nearly equal to that of waves, and the oxygen and organic inputs are sufficiently in balance to just prevent the development of reducing conditions in the deeper sediment. Here, gradients will be physical in the upper layers, tending towards chemical controls in the deeper sediment. In warm climates with elevated metabolic rates such beaches should be capable of processing great quantities of organic materials without becoming anaerobic.

Summary

The interstitial system has its dimensions defined by the granulometry of the sand but its dynamics controlled by the process of water filtration through the beach face. The latter is driven by waves and tides. Reflective beaches typically consist of coarser sand with high permeability; they filter large volumes of water at fast rates and are well flushed and oxygenated. Dissipative beaches, by contrast, consist of finer sands with lower permeabilities and filter smaller volumes at low rates. Waves are more important in reflective systems and tides in dissipative cases. Interstitial chemistry is primarily a response to the balance between inputs of oxygen and organic materials, with the former more vigorous in reflective situations. Surplus organic inputs with concomitant development of anaerobic conditions is more likely to develop in dissipative situations, whereas reflective beaches are more likely to be physically dynamic with strong interstitial flows and desiccation during low tide. It is concluded that optimum conditions for the development of an abundant interstitial fauna rich in species of diverse taxa are likely to occur in intermediate beaches.

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