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Water filtration by dissipative beaches

Abstract—Dissipative or low-gradient beaches are expected to filter low volumes of seawater. This idea was tested on the Oregon coast on two high-energy dissipative beaches with medium and fine sand and found to be correct, filtered volumes being 0.1–7 $m^3\ m^{-1}\ d^{-1}$. Input was mainly due to tidal effects as most wave energy was dissipated in the surf zone. During a very high-energy event on a high tide, however, filtered volume increased by an order of magnitude as a consequence of increased wave input.

Water flow through the intertidal beach is a gravitational process driven by wave swashes. This process is of great importance in introducing water, organic materials, and oxygen to the interstitial system. It controls vertical and horizontal and chemical and biological gradients and nutrient exchanges in this ecosystem. Water filtration is also significant in influencing swash-backwash dynamics coupled to accretion-erosion on the beach face (Duncan 1964) and further interacts with the groundwater table in and behind the beach. The interstitial system of marine beaches is thus driven by the physical energy provided by waves and tides moving the swash zone over the beach face.

The mechanism and measurement of swash water filtration were first described by Riedl (1971) and Riedl and Machan (1972), who showed it to be significant in processing large volumes of seawater through sandy beaches. Subsequently McLachlan (1979, 1982) quantified these inputs over a range of exposed beaches in South Africa. His studies indicated that, for high energy, intermediate beaches, waves were the primary driving force and tides were secondary. Filtered volumes were 3–15 $m^3\ m^{-1}\ d^{-1}$ (mean = 10 $m^3\ m^{-1}\ d^{-1}$). McLachlan (1982) predicted that maximal filtration volumes would occur on steep, coarse-grained beaches under small tidal ranges. This prediction was tested in Western Australia (McLachlan et al. 1985), where reflective microtidal beaches were found to filter large volumes of water (10–91 $m^3\ m^{-1}\ d^{-1}$).

Beaches can be classified as reflective (steep), intermediate, or dissipative (flat) (Short and Wright 1983). As water filtration has been quantified for reflective and intermediate conditions, I attempted to quantify it under dissipative conditions to test the hypothesis that such beaches should filter small volumes and that this water should have long residence times in the interstices.

Oregon's open-coast beaches are modally dissipative, being continuously in this state throughout winter months, but dropping into intermediate states during calmer summer months. Tides on the Oregon coast are mixed, with a maximal daily range of 3.6 m and a mean range of 2 m. Incident wave period ranges from 6 to 13 s and breaker height from 1 to 8 m, with modal breaker height 3–4 m in winter (8 months) and 1–2 m in summer (4 months) (Komar et al. 1976; Fox and Davis 1979). Sand grain size is typically 200–300 μm, leading to modally dissipative beaches with flat slopes and broad surf zones. Dean's parameter (Ω), a quantitative measure of the state of a beach, ranges from 1 to 6 for intermediate beaches, >6 for dissipative beaches, and <1 for reflective beaches (Short 1987). Oregon's beaches score 6–15.

Threemile Beach (124°12′W, 43°45′N), the main study site, is part of the Oregon Dunes National Recreation Area. It has well-sorted fine to medium sand (230–270 μm), a flat slope, and a dissipative ($\Omega \approx 8$) surf zone most of the year. As this beach lies

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near the upper limit of sand particle size for dissipative beaches (Short and Wright 1983), some comparative work was done on a finer grained beach farther south. Whisky Run Beach (124°25'W, 43°10'N) has fine sand (150–220 μm) and is dissipative throughout the year (Ω ≈ 11).

Swash water filtration was measured over seven tidal cycles on Threemile Beach and three tidal cycles on Whisky Run Beach for which predicted differences between the low and high tide elevations ranged from 1.1 to 2.7 m and breaker conditions ranged from 1 to 7 m. Readings were taken for 15 min every hour with the methods of Riedl (1971) as modified by McLachlan (1979) and McLachlan et al. (1985). The dimensions of each wedge of unsaturated sand (filling wedge) that received water from swashes that ran up the beach face above the water table outcrop were measured.

Saturation gaps were measured as airspace in the sand for a range of beach elevations above the water table. Airspace was estimated by taking a 50-cm^3 sand core and adding to it 50 cm^3 of water in a 100-cm^3 measuring cylinder: the saturation gap (%) was twice the difference between the meniscus reading and the 100-cm^3 mark. Linear regressions were fitted to this data. From the volume of each wedge flushed by swashes for a strip of beach 1 m wide and the saturation gap regressions, the input volumes were calculated. These were then integrated over tidal cycles and 24-h days.

A complication arose with long swashes, however, as they did not saturate the sand when the water table was more than 20 cm below the surface. Under these conditions input occurred not as wedges saturated down to the water table, but as surface layers receiving water (Emery 1945). To correct for this phenomenon, I made additional measurements for swashes that gave rise to both wedge and layer input: I measured the distances from where the swash crossed the water table outcrop to the point where the water table was 20 cm below the sand surface and from this point to the upper limit of the swash. This procedure gave the lengths of wedge and layer inputs. To estimate the volumes introduced as layers, I measured the periods of these swashes with a stopwatch and estimated their thicknesses to 5 cm. With a PVC tube graded in centimeters and a stopwatch, I measured the volumes of water seeping into the sand under such conditions as hydraulic conductivity under different heads. This layer correction was done only on Threemile Beach, as Whisky Run Beach experienced no layer inputs.

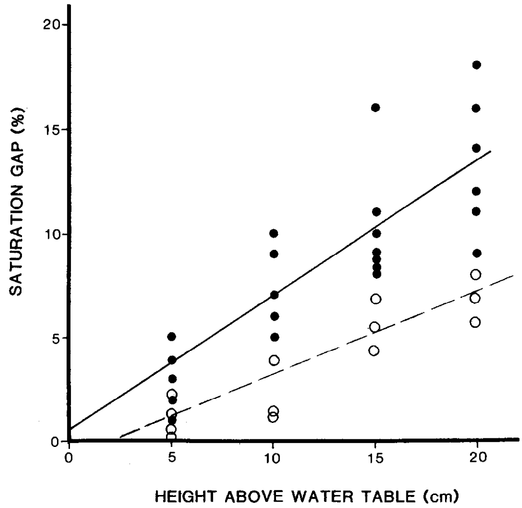

Fig. 1. Saturation gaps (SG) for sands at two beaches. Threemile Beach (●, solid line): SG (%) = 0.67 ht (cm) + 0.05, $n = 23$, $r = 0.84$, Whisky Run Beach (O, broken line): SG (%) = 0.40 ht (cm) − 0.88, $n = 13$, $r = 0.71$.

Environmental conditions recorded during these measurements included wave period (visual estimate with stopwatch), breaker height (mean height of larger breakers estimated with a staff and the horizon), beach slope, water-table profile, groundwater salinity at the water table (refractometer), and slope of the groundwater table behind the backshore. I calculated groundwater flow at Threemile Beach from these readings, taking a hydraulic conductivity of $1\text{–}1.5 \times 10^{-2}$ cm s^{-1} and using the Ghyben-Herzberg relationship (Freeze and Cherry 1979; Raghunath 1982) with flow in an unconfined aquifer assumed. This approach could not be used at Whisky Run Beach because cliffs at the back of the beach precluded water-table profiling.

The saturation gap as a function of elevation above the water table (Fig. 1) is comparable to that recorded from similar sands (McLachlan 1979; McLachlan et al. 1985)

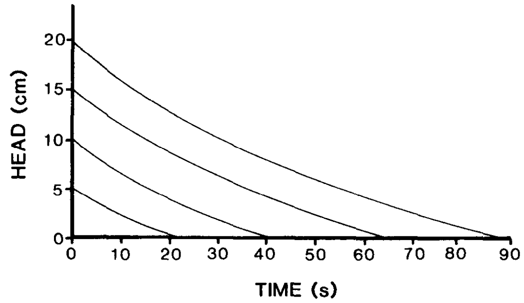

Fig. 2. Hydraulic conductivity or drainage rates of water into the sand from starting heads of 5–20 cm at Threemile Beach.

in the case of Threemile Beach but is very low at Whisky Run because of the fine sand and low permeability. The variance is due to the differences in moisture content between conditions of rising and falling water table as these readings were taken on both incoming and outgoing tides. The volumes of water input to the surface layers at Threemile Beach (Fig. 2) show that for starting heads of 5–15 cm and periods of 10–15 s—typical conditions for this beach—input is 2–5 cm of water draining into the sand.

Two representative profiles of Threemile Beach (Fig. 3) illustrate the positions of the swash zone, the water table, and the infiltration zone (area between the low-tide water-table outcrop, highest swash line, sand surface, and the groundwater table). Characteristic features of these low-gradient beaches are the extensive swash zones and the high position of the water table during low tide, even considering its lag behind the tide (Emery and Foster 1948). The infiltra-

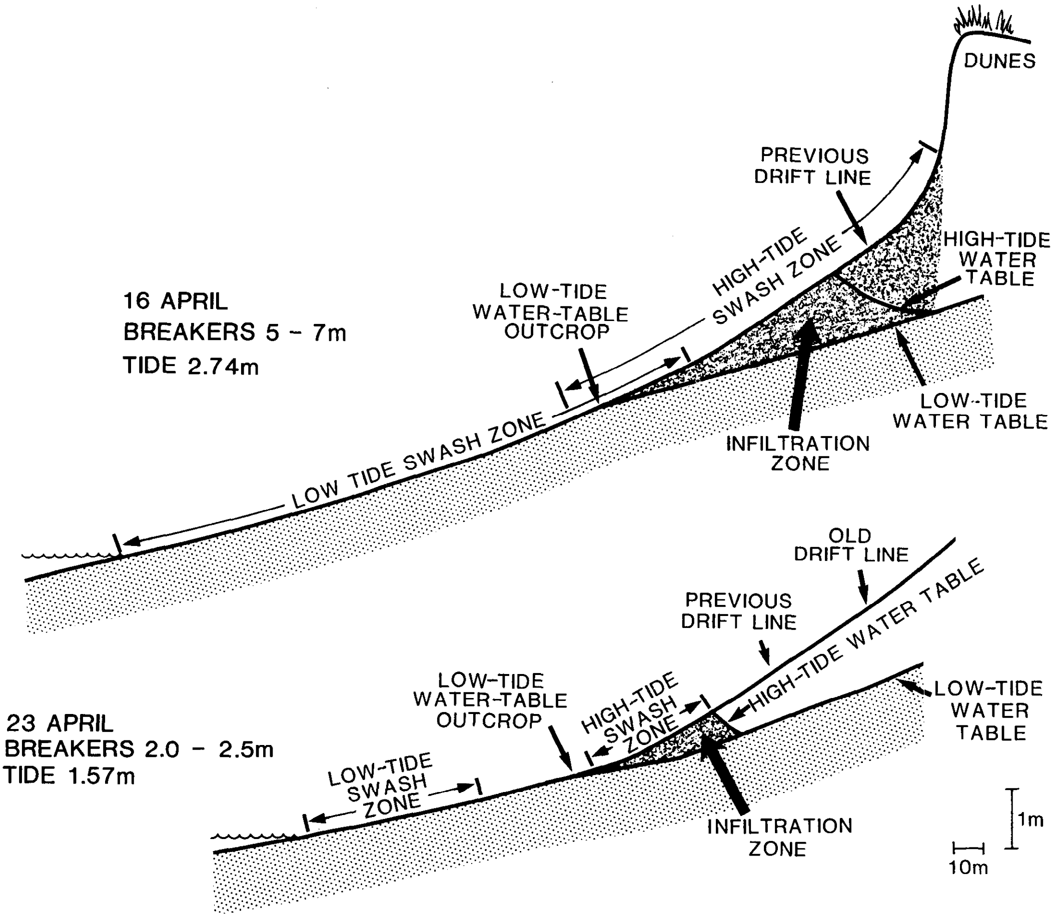

Fig. 3. Profiles of Threemile Beach under very high-energy and moderate-energy conditions showing swash and input zones and water-table positions.

Table 1. Environmental conditions and input characteristics at Threemile and Whisky Run Beaches.

Tidal range	HT elev.*	Wave ht	Wave period	Input swash period	Beach slope	Input characteristics: Vol. ($m^3 m^{-1}$) Min	Max	Total	Input % as layers	wedges
	(m)		(s)	(s)	(°)	(h^{-1})	(h^{-1})	(d^{-1})		
				Threemile Beach						
2.74	2.46	6–7	13	>180	1.4	0.01	4.31	31.9	74	36
2.55	2.15	5–6	12	>225	1.0	0.00	1.70	7.0	42	58
2.31	2.03	3–3.5	9	>129	1.0	0.00	0.29	2.0	0	100
2.25	2.06	2	11	>150	1.0	0.00	0.37	2.7	0	100
1.94	1.97	2	11	>129	1.0	0.00	0.48	2.6	37	63
1.57	1.91	2–2.5	10	>180	1.0	0.00	0.56	2.6	1	99
1.11	2.00	1.5	9	>90	1.2	0.00	0.75	4.4	34	66
				Whisky Run Beach						
2.68	2.15	1–1.5	7	>225	0.7	0.00	0.03	0.1	0	100
1.63	2.37	1.5–2	8	>113	1.0	0.00	0.02	0.1	0	100
2.74	2.49	2.5	9	>300	0.8	0.00	0.02	0.1	0	100

* Predicted elevation of the high tide above datum.

tion zones were short relative to the width of the beach and coupled to the shallow water tables; this restricted most of the input to wedges. Only during storm conditions, when high-tide swashes scarped the dunes, did swashes extend significantly above the point where the water table was 20 cm below the sand surface at Threemile Beach. No such layer inputs were recorded at Whisky Run Beach.

Threemile Beach may be considered fully dissipative under conditions where wave height is >2 m (Short and Wright 1983). Of the seven tidal cycles monitored at Threemile Beach (Table 1), five represent moderate- to high-energy dissipative conditions, one represents very high-energy dissipative conditions with a large tide, and one represents calm conditions with an intermediate surf zone but a dissipative beach. During normal conditions heights of the larger breakers ranged from 2 to 6 m, filtered volumes from 0 to 1.7 $m^3 m^{-1} h^{-1}$ and daily volumes from 2 to 7 $m^3 m^{-1}$. This input occurred mainly as wedges from 3 h before high tide to 2 h after and was associated with swashes of infragravity period—the frequency of input swashes ranging from 0.0 min^{-1} during low tides to 0.3–0.5 min^{-1} during high tides. These daily volumes are small, 20–50% of those recorded from intermediate beaches (McLachlan 1979) and 5–10% of those on exposed, reflective beaches (McLachlan et al. 1985).

Under storm conditions, representing the highest energy state Threemile Beach is likely to experience (Komar et al. 1976), filtered volumes increased by an order of magnitude. Here input occurred throughout the tidal cycle, but particularly as layer input during high tide, when large swashes ran up the face of the dunes. This large volume was due to the great wave energy and high tide reaching the dry upper beach. Since waves >5 m occur <5% of the time (Komar et al. 1976) and only 50% of high tides exceed +2.4 m, the incidence of such high input volumes is estimated at 1–2% of days in a normal year.

Under calm conditions filtered volumes also increased, but less dramatically than during storms. Although infragravity periods still dominated the input swashes, periods were shorter than in the other cases. This higher frequency resulted in more filling wedges during the high-tide period and a maximum infiltration rate of 0.75 $m^3 m^{-1} d^{-1}$.

The three tidal cycles at Whisky Run Beach gave filtered volumes an order of magnitude below those at Threemile Beach (Table 1). Reduced filtration was a consequence of the low saturation gaps and high position of the water table due to poor drainage. Input was thus entirely as wedges. Threemile Beach has sand near the upper grain size limit for dissipative beaches, whereas the sand at Whisky Run is nearer midrange (Short and Wright 1983). Thus the filtered volumes at Threemile Beach may be near the maximum that could occur under dissipative conditions.

Groundwater flow rate at Threemile Beach was estimated to be 11–17 $m^3 m^{-1} d^{-1}$, assuming an unconfined aquifer of unlimited depth and a water-table slope of 0.68° from the backbeach into the dunes. These assumptions, however, would necessitate a sand body 110 m deep. If the actual depth of the sand deposit is only 30 m (Beaulieu and Hughes 1975), the estimate would reduce to a rate of 3–4.5 $m^3 m^{-1} d^{-1}$—double the mean daily filtered volume (Table 1). Reduced salinities would thus be expected in the intertidal as a consequence of this discharge.

Salinities of the interstitial water ranged from 15 to 31‰ in the intertidal with seawater 26–31‰. Salinities were generally highest at upper tide levels (HW mean 29‰) and lowest at lowest tide levels (LW mean 24‰). Discharge thus occurred mainly on the lower shore, implying that the daily swash-water input was overlying a freshwater lens. Although similar measurements could not be taken at Whisky Run Beach, the presence of distinct groundwater seepage indicated a similar situation.

An estimate of the residence time of filtered seawater in the interstitial system can be made by dividing the volume of water held by the intertidal interstitial system at capacity (assuming 25% porosity) by the daily input. At Threemile Beach the sand body is taken as a wedge 150 × 2 m, giving a water volume of 37 $m^3 m^{-1}$ and a residence time of 15 d for a daily input volume of 2.6 $m^3 m^{-1} d^{-1}$. Input volume would increase and residence time decrease toward either end of the wave spectrum, i.e. under conditions of lower or higher wave energy and greater inputs. At Whisky Run Beach residence time for an input volume of 0.1 $m^3 m^{-1} d^{-1}$ in a wedge 200 × 1.6 m would be 400 d.

Values of wave height and period show the profound effect of changing wave energy on swash and coupled water filtration characteristics at Threemile Beach. The high-tide swash period decreased from 50 s at a breaker height of 6 m to 30 s at a breaker height of 2–2.5 m (although only a small proportion of these swashes formed filling wedges). Over the same change in wave energy, mean swash length decreased from 48 m to 13. The input mechanism therefore changes with a change in wave energy. At higher wave energy there are fewer swashes of greater length; input changes from relatively high-frequency, filling wedges at low wave energy to low-frequency layer inputs at high wave energy, the latter resulting in higher inputs.

The relative role of tides and waves in water input changes for different beach types and tidal ranges; on microtidal, reflective beaches input is almost entirely due to waves, but on mesotidal, intermediate beaches tides are almost as important as waves (McLachlan 1979; McLachlan et al. 1985). The relative importance of tides can be estimated by calculating the input volume that would arise without waves if a 2-m tide rose and fell against the beach. This calculation gives a volume of 5.2 $m^3 m^{-1} d^{-1}$ at Threemile Beach—larger than the lower values recorded. Thus the input on Threemile Beach is mainly tidal, wave input being filtered out by the dissipative surf zone and the flat beach slope. At Whisky Run Beach tides exert even greater dominance over waves.

Central to this model is the concept of different beach types—reflective, intermediate, and dissipative—with differences in slope being the key distinguishing feature. Beach slope responds to changes in both supplied sand particle size and wave energy (Bascom 1951; Davies 1972), and the surf zone responds in similar fashion (Short and Wright 1983). The expenditure of wave energy against the beach face is modified by both surf zone state and beach slope. Wider surf zones dissipate more wave energy before waves reach the beach and convert incident wave period to infragravity periods.

Threemile Beach filtered small volumes of water under conditions of normal wave energy but a large volume (as do all other beach types) under very high-energy wave conditions. Whisky Run Beach filtered much lower volumes under low- to moderate-energy wave conditions. Most exposed dissipative beaches should fall between these two

Table 2. Water filtration characteristics of different beach types. (Data from McLachlan 1979, McLachlan et al. 1985, and this study.)

Beach type (location)	Sand Md*	Hb†	Tide type and range (m)	Normal input ($m^3\ m^{-1}\ d^{-1}$)	Storm input ($m^3\ m^{-1}\ d^{-1}$)	Input mechanism	Water residence time
Reflective (Australia)	300–600	0.4	Diurnal, 0.9	10–85	91	Waves	1–5 h
Intermediate (S. Africa)	200–300	2.0	Semidiurnal, 2.1	5–15	—	Waves and tides	15–30 h
Dissipative (Oregon)	150–250	2.5	Mixed, 3.6	0.1–5	31	Tides and waves	10–400 d

* Mean grain size (μm).
† Significant breaker height (m).

extremes of particle size and filter volumes of 0.1–5.0 $m^3\ m^{-1}\ d^{-1}$. Under nonstorm wave regimes, reflective beaches may be expected to filter 20–70 $m^3\ m^{-1}\ d^{-1}$ and intermediate beaches 5–15. Under storm wave conditions all beaches filter more water, but dissipative beaches show the greatest increase when waves take over from tides as the main input mechanism (Table 2).

In dissipative beaches input rates are low under normal conditions, but comparable to those of other beaches during high-energy events. Flushing, aeration, and oxygenation of the sediment should thus be slower than in other beach types. This lowered input rate, plus the longer residence times of the water, should result in lower oxygen tensions and greater possibility of reducing conditions in such beaches. Organic inputs should remain high, as dissipative beaches are associated with productive surf zones having high organic levels and blooms of surf diatoms (Lewin and Schaefer 1983). Low-gradient beaches would therefore be expected to harbor rich interstitial faunas and exhibit well-developed chemical gradients, complicated by the discharge patterns of groundwater.

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Potential microbial utilization rates of sublittoral gastropod mucus trails

Abstract—Mucus trails produced by the herbivorous gastropod *Monodonta turbinata*, a common species of the rocky intertidal and sublittoral zone in the Mediterranean Sea, were found in the laboratory to be rapidly colonized by heterotrophic microbes (bacteria and protists). Bacterial turnover times of 2.2 h were obtained for the mucus-associated microbes during the exponential growth on mucus trails while free-living bacteria in overlying water exhibited a turnover time of 5 h. Heterotrophic nanoflagellates associated with the mucus grazed the bacterial population at rates of 18 bacteria flagellate^{-1} h^{-1}; for the free-living bacteria grazing rates of about 15 bacteria flagellate^{-1} h^{-1} were obtained. Only about 25% of the mucus-derived carbohydrates remained on the substrate after 26 h.

Almost all aquatic animals secrete mucus in considerable quantities for various reasons, e.g. to reduce of drag forces, prevent sedimentation, enhance adhesion, and facilitate locomotion (Denny 1980; Branch 1981). This mucus release constitutes a significant loss of energy in marine invertebrates. Probably the best documented case of mucus release is that of corals, which may expend up to 50% of assimilated energy in the form of mucus (Crossland et al. 1980). It is thought that coral-derived mucus has a significant influence on the water around reefs, leading to enhanced microbial productivity (Ducklow in press). Since mucus consists primarily of polysaccharides and proteins with C:N ratios of 1–5 (Connor 1986), we hypothesized that mucus trails produced by marine invertebrates are readily degradable by microbes (*see also* Calow 1979) and are able to support significant microbial growth. To test this hypothesis, we investigated the course of microbial colonization and decomposition of mucus trails produced by the nearshore herbivorous gastropod species *Monodonta turbinata* in the Adriatic Sea.

Microbes are likely to react quickly to released mucus due to their high turnover rates and their physiological diversity (Pomeroy 1984); bacteria possess a wide range of exoenzymes potentially capable of degrading mucoid polymers (Sutherland 1977). Thus the microbial community colonizing such mucus trails may transform mucus-derived dissolved and particulate matter into living biomass (Azam et al. 1983; Herndl and Velimirov 1986).

Monodonta turbinata specimens as well as ambient water were collected in depths of 0–2 m in the northern Adriatic Sea in October 1987 when ambient water temperature varied between 16° and 18°C. *Monodonta turbinata* was kept in a flow-through aquarium 15 h before being allowed to crawl on pretreated coverslips. Pretreatment of coverslips involved soaking in 0.5 N NaOH for 24 h, rinsing thoroughly with distilled water, and combusting at 450°C for 6 h. Thereafter each specimen was placed onto a preweighed coverslip in 0.2-μm Nucle-

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