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The Effects of a Mid-Foreshore Groundwater Effluent Zone on Tidal-Cycle Sediment Distribution in Puget Sound, Washington

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ABSTRACT

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Standard fluorescent tracer techniques used on beaches with mid-foreshore groundwater effluent zones show a detailed pattern of tidal-cycle sedimentation. Tracer particle distribution on three beaches with wave heights commonly less than 35 cm suggests that the influence of the foreshore slope and average grain size of the beach is more important on swash and backwash transport velocities than the influence of the high water table. The effect of the effluent zone on tidal-cycle sedimentation is only significant near the beginning and end of the tidal-cycle when outflow rates and, consequently, backwash velocities are greatest. During the rest of the tidal-cycle, swash deposition and swash erosion control sediment distribution. Beaches with coarser sediment and steeper foreshore slopes will have narrower surf zones, resulting in greater swash velocities and enhanced landward deposition of sediment. At high tide this effect is especially pronounced due to the steeper gradient of the upper foreshore.

ADDITIONAL INDEX WORDS: *Fluorescent tracer study, fresh-water outflow, Puget Sound, surf zone, swash-backwash zone.*

INTRODUCTION

The presence of a groundwater effluent zone midway up the foreshore has a measurable effect on tidal-cycle sedimentation. Techniques used to characterize the sedimentation pattern on beaches with high water tables have not included any tracer studies. This has resulted in a lack of data detailing the movement of individual particles throughout the tidal-cycle and an inadequate understanding of the relative importance of the various factors governing the sedimentation pattern.

Conversely, much research has been devoted to determining the tidal-cycle sedimentation pattern of predominantly sandy beaches without mid-foreshore groundwater effluent zones. Early work on beach profile fluctuations was published by BRUUN (1962), who stated that over an extended period of time a beach in equilibrium will undergo no significant change due to the repeated flood and ebb of the tides. STRAHLER (1966) described the pattern of profile fluctuations as initial deposition of fine to medium sand near the upper limit of swash, a scour phase in the zone of swash and backwash, and step deposition of sand and pebbles under the breaker zone. These three phases of scour and deposition, shown in Figure 1, translate up

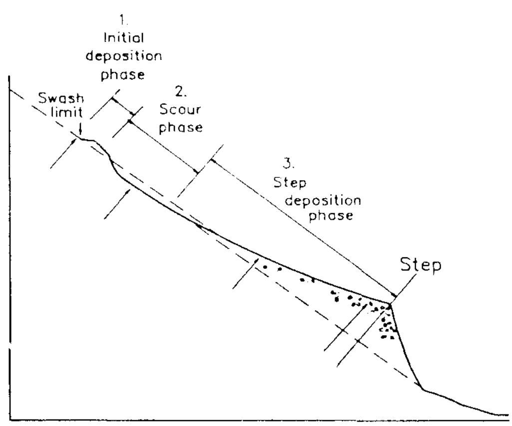

Figure 1. Phases of beach change along a profile during the tidal cycle (after Strahler, 1966).

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and down the foreshore during the tidal-cycle and leave no net change in the beach profile.

SCHWARTZ (1966) indicated a more detailed pattern of foreshore tidal-cycle sedimentation through the use of fluorescent tracers implanted on the beach. The tracers revealed the movement of individual particles of each grain size and provided quantitative measurements of affected depth.

The presence of a groundwater seepage face midway up the foreshore and its effect upon the sequence of cut and fill during the tidal-cycle was studied by DUNCAN (1964). He used measured rods to collect profile data on one beach and found that a high water table maximizes backwash erosion and backwash deposition.

This study expands upon these previous reports and determines the pattern of tidal-cycle sedimentation on beaches with groundwater effluent zones using fluorescent tracer techniques (SCHWARTZ, 1966). The pattern derived from this study is significantly different than that in Duncan's article in that it was developed by tracing the movement of sediment, at the surface and at depth, from one area along the profile to another. The influence of factors other than a high water table on sedimentation was also considered. Consequently, tracer particle distributions were compared between several high water table beaches with different foreshore slopes, widths of surf zones and average sediment grain sizes, as well as with sections of beaches without mid-foreshore groundwater effluent zones.

PREVIOUS WORK

The movement of sand grains in the swash-backwash zone of a beach is basically governed by three processes (INGLES, 1966): (1) the sweeping onshore-offshore motion of the swash and backwash, (2) the alongshore motion generated by the longshore current, and (3) acceleration due to gravity. Compared to the other forces acting on the beach sediment, the force of gravity is virtually constant and insignificant (INGLES, 1966). The movement contributed by the longshore current is also considered negligible in most tracer studies of tidal-cycle sedimentation, because field site beaches are chosen that are struck predominantly by waves that approach nearly parallel to the shoreline. It is the effect of the onshore-offshore motion of the swash-backwash on beach sediment, and the factors influencing that motion, that are observed in such field studies.

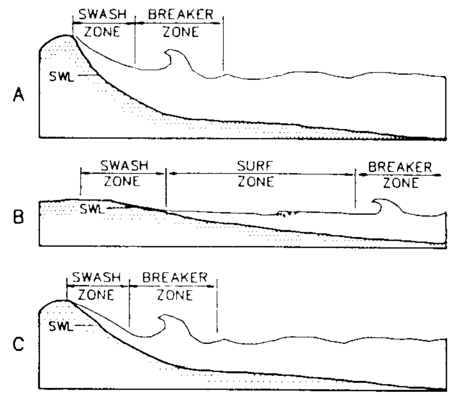

Figure 2. Beach slope and tidal phase govern the existence and width of a surf zone. Beaches with steep slopes rarely possess a surf zone as relatively deep water allows waves to break higher up the foreshore (A). Beaches with gentle slopes possess a surf zone under most conditions as waves must break at some distance from the shore (B). Moderately sloping beaches may lack a surf zone at high tide (C). SWL = still water line (after Ingles, 1966).

Among the most important factors affecting the sediment transported by the swash and backwash are the slope of the foreshore, the average sediment grain size, sorting, and the width of the surf zone. These factors are interrelated: a beach with coarse-grained, well-sorted sediment can support a steeper slope (FINKELSTEIN, 1982), and with an increase in beach slope, the breaker zone moves shoreward and the width of the surf zone is decreased (Figure 2).

The effect of these factors on swash and backwash velocities can be dramatic. A beach with a steep gradient and consequently narrow surf zone will have only a short distance between the breaker zone and the swash-backwash zone, resulting in enhanced swash velocities. In addition, coarse-grained and well-sorted sediment on a beach will facilitate percolation during swash events and decrease the force of the backwash. In both cases, deposition dominates in the upper reaches of the foreshore until slope equilibrium is gradually reached and backwash velocities prevent further net accretion (DUNCAN, 1964).

Tidal-cycle phase also plays a role in deter-

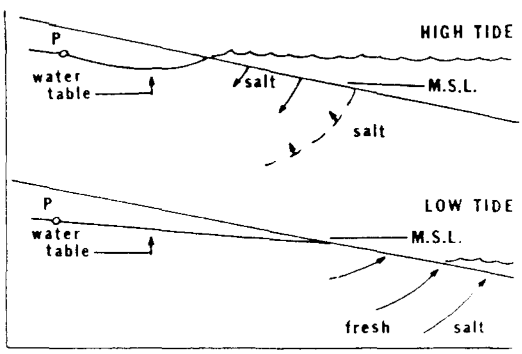

Figure 3. Dynamic coastal groundwater flow pattern. The pilot point, P, is located at a distance shoreward where there is essentially no tidal effect on the water table (after Urish, 1987).

mining the character of the swash-backwash zone. A moderately sloping beach with a surf zone at low tide may not have a surf zone at high tide, due to the steeper gradient of the upper portion of the foreshore (Figure 2). Consequently, greatest swash transport occurs during high tide (INGLES, 1966).

The pattern of tidal-cycle sediment movement becomes even more involved with the presence of a groundwater effluent zone midway up the foreshore. In beach systems with such zones, both the level of the water table and the rates of discharge fluctuate with the tidal-cycle, resulting in variable but appreciable effects upon the swash and backwash velocities.

According to URISH (1987), at low tide the effluent zone is wider (extends lower) and has a greater fresh-water outflow as a result of a steeper phreatic surface. As the tide rises, the water table rises as well, but the tidal movement of the sea water occurs much more rapidly relative to the coastal groundwater system. From the middle of the flood tide (mid flood tide) to the middle of the ebb tide (mid ebb tide), the gradient of the water table is reversed and the fresh-water outflow is blocked by seawater back pressure (Figure 3). Thus, the outflow rate and water table level are controlled, in part, by the tidal-cycle. Maximum fresh-water outflow occurs primarily from mid ebb tide to low tide (URISH, 1987).

In 1964, DUNCAN studied how the presence of a mid-foreshore effluent zone affected sediment distribution during the tidal-cycle. He found that at high tide, swash deposition and swash erosion dominated above the water table, resulting in the formation of a sediment lens on the shoreward side of the swash-backwash zone and a scoured area on the surf side of the zone. Scour occurred here due to the proximity of the high energy breaker zone. Deposition near the upper limit of swash was in large part due to the infiltration of swash into the unsaturated beach sediment, which decreased the force of the backwash. During low tide the backwash, below the water table, was accelerated by the addition of water rising to the surface throughout the effluent zone. Increased backwash velocities facilitated backwash scour and backwash deposition, resulting in the formation of a sediment lens near the boundary of the swash-backwash and surf zones. DUNCAN's generalized profiles of sediment distribution at high and low tide, for beaches with mid-foreshore groundwater effluent zones, are shown in Figure 4.

FIELD SITES

Field work was conducted on beaches in northern Puget Sound in the State of Washington. The Puget Sound coastline is characterized by scoured bedrock and glacial deposits; remnants of the Pleistocene glaciations. The tidal range for the macrotidal Puget Sound region is 2 to 4 meters from neap to spring tide. Three beaches were selected, each with the following characteristics: a predominance of sand-sized sediment, minimal longshore drift and a groundwater seepage face midway up the foreshore. Beaches with a groundwater effluent zone are identified by fresh water seeping out on the lower half of the foreshore. In addition, all three field sites were backed by high bluffs composed of glacial till and outwash.

The first field site is located on Whidbey Island at the Naval Sea Plane Base just north of Maylor Point (Figure 5). The beach faces Saratoga Passage to the east and consists of fine to medium-sized sand overlying a thick deposit of glacial sands and gravels. During the study period, the beach had an average slope of 0.068 and was struck by waves 15 to 25 cm high and with an average period of 4 seconds.

The second field site is a section of the West Beach coastline of Whidbey Island just south of the small settlement of Swantown. The beach faces west northwest and is exposed to Pacific

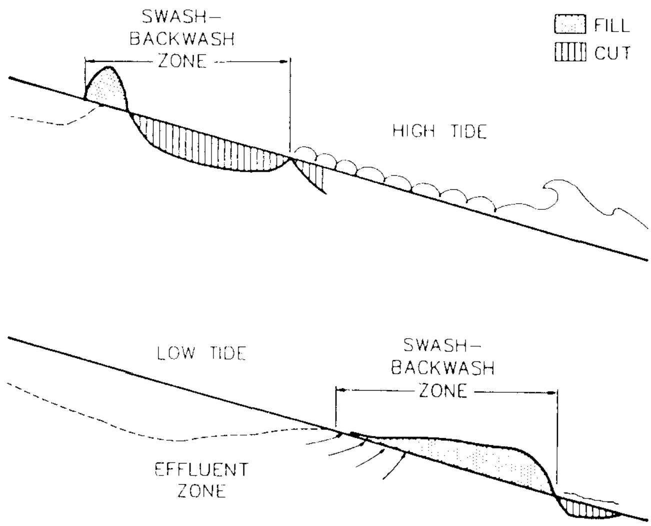

Figure 4. Generalized profiles of sediment distribution in the swash-backwash zone at high tide and low tide on a beach with a mid-foreshore groundwater effluent zone (after Duncan, 1964).

Ocean waves that pass through the Strait of Juan de Fuca. As a result, the wave energies here are noticeably greater than at the other sites. During the field work, the average wave period was 5 seconds and wave heights ranged from 20 to 35 cm. The beach had an average slope of 0.073, although the detailed profile of the foreshore was quite variable due to the higher wave energy. This was the only field site to have a sizable surf zone during low tide, with up to 5 m between the breaker zone and the swash-backwash zone. The predominant sediment size of the beach was that of medium-to-coarse sand particles.

The third beach site is on northwest Lummi Island directly south of Migley Point. Although open to the Strait of Georgia to the northwest, during the field observations this west-facing beach was exposed to less energetic waves driven by prevailing winds from the south. The coarse sand and pebble beach had an average slope of 0.12, virtually no surf zone, a wave period of 4 seconds, and wave heights ranging from 10 to 25 cm.

METHODS

A fluorescent tracer study modifying the techniques of SCHWARTZ (1966) was implemented on the three beaches in order to study the sequence of tidal-cycle scour, transport, and deposition of individual tracer grains. This procedure adds the third dimension of depth to the established sediment transport tracer techniques.

At a minus low tide preceding the day of observation, two 4 cm diameter cores of sediment were removed from the field site (Figure 6). The first, tracer core X, was removed from midway between the water table intersection with the beach profile and the uppermost reach of the sandy portion of the beach. The second core, tracer core Y, was removed the same distance seaward from the water table. The approximate average distance of both cores from the water table was 4.5 m.

The top 12 cm of sediment was removed from each core and divided into three equal (4 cm) horizontal increments. Each of the six increments of sand was dried and subsequently dyed with one of six different fluorescent colors, using the methods described by YASSO (1965). These dyed increments were then returned to the core tubes in their original positions. The fluorescent-colored segments of tracer core X (above the water table) were dyed green, orange and blue-green, from the top to the bottom; whereas the sediments from top-to-bottom for

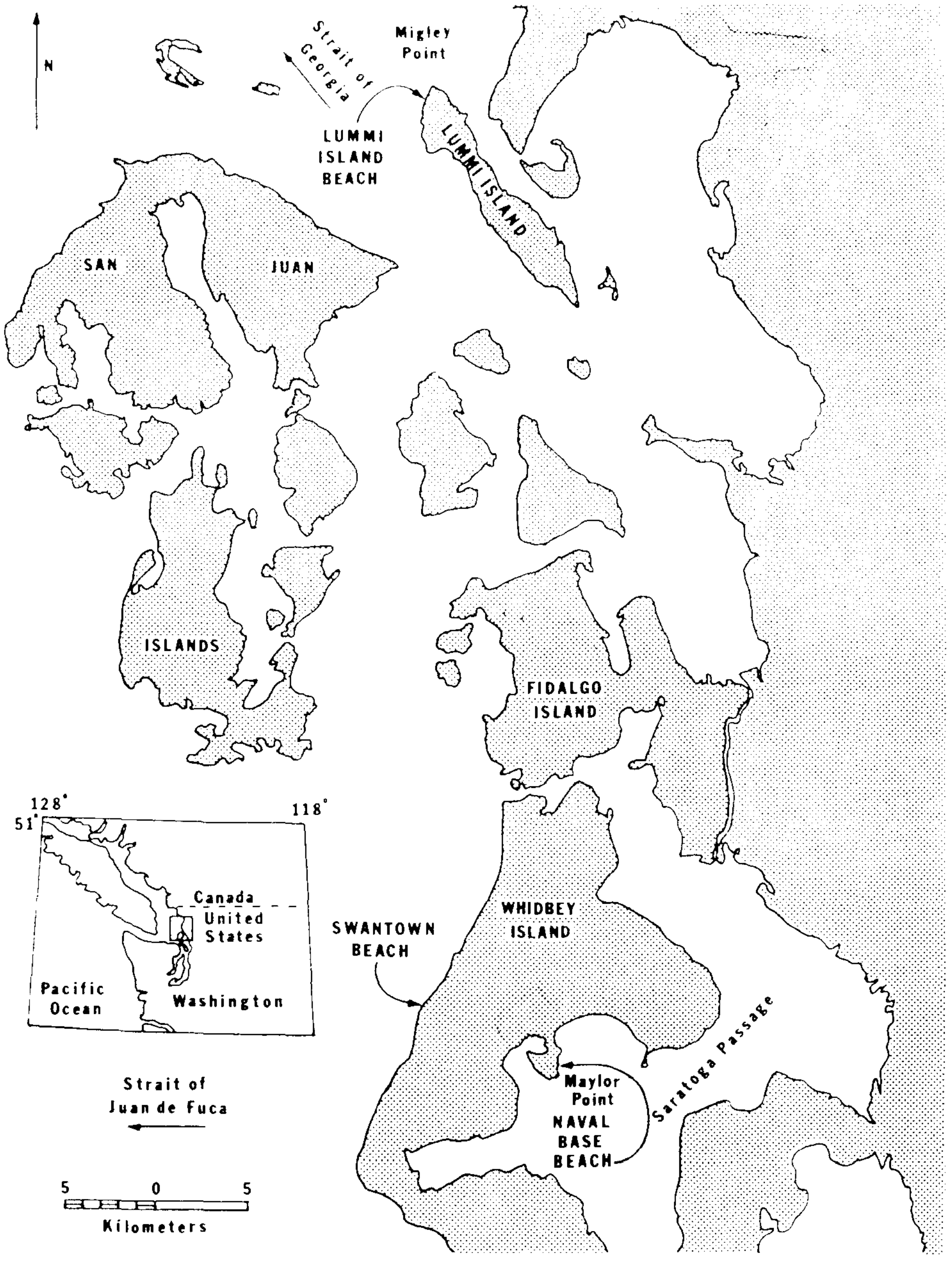

Figure 5. Map of the northern Puget Sound region showing site locations.

tracer core Y were dyed red, yellow and blue, respectively. Tracer core locations along the beach profile are shown in Figure 6.

At low tide on the next day, the increments of dyed particles in the core tubes were implanted in the foreshore close to their original positions, thus preserving the stratigraphy of the beach. After two tidal-cycles (from minus tide to minus tide), scoop samples of approximately 30 grams and only one cm deep were obtained in four

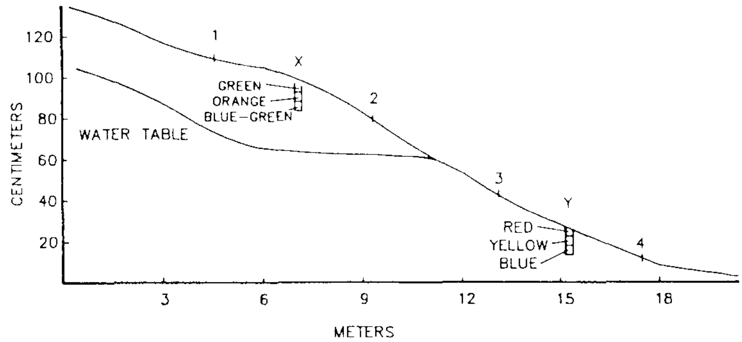

Figure 6. Schematic diagram of tracer cores and sample sites relative to the water table and foreshore profile of the Swantown beach on March 19, 1987.

locations along the profile. Sample sites 2 and 3 were located midway between the cores and intersection of the water table with the beach surface, while sample sites 1 and 4 were located the same distance (approximately 2.25 m) landward and seaward, respectively, from the cores (Figure 6). The samples were then dried, sieved into seven particle sizes (pebbles to fines), and individually examined under the microscope for tracer grains. The number of tracer particles of each grain size and of each color (the color indicating the original position on the beach) was recorded for each sample site.

The field procedures outlined here were conducted twice at the same locations at each beach. Additional observations were also made on higher elevations of each beach during the same tidal cycles. These above-groundwater observations were run as controls to compare to the groundwater observations. The spacings of the cores and sample sites were the same as in the groundwater experiments, with the deepest segment of core Y (12 cm at depth) being above the water table at low tide and with sample site #1 being just within the upper limit of swash at high tide. Unfortunately, due to the narrow widths of the beaches, the upper beach tracers could not be placed high enough above their respective effluent zones to completely avoid groundwater influence with the rising tide. Consequently, the value of these field tests is questionable.

OBSERVATIONS

Tabulations of typical tracer particle counts for samples obtained at the Lummi Island, Naval Base and Swantown field site beaches are recorded in Tables 1, 2 and 3, respectively. In Figures 7, 8 and 9, the information in each table is illustrated with a profile of the beach and pie diagrams that summarize, by percent, the tracer data for each sample site.

In addition to collecting scoop samples after the retreat of the tide on an observation day, core X was located. Scour was never observed to have extended below the orange tracer segment (depth 4 to 8 cm) and sometimes not even below the green tracer segment (depth 0 to 4 cm). In the few samples where blue-green particles were detected, it is assumed that mixing of the blue-green particles with the upper colors occurred during removal of the tracer core tube from the beach face.

Totaling all of the particles of each color found at each sample site for all of the observations, the percent distribution of dominant tracers for each sample site was obtained as follows: predominantly green tracer particles (79%) at sample site #1; predominantly red tracer particles (74%) at sample site #2; predominantly yellow tracer particles (66%) with a number of red tracer particles (21%) at sample site #3 and predominantly blue tracer particles (92%) at sample site #4. Original positions of the tracer colors and the locations of the sample sites can be seen in Figure 6. Percentages of the predominant tracer color at each sample site would have had even higher values if the silt and clay-sized colored particles had not been included in the computations. Tracers of every color with phi sizes greater than 4 were found at all sample sites due to the ease with which they were entrained in the turbulent surf.

Table 1. *Tracer particle distribution of Lummi Island field site beach, June 12, 1987.*

Sample Site	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#1	1	2	–	–	–	–	–
	2	–	–	–	–	–	–
	3	–	–	–	–	–	–
	4	5	–	–	–	–	–
	fines	36	3	–	1	16	4
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#2	1	–	–	–	6	–	–
	2	–	–	–	6	–	–
	3	1	–	–	11	–	–
	4	–	–	–	5	–	–
	fines	2	–	–	14	–	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#3	1	–	–	–	–	–	–
	2	–	–	–	–	2	–
	3	–	–	–	2	6	–
	4	1	–	–	4	13	–
	fines	–	–	–	–	75	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#4	1	–	–	–	–	–	28
	2	–	–	–	2	1	39
	3	–	–	–	–	–	37
	4	–	–	–	1	–	14
	fines	2	–	–	1	1	15

– indicates no tracers found.

RESULTS

The tidal-cycle sequence of tracer particle transport for this study is generalized in Figure 10. Immediately after implanting the tracer cores at low tide (Figure 10A), the fresh-water outflow entrained the very top layer (observed as approximately a sand grain diameter in thickness) of the red segment of core Y and redeposited the tracers at the seaward edge of the swash-backwash zone near the boundary with the surf zone. More red tracers were scoured and deposited seaward when the upper part of the swash-backwash zone reached core Y. Backwash removed the tracer particles until the sediment lens in the seaward portion of the swash-backwash zone buried core Y.

When the swash-backwash zone reached mid flood level and the narrowing surf zone reached core Y (Figure 10B), a significant portion of the red tracer segment of the core was removed by surf scour. The coarse-grained red tracer particles from the top layer of core Y were transported mainly to the higher energy step under the breaker zone. The fine-grained red tracer particles were entrained by the turbulence and deposited landward in the swash-backwash zone.

Initial backwash-dominant scour in the swash-backwash zone resulted in the formation of a sediment lens near the seaward boundary of the swash-backwash zone. However, as the tide continued to rise, the sediment lens was shifted landward in the swash-backwash zone as swash velocities increased. At all field sites, the increased swash velocities were a result of the decreasing width of the surf zones, the dim-

Table 2. *Tracer particle distribution of Naval Base field site beach, April 27, 1987.*

Sample Site	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#1	1	–	–	–	–	–	–
	2	1	–	–	–	–	–
	3	4	–	–	–	–	–
	4	63	1	–	–	–	–
	fines	92	6	–	1	–	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#2	1	–	–	–	–	–	–
	2	–	–	–	1	–	–
	3	–	–	–	1	–	–
	4	–	–	–	9	–	–
	fines	1	–	–	7	1	3
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#3	1	–	–	–	4	–	–
	3	–	–	–	–	3	–
	4	2	–	–	1	15	1
	fines	22	–	–	20	16	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#4	1	–	–	–	–	–	–
	2	–	–	–	–	–	–
	3	–	–	–	–	–	3
	4	–	–	–	–	–	~115
	fines	18	–	–	14	–	~500

— indicates no tracers found.

inution of the groundwater outflow rates, and the increase in both foreshore slope and predominant sediment grain size.

As the tide continued to rise, the mid flood tide swash deposits were eroded by the trailing scour zone and became the primary source of most of the red tracer particles found at sample site #1. The step deposits were not represented in the data, as the breaker zone and associated deposits also translated up and down the foreshore and ended up seaward of the sampling sites at the end of the tidal-cycle.

The progressive landward redeposition of the mid flood tide swash deposits eventually blanketed core X for a short while. By high tide (Figure 10C), the scour zone reached the position of core X, removed the previously deposited blanketing sediment and exposed the upper, green layer of the core. The high tide beaches were characterized by no fresh-water outflow, the steepest foreshore slope and virtually no surf zone. Consequently, deposition of the green and orange tracer particles was predominantly landward, with only the very finest grain-sized particles of either tracer color being carried seaward. Scour did not reach the blue-green tracer particles which were 8 to 12 cm below the pre-tidal-cycle beach surface.

After the high tide had subsided to mid ebb tide levels (Figure 10D), the scour zone, located in the seaward half of the swash-backwash zone from mid flood to mid ebb tide and this time in advance of the swash-backwash deposits, reached core Y. The remainder of the red tracer particles of core Y were then scoured. Most of the particles were subsequently deposited in the vicinity of sample site #2.

Later, during the ebb tide (Figure 10E), the fresh-water effluent zone began to recover from the sea water intrusion that had been caused by

Table 3. *Tracer particle distribution of Swantown field site beach, March 19, 1987.*

Sample Site	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	−1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#1	1	–		–	–	–	–
	2	1	–	–	–	–	–
	3	20	–	–	–	–	–
	4	50	4	–	–	–	–
	fines	450	9	–	–	–	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	−1	–		–	–	–	–
	0	–	–	–	–	–	–
#2	1	1	–	–	–	–	–
	2	–		–	–	–	–
	3	1	–	–	3	–	–
	4	–	–	–	3	1	–
	fines	–	8	–	11	11	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	−1	–		–	–	–	–
	0	–	–	–	–	–	–
#3	1	–	–	–	–	–	–
	2	2	–	–	4	2	–
	3	2	–	–	18	–	–
	4	–	1	–	–	3	1
	fines	–	3	–	3	14	1
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	−1	–	–	–	–	–	–
	0	–	–	–	–	–	–
#4	1	–	–	–	2	–	–
	2	2	–	–	–	–	2
	3	–	–	–	–	–	8
	4	–	–	–	–	1	6
	fines	1	1	–	5	4	9

— indicates no tracers found.

the rising tide. The sediment lens was shifted seaward to the center of the swash-backwash zone and the scour zone was extended underneath the widening surf zone. Scour also became deeper, removing the yellow tracer particles both to the step under the breaker zone and to the center of the swash-backwash zone. Those yellow tracer particles deposited in the swash-backwash zone were predominantly recovered at sample site #3.

As the tide continued to recede, most of the material that was transported by swash was also transported by backwash, due to the addition of water from the effluent zone. Maximum deposition occurred, not in the central or shoreward portion of the swash-backwash zone, but near the surf boundary (Figure 10F). The recovery of blue tracers from core Y (initially 8 to 12 cm at depth) in the scoop samples indicates that the depth of scour was also enhanced by the buoying effect of the groundwater upon the beach sediment. Those tracer particles that were not moved to the sediment lens in the swash-backwash zone were deposited under the breaker zone.

When the swash-backwash zone retreated seaward of sample site #4, the swash and backwash deposited sediment began to broaden and thin out, reflecting the effluent nature of the low tide water table. The sediment was translated seaward and the former profile was eventually re-established. This process explains the presence of the blue grains, as well as the finer-grained red and yellow tracer particles that were recovered seaward of core Y at sample site #4.

Additional runs of the tracer experiment were made on higher elevations of each beach

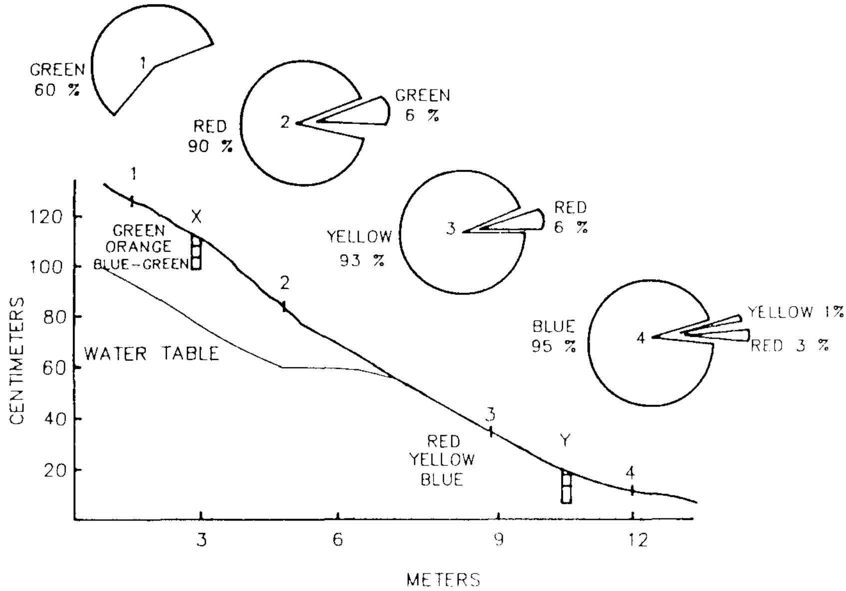

Figure 7. Profile of Lummi Island field site with pie diagrams that summarize the percent of each tracer color recovered at each sample site. Missing sections of pie represent tracer colors that were present only in the 4 Φ or finer grain sizes. The fine-grained tracers found at each sample site are as follows: (1) Yellow 24%, orange 7%, blue 6%, red 3%. (2) yellow 2%, blue 2%. (3) Green 1%. (4) Green 1%.

during the same tidal-cycles. It is evident in the upper beach data that even greater swash transport took place in the field tests above the water table than in the field tests made below the water table. More particles were recovered in these tracer observations instead of being lost to the step under the breaker zone, and core Y tracer particles were found at higher elevations on the foreshore than in the groundwater observations. This discrepancy is especially apparent in the data of the upper-beach test performed on Lummi Island on June 12, 1987, listed in Table 4.

It must be noted that the enhanced swash transport observed in this test and the other field tests performed on Lummi Island is primarily due to the steep foreshore slope, the coarse-grained sediment and the very narrow surf zone of the beach. These factors dominate over the effect of the effluent zone on sediment transport during much of the tidal-cycle.

SUMMARY

Fluorescent tracers implanted on beaches with groundwater effluent zones midway up the foreshore show a pattern of tidal-cycle sedimentation as follows:

Early in the tidal-cycle, backwash erosion is enhanced by groundwater effluence, and backwash deposition occurs in the seaward half of the swash-backwash zone. Most of the sediment scoured by the surf is removed to the step under the breaker zone, although a portion of the finer-grained particles are deposited in the sediment lens of the swash-backwash zone.

At high tide, the fresh-water outflow is blocked. Enhanced swash velocities localize the deposition of the sediment lens in the landward half of the swash-backwash zone. Scour predominates in the seaward half of the swash-backwash zone. From high tide to low tide, groundwater outflow rates steadily increase, shifting both the sediment lens and the scour zone seaward. More sediment is deposited under the breaker zone and scour reaches its greatest depth.

As is apparent, the effect of the water table on tidal-cycle sedimentation is only significant near the beginning and end of the tidal-cycle when outflow rates and, consequently, backwash velocities are greatest. During the rest of

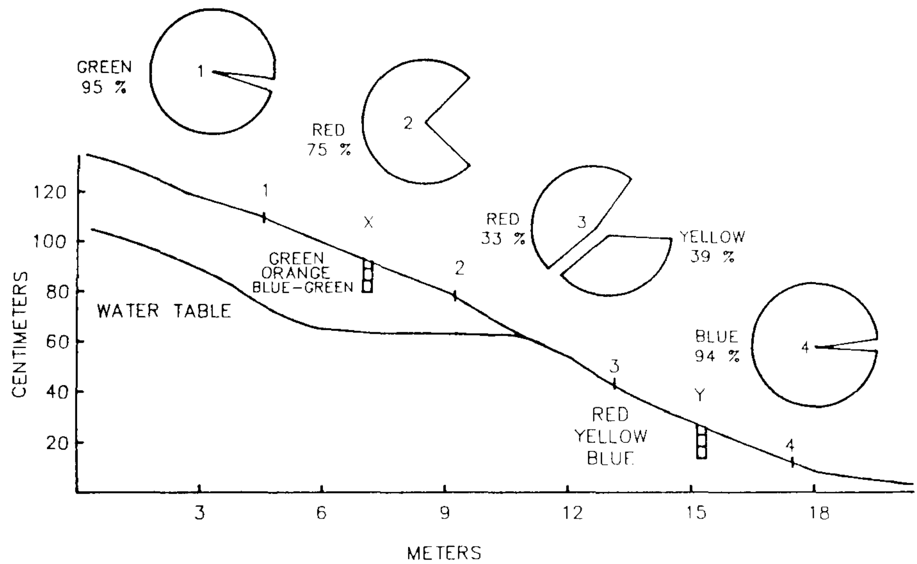

Figure 8. Profile of Naval Base field site with pie diagrams that summarize the percent of each tracer color recovered at each sample site. Missing sections of pie represent tracer colors that were present only in the 4 Φ or finer grain sizes. The fine-grained tracers found at each sample site are as follows: (1) Orange 4%, red 1%. (2) Blue 13%, green 4%, orange 4%, yellow 4%. (3) Green 27%, blue 1%. (4) Green 3%, red 2%, orange 1%.

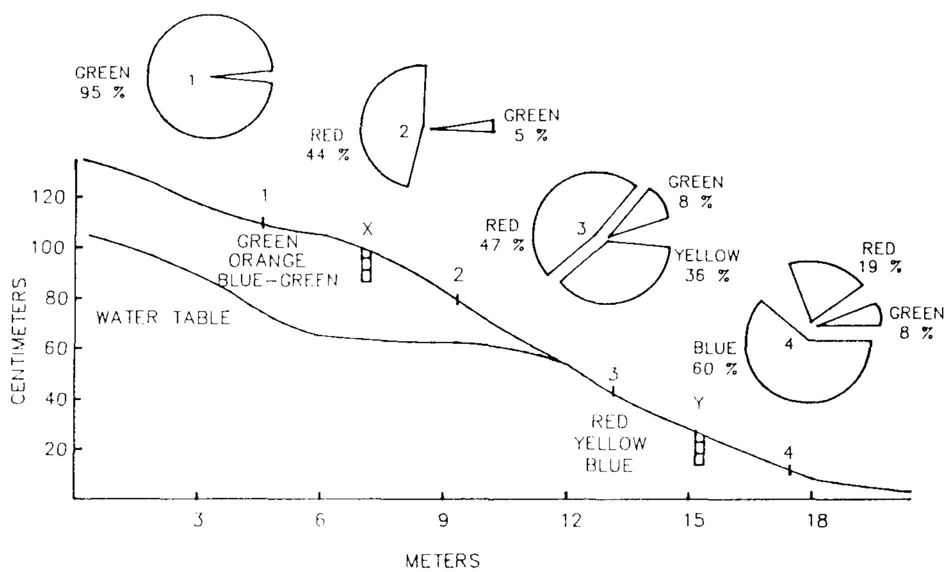

Figure 9. Profile of Swantown field site with pie diagrams that summarize the percent of each tracer color recovered at each sample site. Missing sections of pie represent tracer colors that were present only in the 4 Φ or finer grain sizes. The fine-grained tracers found at each sample site are as follows: (1) Orange 2%. (2) Yellow 31%, orange 20%. (3) Orange 7%, blue 2%. (4) Yellow 12%, orange 2%.

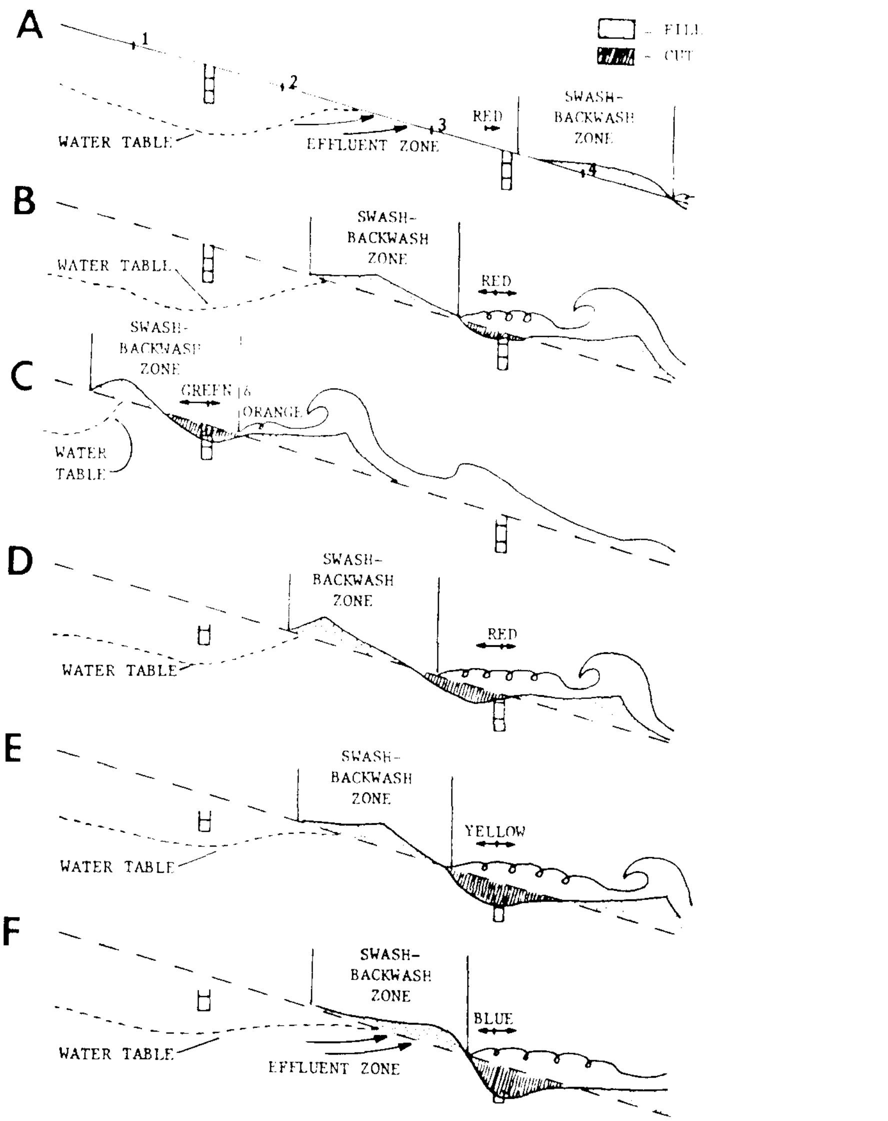

Figure 10. Generalized pattern of beach sediment and tracer particle transport throughout the tidal-cycle on a beach with a mid-foreshore groundwater effluent zone.

the tidal-cycle, swash deposition and swash erosion control sediment distribution.

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Table 4. *Tracer particle distribution of Lummi Island field site beach above the water table, June 12, 1987.*

Sample Site	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–	–		–
	0	–		–	–	–	
#1	1	6	–	–	–		–
	2	10	1	–	–	–	–
	3	135			1	1	1
	4	580		–	8	4	–
	fines	490	3	–	84	29	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–	–		–	–
	0			–	–	–	
#2	1	–	–		–	–	2
	2	1	–	–	1	1	1
	3	–	–	–	20	1	–
	4	–	–	–	170	1	1
	fines	–	–	–	350	6	–
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1		–	–	–	–	–
	0	–		–	–	–	1
#3	1	2	–	–		–	4
	2	–		–	–	–	2
	3	–	–	–		–	–
	4	–	–	–	–	2	7
	fines	3	1		–	17	16
	Φ size	Green	Orange	Blue-G	Red	Yellow	Blue
	-1	–	–		–	–	–
	0	–	–	–			–
#4	1	–		–	–	–	6
	2	–	–			–	38
	3	–	–	–		–	240
	4	2			–	1	360
	fines	4	1	–	3	2	64

- indicates no tracers found.

It must be noted that the enhanced swash transport observed in this test and the other field tests performed on Lummi Island is prmarily due to the steep foreshore slope, the coarse-grained sediment and the very narrow surf zone of the beach. These factors dominate over the effect of the effluent zone on sediment transport during much of the tidal-cycle.

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RÉSUMÉ

Les zones de résurgence de la nappe phréatique sur l'avant plage montrent en détail la sédimentation au cours d'un cycle de marée. La distribution de particules tracées sur 3 plages, où la hauteur des vagues est inférieure à 35 cm, suggère que les influences de la pente de l'avant plage et du grain moyen sont plus importantes que celle de la hauteur du plan d'eau sur les vitesses de transport par jet de rive. Les effets de l'effluence sur la sédimentation du cycle de marée ne sont signifiants qu'aux moments proches du début et de la fin du cycle, lorsque les vitesses, et par voie de conséquence les vitesses de jet descendant sont plus importantes. Pendant le reste du cycle, le dépôt et l'érosion par jet de rive controlent la distribution des sédiments. Des plages composées de matériau plus grossier et dont la pente de l'avant plage est plus forte ont une zone de déferlement plus étroite. Cela résulte des plus grandes vitesses du jet de rive qui se traduit par un dépôt de sédiments en direction de la terre. A marée haute, cet effet est particulièrement prononcé parce que le gradient du haut de plage est plus accentué.—*Catherine Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ RESUMEN □

Las zonas de efluencia de aguas subterráneas muestran un detallado esquema del ciclo de sedimentación mareal. La distribución de partículas trazadoras sobre tres playas con altura de ola, generalmente, menor de 35 cm, sugiere que la influencia de la pendiente y del tamaño medio del grano de la playa es más importante en las velocidades de transporte en el ascenso y descenso del agua sobre el talud que la influencia de las grandes mareas. El efecto de la zona efluente en el ciclo de sedimentación mareal es solamente significante cerca del principio y final del ciclo de marea, cuando el flujo saliente y, consecuentemente, las velocidades de descenso son mayores. Durante el resto del ciclo mareal, la deposición y erosión en el ascenso del agua controlan la distribución de sedimentos. Playas con sedimento grueso y pendientes abruptas tendrán estrechas zonas de rotura, resultando mayores velocidades de ascenso y aumento de la deposición de sedimento en dirección a tierra. En una marea grande, este efecto es especialmente pronunciado debido al fuerte gradiente de la zona superior.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Grundwasser-Austrittszonen am nassen Strand zeigen ein detailreiches Muster der Sedimentation im Gezeitenzyklus. Die Verteilung von Tracer-Partikeln an drei Stränden mit Wellenhöhen von weniger als 35 cm belegen, daβ der Einfluβ der Böschung des nassen Strandes und die mittlere Korngröβe wichtiger für die Schwallprozesse und Schwallgeschwindigkeiten ist als der eines hohen Grundwasserstandes. Der Effekt des Grundwasseraustritts auf die zyklische Gezeitensedimentation ist nur wichtig im Anfang und am Ende des Tidezyklus, wenn die Austrittsraten und damit die Strömungsgeschwindigkeiten am gröβten sind. Während des Restes des Tidezyklus wird die Sedimentverteilung durch Schwallablagerung und Schwallabtragung bestimmt. Strände mit gröberen Sedimenten und steilerer Böschung im nassen Bereich haben engere Brandungszonen, woraus eine höhere Schwallgeschwindigkeit und damit landwärtiger Sedimenttransport resultiert. Bei Hochwasser ist dieser Effekt ausgeprägter wegen des steileren Gradienten des oberen Strandabschnittes.—*Dieter Kelletat, Essen / FRG.*