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Seasonal Patterns of Onshore/Offshore Sediment Movement

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Measurements of beach profiles from southern California spanning a 5-year period have been examined for temporal changes in beach configuration. On an annual time scale the data suggest two distinct seasonal pivotal points separating eroding and accreting regions. Empirical eigenfunction analysis of combined onshore and offshore profiles shows a pivotal point for seasonal onshore/offshore sediment movement at a depth of 2–3 m below mean sea level and suggests another at a 6-m depth. Analysis of accurate reference rod measurements at 4-, 6-, 10-, 14-, and 20-m depths supports the presence of the 6-m pivotal point. A simple model of depth-dependent seasonal sand movement suggests that during initial winter storms, sand is eroded from both the foreshore and from depths of 6–10 m and is deposited in water depths from 2 to 6 m. During less energetic periods, sediment migrates both shoreward (to the beach face) and seaward (to depths of 10 m) from its winter site of deposition (water depths from 2–6 m). This observation of depth-dependent motion contradicts the simple single pivotal point model previously suggested for nearshore seasonal onshore/offshore sediment motion and emphasizes the complexity of nearshore sediment transport. A sediment budget for seasonal onshore/offshore transport, based on the dual pivotal point model, consists of exchanges of 85 m^3/m of beach length across the 3-m pivotal point and 15 m^3/m across the 6-m pivotal point. Over a longer time scale (i.e., the entire 5 years of study) the beaches showed no net erosion or accretion, suggesting that this limited coastal region is stable over these short time scales.

INTRODUCTION

Investigators have long recognized that beaches along the southern California coastline experience a distinct seasonal onshore/offshore movement of sand [e.g., *Shepard,* 1950; *Shepard and Inman,* 1950, 1951; *Inman,* 1953; *Inman and Rusnak,* 1956]. During summer (approximately June through October) the beach foreshore accretes, while the offshore loses sediment. In winter (November through May) the process is reversed, with the subaerial beach eroding and the sediment migrating offshore. These beach changes respond to the seasonal variation in wave frequency and directional properties [e.g., *Pawka et al.,* 1976]. Small-amplitude, long-period waves predominate in summer, while higher-energy, high-frequency storm waves occur more often in winter. This wave climate controls the seasonal redistribution of nearshore sediments.

The magnitude and timing of seasonal sand level changes have not been accurately documented because of the difficulty in measuring offshore sand levels. *Inman and Rusnak* [1956] collected beach profile data for 3 years but could not accurately measure changes between mean lower low water (MLLW) and the 9-m contour. Other studies [e.g., *Gorsline,* 1966; *Sonu and Van Beek,* 1971] have also failed to measure offshore changes accurately. Because of the difficulty in measuring sand levels offshore, models of seasonal onshore/offshore transport have not been previously tested. These models can now be evaluated using the present data set. A pivotal point, as defined in this study, separates eroding and accreting regions. Associated with this erosion/accretion is a measurable phase lag which may range from a few months to half a year. According to this working definition, sand level changes need not be always out of phase across a pivotal point, and sand level changes at a pivotal point are not necessarily small (a pivotal point is not a nodal point).

The present study was performed at Torrey Pines Beach, California, about 3 km north of Scripps Institution of Oceanography (Figure 1). The site is a long (3 km) relatively straight sandy beach with uncomplicated offshore bathymetry, located far enough north that the Scripps–La Jolla submarine canyon system does not significantly affect the refraction of the wave field. There are no offshore bedrock formations (such as reefs) to impede the onshore/offshore or longshore movement of sand, so Torrey Pines Beach is not an isolated pocket beach. The mean tidal range at this site is approximately 2 m. In June 1972, three range lines were established along the beach for this study (Figure 2): North Range (NR), Indian Canyon Range (IC), and South Range (SR).

METHODS

The onshore and offshore portions of the beach profile were measured on at least a monthly basis. Details of the profiling techniques can be found in the work of *Inman and Rusnak* [1956], *Nordstrom and Inman* [1975], and *Aubrey* [1978]. The onshore profile was measured out to MLLW with an engineer's level and rod. The subaqueous profile was measured with a fathometer from the surf zone out to 20-m depths, supplemented by reference rod measurements at 11 offshore stations (Figure 2 and Table 1). The fathometer readings (which have an accuracy of approximately ±30 cm) were corrected by the more accurate reference rod readings to reduce the profiling error. Reference rod stations were nominally located at 5-, 7-, 10-, 14-, and 20-m depths (Table 1). Their position was accurately determined by a microwave range-positioning device, and their mean depth with respect to mean sea level was determined to within 15 cm from a series of lead line soundings taken on different days, corrected for tides, and averaged. Sand level changes near the rods were referenced to the sand level at the time the rods were emplaced (with 30 cm exposed). When possible, the onshore and offshore profiles overlapped.

The onshore and offshore surveys were combined to yield a time series of profiles over the 5-year period. Eigenfunction analysis of the profiles was used to examine the time variability of the beach changes. The eigenfunction analysis was an attempt to objectively separate the time scales of variability and has been applied previously to beach profile data [e.g.,

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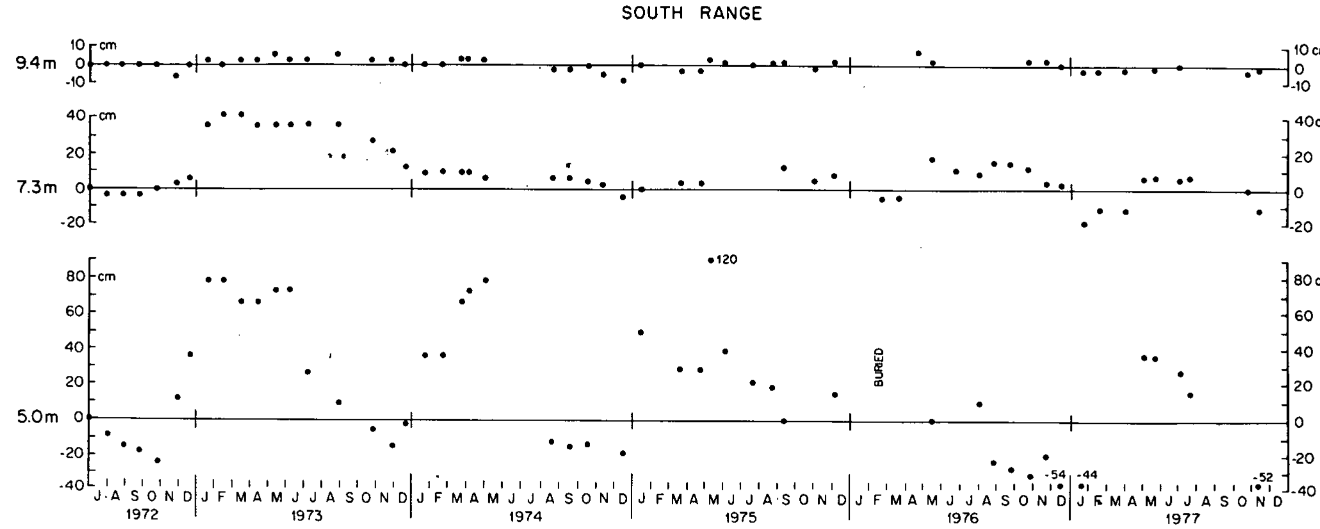

Fig. 8. Sand level changes for three depths along South Range measured from reference rods. Positive values represent accretion; negative values represent erosion.

from the beach backshore and foreshore as well as from depths of 6–10 m. The sediment from both the beach and offshore erosion is deposited in depths of 2–6 m below mean sea level. Following the major storm season, the sediment accumulation in the 2- to 6-m depths disperses, perhaps some moving shoreward under the influence of waves, some moving seaward under the influence of gravity. This sequence is possibly not valid for beaches without dominant seasonal wave climates.

Over the 5-year period of measurements the beach did not experience any net erosion or accretion. Since the study area is at the downdrift terminus of a littoral cell, this stable trend cannot be extrapolated to updrift beaches, which experience erosion much sooner than their downdrift counterparts.

APPENDIX

Empirical eigenfunctions (empirical orthogonal functions) are used to reduce the number of data variables required to represent a specified data set. The eigenfunctions are derived from sample covariance estimates, so the structure of the functions is defined by the actual data set and does not assume some a priori functional form (such as does a Fourier representation). The functions are orthogonal, each function representing a certain amount of the mean square value of the data. The eigenfunction associated with the largest eigenvalue represents the data best in a least squares sense, while the second function (in rank) describes the residual mean square data best in the least squares sense. Thus a large number of data variables can be efficiently represented by a few empirical functions that describe most of the mean square value of the data.

The data are expanded in terms of orthogonal functions both in space and time:

$$h(x, t) = \sum_{l=1}^{n} a_l c_l(t) e_l(x)$$

where a_l represents normalizing factors, $c_l(t)$ is the temporal eigenfunction, $e_l(x)$ is the spatial eigenfunction, and $h(x, t)$

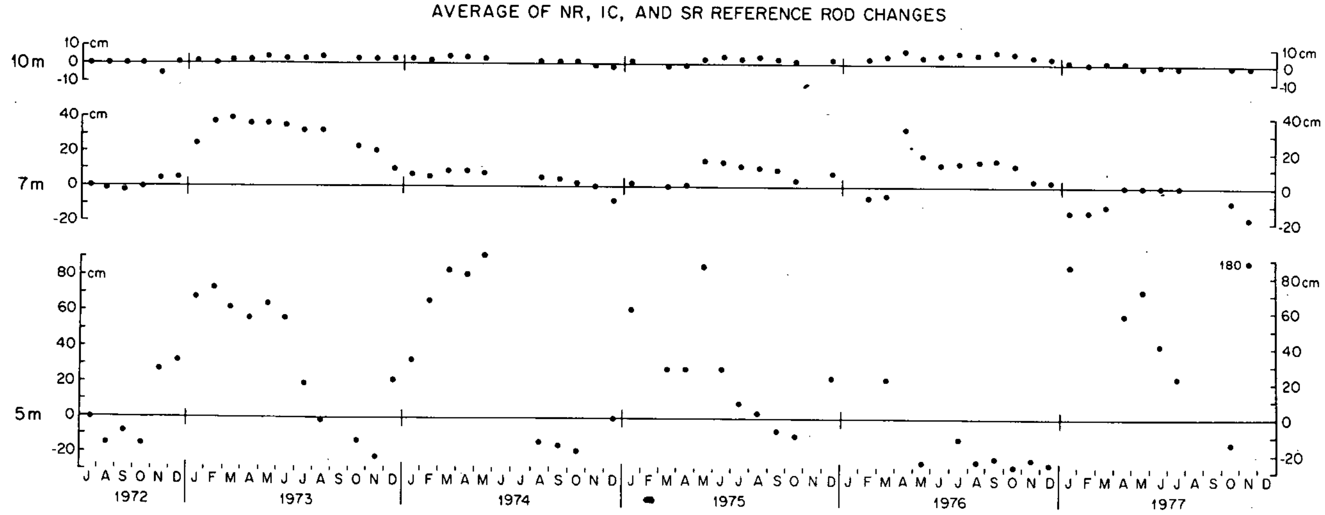

Fig. 9. Mean sand level changes at three depths for North, Indian Canyon, and South Ranges, measured from reference rods. Positive values represent accretion; negative values represent erosion.

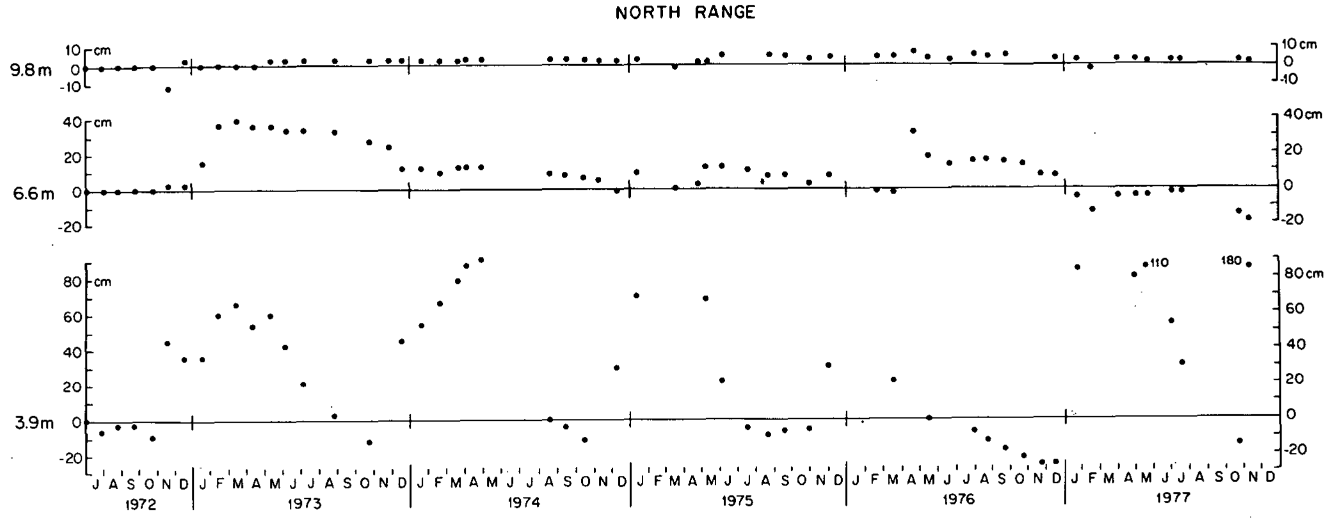

Fig. 6. Sand level changes for three depths along North Range measured from reference rods. Positive values represent accretion; negative values represent erosion.

mately 80–85 m^3/m of sediment, or 5–6 times that passing the seaward pivotal point. The author is unaware of any data sets against which this model can be compared except for some independent data collected by *Inman and Rusnak* [1956] at a nearby beach. Although their study did not define beach changes in depths of less than 9 m and therefore the pivotal point concept cannot be checked, their deep measurements can be checked for consistency with the present model. The magnitude of the sand level changes at depths comparable to the present study agree reasonably well (Table 3).

CONCLUSIONS

Beach profiles spanning a 5-year perod and extending from the beach backshore to depths of approximately 20 m have clarified the onshore/offshore sediment transport on a southern California beach. Eigenfunction analysis of the profile data out to depths of approximately 7 m located the depth of a shallow pivotal point for seasonal sand movement. Seaward of this 2- to 3-m pivotal point, erosion (accretion) occurs at the same time that accretion (erosion) takes place shoreward of this point. The eigenfunction analysis also suggested another pivotal point in approximately 6 m of depth.

To explore the possibility of a second nodal point, the reference rod measurements from 5-, 7-, 10-, 15-, and 20-m depths were examined. These measurements indicate a phase lag between the accumulation and erosion of sand at the 5-and 7-m stations. This phase lag supports but does not establish the pivotal point suggested by the eigenfunction analysis.

The sequence of onshore/offshore sediment motion in southern California consists of storm-induced sand redistribution followed by a return flow during more quiescent conditions. At the time of the first winter storms, sand is eroded

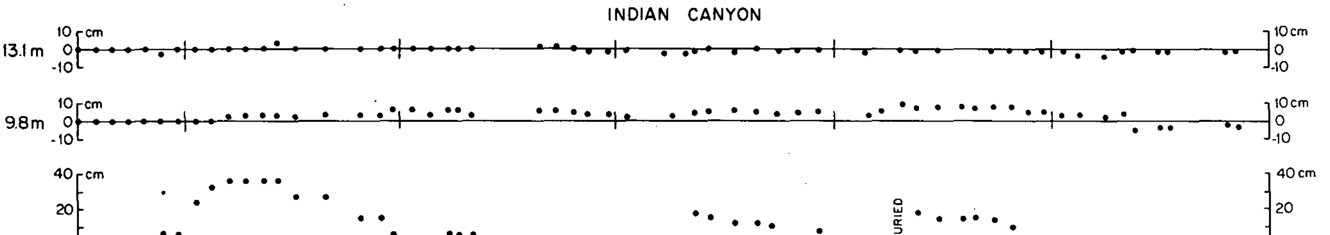

Fig. 7. Sand level changes for four depths along Indian Canyon Range measured from reference rods. Positive values represent accretion; negative values represent erosion. Annotation at the 3.8-m depth explains why rod measurements were not available.

TABLE 2. Percentage of the Mean Square Value of the Data Explained by the First Five Eigenfunctions for the Period June 1972 Through November 1977

Function	North Range		Indian Canyon		South Range	
1	99.36		99.25		99.41	
2	0.25	(40.4)	0.38	(50.6)	0.30	(51.0)
3	0.14	(21.6)	0.13	(17.3)	0.11	(18.5)
4	0.07	(11.0)	0.09	(11.6)	0.07	(11.5)
5	0.06	(9.5)	0.06	(8.3)	0.04	(7.6)
Total	99.88	82.5	99.91	87.8	99.93	88.7

Numbers in parentheses are percentages of residual mean square value explained after removing the first eigenfunction. The term $n_x = 44$; $n_t = 63$. Total mean square value for North Range = 9.78 m^2; Indian Canyon = 9.62 m^2; South Range = 12.55 m^2.

A strong seasonality in sand level changes exists at both the 5- and 7-m stations (Figures 6–8) but with a phase difference in the time response of the sand changes at the two depths. When the 5-m sand level begins to increase, the 7-m sand level decreases. After a lag of 1 or 2 months the sand level begins to increase at the 7-m depth, while the sand level decreases at the 5-m depth, suggesting an onshore/offshore sediment exchange between these two depths. This phase lag is better illustrated when sand level changes at each depth for the three ranges were averaged together (Figure 9).

After the first storm occurrence of every year the beach backshore and foreshore are eroded, and the material is deposited offshore (Figures 9 and 10). At the same time the large storm waves apparently move sediment from 7-m depths shoreward (seaward movement is not supported by deeper reference rod measurements). After a lag of a month or two the sediment returns to the 7- to 10-m depths as the sediment stored in 2- to 6-m depths begins to diffuse both landward and seaward. This seaward sediment movement (associated with decreased storm activity) may be related to the increased down slope gravitational force created by the increase in slope between the 5- and 7-m contours. If the net wave-induced, shoreward-directed bottom shear stress (the skin friction) cannot balance the increased gravitational stress, the sediment will move seaward toward a more stable equilibrium slope as it is acted on by waves.

The sand level remains at this accretionary level until the following fall, when the storm activity begins again, repeating the yearly cycle. The discrete onshore/offshore positioning of the reference rod arrays obscures the shoreward limit of this onshore migration under storm waves. An accurate profiling system that is not influenced by storm waves or bad weather is needed to better define the magnitude of the sand level changes in water depths of 2–6 m.

The detailed mechanics of this sediment redistribution are not understood. Too little is known of sediment transport under combined wave/current flows to accurately predict sediment transport rates and direction. Mass transport velocities, nearshore tidal flows, and wind-induced nearshore currents are also poorly known, so their effect on sediment transport is hard to quantify. The boundary layer structure and variability of the near-bottom rough turbulent flow, which strongly influence sediment transport, need more theoretical and field work before they will be well quantified. Nearshore wave shoaling, a highly nonlinear process, is also poorly understood, both theoretically and observationally. Since velocity asymmetries are reflected in the shear stress, nonlinear wave shoaling influences sediment transport. Each of these topics must be addressed if onshore/offshore sand transport is to be understood on a physical basis.

A crude sand budget schematic combined with phase information describes a simple model of seasonal onshore/offshore sand movement (Figure 10). The sediment exchange associated with the 6-m pivotal point was calculated solely from the reference rod measurements. Assuming no motion at the 6- and 10-m depths and a maximum sand level change of 0.14 m at 7 m, decreasing linearly both seaward to 10 m and shoreward to 6 m, this exchange is about 15 m^3/m of beach length. The sediment exchange associated with the 2- to 3-m pivotal point, calculated from the profile data itself, averages approxi-

TABLE 3. Listing of the Number of Observations *N*, the Mean, and the Standard Deviation of Sand Level Changes for Each Reference Rod Station Over the 5-Year Period of Study

	N	Mean, cm	Standard Deviation, cm	Range in Sand Level, cm
North Range				
9.8 m	55	+2.0	2.6	
6.6 m	56	+10.4	12.5	
3.9 m	49	+29.2	42.8	
Indian Canyon				
21.0 m	38(40)	−0.2	0.6	2 (5)
13.1 m	56(49)	−0.8	1.4	7 (5)
9.8 m	57(45)	+3.1	3.1	16 (9)
6.8 m	56	+6.3	14.4	
3.8 m	40	+17.6	43.3	
South Range				
9.4 m	51	+0.2	3.2	
7.3 m	53	+9.3	14.5	
5.0 m	47	+20.1	37.6	

All measurements are referenced to the sand level at the time the rods were installed. Numbers in parentheses refer to the results of the study by *Inman and Rusnak* [1956].

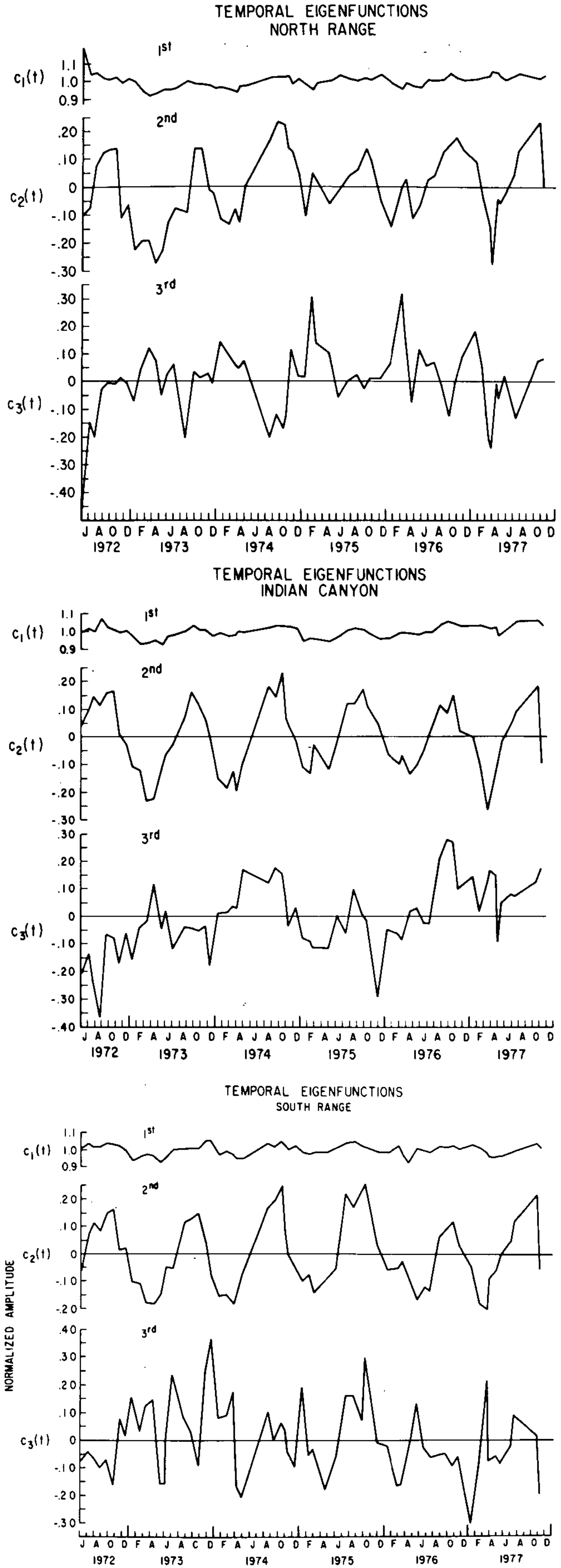

Fig. 5. Temporal structure of the eigenfunctions for the three ranges over the period of June 1972 through November 1977.

ence rod measurements were examined in detail, since they were the most accurate measurements of offshore sand movement and must be used in place of the fathometer traces where bed changes are small. The means and standard deviations of the reference rod readings along with the number of observations for each reference rod station are listed in Table 3. The number of observations varies slightly because of inclement weather, reference rod burial, and on rare occasions lack of time to measure all 11 sets of rods.

Along all three ranges the rod measurements for the 5-m stations are discontinuous in the winter (Figures 6–8) because either the rods were buried or rough seas prevented their measurement. When the rods were buried, a series of lead line soundings was taken, corrected for tides, and used in place of the reference rod readings. Though these are not as accurate, great care was taken to correct them to local mean sea level to obtain a usable number for comparison with the other reference rod measurements.

Sand level changes at the 20-m station at IC never exceeded 1 cm over the entire study and had a standard deviation of 0.6 cm. This is within the limits of measurement error. The reference rod measurements at the 15-m station at IC show no seasonality (Figure 7). Sand level changes never exceeded 5 cm and were generally less than 2 cm. The apparent loss of 1 cm over the 5-year term of the experiment could be a result of kelp gradually pulling the rods slightly out of the sand. The standard deviation of the 15-m rods during the study was approximately 1.4 cm.

The nominal 10-m rod stations for all transects have a mean rod exposure which varied by only 2 cm between the ranges (Figures 6–8, Table 3). Part of this variation could be a diver error in inserting the rods, since all calculations were based on changes from the initial 30-cm exposure of the rods. If NR rods at 10 m were actually installed with 28 cm exposed, then the three mean readings for the 10-m stations would be within 0.2 cm. This suggests that the sand level in depths of 10 m and greater has not undergone any significant net change over the 5-year period of study. The standard deviations for the 10-m stations were remarkably similar, ranging from 2.6 to 3.2 cm. The changes in sand level at the 10-m stations are not very seasonal, so this 10-m depth marks the maximum offshore depth limit for coherent seasonal sand level changes, assuming the 10-m depth is not another pivotal point of sand motion.

The sand level changes became more pronounced in depths less than 10 m. The mean sand level at 7 m consistently shoaled by about 8.5 cm with respect to the depth at which the rods were installed. The standard deviation of the sand level changes (inferred from rod measurements) for the three stations varied only from 12.5 cm to 14.5 cm, or approximately 4.5 times that at the 10-m station.

Sand level changes at the 5-m stations were even greater, the mean position of the sand level being approximately 22 cm above the sand level at the time the rods were initially emplaced. It is no surprise that the reference rods from these depths were buried so often, since their initial exposed length was only 30 cm. The standard deviations of the sand elevations were comparable, ranging from 37.6 to 43.3 cm. Considering the problems with measuring and maintaining the rods at this depth, these standard deviations are remarkably close. The smallest standard deviation was at SR, where the rods were in water 1 m deeper than the two other sets of reference rods, suggesting a noticable decrease in sand movement with even a small increase in water depth.

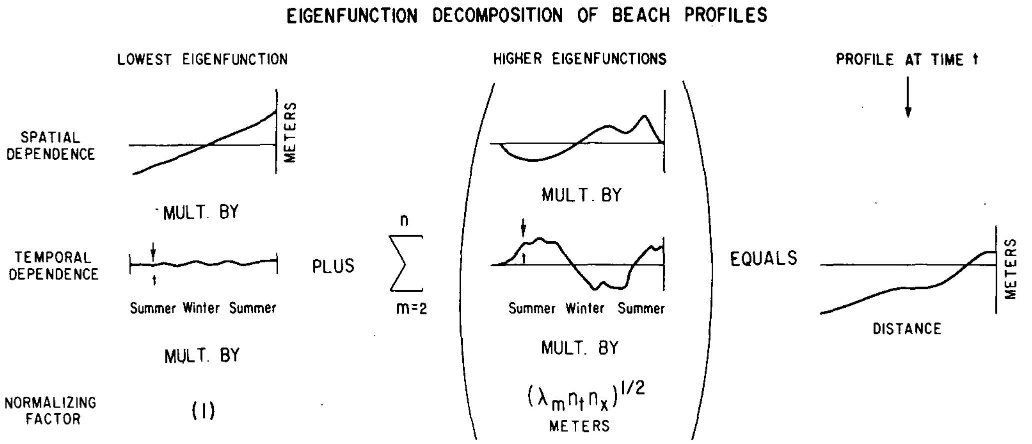

Fig. 3. Schematic of empirical eigenfunction decomposition of beach profile data.

RESULTS

Eigenfunction analysis was performed on monthly profile data taken at each of the three ranges at Torrey Pines Beach over a period of 5 years and covered the beach backshore seaward to a depth of approximately 7 m. The analysis was not carried deeper than 7 m because fathometer errors masked the small sand level changes at these depths. Reference rod measurements alone were relied on for these greater depths. The spatial dependence of the first three eigenfunctions for this interval has a similar shape for all ranges (Figure 4). The second (seasonal) function shows a maximum near the shore and a minimum offshore. The third function has a broad maximum over the low-tide terrace. The first eigenfunctions in all three cases have similar slopes.

Temporal eigenfunctions for the three transects exhibit similar shapes as well (Figure 5). The first function has no net trend to it (based on a linear fit to the data), indicating no net erosion or accretion on this stretch of coastline during the 5 years of observation. The second eigenfunction shows a distinct seasonal dependence. representing the seasonal onshore/offshore movement of sediment. The time dependence of the third eigenfunction is more complicated, consisting of a weak seasonality with superimposed high-frequency changes. This function partly describes how the beach oscillates between a berm profile and a bar profile, since the second eigenfunction (a standing wave) cannot describe the progressive motion of the sand.

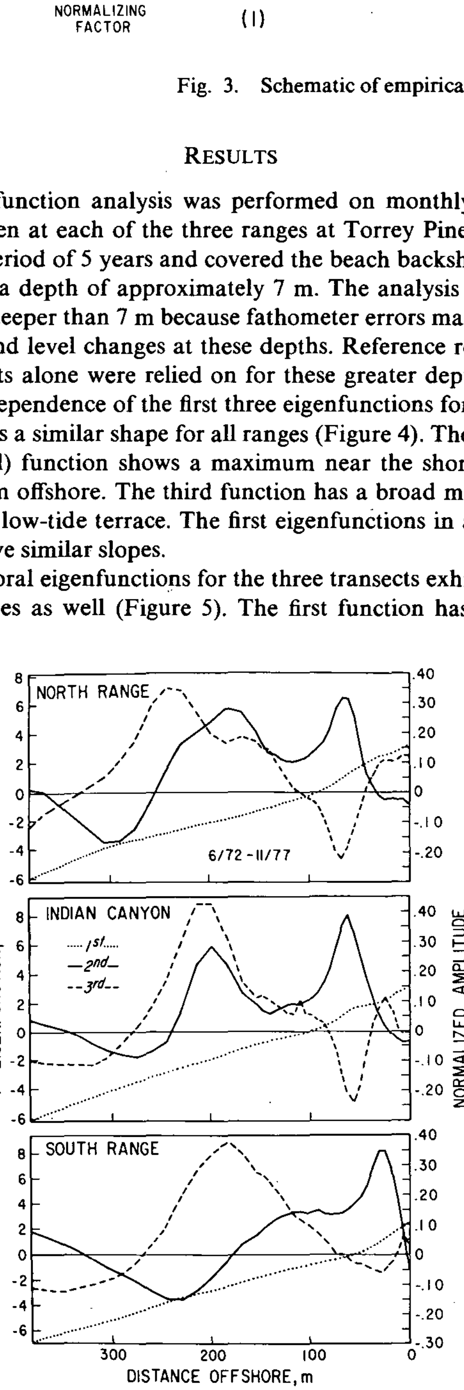

Fig. 4. The spatial dependence of the eigenfunctions for the three ranges over the period of June 1972 through November 1977.

The eigenfunctions are ranked according to the percentage of the mean square value (MSV) of the data they explain (Table 2). The first eigenfunction explains the vast majority of the MSV. After removing the first eigenfunction (the 'mean' profile in this analysis) from the data the seasonal eigenfunction describes an average of one half of the remaining variance, while the terrace function accounts for about one fifth. The remainder of the variance is distributed among the remaining eigenfunctions. Clearly the first three eigenfunctions describe the dominant modes of beach change.

Since the second eigenfunction appears to adequately represent the seasonal onshore/offshore sediment motion, its spatial dependence should yield an estimate of the pivotal point for seasonal profile changes. This pivotal point, defined by the zero crossing of the second eigenfunction, is at a depth of between 2 and 3 m below mean sea level (Figure 4), or approximately 1 m below the depth of MLLW. This pivotal depth can be coupled with a mean wave height for the study site for comparison with other beach studies. The wave climate has been measured at Torrey Pines Beach on a daily basis since February 1973 [*Pawka et al.*, 1976; *Aubrey*, 1978]. The average mean square elevation of the water surface, $\langle\eta^2\rangle$, for this time period was approximately 500 cm^2, where $E = \rho g\langle\eta^2\rangle$. E is the wave energy density, ρ is the density of the water, g is the gravitational acceleration, and $\langle\eta^2\rangle$ is the variance. This is roughly equivalent to an rms wave height of 60 cm. The wave height and tidal range must play an as yet unexplained role in the location of the pivotal point.

A close examination of Figure 4 shows that for all three ranges the seasonal eigenfunction has a second zero crossing at a depth of approximately 6 m. This suggests that the idea of a single pivotal point may be too simplistic a model for the onshore/offshore sediment motion and that another pivotal point may exist. In order to explore this possibility the refer-

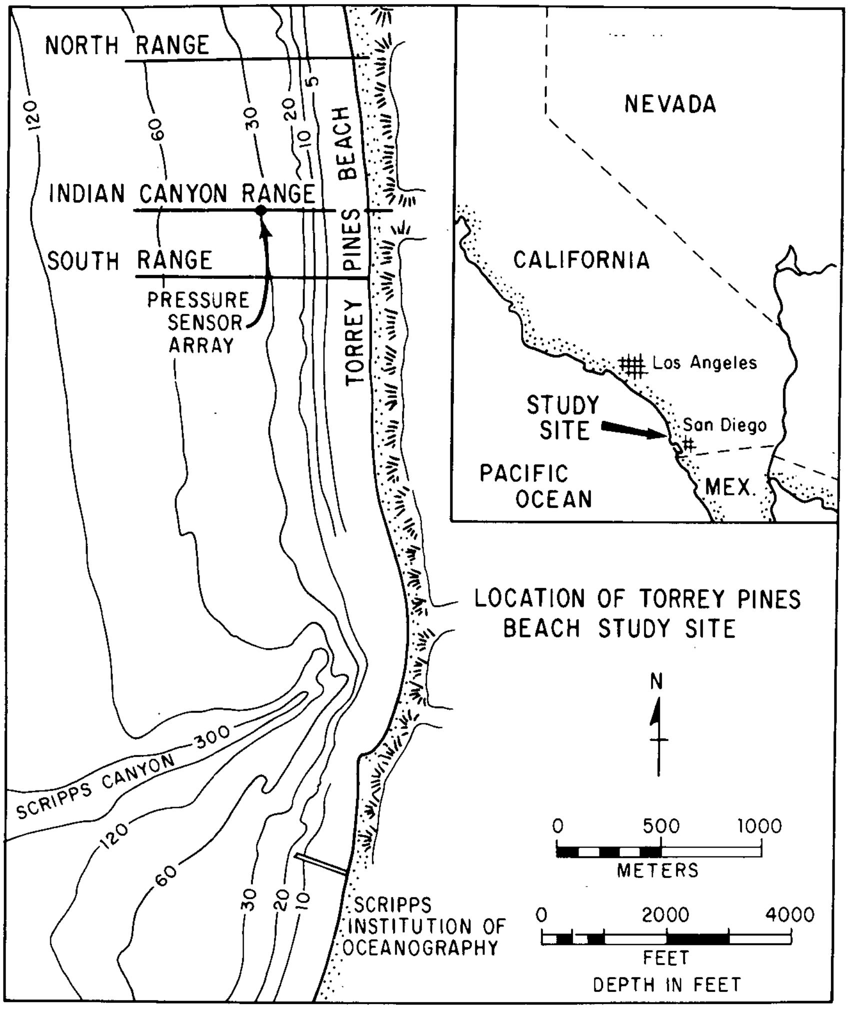

Fig. 1. Map showing location of Torrey Pines Beach and the major rangelines [after *Nordstrom and Inman,* 1975].

Winant et al., 1975; *Aubrey,* 1978]. The appendix contains a brief description of the eigenfunction technique. *Winant et al.* [1975] and *Aubrey* [1978] show that when applied to beach profile data, the eigenfunctions have a physical analog (Figure 3). The first eigenfunction is a mean beach function, analogous to the arithmetic mean profile of the data. If the beach is stable, it has a constant time dependence. The second eigenfunction is the seasonal (or bar-berm) eigenfunction, characterized by a strong seasonal temporal dependence. The third eigenfunction has a broad maximum near the position of the low-tide terrace with a complicated time dependence and is called the terrace function. The higher-order eigenfunctions generally account for only a small percentage of the profile variability.

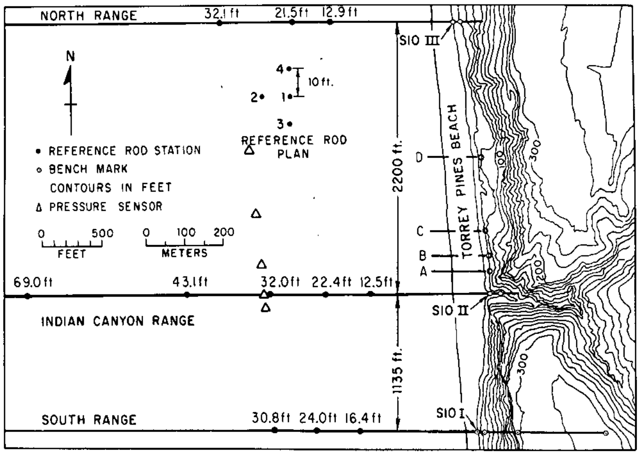

Fig. 2. Map of range line locations and reference rod locations at Torrey Pines Beach.

TABLE 1. Depths and Locations of the 11 Reference Rod Stations

	Mean Depth, m	Distance Offshore, m	Distance Longshore, m*
North Range	9.8	570	+28
	6.6	396	+13
	3.9 (4.1)	300	+4
Indian Canyon	21.0	1148	−42
	13.1	748	−33
	9.8	542	−12
	6.8	417	−10
	3.8 (4.0)	298	−12
South Range	9.4	485	−30
	7.3	390	−30
	5.0 (5.2)	291	−10

Depths in parentheses are the depths of the rods before October 1975, at which time the shallow rods were replaced. The locations refer to the post-October 1975 rod stations. The three ranges were oriented true east-west.

* A + indicates north of range; a − indicates south of range.

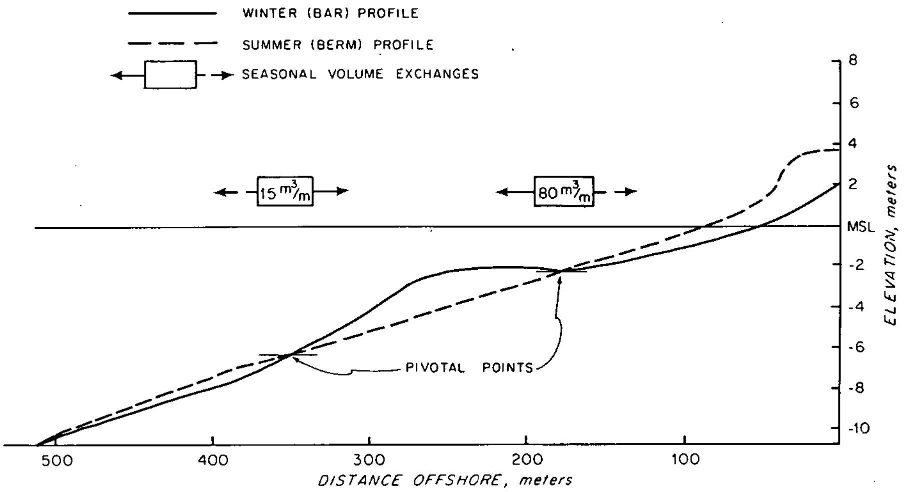

Fig. 10. Schematic of seasonal sand volume changes at Torrey Pines Beach, California, based on a dual pivotal point model.

represents the data. When this method is applied to beach profile data, $h(x, t)$ represents the profile elevation at any point x for any time t. The normalizing factors are determined by

$$a_l = (\lambda_l n_x n_t)^{1/2}$$

where λ_l is the eigenvalue associated with the l^{th} eigenfunction, n_x is the number of points per profile, and n_t is the number of profiles used in the expansion.

The spatial eigenfunctions are simply the eigenfunctions (eigenvectors) associated with the spatial covariance matrix. If a matrix **H** is formed with elements $h(x, t)$, the spatial eigenfunctions are found for the matrix

$$\mathbf{A} = \frac{1}{n_x n_t}(\mathbf{H}\mathbf{H}^T)$$

where T is the matrix transpose operator. The temporal eigenvectors are found for the matrix

$$\mathbf{B} = \frac{1}{n_x n_t}(\mathbf{H}^T\mathbf{H})$$

Alternatively, the temporal eigenfunctions $c_l(t)$ can be found by taking the dot product of the spatial eigenfunctions with the data and dividing by the normalizing factor, analogous to the procedure for calculating weights in Fourier analysis.

Like any Hermitian square matrix, **A** and **B** possess sets of positive real eigenvalues λ_l and eigenfunctions (eigenvectors) which are defined by the equations

$$\mathbf{A}e_l(x) = \lambda_l e_l(x)$$

and, similarly,

$$\mathbf{B}c_l(t) = \lambda_l c_l(t)$$

The sum of the eigenvalues is equal to the trace of the matrices, or in this case the mean square value of the data (mean in both space and time). The matrices **A** and **B** have the same nonzero eigenvalues.

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