MEASUREMENT OF TIDE INDUCED CHANGES TO WATER TABLE PROFILES IN COARSE AND FINE SAND BEACHES ALONG PEGASUS BAY, CANTERBURY

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Abstract

Measurements of changing water table profiles in beaches along Pegasus Bay, Canterbury, show an interchange of water between the sea and beach sand pores throughout a single semi-diurnal tidal cycle. The velocity of water escaping from the water table in response to an ebbing tide does not appear sufficient to elutriate material of silt size or larger from the beach. The low computed velocity is thought to be due to hydrostatic control, by sand dunes at the back of the beach, on water table amplitude. Fresh water and wave wash are considered important supplementary sources to that of tidal water in influencing water table profiles.

INTRODUCTION

Although recent years have seen a rapid growth in literature on various aspects of the coastal environment, few workers have studied interrelationships between beach characteristics and water table profiles in response to fluctuating tidal cycles. Direct contributions have been made in California by Emery and Foster (1948) and Grant (1948) and more recently by Duncan (1964) who examined the response of swash-backwash sediment distributions and sand beach profile development to tide cycle and water table movements. In New Zealand, Kirk (1966) has worked on similar process-response problems in the shingle beaches of Canterbury.

The present study outlines interrelationships between some beach characteristics and changing water table profiles during single semi-diurnal tidal cycles at two beaches along Pegasus Bay, Canterbury. Because of time limitation only two sets of data were collected. The first from a fine grained sand beach at North New Brighton, Christchurch, and the second from a coarse grained sand and pebble beach at Leithfield, North Canterbury (Figure 1). The beaches, separated by about 25 miles of coast, were surveyed on consecutive days (1-2 August 1966) when changes in wind and wave characteristics between days and locations were minimal. A large and contrasting range in beach characteristics between beaches was considered particularly useful in evaluating water table trends relative to tidal change and in providing results for comparison with a similar survey of some Californian beaches by Emery and Foster (1948).
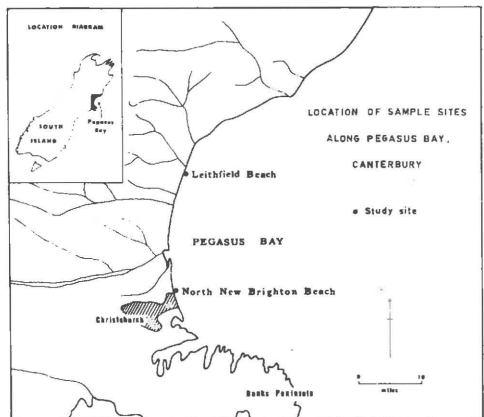

Figure 1.   Location of sample sites along Pegasus Bay, Canterbury.

MATERIALS AND METHODS

Water Table Profiles

Profiles of the water table were measured normal to the shoreline and their changes in response to fluctuating tide levels observed. Equipment and methods of measurement used were similar to those outlined by Emery and Foster (1948, pp. 644-45). A set of pipes, spaced at various intervals along a surveyed sand surface profile (figures 2 and 3), was driven to a point below ebb tide water
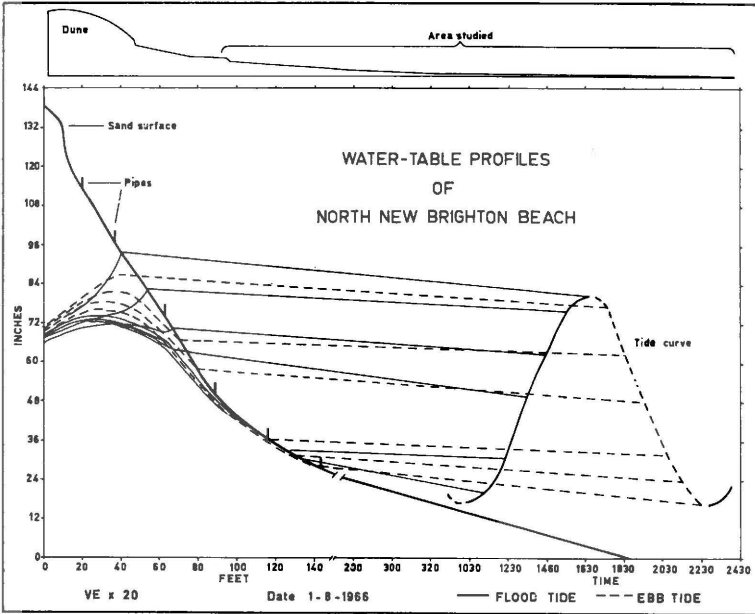

Figure 2. Changes in water table profiles in North New Brighton Beach measured over a single semi-diurnal tide cycle. Insert at top shows the beach with no vertical exaggeration.
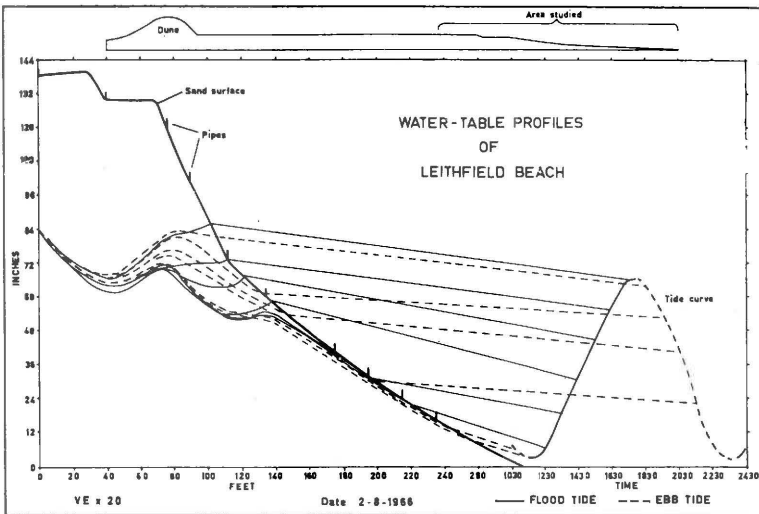

Figure 3. Changes in water table profiles in Leithfield Beach measured over a single semi-diurnal tide cycle. Insert at top shows the beach with no vertical exaggeration.

table level and the distance from sand surface to water table profile measured by inserting a calibrated rod down each pipe. Readings were made easier by painting the rod with black, matt-finish paint which showed glossy when wet. Gauze squares welded over perforations at the sharpened end of each pipe prevented entry of sand from upsetting the measurements.

The location and extent of the effluent zone which marked the intersection of the water table and sand surface was recorded and the relative tide height was observed from a gauge driven into the sand beyond low tide level.

All measurements were repeated at hourly intervals throughout a twelve hour tidal cycle.

Sand Samples

From each survey site one set of five sand samples was collected from within a 2-inch surface layer of sand along the surveyed profile and taken to the laboratory for mechanical analysis where each sample was sorted and classified according to grain size (Krumbein and Pettijohn, 1938). As well, at each site, one set of four sand samples was taken from various depths within the beach for water and salt content analysis. In the laboratory these were weighed, dried, and reweighed; then washed and weighed a third time to gain the percent weight of water, salt, and sand respectively.

A simple measure of permeability was made in the field by timing the passage of a given quantity of water through a cylinder of known dimensions and inserted 1 inch below sand surface.

Porosity values of beach sand at each location were derived by laboratory analysis.

RESULTS

Results of some of the beach and water table characteristics measured are summarized in Table 1.

Table 1. Some Beach and Water Table Characteristics.

Location	Date	Tide height (inches)	Wave height (inches)	Foreshore slope (degrees) Upper	Lower	Median diameter (mm.)	Sorting coefficient
North New Brighton	1/8	60	24	4.5	1.5	0.15	1.23
Leithfield	2/8	62	30	6.0	2.5	2.47	1.84

	Permeability (cc./sec.)	Porosity (vol. %)	Slope of seaward edge of water table (degrees) Ebb-tide	Flood-tide	Water table amplitude under high tide line (inches)
North New Brighton (contd.)	1.85	36.0	2.33	4.33	23
Leithfield (contd.)	8.99	30.0	2.00	2.66	29

Size, Sorting, and Permeability of Sand

Leithfield Beach was the more permeable beach although the nature and arrangement of its material caused considerable irregularity of rates both along and within the surveyed profile (Appendix I). Material ranged in size from fine sand (0.1 mm.) to pebbles (10.0 mm.) in broad surface zones parallel to the shoreline and also at depth in laminations 1 to 6 inches thick.

North New Brighton Beach had fine and well sorted sand and was considerably less permeable.

Water Table Profiles

Actual changes in water table profiles of the Pegasus Bay beaches are illustrated in Figures 2 and 3. The amplitude of the water table under high tide level at the more permeable Leithfield Beach was greater than that at North New Brighton Beach and the decrease in amplitude landward, although irregular, less abrupt. This results from less resistance by interstitial pores to inflowing water from the sea in the more permeable beach (Emery and Foster, 1948, p. 645).

The Figures also show that, 40 feet landward from the high water line, the water tables lagged from 1 to 4 hours behind the tide. The lag was greatest after ebb and least after flood tide and, as expected, was most marked at the less permeable North New Brighton Beach where finer interstitial pores formed greater resistance to water flow.

In response to loss of water from the beach during an ebbing tide and the gain of water to the beach during a flooding tide, the seaward edge of the water table profiles sloped seaward then landward respectively. But because much of the North New Brighton Beach had a very gentle slope, the water table sloped landward only after the mid-point of the flooding tide was reached and, conversely, reverted quickly to a seaward slope soon after high tide. Consequently, at low tide there existed a very broad effluent zone 180 feet landward of the low tide line and the water table could not attain the steepness that the low permeability of the beach might otherwise have allowed — a finding comparable to that made by Emery and Foster (1948).

The wavy character of the water table at Leithfield Beach was apparently caused by the influence exerted by the form of the double berm almost directly above it.

Porosity and Salt Content of Beach Sand

Water and salt content analysis of sand taken from near the high tide water line showed that water content varied from a few percent at the surface to saturation below the water table.

Saturated sand from North New Brighton Beach contained water equal to 36% by bulk volume, which is its porosity value (Appendix II). For the same beach at low water, an average 20.17% by bulk volume was left behind as pellicular water by the falling water table; the remaining 15.83% of bulk volume was, therefore, pore space filled with air. Proportions of water, air, and sand at various depths for the two beaches are shown in Figure 4.
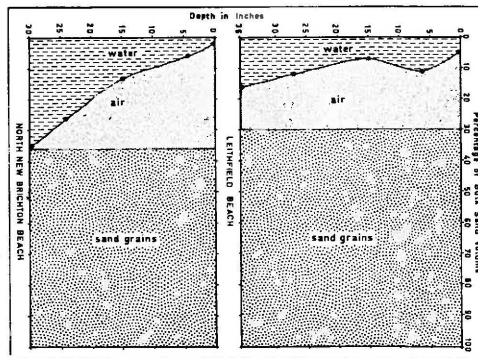

Figure 4. Percentage volumes of interstitial water, air, and solid sand grains in the Pegasus Bay beaches.

Laboratory evaporation of water collected from below the water table at ebb mid-tide yielded salt content by weight of 3.14% from the 80 foot station and 3.18% from the 110 foot station at Leithfield Beach. From North New Brighton Beach results were 2.36% and 3.46% by weight from the 20 foot and 60 foot stations respectively.

DISCUSSION

In their analyses of several beaches along the Californian coast, Emery and Foster (1948, p. 652) found, from the use of porosity values, that the velocity of escaping water from water table to beach surface during an ebbing tide was sufficient to "cause the elutriation and eventual loss of silt from the beach."

The velocity values for beaches along Pegasus Bay did not support that finding even though the Leithfield Beach, at least, was probably more permeable. The escape velocity at Leithfield Beach was calculated as being 0.0056 cm. per second, and, for the less permeable beach at North New Brighton, 0.0036 cm. per second. (The method of calculation is outlined in Appendix III.) These values are about ten and fifteen times less, respectively, than the settling velocity of silt having a diameter of 0.02 mm. For Leithfield Beach, it is almost seven times less than Emery and Foster's value of 0.038 cm. per second for El Segundo Beach, Los Angeles, which was composed of sand with a median diameter of 0.38 mm. and which had a porosity value of 26.0%.

Thus, providing particles of silt size and smaller are brought to and lost from the Pegasus Bay beaches, factors other than elutriation caused by fluctuating water tables in response to tidal change need to be considered. In this regard, two factors, wave-wash and terrestrial water influences, are discussed in rather more general terms below.

Wave-wash Influences

The surveys were made in winter when it is usual for beach morphology to adjust in response to the erosional effects of storm waves and heavy swell (Eagleson, Glenn & Dracup, 1961). Consequently, the lower foreshores of the Pegasus Bay beaches had very long and gentle slopes with water tables situated at or near to the sand surface along much of their length. These conditions were especially prevalent at North New Brighton Beach (which is composed of fine grained, low permeability material) where, for a 1 to 1½ hour period around mid-tide, it was observed that waves repeatedly ran up far beyond the outcropping edge of the water table and soaked into the upper foreshore "infiltration zone" (Grant, 1948). This wave-wash process would appear to provide a source of water to the water table additional to that of tidal change and would, therefore, influence the escape velocity of water from the beach (Emery and Foster, 1948, p. 652).

Wave-wash can also be used to help explain the variations in time-lag of 1 to 4 hours between water table and tide levels referred to on page 26. As tide level rose toward its peak, the number of wave-wash (swash) occurrences increased in frequency because of an increase in the slope gradient of the upper foreshore (Duncan, 1964). Consequently, water quickly flooded into the water table below so that the high peak of the water table was only 1 hour behind high tide. Near time of low tide, the water line was far to seaward due to the gentle slope of the lower foreshore. Because of the broad effluent zone which resulted, and the decrease in the wave-wash period with decreasing slope gradient, flooding into the water table in response to a rising tide and wave-wash did not become effective until soon after flood mid-tide when the water table had reached its lowest point: in the case of North New Brighton Beach there was a lag period of 4 hours at the 40 foot station.
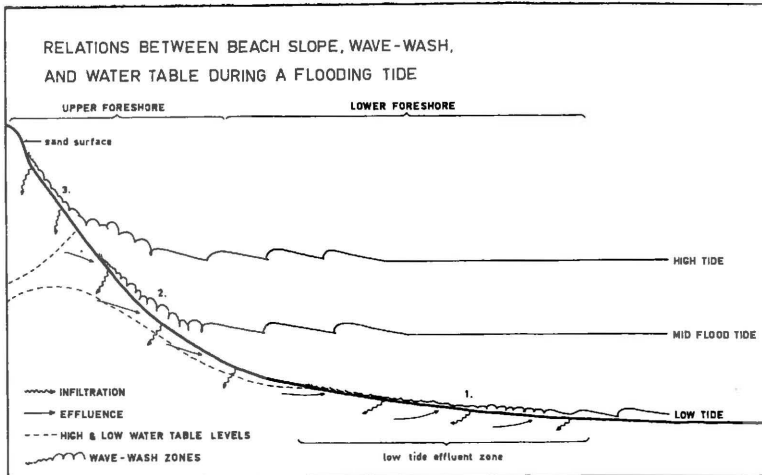
RELATIONS BETWEEN BEACH SLOPE, WAVE-WASH,
AND WATER TABLE DURING A FLOODING TIDE

Figure 5. Relationships between wave-wash, beach slope, tidal, and water table change for North New Brighton Beach. (1) Effluence exceeds infiltration 4-5 hours around low tide; level of water table continues to fall until near mid-tide. (2) Infiltration exceeds effluence as wave-wash occurrences increase with increasing beach slope. (3) Intensification of trend 2 leading to a rapid intake of water with maximum height of water table achieved soon after high tide.

The relationships of wave-wash and beach slope and the sequence of change accompanying tidal fluctuations for North New Brighton Beach are shown diagramatically in Figure 5.

Terrestrial or Fresh Water Influences

Samples of water taken from below the water table at ebb mid-tide from North New Brighton Beach showed a variation in salt content of 1.1% by weight between the 20 foot station (2.36%) and the 60 foot station (3.46%). Since water table fluctuation was negligible 20 to 30 feet landward from the 0 foot station, a strong terrestrial water table influence is suggested. That is, the difference in salt content of the samples may be assumed due to additions of fresh water from the back of the beach to the marine water table. This, too, could influence the escape velocity of water from the beach.

There is also the possibility (suggested earlier by Isaacs and Bascom, 1949) that the terrestrial influence exerted on the water table is associated with sand dunes which have formed behind the back-shore of the Pegasus Bay beaches. (The relative location of these dunes are shown by inserts in Figures 2 and 3.)

The sand dunes' influence on the marine water table, especially towards the back of the upper foreshore, would be to decrease the amplitude through which it could fall, thereby limiting the cross-sectional area between low and high water table levels and, consequently, the velocity with which water could escape to the beach surface.

Furthermore, the existence of a hydrostatic influence associated with the sand dunes and exerted upon the water tables, could help in providing explanations for three interrelated problems which arise directly from the survey. These problems are :

(i) the coarse grained and more permeable Leithfield Beach had a water table amplitude of only 29 inches under the high tide line when the tidal range was 62 inches. For their most permeable beach at Marine Street, La Jolla, Emery and Foster recorded a water table amplitude which was equal to the tidal range of 40 inches.

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(ii) there was only 16 inches difference in amplitude between the more permeable coarse grained and less permeable fine grained beaches of Pegasus Bay when for the Californian beaches, with their less extreme characteristics, the amplitudes ranged from 5 inches at Scripps Institution Beach (tidal range 48 inches; beach slope 0.4° - 1.3°; median diameter of sand 0.18 mm.; porosity 27.6%) to 55 inches for Marine Street Beach (tidal range 40 inches; beach slope 6.8°; median diameter of sand 0.41 mm.; porosity 26.5%).

(iii) the water table rapidly decreased in amplitude landward at the more permeable coarse grained beach relative to the decrease at the fine sand beach.

CONCLUSION

Most of the relationships between beach characteristics and fluctuating water tables in response to changing tide levels reported by Emery and Foster (1948) were observed at the beaches studied along Pegasus Bay. However, contrary to expectations, the water table trends were far less marked for the Pegasus Bay beaches even though their range of beach characteristics were far greater than those of the Californian beaches. But the most notable difference between results of the two surveys rests with the observation that, at the Pegasus Bay beaches, the escape velocity of water from the water table due to tidal fall alone was insufficient to cause elutriation of fine material from the beach.

These differences may be attributable to varying hydrostatic control, associated with sand dunes at the backs of the beaches, upon the water tables.

Further influences upon the water tables and the escape velocity of water from the beach appear to derive from wave-wash and terrestrial water.

ACKNOWLEDGMENTS

REFERENCES

Duncan, J. R., 1964 : The effects of water table and tide cycle on swash-backwash sediment distribution and beach profile development. *Marine Geol.* 2 : pp. 186-197.

Eagleson, P. S.; Glenne, B.; and Dracup, J. A., 1961 : Equilibrium characteristics of sand beaches in the offshore zone. *B.E.B. T.M.* 126.

Emery, K. O.; and Foster, J. F., 1948 : Water tables in marine beaches. *J. Marine Res. (Sears Found. Marine Res.),* 7 (3): pp. 644-654.

Grant, U. S., 1948 : Influence of the water table on beach aggradation and degradation. *J. Marine Res. (Sears Found. Marine Res.),* 7 (3) : pp. 655-660.

Isaacs, J. D.; and Bascom, W. N., 1949 : Water table elevations in some Pacific Coast beaches. *Amer. Geoph. Union,* 30 (2) : pp. 293-294.

Kirk, R. M., 1966 : *Depth of Disturbance by Waves on a Pebble Beach over Shingle.* Unpublished Coastal Studies Research Report, Department of Geography, University of Canterbury.

Krumbein, W. C.; and Pettijohn, J. F., 1938 : *Manual of Sedimentary Petrology.* Appleton, Century, Croft. Inc., New York.

PERMEABILITY

Location	Site	Beach material	Time in seconds to pass 250 cc. of water through a cylinder 4 cm. diameter
North New Brighton Beach:	High-tide zone	Fine sand (moist)	142
	Mid-tide zone	Fine sand (moist)	150
	Top of berm	Fine sand (dry)	130
Leithfield Beach:	High-tide zone	Very coarse sand (moist)	105
	Mid-tide zone (flood)	Granules (moist)	101
	Mid-tide zone (ebb)	Large pebbles (moist)	16
	Top of berm	Very coarse sand and granules (dry)	154

APPENDIX II

POROSITY

$P = 100 \left[1 - \dfrac{v}{V} \right]$, where P is porosity %, V is bulk volume, v is grain aggregate, i.e. porosity is equivalent to the amount of water needed to saturate a given sample of sand and amounts to the total air space (Krumbein and Pettijohn, 1938, p. 506).

North New Brighton Beach :
Bulk volume of sand sample $= 250$ cc.
Volume of water needed to saturate sand $= 90$ cc.
Volume of grain aggregate $= 160$ cc.
$\therefore P = 100 \left[1 - \dfrac{160}{250} \right] = 36\%$

Leithfield Beach :
Bulk volume of sand sample $= 250$ cc.
Volume of water needed to saturate sand $= 75$ cc.
Volume of grain aggregate $= 175$ cc.
$\therefore P = 100 \left[1 - \dfrac{175}{250} \right] = 30\%$

APPENDIX III

ESCAPE VELOCITY OF WATER FROM BEACH SAND

	North New Brighton Beach :	Leithfield Beach :
Porosity	36.00% by bulk volume	30.00% by bulk volume
Average water	20.17% by bulk volume	11.55% by bulk volume
Air	15.83% by bulk volume	18.45% by bulk volume
Time	1730 to 2230 (5 hours)	1830 to 2130 (3 hours)
Cross-sectional area	80 sq. ft.	103 sq. ft.
Volume (1 ft. wide strip)	80 cu. ft.	103 cu. ft.
Escape area from beach surface	90 sq. ft. for 5 hours	90 sq. ft. for 3 hours
Escape velocity of water	0.395 ft. per hour (0.0034 cm./sec.)	0.672 ft. per hour (0.0056 cm./sec.)

As the estimated amplitude 20 feet landward of the 0 foot station at North New Brighton Beach pinched out to 0 inches, the cross-sectional area through which the water table fell in 5 hours (1730 to 2230) was about 80 sq. ft. or, for a 1-foot wide strip down the sand surface profile, a volume of 80 cu. ft. Since approximately 20% water remained in the sand at low water table level, water equivalent to about 16% (15.83% by bulk volume air space) of the 80 cu. ft. escaped from the beach during the 5 hours. Providing evaporation from the sand following the ebb-tide is considered negligible, then, an average 2.56 cu. ft. of water ran down the water table and escaped through the beach sand every hour. Although the escape area down the transverse strip was about 90 sq. ft. (or 18 sq. ft. for 1 hour), only 36% by bulk volume was pore space through which water could flow. Thus, each hour, 2.56 cu. ft. of water passed through

$$\frac{36}{100} \times \frac{18}{1} = 6.48 \text{ sq. ft. of area each hour.}$$

The escape velocity would therefore have been $\dfrac{2.56}{6.48} = 0.395$ feet per hour.