Journal of Coastal Research	17	2	482–489	West Palm Beach, Florida	Spring 2001

TECHNICAL COMMUNICATION

Inter-tidal Dynamics of Surface Moisture Content on a Meso-tidal Beach

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ABSTRACT

ATHERTON, R.J.; BAIRD, A.J., and WIGGS, G.F.S., 2001. Inter-tidal Dynamics of Surface Moisture Content on a Meso-tidal Beach. *Journal of Coastal Research,* 17(2), 482–489. West Palm Beach (Florida), ISSN 0749-0208.

A new device was used to measure the moisture content of the uppermost layers of beach sediments on a meso-tidal beach in the UK. The results showed that drainage of the beach surface was much more limited than previously assumed (< 10 percent of assumed values). The implications of these findings are briefly discussed in the context of beach ground water modelling and coastal aeolian research.

ADDITIONAL INDEX WORDS: *Beach ground water, water tables, ThetaProbe, capillary rise.*

INTRODUCTION

The moisture content of beach sediments is believed to be important to sediment transport (BAIRD and HORN 1996; BAIRD *et al.* 1998; RAUBENHEIMER *et al.* 1999; TURNER and NIELSEN 1997), coastal water resource management (NIELSEN 1998, TURNER *et al.* 1997, TURNER 1998), interstitial faunal activity (MCARDLE and MCLACHLAN 1991, POLLOCK and HUMMON 1971), and aeolian sediment transport (JACKSON and NORDSTROM 1997, NORDSTROM *et al.* 1996, SARRE 1989, SHERMAN and LYONS 1994, SHERMAN *et al.* 1998). Most studies of beach water content have focused on measuring water table elevation, and relatively few have attempted to measure moisture contents above the water table. A notable exception is the study of TURNER (1993) in which the neutron probe method was used to measure water contents above water tables on adjacent microtidal beaches, near Sydney, Australia. The disadvantage of this technique is that it has limited accuracy (estimates of percentage saturation can have errors of up to ± 12 per cent—TURNER, 1993), and averages moisture content over a relatively large volume of porous medium (*i.e.* it cannot provide near surface moisture contents). Its main advantage is that it allows frequent non-destructive measurements of moisture content to be made. To our knowledge, all other attempts at measuring the moisture content of beach sediments have used methods where samples of sand are removed from the beach, oven-dried and the moisture content expressed gravimetrically or volumetrically (see HILLEL, 1980). The disadvantage of such methods is that sample collection and analysis are time consuming, rendering detailed time-series data of moisture contents across a beach practically impossible to collect. To overcome the problems of accuracy (neutron probe) and sample size (gravimetric method), BAIRD and HORN (1996) suggested that moisture contents could be measured using time domain reflectometry (TDR) which has now become established as a standard field method of measuring moisture content. TDR is used to measure the apparent dielectric constant of a medium between a pair or trio of thin metal rods (wave guides). The dielectric constants (Ka) of air, mineral matter, and water are respectively 1, 2–4, and 80 (SOILMOISTURE EQUIPMENT CORPORATION 1993). This allows the apparent dielectric constant of a partially saturated sediment to be reliably correlated with the moisture content of the sediment. Recently, similar techniques have been proposed based on a simplified standing voltage method used to determine the impedance of a sensing rod array and relating voltage outputs to soil moisture content (GASKIN and MILLER 1996; MILLER and GASKIN 1996). One instrument based on this method is the ThetaProbe developed at the Macaulay Land Research Institute, Aberdeen, UK (see previous references), which is particularly attractive because it can sample a relatively small volume of sand (approximately 35 cm^3—see FIELD MEASUREMENTS below) very rapidly (5–30 s). The main aim of this study was to measure time series of near surface beach moisture using a ThetaProbe. More specifically, the aim was to determine the degree to which surface sand dries

99102 received 15 October 1999; accepted in revision 8 August 2000.

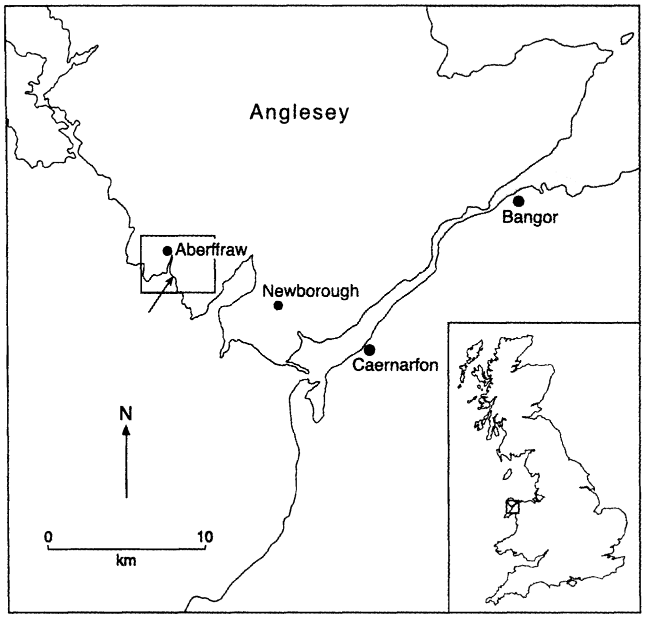


Figure 1. Location of the study site, Anglesey, Wales, UK.

between tidal inundations, and to analyse the relationship of such drying to water table dynamics, since many workers have used water tables as a surrogate measure for general beach wetness.

FIELD MEASUREMENTS

Field Site

Measurements of surface moisture content and water table position were carried out on 20th September 1998 and 9th September 1999 at Aberffraw beach (53°11′00″N; 4°27′40″ W; Figure 1) on the southwest coast of Anglesey, north-west Wales, UK as part of a larger study investigating aeolian sand transport. The results from both deployments are very similar and only those from 1999 are reported here. The beach is meso-tidal with a fairly narrow upper foreshore and an extensive, flatter lower foreshore. There are no major breaks of slope other than one associated with a transition into foredunes. Figure 2 shows the beach profile along which moisture and water table measurements were made. A location approximately two thirds along the beach from its northern boundary was chosen for the deployment. This avoided any complications associated with the presence of a river outlet at the northern end of the beach. A meteorological station at Royal Air Force Valley, 3 km northwest of the field site provided meteorological data on prevailing and antecedent conditions for the experimental period.

Instrumentation and Methods

Surface moisture values and water table positions were monitored at four sampling stations set up along the transect shown in Figure 2. The landward station (station A) coincided with the upper limit of swash incursions during high water, while the most seaward station (station D) was located on the most landward part of the low tide terrace. The remaining two stations were located at intermediate positions such that the stations were approximately equi-distant from each other (see Figure 2). Monitoring began at each station when the water table was still at the beach surface and continued at c. 20 minute intervals. At station A readings were taken for over 8 hours. A complete tidal cycle could not be monitored because the latter part of the flooding tide occurred in darkness. The beach profile and each sampling station were surveyed with a manual Wild NK01 level using standard levelling procedures.

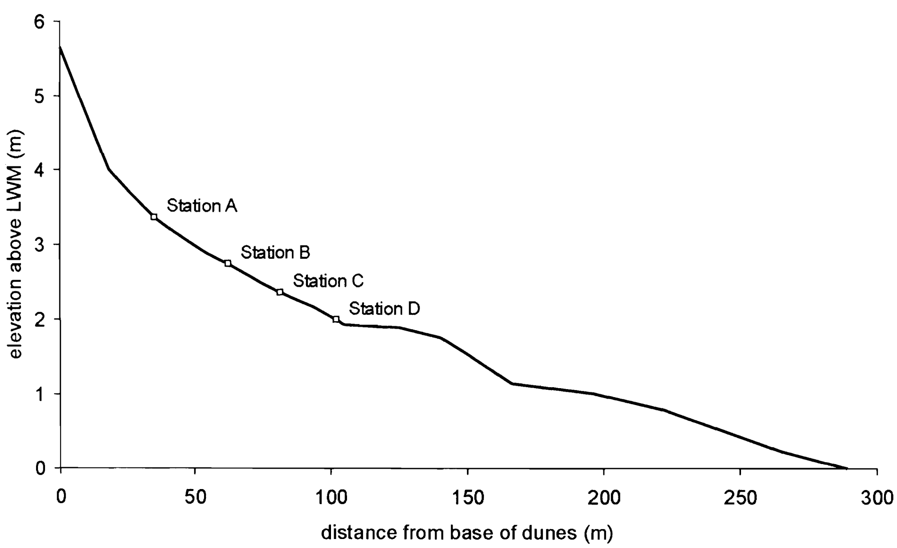
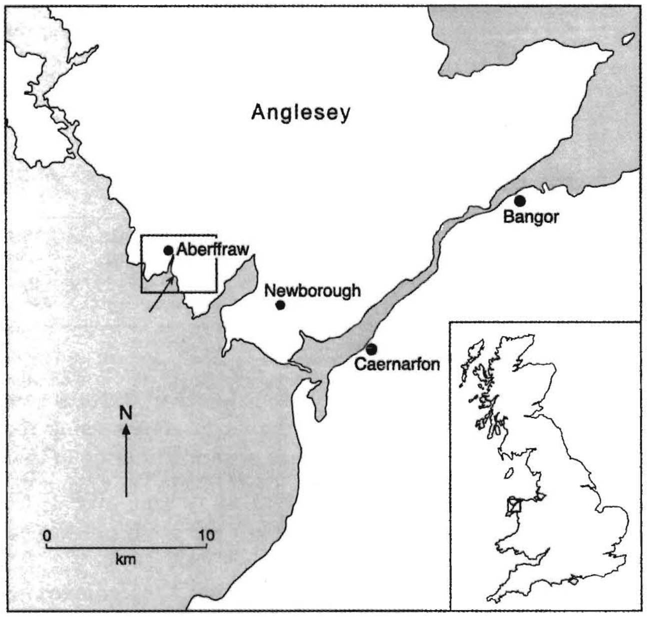


Figure 2. Cross shore profile of Aberffraw Beach showing stations at which moisture and water table measurements were made.



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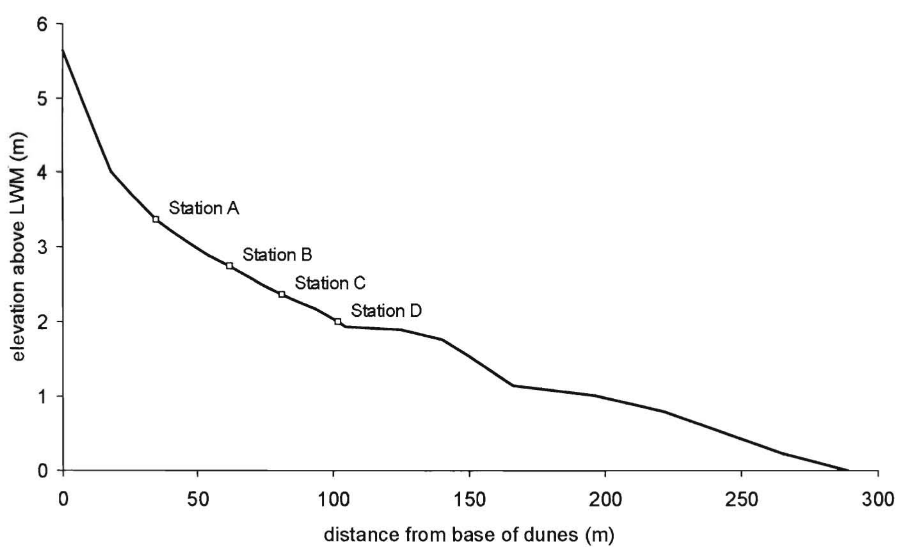

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Water Table Dynamics

Water table position below the beach surface was located by digging shallow pits at each station. A steel ruler was placed across the top of each pit and the depth to the water table measured using another ruler. More sophisticated (but no more accurate) measurement methods could have been used but were not warranted given the shallow depths of water tables in the inter-tidal profile (see below).

Surface Moisture Dynamics

Near-surface moisture content was monitored at each sampling station using a ThetaProbe. Details of the probe design can be found in DELTA-T DEVICES (1998) and MILLER and GASKIN (1996). Briefly, the probe consists of a sensor body which terminates in four parallel stainless steel rods, 60 mm in length. Three shield rods surround a central sensing rod, forming the apices of a triangle in plan. Ninety percent of the sampling volume of the device is contained within a cylinder 25 mm in diameter, and 60 mm long, surrounding the central rod. The sensing body requires an input of 7–15 V DC and returns an output signal in the approximate range 0–1 V DC depending on moisture content of the sediment. Most standard calibrations have been developed for non-saline soils (see MILLER and GASKIN 1996). To our knowledge, no calibrations exist for beach sediments. Thus it was necessary to calibrate the probe for the sediment studied here. This was accomplished by taking a sample of beach sand and sea water back to the laboratory. The sand and water were added to a plastic cuboidal container. To ensure full saturation at the beginning of the calibration, sand and water were added to the container in stages and mixed. Similar mixing probably occurs under swash and waves so that the packing of the calibration sample was probably representative of field conditions. When the container was filled to its surface with saturated sand, the ThetaProbe was inserted. The sediment was then allowed to drain and air dry. During the drying, ThetaProbe readings and the associated weights of the calibration apparatus were recorded at regular intervals. The weights were converted to volumetric moisture contents using standard procedures. The relationship between ThetaProbe voltage and volumetric moisture content is shown graphically in the Appendix. The relationship between the two was described using two fourth-order polynomials with R^2 values of 0.9925 (voltage range of 0.7 to 1) and 0.9981 respectively (V range of 0.25 to 0.7) (see Appendix). Calibration measurements were extended to much drier conditions than found in the inter-tidal zone in the field deployments in the expectation that the calibration will be of use to other researchers.

As partly noted in the introduction, the ThetaProbe was chosen for its portability, efficiency and relative simplicity in terms of deployment. Because readings from the device can generally be obtained in less than c. 5 s, we were able to take a large number of measurements in a short period of time. Readings were taken at five different points at each sampling station using the standard twenty minute period of rotation. In total, 445 measurements were made during the deployment, i.e. several times the number of readings typically taken using gravimetric determinations (*e.g.* NORDSTROM *et al.* 1996). Between each insertion the shield and sensing rods were cleaned so that any moisture or sand adhering to them would not influence the next reading. Drift in the output value was minimal or non-existent.

Table 1. *Sand physical parameters.*

Station	Mean (mm)	Median (mm)	Sorting (mm)	Skewness (mm)	Capillary rise (after DINGMAN) (cm)	Capillary rise (after TURNER and NIELSEN) (cm)
A	0.15	0.15	0.84	1.1	19	48
B	0.16	0.16	0.82	1.23	19	46
C	0.18	0.16	0.67	1.51	16	40
D	0.17	0.16	0.71	1.45	17	42

Sediment Samples

Sediment samples were taken from each of the sampling stations. Particle size analysis was carried out on the dried samples by sieving at 0.5 phi intervals. A number of size parameters were calculated according to the procedures given in BRIGGS (1977).

RESULTS AND DISCUSSION

Sediment Analysis and Estimates of Capillary Fringe Thickness

Table 1 summarises the particle size data for each station. The sand on the beach was in the fine to medium range and should, theoretically, support a relatively thick capillary fringe above the water table. Thus, it might be expected that where the water table remains close to the surface very little drying of surface sediments occurs. Capillary rise can be calculated using

$$h_c = \frac{2\gamma \cos \alpha}{r_m \rho_w g} \tag{1}$$

where h_c is the height of capillary rise, γ the surface tension of water, α the contact angle between water in a pore and the pore side wall (taken to be zero), r_m the mean pore radius, ρ_w the density of water, and g the acceleration of free fall. h_c can be calculated if r_m is taken to be some function of the mean or median grain diameter in the sediment (DINGMAN 1984). TURNER and NIELSEN (1997) note that if cubic packing of spherical grains of uniform diameter (d) is assumed, the equivalent radius of pore spaces ($= r_m$) is $d/5$, so that the thickness of the capillary fringe, B, can be approximated by

$$B = \frac{10\gamma}{\rho_w g d_m} \tag{2}$$

where d_m is the mean grain diameter. However, DINGMAN (1984) and other workers have suggested that for the purposes of calculating the thickness of the capillary fringe, equation (1) can be used in which r_m is simply approximated

Table 2. *Meteorological data for the monitoring period (times are British Summer Time).*

Time	Temperature (°C)	Relative humidity (%)	Wind speed at 10 m (m s^{-1})
1000	15.8	62	6.7
1100	16.5	57	7.7
1200	16.8	55	7.7
1300	17.1	56	7.7
1400	17.1	61	8.2
1500	17.2	60	8.2
1600	16.9	62	7.7
1700	16.3	62	8.7
1800	15.6	68	8.7
1900	14.8	70	7.7
2000	14.5	74	6.7

by $d_m/2$. Both equations were used in combination with the particle size data to estimate B (Table 1); the estimates are discussed in the context of water table measurements below.

Meteorological Conditions

All meteorological data were obtained from hourly measurements taken at the meteorological station at RAF Valley. Hourly temperature, relative humidity and 10 m wind speed are shown in Table 2. Windspeeds were reasonably high and relative humidities quite low, suggesting that some surface drying would be expected during the monitoring period.

Moisture Contents and Water Tables

Surface moisture dynamics and water table position relative to the beach surface are shown in combined plots in Figures 3 to 6. Figure 3 shows conditions at the most landward station, station A. Here it can be seen that the water table showed an initial rapid decline after which the rate of fall slowed. Surface moisture contents showed a slow decline during the part of the inter-tidal period measured. The total reduction in moisture content was modest (of the order of 0.035 or 3.5 percent), is much lower than values of specific yield used in previous modelling studies of beach water tables (for example BAIRD *et al.* 1998 and RAUBENHEIMER *et al.* 1999), and suggests many of the pores in the upper 6 cm of the beach sediment contained capillary water. The detailed pattern of moisture content decline showed a slow rate of decline as the water table fell to about 30 cm below the surface, after which the rate of decline increased. The results from the other recording stations are perhaps even more dramatic. The water table at station B declined by over 15 cm during the monitoring period but was not matched by any discernible decline in surface moisture contents. A similar pattern for surface moisture content is evident for station C. Station D remained in the seepage face for most of the monitoring period except for a brief period in mid afternoon when water tables dropped very slightly below the beach surface. The results from the '98 deployment were very similar.

The estimates of height of capillary rise in Table 1 suggest that the thickness of the capillary fringe varied from about 18 cm if the DINGMAN (1984) method of calculation is used to about 45 cm if the TURNER and NIELSEN (1997) method is used. The results from station A suggest that the capillary fringe thickness was not of the order of 45 cm, since the sediment drained most rapidly when the water table was about 30 cm below the surface, i.e. this suggests that the TURNER and NIELSEN method over-estimates the thickness of the capillary fringe. However, the fact that drainage of the surface layer was slower until the water table reached a depth of 30 cm also suggests that the DINGMAN method gives an underestimate of capillary rise. The lack of drainage of surface sediments at stations B and C is not surprising since at both locations the water table did not decline below either estimate of capillary fringe thickness.

It is clear from these results that very little de-watering of

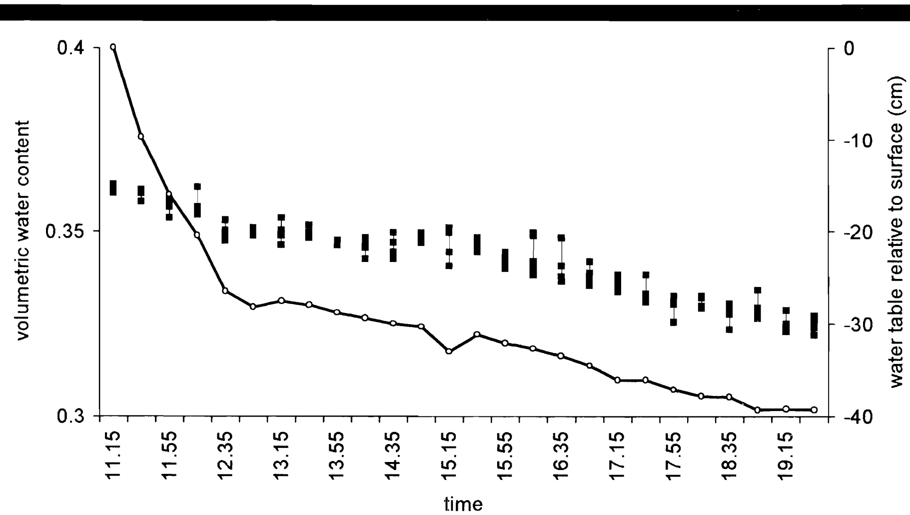

Figure 3. Water table depth (open circles) and surface moisture content: station A (note the differing time and water table scales in this and the next three figures). Times are British Summer Time.

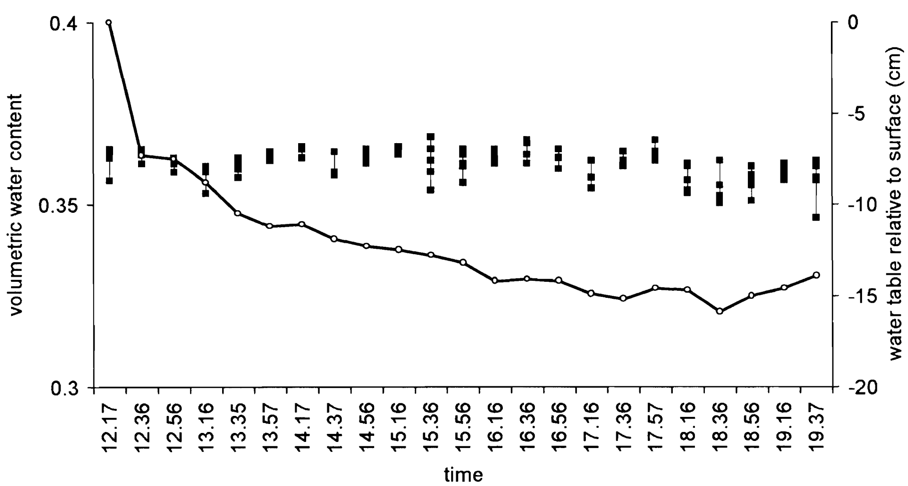

Figure 4. Water table depth and surface moisture content: station B.

the inter-tidal beach at Aberffraw takes place, certainly much less than is commonly assumed in coastal ground water modelling studies where specific yields of 0.2 to 0.3 are widely used. The wider implications of this result are somewhat unclear since previous modelling studies of beach ground water dynamics, especially those based on the Boussinesq ground water equation (see BAIRD *et al.* 1998 and RAUBENHEIMER *et al.* 1999), have been on beaches with coarser sediment than at Aberffraw. Nevertheless, it is likely the extent of beach de-watering has been over-estimated in these studies and that thought needs to be given to the physical meaning of the specific yield parameter used in existing Boussinesq ground water models.

The results also show that, for large parts of the beach face, the capillary fringe extends to the beach surface maintaining a high water content between surface sand grains. Despite the drying conditions observed during monitoring, moisture contents remained at saturation at stations B to C and close to saturation at station A. This shows that water tables are poor surrogates of surface dryness and also that aeolian transport over large parts of the inter-tidal zone is likely to be much more restricted than is implied by drainage of 30 percent of the sediment volume (i.e. as previously assumed in Boussinesq ground water models). Drying of the uppermost grains on the beach face could, of course, still occur. However, such water loss will be replenished by capillary rise. The degree of surface drying will then depend on the balance between moisture loss by evaporation and moisture gain by capillary rise.

One interesting feature of the results is that the water table at stations B and C started to rise when the runup limit was still some distance seawards of the stations (>15 m) and

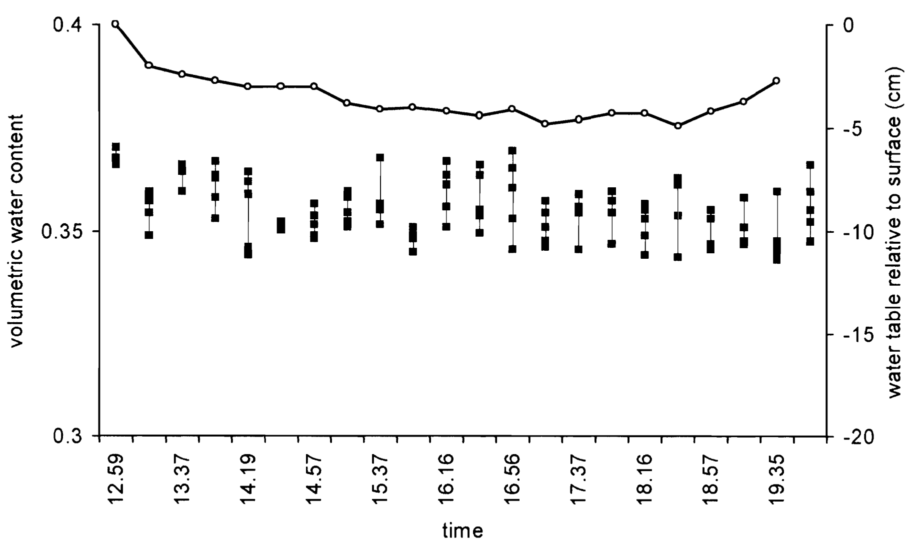

Figure 5. Water table depth and surface moisture content: station C.

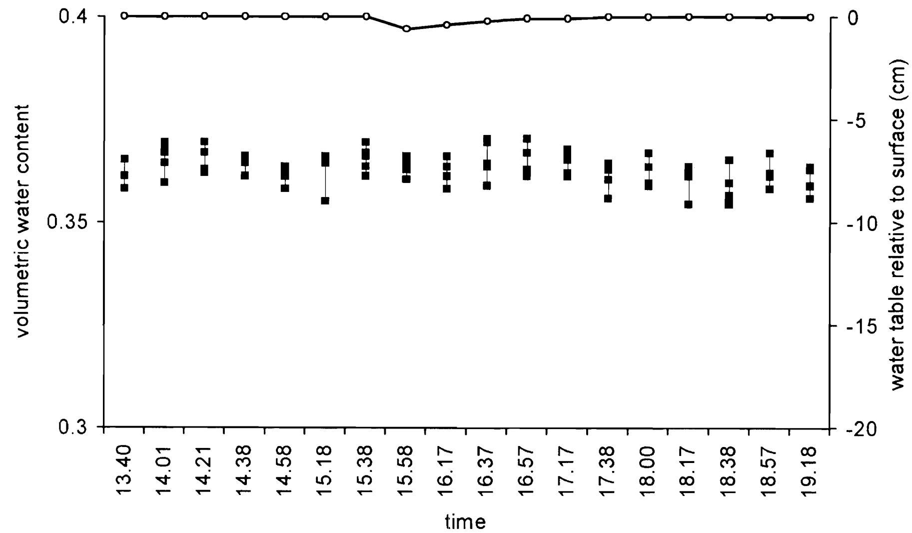

Figure 6. Water table depth and surface moisture content: station D.

below the water table level at the two stations, i.e. the rise of the water table at the two stations was *not* due to a landward-acting hydraulic gradient that had formed due to the flooding tide or wave runup. The water table rise at the two stations was observed to coincide with a landward movement (rise) of the water table exit point. We interpret this behaviour as the water table rising through the capillary fringe as the seaward boundary condition for ground water flow out of the beach changed. Our observations are useful in informing a debate between NIELSEN (1999) and LI *et al.* (1999), and support the suggestion of LI *et al.* (1997) that the exit point can rise (move inland) in advance of a rising tide, i.e. it starts to rise before it is caught by a rising tide.

SUMMARY AND CONCLUSIONS

The results from this study show that beach de-watering during tidal ebb is less than commonly assumed. Although the study was carried out on a beach with relatively fine sand, the results are probably applicable to some extent to beaches with medium sands. The results suggest that existing Boussinesq models of beach ground water dynamics are less physically meaningful than previously thought. It has also been shown that restricted drainage of the beach surface could present a considerable constraint to sand detachment and transport by wind in the inter-tidal zone. Finally, the ThetaProbe has been shown to be a useful tool for measuring beach moisture contents.

ACKNOWLEDGEMENTS

Permission to work on the site was given by Bodorgan Estates whose help with aspects of the project is gratefully acknowledged. The meteorological data were kindly provided by the UK Meteorological Office. The senior author was in receipt of a studentship grant from the UK Natural Environment Research Council when the project was carried out (award reference GT04/97/261/MAS). Ian Turner made a number of useful comments on an earlier version of this paper.

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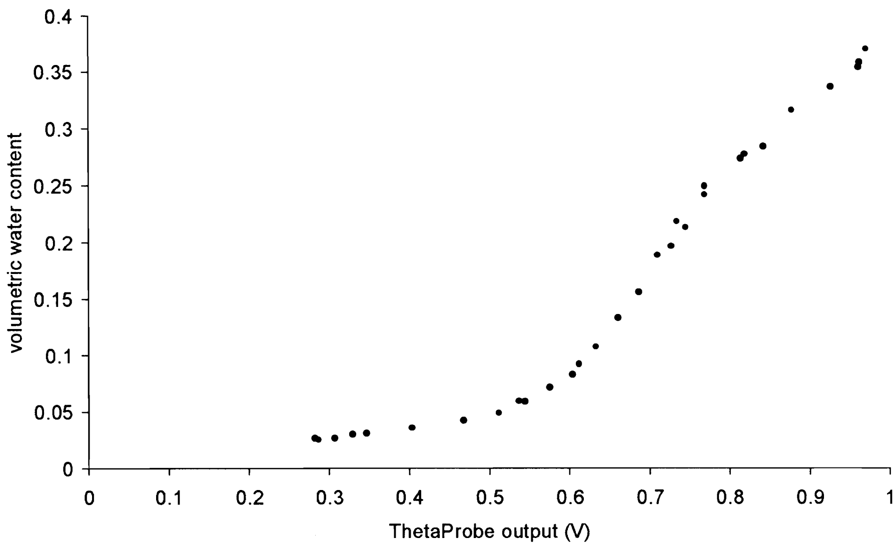

Figure A1. The Theta Probe calibration data for a beach sediment–sea water misc.

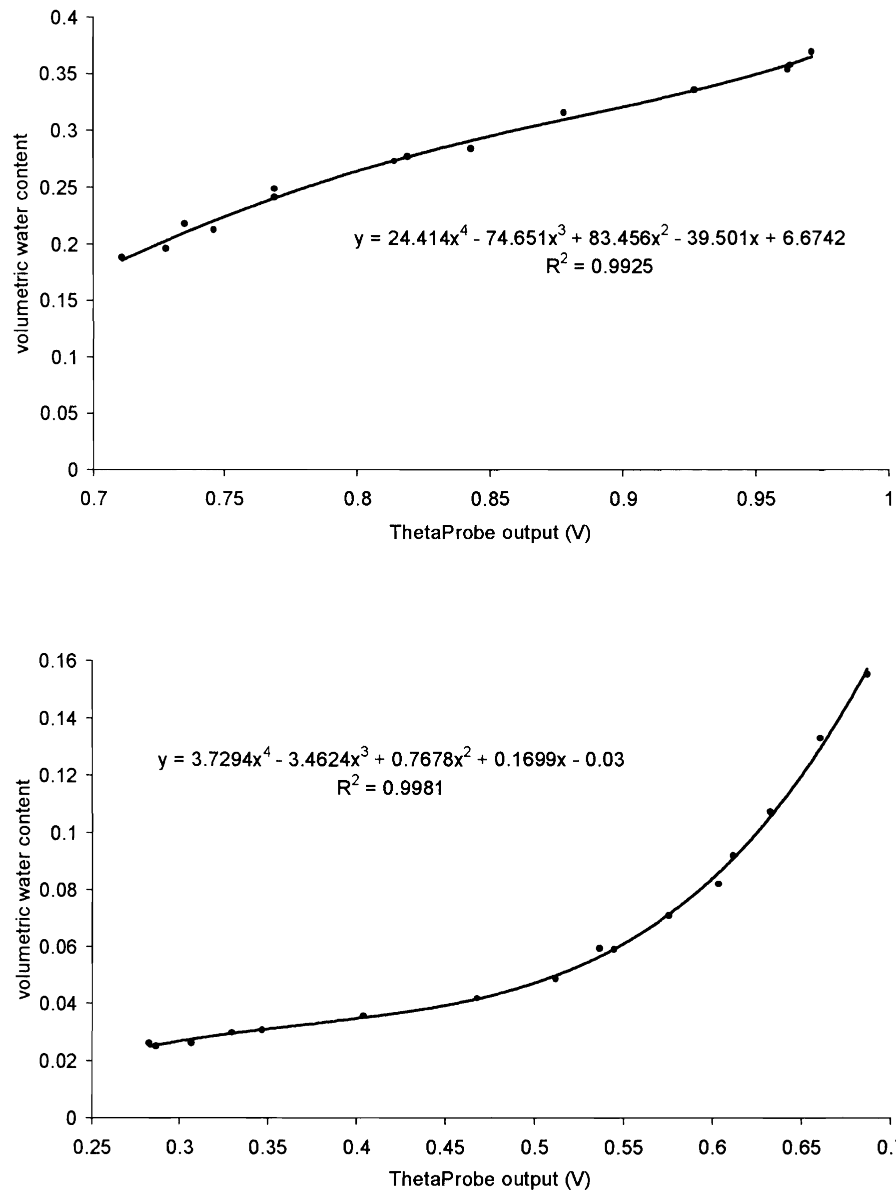

Figure A2. The polynomial functions fitted to the calibration data.