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Measurement and modeling of moisture content above an oscillating water table: implications for beach surface moisture dynamics

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ABSTRACT: This study examined the influence of tidally-induced oscillations of the beach water table in regulating beach surface moisture dynamics. A series of laboratory experiments were conducted to assess the influence of hysteresis and transient flow effects on surface moisture variability. The experimental apparatus utilized a column of well-sorted fine sand partially immersed in a reservoir of water. The water level in the reservoir was raised and lowered via a diaphragm-metering pump to simulate tidally induced fluctuations of the water table, and the moisture content profile within the column was monitored using an array of Delta-T probes. Moisture contents at specific elevations within the column were utilized as proxies to represent various 'surface' elevations (relative to the high water table). Results indicate that surface moisture content behaves in a distinctly hysteretic manner. Examination of water flow scanning curves illustrated that for all surface elevations considered, higher moisture contents for a given pressure head occurred during the drying cycle than during the wetting cycle. This observation is particularly evident with shallow surface elevations (i.e. water table close to the surface) where the Haines Jump phenomenon was found to have a significant influence on moisture content dynamics. Additionally, an assessment of the accuracy of hysteretic and non-hysteretic models to predict the measured moisture contents demonstrated that hysteretic simulations consistently provide a better representation of the observed moisture contents than non-hysteretic simulations. A time lag was found between the respective maxima and minima in water table elevation surface moisture content. At the near surface water table positions the time lag ranged between 30 and 100 minutes, and it increased to 240 minutes (four hours) with the high water table at 60 cm below the surface. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: beach ground water; hysteresis; beach moisture content

Introduction

It has been widely recognized that beach surface moisture content plays an important role in coastal aeolian sediment transport systems (Davidson-Arnott and Law, 1996; Bauer and Davidson-Arnott, 2002; Wiggs *et al.*, 2004a, 2004b; Davidson-Arnott *et al.*, 2005; Ravi *et al.*, 2006; Bauer *et al.*, 2009; Delgado-Fernandez and Davidson-Arnott, 2011; Legates *et al.*, 2011). Since aeolian sediment transport is the primary source of sediment for dune growth, the role of beach surface moisture on aeolian transport may play a significant role in the sediment budget for beach–dune systems over time (Davidson-Arnott and Dawson, 2001; Bauer and Davidson-Arnott, 2002; Aagaard *et al.*, 2004; Houser, 2009). Therefore, an understanding of the principal controls on, and the nature of, surface moisture dynamics is essential for modeling the role of aeolian processes in beach–dune dynamics. Such models have the potential to be an integral part of coastal management schemes (Bauer and Sherman, 1999; Davidson-Arnott and Dawson, 2001; Houser, 2009), but advances in predictive capabilities regarding beach surface moisture dynamics are needed to provide output of sufficient quality for decision-makers. If we cannot determine and represent beach surface moisture dynamics with some accuracy (and currently we cannot in most cases), we cannot hope to develop realistic models of beach–dune interaction and dune development over time.

A key uncertainty in modeling beach–dune interaction and dune development lies in the representation of beach surface moisture content (Yang and Davidson-Arnott, 2005; McKenna Neuman and Langston, 2006; Zhu, 2007, Namikas *et al.*, 2010). A number of recent studies have investigated variability in beach surface moisture content in the context of aeolian processes (e.g. Jackson and Nordstrom, 1998; Sherman *et al.*, 1998; Atherton *et al.*, 2001; Yang and Davidson-Arnott, 2005; Zhu, 2007; Oblinger and Anthony, 2008; Anthony *et al.*, 2009; Darke *et al.*, 2009; Delgado-Fernandez *et al.*, 2009; Edwards and Namikas, 2009; Namikas *et al.*, 2010; Nield, 2011; Nield *et al.*, 2011). However, a practical method to model or simulate the considerable spatial and temporal variability in surface moisture documented by these studies remains to be developed. This is in large part due to the fact that this variability is controlled by complex interactions between a suite of hydrological, meteorological and sedimentary parameters that includes precipitation, evaporation, condensation, tidal oscillations, groundwater flow, capillary transport, hydraulic conductivity and sediment texture (Figure 1). The present study examines the influence of beach hydrological systems on beach surface moisture dynamics, specifically the role of tidally-induced water table fluctuations and associated capillary transport.

The beach groundwater system is strongly influenced by tidal dynamics, which generate cyclic fluctuations in the elevation of the beach water table. This causes corresponding shifts in the capillary zone above the water table and in the vertical profile of sediment moisture content (Raubenheimer *et al.*, 1999; Stauffer and Kinzelbach, 2001; Zhu, 2007). As beach environments often have very shallow water table depths (centimeters to a few meters), the zone above the groundwater table influenced by capillary transport may reach the beach surface (Atherton *et al.*, 2001; Yang and Davidson-Arnott, 2005; McKenna Neuman and Langston, 2006; Zhu, 2007; Namikas *et al.*, 2010). Therefore, the dynamics the beach groundwater system may play a key role in regulating the status of beach surface moisture (Atherton *et al.*, 2001; Zhu, 2007; Namikas *et al.*, 2010).

In theory, the response of beach surface moisture content to beach groundwater dynamics can be established relatively easily and accurately based on knowledge of (i) the moisture profile of the sediment column, (ii) the elevation of the sand surface above the water table, and (iii) the magnitude and rate of water table fluctuation (Raubenheimer *et al.*, 1999; Ruz and Meur-Ferec, 2004; Chuang and Yeh, 2006; Zhu, 2007). In reality, however, the hydrological dynamics of a beach system are rarely simple. Capillary water flow within the sediment column tends to exhibit a non-linear, hysteretic behavior as well as experience transient water flow time lags. The hysteresis effect in the sediment column results in a higher water content occurring at the same pressure head during a falling water table (drying cycle) than during a rising water table (wetting cycle) (Figure 2). Although this hysteresis effect has long been recognized (Haines, 1930), there is some debate in the literature regarding the need for inclusion of hysteresis in modeling of periodic unsaturated groundwater movement. Early studies tended to disregard hysteresis effects for simple, homogenous sediment systems such as beach sand (e.g. Childs and Poulovassilis, 1962; Childs, 1969; Raats and Gardner, 1974; Kessler and Rubin, 1987); however, several recent studies have demonstrated that when hysteresis is accounted for it is possible to obtain significantly improved simulations of observed capillary water flows above a fluctuating water table (i.e. Hinz, 1998; Raubenheimer *et al.*, 1999; Nielsen and Perrochet, 2000; Werner and Lockington, 2003; Cartwright *et al.*, 2005, 2009). Our understanding of the influence of this phenomenon on beach surface moisture dynamics remains incomplete.

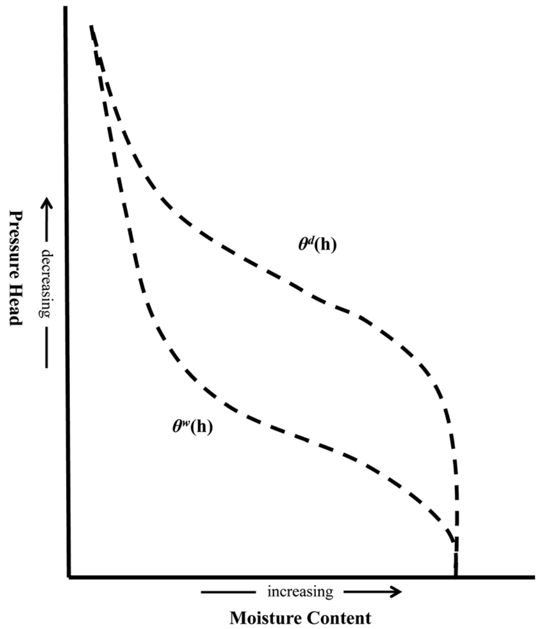

Figure 2. Representation of hysteresis effect in capillary water flow illustrating boundary wetting $\theta^{w}(h)$ and drying $\theta^{d}(h)$ water flow retention curves. After: Childs and Poulovassilis, 1962.

In addition to uncertainty regarding hysteresis effects, time dependent signals in surface moisture content associated with the transient nature of capillary water flow are poorly understood and have largely been ignored within the literature. Conventionally, the rate of change within the moisture profile of the sediment column is determined under steady state conditions independent of the velocity at which the water table fluctuates (Childs and Poulovassilis, 1962). This implies that moisture contents correspond exactly and synchronously with the cyclic movement of the water table. In reality, however, capillary water flows at a faster rate at higher water contents than it does at lower water contents due to the increase in hydraulic conductivity (Childs, 1969; Raats and Gardner, 1974; Kool and Parker, 1987). Therefore, the moisture content at the surface may lag significantly behind water table oscillations, and do so to a degree that increases both proportionally and non-linearly with surface elevation above the water table

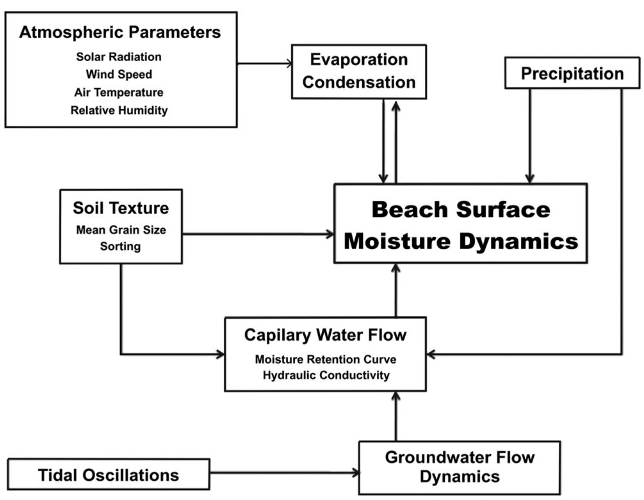

Figure 1. Key processes and parameters that control beach surface moisture dynamics.

(Hinz, 1998). This phenomenon is likely to have a very substantial impact on the temporal dynamics of beach surface moisture content, and this impact will tend to increase moving landwards from the shoreline. As one moves landwards across the beach the water table becomes deeper and the surface moisture contents will decrease, producing slower capillary flows across larger distances and thus increasing the time lag between water table position and surface moisture content.

In summary, our understanding of beach surface moisture dynamics above an oscillating water table includes at least two key sources of uncertainty: (i) the magnitude of hysteresis effects during periods of water table rise and fall; (ii) the time lags associated with transient water flow. To date only a few studies have attempted to link oscillating groundwater dynamics to variability in beach surface moisture content (i.e. Raubenheimer *et al.*, 1999; Atherton *et al.*, 2001; Zhu, 2007; Namikas *et al.*, 2010); and none of these studies incorporated hysteresis effects and transient water flow dynamics in their analyses. The primary objective of the present study is to document the response of surface moisture contents to tidally-induced groundwater dynamics and identify the influence of hysteresis and transient flow effects.

Methods

Laboratory experimental design

The experimental apparatus employed in the study consists of a square PVC (polyvinyl chloride) tube 122 cm in height with a cross-sectional area of 144 cm^2 (12 cm $\times$ 12 cm), partially immersed in a reservoir of water (Figure 3). The tube was filled with a very well sorted fine to very-fine quartz sand obtained from a beach at Padre Island National Seashore on the Texas Coast of the Gulf of Mexico with a mean grain size of 0·13 mm (2·94 phi, Figure 4). The tube was perforated below the low waterline to allow free exchange of water with the tank, and the perforated section was screened with fine mesh to retain sediment in the column. A diaphragm-metering pump was used to raise and lower the water level in the reservoir, to simulate tidally induced groundwater fluctuations. A pressure transducer installed at the base of the water reservoir was used to monitor water table elevation throughout each of the experimental runs.

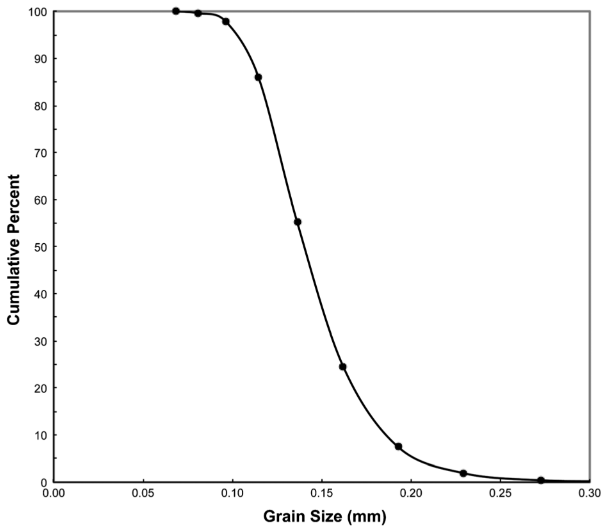

Figure 4. Grain size analysis.

Changes in the vertical profile of moisture content within the sediment column were monitored at five-minute intervals using an array of Delta-T Theta probes inserted in the sediment column at elevations of 35, 55, 65, 75, 85, 95, 100, 110, 120 cm above base of the reservoir (Figure 3). Note that high water was at an elevation of 60 cm above the base in all experiments, so the two lowest probes (35 cm and 55 cm) were within the zone of water table fluctuation, and the remaining probes were at fixed elevations above high water. All sensors were cabled to a Campbell Scientific CR23x data logger for recording. In order to isolate the influence of groundwater oscillation and capillary transport, the top of the PVC tube was sealed with plastic wrap to prevent evaporative losses or condensation inputs at the upper surface of the sediment column.

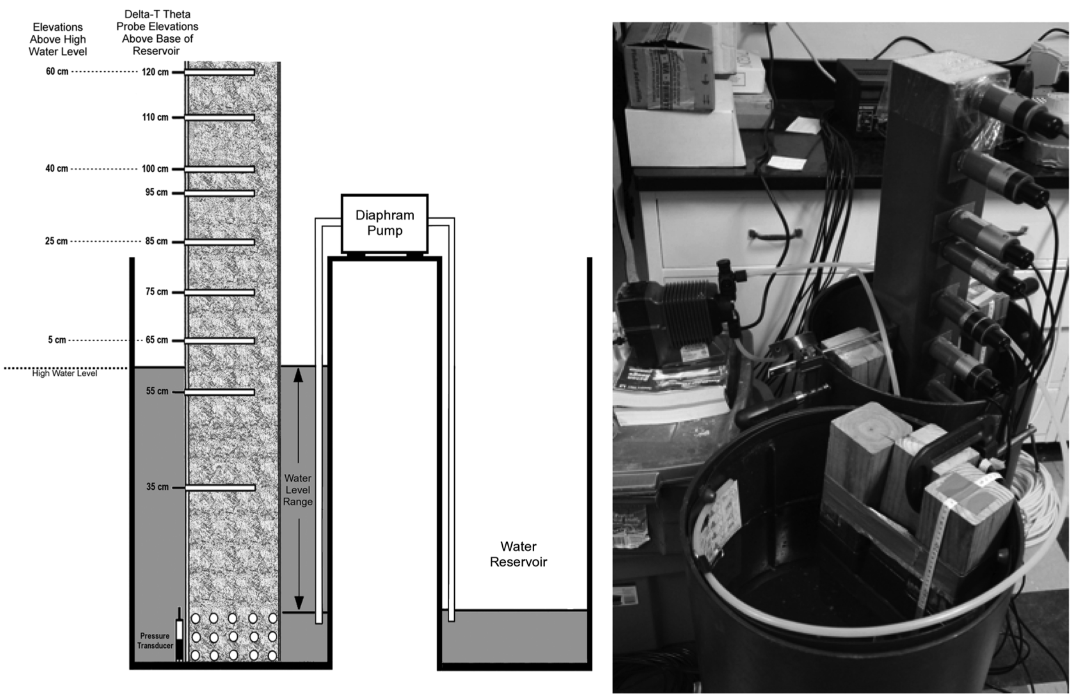

Figure 3. Schematic (left) and photograph (right) of the laboratory experimental apparatus.

Before each experimental run the sediment column was completely saturated. The water level within the reservoir was then set at the high water table elevation, and the system was left undisturbed for 10 days to allow gravitational drainage and moisture retention in the sediment column to reach equilibrium. After this equilibration period the height of the water level in the reservoir was cyclically lowered and raised to desired elevations over controlled time periods via the diaphragm-metering pump for a period of 132 hours (5·5 days). The duration of each oscillation cycle (fall and rise) was set at 24 hours. A transitional period occurred at the start of each experiment as the system shifted from a static equilibrium with a stationary water table to a dynamic equilibrium representative of natural conditions. This transition was generally found to be complete within about 24–30 hours. The analyses presented herein include only the data collected between 36 hours to 132 hours in each experiment, so that this transition does not influence the results.

Three separate experiments were conducted with vertical water table fluctuations of 25, 40, and 55 cm, respectively. The high water elevation was fixed at 60 cm above the base of the reservoir in all three experiments and the elevation of low water was varied, so that the moisture probe positions could be held constant relative to high water. The water table ranges employed here were chosen to be representative of fluctuations reported for various positions (foreshore, mid-beach, backshore) on northern Gulf of Mexico beaches (Zhu, 2007; Namikas *et al.*, 2010).

Surface moisture content data analysis

To represent the influence of water table fluctuations on surface moisture dynamics for various surface elevations above the water table, the measured moisture contents at four Delta-T Theta probe elevations within the sediment column were used as proxies. In the following analyses, the Delta-T Theta probes located at elevations of 65, 85, 100, and 120 cm above the base of the reservoir were employed as representative of moisture contents at 'true' surface elevations of 5, 25, 40 and 60 cm above the high water table, respectively (Figure 3).

The use of these proxies to represent surface moisture content is reasonable because the presence (or absence) of overburden above a given point in the sediment column does not substantively influence capillary transport below that elevation. Rather, the influence of capillary transport on moisture content at a specified height above the water table is a function of the soil matric suction/pressure head at that elevation, as follows. Based on the theory of capillarity, an increase in suction at a given elevation results in the emptying of smaller pores until, at very high suction values, only very narrow pore cavities are able to retain water (Childs, 1969). In essence, an increase in suction is associated with a decrease in the moisture content of the sediment. Under these circumstances, moisture content is associated with the soil matric suction at known heights above the water table. Therefore, since the moisture content of the soil at any specified elevation/pressure head above the water table is related to the prevailing suction at that pressure head, a relationship between soil moisture content and soil matric suction (or pressure head) can be determined. This relationship is known as the soil moisture retention curve (Childs and Poulovassilis, 1962; Childs, 1969; Van Genuchten, 1980). Once this relationship has been established for a given soil, the moisture retention curve can be truncated at any pressure head (i.e. height above the water table), in essence providing a 'proxy' sediment surface layer at that elevation (e.g. Childs, 1969). Figure 5 illustrates this concept, depicting the association between the moisture retention curve and moisture content at the sediment surface for different locations across a beach. Surface moisture content at various locations across the beach can be determined based on the intersection of the moisture retention profile curve with the sediment surface. The point of intersection shifts at different locations across the beach as the elevation of the surface above the water table changes. In essence the moisture retention curve is being truncated at the pressure head elevation of the sediment surface layer. Zhu (2007) has reported this to be the case at Padre Island, Texas. Hence, the use of the 'proxy' surfaces to represent the moisture content dynamics at comparable surface elevations is justified.

Sediment column moisture retention curves

The moisture retention curve, which describes the relation between matric potential and moisture content within a vertical sediment profile, provides a simple but efficient way to assess the moisture distribution of the sediment column. Although a number of models have been developed, the analytical form of the soil hydraulic function proposed by van Genuchten (1980) is generally thought to match experimental data more satisfactorily than others (Stankovich and Lockington, 1995; Cornelis *et al.*, 2001). Based on moisture content measure-

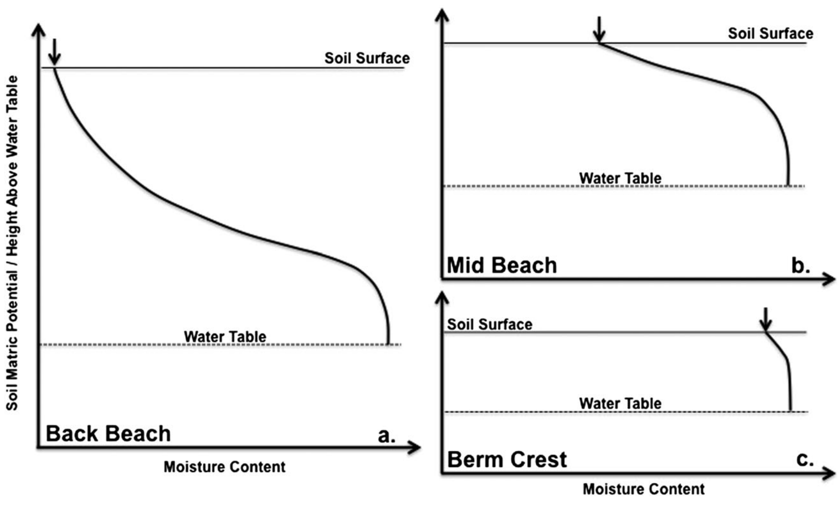

Figure 5. Schematic illustrations of the relationship between surface moisture dynamics and the soil water retention curve in the beach environment: (a) the backbeach; (b) the mid-beach; (c) the berm crest.

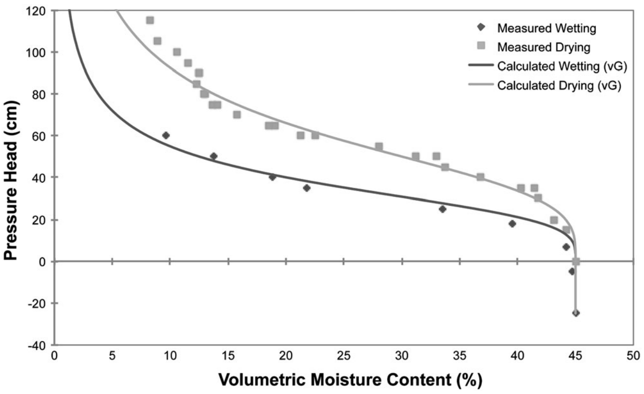

Figure 6. Measured volumetric moisture content measurements collected for both the high water table (wetting) and low water table (drying) pressure head conditions, and the calculated van Genuchten (1980) boundary wetting and drying moisture retention curves.

ments collected at each of the moisture probe elevations for both the high water table (wetting) and low water table (drying) pressure head conditions, a pair of main boundary wetting and drying moisture retention curves was constructed using the van Genuchten (1980) soil hydraulic function (Figure 6), expressed as:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \tag{1}$$

where θ_r is the residual water content at $0 \cdot 0018$ cm^3/cm^3, θ_s is the saturation water content at $0 \cdot 45$ cm^3/cm^3, h is the pressure head, α and n are empirical coefficients, and $m = 1 - 1/n$.

Results

Surface moisture response

The response of surface moisture content to water table fluctuations is illustrated in Figure 7. Several trends in moisture content are clearly apparent among the various sediment surface elevations. First, there is a noticeable decrease in both absolute moisture content and the range in moisture content with increasing elevation at high water level. At an elevation of 5 cm, moisture content varied from a low of 22% to a high

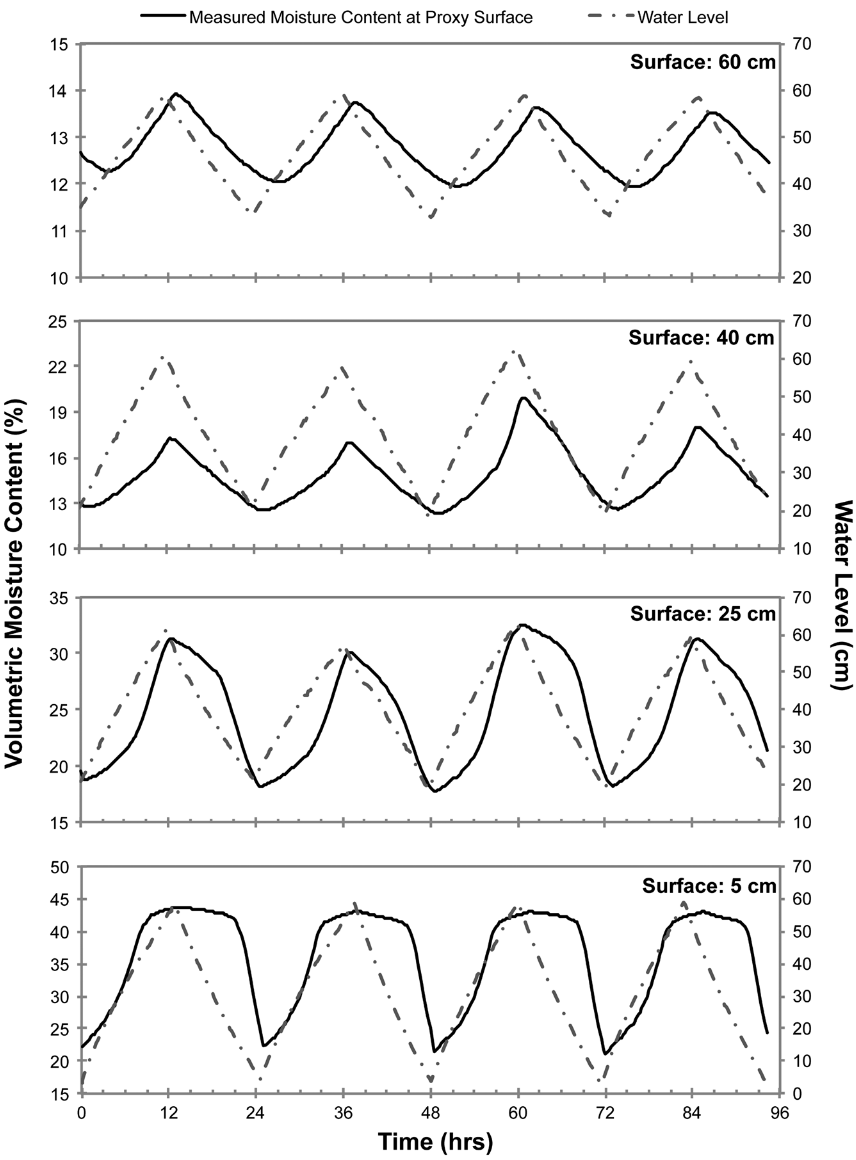

Figure 7. Variations in volumetric moisture contents and water level period at each of the four 'proxy' surface elevations. The 60 cm surface elevation was associated with a water level fluctuation of 25 cm, where as the 40 and 25 cm elevations were subjected to a water level fluctuation of 40 cm, and the 5 cm surface elevation experienced a 55 cm water level fluctuation.

of 44% (by volume). As the surface elevation increases to 60 cm above high water, the range in surface moisture content is reduced to 11–14%.

A second trend apparent in Figure 7 is a decrease in the symmetry of the moisture content traces with decreasing surface elevation. With a near-surface water table, the surface moisture content remains steady for a substantial period of time following the transitions between both a rising and falling water table. This is strongly evident at the 5 cm elevation, and although present at the 25 cm elevation the occurrence is clearly muted. These observations correspond well with the findings of Zhu (2007) for the foreshore zone, and are associated with an aspect of hysteresis known as Haines Jump (after Haines, 1930), or the ink bottle effect. Haines Jump hysteresis is a water flow process dependent upon the nature of the pressure head at which individual pores drain and fill (Miller and Miller, 1956; Childs, 1969). As the pressure head within the soil column increases in association with a drying sequence, the moisture content within the soil column stays at a wetted level until the soil matric suction at a particular pressure head becomes too large. At that point the sediment column will abruptly drain. Conversely, as the pressure head within the soil column begins to decrease associated with a wetting sequence, the soil moisture content will remain at a relatively constant moisture content until the soil matric suction decreases to a point where the soil column will abruptly fill. Of note is that at the 5 cm elevation, moisture contents corresponding with a rising water table reached a maximum saturated level on average a few hours prior to actual high water level occurring (Figure 8). This observation should be expected based on the moisture retention curve of the sediment column, which illustrates a near-saturated capillary fringe extending approximately 18–20 cm above the water table. As the water table rises within the sediment column the advancement of the capillary fringe saturates the surface layer prior to the maximum water level occurring.

Finally, at each surface elevation the measured moisture contents lag significantly behind water table oscillations and the duration of the lag increases consistently with depth above the water table. Table I illustrates the average time lags between the measured maximum and minimum moisture contents and the associated high and low water table levels. The 60 cm surface elevation exhibited the largest lags with maximum and minimum moisture contents occurring at 135 and 240 minutes after the high and low water table levels, respectively. These lags decrease in magnitude with decreasing surface elevations, with time lags as little as 40 minutes at the 5 cm surface elevation after low water table levels occurred (Table I). These results correspond well with the existing literature (Childs, 1969; Kool and Parker, 1987, Hinz, 1998).

Table I. Average time lags (in minutes) between maximum/minimum moisture contents and high/low water table levels

Surface elevaton	High water table	Low water table
5 cm	N/A[a]	38
25 cm	55	58
40 cm	61	105
60 cm	123	237

[a]In every case the surface content reached saturation before high water and remained saturated for some time afterwards.

Water flow scanning curves

An efficient way to assess the hysteretic nature of the surface moisture is through evaluation of a sequence of water flow scanning loops. When a wetted soil begins to drain, or when a dry soil column is rewetted, the relation between the pressure head and the soil moisture content follows some intermediate moisture retention curve as it moves from the main wetting or drying branch to the other. Such intermediate retention curves are called scanning curves. A wetting and drying scanning curve sequence forms a scanning loop that falls between the main wetting and drying moisture retention curves (Childs and Poulovassilis, 1962; Poulovassilis, 1962). Figure 9 shows a single scanning loop (24 hours) for each of the four surface elevations considered in this analysis. In all four cases the scanning loops illustrate that at a given pressure head higher moisture contents occur during the drying cycle than during the wetting cycle. This finding agrees with the results of Werner and Lockington (2003), and demonstrates that tidally-induced groundwater dynamics can have a very strong hysteretic influence on surface moisture contents. At the 5 cm and 25 cm elevations the Haines Jump phenomenon is apparent in the near-horizontal segments of the scanning curve loops. At higher surface elevations (40 and 60 cm) this phenomena is absent. This observation corresponds well with those illustrated in the literature, which indicate that Haines Jump effects are

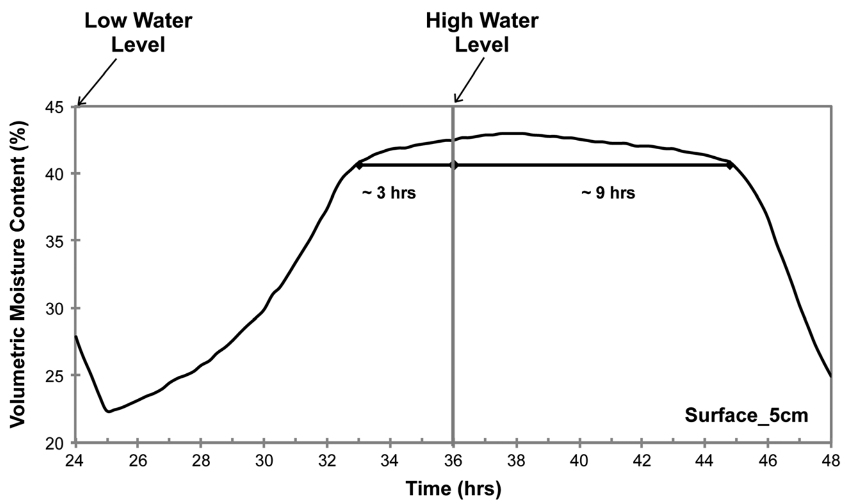

Figure 8. A 24 hour time sequence (24–48 hours) of measured volumetric moisture contents at the 5 cm surface elevation. Moisture content reaches saturated level prior to actual high water level and persists for an extended period of time afterwards.

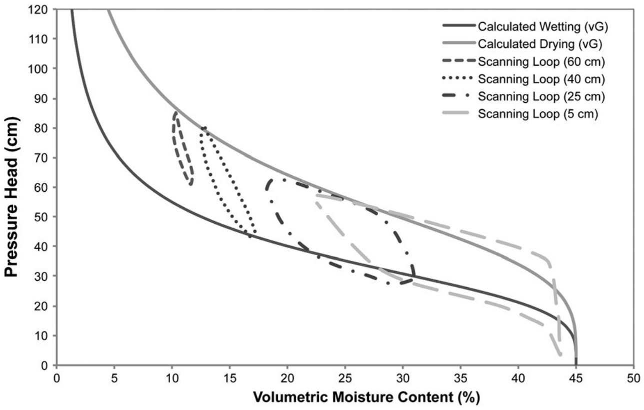

Figure 9. Illustration depicting a single water flow scanning loop (24 hours) for each of the four 'proxy' surface elevations. Also shown are the calculated van Genuchten (1980) boundary curves.

more pronounced in the lower pressure head range where individual pores empty at larger pressure heads than that at which they fill (Hillel, 1971, 1980; Hanks, 1992).

Table II. Standard error (percentage volumetric moisture content) for hysteresis and non-hysteresis model simulations.

Surface elevation	Hysteresis	Non-hysteresis
5 cm	3·39	4·34
25 cm	3·21	9·43
40 cm	3·46	7·72
60 cm	0·93	4·35

Hysteresis and non-hysteresis simulations

The response of surface moisture content to water table fluctuation was modeled using both hysteretic and non-hysteretic simulation approaches. The capillary water flow simulations employed within this study were carried out utilizing the HYDRUS-1D program developed by Šimůnek *et al.* (1998). HYDRUS-1D calculates hysteretic and non-hysteretic water flow in the sediment column by numerically solving the empirically derived hysteretic function developed by Scott *et al.* (1984) and the Richards (1931) one-dimensional non-hysteretic water flow equation.

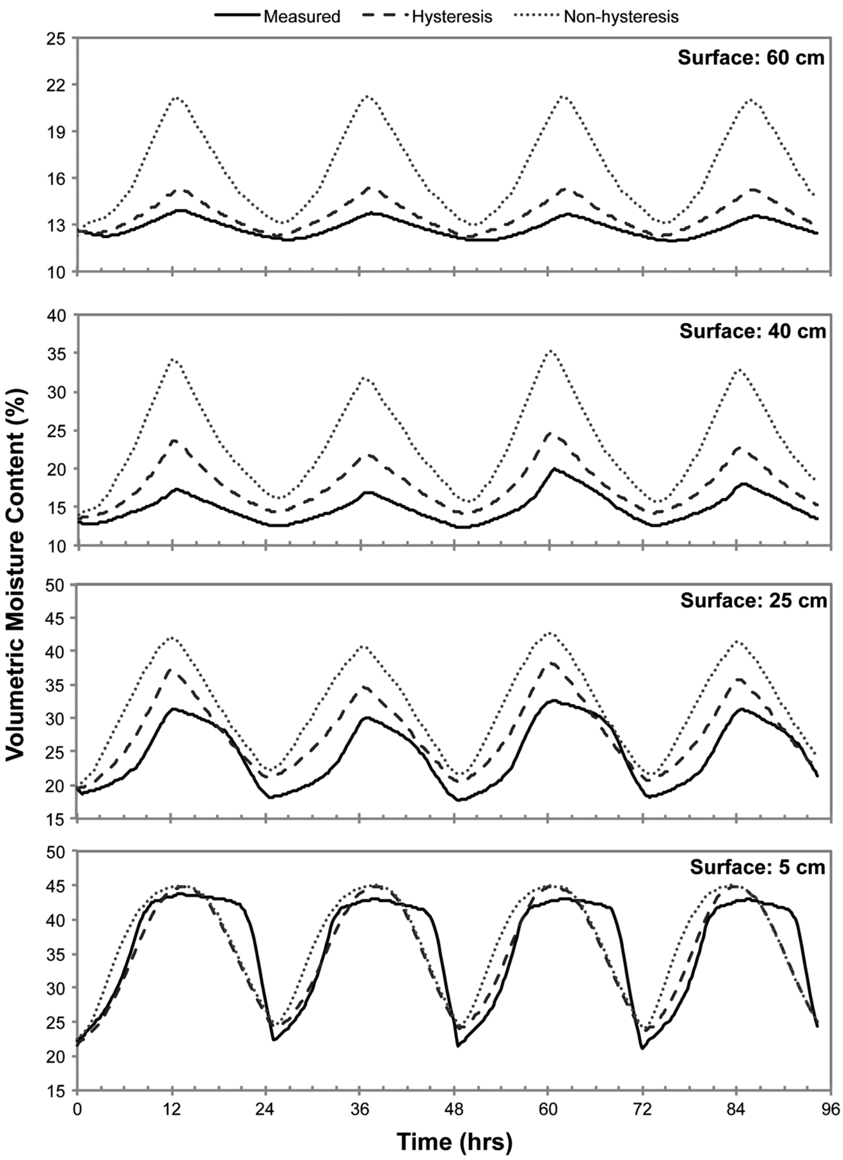

Figure 10. Hysteretic and non-hysteretic model simulations relative to measured volumetric moisture contents for each of the four 'proxy' surface elevations conducted throughout this study.

Table III. Comparison of the average time lags (in minutes) between maximum/minimum moisture contents and high/low water table levels for the measured and hysteresis simulation approach.

Surface elevaton	High water table			Low water table		
	Measured	Hysteresis	Difference	Measured	Hysteresis	Difference
5 cm	N/A[a]	26	N/A	38	27	9
25 cm	55	34	20	58	50	8
40 cm	61	48	13	105	98	8
60 cm	123	103	20	237	135	102

[a]In every case the surface content reached saturation before high water and remained saturated for some time afterwards.

A comparison between the predictions from the two approaches relative to measured surface moisture content is depicted in Figure 10. At the 5 cm surface elevation both models produce values that are quite close in predicting the overall range of surface moisture contents, however, both approaches fail to adequately capture the Haines Jump hysteresis effect. This latter aspect of the system dynamics clearly requires additional attention. Furthermore, with increasing surface elevation above the water table, both model approaches consistently over predict moisture contents, but it is clear that the hysteretic model simulations reduce the extent of this problem. The utilization of hysteretic water flow calculations thus provides a better representation of the observed moisture contents compared to non-hysteretic simulations. These findings correspond well with those previously presented in the literature (Stauffer, 1996; Lehmann *et al.*, 1998; Stauffer and Kinzelbach, 2001; Werner and Lockington, 2003).

A quantitative assessment of the simulations was conducted by calculating the standard error (SE) in predicted volumetric moisture contents for each surface elevation (Table II). It is apparent that the inclusion of hysteresis improves results significantly in each case. Indeed, the smallest error level from the non-hysteresis simulations exceeds the largest error found with the hysteresis approach. Clearly there is benefit to be had from the inclusion of hysteresis in attempts to model surface moisture dynamics.

A remaining question is how well the hysteretic model is able to predict the transient time lags in surface moisture contents. Table III provides a comparison of the average time lags between the measured moisture contents and the predicted moisture content values for the hysteretic model simulation. At the shallowest surface elevations of 5, 25, and 40 cm the hysteresis approach only slightly underestimates the measured lag values after low water table levels. However, at the 60 cm surface elevation the hysteresis approach significantly underestimated the time lag signal of capillary water flow estimating minimum moisture contents occuing over 100 minutes before the measured lag values after low water table levels. Additionally, after the occurrence of high water table levels the hysteresis simulation predicted moisture values that underestimated the measured transient nature of the sediment column at the 25, 40, and 60 cm. Of note is that at the 5 cm elevation after high water table levels occurred, the hysteresis approach calculated a time lag of 26 minutes whereas the measured moisture content values illustrate maximum content occurring hours prior to high water occurring. This is an aspect of the system dynamics that merits additional attention, as there is no obvious explanation why the Scott *et al.* (1984) hysteresis model would not capture the saturation of the sediment column associated with the advancement of the capillary fringe. Nevertheless, the hysteresis model produced values that are quite close in capturing the time lag signals in the measured surface moisture contents, and therefore, indicates that overall the hysteresis model is able to capture the transient nature of beach surface moisture dynamics.

Summary and Conclusion

The primary goal of this study was to examine the response of surface moisture contents to an oscillating water table, specifically the influence that hysteresis and transient flow effects have on surface moisture dynamics. Several useful findings emerge. First, Haines Jump hysteresis exerts a significant influence on surface moisture dynamics. This is particularly true where the surface is close to the water table and moisture contents remain steady for a substantial period of time following the transition between water table fluctuations. Second, a substantial time lag exists between tidally-induced water table oscillations and surface moisture content, and this time lag increases with increasing surface elevation (relative to the water table). These results indicate that for drier areas of the midbeach and backbeach, capillary water flow in the sediment column could produce surface moisture contents that correspond to water table positions that had occurred hours previously.

Furthermore, simulations of moisture contents from hysteretic and non-hysteretic model simulations illustrated that the utilization of a hysteretic model provides a higher degree of accuracy for modeling surface moisture contents than do non-hysteretic models. This finding suggests that studies that employed a non-hysteretic water flow approach to link oscillating groundwater dynamics to variability in beach surface moisture content (i.e. Raubenheimer *et al.*, 1999; Atherton *et al.*, 2001; Zhu, 2007; Namikas *et al.*, 2010); may have drastically overestimated surface moisture contents, particularly across areas of the midbeach and backbeach zones.

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