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Infiltration and Moisture Movement in Coastal Sand Dunes, Studland, Dorset, U.K.: Preliminary Results

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ABSTRACT

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This paper reports the initial findings from a study of soil moisture within a series of three unlithified dune ridges at Studland, Dorset, on the southern coast of England. The infiltration and movement of moisture was monitored at each dune crest, slack and mid position on windward and leeward flanks, using capacitance probe technology. The mean moisture level in the dunes (excluding the troughs) was close to 7% and ranged between 1 and 18%. The rapidity and sensitivity of response of the dune sands to wetting and draining decreased markedly with depth over a distance of 1.3 m, and the behaviour patterns fell into three clear zones: 0–45 cm; 60–90 cm 110–150 cm. The uppermost was the most sensitive and experienced the greatest number of wetting and drying cycles. Differences in moisture regime also varied according to the density of vegetation cover and position over the dune. On well vegetated sands the moisture was concentrated in the upper levels of the dune, corresponding to the thin soil and the rhizosphere, and in unvegetated dunes moisture was retained at depth. Spatially, crests are the driest positions and small but persistent differences in moisture were recorded between windward and leeward flanks which may reflect the movement of subsurface moisture along bedding planes. These observed patterns correspond well with existing knowledge of susceptibility to early diagenetic change within the vadose zone of dune sands.

ADDITIONAL INDEX WORDS: *Coastal dunes, subsurface moisture regimes, vadose hydrology.*

INTRODUCTION

The majority of coastal dune studies have concerned morphology, processes of formation, and sand transport rates. In temperate areas, the movement of water through dunes and the spatial variability in soil moisture in relation to vegetation cover and position on the dune has received relatively little attention since the pioneering work of SALISBURY (1952). A knowledge of subsurface hydrology is, however, relevant to an understanding of dune dynamics, dune ecology and conservation, and in particular, to early vadose diagenesis in dune sands. The initial stages of diagenetic alteration in coastal dunes often results in substantial vertical variation in cementation within the top 1.5 to 2.0 m, including the preferential precipitation of cement in the top 50 cm of the sands, which eventually leads to plugging of the natural porosity. The aim of the current research is to elucidate the extent to which an understanding of modern processes of rainfall infiltration and subsequent movement within the vadose zone of the dunes could help to explain the diagenetic patterns evident in Holocene and Pleistocene aeolianites (see GARDNER and MCLAREN 1993; 1994), including those in temperate environments (*e.g.* Braunton Burrows, Devon). For example, does the thickness of the diagenetically plugged layer correspond to the average depth to which the wetting and drying cycles penetrate in unlithified sands? To date the few studies of vadose subsurface hydrology in dune sands have been conducted in desert environments under conditions of artificial irrigation (AGNEW, 1988). In temperate regions, research has focused on groundwater hydrology rather than vadose hydrology. Developments in monitoring equipment (capacitance probe) have recently provided a simple, sensitive, and nondestructive method of measuring moisture content with a minimum of disturbance to the dune profile. Making use of this technology, the aims of this study were twofold: first, to investigate rainfall infiltration, patterns of soil moisture change with depth, and wetting/drying cycles in the near-surface vadose zones of temperate latitude dune sands; and secondly to examine the effects of vegetation cover and position over the dune on vadose moisture regimes.

FORMER STUDIES RELEVANT TO THE VADOSE ZONE WITHIN DUNES

Precipitation falling upon unsaturated unbedded sands percolates and is redistributed under the influence of gravity, initially very rapidly, and then more slowly until it achieves a constant rate. As a result the wetted zone (which is nearly saturated) deepens quickly at first owing to the steep matric suction gradient. This rate slows down gradually as the wet-

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ted zone penetrates more deeply and the matric suction gradient diminishes. There exists a sharp junction (wetting front) between the wetted zone and below where the soil moisture content is closer to the pre-infiltration rate (MARSHALL and HOLMES 1988). However, dune sands are more complex than simple uniform sand bodies. Dunes have combinations of textural characteristics, bedding structures and morphology that clearly differentiates them from both unbedded sands and hill slopes with sandy regoliths (SALTER and WILLIAMS 1965). It has been recognised for some time that "infiltration of precipitation in sand dunes is a complex phenomenon and a serious challenge in physical hydrology" (DINCER *et al.*, 1974, p. 107).

Texture has been widely recognised as influencing soil moisture characteristics but the precise effect within dunes remains unclear. In fine-textured soils there is a greater availability of total surface area for water to adhere to. DINCER *et al.* (1974) found that following rainfall in Saudi Arabia, fine dune sands did not permit deep redistribution of waters because of high losses due to evaporation, whereas coarse-textured dune sands allowed rapid infiltration and deeper movement of moisture, and evaporation losses were much lower. Where the mean grain size was 0.15 mm precipitation of 1 mm only penetrated 7 mm, but on sands with a mean grain size of 0.3 mm penetration increased to 20 mm. OREV (1984), working in the Negev desert, found that 1 mm of rainfall penetrated 50 mm (but he gives no information on particle sizes). In contrast, BAGNOLD (1941, p. 237) found that the "wetted front travels faster through the material (dune sands) as the proportion of fine materials is increased". Texture in dunes has been shown to differ at several spatial scales: between laminae, according to position on the dune, and across the dunefield more generally.

Only two detailed studies exist on the influence of bedding structures on pore water movement. BAGNOLD (1941) found that the water tended to travel laterally along the foreset laminae rather than moving vertically downwards across the laminae. He also noted that the movement of water was not uniform through all the laminae but that it moved preferentially along certain laminae, whilst other laminae adjacent to the wet laminae remained dry. He did not, however, determine whether textural differences between the laminae were responsible for the observed patterns of water movement. AGNEW (1988) also found that dune hydrology was related to subsurface bedding. Working in Oman, Agnew ascertained that the wetting front on dunes, after irrigation with 20 litres, penetrated little more than 50 cm but that the interdune areas became increasingly wetter for up to 40 days after artificial irrigation of surrounding dunes. If the principle of lateral seepage along bedding planes applies across whole dunes (and there is no reason to suppose that it should not), then it follows that patterns of subsurface moisture movement should differ according to position on the dune and according to dune type, each of which is characterised by distinct and different internal bedding structures (LAND, 1964; GOLDSMITH, 1973, 1985; HESP, 1988).

Evaporation and moisture penetration to depth into dunes has been the subject of a number of investigations, most of which were undertaken using gravimetric analyses of a small number of augered samples. They suggest that in unvegetated dunes the upper 30 cm tend to be relatively dry, and that moisture contents increase below. For example, after a long dry summer in the Negev, TSOAR and ZOHER (1985) found the upper 30 cm to contain 1% (vol.) moisture, but below the sands became wetter up to a maximum of 3% (vol.) at a depth of 80 cm, and thereafter moisture levels declined to 2.25% (vol.) at a depth of 120 cm, the maximum depth measured. Similarly, STEPHENS and KNOWLTON (1986) found that the upper 30 cm in Californian coastal sands contained less than 2–3% moisture by volume, and below 30 cm moisture levels increased to between 5–8% by volume. These findings are consistent with the suggestion that evaporation is limited to the top 30 cm of dune sands (TSOAR and ZOHER, 1985; AGNEW, 1988; PYE and TSOAR, 1990), beneath which temperature gradients are too small to power evaporation. However, the increase in moisture contents at greater depths on unvegetated dunes is not always uniform (SALISBURY, 1952; BALDWIN and MAUN, 1983). For example, SALISBURY (1952) and TSOAR and ZOHER (1985) identified a peak in moisture content in the mid profile position (60–90 cm), below which moisture levels declined. SALISBURY (1952) noted that this tended to occur after very dry spells, and suggested it may be due to condensation from vapour supplied by external sources, and interestingly TSOAR and ZOHER'S' measurements were taken towards the end of a long hot summer.

The interaction of precipitation event characteristics and vegetation cover in affecting the rate and proportion of precipitation infiltrated, and hence the extension of the wetting front in dune sands, has been studied by BALDWIN and MAUN (1983), RANWELL (1959) and SALISBURY (1952). Their work shows that the completeness of vegetation cover, and the associated organic content of the soil, and decreased wind velocity above vegetation may combine to lead to higher moisture retention in the top 20 cm of the sands than in similar unvegetated sands. CHEPIL (1956) recorded up to 33% moisture content at field capacity. SALISBURY further suggested that the raised moisture content in the upper profile may incur a decrease in moisture levels lower in the dunes, and PYE and TSOAR (1990) propose that transpiration may also deplete moisture levels at depths between 30 and 180 cm, leaving vegetated sands at these levels drier than comparable unvegetated ones. OGATA *et al.* (1960) recorded non-uniformity of water uptake from different soil depths when they studied crops of alfalfa. They found that suction gradients from roots can result in water movement in many different directions. However, capillary rise from the watertable is unidirectional and is generally thought only to affect moisture levels up to 1 metre above the phreatic zone (RANWELL, 1959).

Since 1952 there has been no study of water penetration and redistribution within dunes in the UK, and remarkably little detailed systematic analysis of the effects of texture, spatial location over the dune and vegetation cover on subsurface moisture regimes in either the UK or elsewhere in the world. Furthermore, it is noticeable, and understandable, that the studies reported are nearly all from arid and semiarid regions. Recent investigations of coastal temperate dune systems, largely in The Netherlands, have concentrated on their groundwater properties (BAKKER 1990, BAKKER and

NIENHUIS 1990 and LLAMAS 1990); and the water repellency of surface soil horizons (DEKKER and JUNGERIUS 1990) which JUNGERIUS and DEKKER (1990) propose causes overland flow in dry dune soils as a result of impeded drainage.

METHODOLOGY

Studland in Dorset (Figure 1) was considered to be one of the most suitable dune fields in the United Kingdom for a study of vadose moisture for a number of reasons. First, the system comprises a number of well-defined unlithified dune ridges of approximately the same size, morphology and orientation; secondly, the vegetation cover and type differs between ridges and has been carefully documented (RADLEY, 1990); and thirdly the dunes are remarkably uniform in terms of their particle size distribution which means that the study of subsurface moisture regimes is not complicated by substantial variations in texture between different beds or different dune ridges.

Soil moisture measurements were made in the field using a Didcot Instruments capacitance probe. 1.5 metre access tubes were installed in the dunes; the ten access tubes were emplaced along a transect located in the southern part of the dunefield, perpendicular to the coast, and which crossed the three transverse dune ridges. The tubes were located in crest, windward and leeward flank positions, and in the dune slacks (Figure 1). Site 1 is the unvegetated 'control' site and the remainder of the youngest ridge is partially vegetated by marram grass (*Ammophila arenaria*); the middle ridge (sites 4–7) has on average 90% vegetation cover (largely *Calluna vulgaris* and *Campylopus introflexus*); and the innermost ridge (sites 8–10) has 95% cover which is predominantly *Calluna vulgaris*.

The reported capacitance probe readings were taken on a daily basis at approximately midday, at depths of 15, 30, 45, 60, 75, 90, 105, 120 and 130 cm for almost one month. To calibrate the capacitance probe, samples of sand were collected from approximately one metre away from the access tubes. Unfortunately calibration could not be undertaken at the time and exact point of installation as small amounts of water had to be added to facilitate augering during emplacement of the access tubes. The soil moisture content of the sand samples for calibration were determined gravimetrically. Particle size analysis was subsequently carried out on the sand samples collected for calibration purposes, using a standard dry sieving procedure (FOLK, 1974). Bulk density measurements were made on samples of known volume collected from pits dug at five locations (all three dune crests and both flanks of the middle dune) and extracted from depths of 10, 30, 50 and 70 centimetres. Ponded infiltration experiments were carried out on the crests of the seaward (unvegetated) ridge and innermost (heather and moss covered) ridge using a single ring infiltrometer emplaced 7.5 cm into the sands. Infiltration rates were measured for up to 2 hours, with duplicate experiments measured over intervals of 30 minutes.

Rainfall was logged continuously (one minute intervals) on site during the monitoring period between 1 and 26 September by means of a single channel logger connected to a tipping bucket rainguage. The rainfall record is shown in Figure 2, and a total of 119.12 mm was recorded over the 27 days. Rainfall in August, prior to field monitoring, totalled 40.75 mm, and no rain fell after 23 August. The period of monitoring is divided into three phases each with different rainfall characteristics. The first, between 3 and 9 September, included the initial wetting up resulting from the 33.39 mm rain between 7 and 9 September which occurred after a dry spell lasting 14 days. The second, from 15 to 19 September, was the dry period after substantial and prolonged rain (81.50 mm) between 7 and 13 September. The last, from 19 to 26 September, covers the complete wetting and drying cycle associated with the rainfall event of 20 September (15.54 mm). Mean rainfall intensity varied between 1.2 and 7.2 mm per hour; and the maximum one minute intensity reached 48 mm per hour. Spatial variations in rainfall across dune ridges was not measured but it is anticipated to be low owing to the relative low relief of the dunes.

Characteristics of the Dune Sands

The dune sands comprise subrounded quartz particles, with small amounts of heavy minerals and feldspars. Mean bulk densities for 23 samples of unvegetated dune sands is 1.52 g/cm^3 (range 1.45 to 1.61). The mean lies in the middle of the range of 1.2 to 1.8 reported by BRADY (1974) as characteristic of sands. There is no systematic variation either with depth or between sites, apart from where the sands are densely vegetated (inner ridge), where bulk densities in the upper 10 cm decline to between 0.93 and 1.30g/cm^3. In terms of typical particle size distributions, the modal class lies within the fine sands (2–3 phi), mean and median values fall between 2 and 2.5 phi, skewness is low, and the sands are well sorted. Variation in particle size is small both within and between profiles.

Excavation of pits revealed that most of the vegetation is shallow rooting, with roots concentrated in the top 30 cm, although individual marram grass (*Ammophila arenaria*) roots have been noted to depths exceeding 50 cm. Organic-rich soil horizons (sand rankers) are best developed on the inner ridge, where the sandy A horizon is dark brown in colour, and up to 10 cm thick. Fine heather roots extend down to a depth of approximately 25 cm and the soil is capped by a layer of moss and lichens. On the seaward ridge there is no soil development, whereas on the middle ridge early soil development is evident beneath a layer of moss; the organic layer is less than 2 cm thick. (Soil development at Studland is described in more detail by WILSON, 1960.) There is no evidence of buried soils in the profiles studied.

Infiltration rates were initially very high on both the dry vegetated and unvegetated sands. They declined on the vegetated sands to 1.4 mm min^{-1} after 25 minutes, but on the unvegetated sands they remained higher at 42.5 cm min^{-1}. Even after two hours the rate on unvegetated sands had only declined to 5.0 cm min^{-1}. Thus, the infiltration rates are such, even where a dense fine root mat is present under the heather, that runoff will rarely be produced except under conditions of very high rainfall intensity or high water repellency (see JUNGERIUS and DEKKER, 1990). The high infiltration rates on the dry, thin humic sands beneath the vegetation on the inner dune ridge suggests that the water repellency potential is low compared with that on the thicker, unvegetated humic sands in the Netherlands (RUTIN, 1983). No runoff was observed during the monitored period.

General Trends in Dune Moisture

Moisture values within the top 1.3 metres of the sands varied from under 1% to over 35%, but excluding the dune slacks, moisture rarely exceeded 15% by volume and commonly fell between 1 and 10% by volume. The range within the sands other than in the dune slacks is broadly similar to that obtained by AGNEW after saturation during an infiltration test on dunes in the Wahiba Sands of Oman (AGNEW, 1988). Responsiveness, sensitivity and water penetration vary with depth in the profile, which can be classified into three zones using these parameters. The upper zone, between 0 and 45 cm depth, is one of rapid response to both wetting and drainage / evapotranspiration, and it is highly sensitive to small (2–3mm) as well as larger inputs of rainfall. The middle zone, between 45 and 90 cm depth, experiences longer lags in response, usually showing peak moisture levels one or two days after the upper profile; sensitivity is less as shown by a subdued response to the larger events and little response to the smaller rainfall events, and moisture contents are generally less variable than within the upper zone. The lower zone, between 90 and 130 cm, does not record responses to most individual events owing to a combination of long lag times and low sensitivity; only the heavier rains are eventually recorded, with peak moisture levels lagging two to three days behind the upper zone, and generally in a highly subdued manner. The rate of moisture loss/drainage, however, is broadly similar to that in the other zones.

Unvegetated Dunes

Figure 3 shows moisture change over time and with depth for the unvegetated dune sands on the crest of the seaward ridge, the youngest ridge, for September. The first point to note is the sensitivity of the top 30–45 cm of the sands, both in terms of wetting and subsequent drying. Rapid wetting is shown on 8 and 9 September when moisture levels increase from a low of around 2% to over 12% at depths of 30 cm. By 8 September, after the initial burst of 6.5 mm rain, moisture levels have increased down to a depth of 30 cm, but no effect has been recorded at 45 cm. Following prolonged rain overnight moisture levels increased by a further 3% at 30 cm and a similar increase was recorded at 45 cm. A small effect is also seen at this time at 60 cm, but at greater depths the moisture content is still decreasing, reflecting longer term drainage of the sands. The rapid loss of moisture at 15 cm depth on 9 September, within 4 hours of the rain ceasing, illustrates the sensitivity to drying.

The second characteristic is moisture change with depth, whereby the upper 30 cm is generally drier than the lower sands, probably as a result of near-surface evaporation losses. This is consistent with findings from earlier studies. Moisture levels increase slightly with depth in the profile, but at the base of the profile, which remains wetter throughout the monitored period, there is a marked increase.

Thirdly, the depth to which rainwater from any single event infiltrates is a function of the amount of rainfall. (It is also probably a function of the pre-existing moisture content of the sands, although there are insufficient events monitored in the study reported here to test this hypothesis.) For example, the low rainfalls on 15 and 16 September were only recorded in the top 30 cm, whereas the moderate 15.96 mm rain on 20 September just penetrated to the depth of 105 cm, four days after the rain. The heavy rainfall of 10–13 September (80.5 mm) succeeded in wetting the sands throughout the top 1.3 m and its effects were still being felt for at least seven days afterwards in the lower profile. Moisture contents were lowered to between 2 and 5% in the top 30 cm within 48 hours of the rain ceasing, whereas steady drainage characterised the sands below 45 cm depth. This supports AGNEW'S (1988) finding that it is at least a week before drainage ceases in dune sands. The steady change in moisture content with depth also suggests that some vertical or near-vertical penetration of moisture occurs at the dune crest. In contrast to the reports of TSOAR and ZOHER (1985) there was no obvious peak in moisture content in the mid-profile position (60–90 cm).

Fourthly, the data also provide some support for the idea of lateral seepage of water within the dune, which was first proposed by BAGNOLD (1941). There is an imbalance between moisture losses and increases within the unvegetated profile at depths below which evaporation loss is thought to be small (TSOAR and ZOHER 1985; AGNEW 1988). For example, the decrease in moisture volume between 21 and 22 September between depths of 15 and 50 cm is approximately equivalent to the volumetric increase in moisture between 50 and 90 cm, however, the moisture decrease between 22 and 23 September at 30 to 70 cm depths is nowhere near matched by a corresponding increase in moisture between 70 and 110 cm that would be expected if drainage was only occurring vertically (Figure 4). This indicates that either lateral seepage may be more important as a process once the sands have been wetted; or that it occurs more in the mid to lower part of the profile in Studland, where the bedding has perhaps been less disturbed by root penetration, burrowing and human interference; or that the bedding is better defined as a result of the formational processes.

Lastly, shorter cycles of wetting and drying were also observed in the coastal unvegetated sands. Over a three day period with only 1.26 mm rain towards the end of September sand samples were collected from the surface and at a depth of 15 cm on each of the dune crests both in the morning and in the late afternoon. Although there were no moisture variations on the landward crests covered by heather and moss, on the bare youngest dune crest there was a significant diurnal variation that was independent of the small amount of rain. For example, in the morning of the second day the surface sands contained 4% moisture (by weight) but in the afternoon the moisture level had fallen to 1.5%. By the following morning there had been another increase in the moisture to approximately 3%. This is probably supplied by dewfall.

Vegetated Dunes

The effects of vegetation cover, and any associated organic A horizon, on dune moisture regimes are best shown by a

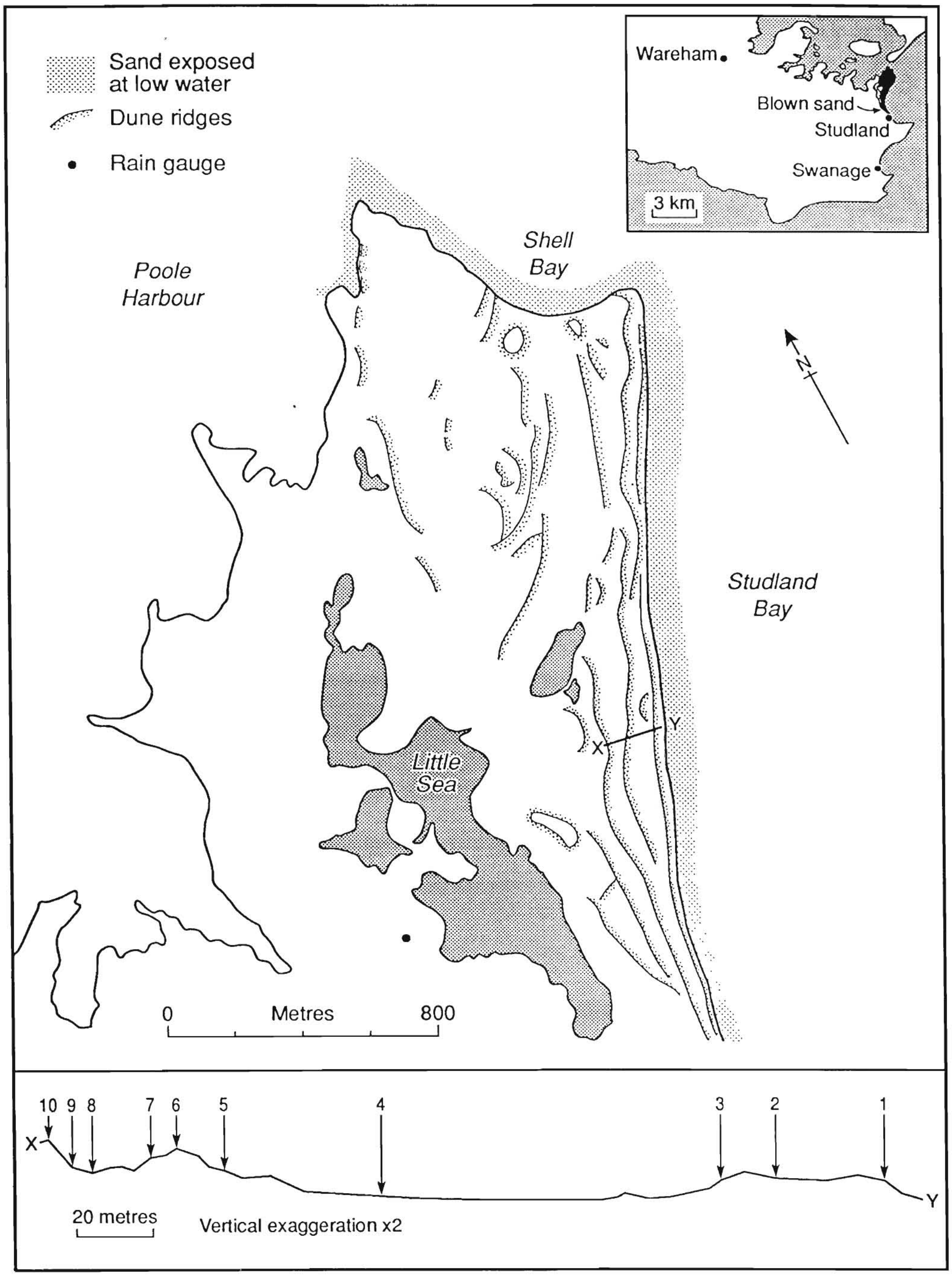


Figure 1. The dune system at Studland showing the location of the capacitance probe access tubes (1–10) across three of the dune ridges.

comparison of the unvegetated site 1 with densely vegetated site 10, both of which are located on dune crests and thus experience the simplest moisture regimes. Data for site 10 are shown in Figure 5. The most obvious difference between the sites lies in the extent to which the moisture contents in the vegetated sands below depths of 60 cm remain low; they rarely exceed 2% by volume, unlike the unvegetated sands which typically exceed moisture levels of 5% throughout the mid and lower profile. This reflects in part the differing propensities for interception and infiltration. For example, on the vegetated crest, moderately high rainfalls, such as on 20 September (15.96 mm), do not penetrate below the upper sands, whereas on the unvegetated site they clearly penetrate to the mid profile positions. Thus, only the highest rain-

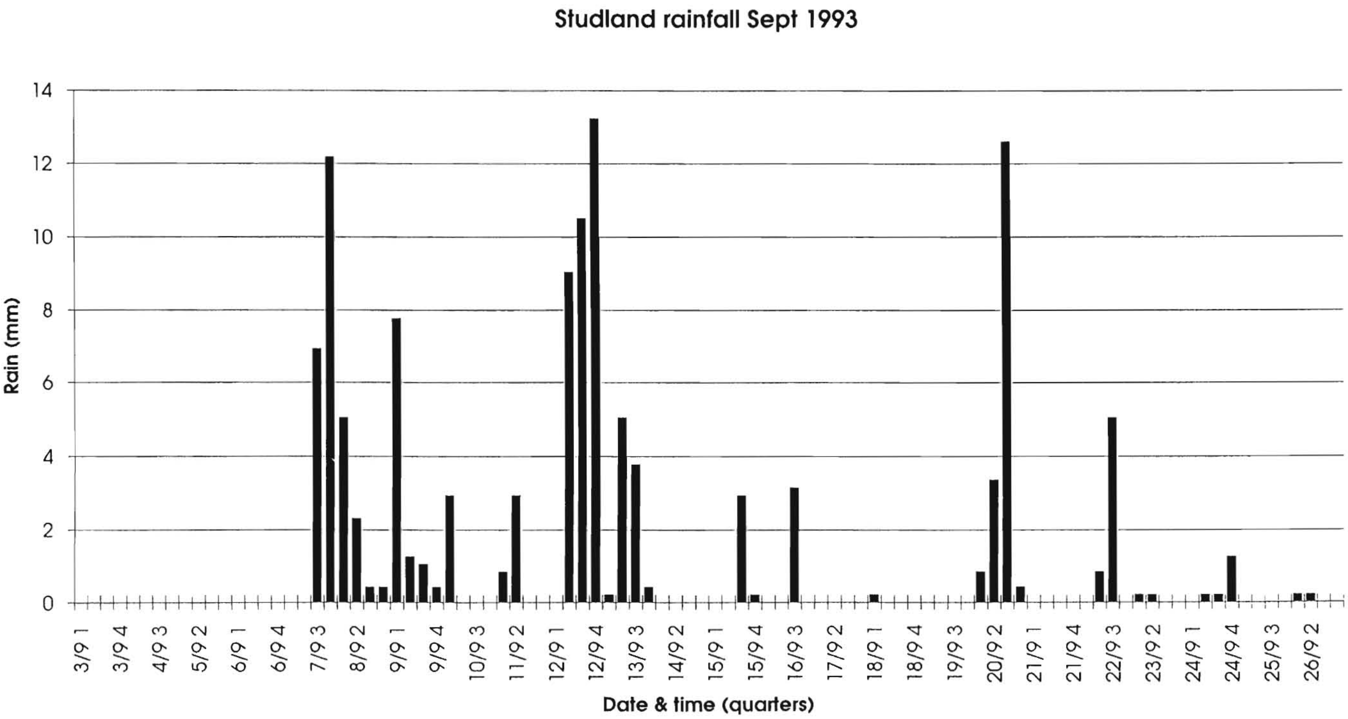


Figure 2. Rainfall amounts at Studland during September 1993 (each day expressed in quarters).

falls will be expected to recharge moisture in mid and lower profile positions beneath well vegetated dune crests, as seen between 10 and 13 September.

The second, and associated, difference is in the degree to which the upper 30 cm of sands wet and dry. For example, following the rainfall on 7 and 8 September, the vegetated crest sands do not wet as much as those on the unvegetated crest, but once wetted the moisture levels tend to remain higher beneath the heather canopy, between 4 and 8%, for the remainder of the monitored period. In contrast, on the unvegetated dune the upper sands wet to over 12% moisture content after the rainfall on 8 September, but then they dry/drain rapidly to moisture levels between 2 and 5% for most of the remaining period. Thus not only does less water infiltrate into the well vegetated sands but it also tends to be retained preferentially within the upper profile, despite likely transpiration losses from the shallowly-rooted heather at the vegetated site.

Moisture Regimes Across the Dune Ridge

It is in the detailed examination of moisture regime across a dune ridge that this study offers most new insights. The manner in which moisture content varies spatially across the dune is shown by a comparison of sites 4 (slack), 5 (windward flank), 6 (crest) and 7 (leeward flank) on the middle dune ridge (Figure 6), which is reasonably well vegetated by mosses and heather. All sites exhibit rapidity of response and sensitivity to rainfall within the upper 45 cm of the sands, and decreasing sensitivity and increasing lag in response with depth. It is noticeable, however, that the upper and mid profile positions on the crest wet less than the other sites. For example, by mid day on 9 September moisture content at a depth of 30 cm on the crest was just over 3% compared with moisture levels between 9 and 12% on the dune flanks and in the slack. This cannot be explained by differences in vegetation cover, and it probably reflects the absence of moisture contributed by lateral seepage at the crest. If this is the case, it indicates that such seepage may occur rapidly on the flanks.

Spatial differences are not restricted to the upper profile. At the dune crest the mid profile remains relatively dry, with less than 3% moisture throughout most of the monitored period. The rainfall of 20 September is barely recorded at a depth of 60 cm and is not felt at all at lower depths. In the dune slack the mid profile records moisture levels of over 8% throughout, and a distinct stepped wetting occurs from 8 to 24 September at a depth of 75 cm, the steps coinciding with seepage from the larger rainfall events. This results in the groundwater table rising almost to the 75 cm depth in the slack until drainage commenced on 25 September. In mid profile positions on the dune flanks (sites 5 and 7) lagged wetting and drying cycles are clearly seen, with pore moisture levels rising to 10.7% and 7.5% on the windward and leeward flanks, respectively. In general, the leeward flank is slightly wetter in the upper profile but drier in the mid profile than the windward flank, and it appears to respond more slowly in mid profile to some rainfall events, such as on 8/9 September. Overall moisture levels on the flanks are much

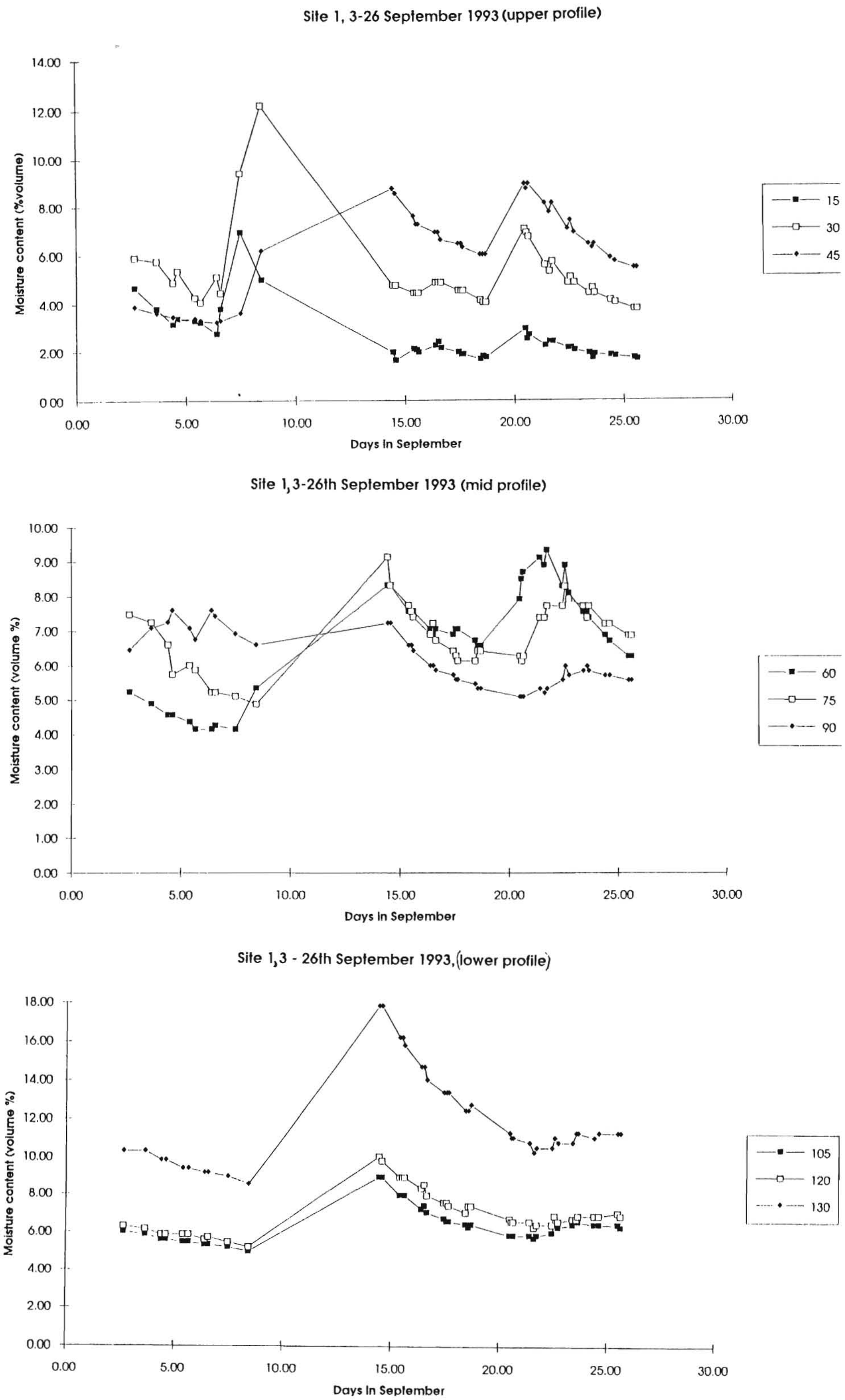


Figure 3. Moisture changes during September at site 1 (the unvegetated crest of the most seaward ridge) at depths between (a) 15–45 cm; (b) 60–90 cm; and (c) 105–130 cm.

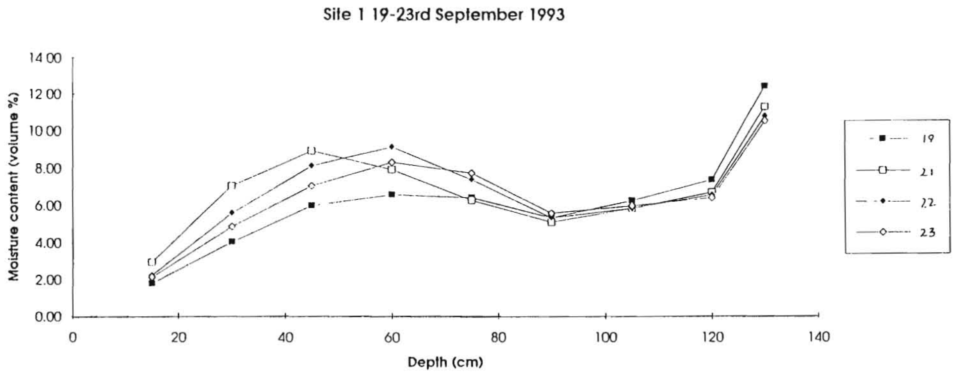


Figure 4. Changes in moisture with depth over the time period of 19–23 September 1993, site 1.

higher in both upper and mid profile than on the crest, but this is not the case in the lower profile.

The greatest difference between windward and leeward flanks occurs in the lower profile below depths of 110 cm. Although both become progressively drier with depth, the leeward flank (1.5–2.5% moisture) is consistently and substantially drier than the windward side (2–6.5%). Moreover, on the leeward there is no response to the heavy rainfall between 8 and 13 September, whereas on the windward the base of the profile continues to become wetter until 19 September, and thereafter remains more or less constant at 5.5% moisture. This suggests little moisture penetrates to depths exceeding 1m on the leeward flank, although overall moisture levels in the mid and upper profile are similar on both flanks. The lower profile on the dune crest has higher moisture levels than in mid profile, and attains levels similar to those on the windward flank at a depth of 130 cm. At depth the crest is therefore wetter than the leeward flank. Unusually high, and at present inexplicable, moistures are recorded at 120 cm depth on the crest (site 6).

Subtle but consistent variations in moisture regime occur spatially over the dune ridge. The variations suggest that near-surface (upper profile) lateral movement occurs on the flanks, especially on the leeward side, and that deeper seepage is more common on the windward flank than on the leeward. This may reflect the nearness of the steeply-dipping foreset beds to the dune surface on the leeward side. The crest, with its limited catchment area, except possibly at depth where contributions may come from the windward flank, remains the driest area on the dune. The lateral seepage contributes to the high moisture levels in the dune slack.

DISCUSSION

The moisture levels measured within the Studland dunes are broadly comparable to those reported in earlier studies of coastal dunes in the United Kingdom (SALISBURY, 1952); indeed the mean moisture content throughout September was close to the 7% average moisture retention for young coastal dunes quoted in PYE and TSOAR (1990). Also it was close to the common summer soil moisture contents of 4–6% at depth given in RANWELL (1959) and 4–8% in the top 90 cm calculated by WILLIS and JEFFERIES (1963). Whereas the water content was found to be relatively more constant at lower

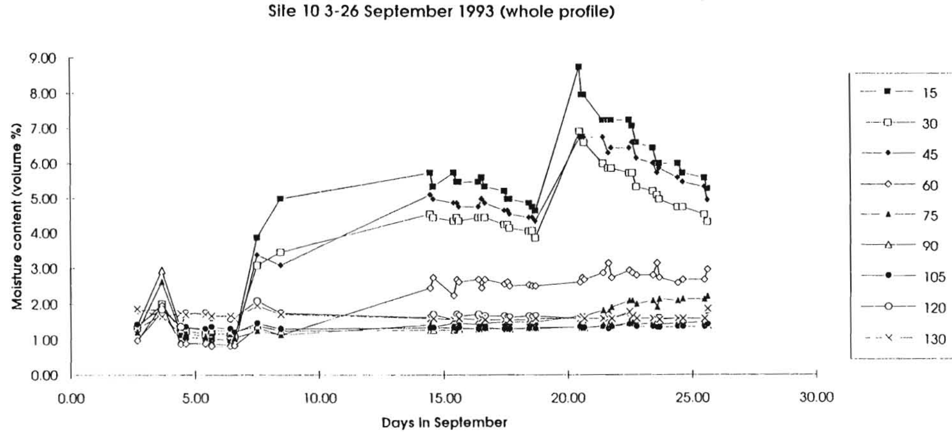


Figure 5. Moisture changes over time through the whole profile at site 10.

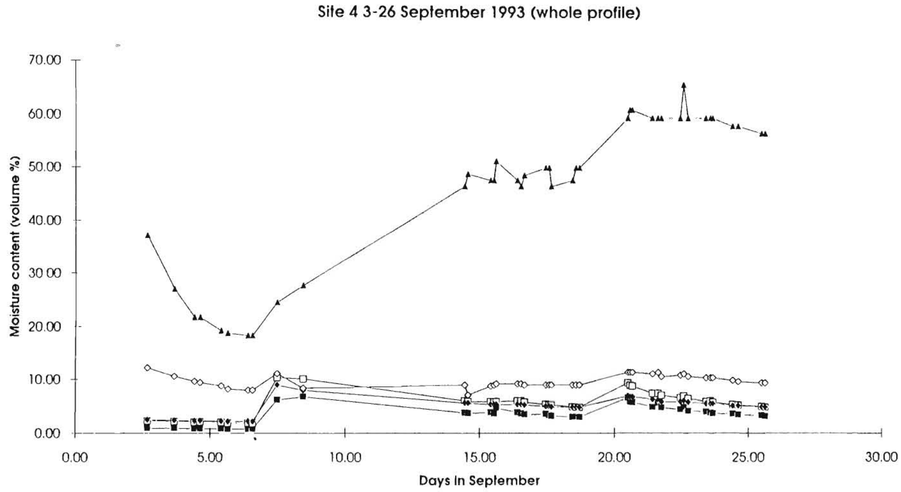


Figure 6. Moisture changes over time at: (a) site 4; (b) site 5; (c) site 6; (d) site 7.

levels (90–130 cm) in the dunes, a finding which supports SALISBURY's suggestion (1952), it did fluctuate noticeably in response to higher rainfall events. Despite periods of five days without rain, it appears that 'stable' field capacity was never reached. However, the indications are that it would lie at the lower end of the 4–10% range cited for active dunes with <1% fines and <1% organic matter (PYE and TSOAR 1990), and that it is significantly lower than the field capacity of 11–13% reported for the Lake Huron dunes (BALDWIN and MAUN 1983). The long period of time during which drainage continues prior to reaching field capacity supports AGNEW's findings (1988) in Oman.

Particularly in the unvegetated dunes, the responsive and sensitive nature of the upper profile (top 45 cm), and especially the upper 30 cm, also echoes earlier findings, which indicate the importance of evaporation and extreme surface temperatures in accounting for the rapid response in the top 30–40 cm (PRILL 1968; SALISBURY, 1952; WILLIS, *et al.,* 1959; TSOAR and ZOHER, 1985). The low levels of surface moisture on the bare sands compared with vegetated sands is consistent with this interpretation. On the bare sands in the top 5 cm, the presence of diurnal moisture change, a component of the near-surface responsiveness, suggests that this moisture is supplied from surface dew. Despite three measurements of moisture content within the body of the sands, (morning, mid-day and late afternoon) having been made on most days there is no evidence of internal dew at any depth (WILLIS *et al.,* 1959; SALISBURY, 1952).

The effects of dense ground vegetation cover are very clear, and these findings contrast with the observations of EVANS *et al.* (1981) who found no differences in soil water content between vegetated and unvegetated desert dunes, and HENNESSY *et al.* (1985) who found no differences in the top 15 cm. In Studland, less water infiltrates under well vegetated surfaces but the pore moisture is retained longer in the thin soils developed in the upper profile of the sands. Moisture levels decline thereafter with depth and are generally lower than on unvegetated dunes, especially between 90 and 130 cm. The characteristic moisture profiles within the upper vegetated sands probably results from a combination of the effects of the vegetation cover on interception, moisture retention in the organic-rich A horizon, and evapo-transpiration loss. In contrast moisture levels in unvegetated dunes are high immediately after rainfall, but the moisture evaporates/drains within a few hours so that pore moisture is generally low within 30–45 cm of the surface. Pore water content increases with depth on the unvegetated sands owing probably to evaporation losses being restricted to the top 30 cm, uninhibited drainage, and no transpiration losses. Difference in *surface* moisture retention was found to be the most discriminating feature between different dune habitats in the Lake Huron dunes (BALDWIN and MAUN, 1983).

Few have studied moisture content in relation to position across the dune forms, although both BAGNOLD (1941) and AGNEW (1988) identified lateral seepage within dune sands, and RANWELL (1959) hypothesised that lateral seepage was partially responsible for the rise in water table observed in the dune slack. Lateral seepage, if controlled by bedding planes, should have a noticeable effect on vertical and temporal changes in moisture levels at different locations across a ridge, depending upon the dune type, as it will substantially affect the surface moisture catchment area, and the pore volume of sand through which the moisture will move, prior to it reaching any identified position on the dune. Unfortunately it was not possible to determine the large-scale dune bedding at the field site owing to restricted access and the need for conservation, together with the difficulties of identifying bedding from small pits. However general patterns of bedding in coastal dunes identified from other locations can be used as a guide (*e.g.* MCKEE, 1979). It is further complicated by the fact that the morphology of the field site would indicate that the dune ridges have suffered some erosion, especially on their windward side, since their formation.

Nevertheless, the field observations show that there are

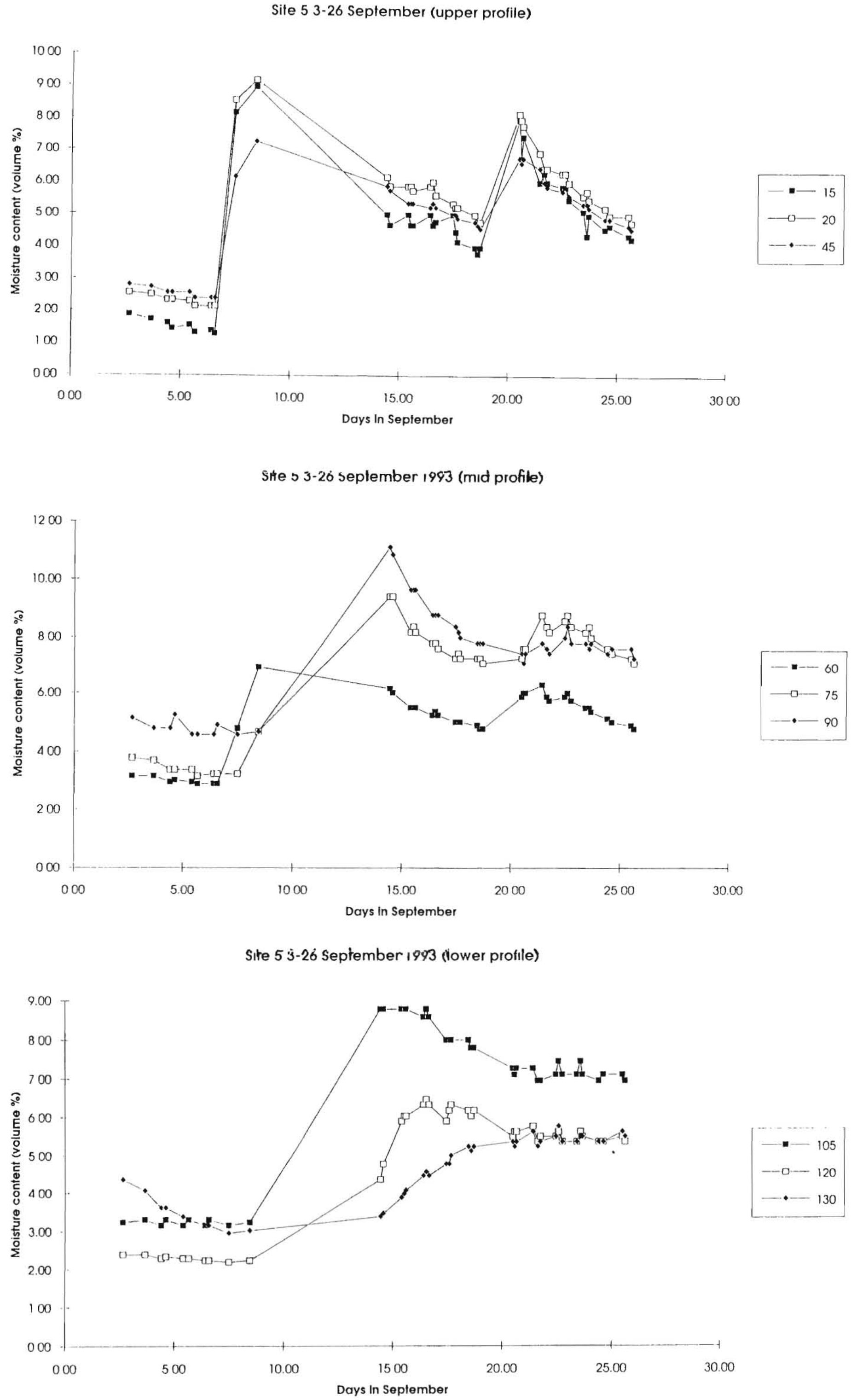
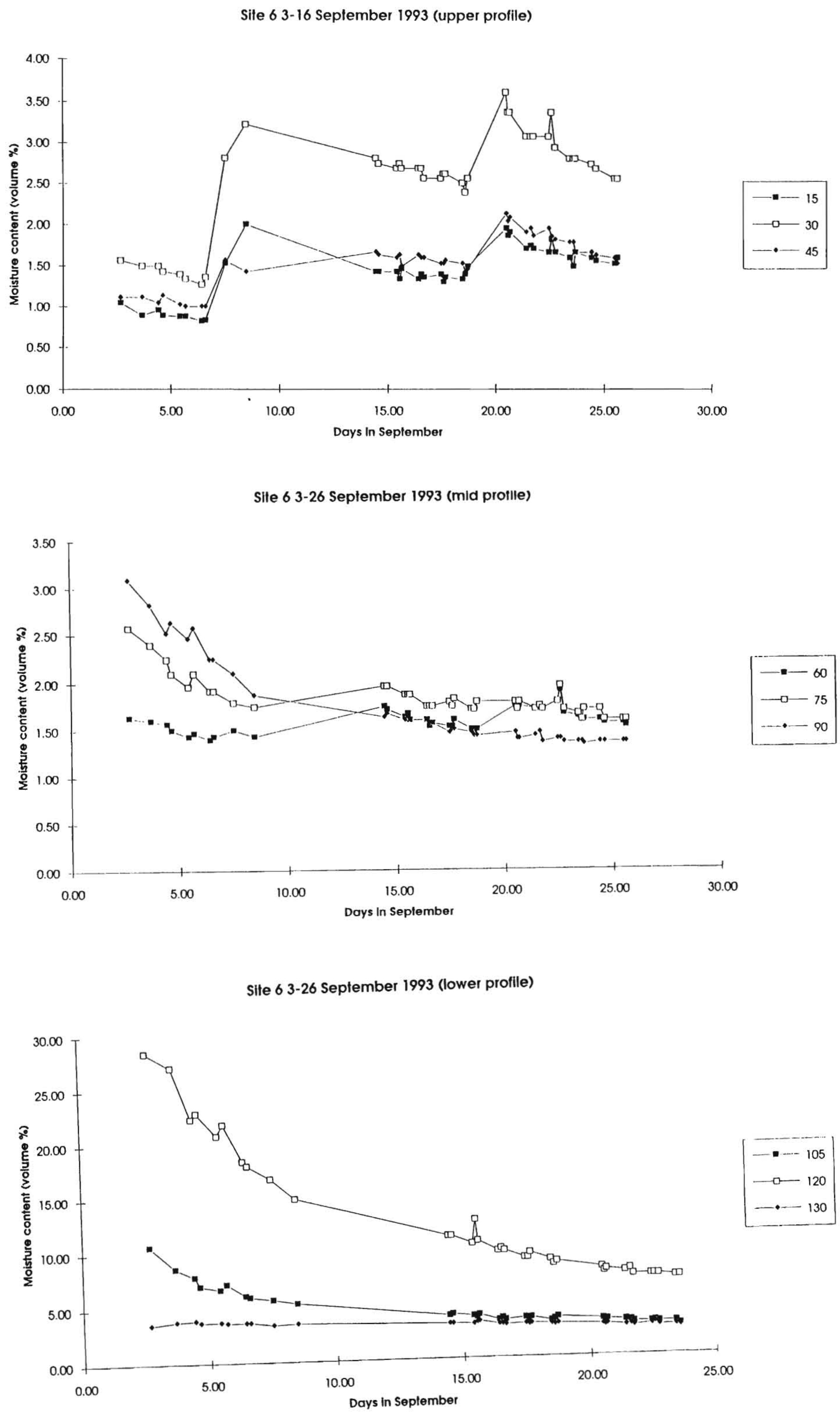


Figure 6. Continued.



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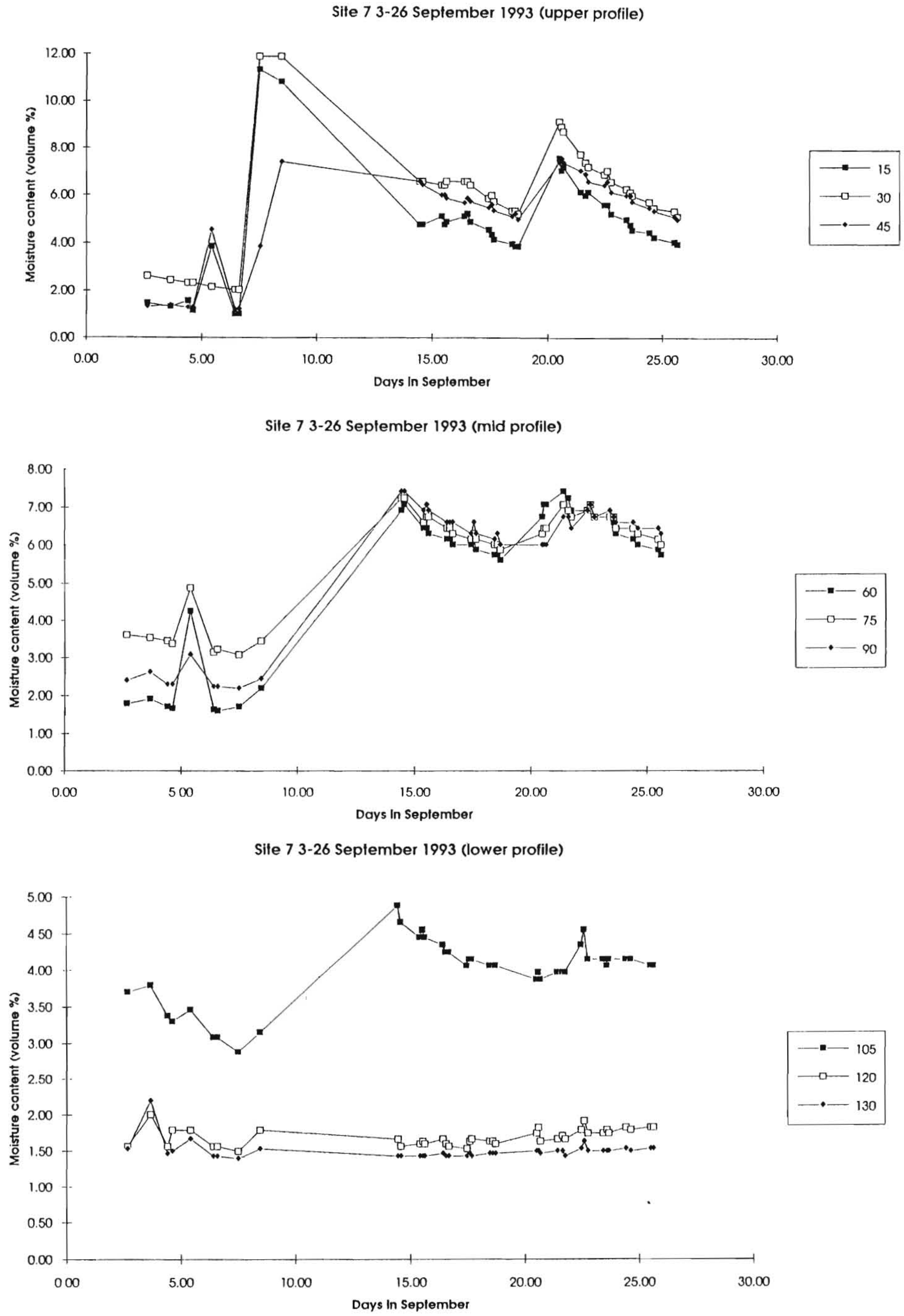

Figure 6. Continued.

clear spatial differences in moisture, at similar depths in the profiles, across the dune. Lateral moisture movements may well be responsible for the observed differences over the dune ridge. The findings do not fully agree with BALDWIN and MAUN'S (1983) report that the dune crest exhibited the lowest moisture values. At Studland the crest had lowest moisture levels in the upper and mid profile positions, but moisture levels increased markedly in the lower profile, possibly owing to lateral seepage from adjacent dune flanks. Also the results do not suggest the development of preferential flow paths, channels and tongues of moisture within the dunes as distinguished by DEKKER and JUNGERIUS (1990). This may have been because the upper surfaces of the dune sands were never so dry as to become water repellent. Moreover, the patches of moisture that developed in the Dutch dunes may have been the result of the drawing in of water by plants to the root zone, as appears to be the case in Photo 2 (DEKKER and JUNGERIUS, 1990, p. 1181).

The findings of this study can be related to the existing knowledge of early vadose diagenesis in dune sands. First, the propensity for greater diagenetic change and cementation within the upper parts of the dune profile, especially the top 50 cm, could well be associated with the greater number of wetting and drying cycles experienced in such locations on unvegetated dunes. These cycles would increase local dissolution of carbonates and aid reprecipitation of fine-grained cements under strongly evaporating circumstances. Certainly, aeolianites (carbonate-cemented dunes) which have a densely plugged upper surface do not generally show widespread evidence of former root mats as rhizoliths, suggesting the dunes were little vegetated.

Secondly, the field evidence from this study suggests that vegetated dunes would be expected to show less overall propensity for cementation from a local source of calcium carbonate, particularly at depth, as less water would be available for dissolution owing to lowered infiltration and preferential retention near the surface, and fewer cycles of wetting and drying would occur. At a small scale, the available water would tend to be drawn towards roots and uptake of water would increase pore water concentrations thus facilitating precipitation of cement preferentially around the roots. Aeolianites in which rhizoliths are abundant tend only to be cemented around the former roots; and interparticle porosity remains high away from the roots (MCLAREN, 1995). Diagenesis is also often weak beneath the root zone.

Thirdly, diagenesis on both vegetated and unvegetated dunes would be expected to decrease with depth until the influence of the phreatic zone (groundwater table) is felt. This would reflect the reduction in number and intensity of the wetting and drying cycles. This has been reported in the literature (see GARDNER and MCLAREN, 1994). In addition, the rate of diagenetic change with depth may vary according to position on the dune and the way in which the bedding structures influence the patterns of subsurface moisture movement. In the case of dunes similar to those at Studland, the leeward flanks may well be less cemented at depth and more plugged at the surface than the windward flank which experiences greater water penetration. Unfortunately few calcareous dunes, away from the extra influence of sea spray on their windward flanks, are cemented in their original form and so there are no data currently available to test this hypothesis.

Fourthly, differential diagenetic change has been observed between adjacent laminae and thin beds, whereas diagenesis is often consistent within beds (FRYBERGER and SCHENK, 1988). The evidence presented here, together with that from earlier work, of lateral seepage along bedding planes provides a mechanism for explaining these observed patterns of diagenesis.

CONCLUSIONS

(1) Mean moisture content measurements (close to 7%) and the predicted stable field capacity (4–6%) of the coastal dunes monitored in Studland are broadly similar to results obtained from earlier investigations of temperate dunes. Cycles of wetting and drying in the dune sands are in the order of days for the upper layers (0–45 cm) of bare dunes, but weeks for better vegetated dunes and sands further beneath the surface (>50 cm). The cycles are not thought to be affected by the development of internal dew, but some formation of diurnal dew occurred in the surface layer of the sand and it was readily evaporated.

(2) The sensitivity and lags in response of moisture movement within the dunes varies with depth over the monitored 130 cm. In general, the upper dunes (0–45 cm) are much more susceptible to rapid changes in moisture levels in comparison to the mid (50–90 cm) positions, in which moisture levels peak 1–2 days after rain and which in turn are more responsive and more frequently wetted than the lower parts (100–130 cm) of the near-surface vadose zone. Evaporation and high surface temperatures help to explain the responses in the upper layers of the bare sands, together with the fact that the low magnitude rainfall only penetrates the upper dune.

(3) Vegetation has an important role in affecting moisture contents throughout the profile. Obviously, less moisture infiltrates beneath a good vegetation cover, but that which does, appears to be retained preferentially within the upper part of the dune: in the soil and the rhizosphere. Unvegetated dune sands, in contrast, retain higher moisture levels at depth compared to the near-surface owing to unhindered drainage and high surface evaporation loss. The differences are small but consistent: generally of the order of 2–3% by volume.

(4) Although lateral seepage has been shown to occur by BAGNOLD (1941) and AGNEW (1988), its potential effects in terms of differential moisture regimes over a complete dune have not been considered before. This study has found subtle differences in moisture regime between the windward and the leeward flanks of the dune, and the crests have been found to be relatively drier at top and mid profile. In the absence of spatial variations in particle size distributions and vegetation cover, these moisture differences would seem to be best explained by the effect of bedding on the lateral routing of subsurface water drainage.

(5) The patterns of wetting and drying in the upper layers of the dune sands do support the diagenetic patterns evident in late Quaternary aeolianites, cemented in the vadose zone, where calcium carbonate induration plugs /caps approximately the upper 50 cm. These cements are generally very fine grained as a result of evapo-transpiration near to the surface. This is followed by a gradual decrease in the amount of cement downwards in the upper 1.5 metres. In addition, the retention of moisture in the rhizosphere may help to explain the preferential accumulation of $CaCO_3$ cements in this zone in aeolianites.

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