

***In situ* experiments on water infiltration in sand dunes traced by temperature**

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Abstract Knowledge of the mechanisms of water infiltration in sand dunes and wadis is the key to understanding the hydrological conditions in arid and semiarid regions. In order to trace infiltration processes in sand dunes, two sites were chosen in Al Ain, United Arab Emirates. An artificial rainfall infiltration experiment was conducted at one site. The other was left in its natural state. The variations in temperature between the sites were compared with soil water tension as well as soil water content at the same depths. Field observations showed that the temperature of the sand dune at the experimental site was more greatly affected by air temperature than that at the natural site, which means that the temperature distribution in the sand dune is closely related to the water content. The vertical distribution of temperature correlated well with the water movement in the sand dune, from which the average velocity of infiltration has been estimated as 3 cm h^{-1} . The results showed that water infiltration in sand dunes is not continuous but stepped, and suggested the possibility of tracing water movement in sand dunes using temperature.

INTRODUCTION

According to current climatological classification, rain will not recharge groundwater in arid regions. However, although rainfall is usually negligible, a heavy rain event occurs every 6–10 years. At these times, flooding occurs in wadis and groundwater is recharged. Therefore, it is necessary to understand the infiltration of rain in dry sand dunes in order to assess groundwater recharge during rain events in arid regions. Ritsema & Dekker (1994) show that spatial distributions of volumetric and gravimetric soil water content were similar, and infiltration water moved as preferential flow in bare dune sands. Berndtsson *et al.* (1996) showed that rainfall changed the temperature patterns from a mainly horizontally layered appearance prior to the rainfall to increasingly vertically shaped patterns. Moisture content heterogeneities in a texturally homogeneous medium can cause the medium to behave anisotropically with respect to fluid flow (McCord & Stephens, 1987a,b). This means that the spatial variation in soil moisture content will largely determine the actual flow pattern within such systems.

In general, the temperature of a sand dune is much higher than the temperature of the rain during a rainfall event. When water infiltrates the dune, the temperature of the

dune will change. The relatively wet soil zones are most easily accessible to infiltrating water, consolidating and even intensifying existing spatial differences in soil water content in the upper and deeper parts of the soil. Hysteresis tends to magnify this phenomenon. This emphasizes the importance of investigating actual soil moisture patterns in bare dune sands. The objective of this study was to examine (a) temperature characteristics in a sand dune; (b) the possibility of using temperature to trace the wetting front during the infiltration processes; and (c) the water movement processes in a dune.

EXPERIMENT SITE DESCRIPTIONS AND METHODS

The experimental site is a typical sand dune near the UAE University farm, Al Ain, United Arab Emirates. According to meteorological observation from 1986 to 1996, the average temperature, annual rainfall, potential evaporation, and humidity were 27°C, 132 mm, 3975 mm and 56.3%, respectively. Rainy seasons at the experimental site extended primarily from January to March and from July to August. Statistically, about 66% and 20% of annual rainfall occur during those two periods, respectively. According to field surveys at the site, there was dry sand on the surface of the dune, and dune soil water content was about 5%. The sand dune consisted of sand (94%) and silt (6%).

Two 3 m × 3 m sites delineated were 5 m apart. At both sites, thermal sensors and tensiometers were set at depths of 10, 30, 60, 120, and 200 cm. An artificial rainfall infiltration experiment was conducted from 3 to 11 March 1997. One hundred and twenty millimetres of artificial rain was sprinkled for 3 h from 11:00 a.m. to 2:00 p.m. on 3 March at one site (site A) without the occurrence of ponding, while the other site (site B) was kept in its natural state. In this paper, we set 0:00 a.m. on 3 March as the starting point for our experiment. During the rain period, the air temperature was over 30°C, and temperature of the water used in the experiment was about 20°C. According to the meteorological station, the highest air temperature and lowest air temperature during the experiment were 33°C and 11°C, respectively. In order to get information about the vertical changes of soil water, soil samples were taken every 20 cm from the surface to 240 cm below the surface before and after rainfall. After the rain stopped, soil samples were taken once every 3 h during the first 9 h, every 8 h during the next 24 h, and once a day for another seven days. All samples have been treated by the gravity method in order to measure the water content. During the experiment, temperatures in the sand dune were measured once a minute. Measurement intervals for tensiometers were once every 10 minutes during the rainfall period, and for 20 minutes during the first 9 h, every 3 h in the next 24 h, and every 8 h for the final seven days.

RESULTS

Temperature variations at site B

Figure 1 shows the daily variation of temperature in the sand dune at site B. There were periodic daily variations of temperature from the surface to depths of 60 cm. The highest and lowest temperatures at 10 cm were 38.1°C and 20.5°C, respectively. The

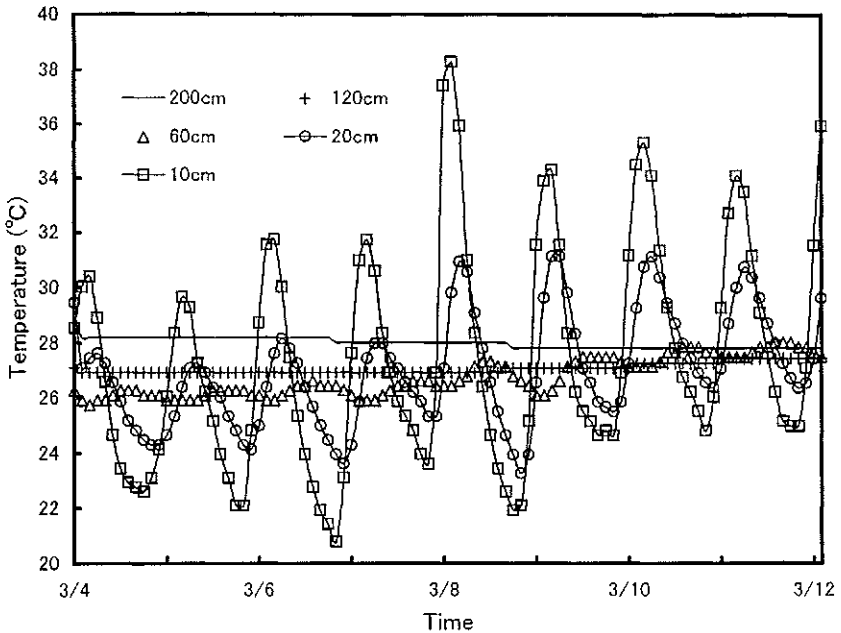


Fig. 1 Variations of temperature at site B during the experiment.

average temperatures were 27.0°C at a depth of 120 cm and 28.0°C at a depth of 200 cm. At midday, the highest temperature was found at the surface and the lowest at a depth of 120 cm. However, before sunrise, the highest temperature was found at a depth of 200 cm and lowest at the surface. The temporal variations in temperature became less and less with depth. At a depth of 200 cm, there was little change in temperature during the experimental period.

Time lags were also associated with the temperature variations with depth. In comparison with temperature at a depth of 10 cm, the time lags for temperatures at depths of 20 cm and 60 cm were about 2 h and 7 h, respectively.

During the experimental period, temperature at a depth of 120 cm changed little. When compared with the tensiometer data, it was found there was a zero-flux plane at this depth. It resists heat flux since no water can move across at this depth, which indicates that the moisture had a very closed relationship with temperature in the sand dune.

Variations of temperature profile at site A

Figure 2 shows the vertical temperature profiles at site A from 2:00 p.m. on 3 March to 6:00 a.m. on 5 March. Compared with Fig. 1, temperature variations only were found above depths of 60 cm, and temperature changed even at a depth of 120 cm. At site B, temperature ranged from 21.9°C to 31.9°C at a depth of 10 cm. On the other hand, temperature changed from 17.4°C to 31.8°C at the same depth in site A. It seems that air temperature had a greater effect at site A than at site B. With the wetting front moving downward, temperature also changed at each depth. The temperature at a depth of 120 cm did not change until 12:00 a.m. on 4 March.

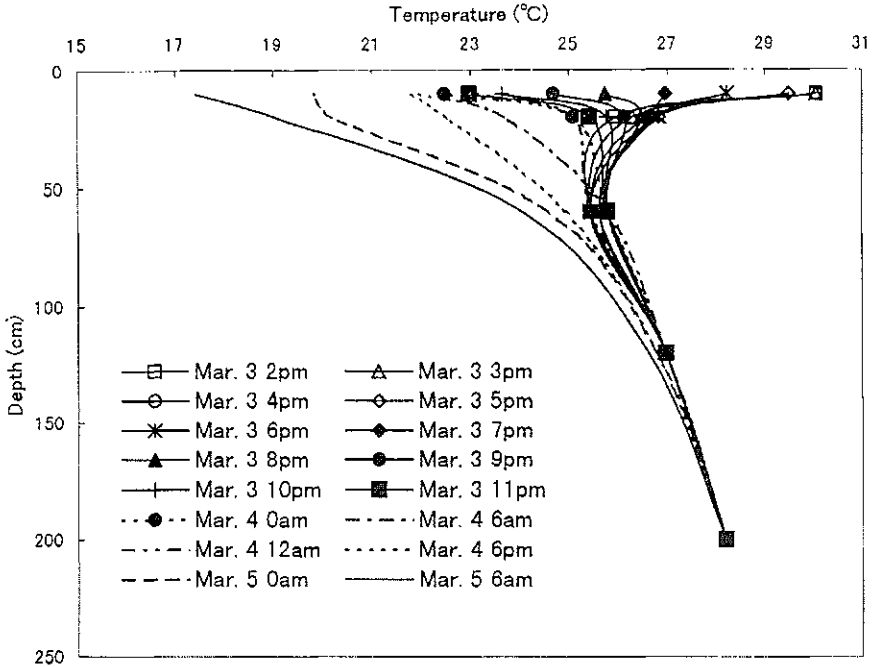


Fig. 2 Variations of vertical temperature at site A during the experiment.

Variation of moisture with time at site A

Figure 3 shows the variation of water content in the 72 h from the start of the experiment. At the beginning of the experiment, vertical water content in the dune ranged from 0% to 5.0%. In the top layer, the wetting front moved downward quickly. It reached a depth of 40 cm after about 12–13 h, and 80 cm after 15 h from the start of the experiment. After the wetting front reached 160 cm, it moved very slowly. The wetting front was found at a depth of 160 cm after 28 h and 200 cm after 61 h from the start. It took about 33 h for the wetting front to move 40 cm. From Fig. 3, it is interesting that the water content reached its highest value of 10.6% at a depth of 75 cm rather than at the surface. At the same time, the water content had a high value at this depth throughout the experiment.

DISCUSSIONS

Wetting front traced with temperature difference

As the water infiltrated into the dune, it changed the temperature distribution as it passed through. In other words, we can use temperature to trace the wetting front. In general, the temperature distribution in a sand dune is affected mainly by infiltration water, composition of the dune and air temperature. It is necessary to have a sensitive index that differentiates between the effects of both air temperature and the temperature of infiltration water. Considering the temperature difference between site B and site A at the same depth, we have the following formula:

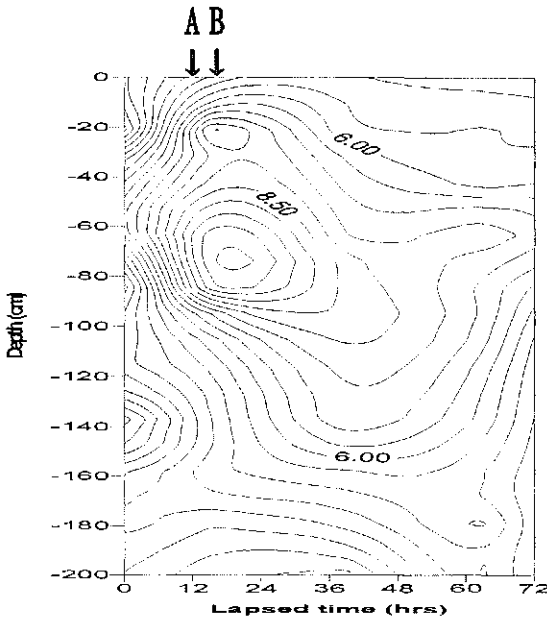


Fig. 3 Variations of water content (%) at site A during the experiment. A: Start of rainfall; B: end of rainfall.

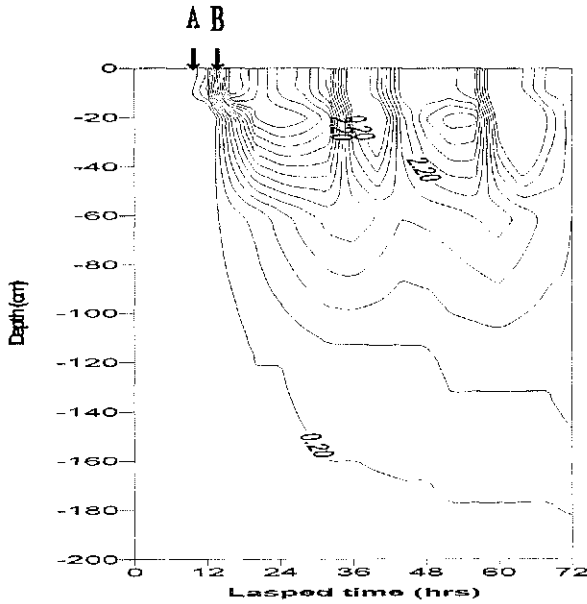


Fig. 4 Variation of temperature difference ΔT_{ij} ($^{\circ}\text{C}$) between site A and site B during the experiment. A: Start of rainfall; B: end of rainfall.

$$\Delta T_{ij} = T1_{ij} - T2_{ij}$$

where, ΔT_{ij} is temperature difference; $T1_{ij}$ is temperature at site B; $T2_{ij}$ is temperature at site A. i is observation time and j is observation depth.

Figure 4 shows variations of temperature difference 0–72 h from the start of the experiment. Comparing Figs 3 and 4, it was found that variations of temperature difference correspond well with both water content and total potential. Especially, the temperature difference at the 0.2° isotherm line was coined with the wetting front. For example, the 0.2° isotherm line moved down to a depth of 10 cm 30 minutes, 20 cm about 1 h, 60 cm about 2 h 40 minutes, and 120 cm 5 h after rain started. This isotherm line matched the response of soil water tension in the sand dune. The wetting velocity became slower, and average infiltration velocity was estimated at 3 cm h⁻¹ in the experiment. Since the water content increased at experiment site A, temperatures in the dune were affected easily by air temperature. As a result, the range of temperature variation became larger at site A than at site B. Since more latent heat could be used for evaporation at site A, the temperature at site A was lower than at site B. At the same time, as heat conductivity efficiency can be improved greatly with an increase in the water content of the sand, the time lag of temperature with depth became shorter at site A.

Water movement in sand dune

In Figs 3 and 4 it was found that the movement of the wetting front was not continuous but in steps. In other words, the wetting front stayed at some depths and moved suddenly at some point in time. The phenomena can be considered as so-called “unwetting” since the water content is so low that water cannot easily enter into dry sand. In bare sand dunes, only a few factors may contribute to spatial differences in soil water content. Unstable wetting fronts may develop in homogeneous sandy soils under non-ponding infiltration. Evidence of unstable wetting in homogeneous sandy soil shows that soil moisture patterns generated by the development of preferential flow paths may persist for long periods. One of the conditions under which unstable wetting fronts may form in sands, which may have a different density, texture and pore configuration compared with those above and below them. Apparently, small density or composition differences can produce significant changes in unsaturated hydraulic conductivity. When gravity dominates the infiltration process at rates lower than saturated hydraulic conductivity, movement of the wetting front will become unstable and can be considered as one kind of fingering phenomena. However, when gravity plays little or no part and capillary action dominates, there is no mechanism to cause instability, and as a consequence the wetting fronts will be stable. According to Yao & Hendrickx (1996), the effect of gravity becomes negligible under two extreme conditions. The first condition is encountered at infiltration rates equal to or higher than the saturated hydraulic conductivity, where viscosity dominates the flow process and no fingers are formed. The second condition is found at very low infiltration rates, where capillary action dominates the flow process and gravity effects are virtually absent.

From observations it was found that the distribution of the infiltration zone on the slope of the sand dune was not the same everywhere, but was thinnest at the top of the dune and became thicker and thicker along the slope. At the foot of the slope, soil water infiltrated vertically. These phenomena suggest that recharge to groundwater can only occur in wadis or at the foot of a sand dune.

CONCLUSIONS

The following conclusions can be drawn:

- (a) There is a very close relationship between temperature and moisture distribution in the sand dune. Temperature variations caused by infiltration water will become smaller and smaller with depth. As a result, it is possible to trace infiltration with temperature in the sand dune.
- (b) Temperature changes less with depth. The temperature at 120 cm changed less because of the existence of zero flux planes. During the experiment period, the temperature at a depth of 200 cm showed little change.
- (c) Movement of the wetting front in dry sand of sand dunes is unstable, and cannot be explained by so-called modern infiltration theories. As a result, water infiltration in the sand dune is a heterogeneous phenomenon that occurs in homogenous porous materials.

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