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Soil water balance of an arid linear sand dune

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A b s t r a c t. The soil characteristics and water balance of an arid sand dune ecosystem were investigated in Nizzana, NW Negev Desert, Israel. The main emphasis was placed on the relations between atmosphere, vegetation and soil moisture. Soil moisture measurements were carried out using time domain reflectometer (Easy Test Co., Poland). The soil investigations required transect- and area mapping, soil characterization and time flow analyses. The abiotic factors, such as relief position and exposure, together with biotic factors affect the water dynamics in the ecosystem through redistribution and accumulation processes. Input and output paths and components of the water balance were identified and then quantified.

K e y w o r d s: soil water balance, TDR, arid ecosystem

INTRODUCTION

Since 1988 a wide range of desert ecosystem research has been carried out at the Nizzana experimental station of the Minerva Arid Ecosystem Research Center (AERC) of the Hebrew University of Jerusalem. This has included both biotic and abiotic studies covering climatology, biology, geomorphology and pedology. While the first decade of the research concentrated on environmental factors and structures of the ecosystem, the more recent projects focused on processes, mechanisms and feedback effects within the soil-plant-atmosphere system.

In an arid environment, water is the major engine controlling ecosystem processes. Plants are influenced by site and soil properties, but primarily by the amount of plant available water and nutrients. The available field capacity (AFC) of the root zone is the most important factor for the productivity of sandy desert ecosystems. The AFC determines the amount of water from rainfall or irrigation that is stored in plant-available form. It also has a close relation with the rates of evaporation and thus the yield of vegetation is mainly determined by the AFC.

Climatic variability, especially rainfall, and changes in soil properties influence spatial variations of plant available water in the study area. Different soil properties, such as infiltration characteristics and potential gradients, induce water redistribution processes in the dune area. The abundance of vegetation, and thus the structure and stability of the dune ecosystem, depends on water redistribution by surface or lateral water flow. On the other hand, vegetation and litter cover can have a significant influence on the overall water balance by interception losses or inhibition of evaporation.

On the basis of soil moisture measurements using time domain reflectometry (TDR) and subsequent modelling of the data, it was possible to identify and quantify water content differences and water redistribution processes as well as components of the soil water balance in different ecotopes. Furthermore, considerable factors of water dynamics in dune fields, such as relief, exposure, vegetation and biological crust, could be identified.

AREA OF INVESTIGATIONS

The Nizzana sand dunes are located in the NW Negev Desert, Israel. This belt represents the eastern extension of the continental Sinai sand field. The Nizzana station is situated at 34°23´ E and 30°56` N. To the north and east of the station are the ephemeral streams Nahal Levan and Nahal Nizzana. The rocky Negev Highlands lie to the south. The western edge of the station faces the Egyptian border. The dune field is characterized by 15-25 m high linear dunes trending from west to east and up to 200 m wide interdunal corridors (Kidron and Yair, 2001). The climate is arid with a mean annual precipitation of about 100 mm which occurs mainly in the winter months from November to March

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(Berkovicz *et al.,* 1995). The main wind directions are from the NW to SW, the average annual temperature is 19°C and the annual potential evapotranspiration (E_{pot}) is about 2600 mm (Evenari, 1985; Yair *et al.,* 1997).

The spatial distribution of soil properties and soil types reflect the conditions in the rooted soil zone as well as the vegetation pattern (Beyer *et al.,* 1998; Tielborger, 1997). The dunes of this desert ecosystem are fixed by several perennial plants including *Retama raetam* and the halophilic Chenopodiaceae *Anabasis articulata* in interdune areas. Only during the rainy season is annual vegetation abundant.

The surface of the linear dune slopes is stable and covered by biological cryptogamic crusts, while the exposed crests of the dunes are mobile (Tsoar and Moeller, 1986). Biological crusts are characterized by smaller pore size distribution and higher organic content than the sandy soils (Verecchia *et al*., 1995). Generally, the crust thickness increases continuously down-slope but is spatially highly variable due to crust destruction and subsequent partial regeneration resulting from both human impact and bioturbation. Furthermore, regarding microclimatic differences *eg* less radiation and evaporation, more dew, the crust in the interspace between shrubs of the northern slope is thicker, more stable and covers the slope to a higher level than on the south-exposed slope. This confirms earlier observations (Kidron and Yair, 2001; Verecchia *et al.,* 1995; Veste and Breckle, 2000) and may reflect the microclimatic influences of the slope aspect on the amount of rainfall, radiation, evaporation, dew, and thus overall soil moisture conditions (Jacobs *et al*., 2000).

SOIL MATERIAL AND METHODS

The typical soils of the Nizzana ecosystem are Calcaric Arenosols on sandy dune slopes and sandy interdune areas. They are associated with Fluvisols of interdunal valleys and Calcisols and Solonchaks of playa areas, which were influenced by depositions of fines from flooding events of Nahal Nizzana (Pfisterer *et al*., 1996). Calcaric Arenosols are poorly developed and their silt and clay content rarely exceed 10%. The selected soil properties of a Calcaric Arenosol on a north-facing dune slope are shown in Table 1.

Due to both within-year and annual rainfall variability of the area, the soil water dynamics will also vary. Accordingly, soil moisture sensors were installed along both north and south-facing slopes, using recordable TDR-devices (Easy Test Co., Poland) working with a needle pulse of 200 ps rise time. The principle of TDR is that the soil moisture is calculated from the electrical permittivity (ε), which is determined from the measurement of the velocity of propagation (v) of an electromagnetic pulse in the soil, as follows (Malicki and Skierucha, 1989):

$$\varepsilon = (c / v)^2 \tag{1}$$

where: ε - relative dielectric constant (-), c - velocity of light in free space (2.9979 10^8m s^{-1}), v - electromagnetic wave propagation velocity (m s^{-1}).

The differences of ε between water (81), mineral soil (4) and air (1) make it possible to determine the water content of the soil.

The collection of data covering seasonal changes in soil water content under and between shrubs in different ecological system units of the study area enabled the estimation of seeping quantities of water and transportation directions as well as the marking of evaporation. Taking into consideration water regime factors such as relief, exposure, soil properties, vegetation and biological crust, 3 stationary TDR devices were installed - each with 10 TDR probes – along a northern (NB – TDR-station north bottom, northern interdune, NM – TDR-station north middle, northern lower slope, NT – TDR-station north top, northern upper slope) and a southern (SB – TDR-station south bottom, southern interdune, SM – TDR-station south middle, southern lower slope, ST – TDR-station south top, southern upper slope) slope. To consider the influence of vegetation, five probes (10, 15, 30, 60, 120 cm depth) at each station were installed under *Anabasis articulata* and five in the neighbouring interspace.

T a b l e 1. Selected properties of a Calcaric Arenosol along a north-facing dune slope

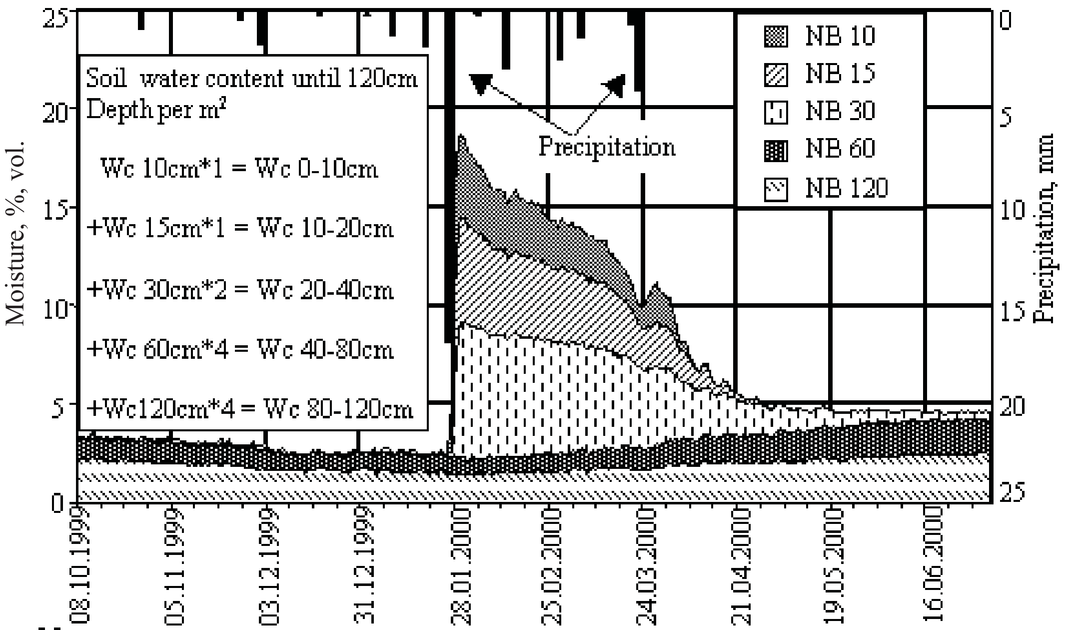
Horizon	Depth (cm)	$C_{org.}$ (%)	pH_{H_2O}	Electrical conductivity* (mS cm^{-1})		Granulometric composition (%)		
				1:2.5	1:5	Sand	Silt	Clay
AK1	1	12.2	8.4	0.425	0.363	62	30	8
AK2	2	11.1	8.6	0.322	0.218	70	22	8
ACk	25	5.3	8.9	0.135	0.101	89	7	4
Ck1	32	5.1	8.9	0.128	0.100	93	3	4
Ck2	47	4.9	8.9	0.092	0.068	93	3	4
Ck3	55	5.0	9.0	0.098	0.062	95	4	1
Ck4	100	5.4	9.1	0.082	0.061	93	6	1

*in solution extract.

The data collected at the TDR stations presented in this paper was from the period 8.10.1999-5.07.2000. Only 35 mm of precipitation was recorded during the period. The soil moisture was registered every two hours, and from this data the daily means were calculated. In order to generate balances for the total water contents of the soil down to a depth of 120 cm m^{-2} at each TDR station, the water content for depths without TDR probes were interpolated and added up (Fig. 1A). The water regime changes could be compared by the computation of the total water content within the measuring periods. Changes in soil water content could be attributed to one large rainstorm yielding 17 mm of precipitation (28.01.2000) and could be divided into the balance components precipitation, inflow, evaporation, transpiration, interception and outflow (Fig. 1B). The other rainstorms yielded less than 5 mm of precipitation per event and had no effect on the water budget. This rain was to some extent intercepted by plants or by the biological crust.

The increase of soil water content δWct_2 was calculated by the difference of maximum water content after (Wct_2) and water content before (Wct_1) the large rainstorm, and corresponded to infiltration. If infiltration exceeded the 17 mm of precipitation, inflow had taken place. Interception was given by the difference of annual precipitation and

A



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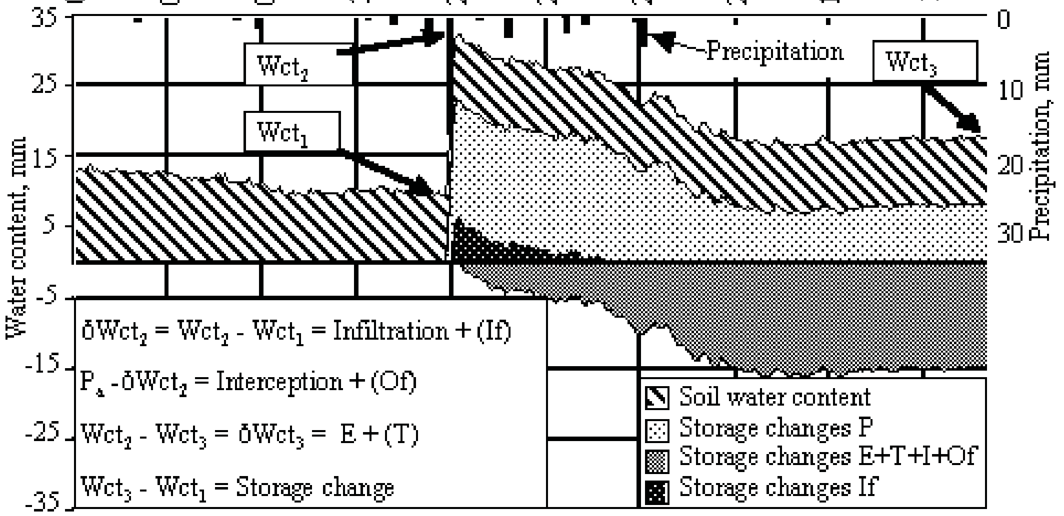

Fig. 1. Soil water content in different depths (A) and soil water content for a soil compartment of 120 cm m^{-2} (B) at NB-TDR-station (E - evaporation, I - interception, If - inflow, Of - outflow, P - precipitation, P_a - annual precipitation, T - transpiration, (mm); Wc - water content, Wct - water content at a given time (%, vol. or mm).

infiltration. Evaporation, or rather evapotranspiration, was the difference of Wct_2 and Wct_3 at the end of the measuring period, and the change in soil water storage was calculated by Wct_3 - Wct_1 (Fig. 1B).

RESULTS AND DISCUSSION

One of the goals of the research was to assess the spatial and temporal variability of soil water content in the Nizzana dune area and to quantify components of the water balance. Of special interest were the redistibution processes affected by different infiltration rates and potential gradients.

Figure 2 shows the essential water balance components in soils down to a depth of 120 cm m^{-2} in different ecosystem units. The annual precipitation was 35 mm. Evaporation or shrub evapotranspiration and soil water storage corresponded to the infiltrated water amount of the prevailing soil compartment.

The exposure affects the soil water directly. There are higher content of fines in wind-protected locations. The longer duration of moisture penetration on north-facing slopes and interdunes is also influenced by the degree of bioturbation. South-facing slopes had less bioturbation. Due to preferential flow, the water infiltration is faster and deeper and evapotranspiration losses are smaller on the north-facing slopes than at the south-facing locations. Thus the total water content as well as the infiltration rate at the north-facing locations is higher than for south-facing sites. Only high precipitation events led to deeper infiltration on the southern slopes. The radiation is greater on south-facing slopes and thus evaporation and interception losses after precipitation events are higher there than for the north -facing slopes. Regarding the faster and deeper infiltration as well as the lower radiation evapotranspiration, losses are smaller and the total water contents are higher on north-facing slopes than on south-facing locations.

The relief position also affects the soil water regime. Regarding the lower content of fines, infiltration by primary pores is in soils at the slopes higher than in interdunal soils. After high-intensity rainstorms, run-off can be induced because of thicker biological crusts on the north-facing slopes and lead to water redistribution in the depressions (NB interspace, Fig. 2). Fines and salts can be removed by

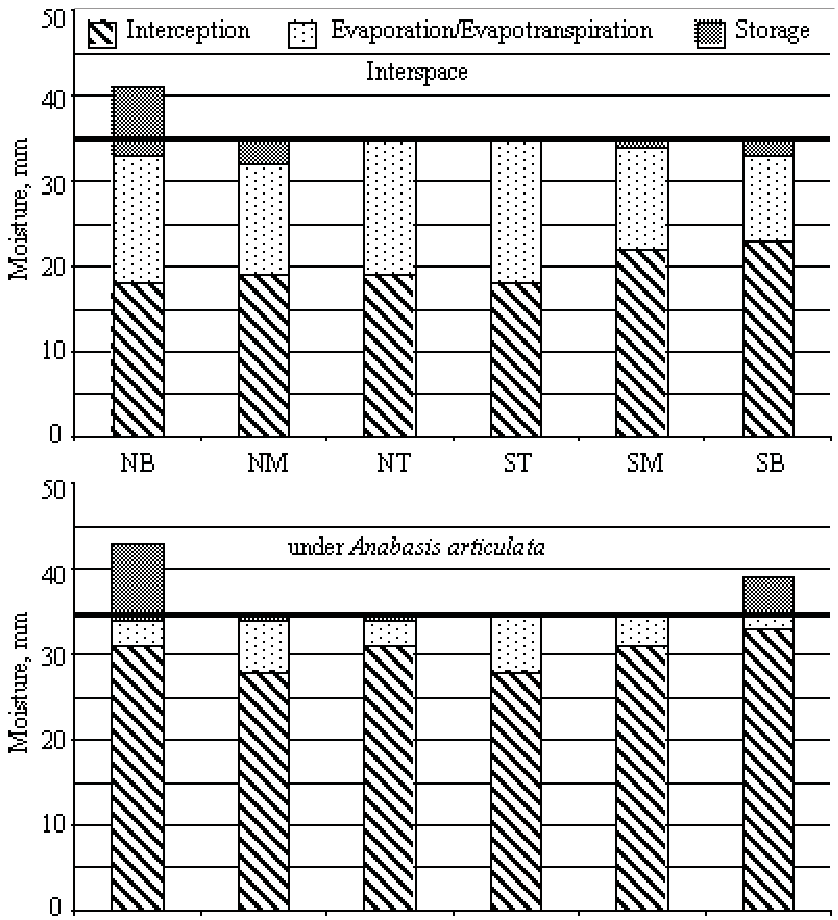

Fig. 2. Water balance in different ecosystem units in Nizzana for the period 8.10.1999 until 5.07.2000.

runoff and deposited in the soils of the interdunes, and thus lower the osmotic and matric potential there (Kidron and Yair, 2001). In addition, soil water moves to places of lower osmotic and matric potential. The water is more strongly bound in the interdunal soils than on the dune slopes. Therefore, losses by evapotranspiration are smaller and total water contents are higher in soils of the interdune valleys than in soils of the upper slope. But often the water in interdune soils is not plant-available.

Due to interception losses, infiltration rates under *Anabasis articulata* are smaller than in neighbouring interspaces. Evapotranspiration processes of the water content in the upper soil under *Anabasis articulata* are generally smaller than in neighbouring interspaces. The actual transpiration rate of the Chenopodiaceae is much higher because the shrub developed a two-part root system that allows it to also obtain water from deeper layers (Veste and Breckle, 1996). Under *Anabasis articulata* salts are barely washed out and instead accumulate in the root area near the surface. This reduces the water conductivity and lowers the osmotic potential. Potential gradients lead, particularly in the interdune, to a vapour inflow of soil water from the interspace to the plant (NB and SB under *Anabasis articulata*, Fig. 2).

The biological crusts have a considerable influence on the water regime of the dune ecosystem. They develop best due to the higher content of fines and the more favourable microclimatic conditions on north-facing slopes (Yair *et al*., 1997). The biological crusts can inhibit infiltration, induce redistribution by run-off, reduce evaporation and reduce wind erosion of the dune ecosystem.

CONCLUSIONS

1. Water content differences and water redistribution processes, as well as essential water balance components, could be identified and quantified, using a TDR-technique and the corresponding computer examinations, in different ecotopes of the Nizzana dune field.

2. Factors that influence redistribution processes in this desert ecosystem were highlighted.

3. Abiotic factors such as relief position and exposure, and biotic factors such as vegetation and biological crusts, affect the water regime in this ecosystem by redistribution and accumulation processes.

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