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Spatial evaporation patterns within a small drainage basin in the Negev Desert

Giora J. Kidron [a,*], Motti Zohar [b]

[a] Institute of Earth Sciences, The Hebrew University, Givat Ram Campus, Jerusalem 91904, Israel
[b] Dept. of Geography and Human Environment, Tel Aviv University, Tel Aviv 69978, Israel

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SUMMARY

Although important, data regarding the spatial distribution of evaporation are scarce. With the development of a small reference atmometer (RAM), studying the spatial distribution of evaporation was made more feasible and consequently carried out at the hilltops (TOP), wadi beds (WADI) and along the northern (NF), southern (SF), eastern (EF) and western (WF) aspects within a second order drainage basin in the Negev Desert Highlands during June 2004 to May 2006.

Evaporation rates showed high variability in accordance with season and aspect following the order: TOP > SF ⩾ EF ⩾ WF > WADI > NF. The data showed (a) an increase in evaporation with elevation; (b) that the average evaporation rates of the stations located at the slopes and the wadi beds were respectively ~14% and ~23% lower than that of the hilltop stations; (c) that while insignificant differences characterized the eastern and the western aspects during summer and winter, significant differences characterized the northern and the southern aspects, and (d) that the ratio obtained between the northern and southern aspects is significantly different from that calculated based on direct-beam shortwave radiation. The findings were explained by the effects of sun and wind upon evaporation, with each factor explaining up to ~45–50% of the results. The findings are in agreement with the dense vegetation at the north-facing footslope and at the wadi bed, and may have important implications towards the understanding of microorganism and plant distribution as well as geomorphological and pedological topics such as weathering rates and soil forming processes.

Introduction

Knowledge regarding evaporation rates is of prime importance for all ecosystems. This is especially true in arid zones where water is the main limiting factor and knowledge regarding soil evaporation is scarce. Rates of soil evaporation may serve as an important tool for the study of agricultural, ecological and geomorphological process-related topics (Holland and Steyn, 1975; Monteith, 1981; Shuttleworth, 1993).

Although evaporation is an important component of the water balance, technical difficulties or shortage in manpower hindered direct spatial measurements within drainage basins, and the measurements were confined in most cases to only a number of stations (Giambelluca and Nullet, 1992; Blackie and Simpson, 1993; Weeks and Wilson, 2006). While lysimeters may potentially provide such information, their use has not hitherto been wide spread. Other devices used, such as the Piché evaporimeter and evaporation pans (Stringer, 1972; Thom et al., 1981; Papaioannou et al., 1996), necessitate leveled ground and therefore cannot adequately represent sloping grounds. The use of other types of evaporimeters was not tested, to the best of our knowledge, on sloping ground (Magliulo et al., 2003).

Lack of suitable measurement devices and the interest in large-scale regional processes gave rise to many equations and models such as the well known and widely used Penman–Monteith equation (Monteith, 1981) or the Shuttleworth–Wallace equation (Shuttleworth and Wallace, 1985; Zhou et al., 2006). Whether requiring variables such as albedo or surface resistance, or even relatively easily-measured meteorological data such as temperature, wind speed, relative humidity and net radiation, the complexity of the natural terrain and the lack of precise measurements at the different locations required estimates of missing data that may cause large inaccuracies in the predicted evaporation rate (Blyth, 1999; Vörösmarty et al., 1998; Amatya et al., 2000). While on very large (regional, global) scales inaccuracies resulting from improper data may cancel each other out (Huntingford et al., 1998), this may not be the case once information for a single drainage basin with sloping topography is sought.

Sloping topography with a relative elevation of 50–100 m characterizes the Negev Desert Highlands, Israel. Narrow wadis that divide most of the hills are responsible for the formation of relatively steep slopes of 20–30° mostly characterized by small terraces with strips of soil (Evenari et al., 1982). All rocks and rock particles are

* Corresponding author. Tel.: + 972 2 676 7271; fax: +972 2 566 2581.
E-mail address: kidron@vms.huji.ac.il (G.J. Kidron).

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covered with microorganisms, mainly lichens that show high variability in species composition and biomass in accordance with aspect and their location along the slope (Kappen et al., 1980). Similarly, there is high variability in plant composition, cover and biomass (Boyko, 1947; Kadmon et al., 1989), all of which attest to variable productivity. Since available moisture duration (i.e., the length of time during which the moisture level is high enough to be used by various organisms) rather than water quantities may be mainly responsible for organism distribution and productivity (Kappen et al., 1980), knowledge regarding the spatial distribution of evaporation may be highly important.

Following Federer et al. (1996), we relate to potential evaporation herein as a generic concept that includes diverse forms of evaporation. According to Federer et al. (1996) PEi, i.e., potential interception is defined as evaporation from surfaces that are completely wet, as a result of a rainfall event. Since lichens lack stomata and the water status of their thallus (body) is in equilibrium with that of the environment (Kershaw, 1985), PEi may largely reflect the rate during which the rock surfaces and the lichens will desiccate following rain. Furthermore, since habitat productivity is largely controlled by evaporation (Noy-Meir, 1973; Vörösmarty et al., 1998), knowledge regarding PEi may assist in explaining plant distribution and biomass. PEi measurements (for the sake of simplicity they will be referred to below as evaporation) along sloping surfaces were thus called for. The construction of a reference atmometer facilitated measurements carried out within a second order drainage basin during 2004–2006.

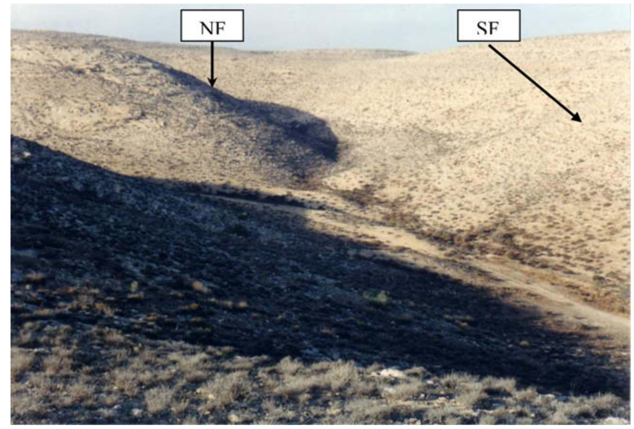

Fig. 2. General view of the drainage basin. Note the shaded northern aspect at the left of photograph, and the opposite southern aspect. The photograph is taken from the top of the western aspect.

The research site and methodology

The research site was located on ~550 m high hills at the heart of the Negev Desert, Israel, overlooking the Kibbutz of Sede Boker, 1.5 km to the east that lies ~50 m lower at a small 5 × 3 km flat. A second order drainage basin with relatively steep slopes was chosen (Figs. 1 and 2). Average annual precipitation is 95 mm, confined to the winter months of November–April. Average daily radiation is 230 W m^2 with mean monthly temperatures varying from 9 °C in January to 25 °C in August (Rosenan and Gilad, 1985). Potential evaporation measured at the Avdat farm (9 km south of Sede Boqer) with a class A evaporation pan is ~2600 mm (Evenari, 1981). While winds from the north-west are dominant during the summer and the transition seasons, winds from the north-east and the south-east occur for ~55% of the time during the winter with winds from the west, mostly of higher velocity, blowing during the remaining time (Bitan and Rubin, 1991).

The bedrock consists of Turonian limestone of three formations: Netzer, Shivta and Drorim, occupying the upper, mid and lower slope sections, respectively (Arkin and Braun, 1965). Whereas massive continuous bedrock characterizes the Shivta formation at the midslopes, Netzer and Drorim formations are strongly jointed limestone, characterized by patches of soil, with slope debris (colluvium) covering part of the Drorim formation. Sparse vegetation cover characterizes the research site (Kadmon et al., 1989), while the rock and stone surfaces are covered by lichens and cyanobacteria (Danin and Garty, 1983). Vegetation cover (perennial shrubs, mainly 30–50 cm high and winter annuals) ranges between 15% and 25% at the northern aspect and 10–20% at all other aspects. It ranges between 60% and 90% at the wadi beds.

Eighteen stations, 1 × 1 m each, located at the hilltops (TOP), the wadi beds (WADI), and at the four main aspects: north (NF), south (SF), east (EF) and west (WF) were demarcated (Table 1;

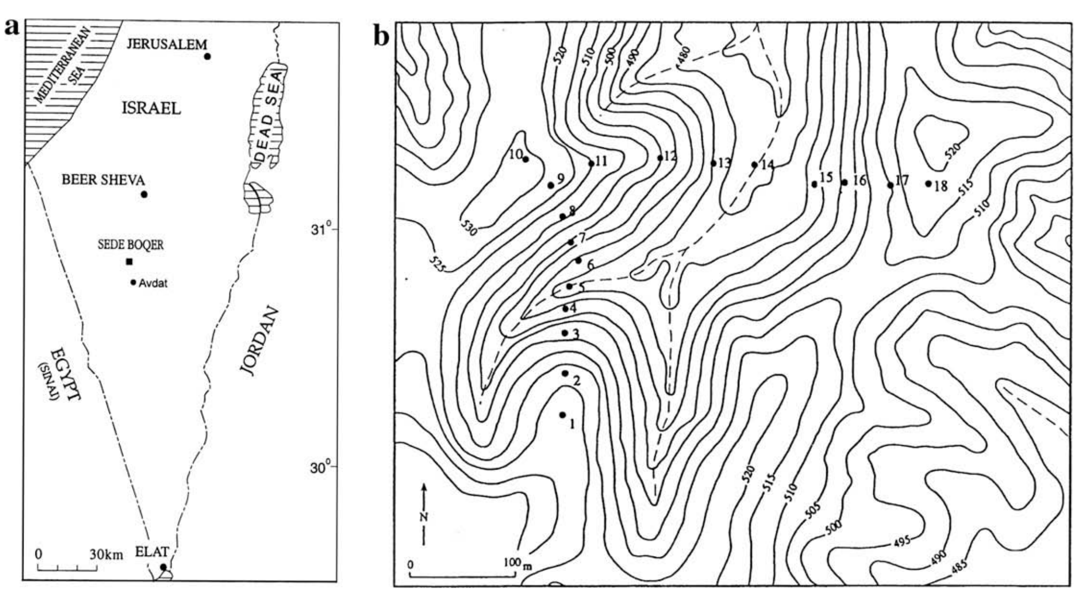

Fig. 1. Location of (a) research site and (b) experimental stations.

Fig. 3), and the evaporation in each station was measured 2–3 times per month (each measurement included the water lost since the preceding measurement) with a novel mini atmometer from July 2004 to June 2006. The atmometer used slightly differed from the first model constructed described in detail elsewhere (Kidron, 2005). Both models consisted of two 9-cm long cylinders (with their upper end being parallel to the slope angle), one (2.15 cm diameter) inserted within the other (2.3 cm diameter) so that a standard cotton wick (used for wetting wet bulb thermometers), located in between the cylinders, creates a disc that serves as the evaporation substrate. Both cylinders and the wick are inserted into a sealed container and the water that evaporates through the disc serves to assess the evaporation rate (calculated per square centimeter of the wick's surface area), which is determined in accordance with the amount of water added (using a syringe) during refilling. However, due to malfunction of the old 0.35 l container, a new container, 1 l in capacity was used (Figs. 4 and 5). The container was protected by 10.5 cm diameter PVC pipe and the gap between the pipe and the container (0.8 cm) was filled with polyurethane. Due to the use of a larger container and due to the insulation, lower water temperatures were guaranteed within the container. Owing to the fact that the water temperatures largely dictate the evaporation rates (van't Woudt, 1960; Davenport, 1967; Bloemen, 1978; Kidron, 2005), slightly lower values were thus obtained in comparison to the first model. As a result of the changes made in the new model, and to distinguish it from the previous model, the atmometer will be referred herein as the reference atmometer (RAM), rather than the previous name mini atmometer (MAM).

When the RAM was compared to a class A evaporation pan, high correlation was obtained (Fig. 6), with the relationship between the evaporation rates of both devices following the equation:

$$\mathrm{PE} = 0.59x + 5.0 \quad (r = 0.97; P < 0.001)$$

When PE is the potential evaporation as measured with a class A evaporation pan and x is the RAM evaporation in millimeters. The higher absolute values recorded by the RAM were explained by the high water temperature of the thin film of water absorbed by the wick in comparison to the large body of water of the pan (Kidron, 2005).

Although inserted within a PVC pipe and thus provided with extra protection against animal damage, animal damage and other technical drawbacks account for the fact that 8.7% of the data had to be gap-filled. The missing data were gap-filled in accordance with the relative change of the neighboring stations as described elsewhere (Kidron et al., 2000). The daily rain depth was measured at a nearby meteorological station at the Kibbutz of Sede Boker, 1.5 km away.

F-test (Post-Hoc, using Bonferroni) was executed in order to find significant differences among the stations and locations. Two-way ANOVA was used in order to study the effect of aspect and season upon the evaporation.

Results

Annual rain amounts as measured during 2004/2005 and 2005/06 were 70.5 and 66.0 mm respectively (Table 2), lower than the long-term mean of 95 mm (Rosenan and Gilad, 1985). The data show that most of the precipitation fell in between November and the beginning of March as was also the case during the last 40 years (Shmuel Melamed, personal communication). Owing to the much cooler temperatures that characterize the winter months of November–February and the higher ecological significance for the cool season rains (Noy-Meir, 1973), these months were also considered the main growing season. This is also in agreement with the fact that for most years, extensive blooming already begins during February (Tadmor et al., 1962).

Average monthly evaporation rates as obtained during the entire research period, winter and summer are shown in Fig. 7a–c. When the three top stations are considered, insignificant differences characterized their annual evaporation rates facilitating the grouping of all three stations. Likewise, differences in annual evaporation for both wadi stations were insignificant, thus facilitating their grouping.

The average annual evaporation rates of the top stations was 4254.0 (SD = 26.6) mm during 2004–2006, corresponding respectively to 2508.9 (SD = 20.7) mm of potential evaporation. When compared to class A pan in the Sede Boqer meteorological station, high correlation (r = 0.986) of the monthly evaporation rates was obtained (not shown), with the pan having similar average evaporation rate of 2482.6 (SD = 13.5) mm.

Overall, an increase in the evaporation with altitude was noted (Fig. 8). When the evaporation rates of all slope stations were averaged and compared to the average evaporation rates of the hilltops and the wadi beds, the annual evaporation rates followed the order TOP > SF $\geqslant$ WF $\geqslant$ EF > WADI > NF (Fig. 9). When a two-way ANOVA

Table 1
Properties of monitoring sites.

Station no.[a]	Slope location	Abbreviated station: name and exposure[b]	Geological formation	Elevation above m.s.l. (m)	Slope angle (°)
1	Top	Top N	Netzer	528	2
2	Upper	Up. N	Netzer	523	15
3	Mid	Mid N	Shivta	505	24
4	Bottom	Bot. N	Drorim	496	19
5	Wadi	Wadi N/S	Drorim	486	2
6	Bottom	Bot. S	Drorim	494	13
7	Mid	Mid S	Shivta	504	31
8	Mid-Upper	Mid-Up. S	Netzer	517	14
9	Upper	Up. S	Netzer	527	10
10	Top	Top S[c]	Netzer	531	2
11	Upper	Up. E	Netzer	520	10
12	Mid	Mid E	Shivta	505	17
13	Bottom	Bot. E	Drorim	485	20
14	Wadi	Wadi E/W	Drorim	478	1
15	Bottom	Bot. W	Drorim	488	13
16	Mid	Mid W	Shivta	496	16
17	Upper	Up. W	Netzer	510	11
18	Top	Top W	Netzer	518	3

[a] See Fig. 3.
[b] The letters N, S, E and W stand for the exposures north, south, east and west, respectively.
[c] Top S is a joint summit also for the eastern exposure.

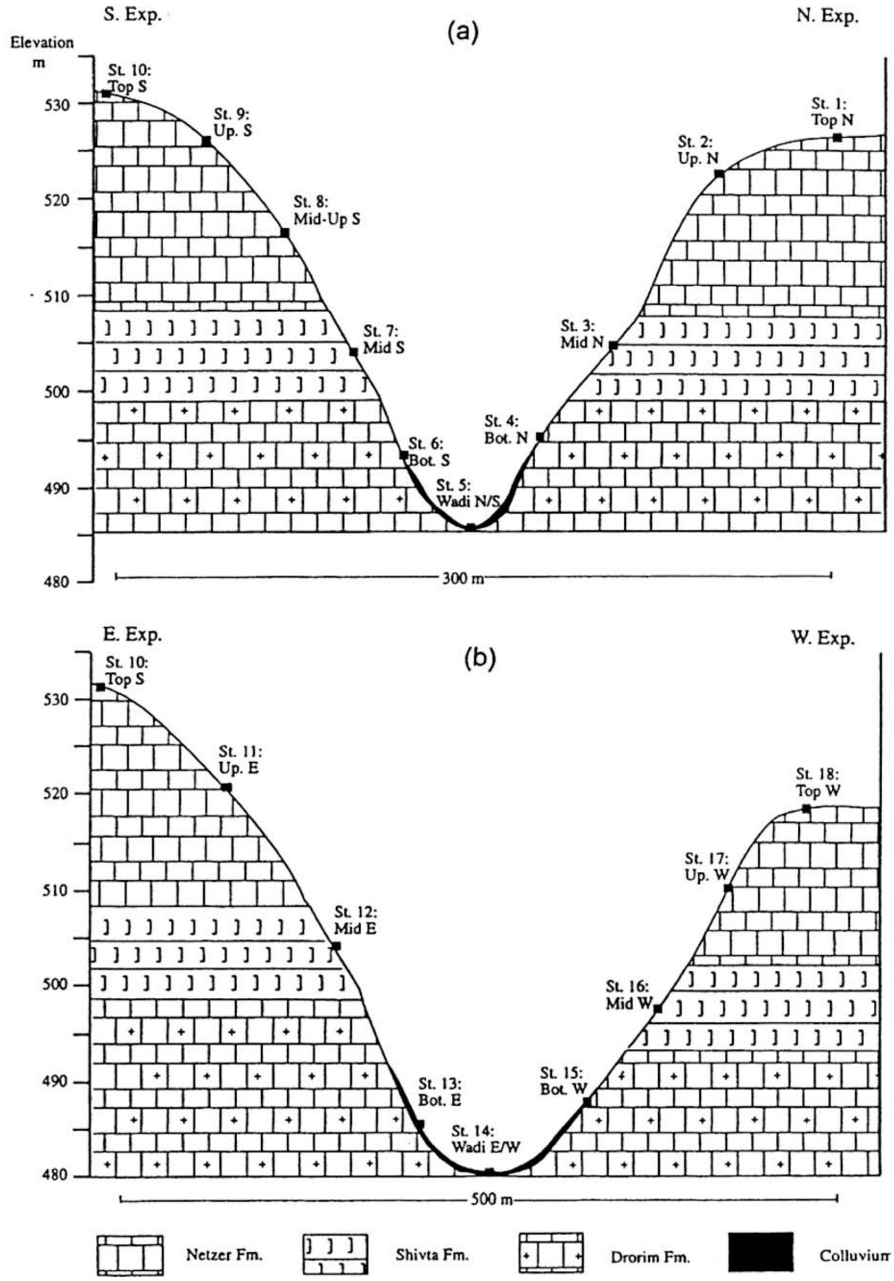

Fig. 3. A schematic cross section of the northern and southern aspect (a) and the eastern and western aspects (b).

was performed on the evaporation rates recorded at the slope stations, both variables aspect and season, yielded significant relationships (Table 3a). However, when a two-way ANOVA was performed separately on each pair of slopes, the aspect and season yielded a significant relationship for NF and SF (Table 3b) but only the season yielded a significant relationship for EF and WF (Table 3c). This implies that while significant differences characterized the winter and the summer values for NF and SF, non-significant differences characterized the evaporation rates recorded at EF and WF.

Discussion

Both study years were dry with annual precipitation being about 25–30% lower than the long-term mean. The average potential evaporation rate recorded in Sede Boqer of 2479.9 (SD = 9.8) mm was slightly lower than the 2611 mm of potential evaporation that were measured in Avdat, ~10 km south of Sede Boqer by Evenari (1981), and lower than the evaporation measured in Nizzana (~35 km west of Sede Boqer), which corresponds to 2789 mm of potential evaporation (Kidron, 2008). The higher evaporation rate recorded in Nizzana is expected in light of its lower elevation (and hence warmer temperatures): 200 m above sea level in comparison to 500–600 m of Sede Boqer and Avdat.

As expected, evaporation was highly dependent upon the slope aspect, the slope steepness and the location along the slope (Oke, 1978; Weeks and Wilson, 2006), with stations along the slope exhibiting lower evaporation rates. Being at a low-lying position and mostly sheltered from the sun and wind, station 4 at NF exhibited the lowest evaporation rates within the drainage basin. Alternatively, the hilltop stations exhibited the highest evaporation rates with evaporation exhibiting a positive linear relationship with altitude. The results are not surprising in light of the lower

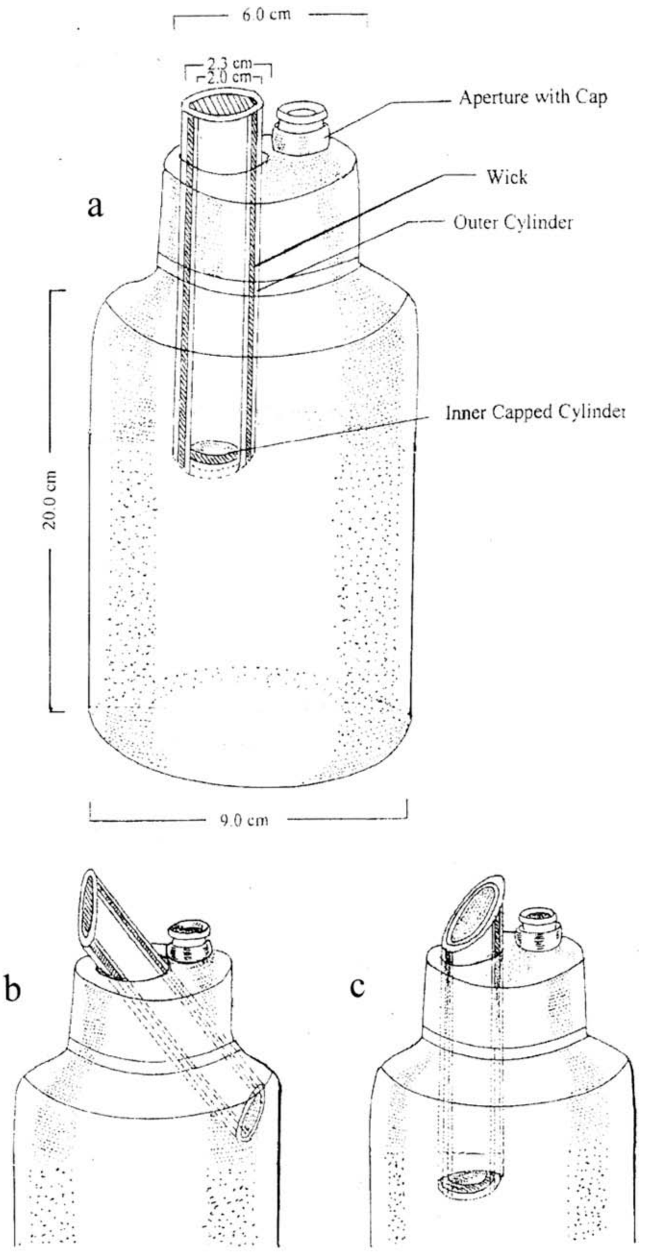

Fig. 4. Schematic description (without the protective pipe) of the RAM at different angles (a–c).

Fig. 5. RAM measurements in the field.

radiation loading (per unit surface) recorded over the slopes (Huntingford et al., 1998; Blyth, 1999) and the mutual shading and wind effects upon evaporation.

Both shading and wind effects had a pronounced impact upon the evaporation rates in agreement with other reports (Davenport, 1967; Nakano et al., 1983). Thus, when a sun-exposed atmometer was compared to a shaded atmometer (located inside a standard meteorological screen), or when a wind-exposed atmometer (produced by fan with average wind speed of 1.1 m s^{-1}) was compared to an atmometer that was not exposed to wind (both located within the same room), the evaporation rates of the sun-exposed and the wind-exposed atmometers were 55.4% and 48.8% higher, respectively (Kidron, 2005). The shading and wind effects also resulted in a substantial decrease in the evaporation rates measured under the shrub canopy in the western Negev Desert being 53% of the inter-shrub habitat (Kidron, 2008).

Wind measurements at the research site furnished supporting evidence for the role played by the wind in determining evaporation rates. When concomitant measurements were carried out periodically at 50 cm above ground at selected stations, a substantial reduction was noted from station 1 (hilltop) to 3 (mid NF) followed by station 5 (wadi) and 7 (mid SF) (Fig. 10a). A similar reduction was also monitored from station 16 (mid WF) to 12 (mid EF) (Fig. 10b). In both cases winds from the north-west prevailed. Alternatively, a considerable reduction from station 12 (mid SE) to 16 (mid WF) took place during easterly winds (Fig. 10c). The findings pointed to the much higher wind speed at the hilltop and the large decline in wind speed from the windward to the leeward stations, with wind speed at the leeward stations being ~60% that of the windward stations.

Both factors, the shading and the wind effects, should be considered when the evaporation rates of the two opposing aspects, NF and SF, and EF and WF are considered. The significant differences that characterized NF and SF may be mainly attributed to the sun angle, while the significant higher evaporation rates recorded in summer at the TOP stations in comparison to the WADI stations despite their near-horizontal inclination should be attributed to the wind effect. The current results may explain contradictory results in regard to adiabatic cooling. While seen responsible for lower evaporation rates in some areas (Lang, 1981; Staudinger and Rott, 1981; Blyth, 1999), this was not the case in others (Johnson, 1985; Giambelluca and Nullet, 1992; Blackie and Simpson, 1993). As in Sede Boqer, higher wind speed at the higher altitude of certain sites may mask the effect of the adiabatic cooling. This was especially the case at the Mauna Loa Mountain in Hawaii that showed at the high-altitude stations an increase in evaporation with altitude (from 1200 m to 3400 m), in agreement with the increase in wind speed (Bean et al., 1994).

The wind effect may also explain the evaporation rates recorded at EF and WF despite the similar radiation loads received at both slopes (Shulgin, 1957; Geiger, 1966). Although not significant, the wind may account for the slightly higher evaporation rates of WF

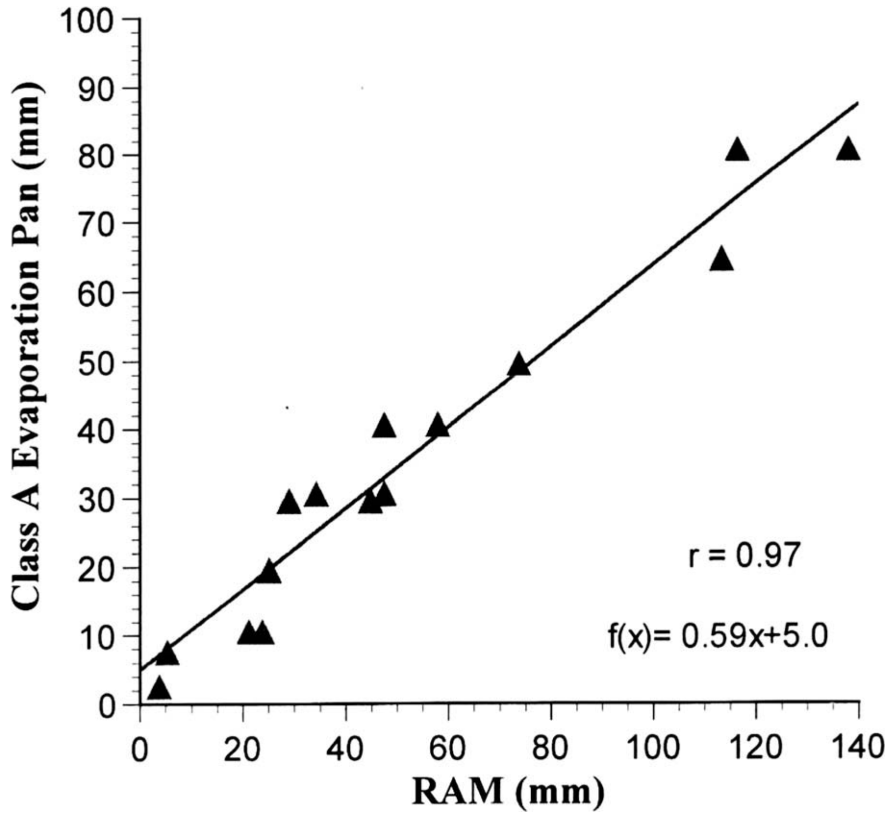

Fig. 6. The relationship between the RAM and class A evaporation pan (in mm).

in comparison to EF during the summer and the opposite trend during the winter. Whereas winds from the north-west prevail during the summer and may thus increase the evaporation from WF, the prevailing easterly winds during winter (Bitan and Rubin, 1991) may explain the higher evaporation rates in EF in comparison to WF. Yet the occasionally high-speed westerly winds during wintertime (Bitan and Rubin, 1991; Kahana et al., 2002) may compensate for the predominant but low- to medium-speed easterly winds and may thus explain the overall low differences in the evaporation rates of both slopes during wintertime.

The current data highlights the complex role that wind may have upon the evaporation. It also highlights the caution required when estimation of evaporation is sought based on simple models, which may be used once data for more accurate models such as net radiation, wind speed and vapor pressure deficit are not at hand. For this purpose, and assuming clear sky conditions, a comparison of two opposing slopes may be carried out based on direct-beam radiation (Smart, 1977). Thus, when the current evaporation rates were compared to those estimated in accordance with the sun inclination, aspect and slope angle (following Smart (1977)) for three north- and south-facing slope locations, substantial differences were obtained. Midslope stations 3 and 7, which were the steepest, exhibited the highest difference (Fig. 11), attesting to the fact that the shading effect may only partially explain the differences in evaporation, while highlighting the role of the wind. Similar results were obtained by Bean et al. (1994) that showed a decrease in correlation between solar radiation and evaporation with the increase in wind speed.

In order to assess the maximal effect of the wind upon evaporation, a comparison between two nearly horizontally lying stations was carried out, the wind-exposed station 10 (at the hilltop) and the wind-sheltered station 5 (at the wadi bed), which, according to Fig. 10, was subjected to half the wind speed of station 10. The comparison was carried out during the months of June and July during which the sun inclination is minimal and consequently the shading effect. While the average monthly evaporation at station 10 was 502.5 (SD = 50.3), it was 345.6 (SD = 62.8) in station 5, yielding a ratio of 1.454. This implies that the wind effect may account for up to 45% of the results. The findings may be regarded as being in good agreement with Penman–Montieth equation. While explaining a 25% increase in the evaporation rate at station 10 due to the wind effect on the aerodynamic resistance (r_a), a similar effect in its magnitude may be expected following the wind impact on the vapor pressure deficit, VPD (Bean et al., 1994; Kidron, 2008). This is in agreement with Blackie and Simpson (1993) that concluded that the wind accounted for ~40% of the evapotranspiration in their research site in the UK, and with Bean et al. (1994) that showed a ~50% increase in evaporation at a station subjected to a twofold increase in wind speed in Hawaii.

Similarly, when the maximal shading effect was sought, a comparison between NF and SF was carried out during wintertime, when the sun inclination is maximal. Yet, in order to eliminate, as much as possible, the effect of the wet ground upon the vapor pressure and hence upon the RAM's evaporation rates, it was carried out during the months of November, 2005, 2006 and December 2006 during which monthly precipitation was relatively low ranging between 0.8 and 8 mm (Table 2). While average evaporation at SF was 209.4 (SD = 44.8), it was 140.2 (SD = 39.4) in NF, yielding a ratio of 1.494. The data thus imply that the shading effect may explain up to ~50% of the differences between NF and SF. One may thus conclude that under the natural conditions prevailing at the Negev, the maximal shading and wind effects are similar, up to 45–50%.

While some researchers claim that the regional radiation balance is not sensitive to gentle slopes (Raupach and Finnigan, 1997), the lower annual evaporation rates at the slopes (~14%) and wadi beds

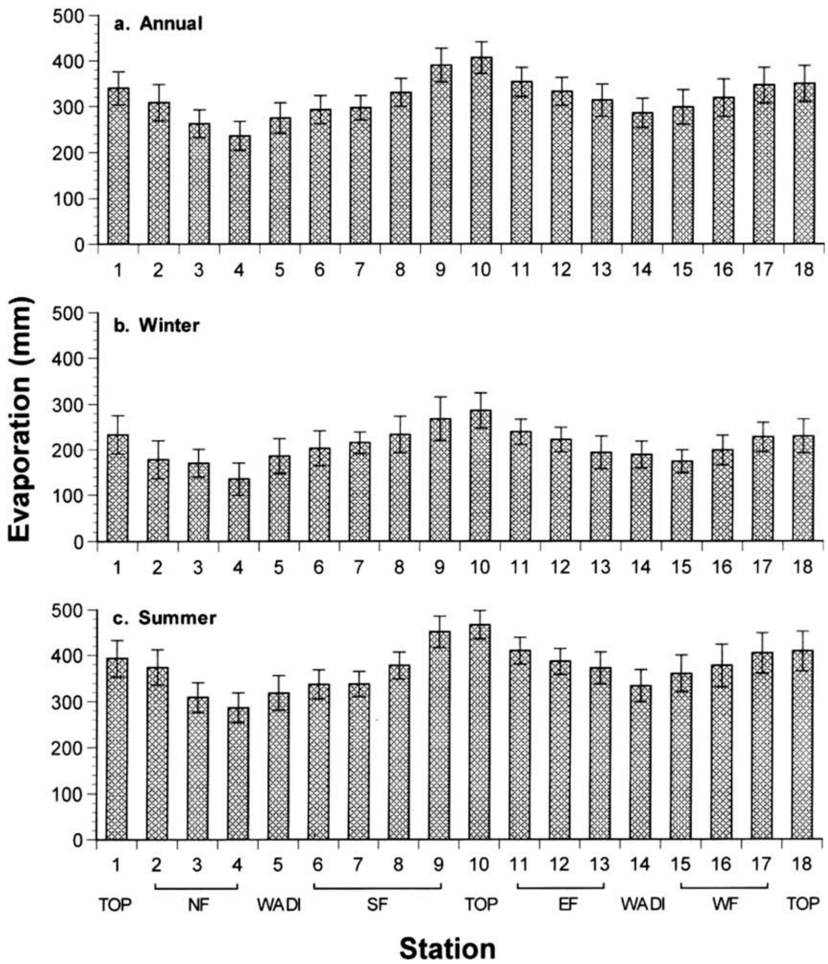

Fig. 7. Average monthly evaporation rates during the year (a) winter (b) and summer (c) for July 2004 to June 2006. Bars represent one SD.

(~23%) in comparison to the hilltops cannot be ignored. These values are much higher than the 5% decrease estimated by Blyth (1999) in the UK over a 20° slope in comparison to a flat terrain. Subsequently, these relatively large differences found during the current research may have important implications as regards the cover and distribution of plants and microorganisms.

Since evaporation rates may well reflect the rate during which surface desiccation will take place and since wetness duration rather than moisture content may be seen as the cardinal factor for microorganism and plant establishment (Kappen et al., 1980), the findings may explain microorganism and plant distribution. The findings indicate that whereas the north-facing footslope, followed by the west-facing footslope, may be preferential habitats as far as evaporation rates are concerned during wintertime, the hilltops and upper slopes, which are relatively exposed to wind and sun, are the harshest habitats. Indeed, when the soil moisture content of hilltops, slopes and wadi beds were studied in the Negev Desert, hilltops were found to be the most xeric habitats, having the lowest moisture content and the higher salinity in comparison to the slopes (Tadmor et al., 1962). Wadi beds were found to be the most mesic habitats.

Apparently, as evidenced from the similar values of evaporation, the harsh conditions that characterize the hilltops also characterize open flats, such as the 5×3 km flat where the meteorological station is located. Consequently, in comparison to a flat terrain and hilltops, wadi beds and slopes increase water availability and thus render an advantage to plant growth in the Negev Desert.

Table 2
Distribution of the rain events during 2004–2006.

2004–2005		2005–2006	
Date	Precipitation (mm)	Date	Precipitation (mm)
29.10.04	3.9	6.11.05	0.1
18.11.04	1.9	20.11.05	3.7
22.11.04	7.9	16.12.05	0.1
23.11.04	0.6	20.12.05	0.4
26.11.04	3.3	22.12.05	0.3
27.11.04	0.3	8.1.06	0.5
7.12.04	0.6	13.1.06	6.2
8.12.04	2.0	17.1.06	1.9
12.12.04	0.4	27.1.06	0.2
14.12.04	0.3	28.1.06	2.0
15.12.04	0.3	2.2.06	0.4
16.12.04	1.4	13.2.06	3.4
24.12.04	6.6	14.2.06	9.5
2.1.05	4.3	15.2.06	9.3
3.1.05	0.5	16.2.06	1.3
5.1.05	5.4	25.2.06	0.1
6.1.05	0.2	26.2.06	1.0
22.1.05	0.1	1.4.06	6.5
23.1.05	1.0	4.4.06	1.1
24.1.05	0.3	16.4.06	18.0
6.2.05	1.1		
8.2.05	4.4		
12.2.05	1.5		
20.2.05	0.4		
3.3.05	0.7		
8.3.05	4.3		
9.3.05	15.9		
10.3.05	0.9		
Total	70.5	Total	66.0

The findings may have important ecological implications. In addition to the fact that wadi beds concentrate runoff and serve as runoff conduits, the lower evaporation at the wadi contributes to the preferential growth conditions of this habitat, and may support higher plant biomass even under conditions during which runoff is not taking place. As for the slopes, the lower evaporation rates there may result in higher plant cover and biomass than that of the hilltops. While argued to result from runoff that is generated at the bare areas and trapped in their way down the slope by the shrubs (Cerda, 1997), the present findings highlight the role of evaporation as a possible explanation for the higher plant cover and biomass at the slopes.

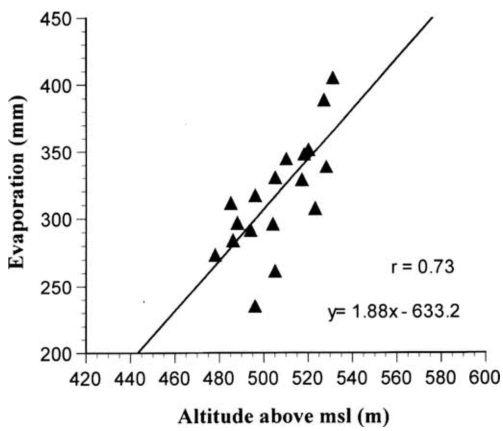

Fig. 8. The relationship between altitude and the average monthly evaporation.

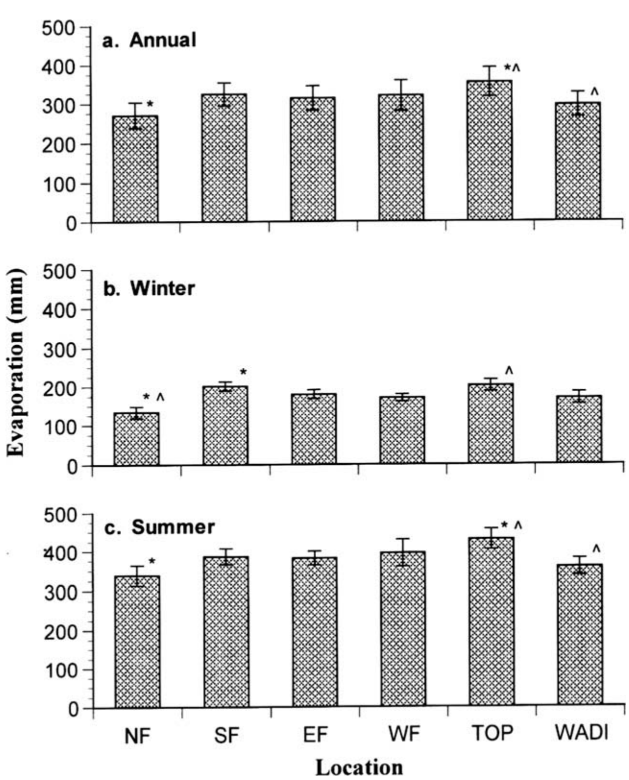

Fig. 9. Average monthly evaporation at the north-facing (NF), south-facing (SF), east-facing (EF), and west-facing (WF) stations and at the three hilltops (TOP) and both wadi beds (Wadi), as obtained during the entire research period (a), winter (b) and summer (c). Bars represent one SE. Similar signs indicate significant differences between locations ($P < 0.05$).

The current findings may facilitate the calibration of the evaporation rates as received from numerical models and may have important implications regarding the estimation of potential evaporation from complex terrains (Boulet et al., 1997; Bronstert and Plate, 1997; Liu et al., 2005). Given the relationships found between the evaporation at the hilltops, the wadi beds and the different aspect-oriented slopes, the role played by the evaporation on the soil moisture content and hence on the vegetation cover and biomass on hilly versus flat terrains may be feasible (Tadmor et al., 1962).

The findings may also have important implications regarding the interrelations between microclimate, microorganisms, vegetation, weathering, erosion, slope evolution and soil formation. While the channeling effect may act to minimize the difference in the rain amounts that fall at the windward and leeward aspects (Burnett et al., 2008), aspect-related differences may have a cardinal role in controlling evaporation and hence the slope water regime. Due to hydration expansion and rapid dissolution of the binding cements, chemical weathering may be enhanced (Churchill, 1982). Moreover, by facilitating microorganism distribution (Kappen et al., 1980), high water availability may enhance biogenic weathering (Schwartzman and Volk, 1989), and hence rock degradation and soil formation (Syers and Iskandar, 1973). While

Table 3
Two-way ANOVA for average monthly evaporation in relation to aspect (north, south, east, west) and season over the entire drainage basin (a), northern and southern aspects (b) and eastern and western aspects (c). *M* = mean, SD = standard deviation, *N* = sample number.

Aspect	Season	
	Winter	Summer
a		
North		
M	133.5	338.7
SD	(35.2)	(76.9)
South		
N	12	24
M	201.3	385.4
SD	(30.9)	(63.1)
N	16	32
East		
M	179.6	381.7
SD	(32.1)	(50.5)
N	12	24
West		
M	170.9	395.0
SD	(27.20	(97.9)
N	12	24

Source of variation	SS	df	F	P-value
Aspect	65,757	3	5.54	0.001
Season	1,419,055	1	358.42	<0.001
Aspect × season	7373	3	0.62	0.603
Within	585,968	148		
Total	2,083,491	155		
b				
Aspect	59,864	1	16.67	<0.001
Season	693,214	1	193.03	<0.001
Aspect × season	2025	1	0.56	0.455
Within	287,296	80		
Total	1,045,434	83		
c				
Aspect	85	1	0.02	0.890
Season	726,506	1	165.41	<0.001
Aspect × Season	1941	1	0.44	0.508
Within	298,671	68		
Total	1,027,761	71		

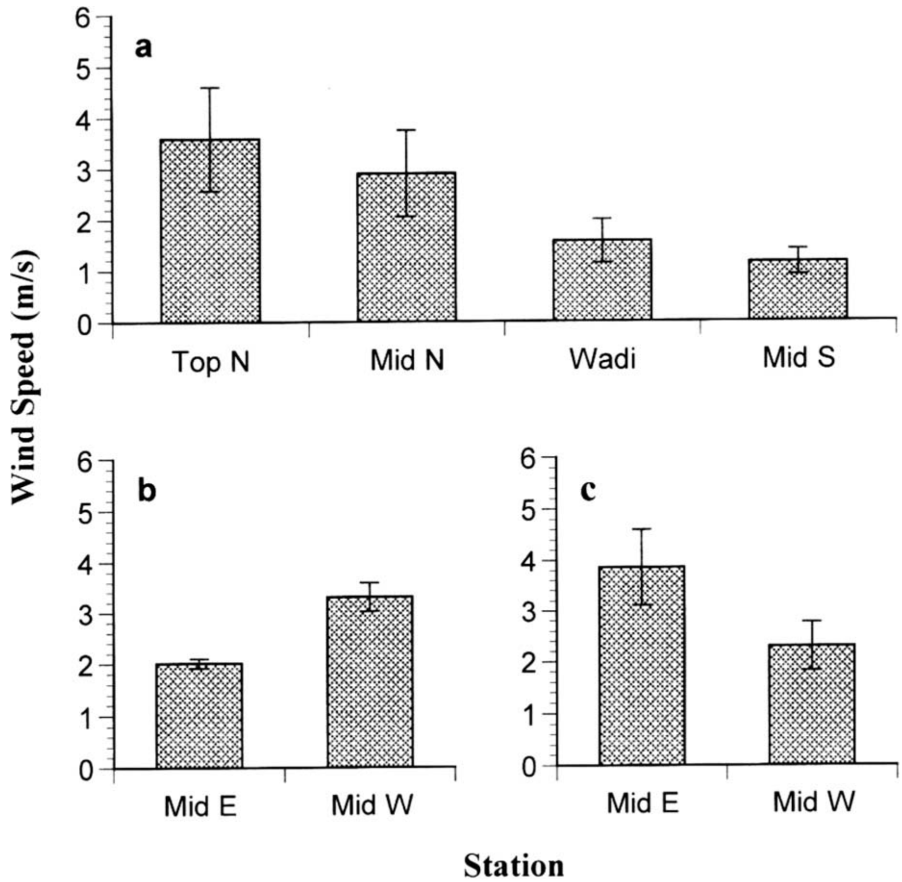

Fig. 10. Average daily wind speed (in m/s) as measured during 5 days of north-westerly wind at (a) stations 1, 3, 4 and 7 (after Kidron et al. (2000)), (b) during 6 days of north-westerly wind at stations 12 and 16 and (c) during 4 days of easterly wind at stations 12 and 16. Bars represent one SE.

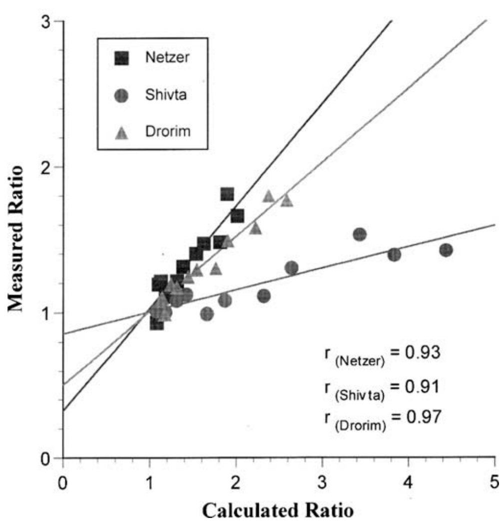

Fig. 11. The annual relationship between the calculated direct-beam radiation ratio and the measured ratio of the average monthly evaporation of the south- versus north-facing habitats of the upper (Netzer formation), middle (Shivta formation) and lower (Drorim formation) slopes. Average north- and south-facing slope angles are 12.5°, 16.0° and 27.5° for the upper, bottom and middle slope sections, respectively.

controlling runoff generation (Churchill, 1982; Kidron, 1999), soil moisture content may also determine plant distribution which in turn may act to check soil erosion (Kirkby, 1995). Microorganisms and plant may both act to determine slope morphology and evolution, affecting slope properties, cliff formation and colluvium distribution (Yetemen et al., 2007; Burnett et al., 2008; Istanbulluoglu et al., 2008).

Conclusions

Measurements of evaporation within four aspects of a second order drainage basin in the Negev Desert showed high variability with TOP > SF ⩾ EF ⩾ WF > WADI > NF. The findings are explained by the shading and wind effects, with each of these factors being responsible for up to 45–50% of the results. Reduced evaporation loading at the slopes and reduced wind speed there explain the lower evaporation rates (~14%) at the slopes while the reduced wind speed at the wadi beds explain the lower evaporation rates (~23%) there. The findings imply that hilltop and flat surfaces are the harshest habitats while the north-facing aspect and the wadi beds are the most mesic habitats.

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