



Does temperature-induced vapor flux trigger desert floods? The Negev example

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Abstract: High-magnitude floods characterize deserts, commonly explained by the high rain intensities coupled with the low vegetation cover, surface smoothness and the sealing capability of biocrusts. Nevertheless, runoff generation and the subsequent high-magnitude floods stand out when considering the high evaporation, the relatively dry desert surfaces and the high stoniness that characterize many of the surfaces. Also, the rain amount that stems from high intensity (convective) rains is not necessarily higher than in subhumid regions, and indeed, based on a study of runoff dynamics over biocrusted sand dunes in the Negev Desert, runoff was generated already at low to medium intensities of 9–12 mm/h, explained by the high-water absorbance of the extracellular polymeric substances (EPS) that is excreted by the variable microorganisms inhabiting the biocrust. In the Negev, convective intensities were found to primarily result from unstable daily atmospheric conditions following by daytime surface heating. Daytime heating, coupled with cool/cold nighttime temperatures, were also found responsible for the occurrence of temperature-induced vapor flux (TIVF) and the subsequent occurrence of wet-dry cycles that may last for up to 1–2 weeks following a rain event. We hypothesize that the wet cycles which stem from an upward vapor movement from the warm subsurface soil towards the cool soil surface during the night result in biocrust saturation, triggering in turn runoff generation. By wetting the surface (commonly already during the late afternoon), TIVF may trigger runoff in deserts. This is supported hereafter following a thorough four year-long analysis (1990–1994) of rain-runoff relationship that took place on a pair of biocrusted plots covering dunes in the Negev. Albeit the ~20% higher intensities measured during daytime that should have resulted in higher runoff, nighttime runoff amount, runoff flow duration, runoff yield per average rain intensities and runoff yield per the average intensity of each event were 1.8-, 1.5-, 1.5- and 3.1-fold higher during nighttime in comparison to daytime. It is suggested that in addition to the role played by runoff intensity and the surface properties, TIVF provides an additional mechanism that explains the high runoff generation already at low- to medium-intensities, also explaining, at least partially, the relatively high runoff yield and potent floods in the Negev and other arid regions.

Keywords: Biocrusts; Dew; Distillation; Runoff; Wet-dry cycles.

1 INTRODUCTION

High-magnitude floods are common in deserts. While resulting from short but high-intensity rain spells, they may last for hours, endangering life and infrastructure. Unstable daily atmospheric conditions, resulting in high rain (and convective) intensities, are commonly thought to explain the potent occurrence of desert floods (Kutiel and Sharon, 1980; Zipser et al., 2006; Rosin et al., 2024), but yet, rain intensities may not necessarily be especially high in comparison to subhumid regions (Biasutti et al., 2013). Runoff may however be promoted by sparse vegetation (Tadmor and Shanan, 1969; Cerdà, 1998), surface smoothness (Dunne and Dietrich, 1980; Kidron, 2007), high sodium content (sodicity) (Tadmor and Shanan, 1969; Keren et al., 1983; Agassi et al., 1985; Zhang et al., 2024), and biocrusts (Kidron and Yair, 1997). Yet, the high-magnitude floods take place despite the high dryness of the surface and the high evaporation that may hinder water accumulation and flow, and despite excessive stoniness that characterize many desert surfaces (Kidron and Starinsky, 2012; Stavi et al., 2019; Tümová et al., 2024), which increases the runoff flow path, thus impeding flow velocity (Lavee and Poesen, 1991) and increasing in turn the amounts of loci that serve as water sinks (Poesen et al., 1990).

Sodicity occurs in sodium-enriched soils during which sodium ions, which are attached to clay particles, cause the particles to repel each other resulting in dispersion (deflocculation). This inhibits fluctuation and subsequently aggregation, which act in turn to promote infiltration (Williams et al., 1995; Or et al., 2007; Rossi et al., 2012; Rodríguez-Caballero et al., 2013; Cantón et al., 2020; Redmile-Gordon et al., 2020). While sodicity may be confined to restricted soil surfaces, mainly to channel banks (Nachshon, 2016) and sabkhas (Bui, 2019), large areas in arid and semiarid regions are covered by biocrusts, which their role in promoting runoff generation was substantiated in recent decades.

Covering extensive surfaces in arid and semiarid regions, biocrusts, mainly composed of cyanobacteria, lichens, mosses, fungi and bacteria and embedded within the surface mineral grains, were found to trigger runoff generation (Kidron and Yair, 1997; Malam-Issa et al., 2009; Wu et al., 2012; Rodríguez-Caballero et al., 2013; Lázaro et al., 2015; Guan and Cao, 2019; Xiao et al., 2019a). Aiming to pinpoint the main variable responsible for the biocrust capability in runoff generation, sprinkling experiments and field measurements were conducted. Verified by lab (Mazor et al., 1996; Kidron et al., 1999) and field (Kidron,

1999; Kidron et al., 2003) measurements, extracellular polymeric substances (EPS), which are excreted by many of the biocrust components (cyanobacteria, lichens, fungi, bacteria) were mainly found responsible for clogging the surface and hinder infiltration, which upon wetting, readily swells and seals the surface (Chenu, 1993; Mazor et al., 1996; Or et al., 2007; Fischer et al., 2010; Yu et al., 2024).

The surface properties, whether the high smoothness, high sodicity or the presence of biocrusts, are closely linked to the mechanism governing runoff generation in arid and semiarid regions. Unlike humid and temperate regions, runoff in deserts does not require the saturation of the entire soil profile, and subsequently, does not take place by saturation overland flow (SOF) (Dunne and Black, 1970; Beven and Kirkby, 1979). Rather, runoff in arid and semiarid regions takes place by infiltration-excess overland flow, also known as Hortonian overland flow (HOF), during which the infiltration capacity of the soil surface skin is surpassed, regardless whether the soil profile is wet or not (Horton, 1933; Kidron, 2021). Under these conditions, during which saturation of the millimeter/centimeter-thick surface suffices to generate runoff, long hours of rain duration are not required, and short-duration rain flashes may suffice to generate runoff, which is facilitated, as mentioned above, by the smooth surface, sodicity and EPS-enriched biocrusts.

High amounts of runoff were also recorded in the Hallamish dunefield in the Negev. Mostly covered by cyanobacterial crusts that inhabit all sandy interdunes and most of the dune slopes, runoff was readily generated on the biocrust-covered sand. Four year-long research (1990-1994) that was conducted at the site established the rain-intensity thresholds required for runoff generation. Commonly, high- (>20 mm/h) and convective- (>30 mm/h) intensity rains take mainly place at the late afternoons (Kutiel and Sharon, 1980). Nevertheless, runoff generation took place already following 1-2 minutes of low (<10 mm/h) to medium (10-20 mm/h) intensities of 9-12 mm/h (Kidron and Yair, 1997), explained by the high amounts of the EPS that characterize the crusts (Kidron et al., 2003). These intensities are one order of magnitude lower than the 300-360 mm/h required to generate runoff on uncrusted sand (Lichner et al., 2010; Xiao et al., 2019b).

Often, runoff was generated during nighttime. In many instances rain was noticed to hit wet surfaces albeit the fact that the previous rain took place days before, sometimes even 10 days before. Surface wetting was often noted during the late afternoon, lasting until the following morning hours, when it dried out, only to be rewetted during the following afternoon. Such wet-dry cycles (WDCs), observed in many deserts (Jackson, 1964; Rose, 1968a, b), were also investigated in the Negev (Kidron et al., 2022, 2024).

The magnitude of the wet phases was monitored in the Negev during daily moisture measurements using cloths attached to the sand surface following rain events (Kidron et al., 2022), substantiating the occurrence of temperature-induced vapor flux (TIVF) i.e., vapor transport that stems during the night from the wet and relatively warm subsurface to the cool/cold surface (Philip and De Vries, 1957; Jackson, 1964; Cary, 1966; Rose, 1968a,b; Hadas, 1968; Cahill and Parlange, 1998; Zeng et al., 2009; Lu et al., 2011). For many mornings, the amounts recorded were ≥ 0.1 mm, i.e., above the threshold which denotes vapor condensation. i.e., liquid (Lange et al., 1992), therefore regarded as distillation (Monteith, 1957; Kidron et al., 2026). Hypothesizing that these wet cycles may promote nighttime runoff even under medium intensities (10-20 mm/h), a thorough analysis of the 1990-1994 data was initiated.

2 THE RESEARCH SITE AND PREVIOUS FINDINGS

The research site lies in the Hallamish dunefield in the western Negev Desert, next to Nizzana (Fig. 1a; $34^{\circ}23'E$, $30^{\circ}58'N$). Classified by Köppen-Geiger as BWh (Kottek et al., 2006), the climate is hyperarid with mean annual precipitation of 95 mm falling during the winter months (November - April). Average annual daily temperature is $20^{\circ}C$; it is $26.5^{\circ}C$ during the hottest month of July and $11.8^{\circ}C$ during the coldest month of January. Potential evaporation is ~ 2600 mm (Evenari, 1981).

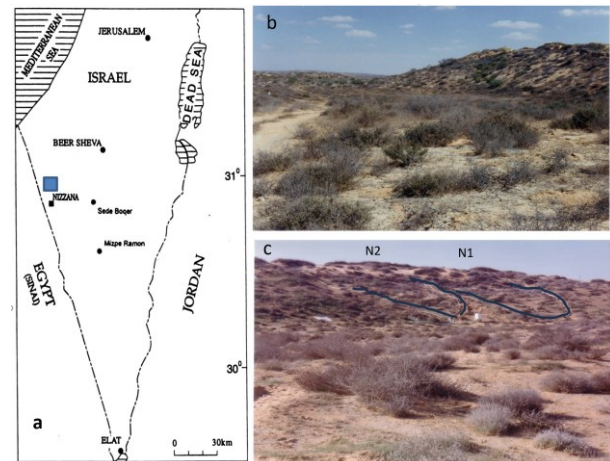


Fig. 1. Location of the research site (a), general view of the research site (b) and photographs of the two runoff plots (c).

West-east trending linear dunes, 8-15 m-high, separated by 50-200 m-wide interdunes characterize the Hallamish dunefield (Roskin et al., 2011). The dunes are comprised of medium size sand of which $\sim 75\%$ is between 250-500 μm with only 2-8% of fines, i.e., silt and clay (Kidron, 2001). Sparse ($\sim 1\%$) vegetation (mainly *Stipagrostis scoparia*) inhabits the dune crest while a cover of 10-20% of shrubs (mainly *Cornulaca monacantha* and *Artemisa monosperma*) characterizes the lower sections of the dunes and the interdunes. Except from the high and mobile dune crests, all the sandy surfaces are covered by biocrusts, mainly by 1-2 mm-thick cyanobacterial biocrusts with *Microcoleus vaginatus* and *Phormidium* sp. predominating (Kidron et al., 2010).

A four year-long study has substantiated the importance of the hydrological role played by these biocrusts. Whereas no runoff was monitored on the non-crusted loose sand (Kidron, 1999), which according to Lichner et al. (2010) and Xiao et al. (2019b) require over 300 mm/h to generate runoff, cyanobacteria readily produced runoff at low to medium intensities of $\geq 9-12$ mm/h, being subsequently responsible for water redistribution (Kidron, 1999). This ecological role was mainly attributed to the high content of EPS within the biocrusts, which upon wetting readily swell, impeding water infiltration (Kidron et al., 2020). Higher biomass cyanobacterial biocrusts were found to yield higher runoff (Kidron et al., 2003) and subsequently, the more developed cyanobacterial biocrusts inhabiting the sun-shaded north-facing slopes, yielded about three times the amount produced by the more xeric cyanobacterial biocrusts inhabiting the sun-exposed south-facing slopes (Kidron, 1999).

Aiming to unveil the water sources of the biocrusts, extensive field measurements were conducted. The water content of biocrusts was recorded in the field, substantiated the central role of rain as a water source. These measurements showed a clear relation between surface wetness duration and crust biomass (Kidron et al., 2009). These measurements also refuted the wide-held belief that biocrust use dew for growth (Kidron et al., 2002; Kidron,

2024). Whether on the biocrusted surfaces of the dunefield or on high-altitude surfaces in the Negev Highlands, where dew yield is higher, dew was not observed to reach the minimum threshold of 0.1 mm found to denote liquid water (Lange et al., 1992). The amount obtained on the soil surface commonly ranged between 0.02–0.03 mm only, explained by the relatively high surface temperatures, which were substantially higher than the dewpoint temperature required for vapor condensation (Beysens, 1995, 2018). These measurements substantiated the role played by WDCs, explained by vapor transfer from the wet soil, due to a temperature gradient that exists during the night between the warm subsurface and the cool/cold surface. Providing water content > 0.1 mm, condensation may thus take place. This process, termed distillation (Monteith, 1957; Kidron et al., 2026), may provide long hours of surface wetness, assumed to explain the establishment and growth of biocrusts (Kidron et al., 2022). The high surface water content recorded during the wet phase of the WDCs led us to hypothesize that rain that hits the wet surface may also promote runoff generation.

3 METHODOLOGY

Rain and runoff were analyzed during 1990–1994. Rain for 1990/91, 1991/92, 1992/93 and 1993/94 amounted to 119.7 mm, 131.4 mm, 85.3 mm and 46.9 mm, respectively, averaging 95.8 mm, similar to the long-term mean of 95.0 mm. The number of rainy days with > 1 mm during these years was 11, 19, 18 and 13, respectively (Table 1). A tipping-bucket rain gauge (Texas Instruments, USA; accuracy 0.1 mm) was used to record the rain amount and rain intensity per 1 min intervals. For runoff analysis, we focused on two north-facing plots. The plots were constructed with 20 cm-high thin metal strips, inserted 10 cm into the sand (Fig. 1c). All plots were equipped with a V-notch weir and a pressure gauge transducer (connected to a Campbell Scientific datalogger), facilitating a comparison with the rain intensities. General properties of the plots are shown in Table 2.

Rain and runoff were recorded in 1-min intervals, which guaranteed a high resolution but also required some discretion. For instance, a consecutive recording of 6, 12, 6, 12 mm/h were interpreted as rain intensities of 9 mm/h. Also, following the limited flow duration (min) of the runoff after the cessation of the rain spell (Kidron, 2011), a rain spell with above-threshold intensities of > 9 mm/h that was followed by > 3 min-long of below-threshold intensities was treated as a separate rain event. Thus, for instance, rain spells of 3 min-long 9 mm/h, followed by 4 min-long 6 mm/h (i.e., below the required threshold) and then by 3 min-long 9 mm/h were considered as two separate (and relevant) rain spells of 9 mm/h each. As for the analysis of the possible effects of the wet phases, hours during which a potential wet phase affected the surface was separately analyzed. Subsequently, rain events that occurred between 16:00 to 09:00 the next day (potential wet phase, termed hereafter as nighttime rain) were separately analyzed from the potential dry phase, i.e., rain that fell between 10:00 and 15:00 (termed hereafter as daytime rain). However, since no vapor transfer (which require a wet soil) could have taken place during rain events that began during the late afternoon or night and fell on a dry soil, these rain events were not regarded as nighttime rains, but rather as ‘daytime’ rains. Also, albeit the fact that during some long rain events, the daytime rain fell on a wet ground, we still considered it as a daytime rain that takes place under the ‘dry’ phase in order to differentiate it from the events that are affected by upward vapor transport. We are aware of the fact that in this way we grant an extra advantage to the daytime rains when judging their ability

to produce runoff, but, as will be seen below, albeit the seemingly advantage given to the daytime rains, the nighttime rains still showed higher responsiveness and higher yields.

Table 1. Daily rain distribution (> 0.1 mm) during 1990–1994.

Date	Rain (mm)	Date	Rain (mm)
1990/1991		1992/1993	
4.1.1991	2.6	24.11.1992	2.5
18.1.1991	3.4	2.12.1992	6.2
25.1.1991	21.0	3.12.1992	1.4
26.1.1991	7.0	8.12.1992	1.3
30.1.1991	2.9	14.12.1992	3.0
7.2.1991	6.3	15.12.1992	1.4
28.2.1991	3.1	16.12.1992	1.2
5.3.1991	17.5	21.12.1992	5.3
6.3.1991	4.8	25.12.1992	5.1
22.3.1991	15.2	7.1.1993	1.4
23.3.1991	23.6	11.1.1993	24.0
		2.2.1993	1.2
		3.2.1993	4.6
		4.2.1993	3.0
		9.2.1993	2.8
		6.3.1993	2.6
		11.3.1993	2.2
		12.5.1993	9.7
1991/1992		1993/1994	
2.12.1991	1.7	26.11.1993	1.2
24.12.1991	5.3	27.11.1993	1.9
1.1.1992	14.3	21.12.1993	8.1
2.1.1992	27.4	22.12.1993	12.1
3.1.1992	7.6	2.1.1994	1.2
30.1.1992	6.0	14.1.1994	3.8
31.1.1992	1.2	23.1.1994	3.1
1.2.1992	1.4	24.1.1994	4.3
2.2.1992	1.2	25.1.1994	1.2
3.2.1992	1.4	27.1.1994	1.4
4.2.1992	2.1	27.2.1994	1.7
8.2.1992	1.4	10.3.1994	2.2
9.2.1992	16.5	12.3.1994	2.7
10.2.1992	16.6		
18.2.1992	2.2		
23.2.1992	1.7		
25.2.1992	4.5		
26.2.1992	8.5		
22.3.1992	3.7		

Table 2. Description of the plot properties.

Plot	Azimuth (°)	Slope (°)	Length (m)	Width (m)	Area (m ²)	Surface characteristics
N1	5	11–17	21	22	301	Smooth
N2	350	10–20	27	22	478	rugged

3 RESULTS AND DISCUSSION

During the study, 1 min-long intensities of up to 72 mm/h were recorded. In total, 31 separated runoff events took place (15 daytime and 16 nighttime), with up to 7 events during a single rain event (eg. 22–23.1.91). Not all rain events yielded runoff. Rain events that generated runoff are shown in Table 3. Runoff was intermittent, taking place only once sufficiently medium and high intensities were recorded. Minimum intensities that were required to generate runoff were 9 mm/h when lasting for ≥ 2 min or 12 mm/min when lasting for ≥ 1 min. These relatively low intensities yielded runoff only over wet surfaces. Much higher intensities failed to yield runoff when falling on a dry surface (Table 3).

Table 3 presents an analysis of the daytime and nighttime runoff events, while the ratios between the nighttime and the daytime events are shown in Fig. 2. The analyses show a clear disparity. Although total and average nighttime rain intensities were 0.74 and 0.79 mm/h that of the daytime intensities, respectively, the time duration of the effective nighttime duration was by 1.18 higher (Fig. 2a). Thus, ≥ 12 mm/h intensities accounted for 32.1% of the daytime intensities in comparison to only 14.2% of the nighttime intensities. As for the runoff, nighttime events

yielded substantially higher runoff and longer flow duration, which resulted in higher yield of nighttime runoff per the effective rain intensities. This is shown in Fig. 2b. The average ratio for both plots between nighttime and daytime events for runoff, flow duration, runoff per all the effective intensities and runoff per average intensity per event was by 1.82, 1.53, 1.45 and 3.11 times higher, respectively, supporting our view that the nighttime wet phase plays a cardinal role in promoting runoff yield.

Table 3. Rain and runoff characteristics during 1990-1994 describing the relevant intensity spells responsible for runoff yield. ND stands for no data.

Date	Hour	Range of intensities (mm/h)	Average intensity (mm/h)	Duration of intensities (min)	Runoff for N1 (L)	Flow duration for N1 (min)	Runoff for N2 (L)	Flow duration for N2 (min)
26.1.91	04:49	9-12	10.5	7	ND	ND	1.9	3
	10:44	6-12	8.8	14	ND	ND	6.1	14
	11:03	6-9	8.0	6	ND	ND	3.5	9
30.1.91	19:56	9-12	8.5	6	10.7	5	3	5
	11:33	24	23.0	4	3.8	4	10.8	7
5.3.91	15:46	9-18	9.0	5	4.8	5	8.7	5
22.3.91	10:30	9-42	14.7	11	17.2	9	11.0	9
	15:19	6-36	18.0	5	12.6	16	7.1	6
	15:31	18-66	42.7	3	39.3	3	39.1	3
23.3.91	02:10	3-18	10.0	9	4.6	11	13.4	10
	02:55	6-24	9.5	22	16.0	17	19.1	22
	15:42	9-15	10.0	6	1.4	3.0	4.1	5
	16:16	12-72	31.8	7	152.0	6	84.6	6
1.1.92	17:01	12-42	21.8	8	18.5	5	13.6	7
	03:50	6-12	9.0	14	15.7	16	9.4	20
	05:54	4-9	8.4	5	0.5	3	2.7	9
	06:37	6-12	9.4	7	0.8	10	1.1	8
	03:06	12-18	15.0	2	3.6	4	2.9	5
	12:43	12-18	16.0	3	5.0	4	3.5	3
9.2.92	12:41	6-12	8	4	4.0	5	2.2	4
	19:07	6-12	6.8	10	8.1	13	8.2	10
	00:35	6-12	9.0	16	44.5	19	50.7	19
	01:15	6-12	5.0	4	3.1	7	2.5	8
	06:09	24-48	34.0	3	61.9	4	46.9	4
	06:37	6-12	9.0	6	36.6	10	10.4	8
	10:41	6-18	6.0	11	50.2	9	28.1	8
	14:34	6-12	5.7	7	4.0	8	1.5	6
12.1.93	15:01	9	9.4	7	3.5	4	0.8	4
	14:34	9-72	34.8	16	23.5	7	8.4	5
22.12.93	21:05	9-54	19.6	15	35.1	9	3.8	5

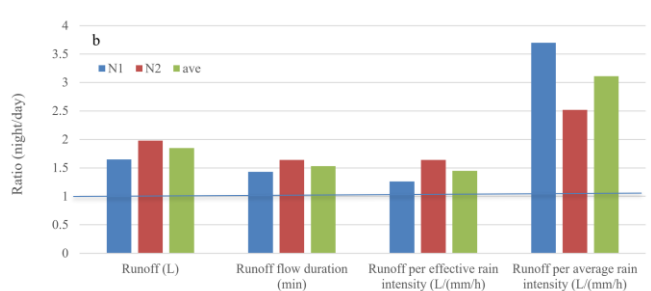
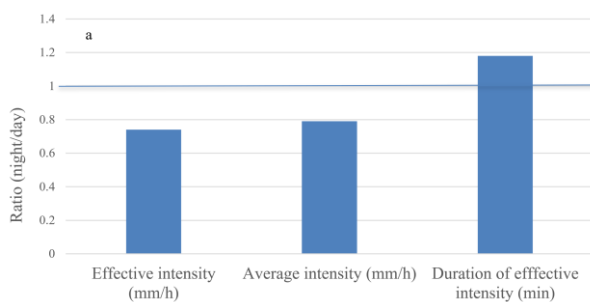


Fig. 2. The ratio between nighttime and daytime effective intensity, average and duration of the effective intensity (a), and the ratios between total runoff volume, runoff flow duration, runoff volume per all effective rain intensities and runoff yield per the average intensity of each event between nighttime and daytime events (b).

The higher likelihood during which runoff generation took place during nighttime is explained by the role played by vapor flux in runoff generation. As shown during a comparison of the rain intensities between the Negev and a Mediterranean coast near Ashdod in the south of Israel (with mean annual rain precipitation of 502 mm), rain intensities were substantially higher next to Ashdod, with 10 mm-long rain intensities of > 9 mm/min amounting to 45.2% of the total rain in comparison to only 13.2% in Nizzana (Kidron and Büdel, 2014). This does not support the view that the potent Negev desert floods (Schwartz and Greenbaum, 2008; Alexandrov et al., 2003, 2009; Greenbaum et al., 1998; Greenbaum and Zilberman, 2017) are only linked to the common occurrence of high intensity rains in deserts, subsequently supporting the involvement of TIVF.

For the occurrence of TIVF, a sharp day-night temperature gradient is required, resulting in WDCs. Indeed, WDCs are mainly confined to arid and semiarid regions where the high daytime radiation is responsible for high downward heat flux during the day while the cool/cold surface temperature during the night facilitate upward heat flux (Rose, 1968a,b; Jackson, 1964). Under wet conditions, these heat fluxes are responsible for an upward vapor transport during the night and ultimately for vapor condensation at the desert surface (Kidron et al., 2022), acting, as currently suggested, to promote runoff generation.

TIVF may trigger runoff generation in two ways: by (i) generating nighttime upward vapor that may hinder downward water infiltration and by (ii) wetting the surface, which implies that nighttime rain may hit a nearly saturated surface, facilitating in turn rapid runoff generation. Whereas the role played by the first mechanism is expected to be marginal due to the minute amounts that are involved, antecedent surface moistness plays an important role in promoting runoff yield (Kidron, 1999; Brocca et al., 2008; Pathiraja et al., 2012). According to Pathiraja et al. (2012), an underestimation of the design flood estimation can reach up to 30% once the antecedent moisture is not fully considered. Antecedent moisture, reflected in surface wetness, was evident during periodic morning observations that took place at our site, during which visible surface wetness was monitored.

Cyclic wetting during consecutive days in December 1994 following a 33.00 mm rain event that fell between December 2nd and 6th 1994 is shown in Fig. 3. Accordingly, whereas the plot surface was almost totally wet during December, 10th at 06:00, it dried several hours later (at 11:15), only to be rewetted by December, 11th (as noted at 06:45) and to partially dry out at 09:00 until drying out completely by 10:30 (not shown). This WDC was enabled by a sharp temperature gradient that facilitated an upward vapor flux (TIVF). Thus, for instance, near-surface temperature gradient during November 1st to November 25th, 1991 showed a gradient of $> 2^{\circ}\text{C}$ at the upper 1 cm (Kidron et al., 2000), substantially higher than the gradient of $0.5^{\circ}\text{C}/\text{cm}$ required to allow for vapor flux (Cary, 1965).

The described mechanism is closely linked to HOF. Accordingly, the soil horizon that controls the hydrological process responsible for runoff is confined to the upper millimeters of the surface. HOF will readily take place on EPS-enriched biocrusts that facilitate high water absorbance, and subsequently surface sealing, enabling runoff generation. This may explain the rapid responsiveness of biocrusts to rain flashes, and the subsequent runoff over biocrusts even when covering porous sand (Malam-Issa et al., 2009; Wu et al., 2012; Guan and Cao, 2019). The above processes build on one another: the wet phase of the WDC, induced by TIVF, trigger biocrust establishment, which promotes in turn surface sealing. While surface sealing may be especially effective on surfaces that are covered with EPS-enriched

biocrusts, cell imbibition and water sorption by clays (which are enriched within the biocrusts following dust entrapment; Danin and Ganor, 1991), may also assist in surface sealing. We postulate that this may also take place on loessial soils, and may thus trigger runoff also over loess, principally biocrusted but also non-crusted.

Facilitating runoff generation and water redistribution (a crucial mechanism that facilitates the relatively high productivity of deserts; Noy-Meir, 1973), this process may also explain the relatively high amounts of runoff that characterize deserts. Moreover, it may elucidate the relatively high amounts of runoff that is already generated at low-to medium intensity rain spells, and may explain, at least partially, the potent floods common in the Negev and other deserts.



Fig. 3. Wet-dry cycles as observed on a plot surface covered by brown-colored biocrusts (with some patches of loose aeolian sand deposited on the biocrust) during which a wet ground is noted during the early morning (06:00) of 10.12.1994 with $>90\%$ of the surface being wet, drying out already by 11:15 (with no wet surfaces), to be wetted again during the following morning (as evident at 06:45 during which 80–85% of the surface was wet) and partially drying out by 09:00 (with $\sim 20\%$ of the surface being wet) before completely drying out by 10:30 (not shown).

4 CONCLUSIONS

A four year-long re-analysis of rain-runoff relation from the Negev is reported. Wet-dry cycles that were observed over biocrusted sand surfaces in the Negev following rain events were hypothesized to affect runoff yield during the wet phase, during which rain falls on a wet ground, subsequently enhancing runoff generation. Indeed, when the rain and runoff events were divided to daytime (between 10:00 and 15:00) and nighttime (between 16:00 and 09:00) sections, much higher runoff yield was recorded during the night during which vapor transport responsible for the wet phase is likely to occur. Albeit the lower intensities that characterize the nighttime rains, runoff amount, runoff flow duration, runoff yield per effective intensities and runoff yield per the average intensity of each event were respectively 1.8-, 1.5-, 1.5- and 3.1-fold higher during nighttime in comparison to daytime. In addition to long-recognized mechanisms such as sodicity, surface smoothness and low vegetal cover that commonly explain the high runoff yields recorded in deserts, it is suggested that TIVF provides an additional mechanism, assisting to explain high runoff generation and the potent floods characterizing desert environments.

Acknowledgment: We Warmly thank the two anonymous reviewers and the Editor of this thematic volume Dr Lubomir Lichner for the constructive comments and support.

REFERENCES

- Agassi, M., Morin, J., Shainberg, I., 1985. Effect of raindrop impact energy and water salinity on infiltration rates of sodic soils. *Soil Science Society American Journal* 49, 186-190 <https://doi.org/10.2136/sssaj1985.03615995004900010037x>
- Alexandrov, Y., Laronne, J.B., Reid, I., 2003. Suspended sediment concentration and its variation with water discharge in a dryland ephemeral channel, northern Negev, Israel. *Journal of Arid Environments* 53, 73-84. <https://doi.org/10.1006/jare.2002.1020>
- Alexandrov, Y., Balaban, N., Bergman, N., Chocron, M., Laronne, J.B., Powell, D.M., Reid, I., Taggar, S., Wener-Frank, I., 2009. Differentiated suspended sediment transport in headwater basins of the Besor catchment, northern Negev. *Israel Journal of Earth Sciences* 57, 177-188.
- Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24, 43-69. <https://doi.org/10.1080/02626667909491834>
- Beysens, D., 1995. The formation of dew. *Atmospheric Research* 39, 215-237. [https://doi.org/10.1016/0169-8095\(95\)00015-J](https://doi.org/10.1016/0169-8095(95)00015-J)
- Beysens, D., 2018. Dew water. *Rivers Publisher* (Gistrup).
- Biasutti, M., Yuter, S.E., 2013. Observed frequency and intensity of tropical precipitation from instantaneous estimates. *Journal of Geophysical Research: Atmosphere* 118, 9534-9551. <https://doi.org/10.1102/jgrd.50694>
- Brocca, L., Melone, F., Moramarco, T., 2008. On the estimation of antecedent wetness conditions in rainfall-runoff modelling. *Hydrological Processes* 22, 629-642. <https://doi.org/10.1002/hyp.6629>
- Bui, E.N., 2019. Evidence for the role of salinity and alkalinity in plant diversification in Australia. *Sabkha Ecosystems VI* (Gul, B., Böer, M.A., Clüsener-Godt, M., Hameed, A., Eds.) Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-04417-6_2
- Cahill, A.T., Parlange, M.B., 1998. On water transport in field soils. *Water Resources Research* 34, 731-739. <http://dx.doi.org/10.1029/97WR03756>
- Cantón, Y., Chamizo, S., Rodríguez-Caballero, E., Lazáro, R., Roncero-Ramos, B., Roman, J.R., Solé-Benet, A., 2020. Water regulation in cyanobacterial biocrusts from drylands: Negative impacts of anthropogenic disturbance. *Water* 12, 720. <https://doi.org/10.3390/w12030720>
- Cary, J.W., 1965. Water flux in moist soil: thermal versus suction gradients. *Soil Science* 100, 168-175.
- Cary, J.W., 1966. Soil moisture transport due to thermal gradients: practical aspects. *Soil Science Society American Journal* 30, 428-433. <http://dx.doi.org/10.2136/sssaj1966.03615995003000040011x>
- Chenu, C., 1993. Clay-or sand- polysaccharide associations as models for the interface between micro-organisms and soil: water related properties and microstructure. *Geoderma* 56, 143-156.
- Cerdà, A., 1998. The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a Mediterranean hillslope. *Hydrological Processes* 12, 661-671. [https://doi.org/10.1002/\(SICI\)1099-1085\(19980330\)12:4<661::AID-HYP607>3.0.CO;2-7](https://doi.org/10.1002/(SICI)1099-1085(19980330)12:4<661::AID-HYP607>3.0.CO;2-7)
- Danin, A., Ganor, E., 1991. Trapping of airborne dust by mosses in the Negev Desert, Israel. *Earth Surface Processes and Landforms* 16, 153-162. <https://doi.org/10.1002/esp.3290160206>
- Dunne, T., Black, R.D., 1970. An experimental investigation of runoff production in permeable soils. *Water Resources Research* 6, 478-490. <https://doi.org/10.1029/WR006i002p00478>
- Dunne, T., Dietrich, W.E., 1980. Experimental study of Horton overland flow on tropical hillslopes. 2. Hydraulic characteristics and hillslope hydrograph. *Zeitschrift für Geomorphologie, Suppl. Band* 35, 60-80.
- Evenari, M., 1981. Ecology of the Negev Desert, a critical review of our knowledge, in: *Developments in Arid Zone Ecology and Environmental Quality* (Shuval, H. Ed.), pp. 1-33. Balaban ISS, Philadelphia, Pa.
- Fischer, T., Veste, M., Wiehe, W., Lange, P., 2010. Water repellency and pore clogging at early successional stages of microbiotic crusts on inland dunes, Brandenburg, NE Germany. *Catena*, 80, 47-52. <https://doi.org/10.1016/j.catena.2009.08.009>
- Greenbaum, N., Zilberman, E., 2017. Palaeogeography and palaeohydrology of fluvial systems in the levant, southeastern Mediterranean. In: *Quaternary Environments, Climate Change, and Humans in the Levant* (Enzel, Y., Bar Yosef, O., Eds.), pp. 401-415. Cambridge University Press, Cambridge.
- Greenbaum, N., Margalit, A., Schick, A.P., Sharon, D., Baker, V.R., 1998. A high magnitude storm and flood in a hyperarid catchment, Nahal Zin, Negev Desert, Israel. *Hydrological Processes* 12, 1-23. [https://doi.org/10.1002/\(SICI\)1099-1085\(199801\)12:1%3C1::AID-HYP559%3E3.0.CO;2-6](https://doi.org/10.1002/(SICI)1099-1085(199801)12:1%3C1::AID-HYP559%3E3.0.CO;2-6)
- Guan, H., Cao, R., 2019. Effects of biocrusts and rainfall characteristics on runoff generation in the Mu Us Desert, northwest China. *Hydrology Research* 50, 1410-1423. <https://doi.org/10.2166/nh.2019.046>
- Hadas, A., 1968. Simultaneous flow of water and heat under periodic heat fluctuations. *Soil Science Society American Journal*, 32, 297-301. <https://doi.org/10.2136/sssaj1968.036159950032000300015x>
- Horton, R.E., 1933. The role of infiltration in the hydrological cycle. *EOS Transactions AGU* 14, 446-460. <https://doi.org/10.1029/TR014;001p00446>
- Jackson, R.D., 1964. Water vapor diffusion in relatively dry soil: II. Desorption experiments. *Soil Science Society American Journal* 28, 464-466. <https://doi.org/10.2136/sssaj1964.03615995002800040006x>
- Keren, R., Shainberg, I., Frenkel, H., Kalo, Y., 1983. The effect of exchangeable sodium and gypsum on surface runoff from loess soil. *Soil Science Society American Journal* 47, 1001-1004. <https://doi.org/10.2136/sssaj1983.03615995004700050032x>
- Kidron, G.J., 1999. Differential water distribution over dune slopes as affected by slope position and microbiotic crust, Negev Desert, Israel. *Hydrological Processes* 13, 1665-1682. [https://doi.org/10.1002/\(SICI\)1099-1085\(19990815\)13:12<1665::AID-HYP1000>3.0.CO;2-7](https://doi.org/10.1002/(SICI)1099-1085(19990815)13:12<1665::AID-HYP1000>3.0.CO;2-7)
- Kidron, G.J., 2001. Runoff-induced sediment yield from dune slopes in the Negev Desert, 2: Texture, carbonate and organic matter. *Earth Surface Processes and Landforms* 26, 583-599. <https://doi.org/10.1002/esp.194>
- Kidron, G.J., 2007. Millimeter-scale microrelief affecting runoff yield over microbiotic crust in the Negev Desert. *Catena* 70, 266-273. <https://doi.org/10.1016/j.catena.2006.08.010>

- Kidron G.J., 2011. Runoff generation and sediment yield on homogeneous dune slopes: Scale effect and implications for analysis. *Earth Surface Processes and Landforms* 36, 1809-1824. <https://doi.org/10.1002/esp.2203>
- Kidron, G.J., 2021. Comparing overland flow processes between semiarid and humid regions: Does saturation overland flow take place in semiarid regions? *Journal of Hydrology* 593, 125624. <https://doi.org/10.1016/j.jhydrol.2020.125624>
- Kidron, G.J., 2024. Is non-rainfall water a likely water source for arid and semiarid biocrusts? A critical perspective. *Ecohydrology* 17, e2647. <https://doi.org/10.1002/eco.2647>
- Kidron, G.J., Büdel, B., 2014. Contrasting hydrological response of coastal and desert biocrusts. *Hydrological Processes* 28, 361-371. <https://doi.org/10.1002/hyp.9587>
- Kidron G.J., Starinsky, A., 2012. Chemical composition of dew and rain in an extreme desert (Negev): Cobbles serve as sink for nutrients. *Journal of Hydrology* 420-421, 284-291. <https://doi.org/10.1016/j.jhydrol.2011.12.014>
- Kidron, G.J., Yair, A., 1997. Rainfall-runoff relationships over encrusted dune surfaces, Nizzana, Western Negev, Israel. *Earth Surface Processes and Landforms* 22, 1169-1184. <https://doi.org/10.1002/esp.1532>
- Kidron, G.J., Yaalon, D.H., Vonshak, A., 1999. Two causes for runoff initiation on microbiotic crusts: hydrophobicity and pore clogging. *Soil Science* 164, 18-27.
- Kidron, G.J., Barzilay, E., Sachs, E., 2000. Microclimate control upon sand microbiotic crust, western Negev Desert, Israel. *Geomorphology* 36, 1-18. [https://doi.org/10.1016/S0169-555x\(00\)00043-x](https://doi.org/10.1016/S0169-555x(00)00043-x)
- Kidron, G.J., Hernstadt, I., Barzilay, E., 2002. The role of dew as a moisture source for sand microbiotic crusts in the Negev Desert, Israel. *Journal of Arid Environments* 52, 517-533. <https://doi.org/10.1016/j.jare.2002.1014>
- Kidron, G.J., Vonshak, A., Abielovich, A., 2009. Microbiotic crusts as biomarkers for surface stability and wetness duration in the Negev Desert. *Earth Surface Processes and Landforms* 34, 1594-1604. <https://doi.org/10.1002/esp.1843>
- Kidron, G.J., Wang, Y., Herzberg, M., 2020. Exopolysaccharides may increase biocrust rigidity and induce runoff generation. *Journal of Hydrology* 588, 125081. <https://doi.org/10.1016/j.jhydrol.2020.125081>
- Kidron, G.J., Kronenfeld, R., Beysens, D., 2026. Dew and distillation are fundamentally distinct mechanisms: A critical viewpoint. *Agricultural and Forest Meteorology* 387, 111263. <https://doi.org/10.1016/j.agrformet.2026.111263>
- Kidron, G.J., Yair, A., Vonshak, A., Abielovich, A., 2003. Microbiotic crust control of runoff generation on sand dunes in the Negev Desert. *Water Resources Research* 39, 1108. <https://doi.org/10.1029/2002WR001561>
- Kidron, G.J., Vonshak, A., Dor, I., Barinova, S., Abielovich, A., 2010. Properties and spatial distribution of microbiotic crusts in the Negev Desert. *Catena* 82, 92-101. <https://doi.org/10.1016/j.catena.2010.05.006>
- Kidron, G.J., Kronenfeld, R., Xiao, B., Starinsky, A., 2022. Wet-dry cycles on sandy and loessial Negev soils: Implications for biocrust establishment and growth? *Ecohydrology* 15, e2379. <https://doi.org/10.1002/eco.2379>
- Kidron, G.J., Kronenfeld, R., Xiao, B., Starinsky, A., McKay, C.P., Or, D., 2024. Vapor flux induced by temperature gradient is responsible for providing liquid water to hypoliths. *Scientific Reports* 14, 23140. <https://doi.org/10.1038/s41598-024-73555-w>
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15, 259-263.
- Kutiel, H., Sharon, D., 1980. Diurnal variation of rainfall in Israel. *Archives for Meteorology, Geophysics, and Bioclimatology. Ser A* 29, 387-395.
- Lange, O.L., Kidron, G.J., Büdel, B., Meyer, A., Killian, E., Abielovich, A. (1992). Taxonomic composition and photosynthetic characteristics of the "biological soil crusts" covering sand dunes in the Western Negev Desert. *Functional Ecology* 6, 519-527. <https://doi.org/10.2307/2390048>
- Lavee, H., Poesen, J., 1991. Overland flow generation and continuity on stone-covered soil surfaces. *Hydrological Processes* 5, 345-360. <https://doi.org/10.1002/hyp.3360050403>
- Lázaro, R., Calvo-Cases, A., Lázaro, A., Molina, I., 2015. Effective run-off flow length over biological soil crusts on silty loam soils in drylands. *Hydrological Processes* 29, 2534-2544. <https://doi.org/10.1002/hyp.10345>
- Lichner, L., Hallett, P.D., Orfánus, T., Czachor, H., Rajkai, K., Šir, M., Tesář, M., 2010. Vegetation impact on the hydrology of an Aeolian sandy soil in a continental climate. *Ecohydrology* 3, 413-420. <https://doi.org/10.1002/eco.153>
- Lu, S., Ren, T., Yu, Z., Horon, R., 2011. A method to estimate the water vapour enhancement factor in soil, *European Journal of Soil Science* 62, 498-504. <https://doi.org/10.1111/j.1365-2389.2011.01359.x>
- Malam-Issa, O., Défarge, C., Trichet, J., Valentin, C., Rajot, J.L., 2009. Microbiotic soil crusts in the Sahel of western Niger and their influence on soil porosity and water dynamics. *Catena* 77, 48-55. <https://doi.org/10.1016/j.catena.2008.12.013>
- Mazor, G., Kidron, G.J., Vonshak, A., Abielovich, A., 1996. The role of cyanobacterial exopolysaccharides in structuring desert microbial crusts. *FEMS Microbiology Ecology* 21, 121-130. <https://doi.org/10.1111/j.1574-6941.1996.tb00339.x>
- Monteith, J.L., 1957. Dew. *Quarterly Journal of the Royal Meteorological Society* 83, 322-341. <https://doi.org/10.1002/qj.49708335706>
- Nachshon, U., 2016. Seepage weathering impacts on erosivity of arid stream banks: A new conceptual model. *Geomorphology* 261, 212-221. <https://doi.org/10.1016/j.geomorph.2016.03.011>
- Noy-Meir, I., 1973. Desert ecosystems: Environment and producers. *Annual Review of Ecology, Evolution, and Systematics* 5, 25-51.
- Or, D., Smets, B.F., Wraith, J.M., Dechesne, A., Friedman, S.P., 2007. Physical constraints affecting bacterial habitats and activity in unsaturated porous media – a review. *Advances in Water Resources* 30, 1505-1527. <https://doi.org/10.2136/vzj2006.0080>
- Pathiraja, S., Westra, S., Sharma, A., 2012. Why continuous simulation? The role of antecedent moisture in design flood estimation. *Water Resources Research* 48, W06534. <https://doi.org/10.1029/2011WR010997>
- Philip, J.R., De Vries, D.A., 1957. Moisture movement in porous materials under temperature gradients. *Transaction of the American Geophysical Union* 38, 222-232. <https://doi.org/10.1029/TR038i002p00222>
- Poesen, J., Ingelmo-Sanchez, F., Múcher, H., 1990. The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. *Earth Surface Processes and Landforms* 15, 653-671. <https://doi.org/10.1002/esp.3290150707>
- Redmile-Gordon, M., Gregory, A.S., White, R.P., Watts, C.W., 2020. Soil organic carbon, extracellular polymeric substances (EPS), and soil structural stability as affected by

- previous and current land-use. *Geoderma* 363, 114143. <https://doi.org/10.1016/j.geoderma.2019.114143>
- Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Lázaro, R., Escudero, A., 2013. Soil loss and runoff in semiarid ecosystems: A complex interaction between biological soil crusts, micro-topography, and hydrological drivers. *Ecosystems* 16, 529-546. <https://doi.org/10.1007/s10021-012-9626-z>
- Rose, C.W., 1968a. Water transport in soil with daily temperature wave. I. Theory and experiment. *Australian Journal of Soil Research* 6, 31-44.
- Rose, C.W., 1968b. Water transport in soil with daily temperature wave. II. Analysis. *Australian Journal of Soil Research* 6, 45-57.
- Rosin, T., Marra, F., Morin, E., 2024. Exploring patterns in precipitation intensity-duration-area-frequency relationships using weather radar data. *Hydrology and Earth System Sciences* 28, 3549-3566. <https://doi.org/10.5194/hess-28-3540-2024>
- Roskin, J., Porat, N., Tsoar, H., Blumberg, D.G., Zander, A.M., 2011. Age, origin and climatic controls on vegetated linear dunes in the northwestern Negev Desert (Israel). *Quaternary Science Reviews* 30, 1649-1674. <https://doi.org/10.1016/j.quascirev.2011.03.010>
- Rossi, F., Potrafka, R.M., Garcia-Pichel, F., De Philippis, R., 2012. The role of exopolysaccharides in enhancing hydraulic conductivity of biological soil crusts. *Soil Biology and Biochemistry* 46, 33-40. <https://doi.org/10.1016/j.soilbio.2011.10.016>
- Schwartz, U., Greenbaum, N., 2008. Extremely high sediment yield from a small arid catchment — Giv'at Hayil, northwestern Negev, Israel. *Israel Journal of Earth Sciences* 57, 167-175.
- Stavi, I., Rachmilevitch, S., Yizhaq, H., 2019. Geodiversity effects on soil quality and geo-ecosystem functioning in drylands. *Catena* 176-372-380. <https://doi.org/10.1016/j.catena.2019.01.037>
- Tadmor, N.H., Shanan, L., 1969. Runoff inducement in an arid region by removed vegetation. *Soil Science Society American Journal* 33, 790-794. <https://doi.org/10.2136/sssaj1969.03615995003300050045x>
- Tůmová, M., Jílková, V., Macek, P., Devetter, M., 2024. Tardigrade distribution in soils of high Arctic habitats. *Ecology and Evolution* 14, e11386. <https://doi.org/10.1002/ece3.11386>
- Williams, J.D., Dobrowolski, J.P., West, N.E., 1995. Microphytic crust influence on interill erosion and infiltration capacity. *Transactions of the American Society of Agricultural Engineers* 38, 139-146. <https://doi.org/10.13031/2013.27822>
- Wu, Y., Hasi, E., Wu, X., 2012. Characteristics of surface runoff in a sandy area in southern Mu Us sandy land. *Chinese Science Bulletin* 57, 270-275. <https://doi.org/10.1007/s11434-011-4728-0>
- Xiao, B., Sun, F., Hu, K., Kidron, G.J., 2019a. Biocrusts reduce surface soil infiltrability and impede soil water infiltration under tension and ponding conditions in dryland ecosystem. *Journal of Hydrology* 568, 792-802. <https://doi.org/10.1016/j.jhydrol.2018.11.51>
- Xiao, B., Sun, F., Yao, X., Hu, K., Kidron, G.J., 2019b. Seasonal variations in infiltrability of moss-dominated biocrusts on aeolian sand and loess soil in the Chinese Loess Plateau. *Hydrological Processes* 33, 2449-2463. <https://doi.org/10.1002/hyp.13484>
- Yu, X., Xiao, B., Cao, Y., Kidron, G.J., 2024. Microbial-induced extracellular polymers are fundamentally responsible for the mechanical stability of biocrusts in drylands. *Catena* 245, 108349. <https://doi.org/10.1016/j.catena.2024.108349>
- Zeng Y., Wan L., Su Z, Saito H., Huang, K., Wang. X., 2009. Diurnal soil water dynamics in the shallow vadose zone (field site of China University of Geoscience, China). *Environmental Geology* 58, 11-23. <https://doi.org/10.1007/s00254-008-1485-8>
- Zhang, X., Liu, Z., Han, Y., 2024. Progress towards the identification and improvement of dispersive soils: A review. *European Journal of Soil Science* 75, e70002. <https://doi.org/10.1111/ejss.70002>
- Zipser, E., Liu, C., Cecil, D., Nesbitt, S., Yorty, D., 2006. Where are the most intense thunderstorms on Earth? *Bulletin of the American Meteorological Society* 87, 1057-1071. <https://doi.org/10.1175/BAMS-87-8-1057>

Received 15 May 2026
Accepted 7 July 2026