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THE EFFECT OF CLIMATE ON OVERLAND FLOW: LABORATORY RAINFALL SIMULATION EXPERIMENTS

El efecto del clima en la escorrentía superficial: experimentos con lluvia simulada en laboratorio

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Abstract: Eight sites were selected in Israel —from the Dead Sea (100 mm) to the Galilee Mountains (900 mm)— for the study of the effect of climate on overland flow generation. Time to ponding, to overland flow generation, and to overland flow contribution as well as soil moisture, percolation and overland flow yield were recorded for each site at three plots were soil was placed. The results show a clear influence of climate on overland flow. The response to rain was quick, and overland flow coefficient was high in the arid sites (< 400 mm y^{-1}). In contrast, ponding and overland flow either failed to occur or were very delayed and overland flow coefficients were very low in the experiments with soils from the humid sites (> 500 mm y^{-1}).

Key Words: *Climate, Overland flow, Ponding, Laboratory simulated rainfall.*

Resumen: Ocho zonas de estudio se seleccionaron en Israel desde el Desierto de Judea (100 mm) hasta las montañas de Galilea (900 mm), para estudiar el efecto del clima sobre la generación y producción de escorrentía superficial. Los suelos de cada una de las zonas fueron trasladados al laboratorio, donde se realizaron los experimentos con lluvia simulada. Se estimó visualmente en cada una de las tres parcelas el tiempo de encharcamiento, de escorrentía superficial, y salida de la escorrentía de la parcela. Y se midió la humedad del suelo, la percolación y la tasa de escorrentía.

Los resultados muestran claras influencias del clima sobre el caudal de la escorrentía. El encharcamiento y la escorrentía se producen rápidamente, y los coeficientes de escorrentía son muy altos en las zonas áridas (< 400 mm $año^{-1}$). Por el contrario, el encharcamiento y la escorrentía, o bien no se producen o bien se producen muy tarde en las zonas húmedas (> 500 mm $año^{-1}$), donde los coeficientes de escorrentía fueron muy bajos.

En general, a mayor precipitación media anual menor es la producción de escorrentía. El tiempo y el lugar en el que se produce el encharcamiento en la parcela, la escorrentía y la distribución de las superficies saturadas sugiere que la escorrentía Hortoniana sólo se produce en las zonas áridas, mientras que la escorrentía saturada y el flujo subsuperficial son los procesos más destacables en las zonas húmedas, incluso a escala métrica.

Palabras Clave: *Clima, Escorrentía superficial, Encharcamiento, Lluvia Simulada en Laboratorio.*

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1. Introduction

The influence of climate on ecosystems structure and behaviour is well known, especially regarding changes in flora and fauna (Brown & Gibson, 1983). The influence of climate on the geomorphological processes has been widely studied (Gregory & Walling, 1973; Embleton & Thornes, 1979) in order to understand the relationships between climate conditions and runoff generation and yield. In this framework field rainfall simulation experiments and measurements under natural rainfall have been widely used (for example, Lavee *et al.*, 1991; Boix *et al.*, 1995; Cerdà, 1998; Imeson *et al.*, 1998). However, such relationships were not investigated in detail under laboratory rainfall simulations.

Differences in climate result in different vegetation species and cover, different pedologic processes and soil types, and thus different geomorphological dynamics (Schumm, 1971). In arid and semiarid environments overland flow is generated quickly, and erosion rates are relatively high (Langbein & Schumm, 1958; Thornes, 1976; Yair *et al.*, 1980; Yair & Lavee, 1981; Imeson *et al.*, 1998). While in humid environments the phenomenon of overland flow is almost negligible and when generated it is mainly due to soil saturation (Amerman, 1965; Whipkey, 1965; Ragan, 1968; Betson & Marius, 1969; Dunne & Black, 1970; Freeze, 1972), in the arid environments overland flow is generated mainly due to rainfall excess over infiltration (Horton overland flow, Horton, 1933; Sala, 1984).

Regarding the spatial distribution of overland flow, the «partial area contribution» model was developed in humid zones (Ragan, 1968; Dunne & Black, 1970; Dunne *et al.*, 1975), which shows that overland flow generation is limited to saturated parts of the hillslope, mainly the lower section of the hillslope. A dynamic approach of this model is expressed in the «variable source area» model (Hewlett & Hibbert, 1967; Hewlett & Nutter, 1970). A similar phenomena, discontinuity of overland flow at the hillslope scale was found in arid zones too, due mainly to the typical very short rainshowers (Yair & Lavee, 1982; Sala, 1984; Lavee & Yair, 1990).

The objective of this research was to study the effect of climate on overland flow generation and contribution in the laboratory where controlled rainfall conditions can be established and the hydrological response can be accurately measured. A better understanding of the soil hydrological response to different climatic conditions may improve our capability to forecast the effects of the expected global climate change on the hydro-geomorphological processes.

2. The study sites

Eight study sites were selected in Israel along an altitudinal/climatological transect running from the Galilee Mountains to the Dead sea (figure 1). The range of height of the sites is between 1120 m above sea level at the Meron site in the Galilee Mountains and 70 m below sea level at Kalia site, near the Dead Sea. The main eco-geomorphological characteristics of the eight sites are presented in table 1. While the parent rock, limestone, and hillslope aspect are similar for all sites, they differ from each other in terms of the climatic conditions, soil type and vegetation characteristics. The differences in the soil type and floristic composition are the result of the long term effect of climate.

The dominant features at the arid sites (< 400 mm y^{-1}) of the Judean desert (KAL, MIS and MAL) are the low vegetation cover and the relatively high cover of physico-chemical and biological crusts, and rock fragments. Lichens and cyanobacteria are the main components of the biologic crust. *Poa bolbosa* exists over relatively large areas in the semi-arid site (MAL). The humid sites (> 500 mm y^{-1}) located in the Jerusalem, Carmel and Galilee Mountains (GIV, CAR, ZAL, AMI and MER) are characterised by a higher vegetation cover, lower rock fragment cover and a negligible amount of biologic crust. At all these sites the vegetation cover is over 70 % and is distributed spatially mainly as a patched mosaic pattern of shrubs and trees. The areas between the patches are dominated by dwarf shrubs and herbs.

The floristic composition in the arid sites is dominated by desert species such as *Sarcopoterium spinosum, Salsola vermiculata, Anabasis articulata, Anagalis arvensis, Halogetan alopecuraides, Zigophyllum dumosum, Plantago ovata* and *Reaumuria hirtella*, whereas in the humid sites, the trees are mainly *Ceratonia siliqua* and *Quercus calliprinus*, and the shrubs *Pistacia lentiscus, Rhamnus palaestinus* and *Calycotome viliosa*. In

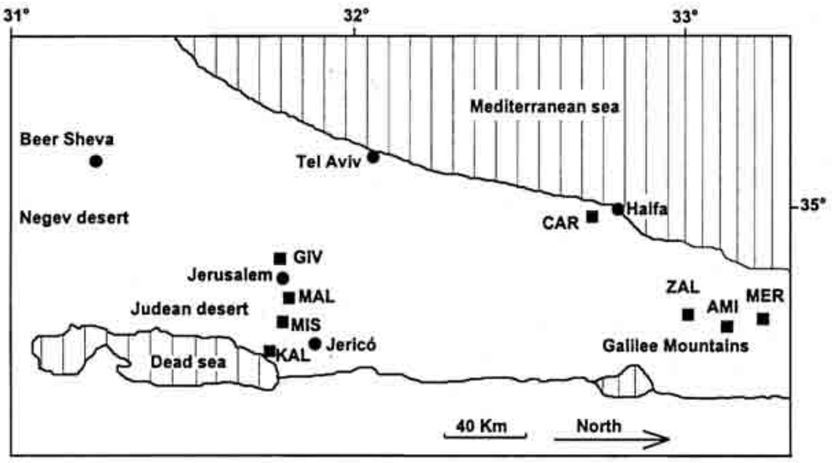

Figure 1. Location map of the eight study sites. Kalia (KAL), Mishor Adumin (MIS) and Ma'ale Adumin (MAL) in the Judean desert. Giv'at Ye'arim (GIV) in the Jerusalem Mountains, Carmel (CAR) in the Carmel Mountain and Zalmon (ZAL), Amirim (AMI) and Meron (MER) in the Galilee Mountains.
Localización de las ocho zonas de estudio. Kalia (KAL), Mishor Adumin (MIS) y Ma'ale Adumin (MAL) en el Desierto de Judea. Giv'at Ye'arim (GIV) en las Montañas de Jerusalén, Carmel (CAR) en las Montañas de Carmel in the Carmel y Zalmon (ZAL), Amirim (AMI) y Meron (MER) en las Montañas de Galilea.

Table 1. The study sites characteristics.
Características de las zonas de estudio.

Study area	*Elevation (a.s.l.) (m)*	*Mean annual precipitation (mm)*	*Mean annual temperature(°C)*	*Aspect (Azimuth) (°)*	*Vegetation Cover (%)*
Kalia	-70	120	23	165	10
Mishor Adumin	230	260	20	140	15
Ma'ale Adumin	330	330	19	145	50
Carmel	115	550	21	205	70
Giv'at Ye'arim	650	620	17	145	80
Zalmon	270	650	19	200	75
Amirim	590	750	17	195	80
Meron	1120	900	15	205	90

the open spaces dwarf shrubs, perennial herbs and annuals like *Sarcopoterium spinosum*, *Phillyrea latifolia*, *Mendicago sp.*, *Plantago sp.*, and *Brachypodium distachyon* exist (Lavee, 1994).

The soils change from a lithic Xerochrept in the relatively wet sites, where they were developed in bedrock pockets, to a lithic Xerothent in the arid sites, where the soil depth is 10-20 cm. The soil structure is characterized by a better aggregation (both size and stability) in the wetter sites due to the high amount of organic matter and clay content. The soluble salts content is higher in the arid sites (Lavee, 1994).

3. Methods

Soil from the topsoil layer (0-4 cm) of each of the above described eight sites was taken during one week in November 1993 to the laboratory, where rainfall simulation experiments were performed at the same week with the Morin rainfall simulator (Morin *et al.*, 1967). This apparatus produces rainfall with a realistic kinetic energy and drop-size distribution over an area of 1.5 m^2 (figure 2a). Three plots of 0.48 m^2 each, surrounded by a buffer area, were exposed to the simulated rain. The slope angle was 10°. The layout of the plots and the soil stratification within the plots is shown in figure 2b and 2c, respectively. The spatial distribution and intensity of the rain at the plots were measured, using 45 raingauges, 15 at each plot. According to these measurements the rain intensity used was 33.5 mm h^{-1} on average. The average intensity at each plot was 29.1 mm h^{-1} at plot 1, 36.5 mm h^{-1} at plot 2 and 34.9 mm h^{-1} at plot 3. Higher intensities were measured at the center of each plot.

An experiment , for each site, was consisted of three «rain events» (runs) under different soil moisture conditions. The first run, on soils having moisture content similar to that they had when taken from the field (table 5), lasts for 60 minutes. The second run started after a break of 60 minutes and lasted for another 60 minutes. The third run, after a break of 30 minutes lasted for 30 minutes. During the experiments time to ponding and time to overland flow generation (i.e. when overland flow appeared somewhere at a plot) as well as time to overland flow contribution (i.e. when overland flow was flowing out of a plot) were measured for each plot.

Figure 2a. View of the Morin rainfall simulator. Photograph by Hanoch Lavee.
Vista del simulador de lluvia de Morin. Fotografía de Hanoch Lavee.

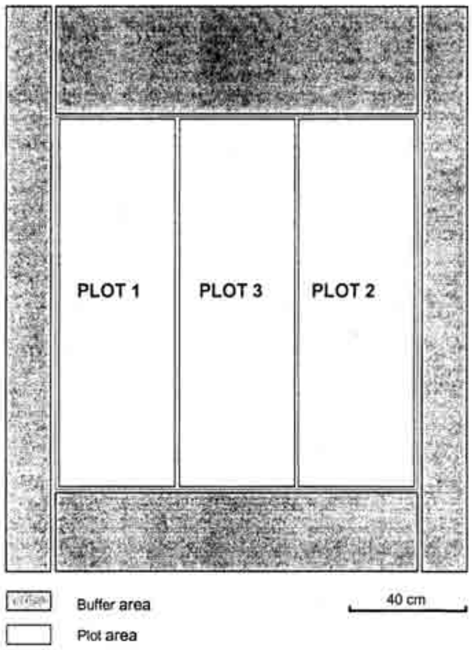

Figure 2b. The layout of the plots under the rainfall simulator.
Disposición de las parcelas bajo el simulador de lluvia.

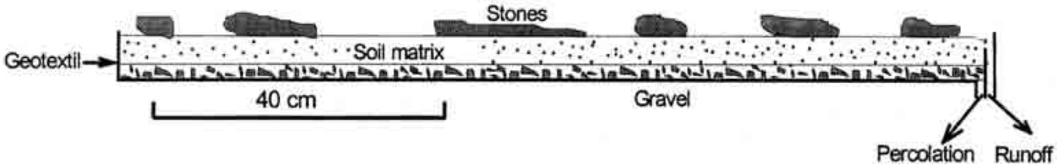

Figure 2c. The soil stratification within the plots. 4 cm of soil covered by rock fragments similar to the natural conditions is lying over a geotextile sheet and 2 cm of gravel.
Estratificación del suelo en las parcelas. 4 cm de suelos cubierto por fragmentos de roca de forma similar a las condiciones naturales descansando sobre un lamina de geotextile y 2 cm de gravas.

Overland flow and percolation rates were measured every three minutes (figure 3) and overland flow yield and runoff coefficients were calculated for each run. After each run one soil sample from the topsoil layer (0-2 cm) was taken from each plot in order to determine the bulk density and the soil moisture content. During the experiments, the location of the ponding and overland flow generation were detected. At the end of the experiment, the saturated areas at each plot were mapped.

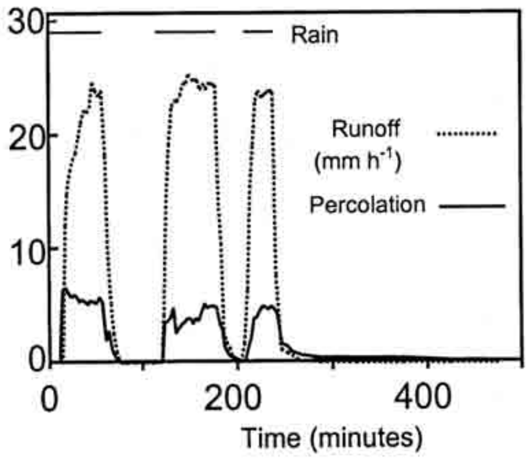

Figure 3. Typical results of the experiments for Kalia. The first run, on relatively dry soil lasted for 60 minutes. The second run began after 60 minutes break and lasted for 60 minutes. The third run, after a break of 30 minutes lasted for 30 minutes. Overland flow and percolation were measured at three minutes intervals.
Resultado típico de los experimentos de Kalia. La primera prueba, sobre suelo relativamente seco duró 60 minutos. La segunda prueba empezó después de 60 minutos y duró otros 60 minutos. La tercera prueba, después de un descanso de 30 minutos, duró 30 minutos. La escorrentía superficial y la percolación se midió a intervalos de 3 minutos.

4. Results

Tables 2, 3, and 4 show the time to ponding, time to overland flow generation and time to overland contribution for the different sites. In table 5 the soil moisture and bulk density dynamics are presented. figure 4 shows the overland flow hydrographs for the wettest and the driest sites respectively, and figure 5 presents the relations-

Table 2. Time to ponding (*Tp*) at each plot and averages, for the different sites.
*Tiempo de encharcamiento (*Tp*) para cada parcela y en valor medio para las diferentes zonas.*

PLOT Tp	*1 (min.)*	*3 (min.)*	*2 (min.)*	*AVERAGE (min.)*
KAL	6.8	5.8	5.9	6.2
MIS	11.2	4.5	9.7	8.5
MAL	15.1	10.1	10.4	11.9
CAR	55.5	38.5	40.5	44.8
GIV	31.0	16.2	19.1	22.1
ZAL	91.0	55.0	170.5	72.2
AMI	195.0	110.0	121.3	142.1
MER	4.1	2.9	2.6	3.20

Table 3. Time to overland flow generation (*Tg*) at each plot and averages, for the different sites.
*Tiempo de generación de escorrentía superficial (*Tg*) para cada parcela y en valor medio para las diferentes zonas.*

PLOT Tg	*1 (min.)*	*3 (min.)*	*2 (min.)*	*AVERAGE (min.)*
KAL	16.7	16.8	15.8	16.4
MIS	23.8	7.8	14.9	15.5
MAL	20.8	23.2	21.1	21.7
CAR	85.1	55.1	50.5	63.3
GIV	57.0	38.3	40.2	45.2
ZAL	146.0	106.0	121.9	124.6
AMI	> 240	129.0	25.5	>164.8
MER	7.5	5.8	4.9	6.1

Table 4. Time to overland flow contribution (*Tc*) at each plot and averages, for the different sites.
*Tiempo de contribución de escorrentía superficial (*Tc*) para cada parcela y en valor medio para las diferentes zonas.*

PLOT Tc	*1 (min.)*	*3 (min.)*	*2 (min.)*	*AVERAGE (min.)*
KAL	19.0	18.0	17.3	18.08
MIS	27.2	14.3	18.0	19.81
MAL	24.2	29.5	22.1	25.3
CAR	104.7	95.8	118.9	106.43
GIV	86.6	77.0	65.9	76.48
ZAL	> 240	> 240	170.9	> 217
AMI	> 240	141.6	133.7	> 172
MER	> 240	> 240	122.7	> 201

Table 5. Soil moisture content and bulk density (averages of three samples) changes during the experiments. A- before the experiment, B- after the first run, C- after the second run, and D- after the third run.
Cambios en la humedad del suelo y en su densidad (media de tres muestras) durante los experimentos. A- antes del experimentos, B- después de la primera prueba, C- después de la segunda prueba, y D- después de la tercera prueba.

Study site	*Run*	*Soil moisture (%)*	*Bulk density ($g\ cm^{-3}$)*
KAL	A	1.83	1.31
	B	30.61	1.38
	C	30.62	1.21
	D	30.77	1.23
MIS	A	1.93	1.10
	B	27.24	1.23
	C	35.96	1.06
	D	36.58	1.03
MAL	A	4.34	1.03
	B	29.78	1.25
	C	26.92	1.15
	D	37.76	1.23
CAR	A	16.14	0.90
	B	49.40	0.91
	C	52.25	1.03
	D	60.47	1.05
GIV	A	7.78	1.02
	B	42.20	1.03
	C	44.17	1.08
	D	44.87	1.14
ZAL	A	20.21	0.87
	B	56.94	0.91
	C	53.79	0.86
	D	59.15	0.90
AMI	A	18.66	0.90
	B	56.21	0.84
	C	53.96	1.03
	D	54.33	1.08
MER	A	14.83	0.65
	B	36.68	0.65
	C	48.23	0.77
	D	45.76	0.80

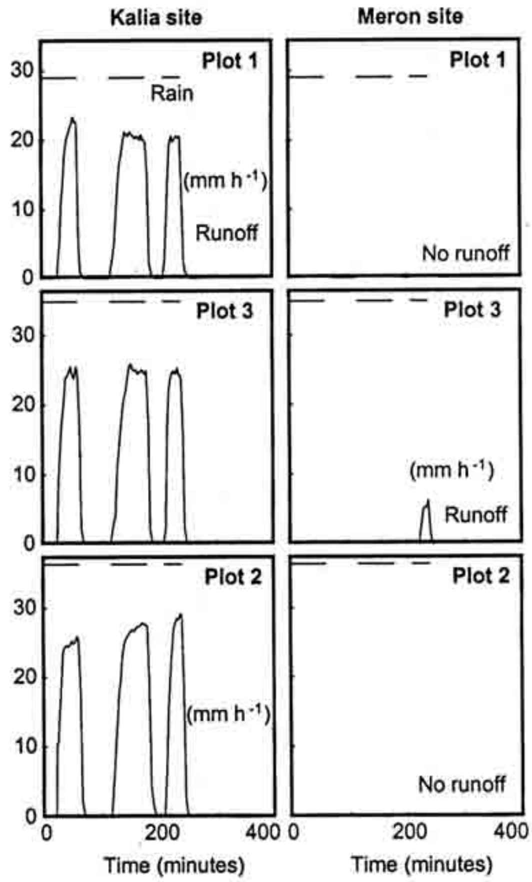

Figure 4. The overland flow response to the simulated rainfall at the driest site, Kalia, compared with that of the wettest site, Meron.
La respuesta de la escorrentía superficial a la lluvia simulada en la zona más árida, Kalia, comparado con la de la zona más húmeda, Meron.

hips between the averages of time to ponding, time to overland flow generation and time to overland flow contribution and the mean annual rainfall. The location of ponding and overland flow generation points and of the saturated areas within the plots are shown in figures 6 and 7. Table 6 and figure 8 present the runoff coefficients at the different plots for the different study sites. In table 7 and figure 9 some indicators of overland flow discontinuity are presented.

Time to ponding, to overland flow generation and to overland flow contribution

At Kalia and Mishor Adumim sites, ponding and overland flow generation were detected shortly after the experiments started: 6.2 and 16.4 minutes for Kalia and 8.5 and 15.5 minutes for Mishor Adumim, respectively, despite the low soil moisture content at the beginning of the experiments (1.83 % and 1.93% on average). At Kalia the soil moisture reached the maximum level of soil moisture

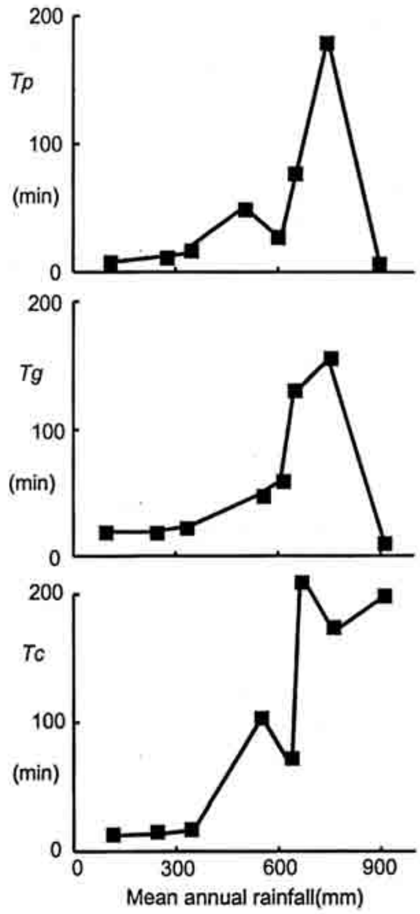

Figure 5. The effect of climate (mean annual rainfall) on the time to ponding (*Tp*), time to overland flow generation (*Tg*) and time to overland flow contribution (*Tc*) (minutes). The values are the averages for the three plots.
El efecto del clima (precipitación media anual) sobre el tiempo de encharcamiento (Tp), *el tiempo de generación de escorrentía superficial* (Tg) *y el tiempo de contribución de la escorrentía superficial* (Tc) *(minutos). Los valores son medias de las tres parcelas.*

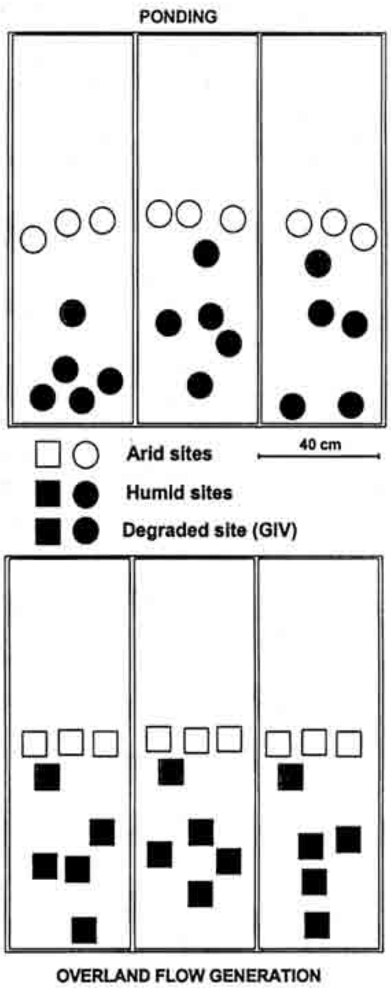

Figure 6. Location of the first ponding and overland flow generation points for the eight study sites.
Localización del punto del primer encharcamiento y de la generación de escorrentía superficial para las ocho zonas de estudio.

content measured during the experiments (30 %) at the end of the first run (table 5). This means that the soil became saturated very quickly. At Ma'ale Adumin site, time to ponding and time to overland flow were a bit longer (11.9 and 21.7 minutes, respectively; tables 2 and 3). In the three arid sites (< 400 mm y^{-1}), the bulk density was relatively high and increased after the first run (table 5). This might be an indication that a mechanical crust have been developed, in these sites, during the first run.

At Giv'at Ye'arim site, time to ponding was 22.1 minutes and time to overland flow was delayed until minute 45.1. Water flow out of the plots started 76.5 minutes after the start of the experiment. A similar response regarding the delay of overland flow generation in relation to ponding and the delay of overland flow contribution in relation to overland flow generation was typical to the Carmel site, too, where time to ponding was 44.5 minutes, time to overland flow generation 63.6 minutes and time to overland

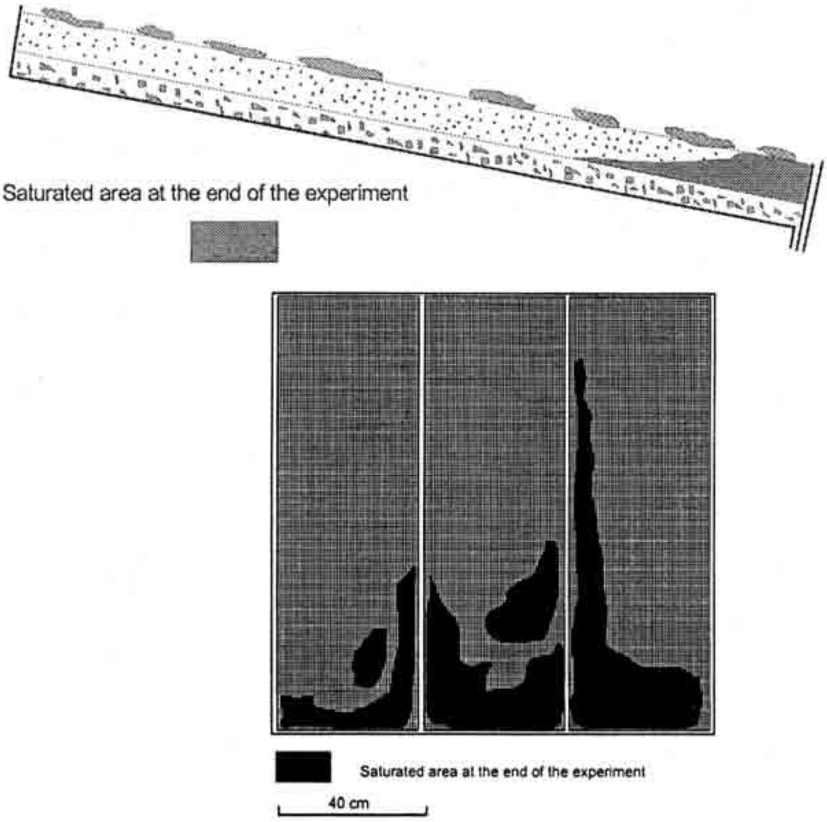

Figure 7. An example from site Amirim of the saturated area after the experiment: a. A cross section; b. Overview.
Un ejemplo de la zona saturada después del experimento (zona de Amirim): perfil y planta.

Table 6. Runoff coefficients for the different sites at each run and in average.
Coeficientes de escorrentía para las diferentes zonas en cada prueba y en valor medio.

Sites	*Runoff coefficient (%)*			
RUN-	*1*	*2*	*3*	*AVERAGE*
KAL	51.5	78.7	80.2	70.1
MIS	42.9	75.8	77.5	65.4
MAL	40.1	64.9	66.6	57.2
CAR	0.0	4.5	13.4	6.0
GIV	0.0	16.2	32.1	16.1
ZAL	0.0	5.8	16.8	7.5
AMI	2.5	5.0	6.0	4.5
MER	0.0	1.4	2.7	1.4

Table 7. Time span (minutes) between time to overland flow generation (Tg) and time to overland flow contribution (Tc), and between time to ponding (Tp) and time to overland flow contribution.
Tiempo de retraso (minutos) entre el tiempo de generación de escorrentía superficial (Tg) y el tiempo de contribución de escorrentía superficial (Tc), y entre el tiempo de encharcamiento (Tp) y el tiempo de contribución de escorrentía superficial.

Study site	*Tc-Tg (minutes)*	*Tc-Tp (minutes)*
KALIA	1.7	11.9
MISHOR ADUMIM	4.3	11.3
MA'ALE ADUMIM	7.9	17.7
CARMEL	42.8	61.6
GIV'AT YE'ARIM	31.3	54.4
ZALMON	92.4	144.8
AMIRIM	7.0	29.7
MERON	194.8	197.7

contribution 106.4 minutes. In Zalmon and Amirim sites the hydrological response was slow. Time to ponding, time to overland flow generation and to overland flow contribution where 72.2 minutes, 124.6 minutes and more than 217 minutes for Zalmon site, and 142.1 minutes, >164.8 minutes and >171.8 minutes for Amirim site, respectively. For Zalmon two plots and for Amirim one plot did not produce any outflow. In the Meron soil there was a quick response regarding ponding (3.2 minutes), and overland flow generation (6.1 minutes) due to the water repellence of the soil which is related to the large amount of undecomposed organic matter in the soil, but there was almost no out flow from the plots due to overland flow discontinuity and high infiltration through preferential paths within the litter.

In conclusion, a rapid hydrological response to rain was found for the arid sites (< 400 mm y^{-1}) while a delayed ponding and overland flow generation and contribution were measured for the humid sites (> 500 mm y^{-1}). With the exception of site Meron, a general trend of decreasing time to ponding and time to overland flow generation was found with increasing aridity. Regarding time to overland flow contribution this trend included the Meron site, too (figure 5). While for the arid sites the bulk density ranged between 1.03 g/cm^3 and 1.38 g/cm^3, for the humid sites the values were lower and ranged between 0.65 g/cm^3 and 1.14 g/cm^3.

4.1 Location of ponding and overland flow generation

Due to the spatial distribution of the simulated rain intensity ponding and overland flow generation have been expected to be found firstly at the central plot and at the center of each plot. Indeed, in the experiments with soils from the arid sites, ponding and overland flow generation always appeared in the central part of the plots (figure 6). However, in the experiments with soils from the more humid sites, ponding and overland flow generation appeared mainly at the lower part of the plots. For the site Giv'at Ye'arim, which is degraded due to human activities (overgrazing, deforestation, overcultivation) that took place till about 40 years ago, the ponding and overland flow generation appeared closer to the center of the plots (figure 6).

At the end of the experiments (more than 75 mm of rain) with the soils from the wet sites the soil at the footplots was saturated (figures 7 and 8) while for the desert soils most of the topsoil layer (0-1 cm) was saturated, but no clear pattern was recognized at the deeper soil layer.

The location of the first ponding and overland flow generation points together with the spatial patterns of the saturated areas lead to the conclusion that in the arid and degraded subhumid areas overland flow was generated by the Horton mechanism, i. e. as a result of rainfall exceeding infiltration, while in the Mediterranean subhumid and humid areas overland flow was generated only when and where the soil was saturated.

4.2 Runoff coefficients

The mean runoff coefficients at each study site for each run and on average are shown in table 6. In Kalia, the driest area, the average runoff coefficient was 70 %, but for the last run, when the soil was saturated, more that 80 % of the rain flowed out of the plots. In Mishor Adumin, runoff coefficients increased from 43 % in the first run to 78 % in the third one. In Ma'ale Adumin, runoff coefficients increased from 40 % in the first run to 67 % in the last one. In Giv'at Ye'arim overland flow did not occur during the relatively dry run. In the wettest run the runoff coefficient reached 32.1% and on average 16 % of the rainfall flowed out of the plots. Fore the site Carmel, too, runoff coefficient was low (6 %) on average, with no overland flow contribu-

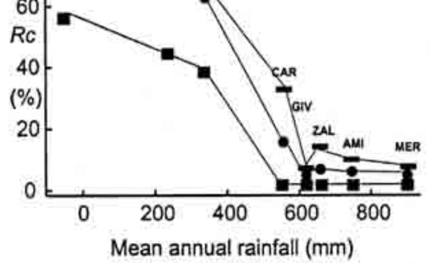

Figure 8. Overland flow coefficients *(Rc, %)* at different climatic conditions. The values are averages for the three plots.
Coeficientes de escorrentía superficial (Rc, %) *bajo las diferentes condiciones climáticas. Los valores son medias de las tres parcelas.*

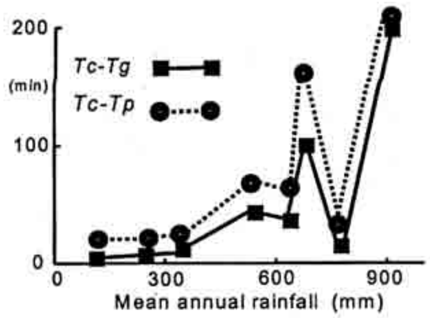

Figure 9. Indicators of overland flow discontinuity for the different sites.
Indicadores de la discontinuidad de la escorrentía superficial para las distintas zonas.

tion during the first run. Similar response was found for the Galilee Mountains: average runoff coefficient was <8% in Zalmon, <5% for Amirim and < 1% for Meron. In Meron, in spite of the facts that ponding and overland flow generation appeared shortly after the experiment started almost all the overland flow reinfiltrated through a preferential macropore flow within the plots. There is a general trend of increasing runoff coefficients with increasing aridity. This trend holds for the dry runs as well as for the wet runs, and also for the average.

5. Discussion and conclusions

Many researchers have shown that runoff, at a basin scale, is directly related to climatic conditions, for example Langbein & Schumm (1958), Fournier (1960), Dendy & Bolton (1976), Schumm (1971) and Douglas (1977). It is well known that water is the controlling factor in semiarid environments (Yair & Lavee, 1985; Cooke *et al.*, 1993; Abrahams & Parsons, 1994). This means that as wetter is the climate there is more potential for the development of a large vegetation cover, an increase in soil aggregate stability, organic matter content and porosity (Lavee *et al.*, 1996). These conditions result in higher infiltration capacity and soil water retention, and thus in a reduction of overland flow yield (Lavee *et al.*, 1991) and sediment discharge (Lavee *et al.*, 1998).

The present study results show a general trend of increasing time to ponding and time to overland flow generation with increasing of the mean annual rainfall. But climate is not the only factor controlling geomorphological processes (Leopold *et al.*, 1964; Schumm, 1971; Morgan, 1986). Some specific soil properties and land use may affect, to a large extent, the hydrological response of the soil. In our case the exceptions from the general trend are sites Meron and Giv'at Ye'arim.

In the wettest site, Meron, the time to ponding and to overland flow generation are relatively very short. This is attributed to the large amount of undecomposed litter at the surface that includes etheric material from *Salvia fruticosa* and resulted in rapid ponding and overland flow generation. This water repellence of the ecto-organic horizon have been also found in other vegetated Mediterranean environments by Sevink (1988), mainly after fire (Sevink *et al.*, 1989; Imeson *et al.*, 1992).

In Giv'at Ye'arim, the time to ponding and to overland flow generation is relatively short due to the degradation history (overgrazing and deforestation which decreased infiltration capacity) of this site. The effect of land use changes, such as grazing, land abandonment and fires on reduction of infiltration rates was found by Cerdà *et al.* (1995), Kutiel *et al.* (1995), Lavee *et al.*, (1991, 1995) and Cerdà (1997a).

The time to overland flow contribution also increased with increasing mean annual rainfall. The hydrophobic characteristics of Meron soil do not affect overland flow contribution as the overland water infiltrated through preferential paths network within the litter and soils macropores. This study confirms the influence of climate on the hydrological behaviour of fluvial systems under controlled laboratory conditions. Similar results were found under field simulated rainfall conditions during the autumn, 1993 (Cerdà, 1998).

The difference between the arid and humid sites is expressed also by the time span between the time to overland flow generation and time to overland flow contribution (*Tc-Tg*) and between time to ponding and time to overland flow contribution (*Tc-Tp*) (Table 7). These two parameters might be used as indicators of overland flow continuity. There is a significant difference, a step like threshold (Figure 8), between the low values of the arid sites and the relatively high values of the humid sites. Exceptions are the degraded Giv'at Ye'arim and Amirim sites. This confirms previous findings

(Lavee *et al.*, 1998) that overland flow is much more continuous in arid areas than in humid areas. While the discontinuity phenomenon showed by Yair & Lavee (1981) and Lavee & Yair (1990) was at the hillslope scale, the present results indicate that overland flow discontinuity in humid areas exists even at the micro-scale of 1.2 m length.

A step-like threshold between the arid and humid sites exists also for the runoff coefficients (Figure 8). The relatively low values of runoff coefficients that characterize the dry conditions experiments (first run) of the arid sites are higher than the highest runoff coefficients values of that characterize the wettest conditions (third run) of the humid sites.

The above mentioned significant differences between the hydrological behaviour of arid and humid areas are explained by the different controlling factors in these two zones. While in the arid sites of the Judean Desert the main controlling factors are a-biotic ones, such as high soluble salts content in the soil, physico-chemical crust at the soil surface, and to some extent biological crusts (mainly cyanobacteria and lichens) (Cerdà & Lavee, 1994; Cerdà & Lavee, 1995), in the more humid sites of the Mediterranean climate areas of Israel, the large vegetation cover, the high soil organic matter content, the litter at the surface and mosses cover are factors that control infiltration, water retention capacity and overland flow generation and continuity (Gallart *et al.*, 1994; M.-Mena, 1995; Lavee *et al.*, 1998).

The results of the present study have shown that arid areas (< 400 mm y^{-1}), the low infiltration capacity of soils due mainly to crust formation causes ponding and overland flow to be generated quickly and to be determined by the rainfall intensity. It also causes subsurface lateral flow to be negligible, and Horton overland flow mechanism to be the dominant hydrological process. Similar behaviour was found in other arid zones such as the badlands (Benito *et al.*, 1993, Cerdà, 1999) and the abandoned agricultural fields in Southeastern Spain (Cerdà, 1997b; Belmonte *et al.*, 1999). However, pedogenic indicators of the cumulative effect of discontinuous subsurface flow at the Judean Desert hillslopes was found by Lavee *et al.*, (1989).

On the other hand, in the humid areas (> 500 mm y^{-1}), the reallocation of the soil moisture is the main controlling mechanism of overland flow generation and continuity. Overland flow was generated mainly at the lower parts of the plots as there the soil was saturated. This confirms the findings of Hewllet & Hibbert (1967), Kirkby (1978), Whipkey (1965) and Dunne & Black (1970) that subsurface flow is an important mechanism in temperate regions and even in Mediterranean environments.

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