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Spatial variability of overland flow in a small arid basin

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Abstract Overland flow generation and continuity along hillslopes in a small arid drainage basin in the northern Negev, Israel, has been assessed on the basis of field measurements. Variables measured included rainfall, overland flow, evaporation, infiltration rates and soil moisture. Data obtained show great spatial and temporal variability among all variables. The most frequent phenomenon encountered was overland flow discontinuity along slopes having lengths ranging from 55 to 76 m. This discontinuity is attributed to the short duration of rain showers and can be enhanced by surface properties (where the infiltration rate increases downslope). A deterministic simulation model for the spatial and temporal variations in overland flow along the hillslopes was developed taking into consideration the spatial and temporal distribution of the variables mentioned above. The model is based upon functions derived from the field measurements and permits the delineation of the hillslope area contributing to channel flow under various rain conditions. Results obtained may explain the use of certain water-harvesting techniques adopted by farmers living in the area some 2000 years ago.

INTRODUCTION

Arid and semi-arid areas are known for the frequent occurrence of Hortonian overland flow (Horton, 1945). Recent studies (Yair *et al.*, 1978, 1980; Lavee, 1982) have shown that overland flow generation is highly non-uniform even within a very small basin extending over 0.02 km^2. These studies drew attention to the phenomenon of flow discontinuity occurring along slopes of lengths 55 to 76 m, and attributed it to pronounced differences in infiltration rates between the upper rocky and the lower soil-covered slope sections.

The possibility however, that overland flow discontinuity can frequently occur over uniform slopes, or even over slopes having a soil-covered upper part and a rocky lower part, has not previously been investigated. Such occurrences may be related to rainfall characteristics rather than to surface properties. If so, overland flow discontinuity along arid hillslopes is not merely a local phenomenon but is in fact general. This has important theoretical and practical applications.

This paper has two main objectives:

(a) to analyse the generality of overland flow discontinuity over arid slopes having different surface properties, and

(b) to apply the phenomenon of flow discontinuity over hillslopes towards an improved understanding of water-harvesting techniques used by the ancient farmers that lived in the region 2000 years ago.

STUDY AREA AND EXPERIMENTAL DESIGN

The experimental site, situated in the northern Negev desert near Sde Boqer, has an area of 0.011 km^2 consisting of the north-facing side of a first order drainage basin (Fig. 1). Slope length varies from 55 to 76 m and slope gradient from 12 to 29.5%.

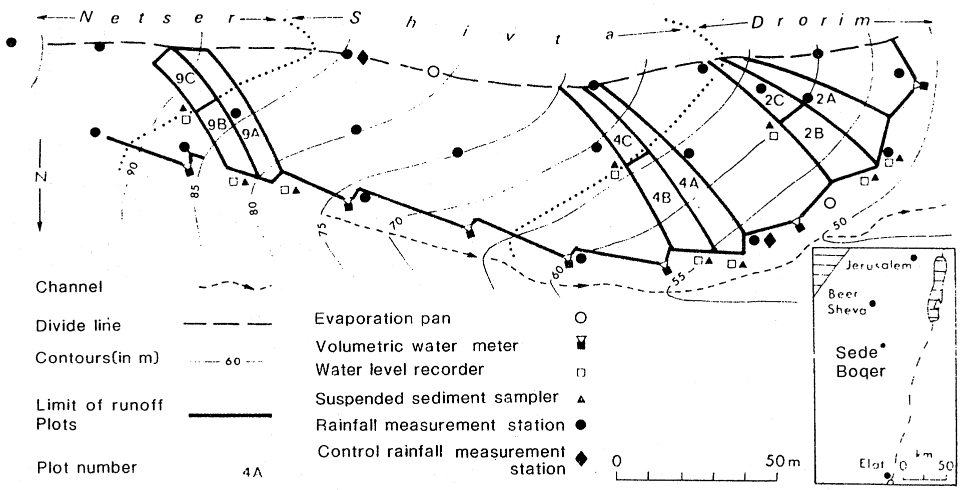

***Fig. 1** Layout of experimental site (elevations are relative).*

Geologically, three limestone formations - Drorim, Shivta, and Netzer - outcrop within this area (Fig. 1). Differences in the structure of the limestone, together with the spatial distribution of soil cover and rock outcrops, have created three different surface units: (a) rocky surfaces devoid of any soil cover; (b) stony soil-covered areas with limited rock outcrops; and (c) intermediate areas with varying rock/soil-cover ratios. Both the Shivta formation and the upper part of the Drorim formation belong to the first surface unit, with narrow and shallow soil-covered strips at the base of rock terraces (Fig. 2). The lower part of the Drorim formation is typical of the second surface unit whereas the Netzer formation forms the third surface unit.

Average annual rainfall in the area is 93 mm. Local rainfall measurements were taken at 21 points (Fig. 1). At each point, twin raingauges were placed 30 cm above the ground; one with a horizontal orifice and the other

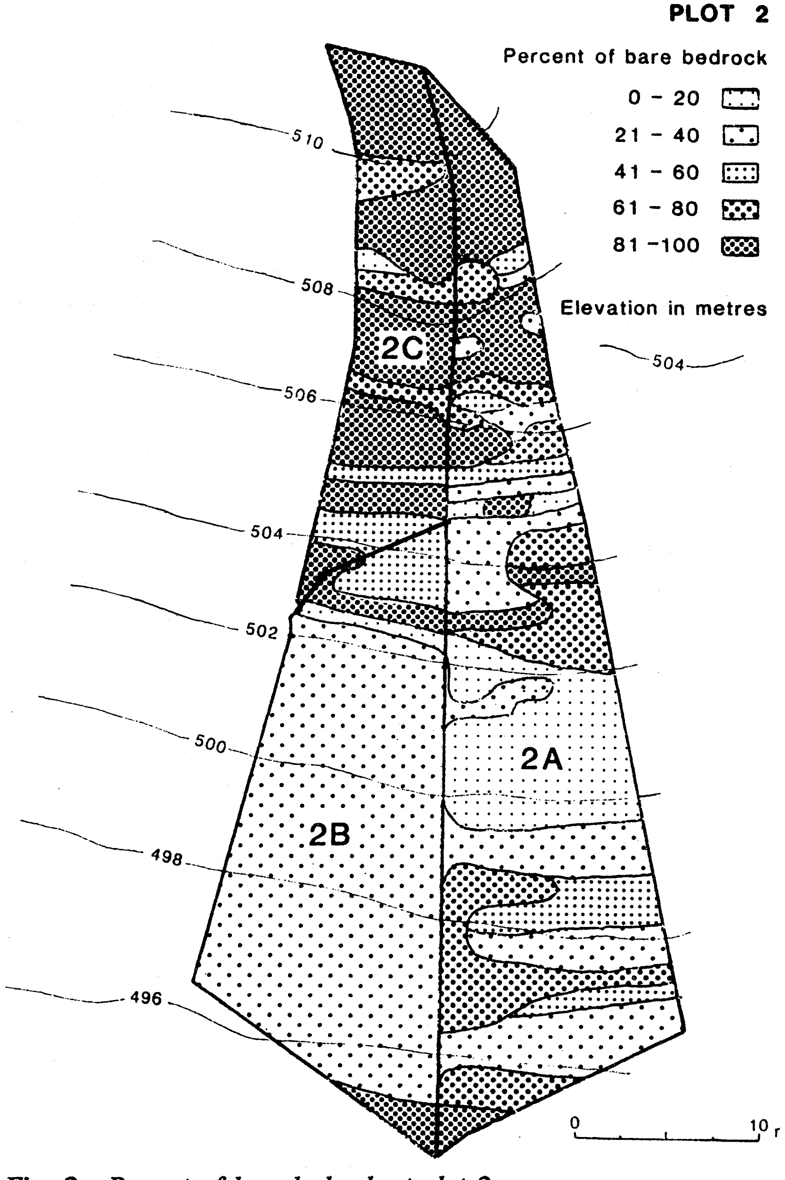

Fig. 2 Percent of bare bedrock at plot 2.

tilted such that its orifice was parallel with the ground. The former measures rainfall in terms of rainfall flux through a horizontal plane and is therefore appropriate for meteorological purposes. The latter, by taking slope inclination and aspect into account, measures the amount of rainfall actually reaching the ground. The second method is suited to hydrometeorological research where rain is an input into the system on the earth's surface (Sharon, 1980). In order to check the relationship between the rain amount at 30 cm and that reaching the ground, raingauges with their orifices at ground level were installed at two control rainfall measurement stations. Rain recorders and evaporation pans installed at these two stations provided information on rain intensity, duration, and on potential evaporation (Fig. 1).

Infiltration rates, representative of the three surface units, have been measured using a rainfall simulator (Morin *et al.*, 1970). Direct measurements of soil moisture within the upper 3 cm of the soil were taken at several points along selected slopes immediately after each rainstorm, and on the first, third, sixth, tenth, etc., days that followed.

Analysis of overland flow generation and continuity was based on three runoff plots, each subdivided into three sub-plots: one long, extending from the divide to the slope base, and two adjoining short ones draining the upper and lower sections of the slope, respectively. Each sub-plot was equipped with a water level recorder (Fig. 1).

RESULTS AND DISCUSSION

Rainfall measurements revealed that:

(a) Rainstorms are composed of series of short showers with most showers lasting less than 30 minutes (Fig. 3) and yielding less than 3 mm (Fig. 4). There are intervals of at least 6 min between showers.

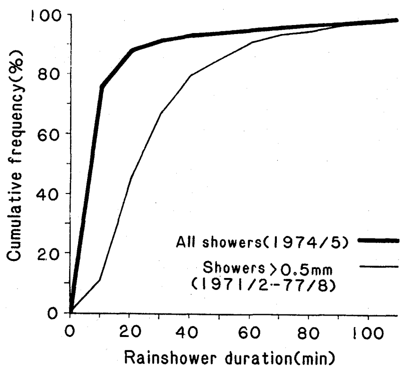

Fig. 3 Rain shower duration frequency.

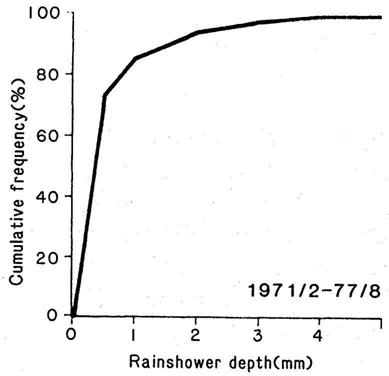

Fig. 4 Rain shower depth frequency.

(b) The spatial distribution of the hydrological rainfall, as measured by the tilted raingauges, differs greatly from the meteorological rainfall distribution, as measured by the horizontal orifice raingauges (Fig. 5). Differences in rainfall at any point varied from 10 to 40%. In measuring hydrological rainfall, differences of 20 to 80% were found to exist over distances of less than 100 m. As rainstorm duration was the same for the study area as a whole, the spatial differences in the rainfall depth represent differences in rainfall intensity.

(c) There is a constant ratio between rainfall depth at 30 cm above the ground and at ground level. This ratio is close to unity, but at the slope base it is slightly lower (1.07) than for the ridge (1.13) where the wind

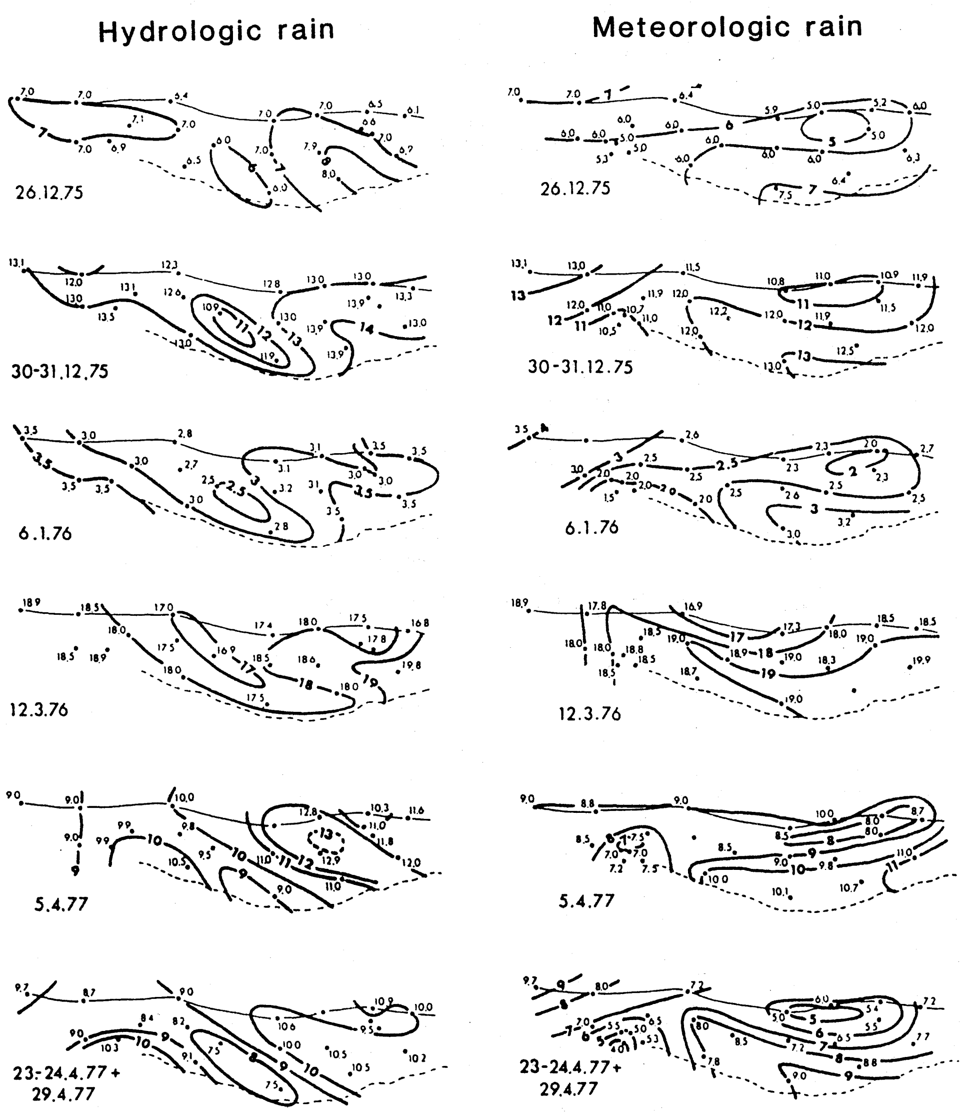

Fig. 5 Spatial distribution of rainfall.

speed gradient near the ground is greater. Between these two points we may assume that this ratio has intermediate values.

Infiltration capacity curves for each surface unit are shown in Fig. 6. An example of the results of evaporation and soil moisture measurements is shown in Fig. 7. The average potential evaporation in the summer is 7 mm day^{-1} and in winter it is 3 mm day^{-1}. Immediately after each rainstorm there is a sharp increase in soil moisture followed by a decline due to soil moisture losses. As evaporation during the short rainstorms is negligible, soil moisture losses from the upper 3 cm of the soil during these periods can be attributed to soil drainage. The soil moisture decay curves were used for the computation of soil moisture losses during the storm as a function of soil water content (Fig. 8). Soil moisture losses equal zero when soil water content is equal to zero, and soil moisture will not exceed a maximum value which represents field capacity (Lavee, 1982).

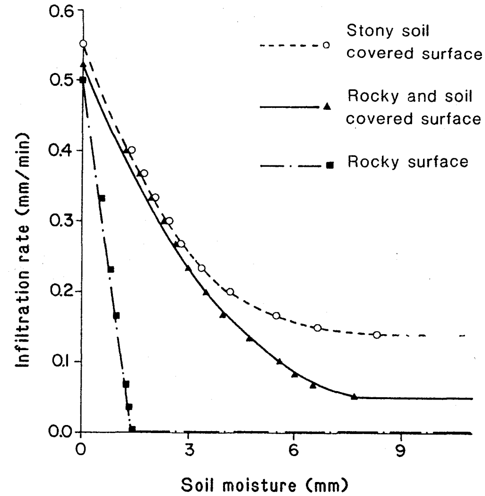

Fig. 6 Infiltration rates on different surface units.

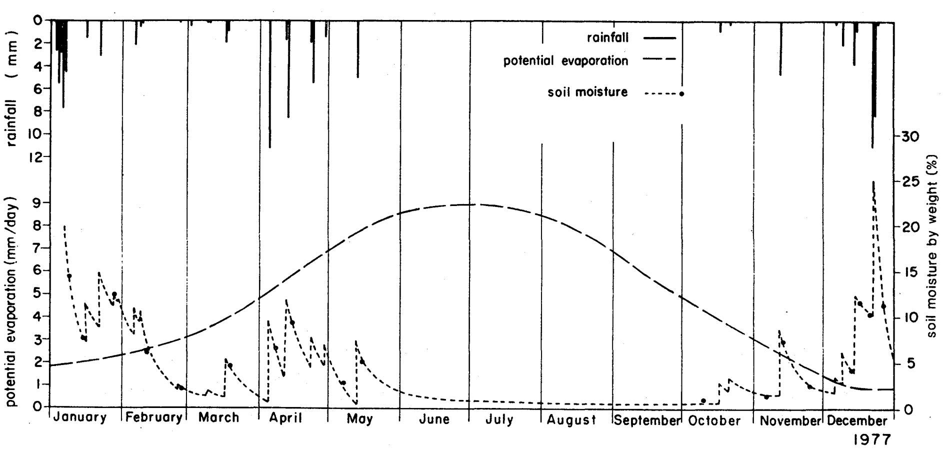

Fig. 7 Temporal variations of rainfall, evaporation and soil moisture.

Runoff response to rainfall is very quick (Fig. 9) and indicates that Hortonian overland flow occurs frequently in the study area. Overland flow data analysis (Table 1) shows that:

(a) Overland flow generation is spatially non-uniform due to pronounced differences in infiltration rates. Figure 10 for example, illustrates that the specific overland flow yield from plot 4C, which drains a rocky surface, is always greater than that of plot 4B, which drains a stony soil surface.

(b) The specific overland flow yield from the plots draining the whole slope (A) is lower than from the two adjacent short plots (B + C) combined (Fig. 11). This indicates significant infiltration within the hillslope before reaching the channel (Yair *et al.*, 1980). These results were obtained not only in plot 4, where infiltration losses increase downslope on passing from the rocky to the colluvial slope section (Fig. 11(a)), but also in plot 9 where the rocky section forms the lower part of the slope (Fig. 11(b)).

We may conclude, therefore, that overland flow discontinuity can be explained in terms of rainfall characteristics and the possible compounding effect of surface properties. Due to the short duration of rain showers, the infiltration rate at the end of the shower does not reach the minimum infiltration rate and

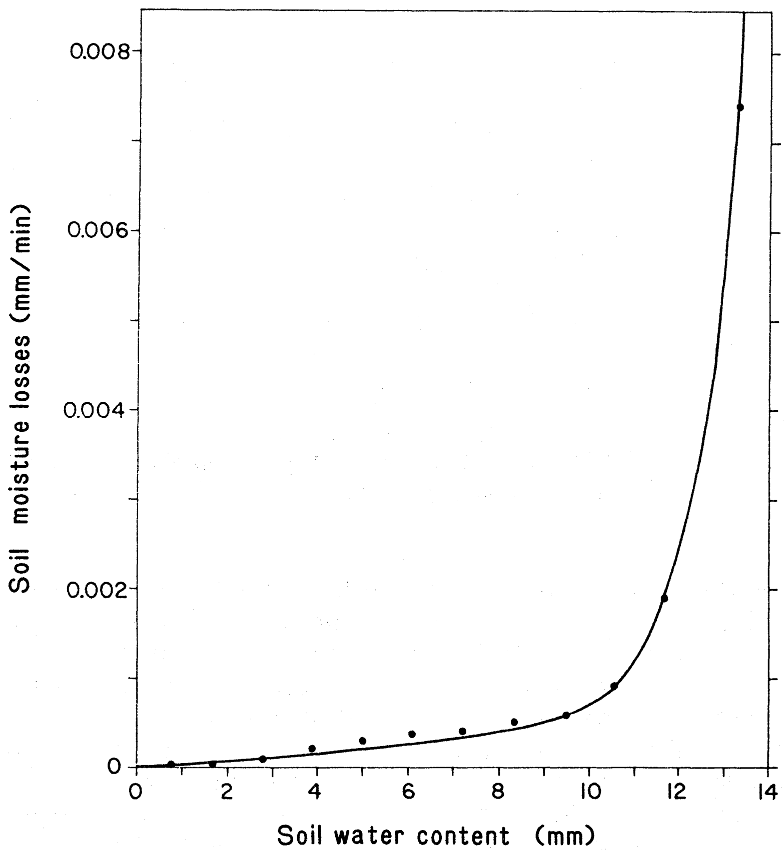

Fig. 8 Soil moisture losses rate.

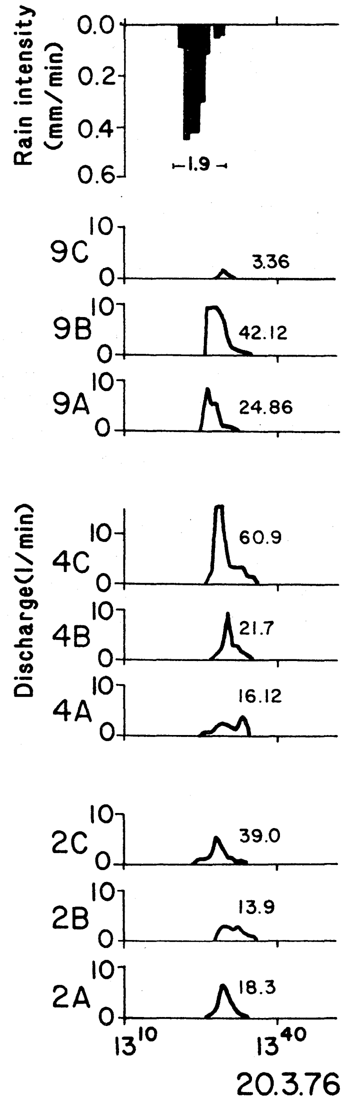

Fig. 9 Overland flow response to rainfall, 20 March 1976 (figures indicate runoff yield in l).

remains relatively high. Under such conditions the recession time is short, lasting 3 to 10 min. The combination of short rain showers, short recession time, and low flow velocities (1–3 m min^{-1}) cause the total duration of the flow to be shorter than the concentration time. In other words, the overland flow contributing area is limited to a belt close to the channel. The length of this belt can be expected to increase with rain shower duration and intensity. In a few instances plot 9A yielded more overland flow than plots 9B and 9C combined. This occurred when rain amount and intensity over plot 9A were greater than over plot 9B and 9C (Lavee, 1982).

*Table 1 Specific overland flow yield ($l\ m^{-1}$); * indicates no data*

DATE	4A.	4B	4C	4B+4C	9A.	9B	9C	9B+9C	DATE	4A.	4B	4C	4B+4C	9A.	9B	9C	9B+9C
11.11.75	*	0.020	0.799	0.098	0.209	*	0.000	*	24.04.77	0.000	0.000	0.016	0.006	0.000	0.025	0.000	0.015
26.12.75	0.506	*	*	*	0.589	0.789	0.554	0.691	24.04.77	0.000	0.000	0.023	0.009	0.000	0.033	0.000	0.019
26.12.75	0.013	0.000	*	*	0.051	0.075	0.030	0.056	13.05.77	0.812	0.739	1.292	0.948	0.680	1.045	1.168	1.097
26.12.75	0.000	0.000	*	*	0.024	0.025	0.032	0.028	12.11.77	0.008	0.000	0.295	0.109	0.099	0.215	0.085	0.162
30.12.75	0.000	0.000	*	*	0.032	0.071	0.000	0.041	12.11.77	0.000	0.000	0.203	0.075	0.047	0.100	0.000	0.058
30.12.75	0.000	0.000	*	*	0.000	0.000	0.000	0.000	09.12.77	0.000	0.000	0.116	0.043	0.021	0.077	0.000	0.045
30.12.75	0.171	0.179	*	*	0.193	0.254	0.363	0.300	14.12.77	0.034	0.093	0.315	0.177	0.154	0.286	0.116	0.215
30.12.75	0.000	0.000	*	*	0.011	0.019	0.000	0.011	14.12.77	0.000	0.000	0.105	0.039	0.047	0.154	0.034	0.104
31.12.75	0.000	0.000	*	*	0.011	0.023	0.000	0.013	22.12.77	0.863	1.517	1.706	1.595	1.265	1.240	1.234	1.240
06.01.76	0.000	0.000	0.117	0.043	0.000	0.033	0.000	0.019	22.12.77	0.406	0.600	0.699	0.640	0.710	*	0.448	*
03.02.76	0.000	0.000	0.094	0.035	0.011	0.067	0.000	0.039	22.12.77	0.156	0.309	0.482	0.388	0.529	*	0.160	*
23.02.76	0.000	0.000	0.000	0.000	0.090	0.229	0.000	0.133	22.12.77	0.281	0.407	0.424	0.415	0.411	*	0.338	*
24.02.76	0.000	0.000	0.031	0.011	0.000	0.020	0.000	0.012	23.12.77	0.000	0.070	0.187	0.114	0.064	*	0.086	*
25.02.76	0.000	0.000	0.016	0.006	0.000	0.020	0.000	0.012	23.12.77	0.010	0.087	0.177	0.120	0.024	0.000	0.084	0.035
12.03.76	0.000	0.000	0.126	0.047	0.014	0.094	0.031	0.070	23.12.77	0.000	0.028	0.123	0.063	0.010	0.020	0.000	0.012
12.03.76	0.571	0.460	1.554	0.867	0.604	0.947	0.844	0.904	23.12.77	0.000	0.011	0.213	0.086	0.000	0.000	0.000	0.000
12.03.76	0.195	0.232	0.561	0.355	0.299	0.397	0.274	0.346	23.12.77	0.218	0.264	*	*	0.056	0.000	0.116	0.048
12.03.76	0.000	0.000	0.095	0.035	0.027	0.042	0.000	0.024	23.12.77	0.000	0.000	0.017	0.006	0.000	0.000	0.000	0.000
12.03.76	0.097	0.108	0.424	0.225	0.247	0.344	0.167	0.270	30.03.78	0.015	0.062	0.301	0.151	0.111	0.221	0.054	0.151
12.03.76	0.000	0.000	0.022	0.008	0.012	0.024	0.000	0.014	24.04.78	0.010	0.024	0.220	0.095	0.111	0.160	0.046	0.112
20.03.76	0.027	0.064	0.311	0.156	0.074	0.232	0.026	0.146	15.10.78	0.032	0.052	*	*	0.088	0.187	0.070	0.138
12.04.76	0.000	0.000	0.034	0.012	0.000	0.030	0.000	0.018	12.12.78	0.142	0.243	0.577	0.369	0.156	0.451	0.268	0.375
13.04.76	0.000	0.000	0.021	0.008	0.000	0.061	0.000	0.035	12.12.78	0.953	0.911	1.241	1.038	1.102	0.858	1.401	1.085
18.05.76	0.000	0.000	0.038	0.014	0.000	*	0.031	*	12.12.78	0.800	0.944	1.072	0.997	0.812	0.611	1.018	0.781
24.10.76	0.000	0.000	0.249	0.092	0.099	0.244	0.000	0.142	12.12.78	1.292	1.149	1.843	1.412	1.548	0.820	1.424	1.072
04.01.77	0.126	0.291	0.750	0.462	0.234	0.506	0.135	0.351	12.12.78	0.066	0.145	0.235	0.179	0.228	0.127	0.122	0.125
04.01.77	0.000	0.000	0.018	0.007	0.000	0.000	0.000	0.000	12.12.78	0.280	0.309	0.505	0.383	0.241	0.083	0.253	0.154
05.01.77	0.000	0.000	0.143	0.053	0.012	0.000	0.000	0.000	08.01.79	0.007	0.039	*	*	0.081	0.177	0.030	0.116
06.01.77	0.000	0.019	0.357	0.144	0.090	0.187	0.000	0.109	08.01.79	0.099	0.129	*	*	0.201	0.275	0.230	0.256
06.01.77	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.018	08.01.79	0.173	0.215	*	*	0.119	0.086	0.310	0.179
06.01.77	0.104	0.237	0.490	0.332	0.156	0.525	0.245	0.408	09.01.79	0.049	0.101	*	*	0.104	0.074	0.308	0.171
06.01.77	0.000	0.000	0.061	0.023	0.000	0.039	0.000	0.022	09.01.79	0.674	0.834	*	*	0.838	0.820	2.277	1.429
06.01.77	0.000	0.000	0.117	0.043	0.000	0.039	0.000	0.022	09.01.79	0.000	0.000	*	*	0.017	*	0.000	*
07.01.77	0.000	0.000	0.020	0.008	0.000	0.000	0.000	0.000	09.01.79	0.843	1.671	*	*	1.261	0.912	0.815	0.871
07.01.77	0.025	0.053	0.511	0.223	0.075	0.143	0.168	0.154	22.01.79	0.245	0.289	0.276	0.285	0.085	0.138	0.000	0.080
22.01.77	0.000	0.000	0.015	0.006	0.000	0.017	0.000	0.010	23.01.79	0.000	0.000	0.077	0.028	0.000	0.060	0.000	0.033
22.01.77	*	0.040	0.250	0.092	0.096	0.110	0.077	0.096	23.01.79	*	0.416	0.546	0.466	0.335	0.509	0.589	0.542
06.02.77	0.000	0.000	0.054	0.020	0.000	0.035	0.000	0.020	07.02.79	0.000	0.000	0.000	0.000	0.016	0.114	0.000	0.066
17.03.77	0.000	0.000	0.000	0.000	0.000	0.031	0.000	0.012	09.02.79	0.060	0.350	0.771	0.508	0.242	0.513	0.401	0.466
05.04.77	*	2.330	4.937	3.213	3.495	5.442	4.592	5.086	09.03.79	0.000	0.000	0.000	0.000	0.013	0.138	0.000	0.080
13.04.77	0.061	0.030	1.863	0.708	0.312	1.046	0.702	0.902	09.03.79	0.000	0.000	0.000	0.000	0.043	0.118	0.059	0.093
24.04.77	0.116	0.163	0.836	0.413	0.286	0.587	0.462	0.535	04.05.79	0.137	*	0.469	*	0.130	0.176	*	*

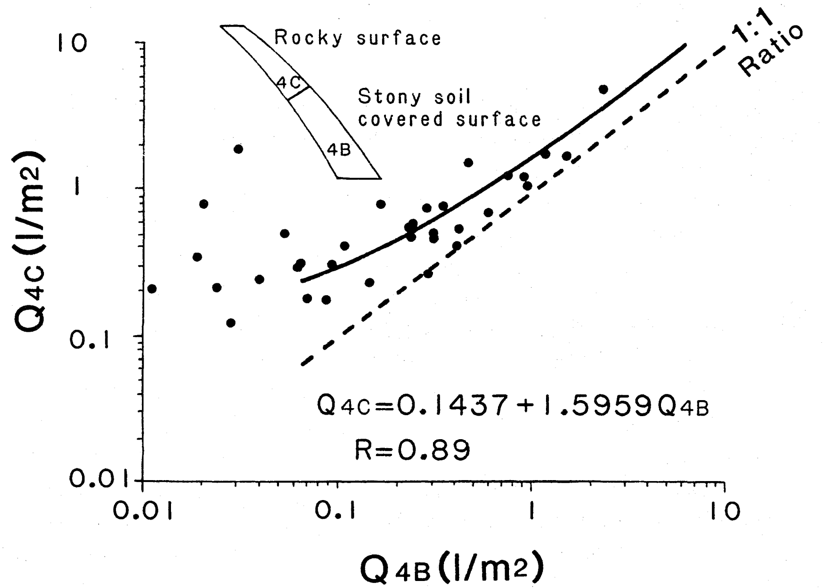

Fig. 10 Specific overland flow yield: the effect of surface properties.

COMPUTER SIMULATION OF OVERLAND FLOW

Given the above, it is clear that overland flow in the study area is very dynamic both in time and space due to two main factors; the great temporal and spatial variability of the rainfall intensity and infiltration rate, and the typically short duration of rain showers and resulting limited rainfall.

Given this complex situation, statistical rainfall-runoff relationships, which are based on average values for large areas and long time units, do not describe the actual field condition. In order to show the influence of the spatial and temporal variability of hydrological rainfall as well as that of the infiltration rate on the spatial and temporal variability of overland flow generation and its continuity along a slope, a computerized deterministic simulation was developed (Lavee, 1986).

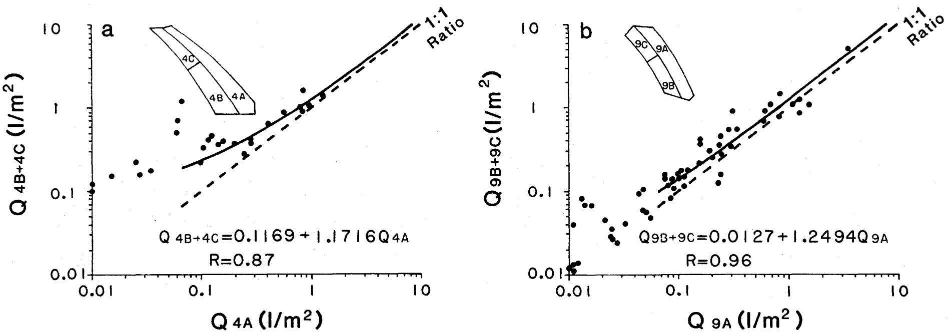

Fig. 11 Specific overland flow yield: the effect of rainfall properties.

DESCRIPTION OF THE SIMULATION

The computer program is written in version 360 of the Continuous System Modelling Program (CSMP) language (IBM, 1969; Hillel, 1977). The model provides a quantitative description of the generation and continuity of overland flow as a function of specific rain conditions and surface properties. It is based on the Hortonian approach to overland flow generation. Therefore the depth of overland flow at any given time and point represents the difference between the combined amount of direct rain and overland flow which had reached the point up to a given time, and the quantity of water which had left the point by infiltration, evaporation and overland flow up to that time.

The model takes into account the spatial variability of surface properties and rain characteristics by dividing the hillslope into *N* compartments, all parallel to the slope contours. Within each compartment, the processes associated with overland flow generation are simulated, i.e. rainfall, infiltration, evaporation and soil moisture losses. Though these processes occur simultaneously, they do not necessarily occur at the same rates. The computer solves a set of differential equations which describe the dynamic system by computing numerically over short time intervals of one minute. At the end of each interval, the overall effect is summed and the surface water from each compartment "flows" to the adjacent compartment further down the slope. Each variable is then updated and reset for the beginning of the next time interval.

THE VARIABLES

The model variables are shown in Fig. 12.

Hydrological rainfall intensity (*RAIN*) in each time interval and compartment is calculated by:

$$RAIN\ (1,N) = RAINR \times RRR\ (1,N) \times RR\ (1,N)$$

where *RAINR* = rainfall intensity measured by a recorder; *RRR* = ratio between rainfall amounts in tilted gauge and recorder; and *RR* = ratio between rainfall amounts at 30 cm and at ground level.

The **potential evaporation rate** *(EVAP)* and the **infiltration capacity** (*INF*) both vary in time and over space. Data entered to the program are based on field measurements.

Actual evaporation (*RVAP*) and **actual infiltration** (*RF*) for each compartment and time interval are calculated as follows:
(a) If $TRUN + RAIN \geqslant INF + EVAP$, then $RF = INF$ and $RVAP = EVAP$;
(b) If $INF + EVAP > TRUN + RAIN > INF$, then $RF = INF$ and $RVAP = TRUN + RAIN - INF$;
(c) If $TRUN + RAIN \leqslant INF$, then $RF = TRUN + RAIN$ and $RVAP = 0$;
where *TRUN* = overland flow depth at the beginning of the time interval.

Soil moisture (*STOR*) in each compartment has an initial value (*ISTO*) at the beginning of each storm. Soil moisture increases by actual infiltration and decreases with actual soil moisture losses through evaporation from the soil and by seepage.

The **potential soil moisture losses rate** (*LOSS*) in each compartment varies with time as a function of soil water content (Fig. 8). **Actual soil moisture losses** (*SLOS*) are calculated as follows:
(a) If $STOR < FCAP$, then $SLOS = LOSS$;
(b) If $STOR \geqslant$ FCAP and $RF \geqslant$ LOSS, then $SLOS = RF$ (soil moisture does not change);
(c) If $STOR \geqslant FCAP$ and $RF < LOSS$, then $SLOS = LOSS$ (soil moisture decreases);
where *FCAP* = field capacity.

Depth of overland flow (*RUN*) on each compartment equals zero at the beginning of the simulation. It changes in each time interval according to the above-mentioned processes. At the end of each time interval, the water is moved lower down the slope to the adjacent compartment.

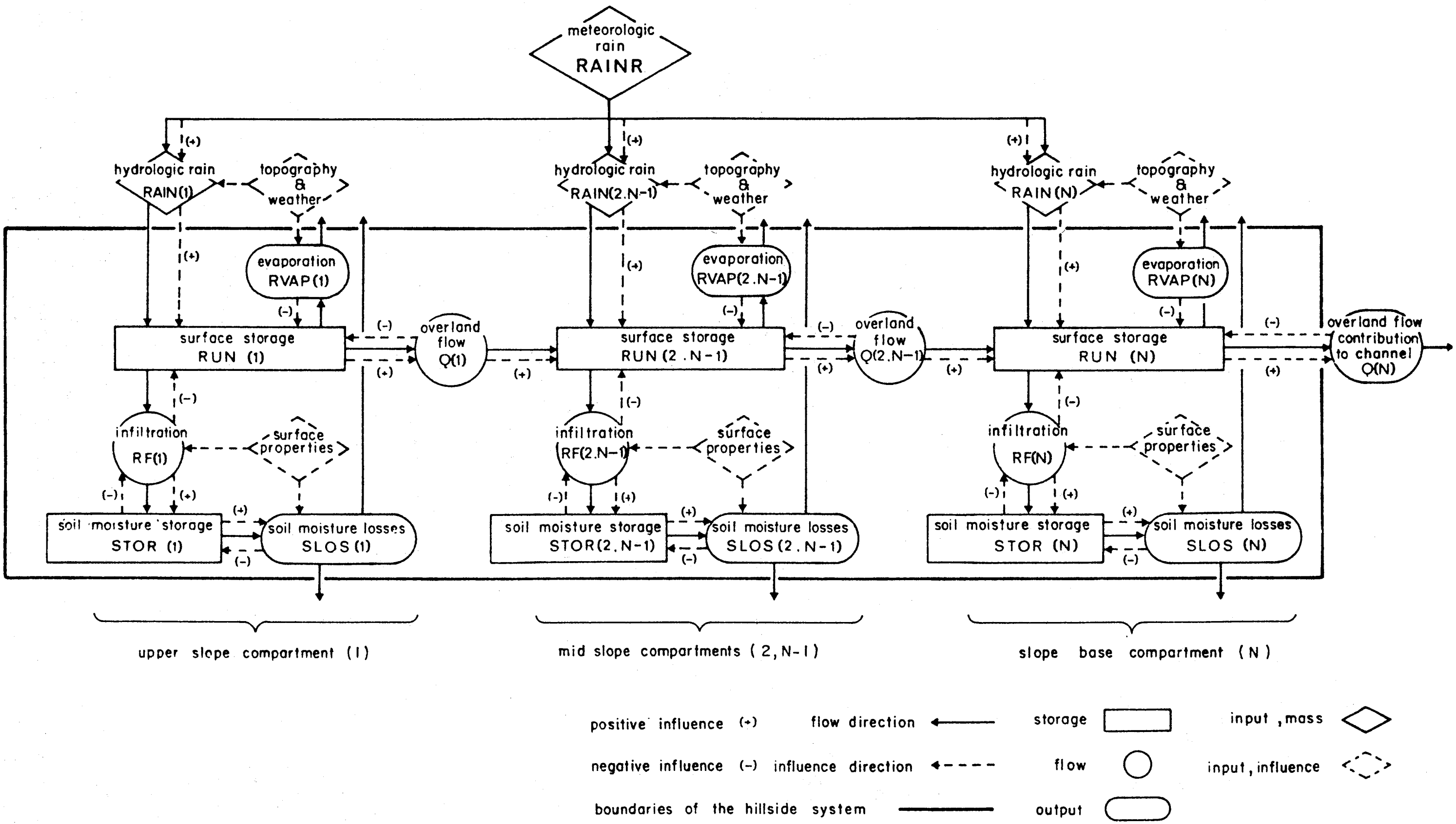

Fig. 12 The model variables.

APPLICATION TO OVERLAND FLOW CONTINUITY

The simulation program was verified by comparing simulated hydrographs with the actual ones (Fig. 13). The results show that the model fits well with the actual field situation. The model was then used to check the effect of short rain showers on overland flow continuity along slopes having uniform surface properties. The program was operated on six hypothetical plots. The infiltration capacity over the whole plot area was chosen to be equivalent to that of the stony soil cover surface; thus surface property differences do not

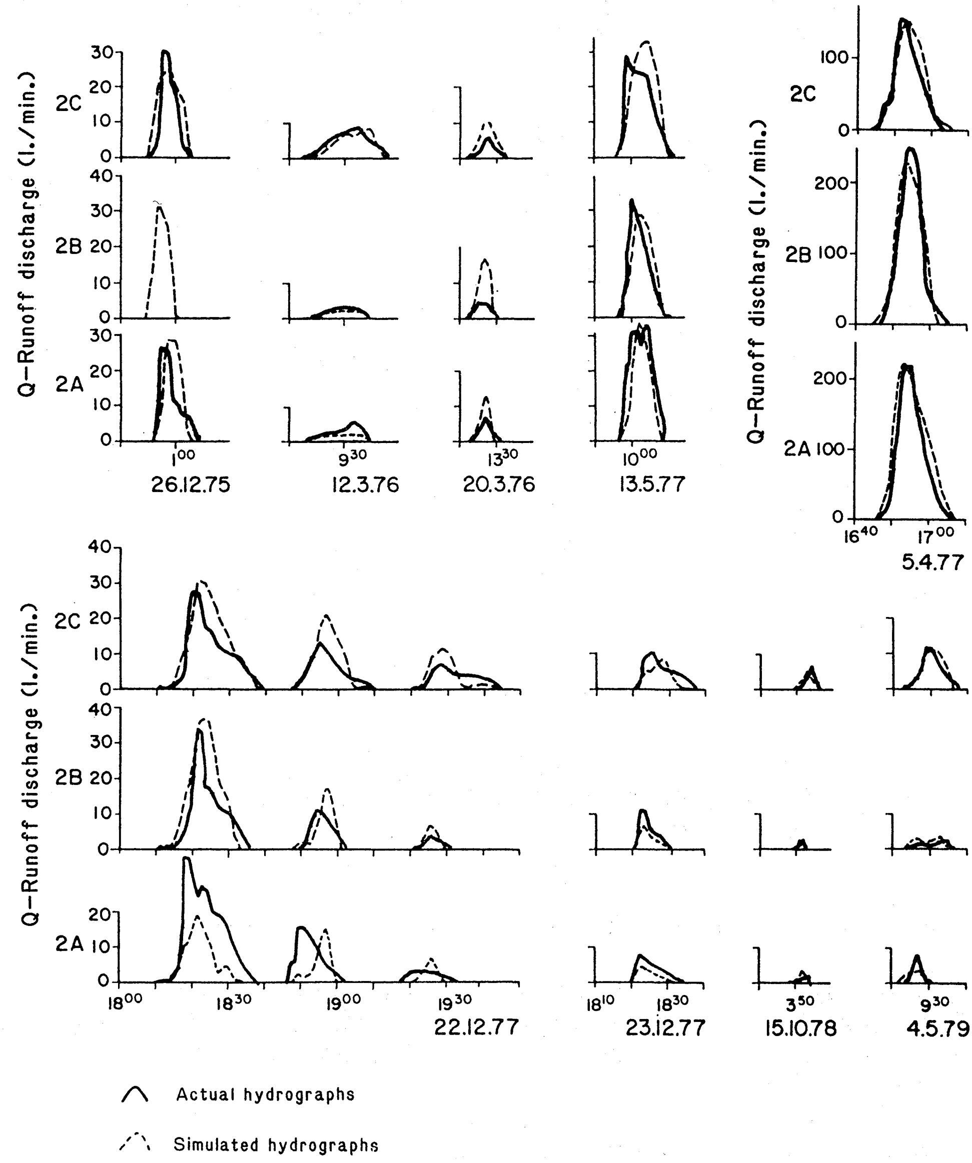

Fig. 13 Actual and simulated hydrographs.

affect the continuity of the flow. The only difference between the plots was in their respective lengths - 15, 30, 45, 60, 75 and 90 m. Sixteen rain showers were simulated on each plot for four different durations and for four different intensities (Fig. 14). The intensities and durations were chosen on the basis of an analysis of the rainfall properties at the experimental site. The relationship between runoff yields from the six plots and their lengths identifies the length of the slope contributing overland flow to the channel. Figure 14 indicates that for the above-mentioned surface properties, with a rain shower lasting 30 min with an average intensity of 12 mm hour^{-1}, the length of the slope contributing overland flow to the channel is 30 m. An increase in the contributing slope length is expected with increasing rain shower duration and/or intensity.

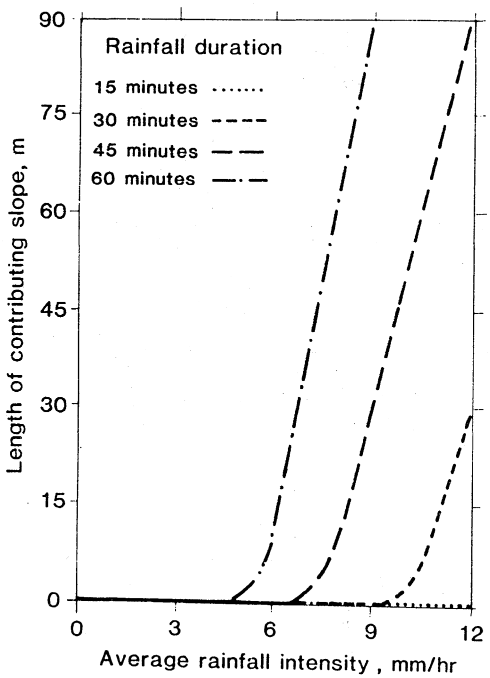

Fig. 14 Contributing slope length as a function of rainfall intensity and duration.

APPLICATION TO ANCIENT FARMING IN THE NEGEV

Intensive agricultural activity took place in the northern Negev in the past. The most flourishing period began in the third century BC during the Nabatean era, and lasted approximately 1000 years, throughout the Roman and Byzantine periods.

One of the main agricultural techniques used was water harvesting from hillslopes, using small conduits leading into the cultivated fields of adjoining valleys. These conduits can be seen today (Fig. 15) crossing the contour lines

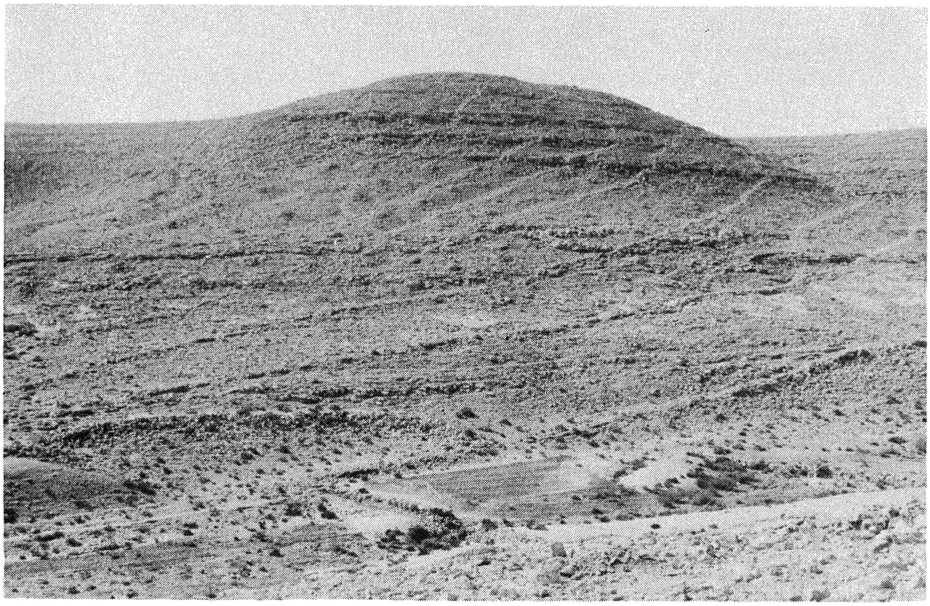

Fig. 15 Overland flow collecting conduits.

at an acute angle. Parallel conduits, sometimes as many as 10 on one slope, can be seen. The distance between two adjoining conduits is usually 10 to 15 m.

The distribution of the conduits raises a question. Why are they so numerous on the slopes and why were the ancient farmers not satisfied with one conduit at the base of the slope? Evenari *et al.* (1982, p. 109-110) have dealt with this question and state "in this way the overall runoff was divided into small streams of water so that large flash floods were prevented."

A complementary explanation can be provided by the hydrological results presented in this paper. Under typical short rain shower conditions, which prevail in the study area, a continuous overland flow usually occurs for slope lengths of 10 to 15 m. Therefore the spatial distribution of the conduits provides the most efficient system for water harvesting.

Apparently the ancient farmers were well aware of the phenomenon of overland flow discontinuity. Through observation, they may have come to realize that the overland flow generated at the upper part of the slopes had little chance of reaching the valley and would be lost without conduits to collect the overland flow on its way downslope. They also appear to have recognized that a shorter separation between conduits would enable them to receive water even for lower-magnitude rainfall events when flow distance is relatively limited.

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