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Research article

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Complex Hydrological Regimes, and Processes, In the Negev Arid Area, Israel

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1. Introduction

Spatial relationships, or connectivity, represent a basic concern in our understanding of geomorphic processes, and their effects on the degree of connectivity along hillslopes, at the interface hillslopes-channels, and along streams, will affect the spatial redistribution of water resources, sediment movement, sediment deposition and consequently the operation of biological fluxes. High values of connectivity are indicative of an efficient system; while a low connectivity would encourage infiltration losses, sediment deposition, and spatial redistribution of water resources. Many factors may affect the degree of connectivity, and the importance of a given factor may vary in a wide range of local conditions. Climatologist use aridity indices to express the relationships between climatic and environmental variables. This approach leads to the idea that average annual rainfall, up to 300 mm, controls water availability for plants, soil properties, runoff generation and soil erosion [1, 2, 3, 4]. This approach may be valid for soil covered areas, and annual crops, very sensitive to rainfall. Its validity is questionable in drier areas where most of the surface is rocky, and the limited soil patches are saline.

The present study deals with the hydrology of three watersheds (Figure 1).

One of them is the SEDE BOQER watershed, located in the southern part of the area, where average annual rainfall is 90 mm. The two other sites (Lehavim and Haggedi watersheds) are located in an area where average annual rainfall is 280 mm. The Haggedi watershed is located in a loess covered area, and the Lehavim watershed in a rocky area. Hydrological data collected, in the loess covered area, point to a very high frequency of channel flow. However, even in extreme rain events, peak flows are extremely low pointing to a limited contributing area. The hydrological regime in the rocky areas is opposite. The frequency of overland flow is high. However, a hydrological dis-connectivity at the hillslope-channel interface is frequent. The aim of the present manuscript is to draw attention to the complex hydrological processes in three watersheds, located in the arid Negev desert of Israel.

2. Sede Boqer Watershed

The Sede Boqer experimental site extends over an area of 11,335 m2. The whole area is composed of limestone formations. The site was subdivided into 10 plots, which drain one half of the watershed area (Figure 2). A rain recorder was installed at the lower central part of the watershed. In order to get an idea regarding the spatial variability of rainfall within the experimental area a network of 18 rain collectors was spread over the whole experimental area. Runoff, and sediment removed were collected in barrels, at the bottom of each plot.

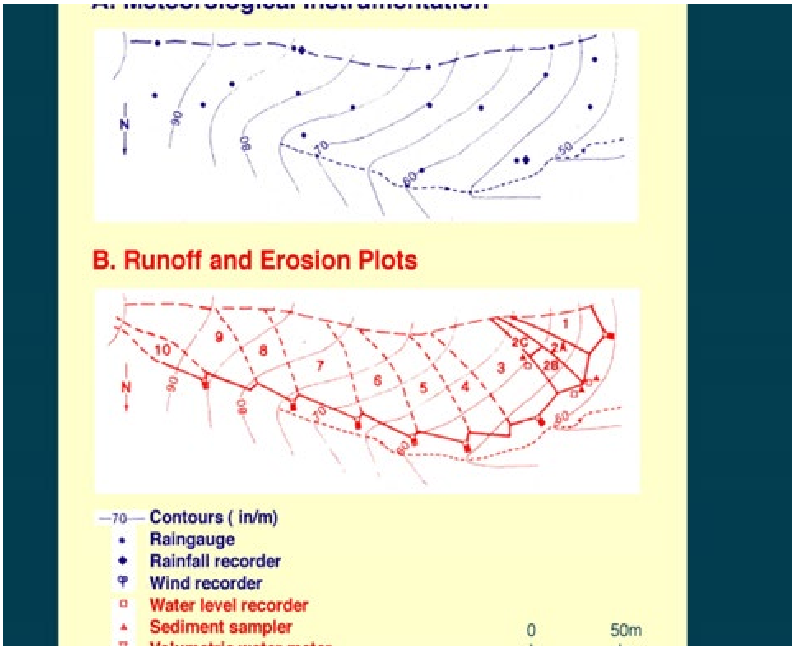


Figure 2: Sedeh Boqer Experimental Site

2.1 Results

Rainfall data collected in the rain recorder are presented in Figure 3. Rain-showers are highly intermittent, with very low rain intensities.

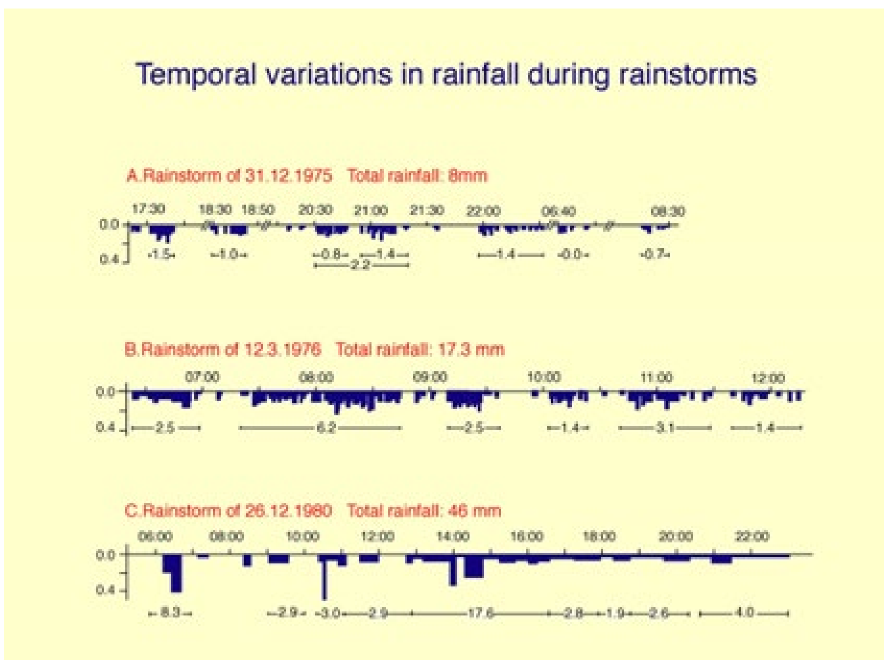


Figure 3: Rainfall data collected in the rain recorder.

A detailed analysis of rainfall in a relatively wet year (131 mm) shows that out of 170 individual rain-showers recorded 130 were below 0.2 mm, and additional 35 rain-showers were below 1 mm [5]. The spatial distribution of rainfall within the experimental area, in various rain events, is shown in Figure 4. Rainfall is not uniform, and varies from one rain event to another. The differences are not negligible. In the lowest rain event the difference is between 1 and 4 mm. In the higher rain event the difference is between 9 and 13 mm. It seems that the lowest values are at the central, lowest part, of the research site.

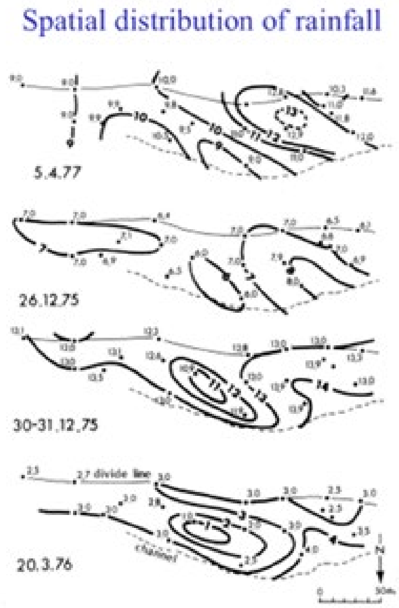


Figure 4: Spatial variability of rainfall

Figure 5 shows the runoff and sediment data collected in the rainfall year 1972-1973. Annual rainfall was 131 mm. The highest runoff was collected in three plots (7, 8 and 9). Figure 6 clearly shows that runoff in the other plots is quite negligible. Similar results refer to the sediment data (Figure 5). Details field observation drew our attention to the activity of burrowing animals, such as Porcupines, and Isopods (Yair, 1993). The biological activity is concentrated in the Shivta geological formation, which is located at the central part of the research site (Plots 5-7). The surface is bear, allowing runoff generation at low rain intensities. Strata thickness are 30-80 cm, with wide and deep cracks, filled of soil. Soil moisture in the joints is high, up to 30%, during the wet season. The characteristic plant association is that of Vertemia Iphionides- Origanum Dayi, which is indicative of a high soil water content [6].

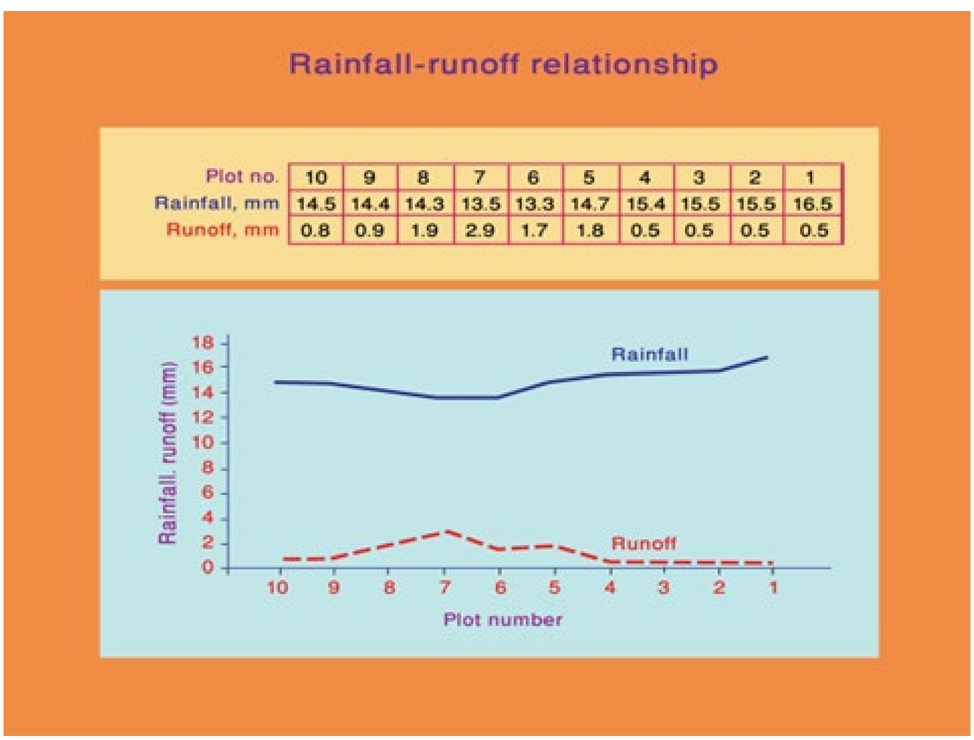


Figure 5: Rainfall and Runoff data in a wet year (131 mm).

There is no relationship between annual rainfall and runoff. The highest runoff was recorded in plots 5-7 where rainfall was low. and the lowest runoff was recoded where rainfall was high. The explanation proposed is that runoff generation is controlled by the geology. Plots 5-9 are located where the geological Shivta formation, characterized by thick layers with very extensive bare areas, where runoff develops, even at low rain intensities. The other geological strata (Drorim and Netzer) are composed of chalky limestone, thin layers, with a gravelly surface, and soil patches, limit runoff generation. Figure 6 presents the runoff and the erosion data. The results are quite similar to the runoff data. The highest sediment values were obtained in plots 6-9. Field observations drew our attention to the intense activity of biological elements [7]. Isopods and Porcupines feed on underground geophyte bulbs that grow in the deep cracks of the bedrock, where soil moisture is high. As the deep cracks are mainly found in the Shivta formation, the biological activity is concentrated in plots 7-9 (Figure 6).

Rainfall Year 1972-1973, Runoff & Sediment data

Surface properties					Runoff & Sediment data		
Plot no.	Plot (m^2)	% of total drained area	Slope length (m)	Slope angle (m)	% of total runoff	Sediment removed (g per $100m^2$)	% of total sediment
1	590	5.2	55	27	4.3	220	1.7
2	870	7.7	63	27.5	3.6	132	1.5
3	1830	16.2	68	28.5	9.1	169	4.0
4	1025	9.1	72	29	9.6	no data	no data
5	1230	10.9	72	29.5	13.5	235	3.7
6	1250	11.0	70	25	9.7	333	5.4
7	1520	13.4	70	24	21.4	2168	42.3
8	1050	9.3	63	26	12.1	1653	22.3
9	1440	12.7	75	17.5	12.8	928	17.2
10	510	4.5	76	11.5	3.9	302	2.0

Figure 6: Runoff and Sediment data

In order to improve our understanding of the hydrological system in the dry area, especially on the flow continuity along a slope we decided to conduct sprinkling experiments on one of the hillslopes in the study area (Figure 7). The first run was conducted at an intensity of 15 mm/hr-1 during 30 minutes. Flow lines were mapped using a dye. Runoff infiltrated at the upper part of the colluvial area. The second run was conducted at an intensity of 30 mm/hr1. Runoff was absorbed at the top of the colluvium. The third run was conducted at an intensity of 60 mm/hr1, under very wet surface conditions. Continuous flow lines were observed after 10 minutes, down to the bottom of the colluvium. Needless to say, that under the rainfall prevailing in the study area, the chances for such a flow, are negligible. The said above is strongly supported by the soil properties along a colluvium

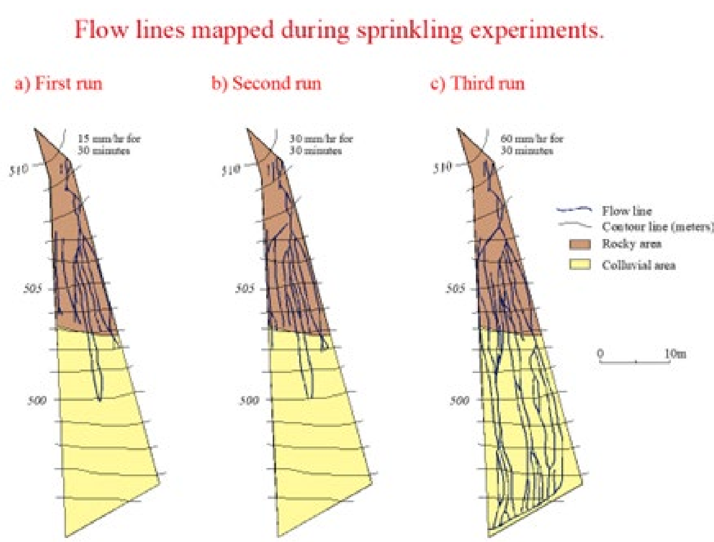


Figure 7: Sprinkling experiment along a slope

Figure 8 shows the pedology of the colluvium. Concentrations of gypsum and calcium are found along the colluvium, down to a depth of 2 meters. Such results may be indicative that the hydrological regime did not change, despite the changes of the rainfall regime during the upper Pleistocene.

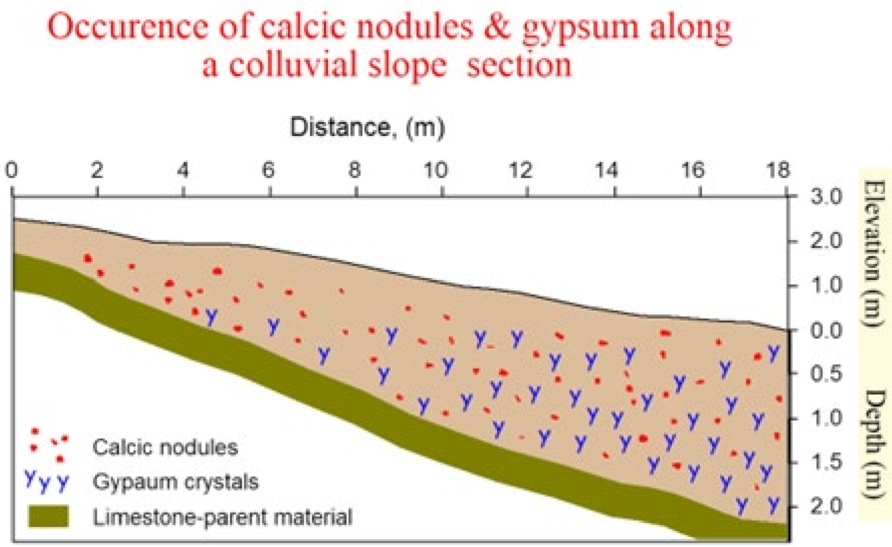


Figure 8: Calcic and Gypsum nodules, along the colluvium

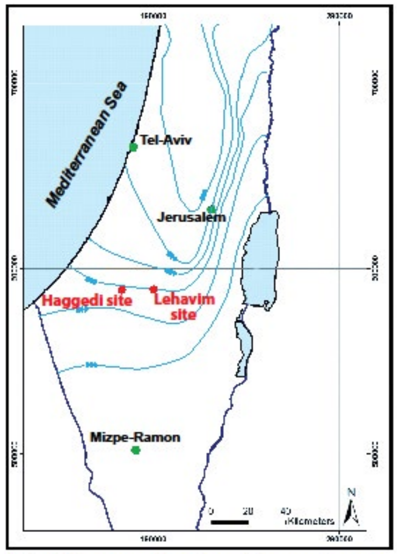
2. Discussion and Conclusions.

Models dealing with the possible effects of climate change on the environment assume that average annual rainfall is a good indicator of water resources, vegetal cover, soil properties and soil erosion, up to 300 mm annual rainfall. This assumption encounters serious difficulties when applying it to the Northern Negev arid area in Israel.

1.Average annual rainfall disregards two important factors that affect the spatial redistribution of water resources. The first is that rainfall, during a rain event is not uniform, even over small distances of 40-50 meters (Figure 4). Since the rainfall duration is similar over the experimental site, difference in rain depth represent differences in rain intensities. In addition, the average annual rainfall disregards the effective duration of individual rain-showers. This duration is very often too short to allow a continuous flow, along slopes of 50-70 m long. Another critical factor is the rain intensity of the individual rain-showers. Data obtained shows that about 80 % of the rain events are below 5 mm/h-1. Similar results refer to the issues of runoff and soil erosion. Data obtained clearly show the spatial non-uniform runoff, and erosion rates, encountered in the study area. These results cannot be explained in terms of the physical variables usually considered, such as slope length, slope angle, and annual rainfall energy. The Importance of the biological activity is ignored. In addition, the regulatory role of the biological activity, by porcupines and isopods, allows the removal of salts, from the rocky areas; while limiting salinization processes, and preserving a good environment. At the same time, salts removed from the rocky areas are deposited within the colluvium, creating saline soils, along the whole colluvium (Figure 8).

2. Haggedi Watershed

The Haggedi watershed is located in the northern part of the Negev Desert (Figure 1), where average annual rainfall is 280 mm.



Rainfall map and location of research areas

Figure 1

The area is characterized by an extensive loess cover, deposited during a wet climatic phase, in the Upper Pleistocene [8, 9, 10, 11]. The loessial soil is classified as a brown-grumosolic soil with a clay-loam texture (Wieder et al., 2008). The watershed covers an area of 11km2 (Figure 1). Hydrological data available for the Haggedi watershed point to a high flow frequency (4-8 channel flows every year). However, even during extreme rain events peak discharges are extremely low (0.23-0.4 m3 s-1), representing no more than -0.003% of the rain received by the whole watershed. In addition, channel runoff occurred even at rain intensities as low as 4 mm/hr1 (Figure 2). Such rain intensities are below the final infiltration rates reported for the loess soils in the study area: 10-15 mm/h [12, 13, 14]. The limited runoff in the Haggedi watershed sharply also contrasts with hydrological data reported for the hyper arid area, near the Dead Sea area, and the southern part of the rift depression, where average annual rainfall is below 100 mm. Recorded peak flows in the drier areas, for basins draining ~ 10 km2, vary in the range of 80-1203 [15, 16]. The hypothesis advanced for the high frequency of channel flow, with low peak flows, even at high rain intensities, is that the contributing area is limited to the channel area, with negligible contribution from the adjoining hillslopes. This hypothesis is based on the sharp shape of the hydrographs. Very steep rising and falling limbs, indicative of a nearby contributing area; as well as the very low peak flows, even in extreme rain events. Channel runoff occurred even at low rain intensities below - 4 mm/h1 (Figure 2).

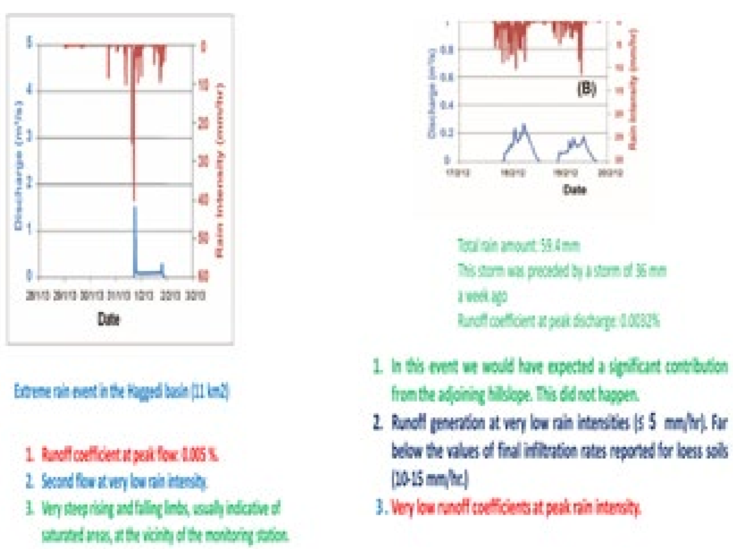


Figure 2: Representative hydrographs recorded in the Haggedi basin.

Figure 3 presents the rainfall data for two consecutive years. In both years rain intensities were very low; about 80% were below 5 mm/hr[1].

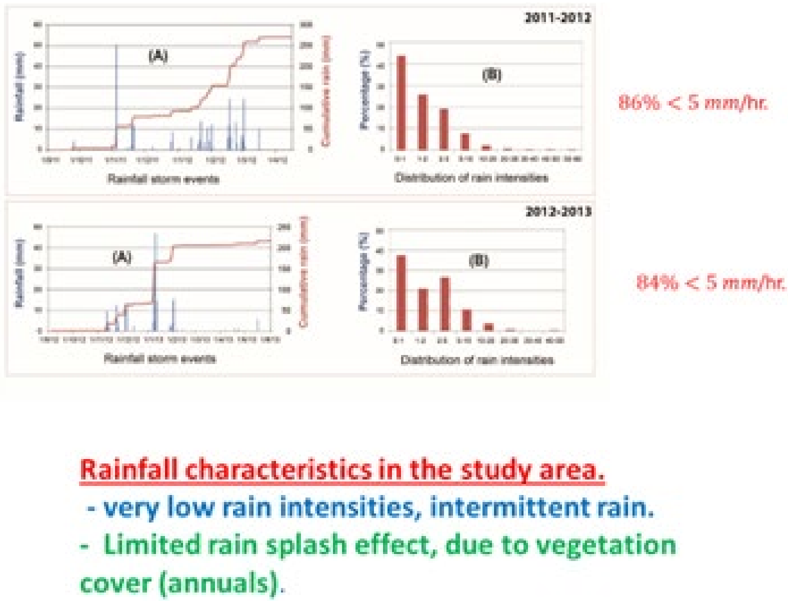


Figure 3: Rainfall data

3.1. Methodology

The very low peak flows, as well as the steep hydrographs, even at low rain intensities, led us to assume that the contributing area is limited to a small area located near the monitoring station. This included the following variables: Stratigraphy; porosity of the alluvium; particle size composition of the alluvium, and mineralogy of the alluvial fill. Such an approach means that hillslope overland flow contribution is negligible. In order to verify this hypothesis, a detailed study of soil properties along a hillslope in the study area, was conducted. According to the soil pedologists [17, 18, 19, 20,21] one would expect a gradual change in soil properties along the hillslope, due to overland flow from upper part of the slope to its lower part. In order to eliminate the possible contribution of overland flow, a detailed study of the soil properties along a hillslope, 400 m long, was conducted (Figure 4).

Figure 4: Location of boreholes

3.2 Results

Chemical data are presented in Figure 5.

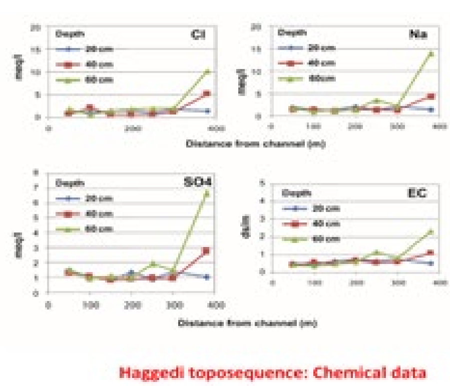


Figure 5: Chemical data, along the hillslope

No differences can be observed in the chemical data, along the hillslope. In fact, the highest values were obtained at the top of the slope, where a thin geological formation, with special properties exist.

Similar results were obtained for the particle size distribution (Table 1). In fact, the highest clay content is found in the channel.

Clay content along the Haggedi topsequence (%)

Borehole number	1	2	3	4	5	6	7	8 (Channel)
Depth (cm)								
0-20	34	35	27	27	27	37	35	45
20-40	38	35	32	27	34	27	35	43
40-60	45	40	32	33	34	33	36	43
60-80	47	41	37	36	36	35	34	39

Table 1: Changes in clay content along the hillslope.

In addition, the stratigraphy, at the top of the alluvial sediment was analyzed, as well as the mineralogical composition, at the top of the alluvium. Figure 6 shows the stratigraphy, at the top of the alluvium.

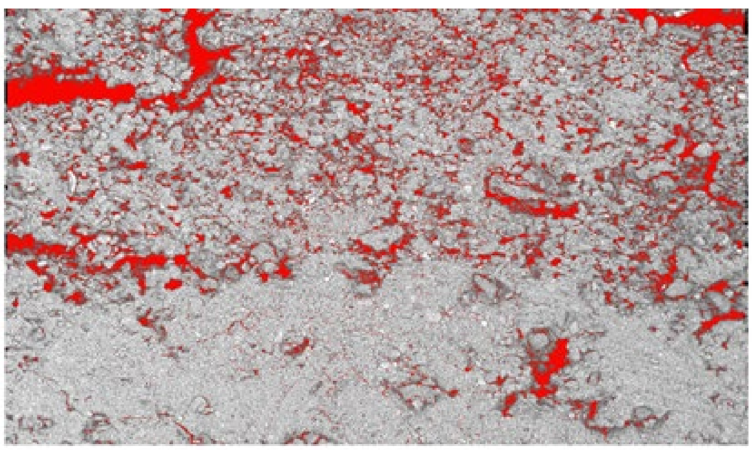


Figure 6: ESM image of the stratigraphy at the top of the alluvium.

The porosity of the upper layer is 17 %, with relatively, good hydrological connectivity; while the porosity of the lower layer is ~ 4%, with much lower connectivity. In addition, of special interest is that the clay content, down to a depth of 60 cm, is very high (Table 1). In addition, the mineralogical composition of the upper part of the colluvium was analyzed. XRD analysis of the top of the colluvium clearly shows that the dominant clays are Smectite and illite (60-70%). This result fits the composition of the clay fraction reported in previous studies in the loess covered areas [22].

3.2 Discussion and conclusions

Data presented clearly show that the structure, and composition of the top of the alluvial fill (mineralogy, particle size composition, and stratigraphy), reduce the porosity of the top of the alluvium, allowing runoff generation at very low rain intensities. At the same time, the properties of the soil over the hillslopes limits overland flow. The vegetated area is ploughed. Surface roughness is high, as the furrows are 10-15 cm deep, allowing rain infiltration. In addition, as 85% of the rain are below 5 mm mm/h, the kinetic energy is very low, insufficient for the disaggregation of large soil clods. in addition, the clay content over the hillslopes (27-35%) is below the amount required for effective sealing (> 40%).

Figure 7: Stratigraphy of the upper part of the alluvium

The porosity of the upper layer is 17 %, and good hydrological connectivity; while the porosity of the lower layer is ~ 4%, with much lower connectivity. In addition, of special interest is that the clay content, down to a depth of 60 cm, is very high (Table 1). In addition, the mineralogical composition of the upper part of the colluvium was analyzed. XRD analysis of the top of the colluvium clearly shows that the dominant clays are Smectite ***and Illite (60-70"). This result fits the composition of the clay fraction reported in previous studies in the loess covered areas (Katzman et al., 1983; Singer, 2002; Sandler, 2013).***

3. Lehavim Research Site

The Lehavim Site represents a rocky area, with steep hillslopes, and soil patches. The location of this site is presented in Figure 1 of the section dealing with the loess area. Long term hydrological monitoring conducted at the Sede Boker watershed, where average rainfall is 90 mm, clearly show that runoff generation is faster on impervious rocky areas, than over soil covered areas. Under such conditions, a higher frequency of runoff events should be expected in arid areas, where rocky surfaces prevail, compared to semi-arid areas, where soil and vegetation cover are more extensive. On the other hand, it may well be that the hydrological response to rainfall is offset in semi-arid areas by the higher frequency of low storm rain amounts [23, 24]. In order to test the validity of the above approach an additional instrumented site, has been established in the northern Negev area: Lehavim Watershed [25]. This watershed covers an area of 9 Ha. The hillslopes, carved in thinly bedded chalk limestone, are 12-+m long. The thinly bedded bedrock forms rocky steps. The soil, at the bottom of the steps is a *regolith, with fine grained material from eolian origin. Soil cover is more extensive than at the Sede Boqer site.*

1. Methodology.

The study is based on a small watershed. Runoff was measured in plots that vary in their dimensions. Channel flow was measured close to the watershed outlet, with a Parshall flume, equipped with a stage recorder (Figure 1). Rainfall was measured with small orifice rain gauges, and a rain recorder.

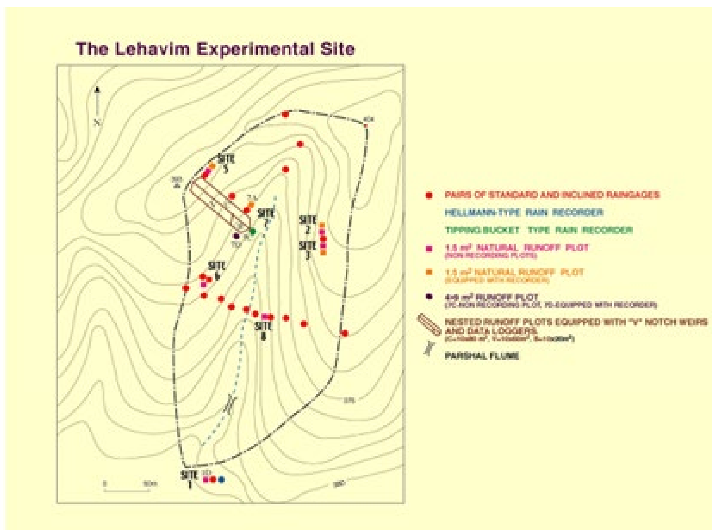


Figure 1: Lehavim Experimental site

2 Results

Annual rainfall was 266 mm for the first year, and 376 mm for the second year. An extreme rain event of 105 mm occurred in March 1991.

Figure 2: Extreme rain event of March 1991.

The recurrence of such a storm is estimated at 50-75 years. Peak rain intensities of 85-93 mm/h were recorded. However, during most of the storm rain intensities were below 5- 10 mm/h.

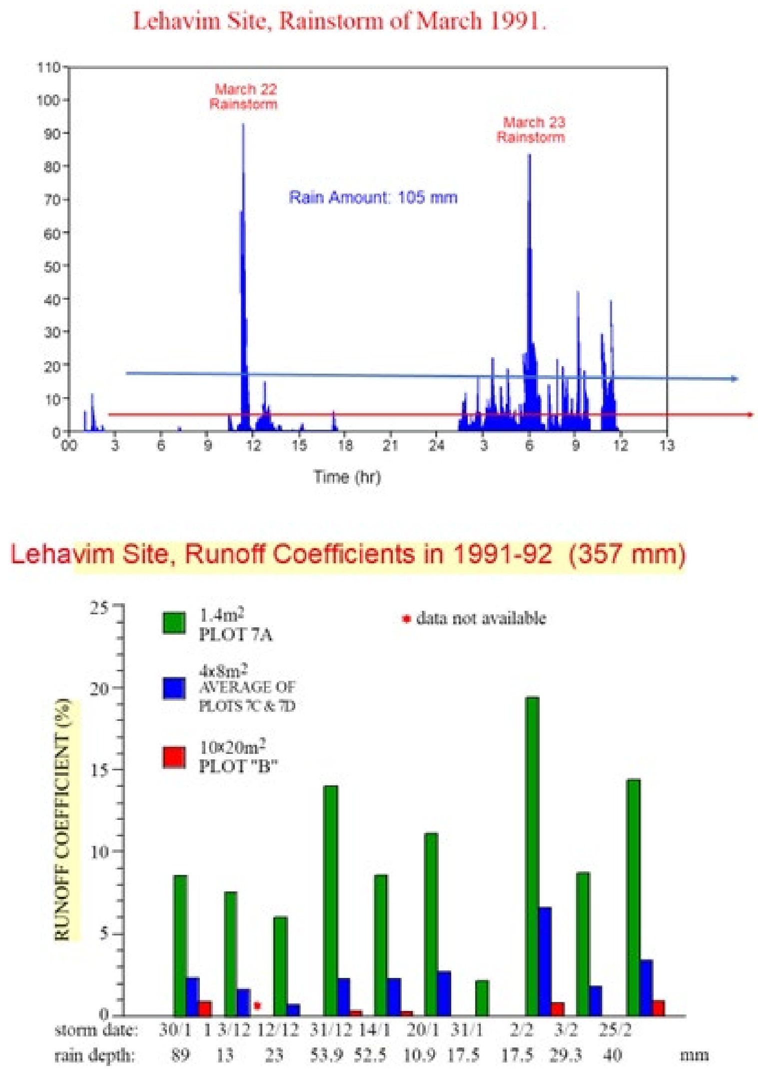


Figure 3: presents runoff data collected in 1991-92.

Overland low frequency is high. However, a sharp decrease in runoff is obtained on passing from a plot 1.4 m long to a plot 8 m long. Negligible runoff was obtained in a plot 20 m long. Very similar data were obtained in the following year (Yair and Kossovsky, 2012). No runoff was recorded by the Parshal flume located at the watershed outlet.

3. Discussion

Many hydrological works are often based on the average annual rainfall. Data presented draws attention to two important factors, often disregarded. The first is the duration of individual rain showers. The duration of many individual rain showers is shorter than the time required for a continuous flow along a long hillslope, preventing overland flow contribution to the channel. The other factor, very often disregarded, is the spatial distribution of the rain over small distances of 10-20 meters (See chapter on the Sede Boqer site). The discussion will focus on the response of the two watersheds (Sede Boqer and Lehavim watersheds) to an extreme rain event. The rain-storm at the Lehavim site was 105 mm, with peak rain intensity of 80-90 mm in two minutes. The rainstorm at the Sede Boqer site was lower, only 45mm, equivalent to 50% of the average annual rainfall. Peak rain intensities were lower than at the Lehavim Site. Channel runoff coefficient, at the Upper channel was 65%; and 37%, at the lower channel. Data obtained, at the extreme rain event, clearly indicate that surface properties, at a scale of 10-15 meters represent the major control of overland flow generation. Such a result may indicate that most of the runoff reaching the lower channel station had its origin, within the very rocky headwater area, where an extremely high runoff coefficient of 65% was recorded. Despite the higher storm rain amount, and higher rain intensities recorded at the Lehavim site, runoff rates at all scales considered, were much lower than at the southern more arid area. The explanation proposed is the extent of the rocky surfaces. At the Sede Boqer site rocky surfaces represent approximately 60%, but only some 30% at the northern Lehavim site.

Conclusions

The main conclusion derived from data presented is that runoff generation, within the arid and semi-arid areas, is not the average annual rainfall. More attention should be accorded to the spatial distribution of the rain, and the distribution of rain intensities. This distribution is not uniform, over distances of 20-30m (See chapter dealing with the Sede Boker site). In addition, more attention should be accorded to the duration of individual rain-showers. This duration is often shorter than the time required for the hillslope-channel connectivity. In view of the fact that about 85% of the rain are below 5 mm/hr1, only specific areas with low infiltration rate, such as rocky surfaces, and alluvial areas, clay rich (above 40%), and specifique mineral composition (Muscovite, and Illite), known for their high-water absorption especially Muscovite. The sealing of the top of the alluvium, create an impermeable surface that allow channel flow at very low rain intensities.

obtained show a great spatial variability in rainfall over short distances, as well in runoff and as erosion rate, mainly controlled by burrowing activity of porcupines and isdopods, usually disregarded in most studies dealing with biological activities. Data obtained clearly show that average annual rainfall is not an important factor in the hydrological processes in drylands areas. The reason for that is not uniform, and varies from one site to another [26-31].

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