LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **9**, 407–422 (1998)

THE IMPACT OF CLIMATE CHANGE ON GEOMORPHOLOGY AND DESERTIFICATION ALONG A MEDITERRANEAN-ARID TRANSECT

H. LAVEE,[1*] A. C. IMESON[2] AND P. SARAH[1]

[1]*Department of Geography, Bar Ilan University, Ramat Gan, Israel*
[2]*Landscape and Environmental Research Group, University of Amsterdam, Amsterdam, The Netherlands*

Accepted 3 November 1997

ABSTRACT

From the perspective of geomorphology, three important aspects of climate should be considered if conditions become more arid: (a) any decrease that might occur in the annual rainfall amount; (b) the duration of rainfall events; and (c) any increase in the intervals between rainfall events. These, together with increasing temperature, lead to less available water, less biomass and soil organic matter content and hence to a decrease in aggregate size and stability. As a consequence, the soil permeability decreases, soils develop surface crusts and infiltration rates decrease dramatically. Such changes in vegetation cover and soil structure lead to an increase in overland flow and in the erosion of the fertile topsoil layer. Positive feedback mechanisms may reinforce these effects and lead to desertification. This paper considers the results of field investigations into the spatial variability of a number of 'quick response' variables at two scales: the regional and the plot scales.

Concerning the regional scale spatial variability, results of experimental field work conducted along a climatic transect, from the Mediterranean climate to the arid zone in Israel, show that: (1) organic matter content, and aggregate size and stability decrease with aridity, while the sodium adsorption ratio and the runoff coefficient increase; and (2) the rate of change of these variables along the climatic transect is non-linear. A steplike threshold exists at the semiarid area, which sharply separates the Mediterranean climate and arid ecogeomorphic systems. This means that only a relatively small climatic change would be needed to shift the borders between these two systems. As many regions of Mediterranean climate lie adjacent to semiarid areas, they are threatened by desertification in the event of climate change.

Concerning spatial variability at the plot scale, different patterns of overland flow generation and continuity characterize hillslopes under different climatic conditions. While in the Mediterranean climate area infiltration is the dominant process all over the hillslope, in the arid area overland flow predominates. In contrast to the uniform distribution of processes in these two zones, a mosaic-like pattern, consisting of locally 'arid' water contributing and 'moist' water accepting patches is typical of the transitional semiarid area. Such pattern is strengthened by fires or grazing which are characteristic of this area. The development of such mosaic pattern enables most rainfall to be retained on hillslopes.

Changes in the spatial pattern of contributing versus accepting water areas can be used as an indicator of desertification and applied to developing rehabilitation strategies.

KEY WORDS: climate change; climatological transect; desertification; ecogeomorphological processes; soil properties; spatial patterns

*Correspondence to: H. Lavee, Department of Geography, Bar Ilan University, Ramat Gan, Israel.

Contract grant sponsor: Research supported by Israeli Ministry of Science and the Arts.
Contract grant sponsor: GSF-Forschungszentrum für Umwelt und Gesundheit GMBH, Neuherberg, Germany (DISUM-029).
Contract grant sponsor: Commission of the European Community in the Climatology and Natural Hazards Program (Project ERMES II-EV5V-CT91-0023.

CCC 1085–3278/98/050407–16$17·50

CLIMATIC CHANGE RELEVANT TO GEOMORPHOLOGY

Mediterranean climate and semiarid zones which are adjacent to arid zones are probably the most sensitive to desertification in a case of climate change. Köppen defined the Mediterranean climate (Csa) as one in which:

1. The mean temperature of the coldest month is between $-3\,^{\circ}C$ and $18\,^{\circ}C$.
2. The summer is dry, and the rainfall amount of the wettest month is at least three times greater than that of the driest month.
3. The mean temperature of the warmest month is above $22\,^{\circ}C$.
4. The mean annual rainfall amount (in mm) is higher than 20 times the mean annual temperature (in degrees Celsius).

The first three conditions, (1, 2 and 3), also hold for semiarid and arid regions adjacent to Mediterranean climate zones. The crucial difference between the Mediterranean and adjacent arid climate zones is therefore the mean annual rainfall.

Rainfall is very important, especially in Mediterranean, semiarid and arid zones, as it exerts a dominant control on the most important geomorphological processes. Regarding the expected climate change, there is a general agreement that higher temperatures are expected over most continental areas which are now already hot and dry, but the scenarios for changes in precipitation vary from one model to another and are unreliable (Wigley, 1992; Bolle, 1996; Palutikof, *et al.*, 1996). This means that no reliable information exists about the future conditions of the most important factor that controls geomorphological processes and determines the shift from arid to Mediterranean climate or vice versa.

To forecast the potential impact of climate change on geomorphological processes and desertification, it is necessary to assume logical future scenarios of changes in precipitation. These must include not only the mean annual rainfall amount, but also changes in rainfall intensity and temporal distribution. One scenario assumes that, along with higher temperature, rainfall characteristics will change similarly to the present differences in rainfall that occur when shifting from the Mediterranean climate zone, which is characterized by relatively low temperatures, to the semiarid and arid zones that have higher temperatures.

Since 1990, temperature and rainfall, as well as soil properties and geomorphological processes (details below), have been monitored along a sharp climatological transect in Israel (Figure 1) from the Judean mountains near Jerusalem, (mean annual rainfall 700 mm and mean annual temperature $17\,^{\circ}C$), over a distance of 35 km to the Dead Sea area (mean annual rainfall <100 mm and mean annual temperature $23\,^{\circ}C$).

Figures 2 and 3 shows the daily rainfall distribution at three sites along this transect representing Mediterranean climate (Giv'at Ye'arim; GIV), mildly arid (Mishor Adumin; MIS) and arid climate

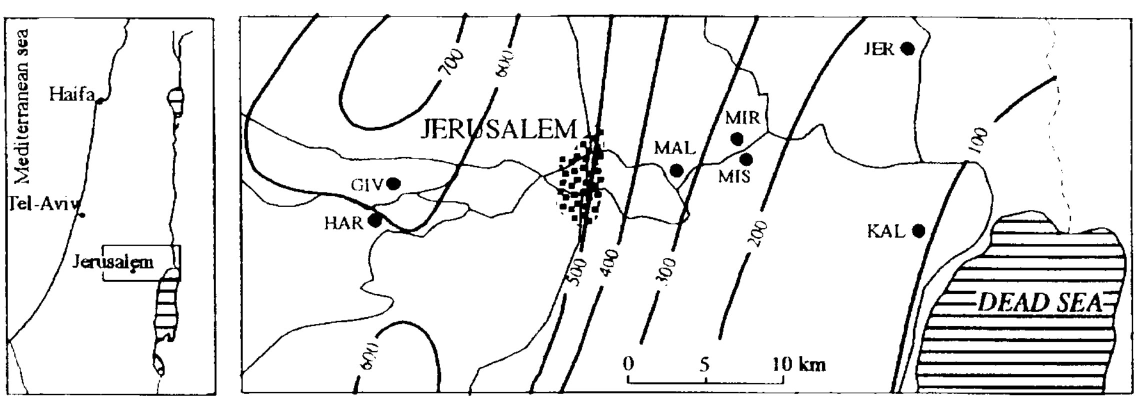

Figure 1. Location of research sites along the climatological transect (mean annual rainfall, in millimetres, is indicated by isohyetes).

conditions (Kalia; KAL). Figure 2 presents an example of a rainy winter, 1991–92, in which rainfall amounts were about twice the annual mean, while Figure 3 presents an example for the relatively dry winter of 1993–94.

Analysis of the distribution of rainfall events, on the basis of the definition of a 'rainfall event' including the requirement of having an interval of at least one hour between two consecutive rain events, shows that:

1. An average rainfall event in the arid site (KAL) lasts for less than 30 minutes and the duration increases with increasing mean annual rainfall and reaches more than two hours at the Mediterranean climate site (GIV) (Figure 4).
2. The intervals between rainfall events increase with aridity (see Figure 5). The median interval lasts about three days in the Mediterranean climate zone, five days in the mildly arid zone and seven days in the arid zone. A similar trend was found by Kutiel (1985).

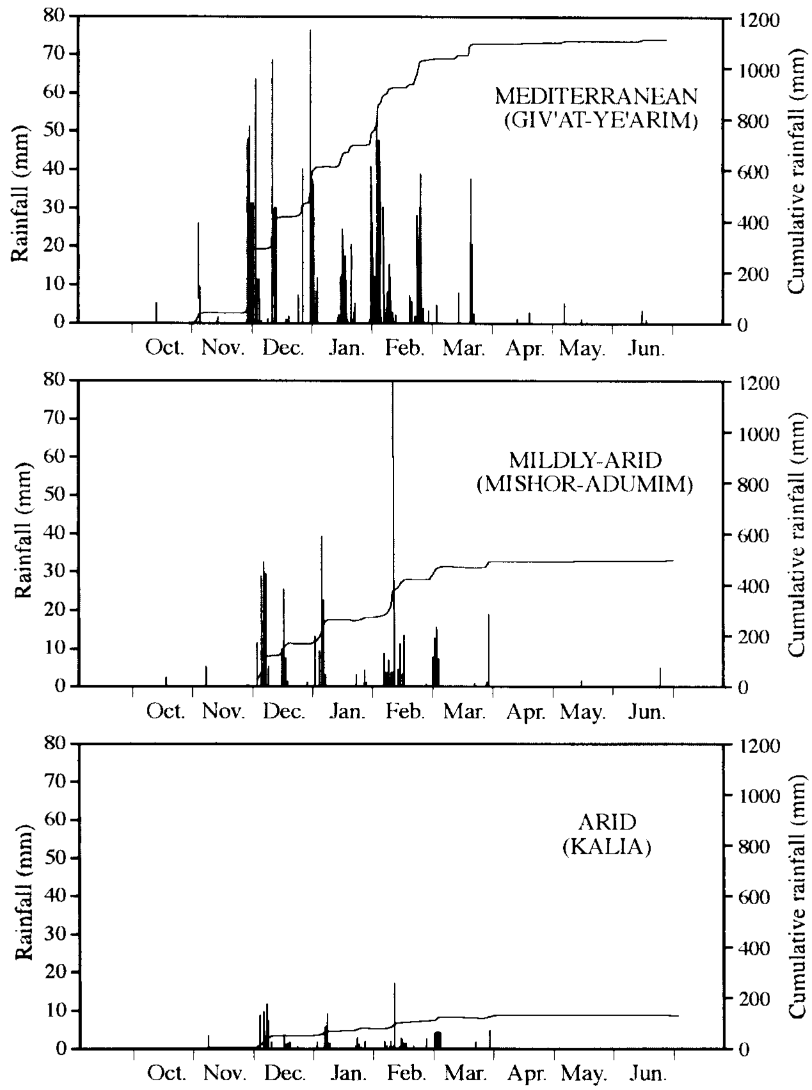

Figure 2. Daily rainfall distribution of a very wet year, 1991–92, at three stations along the climatological transect.

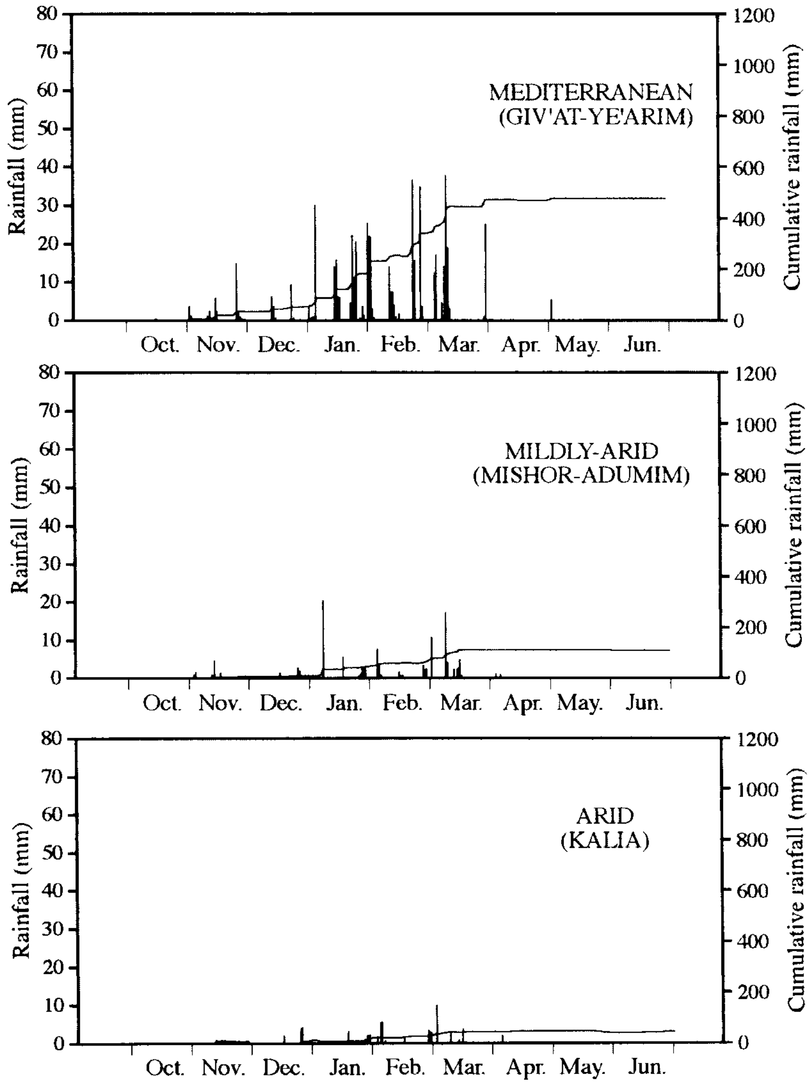

Figure 3. Daily rainfall distribution of a relatively dry year, 1993–94, at three stations along the climatological transect.

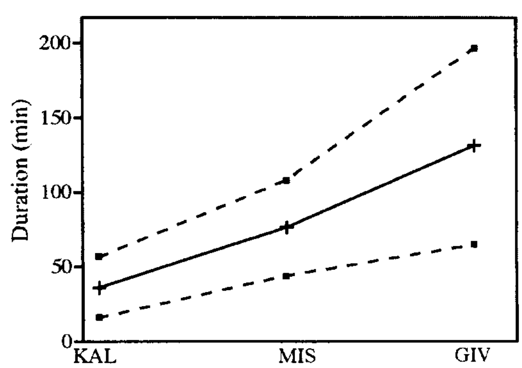

Figure 4. Average rain event duration at the arid (KAL), mildly arid (MIS) and Mediterranean climate (GIV) sites. The dashed lines represent the confidence interval.

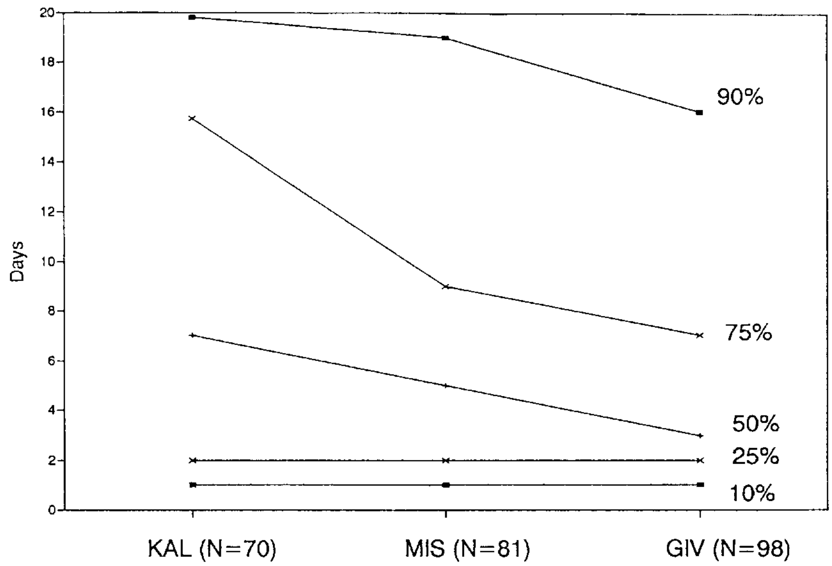

Figure 5. Distribution (by percentiles) of the duration of intervals (in days) between rain events at three stations along the climatological transect. Each line represents the percentage of intervals that lasted less than a certain duration.

Sharon and Kutiel (1986) found that the percentage of the total annual rainfall, falling during peaks >30 mm h^{-1}, increases with aridity. These features – decreasing annual rainfall amount and duration of rainfall events, and increasing rainfall intensities and intervals between rainfall events, together with increasing temperature – are from a geomorphological point of view, the most important features of climate change regarding increasing aridity.

THE CLIMO-ECOGEOMORPHOLOGICAL SYSTEM

Unraveling the response mechanisms, within the soil–water–vegetation–erosional system, (termed here the 'ecogeomorphologic system') to changes in climatic conditions in the direction of increasing aridity constitutes the object of the present research.

A decrease of annual rainfall (see Figure 6) and increase of intervals between rain events, especially when coupled with increasing temperature, will lead to less available water for vegetation germination and growth and for microbial activity (Thornes, 1985); the organic matter content in the soil will decrease and soluble salt concentration increase, mainly due to an increase in sodium content (Imeson, *et al.*, 1982). These are very rapid responses. In the long-term, the clay content in the soil will decrease. That will affect aggregation processes: aggregate size and stability will decrease (Reid and Goss, 1981; Tisdall and Oades, 1982; Rengasamy and Olsson, 1991). All of this will lead to lower water holding capacity, lower permeability, higher probability of crust formation (Farres, 1978), and thus to a dramatic decrease in infiltration rates (Dunne, *et al.*, 1991; Lavee, *et al.*, 1991), even if rainfall intensity does not increase. The result is less water in the root zone, and more water moving as overland flow and eroding the most fertile topsoil layer (Bryan, *et al.*, 1984; Imeson, 1986; Kirkby, 1987; Thornes, 1990). Consequently the seedbank and nutrients content diminish, and a second cycle of decreasing soil organic matter content starts. This positive feedback leads to desertification.

FIELD INVESTIGATIONS

In order to investigate the relationships between climatic conditions and the quick response processes and variables mentioned earlier, seven research sites were established on hillslopes along the climatological

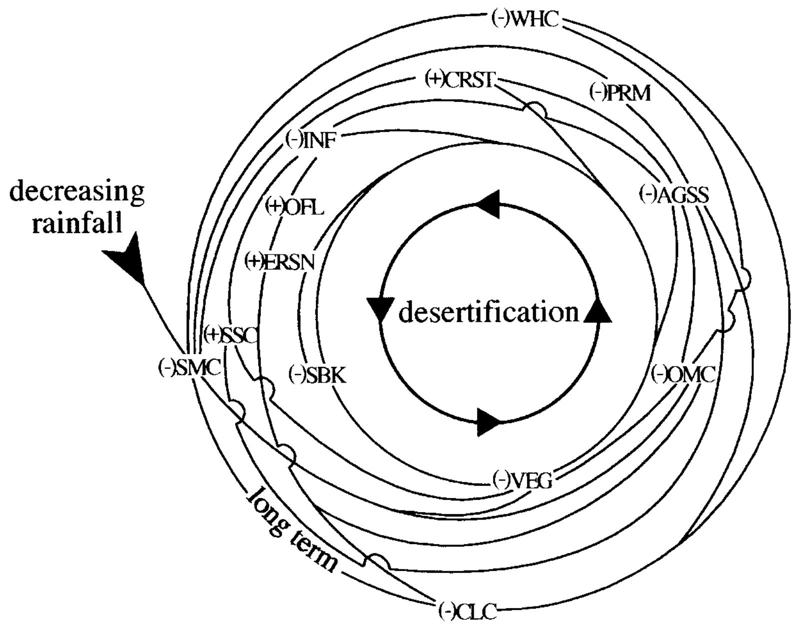

Figure 6. Interrelationships within ecogeomorphological system in response to climate change. The lines connect between variables/processes that have direct relationships. AGSS = aggregate size and stability; CLC = clay content; CRST = crusting; ERSN = erosion; INF = infiltration; OFL = overlandflow; OMC = organic matter content; PRM = permeability; SBK = seedbank; SMC = soil moisture content; SSC = soluble salts content; VEG = vegetation; WHC = water holding capacity.

transect. All have a similar lithology (limestone), similar gradient, and similar aspect. The sites differ in their elevation above sea level and climate conditions (Table I). At sites GIV, MIS and KAL instrumented plots were established, containing rain gauges, temperature probes at 30 cm above the ground surface and 5 cm and 20 cm beneath the surface, 18 gypsum blocks for measuring soil moisture, 9 blocks at 5 cm depth and 9 blocks at 20 cm depth, 3 runoff plots having different lengths, and runoff and sediment collectors. The instruments were connected to data-loggers.

Soil samples, taken from each site four times a year, to represent the different seasons, were taken to the laboratory to determine physical and chemical soil properties such as aggregate size and stability, organic matter content and soluble salts ions concentration. Rainfall simulations were conducted in the field and the laboratory.

For any variable, the regional scale spatial variability, i.e. the differences between climatic zones of the overall average for each zone (for all seasons and for the several samples of each sampling date), reflects

Table I. Basic characteristics of the studied sites

Site	Mean ann. Rainfall (mm)	Mean ann. Temp. (°C)	Elev. a.s.l. (m)	Slope grad. (deg.)	Orient. (azim.)
Giv'at Ye'arim (GIV)	620	17	650	13	142
Har Hatayasim (HAR)	600	17	740	12	150
Ma'ale Adumin (MAL)	330	19	330	13	145
Mishor Adumin A (MIS)	260	20	230	11	140
Mishor Adumim B (MIR)	260	20	270	11	135
Jerico (JER)	180	23	−70	14	140
Kalia (KAL)	120	23	−60	12	150

the long-term effect of average climatic conditions at each of the zones. The temporal variability, i.e. the differences, at each zone, between average values of seasons and/or years, reflect the short-term effect of climate conditions; and the plot scale spatial variability, i.e. the differences between values obtained at each research plot (zone) at each sampling date (season), reflects the functioning of the systems in terms of the patterns of water redistribution.

REGIONAL SCALE SPATIAL VARIABILITY

Figures 7 to 12, which are based on field and laboratory experiments, show the averages of several variables and processes change along the climatic transect. The results lead to two main conclusions.

The first one is that there is a high correlation between the average climatic conditions and the relevant variables and processes. Average soil organic matter content decreases with aridity (Figure 7) while average soluble salts concentration increases with aridity (Figure 8). Average aggregate stability decreases sharply with aridity (Figure 9) and so does the infiltration rate (Figure 10). Runoff increases from the Mediterranean site towards the arid sites (Figure 11), and the runoff coefficient is almost zero in the Mediterranean site and increases with aridity (Figure 12). These trends are a result of the different average climatic conditions that

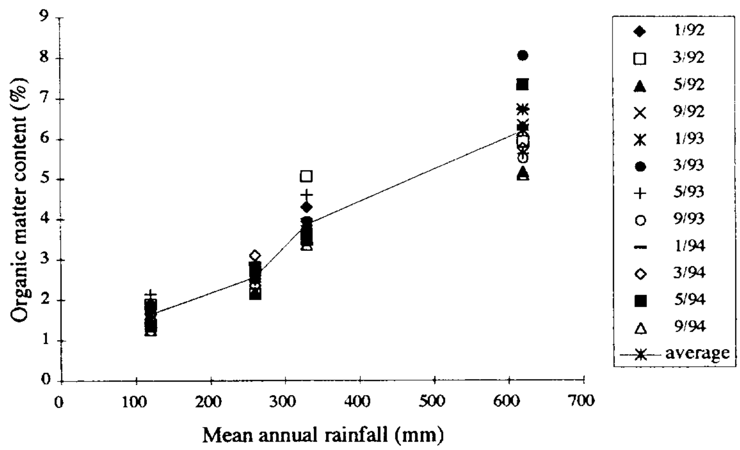

Figure 7. Organic matter content in the soil (0–2 cm depth) at several sites along the climatological transect. Each site is represented by the mean annual rainfall at the site. Each point is the average of several samples (at least six) that were taken at each sampling date.

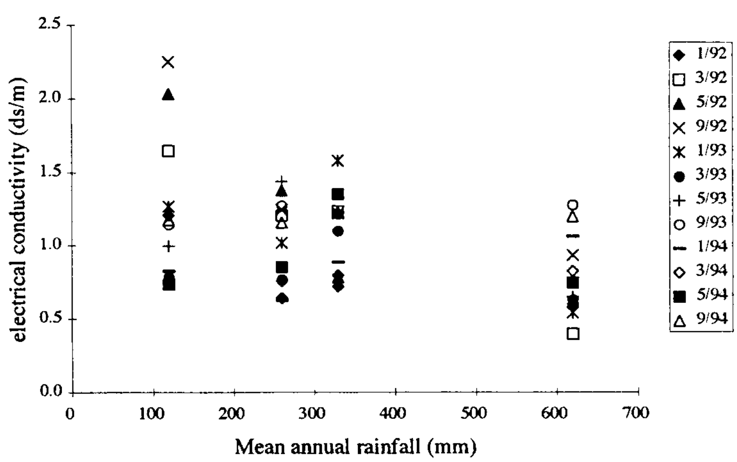

Figure 8. Electrical conductivity variations along the climatological transect. Each point is the average of several samples that were taken at each sampling date.

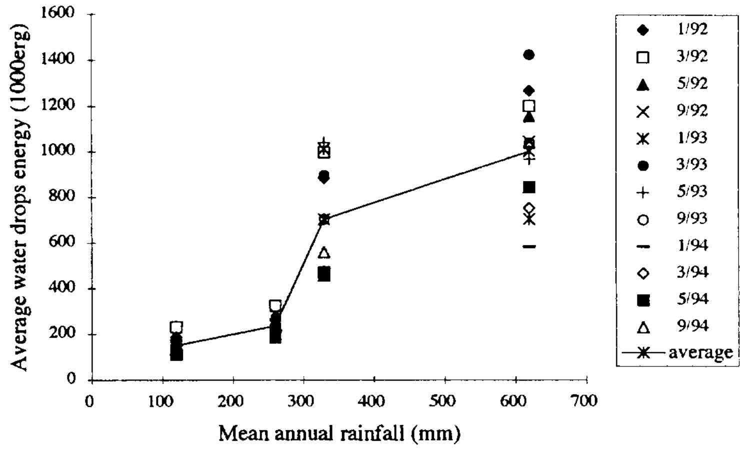

Figure 9. Aggregate stability variations along the climatological transect. The aggregate stability is represented by the average energy needed to destroy aggregates. From each soil sample 30 aggregates, 4–5 mm in size, were tested, using the single drop test. The average of the 30 aggregates was averaged for the several soil samples that were taken at each site at each sampling date. This average of averages is represented by each point in this figure.

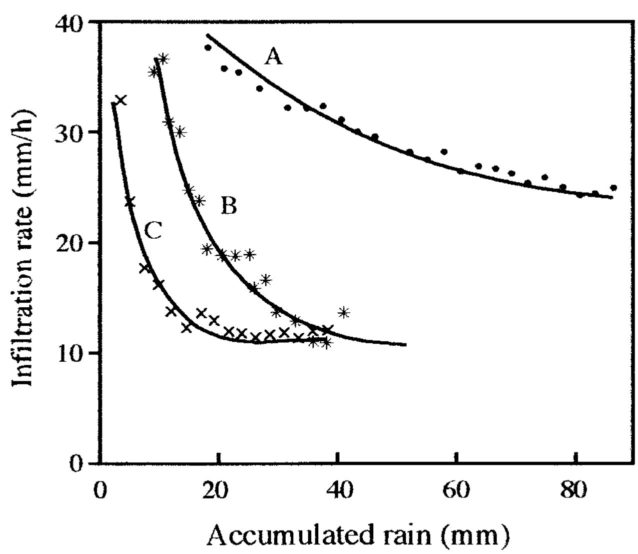

Figure 10. Infiltration curves typical for the Mediterranean-semiarid (A), mildly arid (B), and arid (C) areas along the climatological transect (after Lavee, *et al.*, 1991).

exist, for a relatively long period of time, at the different climatic zones along the climatological transect, which led to the development of different soil types and vegetation communities.

The second conclusion is that the rate of change of most of the variables and processes along the climatic transect is non-linear. A steplike threshold exists at the semiarid area (about 300 mm annual rainfall), which sharply separates the Mediterranean and arid ecogeomorphic systems. This can be clearly seen regarding the organic matter content (Figure 7), the aggregate stability (Figure 9) and the overland flow (Figure 11). This threshold at the semiarid zone means that only a relatively small climatic change is needed to shift the border between the Mediterranean and the arid ecogeomorphic systems. As many Mediterranean climate and semiarid regions lie adjacent to ones, they are threatened by desertification, even by a small climatic change

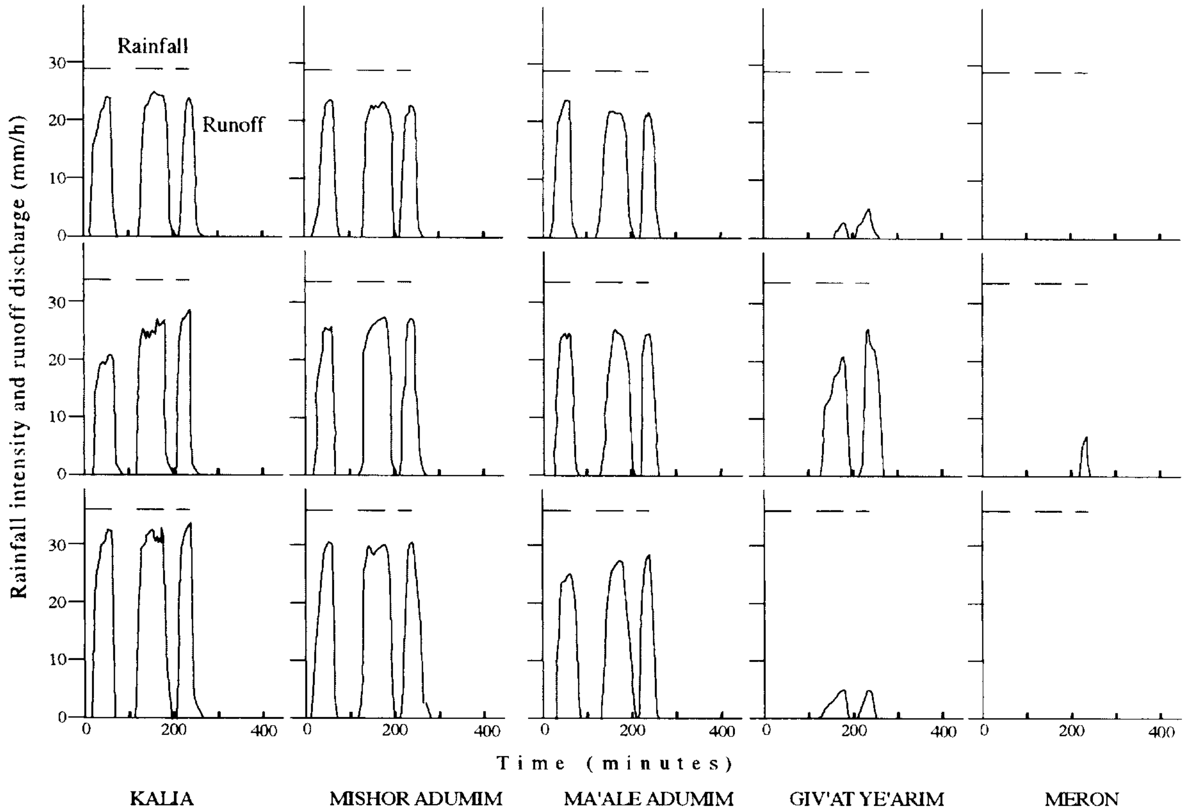

Figure 11. Runoff obtained in laboratory rainfall simulation experiments that were conducted on soils from several sites along the climatological transect and from Mount Meron in the Upper Galillee, Israel, where mean annual rainfall is 900 mm. For each of the soils three parallel experiments were conducted, each consisting of three rain showers.

PLOT SCALE SPATIAL VARIABILITY

The spatial redistribution of rainfall at the plot scale, at each of the main climatic zones along the climatic transect, depends on the level of values and on the spatial variability of the factors affecting rainfall–infiltration relationships, especially soil organic matter and aggregate stability.

The Mediterranean Climate Zone

At Giv'at Ye'arim, the temporal variability of soil organic matter (Figure 7) and aggregate stability (Figure 9) is relatively high. The spatial variability of these two soil properties (Figures 13 and 14, respectively) is also relatively high. This relatively high heterogeneity is a result of degradation of this site due to a long history of intensive grazing, until about 40 years ago, that destroyed most of the trees and left behind mainly shrubs and some bare soil patches. Nevertheless, despite this heterogeneity, due to the dense vegetation cover and to the fact that even the lowest values of organic matter content and aggregate stability are high enough to cause high permeability and to prevent crust formation, most of the raindrops infiltrate at the points where they hit the soil surface. This explains the very small amount of overland flow (Figure 11) and the close to zero runoff coefficient (Figure 12) at this site. Over similar but non-degraded Mediterranean climate soils, such as at Mount Meron in the Upper Galillee where average rainfall is 900 mm, almost no overland flow was generated in the laboratory (Figure 11).

This means that in Mediterranean ecogeomorphic systems, in spite of containing different ecological patches, from the geomorphological viewpoint of probability for overland flow generation, the entire area

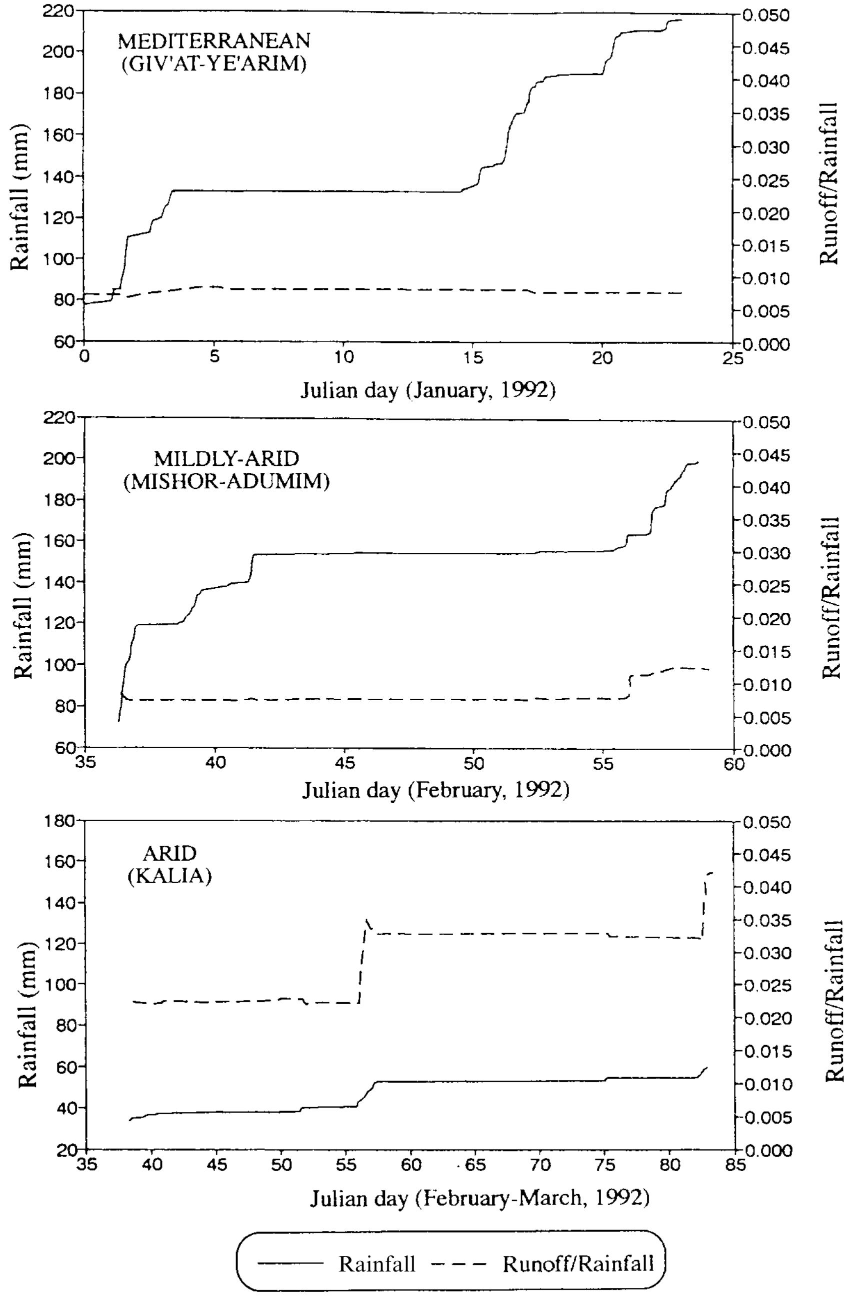

Figure 12. Accumulated rain and runoff coefficient at three research stations along the climatological transect. The runoff coefficient was calculated on the basis of measurements at runoff plots, 3 m wide and 21 m long.

behaves uniformly as infiltration is the dominant process all over the hillslope. This conclusion is in agreement with the previous conclusion (Whipkey, 1965; Kirkby and Chorley, 1967; Dunne and Black, 1970) that in humid areas overland flow is generated only when and where saturation conditions have been reached.

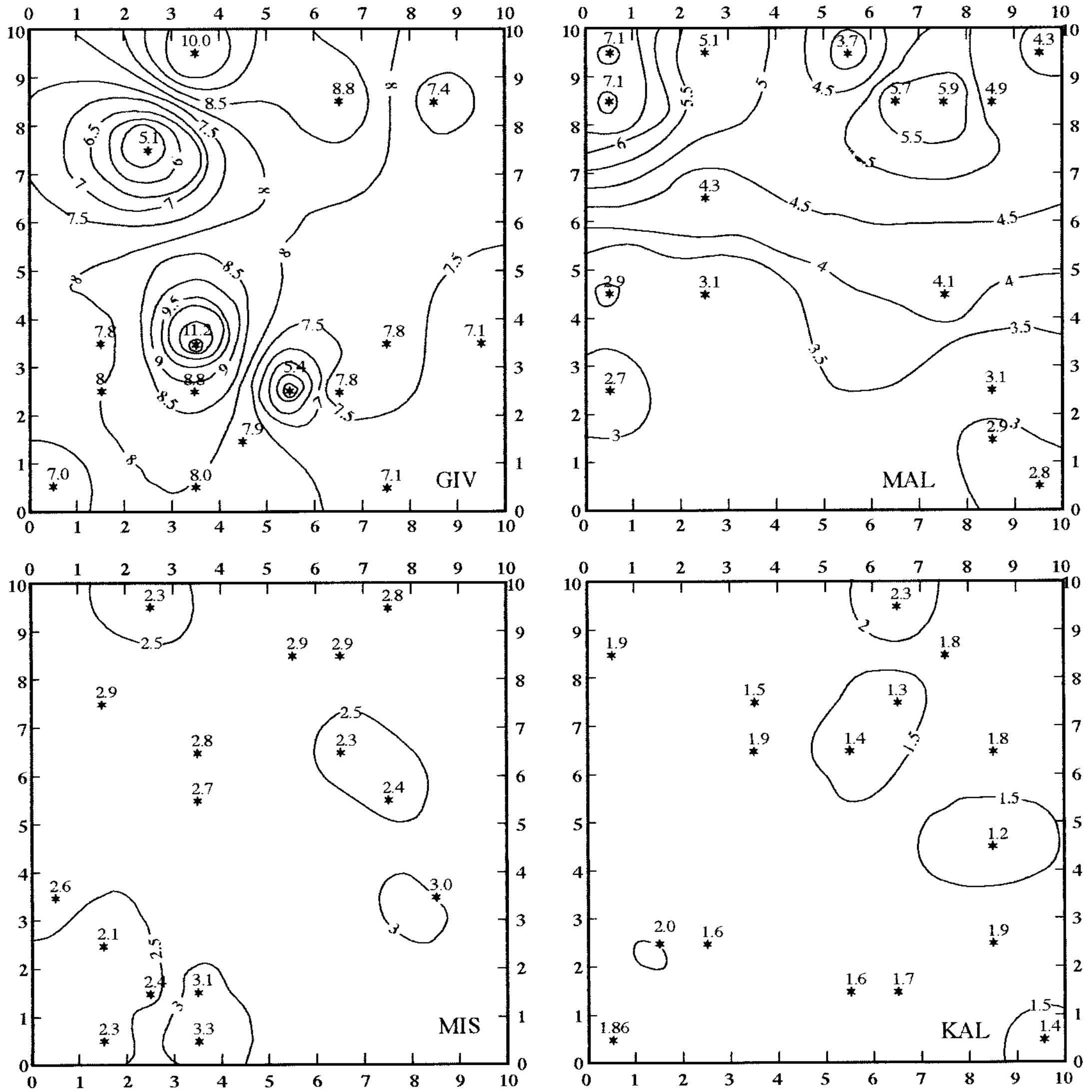

Figure 13. The spatial distribution of organic matter content (%) at four research sites along the climatological transect. The maps are based on 16 soil samples that were taken at each site on March 1993 from a plot, 10 × 10 m in size.

The Arid Zone

In the arid sites, Mishor Adumim and Kalia, the temporal variability of organic matter content (Figure 7) and aggregate stability (Figure 9), as well as their spatial variability (Figures 13 and 14, respectively) are very low. Due to the low aggregate stability and organic matter content, and the almost absence of vegetation cover, the infiltration rate is dramatically low (Figure 10), and overland flow is large (Figures 11 and 12) over the whole area.

An interim conclusion is that the spatial response to rainfall of both the Mediterranean climate and the arid systems is homogeneous, but in opposite directions. While in the Mediterranean climate zone infiltration is the dominant process all over the area, in the arid zone overland flow is generated over the whole area. Nevertheless, in the arid zone the overland flow is discontinuous at the hillslope scale due to both rainfall and surface properties. Lavee and Yair (1990) showed that as the overland flow is of Hortonian-type

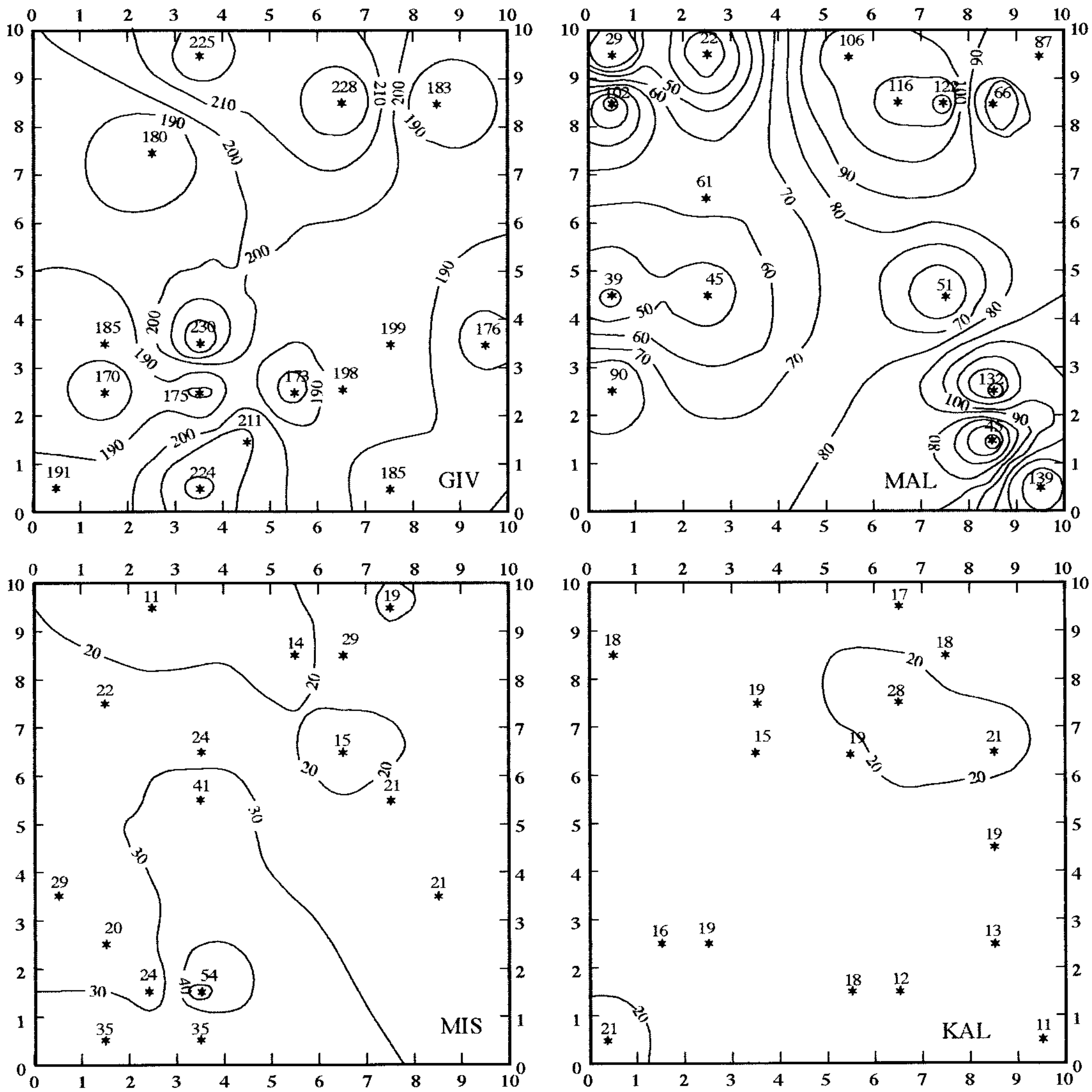

Figure 14. The spatial distribution of aggregate stability (average number of drops needed to destroy an aggregate) at four research sites along the climatological transect, March 1993.

(rainfall excess over infiltration) and rain events are typically very short, the soil is relatively dry and the infiltration rate is high even at the end of the rain event. Taking into account that overland flow velocity is in the order of 0·5–3·0 m/min, the overland flow runs only a short distance, usually not greater than 20–30 m before infiltrating into the shallow soil. Overland flow that has been generated at the upper part of the hillslope will hardly reach the channel. This is even more so if and when the lower hillslope is covered by a colluvium having a high infiltration rate. This explains why overland flow yields from both short and from long runoff plots were in most cases very similar (Yair and Lavee, 1985; Lavee and Yair, 1990).

The Semiarid Zone

The boundary area between the arid zone and the Mediterranean climate zone, i.e. the semiarid area, is characterized by high temporal and spatial variability of organic matter content and aggregate stability

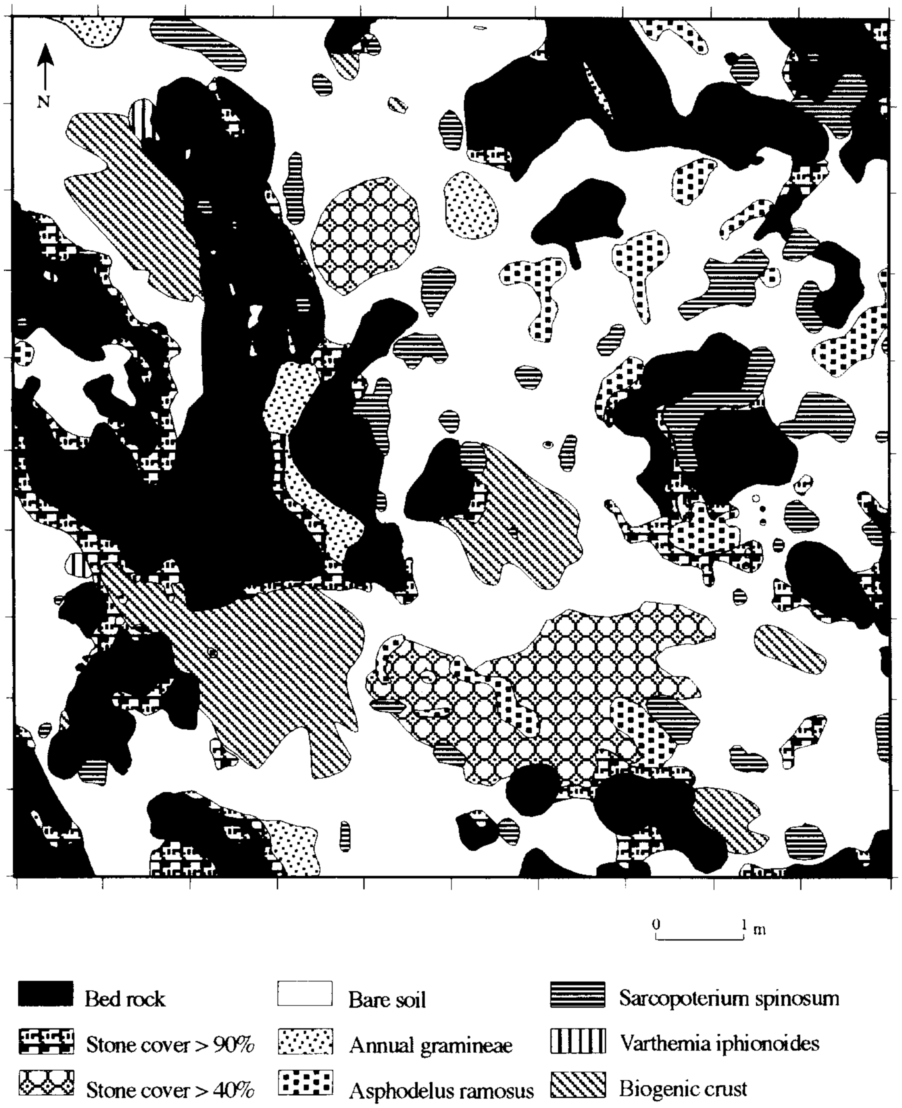

Figure 15. Spatial distribution of surface characteristics in a 10 m × 10 m plot at the semiarid site (Ma'ale Adumin, MAL); March 1993.

(Figures 7, 9, 13 and 14). This high variability reflects the spatial heterogeneity of surface characteristics and the existence of different patches which are controlled mainly by the spatial distribution of shrubs, stones, several types of crusts and a bare soil (Figure 15).

These different patches function differently regarding their response to rainfall and their effect on water conservation and redistribution. At some patches, such as those dominated by a bare soil, a mechanical crust or big stones, especially when partly embedded in the topsoil (Lavee and Poesen, 1991), overland flow generations is the dominant process. At other patches, like those covered by shrubs, mosses or small stones that lie on the soil surface, the rainfall plus the overland flow from adjacent patches infiltrate into the soil. In other words, the semiarid area is characterized by a mosaic-like pattern, containing 'arid'/'dry' patches that contribute overland and 'humid'/'wet' patches that accept overland flow. Within such a mosaic the different patches might be distributed regularly, in clusters, or randomly.

Similar spatial patterns and functions have been reported in several semiarid areas by Mabbutt and Fanning (1987), Schlesinger, *et al.* (1990), Tongway and Ludwig (1990), Cornet, *et al.* (1992), Montana (1992), Gallardo and Schlesinger (1992), Moeken and Shachak (1994), Sanchez and Puigdefábregas (1994), Dunkerly and Brown (1995), Thiéry, *et al.* (1995) and Bergkamp, *et al.* (1996).

SUMMARY AND CONCLUSIONS

Figure 16 presents the different water redistribution processes and spatial patterns under different climatic conditions, from arid through semiarid, to humid zones.

The Mediterranean climate zone, having between 450 mm and 700 mm of rainfall per year, may belong to the semiarid or to the humid type system, depending on the degree of human interference; through introducing fires, grazing or deforestation.

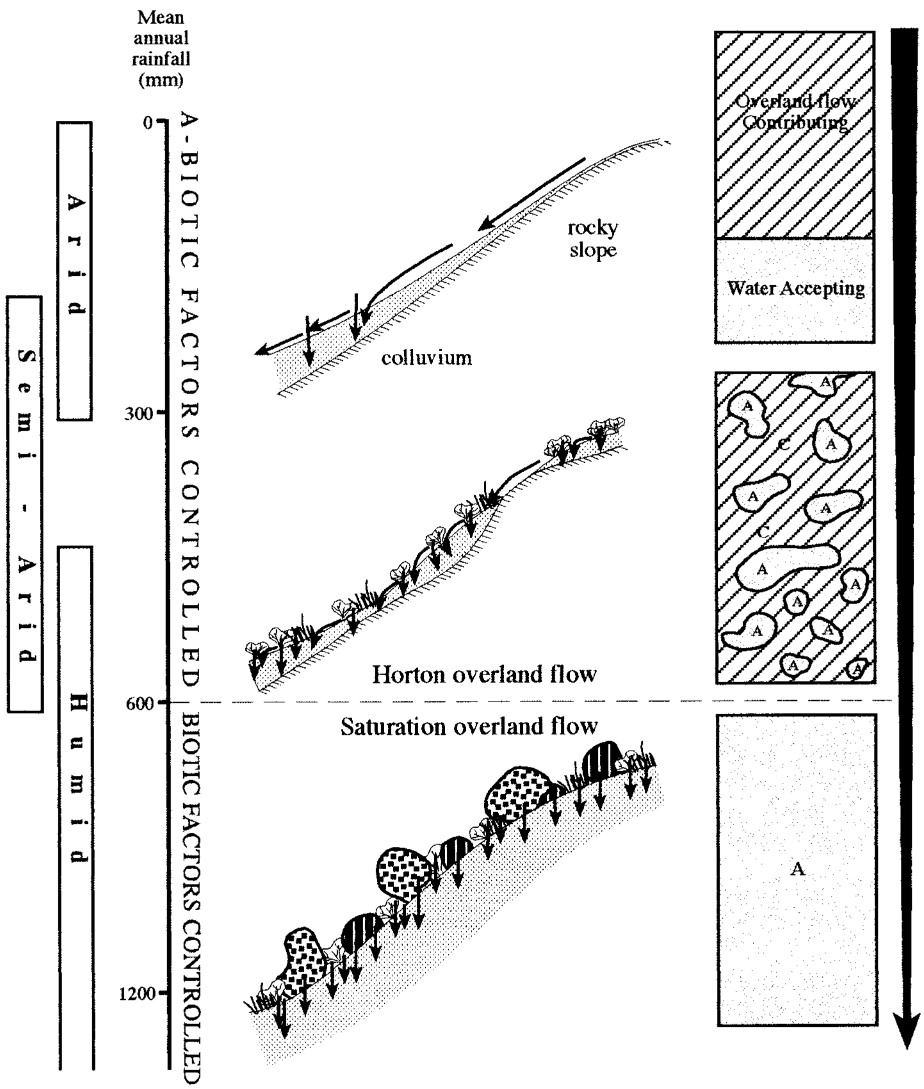

Figure 16. Rainfall redistribution under different climatic conditions (A = water accepting area; C = overland flow contributing area).

A sharp threshold separates the arid ecogeomorphic systems, controlled by abiotic factors such as soluble salts content and mechanical crust formation, from the humid ecogeomorphic systems, controlled by biotic processes such as plant growth, microbial activity and organic matter production and decomposition.

From the functional point of view of conserving water resources for germination and vegetation growth, the humid system has enough rainfall. Thus the entire hillslope can absorb the rainfall and vegetation cover can reach 100 per cent. Spatial differences in water uptake can be observed only at a scale smaller than a patch. Hortonian overland flow usually does not develop, unless saturation has been reached.

The semiarid area has not enough rainfall to maintain 100 per cent vegetation cover. Thus overland flow contributing areas and water accepting areas develop. The rainfall amount is enough to support vegetation growth in the accepting areas if the contributing areas have a size of patch that is between 0·25 m^2 and 3 m^2.

Under arid conditions, the redistribution of water can be observed only at the hillslope scale. A water contributing area having the size of a patch is not enough to maintain perennial vegetation growth due to the low amount of rainfall. The entire upper part of the hillslope contributes overland flow, sediments and nutrients to the lower colluvial section, and in some cases the whole hillslope contributes overland flow to the channel, and the perennial vegetation is limited to the channel area only.

If climate change should lead to a decrease in available water in the ecogeomorphic system, the spatial distribution of surface cover components might be changed in the following ways.

Mediterranean climate systems will lose their trees and some shrubs and only the stronger shrubs will survive. Mechanical and biogenic crusts will appear at the open bare soil patches that will develop. These patches will function as water and sediment contributors and the spatial pattern will become similar to that of semiarid areas. Increasing human pressure in response to resources degradation will accelerate this process.

In semiarid areas the size of the accepting patches will decrease due to both less direct rainfall on the accepting patches and less water supply from the contributing patches. The plants at the lower part of the accepting patches will die. Such a mechanism will cause a gradual increase in the size of the contributing patches and the disappearance of all shrubs from the drier upper part of the hillslope. As the erosion rate increases, more stones and bedrock outcrops will appear at the surface. Most if not all of the hillslope will become a contributing area. In such a way, the semiarid systems will become true arid ones.

In conclusion, the absolute size of each contributing unit, as well as the ratio contributing/accepting area, increase with aridity. Changes in these factors together with a change in the spatial patterns of contributing versus accepting water areas can be used as indicators of desertification. Moreover, the results are of great relevance for rehabilitation strategies as they illustrate how valuable the vegetation–soil mosaic is in trapping soil moisture on slopes. Triggering the regeneration of appropriate patterns in the semiarid zone should be preferred as a more sustainable option than treating areas as homogeneous landscape units.

ACKNOWLEDGEMENTS

This reach was supported by grants of the Israeli Ministry of Science and the Arts, GSF-Forschungszentrum für Umwelt und Gesundheit GMBH, Neuherberg, Germany (DISUM-029) and the Commission of the European Community in the Climatology and Natural Hazards program (Project ERMES II-EV5V-CT91-0023).

REFERENCES

Bergkamp, G., Cammeraat, L. H. and Martinez-Fernandez, J. 1996. 'Water movement and vegetation patterns on shrubland and an abandoned field in two desertification-threatened areas in Spain', *Earth Surface Processes and Landforms*, **21**, 1073–1090.

Boeken, B. and Shachak, M. 1994. 'Desert plant communities in human-made patches – implications for management', *Ecological Applications*, **4**, 702–716.

Bolle, H.J. 1996. Global climate change and desertification, pp. 52–54 *in Abstract Book*. 28th International Geographical Congress, The Hague.

Bryan, R. B., Imeson, A. C. and Campbell, I. A. 1984. 'Solute release and sediment entrainment on micro catchments in the Dinosaur Park badlands, Alberta', *Canadian Journal of Hydrology*, **71**, 79–106.

Cornet, A., Montana, C., Delhoume, J. P. and Lopez-Portillo, J. 1992. Water flows and the dynamics of desert vegetation strips, pp. 327–345 *in* A. J. Hansen and F. di Castri (eds.), *Landscape Boundaries – Consequences for Biotic Diversity and Ecological Flows*, Springer-Verlag, New York.

Dunkerly, D. L. and Brown, K. J. 1995. 'Runoff and runon areas in pattern chenopod shrubland, arid western New South Wales, Australia: characteristics and origins', *Journal of Arid Environment*, **30**, 41–45.

Dunne, T. and Black, R. D. 1970. 'Partial area contribution to storm runoff in a small New-England watershed', *Water Resources Research*, **6**, 1296–1311.

Dunne, T., Zhang, W. and Aubury, B. F. 1991. 'Effects of rainfall, vegetation and microtopography on infiltration and runoff', *Water Resources Research*, **27**, 2271–2285.

Farres, P. 1978. 'The role of time and aggregate size in the crusting process', *Earth Surface Proceedings*, **3**, 243–254.

Gallardo, A. and Schlesinger, W. H. 1992. 'Carbon and nitrogen limitations of soil microbial biomass in desert ecosystems 1', *Biogeochemistry*, **18**, 1–17.

Imeson, A. C. 1986. An eco-geomorphological approach to the soil degradation and erosion problem, pp. 110–125 *in* R. Fantechi and N. S. Magaris (eds.) *Desertification in Europe*, Reidel, Dordrecht.

Imeson, A. C., Kwaad, F. J. P. M. and Verstraten, J. M. 1982. The relationship of soil physical and chemical properties to the development of badlands in Morocco, pp. 44–70 in R. B. Bryan and A. Yair (eds.) *Badlands Geomorphology*, GeoBooks (Elsevier), Norwich.

Kirkby, M. J. 1987. 'Modelling some influences of soil erosion, landslides and valley gradient drainage density and hollow development', *Catena Supplement*, **10**, 1–14.

Kirkby, M. J. and Chorley, R. J. 1967. Throughflow, overland flow and erosion, *Bulletin International Association of Science and Hydrology*, **12**, 5–21.

Kutiel, H. 1985. 'The multimodality of the rainfall course in Israel as reflected by the distribution of dry spell', *Archive für Meteorologie Geophysik and Bioklimatologie*, **36B**, 15–27.

Lavee, H. and Poesen, J. W. A. 1991. 'Overland flow generation and continuity on stone-covered soil surfaces', *Hydrological Processes*, **5**, 345–360.

Lavee, H. and Yair, A. 1990. 'Spatial variability of overland flow in a small arid basin', *IAHS Publications*, **189**, 105–120.

Lavee, H., Imeson, A. C., Pariente, S. and Benyamini, Y. 1991. The response of soils to simulated rainfall along a climatological gradient in an arid and semi-arid region, *Catena Supplement*, **19**, 19–37.

Mabbutt, J. A. and Fanning, P. C. 1987. Vegetation banding in arid Western Australia, *Journal of Arid Environments*, **12**, 41–59.

Montana, C. 1992. 'The colonization of bare areas in two-phase mosaics of an arid ecosystem', *Journal of Ecology*, **80**, 315–327.

Palutikof, J. P., Conte, M., Casimiro Mendes, J., Goodess, C. M. and Espirito Santo, F. 1996. Climate and climatic change, pp. 43–86, *in* C. J. Brandt and J. B. Thornes, (eds.) *Mediterranean Desertification and Land Use*, Wiley, Chichester.

Reid, J. B. and Goss, M. J. 1981. 'Effect of living roots of different plant species on the aggregate stability of two arable soils', *Journal of Soil Science*, **32**, 521–541.

Rengasamy, P. and Olsson, K. A. 1991. 'Sodicity and soil structure', *Australian Journal of Soil Research*, **29**, 935–952.

Sanchez, G. and Puidefábregas, J. 1994. Interactions of plant growth and sediment movement on slopes in a semi-arid environment, *Geomorphology*, **9**, 243–260.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A. and Whitford, W. G. 1990. 'Biological feedbacks in global desertification', *Science*, **247**, 1043–1048.

Sharon, D. and Kutiel, H. 1986. 'The distribution of rainfall intensity in Israel, its regional and seasonal variations and its climatological evaluation', *Journal of Climatology*, **6**, 277–291.

Thornes, J. B. 1985. 'The ecology of erosion', *Geography*, 222–235.

Thornes, J. B. 1990. The interaction of erosional and vegetation dynamics in land degradation: spatial outcomes, pp. 41–54 *in* J. B. Thornes (ed.) *Vegetation and Erosion*, Wiley, New York.

Thiéry, J. M., d'Herbes, J.-M. and Valentine, C. 1995. 'A model simulating the genesis of banded vegetation patterns in Niger', *Journal of Ecology*, **83**, 497–507.

Tisdall, J. M. and Oades, J. M. 1982. 'Organic matter and water stable aggregates in soils', *Journal of Soil Science*, **33**, 141–163.

Tongway, D. J. and Ludwig, J. A. 1990. 'Vegetation and soil patterning in semi-arid mulga lands of Eastern Australia', *Australian Journal of Ecology*, **15**, 23–34.

Whipkey, R. Z. 1965. 'Subsurface stormflow on forested slopes', *Hydrological Sciences Bulletin*, **10**, 74–85.

Wigley, T. M. L. 1992. Future climate of the Mediterranean basin with particular emphasis on changes in precipitation, pp. 15–44 *in* L. Jeftic, J. D. Milliman and G. Sentini (eds.) *Climatic Change and the Mediterranean*. Arnold, London.

Yair, A. and Lavee, H. 1985. 'Runoff generation in arid and semi-arid zones', pp. 183–220 *in* M. G. Anderson and T. P. Burt (eds.) *Hydrological Forecasting*. Wiley, Chichester.

