Tracers for runoff generation studies in a Mediterranean region: comparison of different scales

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Abstract Natural and artificial tracers were used to investigate runoff generation processes at different spatial scales in steep carbonate hillslopes of the Judaean Mountains, West Bank and Israel. At the 180-m^2 plot scale, artificial tracers, added to the waters of a two-day sprinkling experiment, enabled a two-component hydrograph separation emphasizing the important role of shallow surface depressions, soil cover and subsoil morphology in runoff generation. At the hillslope scale, the contents of magnesium and calcium in overland flow followed the large scatter found in the precipitation of three storm events. Tracer concentrations in subsurface sources remained rather constant with only one exception. In the 2.6 km^2 small catchment, a group of samples with low mineral content indicated dilution during storm events. During one event the temporal dynamics of deuterium provided independent evidence for storm water impact both at the hillslope and the small catchment scale. It is hypothesized that most of the hillslopes investigated act as a flood generating zone rather than as an area of pronounced infiltration and recharge to the underlying regional karst aquifer, at least during high magnitude rainfall.

Key words Mediterranean regions; overland flow; runoff generation; spatial scales; tracers

INTRODUCTION

Mediterranean catchments are generally known to produce catastrophic floods (e.g. Bull *et al.*, 1999; Camarasa Belmonte & Beltrán, 2001). Large flash floods also occur in the ephemeral streams which drain the limestone and dolomite rocks of the Judaean anticlinorium into the Mediterranean Sea (e.g. Khavich & Ben-Zvi, 1995). As the area is underlain by a major underground freshwater source for Israel, the Yarkon-Taninim aquifer (Weinberger *et al.*, 1994), hydrological research has mainly focused on groundwater recharge, whereas knowledge of flood generation processes is rather limited. Sprinkler experiments on plots with natural vegetation in the Galilee, Carmel and Judaean Mountains yielded high infiltration rates (Cerda, 1998). Infiltration rates were significantly lower over soils of bare natural hillslopes due to the formation of surface crusts (Morin *et al.*, 1989). It was found that vegetation apparently stabilizes the soil structure and prevents surface crusting. These small-scale findings, however, cannot explain flood generation mechanisms in the steep fractured carbonate headwaters of the Judean Mountains. The main unclear issue is whether floods are generated mainly by rainstorm water falling directly over rock surfaces and near-surface flow paths, or by a piston flow triggered quick reaction of a deep underground karst system.

The present study seeks for a contribution to this question through the application of tracers at different spatial scales. Very few tracer studies have investigated the generation of floods in ephemeral streams of dry regions. Dody *et al.* (1995) used environmental isotopes to evaluate the volume of surface depression storage during ephemeral floods in a 2 ha catchment in the Negev Desert, Israel. Applying end-member mixing analysis with calcium and potassium, Sandström (1996) showed that streams in the semiarid tropics of east Africa are clearly dominated by stormwater. In a 0.91 km^2 cultivated Mediterranean catchment in southern France, Ribolzi *et al.* (2000) identified three main runoff components using chloride and nitrate.

The present study area, the Judaean Mountains, consist of Upper-Cretaceous carbonate rocks—mainly dolostones (dolomites/limestones)—dipping westward towards the coastal plain of Israel where they are overlain by younger rocks up to the Quaternary. The climate is semiarid typical of the eastern Mediterranean with mean annual rainfall ranging from 500 to 600 mm. Rainstorms occur mainly during the winter season (October–April), while the summer is dry and hot. On the steep western and northwestern slopes, agricultural terraces were built to prevent soil erosion. In the absence of terraces, bare limestone outcrops dominate the steep terrain, with a discontinuous shallow soil cover. Field investigations were carried out in the south-eastern headwaters of Nahal Natuf, a 250 km^2 catchment draining steep, mountainous terrain westward towards the Mediterranean Sea (Fig. 1).

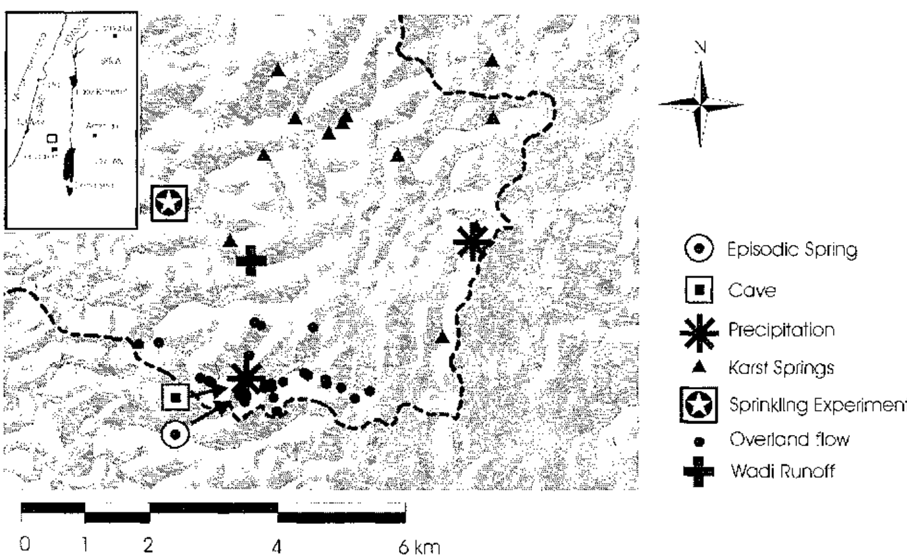

Fig. 1 Tracer sampling locations in the upper headwaters of Nahal Natuf.

ARTIFICIAL TRACERS AT THE PLOT SCALE

In a two-day sprinkling experiment over a 18 × 10 m plot of a representative steep (25%), rocky dolostone hillslope, runoff generation processes were investigated (Lange *et al.*, 2003). The sprinkling system consisted of a network of orthogonal pipes with six sprinkling units. Across the plot, 15 plastic cans with a catch diameter of 82 mm, installed 10 cm above ground, served as rainfall totalizers. All surface runoff left the plot through a pipe at its lower end and was measured volumetrically at one minute intervals. On the first day, 37 mm of rainfall were applied. Rocky parts close to the outlet responded almost immediately, but about 16 mm of rainfall were needed before the first soil pockets started to generate runoff. On the second day, 20 h later, 60 mm of rainfall were applied. A constant flow rate was measured after 16 mm of rainfall indicating almost entire soil saturation. At that time 80–90% of the applied rainfall was converted into surface runoff. To obtain additional insights into the processes of runoff generation, the anions chloride, nitrate and sulphate served as artificial tracers. Tracer concentrations were determined in the sprinkling water and, at fixed time intervals, in the surface runoff collected. The water tank supplying the sprinkling system was filled with water from different springs draining different local aquifers with different water quality. The sprinkled water in the first day contained a high concentration of chloride (195 mg l^{-1}), a low concentration of nitrate (2.3 mg l^{-1}) and an intermediate sulphate concentration (52.6 mg l^{-1}). On the second day, the sprinkled water contained significantly lower concentrations of chloride (29.5 mg l^{-1}) and sulphate (23.4 mg l^{-1}) but ten times more nitrate (21.7 mg l^{-1}). The different chemical fingerprints of the two sprinkling waters enabled the use of all three tracers for a two component hydrograph separation of the second day's runoff (Fig. 2). Using the tracers sulphate, chloride and nitrate in the end member mixing analysis, 19%, 14% and 9% of the first day waters, respectively, were identified in the total runoff volume collected during the second day. All three tracers indicated that during the second day, both first day and second day waters were mixed in the saturated soil storage and later contributed in variable percentages to surface flow.

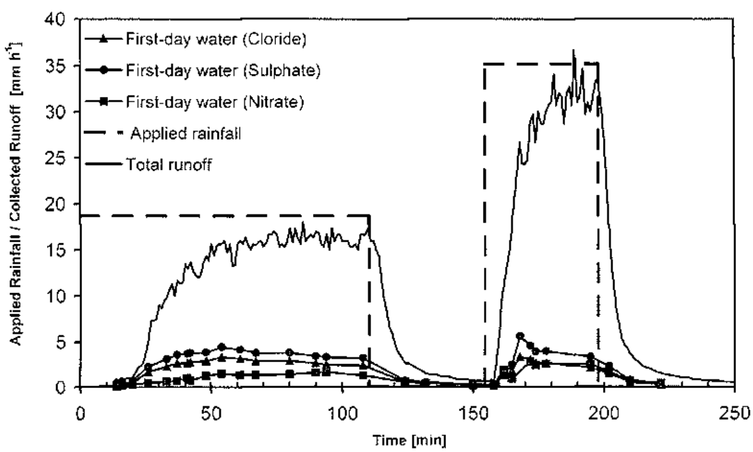

Fig. 2 Two-component hydrograph separation of runoff collected from the 180 m^2 experimental plot on the second day of sprinkling.

NATURAL TRACERS AT THE HILLSLOPE AND SMALL CATCHMENT SCALE

Calcium and magnesium

Early in the year 2000, three individual rainstorms were measured by four tipping bucket raingauges: a six-day storm with 80–100 mm of rainfall, a four-day event with 50–60 mm of rain and snow, and a four-day storm with 30–50 mm of rainfall. During these events, different water sources were sampled several times for natural tracers (Fig. 1). Precipitation was sampled at two locations. On hillslopes, samples were taken from observed continuous overland flow at 25 locations, from a small episodic hillslope spring, from dripping water inside a cave and from the standing water of a small rock-pool. These were compared with samples from channel flow runoff in a 2.6 km^2 catchment and with single samples from ten different karst springs. Among other major ions, calcium and magnesium contents were investigated (Fig. 3). As expected, the majority of the precipitation samples showed rather low contents of both ions. However, at the beginning of rain events, wet deposition of airborne dust provided high values of magnesium and calcium (more than 20 mg l^{-1} and 80 mg l^{-1}, respectively). Overland flow concentrations followed the large variability of the precipitation; the enrichment of the concentrations of both ions is related to the contact with the ground. Filled by surface runoff from the hillslope during rain events, the rock pool showed similar characteristics to those of overland flow. In Fig. 3, distinct groups with high mineralization are formed by multiple samples from the ephemeral hillslope spring and the cave. Located on the same dolomitic hillslope, these underground sources showed comparable Mg/Ca-ratios. However, one isolated sample of the ephemeral spring contained only 60 mg l^{-1} of calcium. Tracer concentrations of ten different karst springs varied widely, indicating the individual character of their underground basins. The majority of the catchment-scale wadi samples had rather similar tracer concentrations, typical both for surface and underground water. A few, however, plotted inside a low concentration range only made of precipitation and overland flow (Fig. 3).

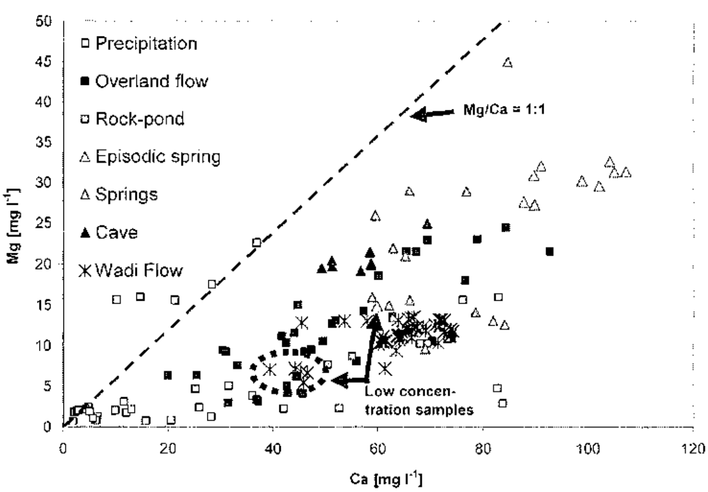

Fig. 3 Calcium and magnesium concentration of different water sources collected during three natural storm events.

Temporal dynamics of deuterium

The temporal dynamics of the same water sources were studied during the second rainfall event by deuterium δ-values against VSMOW (Fig. 4). The records of one selected raingauge showed two days of rainfall with several high intensity showers on 26 and 27 January with most of the rain falling in one isolated spell at midday on 27 January. In the following night, rain fell as snow which slowly melted during the following days as indicated by single tips of the tipping bucket raingauge. Only in the early afternoon of 29 January was additional rain recorded; the deuterium sample for this day was lost, unfortunately. During the first two days δ-values in rainfall became more and more negative reaching –50‰ during the last high intensity shower. The snow sample was even lighter (–82‰). On the hillslopes, collected overland flow followed the general trend of the precipitation with a rather large variability. The final set of overland flow samples, collected in the afternoon of 29 January, consisted of a mixture of snowmelt and newly fallen rain with unknown deuterium content. The different characteristics of the two underground sources could be detected by their deuterium dynamics. On the one hand, the dripping water inside the cave showed rather constant deuterium δ-values. The ephemeral hillslope spring, on the other, reacted to the high intensity shower of midday 27 January with a significant drop in the δ-values. The impact of this high intensity shower with its negative deuterium δ-values could also be traced in the 2.6 km^2 scale wadi runoff samples. The first two wadi samples resemble the characteristics of the precipitation and overland flow preceding this rain shower. Together with snowmelt, the shower caused a 10‰ drop in deuterium δ-values until the following day. Then δ-values gradually rose again.

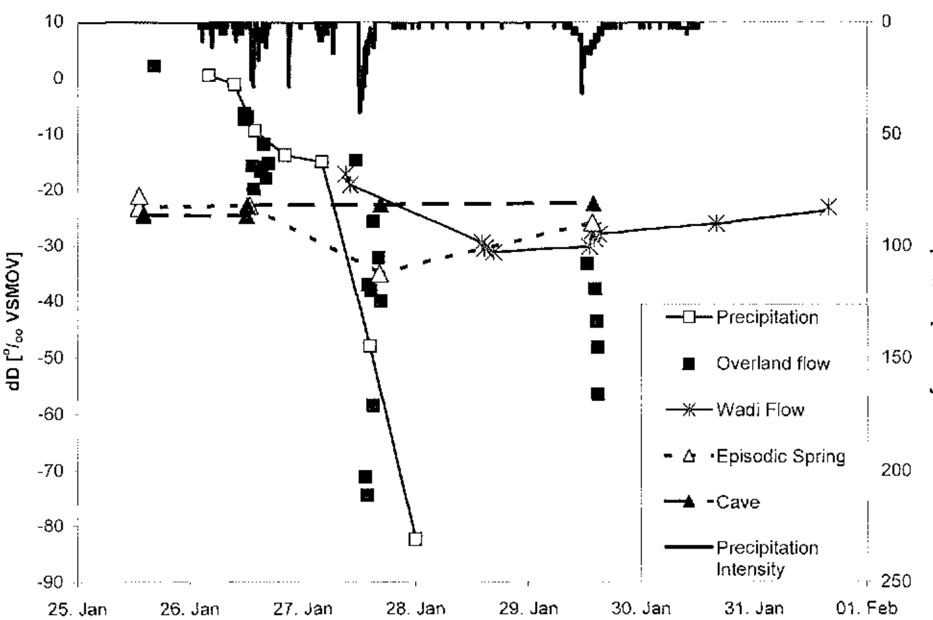

Fig. 4 Deuterium dynamics of different water sources during one storm.

DISCUSSION AND CONCLUSIONS

In a two-day sprinkling experiment on a 180 m^2 plot, three different anions facilitated a two-component hydrograph separation. Depending on the tracer used, 9–14% of the flow collected during the second day was traced to originate from water applied during the first day. For almost 20 h of this first day water had remained in hydrological reservoirs close to the surface (e.g. soil pockets or shallow rocks) and did not infiltrate into deeper underground water systems. Most of these surface reservoirs had to be filled to allow runoff generation on the entire plot. Then, 90% of the applied rainfall turned into immediate surface runoff. At the plot scale, two independent experimental findings suggested negligible deep infiltration and near-surface runoff generation. Tracers indicated that water may be stored for a long time close to the surface and quantitative measurements showed a very small infiltration rate at saturation state.

Natural tracers were used to extrapolate these plot-scale findings to the hillslope and small catchment scale. During storm events surface and underground water sources were sampled for major ions and plotted on a magnesium–calcium diagram. On this diagram precipitation and overland flow exhibited a huge variability, while multiple samples from two underground sources on the same hillslope, dripping water inside a cave and water originating from an ephemeral hillslope spring, formed rather distinct groups. These groups suggest only minimal dilution effects by rainfall water and a complete mixing and a delayed passage of the infiltrating water in the unsaturated zone. These findings correspond to those of the plot scale: effective water storage in surface reservoirs and negligible deep infiltration. Moreover, for the dripping cave water, these results are in line with those obtained by Ayalon *et al.* (1998) in the Soreq Cave, a karstic cave nearby. Measuring time lag, temperature and the isotopic concentration of water dripping from the cave ceiling these researchers could not trace a quick response to rainfall events. However, on the hillslope investigated, one isolated sample from the ephemeral hillslope spring showed considerably lower tracer contents suggesting a direct response to one high magnitude storm event. At the catchment scale, direct runoff components might also have caused the group of low concentration wadi samples. Independent evidence for these suggestions was provided by the temporal dynamics of deuterium during one storm event. Despite the very clear isotopic signal in precipitation and overland flow, no response could be identified in the cave water, while both the ephemeral hillslope spring and the 2.6 km^2 wadi followed the precipitation signal.

In general the present study shows that tracers are effective tools for investigating runoff generation in the steep carbonate hillslopes of the Judaean Mountains, at the plot-, hillslope- and small catchment scale. The following conclusions can be drawn:

- Hydrological reservoirs close to the surface (e.g. soil pockets or shallow rocks) play active roles in runoff generation. They may retain water for long periods, preventing deep infiltration and contributing to runoff generation after saturation.
- No quick passage into an underlying karst system could be found. Tracer signatures of dripping water inside one specific cave rather suggest a significant lag time in the passage of the water through the unsaturated zone.
- The importance of quick, direct, and near-surface runoff components could also be traced at the small (2.6 km^2) catchment scale. These components may either

trigger episodic water courses, as observed in the episodic hillslope spring, or act as true overland flow all along steep hillslopes.

Hence it may be hypothesized that, at least during high magnitude rainfall, most of the steep carbonate hillslopes investigated act as a flood generating zone rather than an area of pronounced recharge into the underlying regional karst aquifer.

Acknowledgements This study was funded by the Deutsche Forschungsgemeinschaft (DFG), grant no. LE-698/10.

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