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Urban hydrology in mountainous middle eastern cities

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Abstract

The Mediterranean climate together with the type of urban setting found in mountainous Middle Eastern cities generate much lower runoff yields than previously reported and than usually estimated for urban design. In fact, a close analysis shows that most of the rainwater remains within the cities as a possible source for urban groundwater recharge. The present study examined two locales – Ramallah, an old traditional Palestinian Arab town, and Modiin, a new township in Israel – both situated on the karstic Yarkon Taninim aquifer. This aquifer supplies the only high-quality drinking water in the region (one quarter of the Israeli-Palestinian water demand), which is characterized by dense populations and limited water resources. This paper provides the first measured information on the hydrological effects of urbanization in the area. It was found that the shift of the mountainous natural steep slopes into a series of closed-terraced homes and gardens created areas that are disconnected from the urban runoff response. Roofs drained into the attached gardens and created favorable recharge units. Mainly low-gradient roads became the principal source for urban runoff already following 1–4 mm of rainfall. Parallel roads converted single peak hydrographs towards multi-peak runoff responses, increasing flow duration and reducing peak discharges. The remaining urban area (public parks, natural areas, etc.) generated runoff only as a result of high-magnitude rainstorms. All of the above conditions limited urban runoff coefficients to an upper boundary of only 22% and 30% (Ramallah and Modiin, respectively). During extreme rainstorms (above 100 mm) similar runoff coefficients were measured in urban and natural catchments as a result of the limited areas contributing to runoff in the urban areas, while natural terrain does not have these artificial limits. Hence, it was found, the effects of urbanization decrease with event magnitude and there is significant potential for urban groundwater recharge. However, frequent low-magnitude rainstorms often generate highly polluted stormwater in urban sewer systems and this water should only be used with great caution.

1 Introduction

Urban hydrology is ambiguous and depends on the combined effect of local climate and urban characteristics (Trowsdale and Lerner, 2007). Impervious surfaces (roads, parking lots and roofs) control urban stormwater and cause: (i) an increase in peak discharges and volumes (e.g., Dunne and Leopold, 1978; Cheng and Wang, 2002) that in turn increases flooding risk compared to pre-urbanization hydrology (e.g., Wolman and Schick, 1967; Trimble, 1997); and (ii) deterioration of the water quality by pollution from various sources (Gnecco et al., 2005; US-NRC, 2008; Piguet et al., 2008). Worldwide water crises brought urban planners to adopt "Best Management Practices" (BMP) that prevent urban flooding and minimize stormwater pollution for further usage (e.g., Akan and Houhtalen, 2003; Ashley et al., 2007; US-EPA, 1999, 2002; Martin et al., 2007).

In urban catchments, roads are primary runoff generators. They replace natural drainage systems with relatively high runoff coefficients, limited flow capacity and higher drainage densities (e.g., Gregory and Gardiner, 1975; Ramier et al., 2004). This presumably results in increased runoff. However, some studies suggest that roads, roofs and other paved surfaces may absorb and evaporate significant amounts of rainwater (Hollis and Ovenden, 1988; Berthier et al., 1999; Ragab et al., 2003a, b). For example, in the hyperarid town of Elat, Israel, roads and parking lots were found to retain most of the rainwater (Grodek et al., 2000). In a coastal Mediterranean town with a large urban area no change in runoff peaks and volumes were detected over three decades (Garti et al., 1993). Moreover, urbanization impacts on groundwater quantity and quality were found to be inconsistent: Kondoh and Nishiyama (2000) described limited aquifer recharge, while others showed rising groundwater levels beneath a city and deteriorated groundwater quality following extensive irrigation and other losses from urban water and sewer systems (Rieckermann and Krebs, 2006; Lerner, 1989; Schot and Van Der Wal, 1992).

The population growth in Israel and the Palestinian territories (the West Bank and Gaza), from 2 million in 1950 to 11 million today, created tremendous pressure on the region's limited water resources. The Coastal Aquifer along the Mediterranean shore is heavily populated (70% of the area) and polluted (Graber et al., 2008). The less-populated Yarkon-Taninim mountainous karstic aquifer (Weinberger et al., 1994) still supplies relatively high-quality water, but in recent years aquifer levels have decreased and water quality deteriorated. And due to its karstic nature this deeper limestone aquifer is especially prone to contamination. Yet, to date there is still a complete lack of measured hydrological data concerning pollution potentially originating from urban areas located above this aquifer. Similarly, no measured runoff data exist for these rapidly expanding cities. Without such data the results of urban runoff models (e.g., Bedient and Huber, 1992; Maidment, 1993; Zoppou, 2001) largely depend on crude assumptions without the necessary justification.

This study examines and compares the hydrological characteristics of two different Mediterranean towns: (a) Ramallah (West Bank, Palestinian territories), an old, traditional Arab town, located on the top of the Judean Mountains, and (b) Modiin (Israel) a new township built at the mountains foothills (Fig. 1). Different urban settings and designs are analyzed together with their impacts on urban stormwater generation. As such a comparison is made between a traditional and a new town, it will provide guidelines towards sustainable urban water planning in this thirsty region.

2 Study area

The study area encompasses two towns, Ramallah and Modiin, situated at different locations within the vicinity of the Ayalon drainage basin (Fig. 1). At an elevation of 800 m a.s.l. Ramallah straddles the main north-south water divide of the Judean (West Bank) Mountains influencing both the surface flow and groundwater of Israel and the Palestinian Authority. Whereas groundwater below the city primarily flows eastwards, surface drainage is channeled mainly to the west (Ayalon basin), reaching the Mediterranean Sea (Fig. 1). At the water divide topography is relatively flat, but nearby it changes to steep (almost 30%) westward and eastward facing slopes. Modiin is located

15 km west of Ramallah at the mountain foothills, at elevations of 200–300 m a.s.l. The relief is dominated by a series of rounded hills with relatively steep slopes. Despite an elevation difference of 500 m, both cities are located in similar mountainous karstic lithology.

The regional climate (Csa-Koeppen classification) is characterized by: (i) November–March winter-rains (above 85% of the mean annual rain) and (ii) hot-dry summers, May–September (Table 1). During the winter, the region is affected by eastern Mediterranean low pressure systems (e.g., Goldreich, 2003), termed Cyprus Lows. They are responsible for about 95% of the rainfall over the Nahal Ayalon drainage basin (Sharon and Kutiel, 1986). The Red Sea Trough can generate short-duration rain bursts of high intensities. In rare synoptic conditions, the Red Sea Trough and Cyprus Depression act together and can influence the region by severe rainfall and floods (Dayan et al., 2001). The mean annual precipitation in the Ayalon drainage basin is about 540 mm with a range from 240 to 1200 mm in extreme years (Morin et al., 1994). Most of the precipitation (80%) occurs at relatively low intensities (under 6 mm/h); only 1% of rainfall falls with intensities exceeding 50 mm (Sharon and Kutiel, 1986). A single rainstorm may last from a few hours up to several days, characterized by several separate rain spells (minutes to hours) interrupted by dry intervals, which can last for several hours (e.g., Ramier et al., 2004).

The regional Mountain Aquifer (also termed Yarkon-Taninim) is comprised of karstified carbonate rocks (limestone, dolomite and marl) from the Cenomanian-Turonian period. Aquifer levels lie about 800 m beneath the town of Ramallah and 200 m beneath Modiin (Weinberger et al., 1994). On some slopes ancient agricultural terraces prevent soil erosion and are still used for crops and olive plantations. Where there are no terraces bare carbonate rocks dominate the steep terrain, and the discontinuous shallow soils are characterized by a xeric moisture regime. In general, there are two types of soils in the area: (i) Brown Rendzinas are rather shallow with a clay-loam texture; and (ii) reddish Terra Rossa soils of a typical clay-silt texture may extend up to a few meters in shallow depressions on top of the mountains but are usually much shallower

(National soil classification system, committee on Soil Classification in Israel, 1979). The soils contain high organic matter (2–8%) and show coarse soil texture and structure, which makes them susceptible to erosion (Mizyed, 2001). In the foothills close to Modiin, Cenomanian-Touronian carbonates alternate with less permeable chalks and marls from the Senonoian period, partly covered by Calcrete crusts (Nari) and shallow Rendzina soils.

Since biblical times, large areas of the Judean Mountains have been terraced and used for intense agriculture. As noted, some of them are still in use for small traditional farming. Overland flow remains within the leveled topography of the terraces and infiltrates into relatively deeper soils (Zgaier, 2008). Uncultivated un-terraced areas characteristically display bare rocks with only patches of soils of various depths. When these soil patches are saturated, the bare rocky slopes may generate runoff following high magnitude rainfall (Lange et al., 2003).

Ramallah (Fig. 2b, d) is a traditional Arab town built around an old quarter, which is the center for daily life and small commercial businesses. In historic times a small spring served as the main water supply. Today about 19% of the houses are connected to actively operated cisterns for drinking and irrigation in addition to the conventional water supply. Both modern and traditional houses are found around the city core. These areas also contain rural parts consisting of natural karstified landscape and cultivated terraces, mainly on the western side of the city. In the entire city only 40% of the area is connected to the stormwater draining system. In contrast, Modiin, founded in 1990, is the most rigidly planned town in Israel (Table 2, Fig. 2a, c). Planning principles included the following: (i) the steep slopes were altered into series of low-gradient roads following the contour lines and terraces were used to build residential neighborhoods; and (ii) the main natural valleys were filled and leveled for public use (i.e., main transportation routes, parks, schools and small commercial businesses). The urban sewer system carries flows from the roads to Nahal Anaba, a tributary of Nahal Ayalon (Fig. 2a, Station M).

3 Methodology

The investigation was conducted during two periods: in Ramallah during the winter seasons of 1999/2000 and 2000/2001; in Modiin preliminary work was carried out during the winter season 2001/2002 and the complete set of measurements was collated in the following winter of 2002/2003.

3.1 Maps and urban surveys

Topographic maps of 1:50 000, detailed air photographs and GIS-based data layers of roads, dwellings, etc. were obtained from both municipalities and used for high accuracy mapping of small urban segments. In addition, a 1 m resolution topographic contour map was obtained for Modiin. The natural topography prior to urbanization was available in Modiin and used to define changes created by urban development. In both cities field surveys yielded information on the use of roof water and urban stormwater.

3.2 Rainfall

Tipping bucket raingauges (ULTIMETER TB Rain Gauge fitted with Hoobo event datalogger) enabled us to precisely determine rain intensities in both towns. In Ramallah a network of nine rainfall gauges was installed to correctly measure rainfall variability caused by the sharp relief (Fig. 2b). To obtain a representative value for catchment rainfall CR (mm) the following relation was used (Sharon 1970; Sharon 1972; Arazi et al., 1997; Sharon and Arazi, 1997):

$$\mathrm{CR} = (\mathrm{MR} + \mathrm{VR})/2 \qquad (1)$$

where: MR (mm) is the average rainfall collected by the mountain stations and VR (mm) is the average rainfall collected by valley stations.

In Modiin, although the built-up area is situated on steep slopes, the general topography is less accentuated and valley/hill elevation differences reach 50 m at most;

therefore, an average value of three rainfall stations was assumed to adequately represent catchment rainfall (Fig. 2a).

3.3 Runoff quantity and quality

In Modiin runoff was measured at three locations (Fig. 2). Station J was placed in a bedrock channel to measure the runoff response of a 1.1 km^2 natural first-order catchment in the town vicinity. Station I measured 5.5 km^2 of rural areas upstream from the city – small villages, agricultural fields, natural areas and adjacent roads. It was installed at the inlet of the main storm water concrete culvert (2 × 2 m) pass through the town. At the outlet of this culvert, 2.2 km downstream, Station M measured both rural runoff passing station I and the runoff created in urban parts between the stations (total contributing area: 8.4 km^2). The difference between Stations M and I yielded the amount of urban runoff from the town core (2.9 km^2), referred to as M-I. At Station M, electrical conductivity (range 0–5 mS/cm) and temperature (accuracy of 2% and 0.1%, respectively) were logged by LTC levelloggers (Solinst). These data were used to characterize urban contamination fluxes (Pellerin et al., 2008).

In Ramallah stations were distributed following a nested approach (Fig. 2b). Two neighborhoods were measured separately. Station LS (0.11 km^2) was installed inside a concrete road manhole, which was later found to have limited inlet capacity during high storms. Station WA (0.41 km^2) measured flow inside an open concrete culvert (0.6 × 0.6 m). From both neighborhoods runoff joined in the main urban storm water sewer for a short distance and flooded a large open area before being conveyed again to the urban drainage system. At this point Station L (0.69 km^2) was located inside a concrete through-flow pipe of 1.6 m diameter.

At all runoff stations pressure transducers (Druck, 0–1 m and accuracy 1%) recorded water levels at 1-min time intervals. These values were converted to discharge using HEC-RAS hydraulic modeling (US Army Corps of Engineers, 2001). Runoff coefficients, c (%) for single storm events in each station were calculated as follows:

$$c = \mathrm{Sv}/\mathrm{Rv}(^*100) \quad (2)$$

where Sv (m^3) is the total runoff volume measured per event and Rv (m^3) is the total rainfall volume obtained by multiplying average rainfall by the area of the contributing catchment.

3.4 Drainage Density Index – DDI

To quantify the urbanization impact on runoff concentration the drainage density index (DDI) is defined:

$$\mathrm{DDI} = \mathrm{DDr}/\mathrm{DDn} \quad (3)$$

where DDr is density of the urban road network and DDn is the pre-urbanization drainage density. DDn was calculated by standardized GIS-analysis (using a 25 m DTM). The total length of (theoretically existing) streams was divided by catchment area. For DDr the length of all urban roads were summarized and divided by the catchment area.

4 Results

4.1 Rainstorms

In the first season (1999/2000) the sharp relief in Ramallah generated constant differences and a close linear regression ($R^2 = 0.96$) of rainstorm totals was observed between valley and mountain stations (Table 3, Fig. 3). During the second year (2000/2001) valley stations were only partially operated, thus the catchment rainfall was evaluated using mountain stations only:

$$\mathrm{CR} = [\mathrm{MR} + (a^*\mathrm{MR}b)]/2 \quad (4)$$

where *a* (1.80) and *b* (0.57) are regression coefficients obtained during the first season. In Modiin the three raingauges showed fairly similar rainfall except during one storm under 10 mm (Table 4).

4.2 Rainfall-runoff relationships

In Ramallah a large scatter of runoff coefficients was observed for all stations (Table 3), and no clear dependency on rainfall volume could be determined (R^2 values ranging between 0.24 and 0.28; Fig. 4). The upper stations LS and WA responded almost instantaneously to 1–4 mm of rainfall, with maximum runoff coefficients of 24% and 15%, respectively. These coefficients were already calculated for moderate storms (rainfall under 42 mm). Downstream the open area a threshold of about 12 mm was required for runoff initiation at station L. There the maximum runoff coefficient of 22% was already reached for a rainstorm of 20 mm. During the largest storm (109 mm) a similar response (20% runoff coefficient) was observed. In Modiin, the runoff coefficients generally increased with total storm rainfall (Table 4, Fig. 4). In the urban station M-I the correlation was weaker with a larger scatter ($R^2 = 0.61$) than in the rural area (Station I, $R^2 = 0.89$). In Modiin, the maximum runoff coefficients reached 30% in station M-I (Fig. 4, Table 4).

4.3 High magnitude events

During the study periods one rainstorm in each town exceeded 100 mm (Table 3, 4). Both events were characterized by a distinct configuration. A few days of continuous low-intensity rainfall was followed by a short high-intensity rainfall spell (Table 5). In Ramallah a rainstorm of 107 mm occurred after a week of dry weather and included two main sub-storms: 23.5 mm within a period of 15 h and 83.6 mm within 24 h, 34 h later (Fig. 5). The first rain spell produced roughly equal runoff coefficients at all stations: LS (12.6%), WA (10.9%) and L (11.4%). The second rain spell increased the runoff volume at station LS by a factor of 3, but the runoff coefficient (14.1%) remained almost the same. This was explained by the limited inlet capacity of the stormwater culvert. At stations WA and L the runoff volume during the second rain spell was approximately 6 times higher than during the first spell and the runoff coefficient doubled, reaching 19.3% and 20%, respectively. In Modiin a rainstorm of 190.1 mm occurred after three and a half days of dry weather and was characterized by two main storm cores: 46.4 mm within a period of 18 h and 143.7 mm within a period of 17 h, 3.5 days later (Fig. 6). The first rain spell resulted in runoff coefficients of 1.8% in the rural area (Station I) and 10.1% in the town core (Station M-I). The second rain spell increased the runoff volume at Station I by a factor of 16 and the runoff coefficient by a factor of 5. At Station M-I the runoff volume was 9 times higher and the runoff coefficient increased by a factor of 3. In the neighboring natural area (Station J) runoff was generated only during the second rain spell with a runoff coefficient of 30%.

4.4 Hydrograph shape

In general, all urban hydrographs were characterized by instantaneous runoff responses, 1 to 11 min after rain onset with steep rising limbs reaching peak values after an additional 5 to 10 min. Flow recession lasted for about one hour following the cessation of rainfall. However, the geometry of the urban drainage network dictated hydrograph shape (Fig. 7): (i) a single main flow route generated single peak hydrographs (Fig. 7a; Station LS in Ramallah); (ii) a more complex road network generated secondary, smaller peaks (Fig. 7b; Station WA in Ramallah), while (iii) the new urban setting in Modiin, characterized by a dense network of parallel and perpendicular roads, generated a sequence of similar runoff peaks (Fig. 7c). Although Station I drained a large rural area, during small rainfalls only a nearby main road contributed to runoff and produced a single discharge peak. While a similar peak magnitude was observed at Station M, the larger draining road area caused a higher runoff volume and longer flow duration of sequentially arriving runoff peaks (Station I: 0.15 $\mathrm{m^3 s^{-1}}$, 65 $\mathrm{m^3}$/20 min, Station M: 0.12 $\mathrm{m^3 s^{-1}}$, 137 $\mathrm{m^3}$/90 min).

4.5 Urban pollution

In both towns the time span between winter rainstorms was a few weeks, allowing urban contaminants to concentrate on the road network. The first rain spell after a dry period flushed these contaminants away. As a result, peaks in electrical conductivity were observed at Station M in Modiin. Throughout the year (during both the rainy and dry seasons) flows from a variety of urban sources (e.g., leaks in water/sewage pipes and irrigation systems, water from car washes, etc.) were observed entering road receptors in the storm sewers of Modiin. These flows were additionally polluted by residential waste deposited in the sewer system and entered the natural river downstream the city without any treatment. An example was flow with electrical conductivity values reaching almost 4 Ms/cm in the sewer pipe in Modiin at Station M without preceding rainfall (Fig. 8), just before the first seasonal rain. Later, following natural rainfall, a typical urban runoff hydrograph was recorded with a high electrical conductivity peak documenting the first flush at the onset of urban storm runoff which diluted the urban pollution later on.

5 Discussion

Urban design on steep mountainous terrains forces planners to level topography into a series of parallel roads and terraces. The latter are used for houses with adjoining gardens, usually bounded by concrete walls. These dwelling units are hydrologically disconnected from the urban drainage system and create favorable areas for direct in situ recharge. Roofs make up about 50% of the dwelling area and normally contribute rainwater to irrigate the attached gardens. This additional water is important, especially during small rainstorms when almost all rainfall evaporates immediately. In Ramallah about 20% of the houses still use cisterns to collect rainfall from the roofs.

Excluding the dwelling units, road networks become the main source for urban storm runoff. Roads can also explain immediate runoff responses following small rainstorms

(2/3 of the rainstorms did not exceed 15 mm). Small rainstorms are totally absorbed in the surrounding natural terrains (Station J; Table 3). Relatively small runoff coefficients show that quite considerable water volumes are lost along the road or sewer systems. Hence, only marginal contributions from sources other than roads can be expected during small events. One exception is Station LS, the smallest catchment where water losses are less pronounced. A scale effect of urban runoff generation can thus be observed with higher stormwater losses in larger catchment areas. This effect is even more significant in the complex and less-organized sewer system of the traditional town of Ramallah.

Interestingly, a paradox was observed during the heaviest rainstorm in Modiin (143.7 mm; Table 5): a similar runoff coefficient (30%) was measured from both the city (Station M-I) and the natural terrain nearby (Station J; Table 3). While in town, public parks and natural areas were observed to contribute runoff, the closed dwelling units were still disconnected from the runoff response. In contrast, in natural terrain the entire catchment area could contribute to runoff. A runoff coefficient of 30% is suggested to be the maximum runoff which can be expected from mountainous Middle Eastern cities. This value is well below any textbook value usually used for urban design, In the Rational Method, for example, runoff coefficients typically exceed 50% or even 70% for downtown areas (Akan and Houghtalen, 2003).

These single extreme events dominate the seasonal water balance in the Mediterranean climate. For Modiin similar runoff rates in urban and natural areas (44 l/m^2 and 43 l/m^2, respectively) were observed. However, their annual share was markedly different. In the natural catchment (Station J) this event was responsible for almost the entire seasonal flow (96%). Previous small rainfall events were absorbed on the natural hillslopes and a seasonal threshold of about 400 mm of rainfall was required for first runoff generation. At the same time, urban areas had already reacted several times following small rain storms passing a marginal seasonal rainfall threshold of 1–4 mm. Consequently, the high magnitude storm made up only 34% of seasonal runoff. The similar runoff rates of both natural and urban areas during the most intense rainstorm is related to non-contributing areas, artificial terraces and fenced gardens, while in the natural areas, theoretically, the entire catchment may contribute runoff (e.g., Lange et al., 2003). Such a response of urban terrains may be summarized in a conceptual model, as represented in Fig. 9.

Our analyses of the impact of urbanization on runoff concentration suggest that DDI – the ratio between the natural and urban drainages densities – may be a practical tool (Table 6). Natural runoff is generated as overland flow on slopes and concentrated into channels where flows are routed downstream. In contrast, urban runoff is generated mainly on roads and only later (if the storm is large enough) other urban units add their share. In all urban stations DDr was found to be higher by an order of magnitude than DDn. Hence, the proposed index DDI may serve as a measure for the rate of hydrologic urbanization of an area. As the result of the presence of mainly agricultural/natural areas and only two small villages, the DDI index in Modiin for the rural area Station I was found to be the smallest (3.3; Table 6). The urban Station M-I had higher DDI (5.3), which was still lower in comparison with the Ramallah stations since it included recreation areas and natural reserves. In Ramallah all stations showed rather high DDIs, suggesting high urban impact.

The open area in Ramallah influenced the flow pattern between the stations WA and L by delaying the runoff response at L by almost 30 min and reducing hydrograph peaks. During small rainstorms (under 8 mm or 400 m^3) the open area in Ramallah acted as a runoff barrier detaining urban runoff from the upstream stations (Fig. 10). During larger rainstorms runoff volumes between the stations were comparable. Then, runoff losses in the open area tended to be balanced by lateral runoff contributions. During the largest rainstorm the open area also generated runoff, and the runoff volume at Station L was larger than the combined flow from Stations LS and WA. Since, urban areas respond during relatively small events, discontinuities in urban systems may be seen as favorable spots for groundwater recharge.

However, special care must be taken when managing stormwater in the investigated region for two main reasons. First, the long dry summers and the dry periods between rain events allow urban contaminants to concentrate on the road network. These contaminants reach natural rivers downstream the city (or open areas inside the town, as illustrated in the case of Ramallah) with the first rain flush.

Second, observations in Modiin proved that polluted artificial flows from various urban sources reach the storm water sewers even during times of zero rainfall. The conductivity values for such flows were found to exceed 4 mS/cm, suggesting high concentrations of various pollutants. This type of pollution can hardly be controlled and the polluted water is not diluted as it is in the case of natural rainstorms. Hence, it must be seen as an extreme hazard for the underlying karstic aquifer and for people living in areas downstream.

6 Conclusions

The two cities investigated located in mountainous terrain are typical examples of many Mediterranean towns. The following conclusions may thus serve as hydrological guidelines for urban development in this specific region.

1. Although the road network typically covers only 10–13% of the urban area, it dominates the hydrological response and the major hydrological change between urban and natural areas: (a) Roads, the first and principal urban runoff generators, respond following 1 mm of rainfall and form the only storm water source area during small to medium events. Additional urban units contribute runoff only during high-magnitude events. (b) The structure of the road network has a direct impact on hydrograph shape, runoff volume, peak discharge and lag time. Flow along parallel roads generates multi-peak hydrographs from single rainstorms with increased duration and reduced peak discharge. In well-planned modern cities this effect tends to be more pronounced than in old traditional townships.

2. The mountainous Mediterranean cities have relatively limited area for runoff generation. This phenomenon is valid for all storm magnitudes. Maximum runoff

coefficients do not exceed a certain upper limit, which can partly be attributed to artificial terraces and fenced gardens inside cities. The upper limit of urban runoff generation suggests that in both cities larger volumes of urban stormwater may contribute to groundwater recharge than expected. Here especially, open areas inside urban storm water drainage systems may add a significant portion.

3. The use of urban storm runoff requires caution, because of the reduced quality which is mainly caused by flushing pollutants from urban roads (runoff generators and distributors) or by illegal waste water disposal in the urban sewer systems. In general, the limited runoff generation from both cities implies a large potential for urban groundwater recharge. However, additional measures to monitor and improve water quality are needed to safeguard groundwater quality.

For the first time in the eastern Mediterranean, this paper provides measured hydrological data to assess the impact of urbanization in mountainous limestone terrain. In the light of a tremendous population growth, this data may help to arrive at sapient decisions for a sustainable future water management in this water scarce region.

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Table 1. Average climate data in the Ayalon basin. Note zero precipitation between May–September (Meteorological Service, Beit-Dagan station).

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Evaporation, mm/d	1.9	2.3	4.2	5.4	6.1	7.1	7.1	6.7	5.7	4.2	2.8	2
Temperature max ˚C	17.8	18.1	20.1	24.5	27	29.2	30.8	31.2	30.4	28.3	24.1	19.7
Temperature min ˚C	7.2	7.1	8.8	11.5	14.6	17.9	20.6	21.2	19.4	16	11.8	8.6
Rain, mm	140	97	66	18	2	0	0	0	0.4	20	76	130
Rain days	10.1	8.6	6.5	2.3	0.5	0	0	0	0.2	2.3	5.8	8.9

Table 2. Characteristics of different hydrometric stations (Area km^2; Length km).

Town	Station	Roofs	Roads	Roads	Nature	Private	Public	Parks
	Code km^2	Area %	Area %	Length %	Area %	Area %	Area %	Area %
Ramallah	LS	0.02	0.01	1.53	0.08			
	0.11	16.2	10.8	11.2	73			
	WA	0.1	0.05	8.69	0.27			
	0.41	23.2	13.2	21.2	63.6			
	L	0.105	0.09	12.48	0.476			
	0.69	19	13	18.1	69			
Modiin	I	0.15	0.05	29	1.8	0.04	0.15	29.5
	5.5	2.7	0.9	5.3	33	7.2	2.7	53.5
	M	0.30	0.61	40.1	0.54	0.48	0.49	0.53
	3	10.3	20.5	13.4	18.3	16.3	16.6	17.9
	J				1.1			
	1.1				100			

Table 3. Storm events in Modiin, winter 2002/2003.

	Rain,	Station I			Station M			Station J		
Storm dates	mm	Qp $m^3 s^{-1}$	Vol m^3	Runoff %	Qp	Vol	Runoff	Qp	Vol	Runoff
5/11/02	5.2	0.1	65	0.2	0.1	118	0.7	0	0	0
23–25/11/02	7.5	0.1	198	0.5	0.1	200	0.9	0	0	0
29/11/02	4.6	0.1	70	0.3	0.1	237	1.7	0	0	0
9–10/12/02	12.9	–	–	–	0.1	545	1.4	0	0	0
11/12/02	8.6	–	–	–	0.1	349	1.3	0	0	0
16/12/02	7.5	–	–	–	0.1	363	1.6	0	0	0
17–18/12/02	30.0	–	–	–	6.4	7257	8.1	0	0	0
20–22/12/02	58.3	–	–	–	6.4	28 270	16.2	0	0	0
24–25/12/02	21.2	0.2	2189	1.9	5.6	12 108	19.0	0	0	0
27/12/02	12.0	0.01	64	0.1	5.6	5240	14.6	0	0	0
31/12/02	7.1	0.1	530	1.4	0.1	1225	5.7	0	0	0
3–4/1/03	24.0	0.7	1210	0.9	11.4*	21 428	29.8	0	0	0
20–21/1/03	53.9	0.2	3982	1.3	5.8	25 690	15.9	0	0	0
4–5/2/03	15.9	0.1	897	1.0	0.9	3809	8.0	0	0	0
8–10/2/03	25.7	0.1	1441	1.0	1.0	7551	9.8	0	0	0
13–15/02/03	57.3	0.2	10 037	3.2	4.8	35 696	20.8	0	0	0
19–22/2/03	46.4	0.2	4508	1.8	6.4	14 030	10.1	0.01	2	0.01
24–26/2/03	143.7	1.5	71903	9.1	6.4	130 722	30.3	1.3	47265	29.9
27–28/2/03	17.8	–	–	–	2.9	6627	12.4	0	0	0
18–22/3/03	75.4	–	–	–	4.8	15 477	6.8	0	0	0
24–26/3/03	88.2	1.8	33 446	6.9	6.4	67 294	25.4	0	0	0
21/4/03	5.5	–	–	–	0.5	541	3.3	0	0	0
27/4/03	14.8	–	–	–	1.0	3615	8.1	0	0	0

* reconst. peak Q

Table 4. Storm events in Ramallah during winter seasones 1999/2000 and 2000/2001.

Storm dates	Rain, mm	Station WA Qp m^3s^{-1}	Vol m^3	Runoff %	Station LS Qp	Vol	Runoff	Station I Qp	Vol	Runoff
14–15/12/99	11.4	0.03	71	1.5	–	–	–	0.00	1	0.0
24/12/99	1.6	0.01	8	1.2	–	–	–	0.00	0	0.0
4–6/1/00	70.6	0.12	1485	5.0	0.02	–	–	0.13	1820	4.6
10–11/1/00	3.4	0.02	14	1.0	0.00	2	0.7	0.00	0	0.0
18–23/1/00	109.0	0.99	5433	11.9	0.25	1644	15.1	0.86	12 041	19.7
26–31/1/00	69.6	0.50	2194	7.5	0.14	1390	20.0	0.44	3415	8.8
12–14/2/00	54.1	0.32	2015	8.9	–	–	–	0.32	3065	10.1
1–2/3/00	51.7	0.46	1898	8.7	0.1	946	18.3	0.37	3446	11.9
1/12/00	6.8	0.18	174	6.1	0.07	97	14.4	0	0	0.0
9/12/00	9.3	0.07	291	7.5	0.07	84	9.1	0.004	33	0.6
11–14/12/00	31.6	0.51	1677	12.6	0.18	634	20.1	–	–	–
23–25/1/01	41.4	0.09	901	5.2	0.22	995	24.0	–	–	–
3–4/2/01	31.8	0.10	1331	10.0	0.10	607	19.1	0.342	1865	10.5
5/2/01	2.3	0.02	71	7.5	0.02	35	15.6	0	0	0.0
17/2/01	11.4	0.20	359	7.5	0.11	231	20.4	0.402	874	13.8
20–21/2/01	20.8	0.43	824	9.5	0.11	274	13.2	0.226	782	6.7
2/5/01	20.1	0.56	1293	15.3	–	–-	–	0.518	2521	22.4

Table 5. Runoff response during two high-magnitude events: Ramallah (a1–a2) and Modiin (b1–b2).

Ramallah	Pre-storm date (a1) 18–19/1/00 Volume m^3	rain 23.5 mm Runoff %	Main-storm date (a2) 20–21/1/00 Volume m^3	rain 83.6 mm Runoff %
LS	368	12.6	1.230	14.1
WA	793	10.9	4.791	19.3
L	1.853	11.4	11.566	20.0
Modiin	Pre-storm date (b1) 19–23/2/03 Volume m^3	rain 46.4 mm Runoff %	Main-storm date (b2) 24–26.2.03 Volume m^3	rain 143.7 mm Runoff %
St. I	4.508	1.8	71.903	9.1
St. M	19.121	4.8	202.605	16.6
St. M-I	14.613	10.1	130.722	30.3

Table 6. Drainage density (DDI): natural areas previous to urbanization versus roads – Modiin and Ramallah.

City	Station	Area, km^2	Channel L km	Natural Den., DDn km^{-1}	Road L km	Roads den, DDr km^{-1}	Den. index DDI DDr/DDn
Ramallah	LS	0.11	0.24	2.18	1.53	13.9	6.4
	WA	0.41	0.97	2.37	8.69	21.2	8.9
	L	0.69	1.82	2.64	12.48	18.1	6.9
Modiin	I	5.3	8.8	1.6	28.9	5.4	3.3
	M*	2.98	7.6	2.5	40.1	13.9	5.3

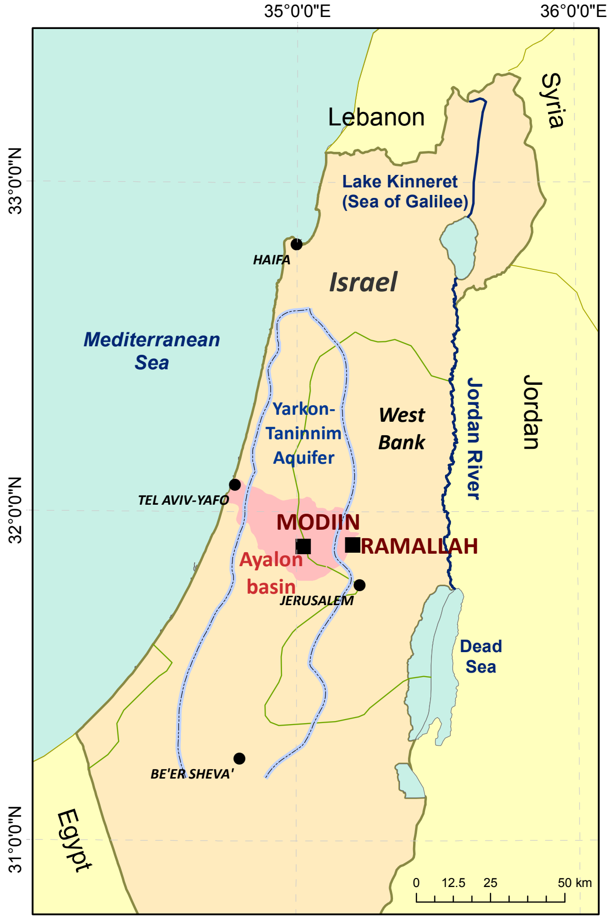

Fig. 1. Location map: the towns of Ramallah and Modiin within the Ayalon basin.

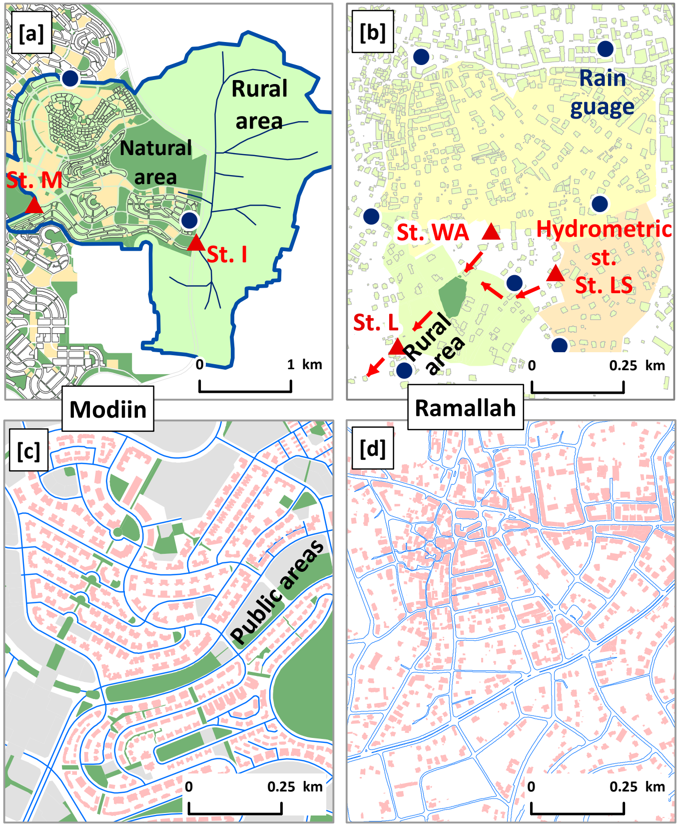

Fig. 2. (a) Modiin: The rural area upstream the town is measured by hydrometric Station I (St. I). Station M (St. M) at the town outlet measures both the rural area (measured by St. I) and urban areas; **(b)** Ramallah: Two basins are measured by the hydrometric stations WA and LS uniting through an open area at station L. Both in Modiin and Ramallah not all rainfall gauges are located in the map area; **(c)** Zoom into the urban center of Modiin and **(d)** Ramallah.

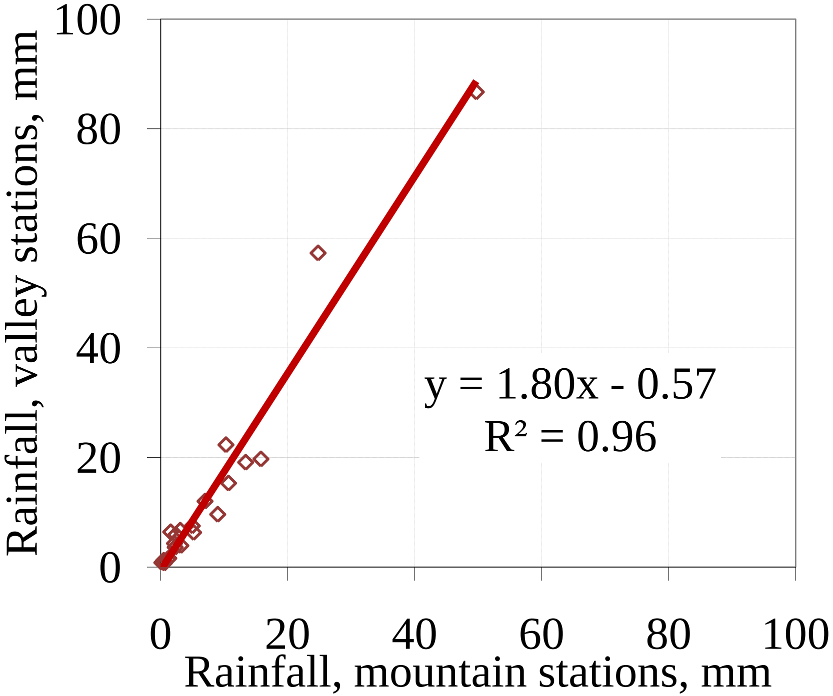

Fig. 3. Valley stations plotted against mountain stations (season 1999/2000). The analysis was performed with 22 sub-storms in Ramallah.

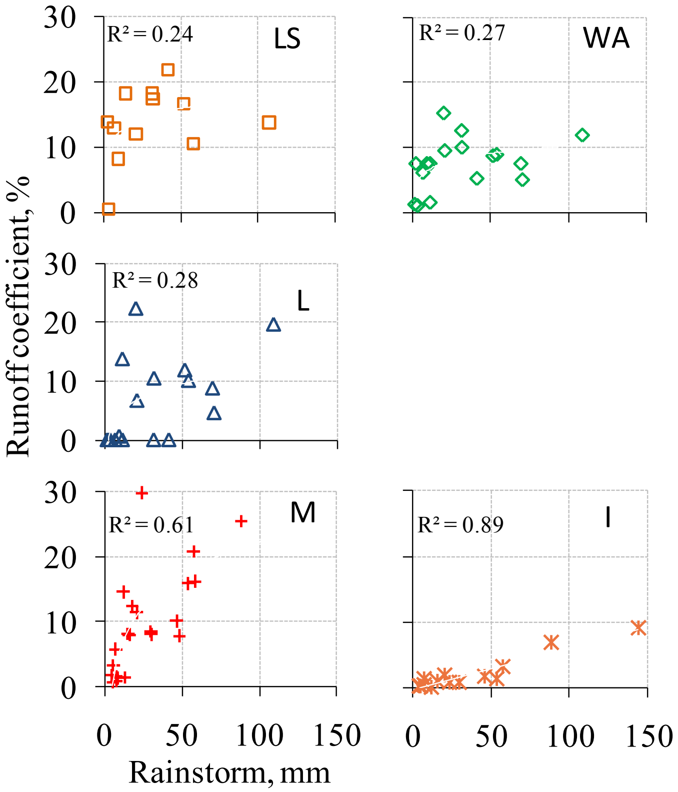

Fig. 4. Complete record of runoff percentages for the hydrometric stations in Ramallah (WA, Ls and L) and Modiin (I and M). Station J (Modiin) is not included as only one storm generated runoff during the investigated period.

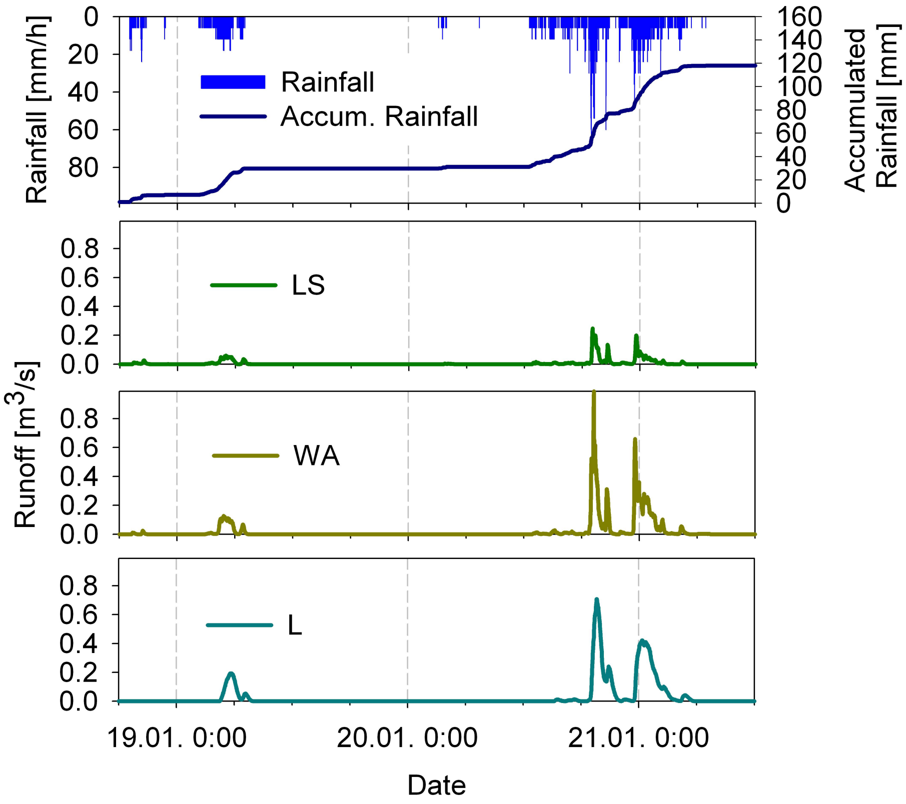

Fig. 5. The high-magnitude event measured at three gauging stations in Ramallah. Note: rainfall is taken from valley station.

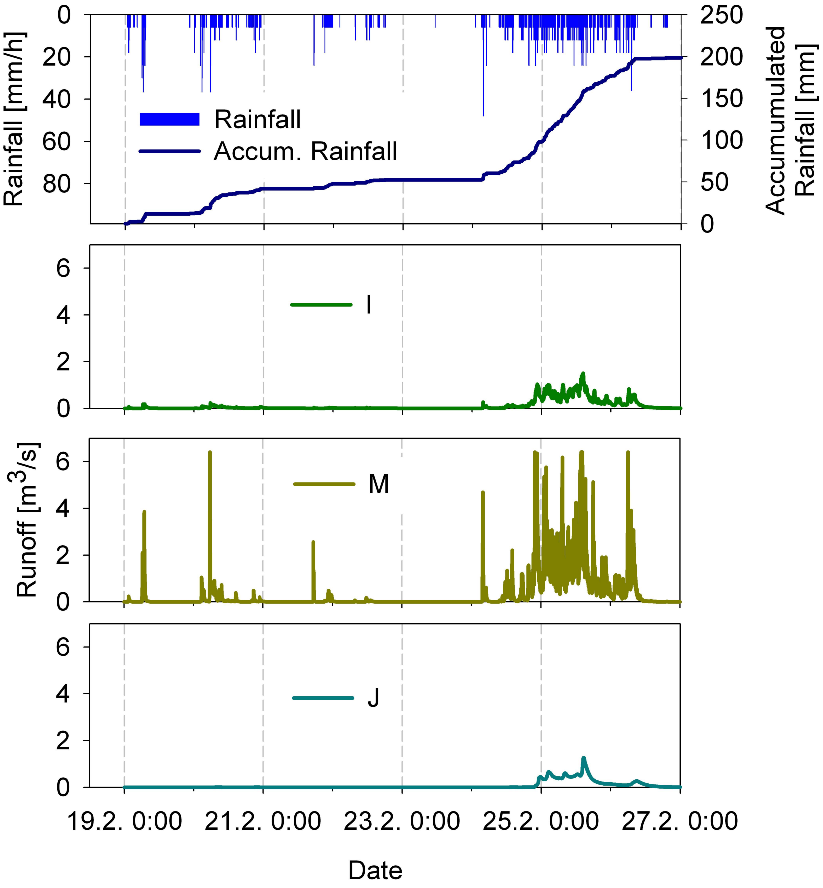

Fig. 6. The extreme event in the Modiin region. Note that station M runoff includes runoff from station I.

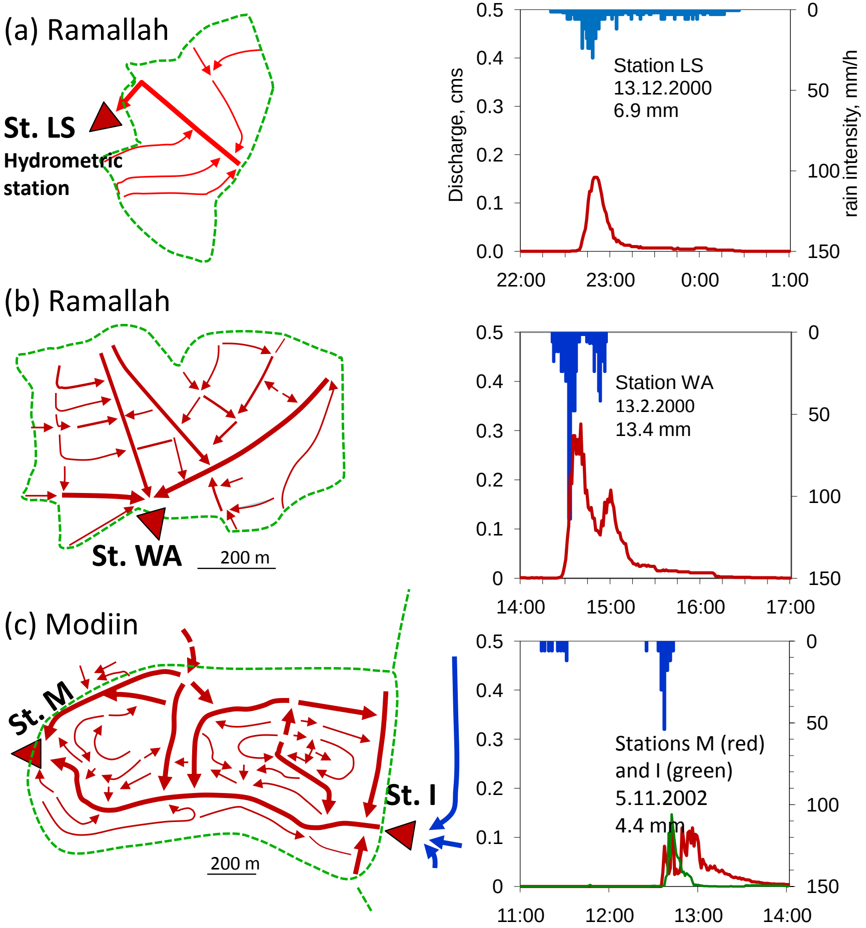

Fig. 7. Urban road network design and the hydrological response following small rainstorms.

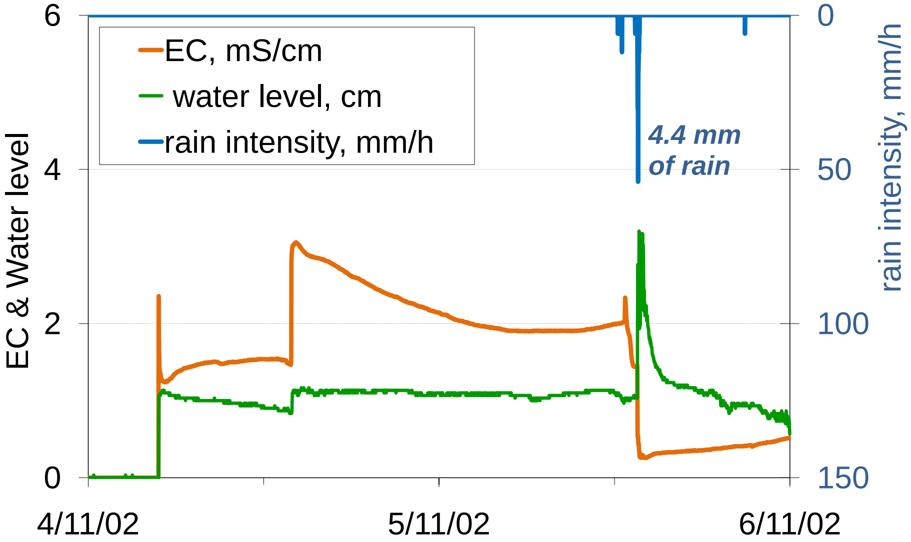

Fig. 8. Measured runoff quantity and quality at Station M, Modiin at the beginning of the rainy season.

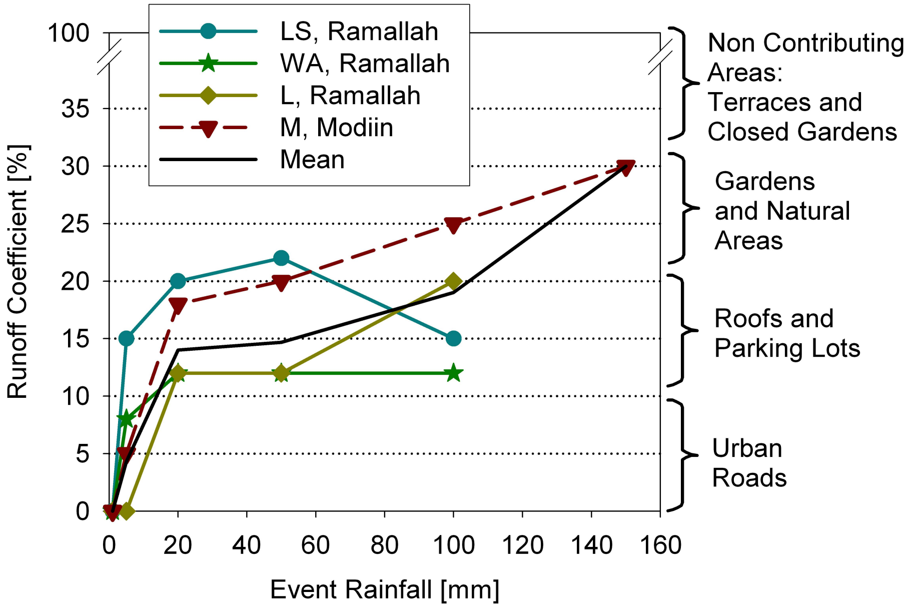

Fig. 9. Conceptual model for sequential runoff generation inside the two cities.

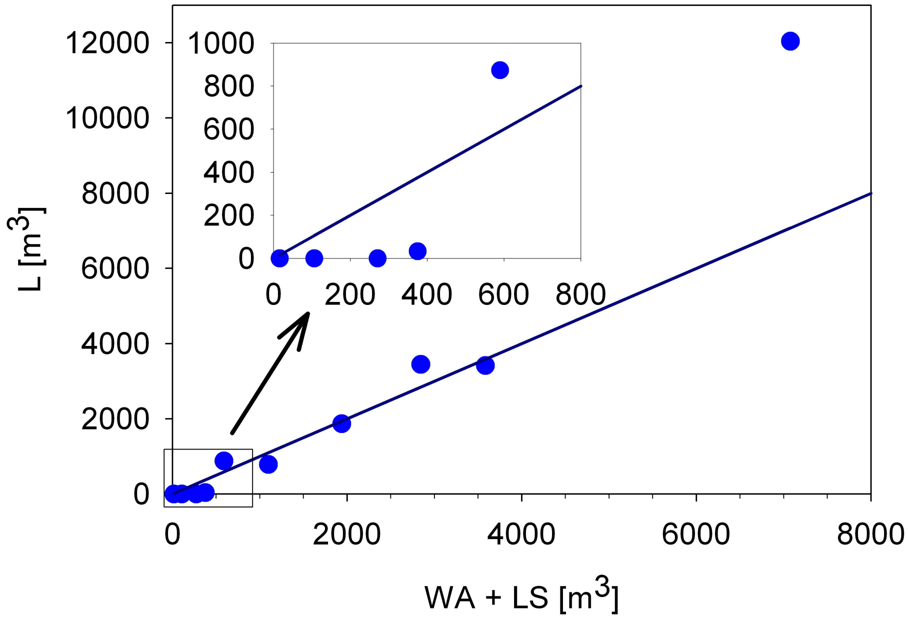

Fig. 10. Runoff volumes measured up and downstream the open area in Ramallah. Note: up to an inflow volume of about 400 m^3 the water is totally stored inside; only higher volumes pass the open area contributing to runoff downstream.