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The characteristic time scale for basin hydrological response using radar data

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Abstract

The transformation of rainfall into runoff at a basin outlet is the combined effect of many hydrological processes, which occur at a wide range of spatial and temporal scales. However, determining the scale of the combined hydrological response of the basin is still problematic and concepts for its definition are yet to be identified. In this paper high-resolution meteorological radar data are used for the determination of a characteristic temporal scale for the hydrological response of the basin — the 'response time scale' (T_s^*). T_s^* is defined as the time scale at which the pattern of the time-averaged radar rainfall hietograph is most similar to the pattern of the measured outlet runoff hydrograph. The existence of such similarity at a relatively stable time scale for a specific basin indicates that it is an intrinsic property of the basin and is related to its hydrological response. The identification of the response time scale is carried out by analysis of observations only, without assuming a specific rainfall-runoff model. T_s^* is examined in four small basins (10–100 km^2) in Israel. The spatial scale is assumed as the entire basin. For all analyzed basins a stable response time scale is identified. Relatively short time scales are found for the urban and arid basins (15–30 min), while for the rural basins longer time scale are identified (90–180 min). The issues of relationship between the response time scale and basin properties and modeling at the response time scale have yet to be determined. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The term *scale* is defined by Bloschl and Sivapalan (1995) as a characteristic time or length of a process, an observation or a model. Their work demonstrates that hydrological process scales span over several orders of magnitude; from unsaturated flow in a 1 m soil profile to floods in river basins of a million square kilometers; from flashfloods of several minutes duration to flow in aquifers over hundreds to thousands of years. The range of scales of the different processes is still large even when limiting the discussion to the processes involved in the generation of runoff at the basin outlet. For example, infiltration excess (i.e. Horton overland flow) is associated with small time and space scales (<100 m, <30 min) while channel flow is associated with larger scales between hours to days and between a few kilometers to the size of the largest river basins (Bloschl and Sivapalan, 1995).

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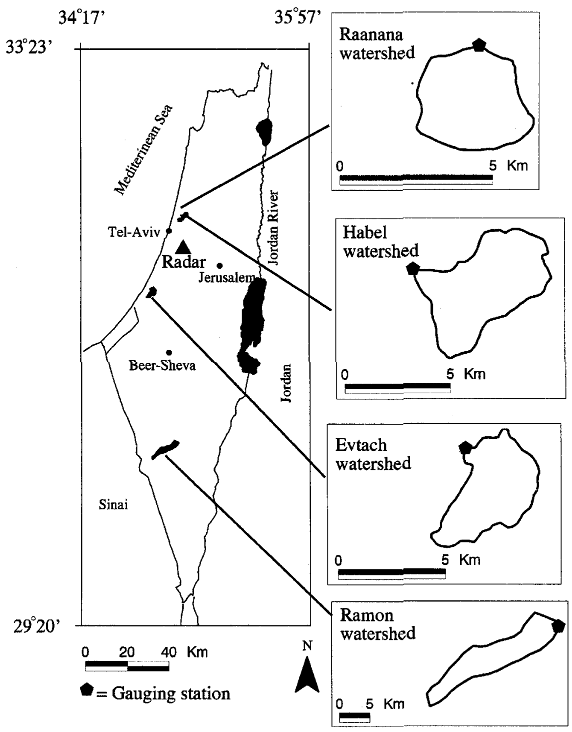

Fig. 1. Map of Israel showing radar location and the four basins.

The hydrological response of a drainage basin is a combination of the individual processes. The question then arises as to the characteristic scale of the combined hydrological response. A possible approach to study this scale is to test the effect of spatial and temporal variability of rainfall and basin properties on the outlet runoff hydrograph. Julien and Moglen (1990) have used a physically based one-dimensional finite element model to study the influence of spatial variability in slope, surface roughness, surface width, and excess rainfall intensity on surface runoff characteristics. They determine a length scale as a function of basin parameters and storm characteristics, under which the rainfall-runoff relationship becomes nearly independent of the spatial variability in the hydrological parameters. Faures et al. (1995) have shown for a small (less than 1 km^2) semiarid basin, high sensitivity of modeled runoff to spatial variability of rainfall, and relatively small sensitivity to wind direction and velocity. Outlet runoff was estimated using the KINEROSR rainfall-runoff model. In studying the effect of radar input aggregation on computed runoff, Winchell et al. (1998) found a significant reduction in runoff volume assuming infiltration excess mechanism when the spatial and temporal scales of the rainfall input have been increased.

All the above studies are using hydrological models to conduct the analyses and to derive their conclusions. Apparently, modeling is the most appropriate tool available for testing sensitivity of basin outlet runoff to basin and rainfall characteristics. However, the difficulty inherent in this approach is that the laws governing the model and parameters may be scale-dependent, both for physically based and for conceptual models. In their work, Bloschl and Sivapalan (1995) suggest that in the transfer of a model between scales the state variables, parameters, inputs and the conceptualization itself should be scaled. In practice, however, usually only one member of the list above is scaled while the others are assumed to hold true at either scale. For example, Beven (1996) claims that Darcy's law, which is known to be a good description of subsurface flow in laboratory soil columns, is not valid at the plot scale or larger. However, many models assume Darcian flow at scales much larger than the laboratory scale and must include adjustment of parameters to get reasonable model results. The study of Finnerty et al. (1997) also indicates a significant scale dependency of the Sacramento model parameters. These findings suggest that hydrological models and their parameters are by themselves scale-dependent and their use as a tool for determining characteristic scale is therefore questionable. Different approaches, not assuming a specific hydrological model and parameterization, may therefore be required for investigating the characteristic scale of the basin hydrological response.

The question of scale has an additional importance when meteorological radar data are used for runoff prediction. An intensive research effort has been aimed to develop methods for accurate prediction of rainfall intensities from radar reflectivity data (see review by: Atlas et al., 1997). Still, the local instantaneous radar data can include large errors. Collier and Knowles (1986) describe the potentially large effect of such inaccuracies on forecasted hydrographs. Georgakakos et al. (1996) identified substantial sensitivity of modeled runoff to radar data input uncertainty. Integration of radar rainfall data in space and time reduces the error (Seed and Austin, 1990), but can

Table 1
Characteristics of selected basins

Name	Size (km^2)	Annual rain depth ($mm\ year^{-1}$)	Relief ratio[a]	Main channel length (m)	Main channel slope	Drainage density[b] (m^{-1})	Land use	Dominating soil type[c]
Raanana	10	600	0.0089	3500	0.009	0.0100[d]	Urban	E
Habel	24	600	0.0111	7100	0.007	0.0007	Rural	E
Evtach	43	460	0.0079	10600	0.004	0.0015	Rural	K
Ramon	98	80	0.0197	27400	0.011	0.0038	Natural	Y

[a] Maximum relief divided to main channel length.
[b] Total stream length divided to basin area.
[c] E: Hamra soils, K: Dark brown soils and Y: Reg soils and coarse desert alluvium (Dan and Raz, 1970).
[d] Estimated value.

cause the loss of valuable information. It is therefore important to identify what spatial or temporal scales are appropriate for different hydrological applications, in order to provide to these applications an input, which is informative enough and contains the smallest error possible.

In the present study we introduce the concept of the response time scale, a characteristic time scale for the basin's hydrological response. The response time scale is derived by analysis of radar rainfall and runoff observations and without the use of a hydrological model. The current paper presents the response time scale of small (10–100 km^2) semiarid and arid basins.

The objectives of this paper are: (a) to define the concept of the response time scale, (b) to describe a procedure for the derivation of the response time scale, (c) to demonstrate the procedure in four small basins in Israel, and (d) to test the stability of these scales for various storms.

2. Background information

Reflectivity data were measured by a C band meteorological radar system, located at Ben-Gurion Airport near Tel-Aviv (see Fig. 1). The spatial resolution of the radar data is 0.5–4 km^2 (depending on the distance from the radar system) and the temporal resolution is 5 min. Reflectivity data were transformed into rain intensities by using the power law equation (Marshal and Palmer, 1948)

$$Z = 200R^{1.6} \qquad (1)$$

Where Z is the reflectivity in $mm^6\ m^{-3}$, and R is the rain intensity in $mm\ h^{-1}$.

The research has concentrated on small basins (10–100 km^2) in the semiarid and arid regions of Israel. Four basins different in size, land-use, soil types, and climatic regimes were selected for the analysis: Raanana, Habel, Evtach and Ramon. Fig. 1 represents the location and boundary of the basins. Table 1 specifies some of the basins main characteristics. In all selected basins surface water is the primary source of runoff. For each basin few storms were selected for the analysis. Table 2 lists the storms dates and total depth (storm depth was derived from a daily rain gauge located in or near the basin).

Runoff data were obtained from two types of instruments: a) in the Evtach and the Ramon basins an analog water level continuous recorder; b) in the Raanana and the Habel basins a digital instrument which measures and logs pressure every 5 min. The instrument is located near channel bottom, and the recorded pressure is transformed into water level. An important advantage of the digital logger is its accuracy in time, which may not be the case for the analog instrument. Discharge is estimated from water level data using a stage-discharge curve. The graphs of runoff presented in this study are in terms of either discharge or stage, depending on the best data available. Although the two representations of the runoff might have some differences in pattern as a result of the non-linear transformation linking them, the 'peak-structure' of the graph is retained.

The selected events for the analysis are those that have the most reliable and consistent data. Still, some difficulties with the observed data

Table 2
Analyzed storms in the four basins and their total rain depth measured by a representative rain gauge

Storm date	Basin	Measured storm depth (mm)
22 February 1997	Raanana	68
17 March 1997		32
30 November 1997		27
24–25 January 1998		27
17–18 March 1998		49
19 March 1998		44
29–30 March 1998		11
22–23 January 1997	Habel	73
21–23 February 1997		168
15–16 March 1997		147
17–19 March 1998		51
30 November–5 December 1991	Evtach	277
11–16 December 1991		159
2–11 February 1992		136
23–25 November 1994		138
18–22 December 1994		68
2–6 December 1994		63
13 October 1991	Ramon	12
2–3 November 1994		19
8 February 1996		18

occasionally exist, which increase the uncertainties associated mainly with the magnitude and timing of the runoff hydrographs. In addition, relatively large uncertainty is associated with rainfall intensities estimated from radar reflectivities (e.g. Austin, 1987). This uncertainty affects mainly the magnitude of the rainfall graphs. However, the effect of the uncertainties in the rainfall and runoff graphs on the analysis results is believed to be insignificant in the current study, since the existence of peaks in the graph is examined rather than their magnitude or exact time.

3. The response time scale concept

The concept of the response time scale is introduced here through an example. A rainfall-runoff event occurred on 22 February 1997 in the Raanana basin, a 10 km^2 urban basin, on the coastal plain in Israel. Let T_s be the time-interval at which the radar rainfall data are averaged. Fig. 2 presents the radar rainfall intensities averaged spatially over the entire basin and temporally for three T_s : 5 min (original scale), 15, and 60 min. Each rainfall representation is compared with measured runoff stage. For $T_s = 5$ min (Fig. 2a) the pattern of the rainfall graph is noisy comparing to the pattern of the runoff graph; for each runoff peak there are few rainfall peaks. At the other extreme, for $T_s = 60$ min (Fig. 2c) the pattern of the rainfall graph is 'smeared' comparing to the runoff and there are few runoff peaks for each rainfall peak. Obviously, longer time intervals would produce an even flatter pattern of rainfall graph. For $T_s = 15$ min (Fig. 2b) the two graphs seem similar in their pattern, meaning that almost every peak in the rainfall graph can be associated with a peak in the runoff graph. If the analysis of other storms in the basin will bring about the same result, namely, similarity of rainfall and runoff graphs' patterns at temporal scales that narrowly range around 15 min, then this time scale can be assumed to represent a characteristic time scale for the hydrological response of the Raanana basin. T_s^*, the response time scale, is defined as the T_s at which the pattern of the time-averaged radar rainfall hietograph is most similar to the pattern of the measured outlet runoff hydrograph. Similarity, in the current study, is objectively identified using a heuristic method based on matching rainfall and runoff peaks and finding the minimum number of unmatched peaks. The five steps for

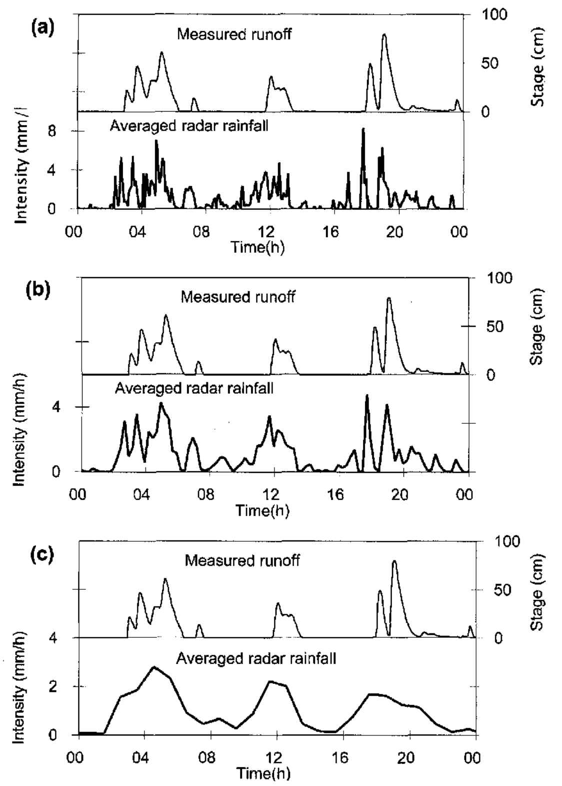

Fig. 2. Radar rainfall intensity of the 22 February 1997 storm averaged over the entire Raanana basin at three T_s of: (a) 5 min which is the measured interval, (b) 15 min, and (c) 60 min; compared with the measured runoff at the basin outlet represented by stage.

identifying the response time scale are described below.

(1) Radar rainfall intensities are averaged over the entire basin for various T_s and compared to outlet measured runoff. In the Raanana basin eight values of T_s were tested: 5, 10, 15, 20, 25, 30, 40 and 60 min. Fig. 2 shows the 22 February 1997 storm with three T_s : 5, 15 and 60 min averaged rainfall and the measured runoff.

(2) For each T_s, the peaks in the rainfall and runoff graphs are associated with each other and classified as follows: Type A: matched peak — a runoff peak which has a matched rainfall peak; Type B1: unmatched peak — a rainfall peak which does not have a corresponding runoff peak; Type B2: unmatched peak — a runoff peak which does not have a matching rainfall peak.

The peak matching requires consideration of a certain time delay between rainfall and runoff. While the delay is influenced by rainfall intensity and prior conditions of the basin, the variations do not cause difficulty in deciding which peaks match.

Rainfall peaks are excluded from the analysis when: (a) they are lower than a defined threshold, or (b) they occurred prior to the beginning of flow. These decisions are made subjectively to eliminate from the analysis rainfall peaks that did not produce runoff.

The classification of peaks for the Raanana basin is presented in Fig. 3, which also shows the selected thresholds. For $T_s = 5$ min (Fig. 3a) there are 12 A-peaks (numbered), 15 B1-peaks (circled), and no B2-peaks; for $T_s = 15$ min (Fig. 3b) there are 12 A-peaks, one B1-peak and no B2-peaks; and for $T_s = 60$ min (Fig. 3c) there are four A-peaks, no B1, and eight B2-peaks (in squares). For each T_s tested, the peaks of types A, B1 and B2 are counted.

(3) The T_s with the minimum number of B-peaks (B1 + B2) is identified as T_s^* of the storm. The first row of Table 3 shows the number of A, B1, B2 peaks for each time scale in the 22 February 1997 storm in Raanana. The 15 min time scale has the minimum number of B-peaks (one B1-peak and no B2-peaks). Therefore, T_s^* for this storm in Raanana is 15 min.

(4) The procedure (steps 1–3) is repeated for all available storms in the basin. The response time scale of the basin is determined by taking the minimum number of B-peaks for all these storms. Table 3 lists peak numbers for the all seven storms available in Raanana and the totals. $T_s = 15$ min has the least B-peaks, and is therefore suggested to be the response time scale, T_s^*, of Raanana basin.

(5) It is most likely that T_s^* has a certain range around the determined value. A X^2 test is applied to test whether there is a significant difference in the distribution of the number of peaks of the three types (A, B1, B2) between the selected T_s^* and the other tested T_s. For each pair of distributions, the null hypothesis is that a significant difference *does not* exist between the two. The null hypothesis is rejected (i.e. a significant difference does exist) when the probability of X^2 is lower than a significance level of 5%. For example, in the case of Raanana, the 15 min (the determined T_s^*) and the

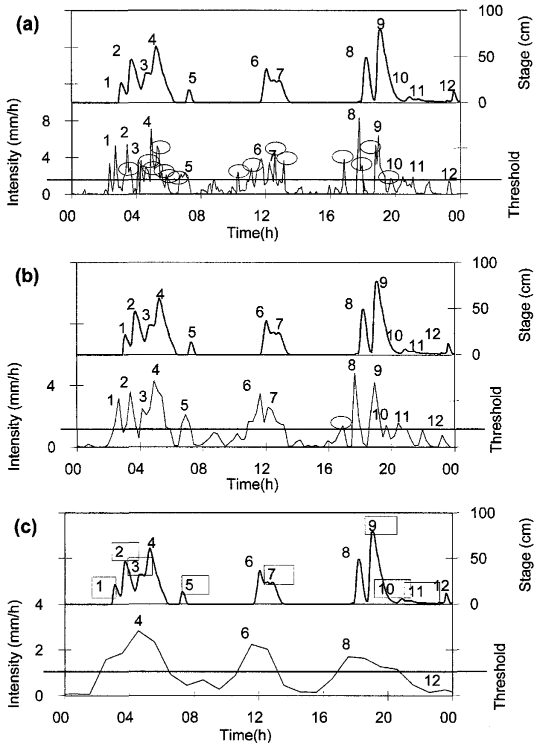

Fig. 3. Same as Fig. 2 and matched rainfall and runoff peaks are marked. If a runoff peak has a matched rainfall peak both peaks are marked with the same number (type A); if a rainfall peak does not have a matched runoff peak it marked by a circle (type B1); if runoff peak does not have a matched rainfall peak it is marked by a rectangle (type B2). Rainfall peaks lower than the indicated threshold are not considered as B1-peaks even if they do not have a matched runoff peak.

10 min distributions are (A = 66, B1 = 4, B2 = 2) and (A = 68, B1 = 18, B2 = 0), respectively. The X^2 test results in a probability of 0.0075, and therefore a significant difference exists between the peaks distributions for 15 and 10 min time scales. Table 4 summarizes the results for all pairs compared in Raanana. It implies that the response time scale is in the range of 15–20 min.

4. Results

4.1. The response time scale for the analyzed basins

The application of the response time scale procedure to the four studied basins yielded the following results:

1. Raanana basin (Fig. 1): As shown above, T_s^* for Raanana is 15 min with a range 15–20 min (see Figs. 2 and 3 and Tables 3 and 4). Two additional storms are presented as an example in Fig. 4.
2. Habel basin (Fig. 1): T_s of 15, 30, 60, 90, 120, 150, 180 and 240 min were tested. Examples of two storms are shown in Fig. 5. T_s^* (i.e. the scale with the minimum B-peaks number) is 90 min (Table 5). The range of T_s^* determined by the X^2 test is 60–150 min (Table 6).
3. Evtach basin (Fig. 1): Two storms are presented in Fig. 6. Tested T_s are: 60, 120, 150, 180, 210, 240, 300, 360 and 480 min. T_s^* is 180 min (Table 7) ranging from 150 to 210 min (Table 8).
4. Ramon basin (Fig. 1): Two storms are presented in Fig. 7. Tested T_s are: 5, 10, 20, 30, 40, 60, 90 and 120 min. Table 9 shows the peaks number for three storms in the Ramon basin. It indicates that T_s^* is at least 20 min, but a minimum value of the peak number could not be determined. Typically to arid region, all the three analyzed runoff hydrographs of the Ramon basin consist of a single peak. Following the above method, at small T_s the rainfall graph is noisy and consists of more than one peak (Fig. 7, $T_s = 5$ *min*), the surplus rainfall peaks are classified as B1-peaks and the number of B-peaks is grater than zero. As the rainfall data are averaged at increasing T_s, the noisy rainfall graph become smoother and at a certain T_s it consists of a single peak. At this point the single rainfall peak can be associated with the single runoff peak and the number of the B-peaks is zero (Fig. 7, $T_s = 30$ *min*). Additional increase in T_s makes the single rainfall peak to be wider (Fig. 7, $T_s = 2$ h), but still it match the single runoff peak. B2-peaks (i.e. runoff peak that does not have a corresponding rainfall peak) do not appear at large T_s as in the case of multiple peak hydrographs. As a result the number of B-peaks remains zero and a minimum value cannot be determined. The suggested procedure for determining the response time scale T_s^* is probably not suitable for arid regions where runoff typically has a single peak. Another test for similarity, which involves other considerations, is suggested to be used when studying hydrological response of arid drainage basins. We suggest 30 min as the response time scale for the Ramon basin with a

Table 3
Peak classification for tested T_s in the Raanana basin, seven storms and total

Storm	Date	Peak type	5 min	10 min	15 min	20 min	25 min	30 min	40 min	60 min
1	22 February 1997	A	12	12	12	10	10	9	7	4
		B1	15	5	1	1	1	1	0	0
		B2	0	0	0	2	2	3	5	8
2	17 March 1997	A	5	5	4	4	4	4	4	3
		B1	3	1	0	0	0	0	0	0
		B2	0	0	1	1	1	1	1	2
3	30 November 1997	A	3	3	3	3	2	2	2	2
		B1	0	0	0	0	0	0	0	0
		B2	0	0	0	0	1	1	1	1
4	24–25 January 1997	A	11	11	11	11	11	11	7	5
		B1	3	0	0	0	0	0	0	0
		B2	0	0	0	0	0	0	4	6
5	17–18 March 1998	A	15	15	14	13	11	11	11	8
		B1	13	4	1	1	1	1	0	0
		B2	0	0	1	2	4	4	4	7
6	19 March 1998	A	14	14	14	13	12	11	8	7
		B1	7	6	2	1	0	0	0	0
		B2	0	0	0	1	2	3	6	7
7	29–30 March 1998	A	8	8	8	8	8	7	6	5
		B1	8	2	0	0	0	0	0	0
		B2	0	0	0	0	0	1	2	3
Total		A	68	68	66	63	58	55	45	34
		B1	49	18	4	3	2	2	0	0
		B2	0	0	2	6	10	13	23	34

range of 20–40 min, due to observation that the characteristic shape of the rainfall peaks at longer intervals becomes wide relative to the shape of the measured runoff peak.

4.2. Stability of the response time scale

One way to define the stability of T_s^* is by requiring that it remain constant for many storms. It may, however, turn out to be depending on the rainfall event. Fig. 8 shows the T_s^* identified for the individual storms (horizontal bars) for Raanana, Habel, Evtach and Ramon basins in relation to the T_s^* derived in each basin for all storms combined (vertical bars). In most cases, the individual T_s^* lies inside the range of the combined T_s^* or only slightly beyond. However, in few occasions, the individual values are much broader (for example, storms 1 and 3 in the Habel basin). It appears that this phenomenon occurs in runoff hydrographs with a small number of peaks separated by long time intervals. In these cases, as in the case of a single peak hydrographs, averaging rainfall over large time intervals makes rainfall peaks wider, but there is no merging of several peaks into one. B2-peaks do not appear in these cases, and it is impossible to detect a minimum value for the B-peaks number. Apparently, analysis of these cases will need the application of other approaches. Beside these mentioned exceptions, Fig. 8 indicates that the response time scale is stable.

Table 4
X^2 test of peaks number distributions, comparison of T_s^* (15 min) and other tested T_s in the raanana basin (Italicized numbers: no significant difference exists ($p > 0.05$)

Compared T_s (min)	Prob(X^2)
15-5	< 0.0001
15-10	0.0075
15-20	*0.3229*
15-25	0.0390
15-30	0.0078
15-40	< 0.0001
15-60	< 0.0001

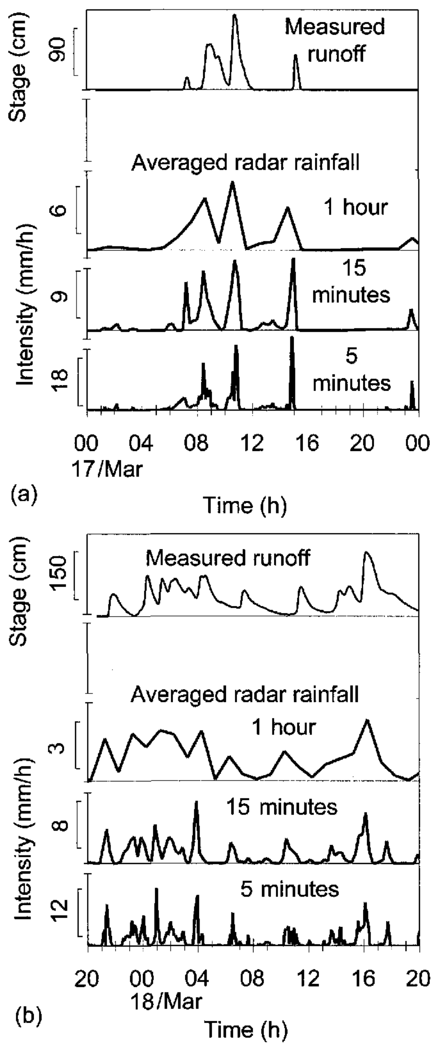

Fig. 4. Radar rainfall intensity averaged over the entire Raanana basin at: $T_s = 5$, 15 min and 60 min compared with the measured runoff at the basin outlet represented by stage (upper line), for the: (a) 17 March 1997 and (b) 17–18 March 1998 storms.

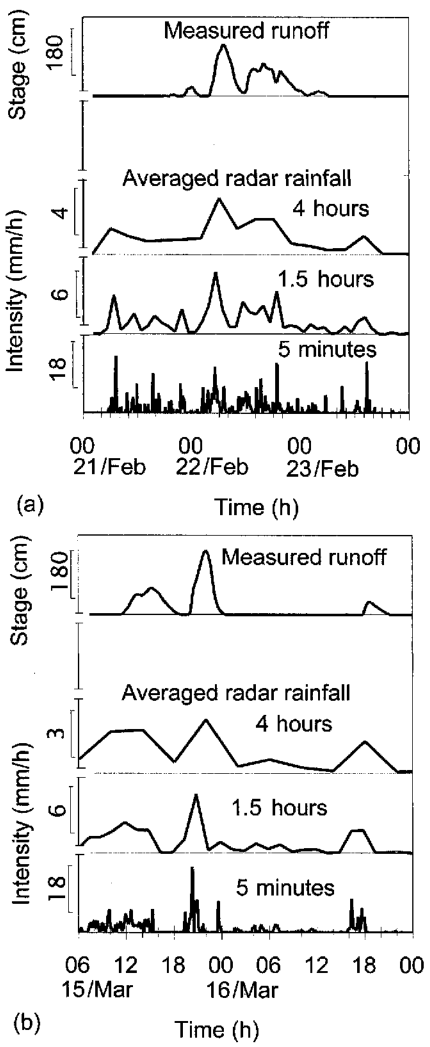

Fig. 5. Radar rainfall intensity averaged over the entire Habel basin at: $T_s = 5$ min, 1.5 and 4 h compared with the measured runoff at the basin outlet represented by stage (upper line), for the: (a) 21–24 February 1997 and (b) 15–17 March 1997 storms.

4.3. Comparison with other approaches for determining characteristic time scales

In the present study the characteristic time scale is determined by examining similarity of rainfall and runoff patterns. For comparison, two other approaches are presented:

1. Spectral analysis is often used to study the scaling properties of time series (e.g. Tessier et al., 1996) and it is used here to search for preferable frequencies in the measured runoff hydrographs. Fig. 9 shows the log–log plot of Fourier analysis of measured runoff hydrographs for selected storms in the four basins. In the figure it is shown that for frequencies higher than a certain threshold the power spectrum is significantly reduced in comparison with the low frequencies. This implies that the basin filters out high frequencies; i.e. the basin behaves as a low-pass filter. The threshold

Table 5
Peaks classification for tested T_s in the Habel basin, total of four storms

Peak type	15 min	30 min	60 min	90 min	120 min	150 min	180 min	240 min
A	24	23	22	22	20	17	15	13
B1	26	17	4	0	0	0	0	0
B2	0	1	2	2	4	7	9	11

frequency is probably basin dependent. If this threshold frequencies are found to be stable for different storms in the same basin then the time scale associated with this frequency can be determined as the characteristic time scale of the basin. An analysis of one storm for each studied basin is presented in Fig. 9 and indicates the following time scales: 45 min for the Raanana basin, 200 min for the Habel basin, 540 min for the Evtach basin and 70 min for the Ramon basin. Apparently, these scales correspond to the T_s^* values, but are two to three folds larger. These relationships are quite reasonable if we recall that the time scale associated with the threshold frequency represents a characteristic signal (e.g. sine) and that T_s^* represents averaging time scale. It should also be noted that the point of the threshold frequency is not always clear and subjective judgement may be needed to locate it in the graph.

2. One of the most common characteristic time scales used in theoretical and practical hydrology is the 'time of concentration',which is defined as the time required for a drop of water falling on the most remote part of the drainage basin to reach the basin outlet

Table 6
X^2 test of peaks number distributions, comparison of T_s^* (90 min) and other tested T_s in the Habel basin (Italicized numbers: no significant difference exists ($p > 0.05$)

Compared T_s (min)	Prob(X^2)
90–15	< 0.0001
90–30	0.0010
90–60	*0.1561*
90–120	*0.3827*
90–150	*0.0645*
90–180	0.0162
90–240	0.0035

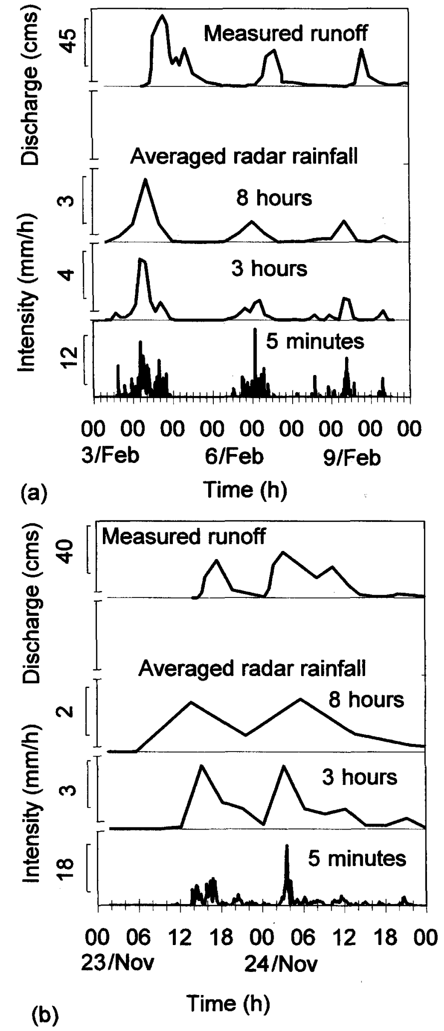

Fig. 6. Radar rainfall intensity averaged over the entire Evtach basin at: $T_s = 5$ min, 3 and 8 h compared with the measured discharge (upper line) at the basin outlet for the: (a) 3–10 February 1992 and (b) 23–25 November 1994 storms.

Table 7
Peaks classification for tested T_s in the Evtach sin, total of six storms

Peak type	60 min	120 min	150 min	180 min	210 min	240 min	300 min	360 min	480 min
A	35	35	35	34	32	27	24	22	18
B1	33	11	5	2	2	1	0	0	0
B2	0	0	0	1	3	8	11	13	17

(Singh, 1992, pp. 451–452). One example for using the time of concentration parameter is by incorporating it into the rational formula, which relates the runoff peak discharge to the maximum rainfall intensity for the time of concentration (Singh, 1992, p. 595). In reality, it is impossible to measure the time of concentration and therefore this parameter is estimated according to one of several empirical formulas, which usually corporate length of the main channel, slope and some other parameters (e.g. Kirpich, 1940). In this study, we adopted the formula used by the Soil Conservation Division in the Israeli Ministry of Agriculture and Rural Development (Garti et al., 1998)

$$t_c = 5.4\left(\frac{L}{S^{0.5}}\right)^{0.75} \qquad (2)$$

where t_c is the time of concentration in minutes, L the length of main channel in km and S is the average slope of main channel. The time of concentration of the four studied basins according to Eq. (2) is 80 min for the Raanana basin, 150 min for Habel, 250 min

Table 8
X^2 test of peaks number distributions, comparison of T_s^* (180 min) and other tested T_s in the Evtach basin (Italicized numbers: no significant difference exists ($p > 0.05$)

Compared T_s (min)	Prob(X^2)
180–60	< 0.0001
180–120	0.0419
180–150	*0.3351*
180–210	*0.5884*
180–240	0.0375
180–300	0.0025
180–360	0.0006
180–480	< 0.0001

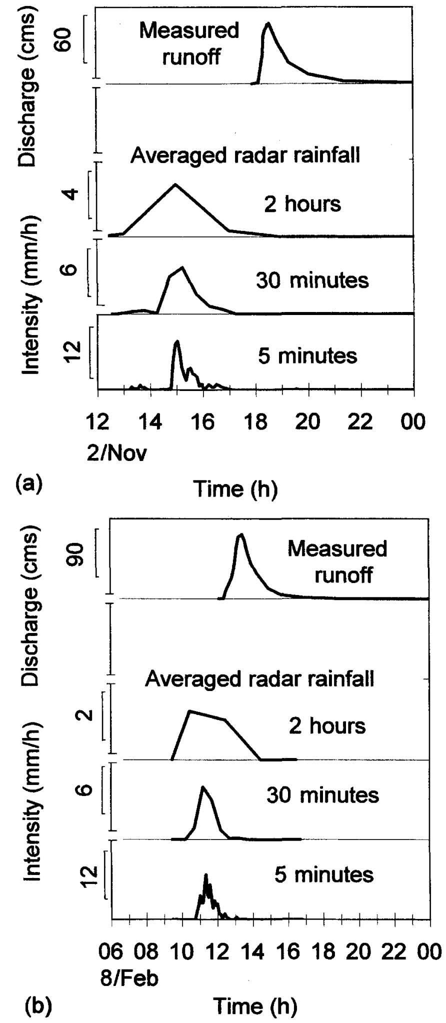

Fig. 7. Radar rainfall intensity averaged over the entire Ramon basin at: $T_s = 5$, 30 min and 2 h compared with the measured discharge (upper line) at the basin outlet for the: (a) 2 November 1994 and (b) 8 February 1996 storms.

Table 9
Peaks classification for tested T_s in the Ramon basin, total of three storms

Peak type	5 min	10 min	20 min	30 min	40 min	60 min	90 min	120 min
A	5	5	5	5	5	5	4	4
B1	7	3	1	1	0	0	0	0
B2	0	0	0	0	0	0	1	1

for Evtach and 350 min for Ramon. The first three values correspond (in their relative order) to T_s^*, although they are larger. For the Ramon basin, however, the large time of concentration is in contrast to the small T_s^* value determined for this basin in the current study. This contradiction is not due to the formula used for estimating the time of concentration or the method used for determining the response time scale. Going back to the definition, it must take several hours for the last drop of water to travel more than 27 km (the length of Ramon's main channel) even if its velocity is high, while the small T_s^* value of the Ramon basin relates probably to the rapid hydrological response of the main volume of the hydrograph that is known to characterize arid basins. It appears that these two time scales quantify different aspects of the hydrological response. The time of concentration measures the time of flow along the entire length of the basin, while the response time scale measures the amount of integration performed on the rainfall when transformed into runoff.

5. Summary and discussion

The objectives of this study were to present and develop the concept of the response time scale. The response time scale quantifies the integration processes performed by the drainage basin in transforming rainfall into runoff. Its main strength is that it is based on analysis of radar rainfall and runoff observations without assuming a specific hydrological model and parameters that are known to be scale-dependent (e.g. Beven, 1996). Reflections on the possible applications and the physical interpretation of the response time scale concept are presented below, but further research is required to fully understand the significance and usefulness of this concept.

The described procedure for determining the

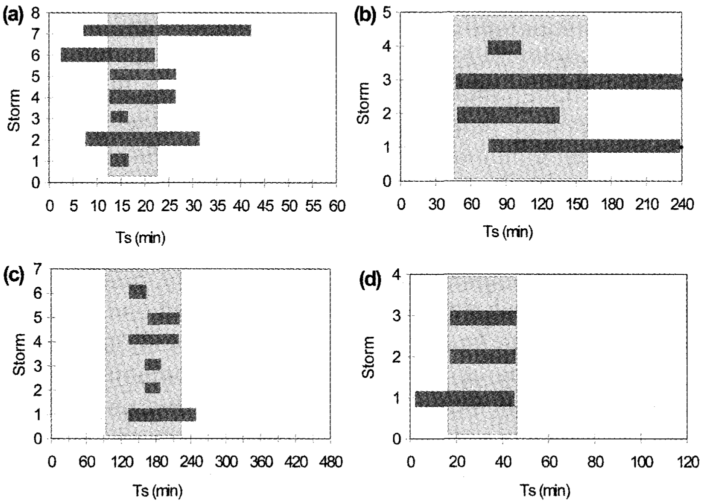

Fig. 8. T_s^* for the individual storms (striped bars) represented over T_s^* for the all storms (dotted bars) for: (a) Raanana, (b) Habel, (c) Evtach and (d) Ramon basins.

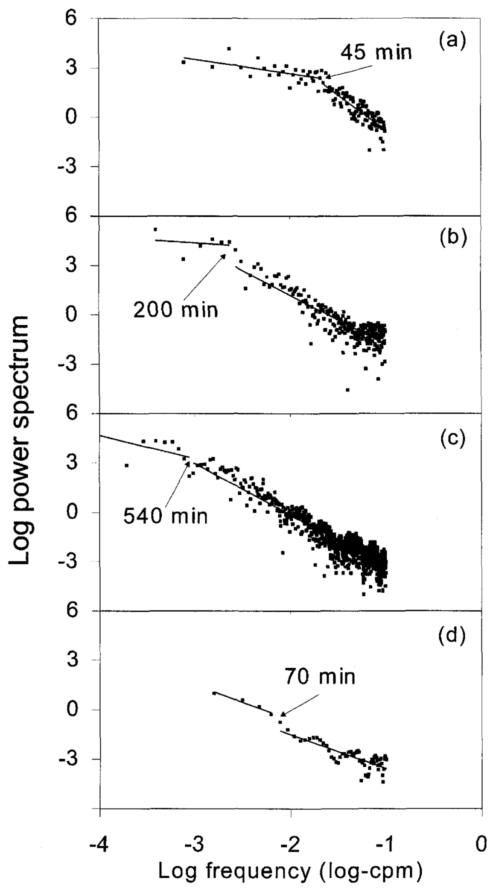

Fig. 9. Fourier analysis, presented in a log–log plot, of the runoff hydrographs for: (a) the February 22, 1997 event in the Raanana basin, (b) the 21 February 1997 event in the Habel basin, (c) the 30 November 1991 event in the Evtach basin, and (d) the 8 February 1996 event in the Ramon basin. The time scale associated with the breakpoint frequency is shown.

response time scale is based on the identification of a putative 'best similarity' between the rainfall graph, when averaged over different time intervals, and the runoff hydrograph. Spatially, the radar rainfall data are averaged over the entire basin. Although the use of basin-averaged rainfall may be problematic because it ignores the intra-basin rainfall variability, it allows studying the temporal scale separately from the spatial scale. For larger basins (a few hundreds km^2 and larger) a different approach should probably be applied.

The similarity of the rainfall and runoff graphs is identified by examining corresponding peaks in the two time series. The procedure was applied to four small basins in Israel: the Raanana basin, the Habel basin, the Evtach basin and the Ramon basin; their main basin characteristics are specified in Table 1. For all basins analyzed it was possible to identify a stable response time scale, as summarized in Table 10. These results indicate that the response time scale is indeed an intrinsic property of the basin. In addition, the response time scale parameter succeeds in capturing the inherent differences between the fast response of the urban (Raanana) and arid (Ramon) basins and the relatively slow response of the rural basins (Habel and Evtach).

It was shown that the criterion for similarity is best suited for multiple and closely spaced peaks runoff hydrographs, while for single peak hydrographs (typical for arid basins) or hydrographs with peaks widely spaced in time, another criterion should be considered. Therefore, for the arid Ramon basin we have used a simple visual comparison to identify similarity.

There are two main issues yet to be explored corresponding to the response time scale: (a) relationships with basin properties, and (b) rainfall-runoff modeling at the response time scale. These issues are currently subject to continued research and are discussed briefly in the following sections.

5.1. Relationships with basin properties

The physical reasons for achieving similarity in rainfall and runoff patterns by a simple temporal averaging are not at all clear. Considering the variability in space and time of rainfall intensities and the complex sequence of hydrological processes involved in transforming the rainfall into outlet runoff, it is surprising to find significant resemblance between the two. It implies that organization does exist in the basin, in spite of the complexity of rainfall and runoff generation processes. Organization and order in drainage basins were already identified by Horton (1945). More recently, basin organization and response have been explored and linked to scaling issues (Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1986; Bras and Rodriguez-Iturbe, 1989; Rinaldo et al., 1995). The similarity between radar rainfall and outlet runoff at a specific temporal scale proposed in this study can be interpreted as a different demonstration of a phenomenon already observed in previous works.

The response time scale represents the integrative

Table 10
T_s^* for analyzed basins

Basin	Number of storms analyzed	Response time scale (min)	Range (min)
Raanana	7	15	15–20
Habel	4	90	60–150
Evtach	6	180	150–210
Ramon	3	30	20–40

properties of the drainage basin in transforming rainfall into runoff. The wide range of T_s^* values (15 min to 3 h), on one hand, and the relative stability in each of the basins for variety of storms, on the other, implies that T_s^* is controlled and affected by at least some of the basin characteristics. More analyses are required to identify which parameters are involved in hydrological time scale control. However, by examination the T_s^* values (Table 10) and the basin characteristics (Table 1) one can raise a speculation that hillslope travel time has a dominant effect on the response scale. Hillslope travel time depends on hillslope length and surface water velocity. Recall that mean hillslope length is roughly $1/2D$, where D is the drainage density, and that flow velocity relates to hillslope gradient, it is expected that low T_s^* values correspond to high drainage density and high gradients. In Table 10 the drainage density values are listed with two gradient parameters indicating the overall steepness of the basin. The two basins associated with small T_s^* values, Raanana and Ramon, are characterized by short average travel lengths −50 and 132 m, respectively. In addition, the Ramon basin also has high gradients. The drainage networks of the other two basins are less dense and correspond to average hillslope length of 714 m in Habel and 333 m in Evtach. Travel length in Habel is longer than in Evtach but the slopes there are steeper. The combined effect of the two parameters can explain the higher T_s^* value of Evtach in relation to Habel.

A number of previous studies have shown that runoff production at small basins is dominated essentially by hillslope processes. Beven and Wood (1993) examined the relative roles of hillslope and network responses over a range of basin sizes. Using hydrological modeling they have shown that small basin response is affected essentially by hillslopes processes, while large basin response is determined primarily by stream network geometry. Robinson et al. (1995) confirmed this finding using a physically based model. These studies used models to represent the different components of the hydrological response. In our work only observed data are analyzed and no specific hydrological model is applied. If T_s^* is indeed controlled by hillslope travel time, it will be a complementary indication for the major role of hillslope processes in small basins runoff generation.

5.2. Rainfall-runoff modeling at the response time scale

The existence of a stable response time scale implies that simple averaging can generate a rainfall graph, which already contains the basic shape of the measured runoff hydrograph. A question is then raised whether one can predict outlet runoff by transforming the averaged rainfall into runoff using a relatively simple function. In other words, does modeling at the response time scale is possible and does it have benefits over modeling at smaller or larger scales? In the current paper we have developed a method for identifying *pattern* similarity between the rainfall and the runoff graphs. However, modeling at the response time scale demands that quantitative relationships will also be established in order to allow the transformation of the radar rainfall into outlet runoff. Figs. 2 and 4–6 indicate that for the same rainfall period the relative magnitude of peaks is preserved, i.e. a high rainfall peak generates a high runoff peak and vice versa (Fig. 2b: Raanana, 22 February 1997 00–09; Fig. 5b: Habel, 15–17 March 1997; Fig. 6a: Evtach, 3–10 February 1991). Differences that do exist, especially in different rain periods, may be related to changes either in the Z–R (radar reflectivity–rainfall intensity) relationships, differences in the hydrological conditions of the basin (for example, difference in initial conditions), or other as yet unknown factors.

Whether or not modeling at the response time scale will be found possible and worthwhile, it is important to explain the benefits of this approach. Consider for example physical hydrological models. The basic problem in applying such models for estimating basin outlet runoff is that the physical laws are applied at scale much larger than the one they were developed. The models, formulated in laboratory conditions and in well-controlled experimental situations, are assumed to extend to other situations and scales. Unfortunately, in many cases, the extension is not necessarily valid (Beven, 1996). Gupta et al. (1986) suggest searching for physical 'laws' governing the transformation of rainfall into runoff at the scale of interest, i.e. the basin scale. Developing a model to transform rainfall at the response time scale into outlet runoff hydrograph is an attempt to identify such laws and may be a step toward this goal.

5.3. Approaches for determining similarity and characteristic time scales

In the present study similarity of rainfall and runoff graphs is examined using a heuristic method, which is based on association of peaks between the two graphs. The heuristic approach has enabled us to construct a method, which formulates our visual inspection of graph similarity, and avoids the artifacts that may exist when using formal methods. However, two disadvantages exist in the suggested method. First, although we believe that the procedure is reasonably robust, some subjective judgments are involved in defining the threshold and in the process of rainfall-runoff peaks association (see Section 3, step 2). Second, the method was found to be inappropriate for single peak hydrographs (typical for arid basins) and to hydrographs with peaks widely spaced in time. Different methods, based on known techniques from the fields of statistics, pattern recognition and spectral analysis, should therefore be considered. Identifying a characteristic time scale using spectral analysis for one storm in each basin is exemplified in Section 4.3. The time scales determined using spectral analysis show positive correlation with the T_s^* values obtained, but are two to three times larger. As mentioned earlier, this can be related to the different time characteristic each scale represents. While the spectral analysis method refers to a typical signal time length, the response time scale is based on averaging time length. In addition, it should be noted that in applying the spectral analysis method, as in the method introduced in the current study, subjective judgment has to be involved in determining the characteristic time scale.

6. Conclusions

A response time scale for small basins exists, at least for the basins examined. It is stable over several storms and has a relatively narrow range in each of the basins. These results indicate that this scale is an intrinsic property of the basin. The issues of the relationships between the response time scale and basin properties and modeling at the response time scale have yet to be determined.

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