Weather Radar Information and Distributed Hydrological Modelling (Proceedings of symposium HS03 held during IUGG2003 at Sapporo. July 2003). IAHS Publ. no. 282, 2003.

Investigating the effect of catchment characteristics on the response time scale using a distributed model and weather radar information

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Abstract The response time scale (RTS) is a characteristic time scale of the catchment that represents the amount of smoothing performed by the hydrological system in transforming the rainfall input into runoff. Previous studies using catchments in Israel and Panama indicate that the RTS is stable for a given catchment and it depends on the catchment characteristics. In order to study the relationship between catchment characteristics and the RTS, a physically-based, non-calibrated distributed hydrological model is applied to a 24-km^2 rural catchment in Israel. The radar rainfall data are used to obtain the computed runoff hydrographs, and these computed data are then used to derive the RTS of the modelled catchment. The effect of catchment parameters (such as length and roughness of hillslopes and channels) on the RTS is examined by changing parameter values and deriving the RTS for each case. Special emphasis is placed in distinguishing the effects of hillslope *vs* channel processes. The results indicate that the effect of hillslope processes on the response time scale is greater than the effect of the channel processes for the study catchment.

Key words catchment response; characteristic time scale; distributed hydrological model; hydrological processes; small catchment; weather radar

INTRODUCTION

The hydrological response of a catchment is a composition of the response of different processes with a variety of characteristic time scales. Associating the catchment response, as a whole, with one representative characteristic scale is important in many aspects of hydrology, both theoretical, for better understanding the integration of different processes for the production of runoff and stream flow, and practical, for modelling and design purposes. In the current study we present a characteristic time scale for the catchment hydrological response and investigate the relationships of this time scale with the hydrological processes and the catchment characteristics.

THE RESPONSE TIME SCALE (RTS)

The RTS concept

Consider a general system that receives an input time series and generates an output time series. One can characterize the time scale of the system by measuring the amount of smoothing that is performed on the input in this transformation. A possible way to obtain this measure is to compare the input time series, smoothed over different time scales, with the corresponding output time series, and to select the time scale that generates a similar measure of smoothness for the two series. Thus, the characterization involves analysis of the two time series, without assuming a specific model for representing the system. For a system that represents the catchment hydrological response, application of this approach implies analysis of rainfall and runoff time series. This is the idea behind the concept of the "response time scale" (RTS) that was developed to characterize the time scale property of catchment hydrological response (Morin *et al.* 2001, 2002).

Identifying the RTS based on rainfall–runoff observations

Morin *et al.* (2002) presented an objective algorithm to determine the RTS of a catchment based on observed gauge or radar rainfall and observed outlet runoff for a single rainfall–runoff event or for a group of events. The algorithm was applied to five small catchments (10–150 km^2) in Israel and in Panama. Table 1 presents the estimated RTS for the analysed catchments. In general, all the RTS values found are reasonably stable and the algorithm was shown to be relatively robust to errors in rainfall and runoff data. It was shown that stable RTS values are more likely to be estimated for high flows with multiple peaks. These RTS values indicate that, as expected, the urban and arid catchments have faster hydrological response compared to the rural and forested catchments. The RTS algorithm successfully captures this inherent difference in catchment response.

Table 1 Catchment characteristics and RTS.

Catchment	Size (km^2)	Climate	Land use	RTS (min)	Uncertainty range (min)
Habel	24	Mediterranean	Rural	70–85	60–125
Raanana	10	Mediterranean	Urban	10–15	5–15
Evtach	43	Semiarid	Rural	125–130	90–215
Ramon	98	Arid	Natural	30–35	10–85
Rio Pequeni	133	Tropical	Forested	120–180	120–180

Relationships of the RTS with catchment characteristics

In order to study the relationships of the catchment characteristics to the RTS, a physically-based, non-calibrated distributed hydrological model was used. The rest of the current paper deals with this issue. The model allowed investigation of what hydrological processes primarily govern the RTS, where emphasis was placed on comparing hillslope *vs* channel processes. The model was applied to the Habel catchment, a 24-km^2 rural catchment with a Mediterranean climate. The only significant runoff-generation process in the catchment is surface runoff.

THE HYDROLOGICAL MODEL AND ITS APPLICATION

Model description

The model assumes that the catchment is composed of a sub-catchment network. Each sub-catchment has a book-like structure: two equal sloping plains (the hillslope) that drain into a sloping channel. The rainfall input to each sub-catchment represents the mean areal rainfall over the sub-catchment area. The rainfall intensities are estimated from weather radar reflectivity data using a power law relationship (Marshall & Palmer, 1948) with bias removal according to raingauge storm depth (Wilson & Brandes, 1979). The rainfall time resolution is 5 min.

An infiltration model used to calculate rainfall excess for each sub-catchment is based on Morin & Benyamini (1977) and on Morin & Kosovsky (1995). It assumes an exponential decay of infiltration capacity with accumulated rain depth and a surface storage. The model also allows the specification of the relative contributing area. The model was found suitable for application to the environment as the study catchment.

The rainfall excess generated over the hillslope is routed toward the channel using the kinematic flow equation. The kinematic flow equation is a simplification of the continuity and momentum equations combined with the Manning equation (see for example Eagleson, 1970). A numerical solution with an explicit, backward difference approximation scheme is used to solve the above equations for time varying rainfall excess. The initial condition is zero (dry) and the boundary condition is the rainfall excess. The runoff discharge at the hillslope bottom enters the channel as lateral flow.

The kinematic flow approximation is also used for channel flow with a similar numerical solution algorithm. The outflow from the sub-catchment is the runoff discharge at the channel's downstream end. The initial condition is zero. The boundary conditions are zero for first-order channels and the sum of outflow from the two contributing upstream channels for higher order channels.

Model application to the Habel catchment

The delineation of the Habel catchment into sub-catchments was done using geographical information system (GIS) algorithms applied on a 50 m digital elevation model (DEM). A 0.5 km^2 threshold area was used to define the channel network, and this resulted in 27 sub-catchments (Fig. 1). The geometrical parameters (area, length,

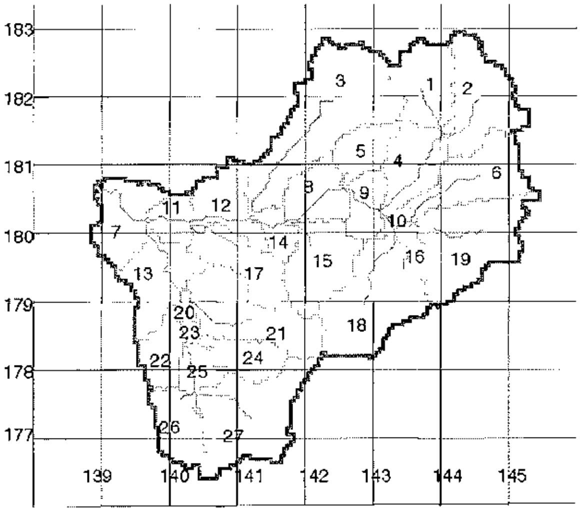

Fig. 1 Delineation of the Habel catchment from the DEM with a threshold area of $0.5\ \mathrm{km}^2$. Numbers indicate basin ID from 1 to 27. The grids represents local coordinates system with 1 km spacing.

slope) of hillslopes and channels are identified using GIS. The infiltration model parameters were obtained from published and unpublished studies according to soil type and land use (Morin & Benyamini, 1977 and Morin, personal communication). Manning's roughness parameters were set based on published tables (for example, Chow *et al.* 1988) as $0.1\ \mathrm{s\ m}^{1/3}$ and $0.035\ \mathrm{s\ m}^{1/3}$ for hillslope flow routing and channel flow routing, respectively. All the model parameters were selected *a priori* and no calibration step was conducted.

RESULTS AND DISCUSSION

RTS of measured and computed outlet runoff

The RTS of each of the events and for the group of three events is given in Table 2. For the first two events the RTS based on the measured and computed runoff agree quite well with each other, while for the third event, the computed runoff hydrograph is too smooth relative to the measured hydrograph and that results in a higher RTS

Table 2 RTS of the analysed events based on measured and computed runoff.

Event	RTS based on measured hydrographs (min)	RTS based on computed hydrographs (min)
17–20 Jan 1996	85–125	65–125
22–23 Jan 1997	60–85	60–85
21–23 Feb 1997	85–115	120–185
All events	70–85	70–85
All events (uncertainty range)	60–125	60–225

value. The RTS for a group of events is a more stable value (Morin *et al.*, 2002). For the current case study the three-events RTS is 70–85 min (60–125 min range) based on the measured runoff and 70–85 (60–225 min range) based on the computed runoff. The fit of the RTS is good considering the model was not calibrated. It suggests that the model sufficiently represents the hydrological processes affecting the RTS. In the following analysis we use the model to identify these processes.

RTS of hydrological processes

The three main processes represented by the model are: (a) infiltration, (b) hillslope routing, and (c) channel routing. The amount of smoothness performed in each one of these processes can be estimated by applying the RTS algorithm to the inputs and outputs of the related model components for the different sub-catchments. Figure 2 demonstrates this for the first-order sub catchment number 19 for the February 1997 storm. The RTS of the infiltration process is estimated from the analysis of rainfall and rainfall excess, the RTS of the hillslope routing process is estimated by analysis of rainfall excess and hillslope outflow (lateral inflow into the channel) and the RTS of the channel routing process is estimated by analysis of lateral inflow and channel outlet flow. The RTS of the combined hydrological response is estimated from the analysis of the rainfall and channel outlet flow. For non-first-order sub-catchments the channel routing includes additional

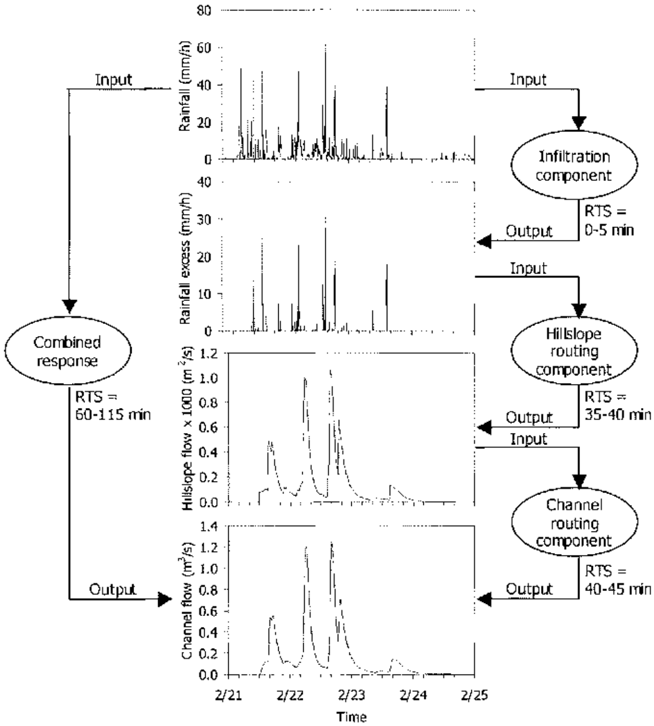

Fig. 2 Example of RTS calculated for the three model components and for the combined response for sub-catchment 19 and the February 1997 event.

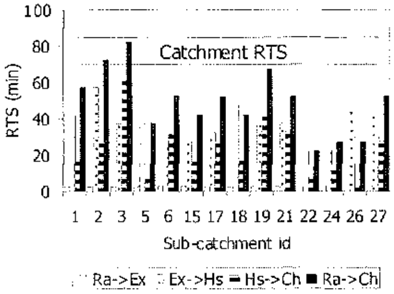

Fig. 3 RTS of first-order sub-catchments for each of the three model components and the combined response. The RTS of the whole catchment response is indicated.

input from the upstream channels. Figure 3 shows for first order sub-catchments the RTS of the three individual components and of the combined response. The RTS is computed for the three events group and the value shown in the figure is the mid-point of the resulted range. The RTS identified for the infiltration process is 0–5 min for all the sub-catchments, indicating no significant smoothness in this process according to the model (recall that the data time interval is 5 min). The RTS values of the hillslope routing and channel routing processes lie between 20 and 60 min and between 0 and 65 min, respectively. For most sub-catchments the RTS associated with the hillslope routing is larger than that associated with the channel routing, suggesting higher importance of the hillslope process for the first order sub-catchments.

We examine next the change in RTS moving to higher order sub-catchments, proceeding toward the catchment outlet. The RTS for each sub-catchment outlet point is shown in Fig. 4(a) as a function of the contributing area. It is calculated from the rain over the contributing area and the modelled runoff at the sub-catchment outlet. To associate the RTS with hillslope and channel routing processes we calculated for each sub-catchment the average flow length over hillslopes and in channels up to the examined outlet point. We assume that water that falls on a hillslope of a given sub-catchment flows on average for half the length of the hillslope, half the length of the local channel and then the full length of downstream channels. For any given outlet of a sub-catchment, the average hillslope flow length and the average channel flow length is calculated from all the sub-catchments that drain into this outlet and it is weighted by sub-catchment area. Figure 4(b) plots the change of hillslope and channel average flow length as a function of contributing area. The flow length on hillslopes is not accumulated downstream. It is relatively variable for small areas, first- or second-order sub-catchments, and it becomes constant toward the catchment outlet. The flow length in channels, on the other hand, is accumulated and is increasing toward the catchment outlet. The RTS at the small contributing areas (smaller than 10 km^2) seems to reflect the variability in the hillslope average flow lengths. At the larger contributing areas the RTS generally increases with contributing area similarly to the increase of the average channel flow length. Recall that flow velocity is considerably smaller over hillslopes than in channels, the overall change of RTS can be associated with average flow time. For typical velocities of 0.1 m s^{-1} and 2.2 m s^{-1} on hillslopes and in channels, respectively, the average flow length can be transformed into average flow time.

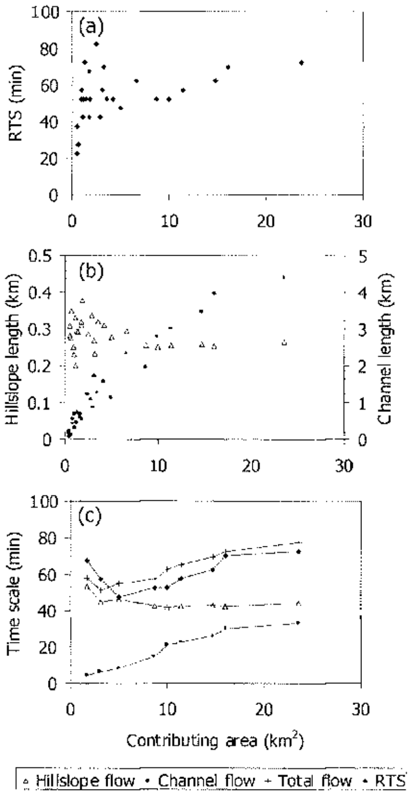

Fig. 4 (a) RTS of all the sub-catchments, (b) average flow length to sub-catchment outlets on hillslopes and in channels, and (c) estimated duration of flow to points along the main channel assuming velocities of 0.1 m s^{-1} over hillslope and 2.2 m s^{-1} in channel, and the RTS for the same points.

Figure 4(c) presents for points along the main channel (from sub-catchment 19 to the outlet) the average flow durations over hillslopes, in channels the total flow duration in hillslopes and channels, and the RTS of the same points. The RTS agrees quite well with the total flow duration.

The above results suggest that the RTS represents the average flow time to the point of interest. Because flow on hillslopes is slower than in channels, at the small catchment areas the hillslope routing process affects more the RTS, while at large catchment areas the time of flow in the channel becomes more dominant and has a larger effect on the RTS. The 24 km^2 studied catchment is still largely affected by the hillslope routing, but the channel effect is expected to be more dominant as we move downstream from the examined outlet point.

Effect of model parameters

The effect of hillslope *vs* channel processes on the RTS is examined also by changing related model parameters. Figure 5(a) presents the change of RTS when lengths of

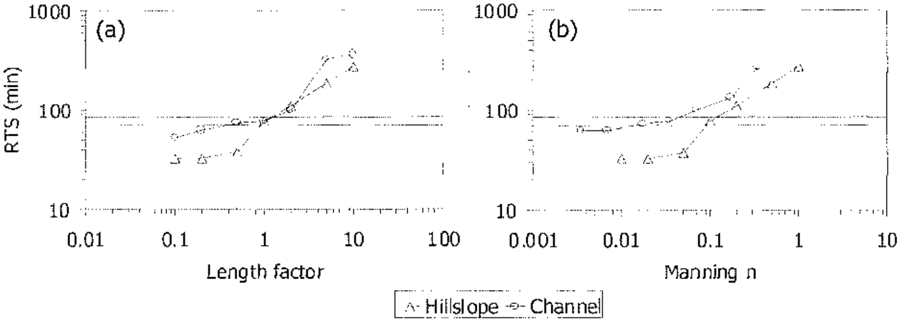

Fig. 5 Effect on the RTS of changing (a) length and (b) roughness parameter for hillslopes and channels. The RTS with the original parameters is indicated.

hillslopes and channels were multiplied by a factor between 0.1 and 10 and Fig. 5(b) presents the change in RTS with changes in roughness parameter. The RTS with the original parameters is indicated in the figures for comparison. We see that for the lower range of parameter values the RTS is more sensitive to changes in hillslope parameters than in channel parameters. For the higher range of parameter values this trend is not as clear and even shows larger effect of channel parameters for large increase of length. This result agrees with the above explanation associating the RTS with the average flow duration. Since originally the channel flow duration is already relatively small, reducing it more hardly changes the RTS. The hillslope flow duration however is significant and its reduction directly affects the RTS. When considerable slowing in channel response is implied the channel flow duration becomes long enough to be significant in its effect on the RTS.

CONCLUDING REMARKS

The response time scale represents a measure of the characteristic time of the catchment hydrological response. It quantifies the amount of smoothness performed on the input when transformed into output by identifying the equivalent averaging that has to be applied to the rainfall such that it will have the same smoothness as the runoff. In the current study a radar-based distributed hydrological model is used to study what controls the response time scale. The results suggest that this time scale represents the average flow duration to the examined concentration point. In small catchments this duration is more affected by hillslope routing processes while as the catchment increases in size channel routing processes become more dominant. This result still needs to be validated by modelling different catchments in a variety of geomorphologic and climatic regimes.

Acknowledgements This study was funded by grants from the United States–Israel Binational Science Foundation (Grant 97-00026), the International Arid Lands Consortium (IALC, 00R-11) and the United States–Israel Binational Agricultural Research and Development Fund (BARD, FI-303-2000). Additional support was provided by a cooperative agreement between HRC and the Hydrology Laboratory (HL) of the US National Weather Service, National Oceanic and Atmospheric Administration.

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