A field-based hydrological model to study the impacts of urbanization on regional water resources

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Abstract The 250 km$^2$ Natuf catchment drains mountainous, partly karstified limestone terrain of the Judean Mountains westward into the coastal plain of Israel. Typical for Mediterranean climate, rainfall is concentrated from October to April, approaching 600 mm per annum at the water divide. The catchment is underlain by the most important regional freshwater resource: the Mountain Aquifer jointly used by Palestinians and Israelis. To assess the regional impacts of urbanization on water resources, field evidence on runoff generation processes is incorporated into a physically-based, non-calibrated rainfall-runoff model. A historic high magnitude flood is used for a first model test. Reconstructed peak discharges at 15 sites along the drainage network and hydrometric data at the outlet help to validate model simulations. Three independent model runs document the impact of urban development on volume and peak flow in the regional scale (250 km$^2$). Urbanization on 7.7% of the area results in an increase of 16% in peak flow and 35% in runoff volume. Despite the high uncertainty determined, the model helps to detect possible shortcomings in hydrometric streamflow data.

Key words regional impacts of urbanization; Mediterranean climate; non-calibrated rainfall–runoff model; high magnitude floods; model uncertainty

INTRODUCTION

The 250 km$^2$ Natuf catchment drains mountainous, partly karstified limestone terrain of the Judean Mountains westward into the coastal plain of Israel. Typical for Mediterranean climate rainfall is concentrated from October to April, approaching 600 mm per annum at the water divide. The catchment is underlain by the most important regional freshwater resource: the Mountain Aquifer jointly used by Palestinians and Israelis. Within the Natuf catchment urbanization is extensive as determined by airphoto analysis. In 1967 1.5% of the area was affected, this rose to 7.7% in 1994 (Fig. 1). A trilateral (German–Israeli–Palestinian) research project was
initiated in 1999 to assess the impacts of this pronounced urbanization on the limited water resources of the region.

In general, changes caused to a rural area by urbanization directly affect drainage basin hydrology, in terms of both quality and quantity (e.g. Wolman & Schick 1967). Changes in the runoff response of urbanized catchments, i.e. increased peaks and volumes of generated floods, with reduced lag time and time to peak, may be assessed by time series analysis of hydrometric data. In Mediterranean catchments Sala & Inbar (1992) identified hydrological effects of urbanization by comparing cumulative curves of annual precipitation and runoff. Breaks in the latter could be associated with times of increased industrial or urban development. However, only if different stages of urban growth are simulated as scenarios of a rainfall-runoff model, can the hydrological effect of urbanization be illustrated directly. Moreover, only then are quantitative forecasts of future developments possible.

Most existing rainfall-runoff models have been developed for applications in humid catchments with existing streamflow data. In general their parameters are determined by calibration, i.e. “fitted” by comparing model simulations with gauged streamflow data. If long time series of hydrometric data exist and only close fits of simulated and gauged hydrographs are desired, these conventional models may suffice even in Mediterranean, partly urbanized catchments, as shown in a sample study by
Berndtsson et al. (1986). In the present context, however, the use of calibrated humid rainfall-runoff-models is restricted for two main reasons:

(a) Their structure with all the necessary assumptions and simplifications was set up to describe hydrological processes of humid settings. Even if calibrated successfully, it will be difficult, or even impossible, to relate parameter values to environments with entirely different characteristics and ongoing hydrological processes.

(b) Long series of gauged runoff events are the prerequisite for a successful model calibration. These are rare, especially for high magnitude floods in Mediterranean catchments. Even if they do exist, an adequate series may extend over decades and the characteristics of the simulated catchment itself change within the calibration period. Hence calibrated model parameters only reflect a mean state and cannot be used to analyse ongoing changes.

The objective of this paper is to simulate the hydrological effects of urban developments on high magnitude floods in the regional Mediterranean context, the 250-km² Natuf catchment. Not to depend on pre-defined model structures and non-meaningful model parameters, hydrological flood generation processes are studied in the field and subsequently incorporated into a non-calibrated rainfall-runoff model. For a first model test, the high magnitude flood of the New Year 1992 is chosen.

FIELD EVIDENCE AND MODEL STRUCTURE

On two days in succession, runoff generation on a steep (25%) limestone hillslope was studied by sprinkling experiments. The experiments were on a 180-m² plot using a set of quantitative measurements and tracer hydrological techniques (Lange et al., 2001). Runoff was found to be a mixture of Hortonian type runoff on rocky parts and saturation excess runoff on soil covered parts. It was concluded that the runoff response of these hillslopes is dominated by lateral flow processes at, or close to the surface. These findings were corroborated by in-storm field observations, where continuous overland flow (from the top of the hillslope down to the channel) was observed on limestone hillslopes even during fairly small runoff events.

Using this experience, a non-calibrated rainfall-runoff model for the arid zone (Lange et al., 1999) is adopted for urbanized Mediterranean catchments. To parameterize runoff generation, two specific areas are chosen:

(a) Natural, non-terraced slopes delineated according to 1:50 000 land-use maps and a 25 m digital terrain model (DTM). For these areas runoff generation is quantified according to the results of the sprinkling experiments.

(b) Urban areas delineated according to aerial photography and existing land-use information. On these surfaces, as a first assumption, all rainfall turns into immediate runoff.

According to topography, the 250 km² Natuf catchment is divided into 488 tributary catchments (model elements). Once generated, the model transfers all surface flow from the model elements to the nearest main channel. In a discrete channel network, separated into about 1 km segments each delimited by nodes, the VPMC4-method of the Muskingum-Cunge technique (Ponce & Chaganti, 1994) is used for streamflow routing from one channel node to the other. Owing to the limited amount of channel alluvium, transmission losses are disregarded.
APPLICATION TO A HIGH MAGNITUDE FLOOD

Around New Year 1992, a high magnitude flood was recorded in Wadi Natuf. In addition to the hydrometric data at the catchment outlet, results of a detailed palaeoflood analysis (Ettinger, 1996) are available. At several cross sections, two to three independent reconstructions of peak flow were carried out by hydraulic calculations on the basis of high water marks. For the present model 25 h of rainfall radar images in a 5-min step serve as input. However, only two ground stations, one in the headwaters and one close to the catchment outlet, are available to calibrate radar values with ground-measured rain intensities. As differences between the two stations are apparent, a mean value is used for model input, while the two extremes serve as boundary values for the analysis of model uncertainty.

For the first model run all areas affected by urbanization in 1994 are included, the data corresponding best to catchment characteristics during flood occurrence. Owing to missing information on the input rainfall, the entire hydrograph cannot be simulated (Fig. 2). In particular, the first peaks and the delayed recession of the observed hydrograph suggest additional rainfall input, before and after the period of radar data accounted for. Taking into consideration that no calibration, i.e. "fitting" of the simulated hydrograph is carried out, the overall model results are encouraging. Timing, the sharp rise and the first small sub-peak in the main flood phase of the second half of 1 January 1992 plot close to the observed hydrograph. As the most striking difference, the model simulates a second main flood peak (215 m$^3$ s$^{-1}$, 20:00 h) not recorded by the hydrometric station.

Due to the fully distributed model structure, simulations at 15 channel nodes throughout the catchment are possible and serve for internal model validation (Fig. 1). To illustrate the impacts of urban development two additional model runs are

![Graph](image-url)
Table 1 Internal validation of the three model scenarios, site no. refers to Fig. 1.

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Contributing catchment (km²)</th>
<th>Range of reconstructed peak discharges (Ettinger, 1996) (m³ s⁻¹)</th>
<th>Urban areas disregarded (m³ s⁻¹)</th>
<th>1967 (m³ s⁻¹)</th>
<th>1994 (m³ s⁻¹)</th>
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* Not reconstructed, but measured at the hydrometric station.

DISCUSSION AND CONCLUSIONS

Before the results of this modelling exercise can be fully judged, its basic idea, data restrictions and underlying assumptions should be recalled. First, on purpose, all model parameters are determined without calibration. This means, the simulated hydrograph is not fitted against the observed one by changing any parameter value. Second, the runoff generating zones, i.e. natural, non-terraced slopes and urban areas, are treated uniformly with rather simple conceptualizations of runoff generation. Third, the rainfall radar data for the model input obviously does not cover the entire storm length and shows a high uncertainty. Fourth, additional processes (e.g. channel transmission losses or losses into karstic depressions) are not included at this stage.
Still the simulated catchment response (Fig. 2) illustrates two general fields for the application of this type of model:
(a) The timing and the overall magnitude of the catchment response are satisfactorily simulated. Hence model applications to ungauged catchments seem reasonable.
(b) The simulation of a second main peak not evidenced by the hydrometric data, suggests missing data in the gauged hydrograph. Although reconstructed values upstream (Table 1) also point to a much higher flood peak, no rash conclusions should be drawn considering the high model uncertainty. However, in principle, only a non-calibrated approach, independent from observed streamflow data, is able to detect shortcomings in this type of data, normally blurred by the parameter fitting procedures needed for calibrated models.

In general, the present model shows that the impact of urbanization in this type of environment is not only a local problem but adds up to a regional one in a 250 km² catchment. For one particular event a catchment-wide urbanization of 7.7% results in a simulated 16% increase in the runoff peak, a 35% increase in runoff volume corresponding to a (maximum) 35% reduction in groundwater recharge. These results are interim depending on event and catchment characteristics, but prove, on a regional scale, the negative impacts of urbanization in an area with restricted water resources. Ongoing research aims to decrease model uncertainty and to incorporate more field information. As such, information of catchment morphology and vertical reflectivity radar profiles will help to improve radar calibration. In addition, results of a multi-scale measuring campaign within a city will be used to better parameterize runoff generation in urbanized areas.

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REFERENCES


