Non-calibrated arid zone rainfall–runoff modelling

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Abstract Two high-magnitude rainstorm floods were simulated using a distributed rainfall–runoff model of the 1400 km^2 arid catchment of Nahal Zin, northern Negev, Israel. No calibration with measured flow data was performed. The simulations used the October 1991 storm when almost the entire catchment was covered by high intensity rainfall as detected by rainfall radar, and a storm in October 1979 when only one ground station in the uppermost headwaters recorded heavy precipitation, while the majority of the catchment remained dry. For the latter event the distributed model served as a "runoff-rainfall model" to reconstruct the model input. The resulting two-dimensional description of the rainfall was then transferred to an ungauged tributary to produce a field-based scenario of a high magnitude flood. The results compared nicely to maximum observed discharges in the region. For the October 1991 event the model served as a tool to analyse the role that different major tributaries played during flood generation.

Key words 2-D rainfall description; arid region; high magnitude floods; non-calibrated approach; rainfall radar; rainfall–runoff modelling

INTRODUCTION

Hydrological models are only as good as their ability to incorporate the underlying processes of flood generation. Except for terrain with active erosion or sedimentation (e.g. recent channel alluvium, mobile sand dunes), infiltration rates of sparsely vegetated arid areas do not reach the rainfall intensities of high-magnitude convective rainstorms. During these events Hortonian overland flow accumulates on the ground surface, concentrates quickly and induces episodic floods in ephemeral streams (Pilgrim *et al.*, 1988; Yair & Lavee, 1985; Schick, 1988). While a large amount of floodwater may be lost by transmission losses into dry channel beds, direct runoff components prevail since contributions from underground storage are negligible.

For most climatic regions a large variety of rainfall–runoff models are available. However, not all of their parameters can be measured in the field. Some require calibration by fitting simulated with gauged runoff data. As a consequence, high quality hydrometric data are required for a successful model application—a precondition often fulfilled in the perennial streams of developed countries in humid areas. However, in most arid zone countries it is too costly to install and maintain a hydrometric gauging network, hence practically all arid catchments are ungauged. Where gauging stations do exist, measurement problems during high-magnitude desert floods considerably reduce data quality. To date only calibrated rainfall–runoff models have been applied to arid catchments (e.g. El-Hames & Richards, 1998; Sharma & Murthy, 1998).

To overcome problems with model calibration a distributed, non-calibrated rainfall–runoff model was developed for the 1400 km^2 catchment of Nahal Zin, Israel. For details on model structure and parameter determination see Lange *et al.* (1999a).

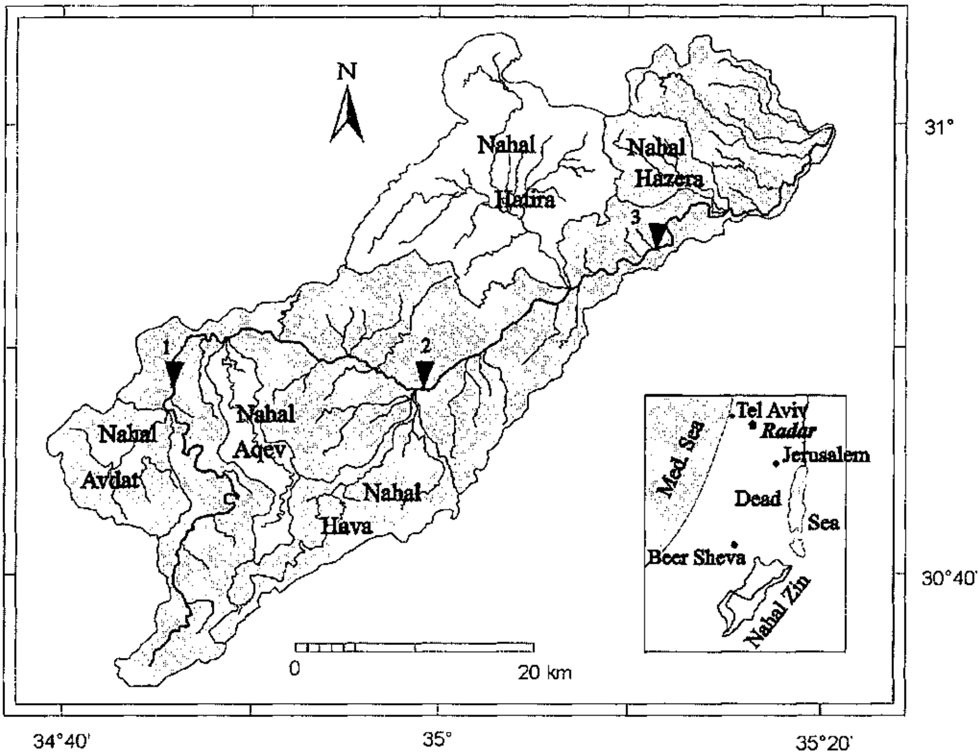

Fig. 1 Location map and hydrometric stations. 1: Mapal, 2: Massos, 3: Aqrabim.

The Zin Wadi is the main artery draining the arid rocky northern Negev, into the Dead Sea (Fig. 1). Exposed bedrock and shallow rocky soils dominate the terrain, with only small areas covered by fluvial deposits or silty/sandy sediments of aeolian origin. The model is applied to two different high-magnitude events.

THE MODEL

For each dominant flood generation process a separate model routine is passed and, in turn, for each routine the catchment is subdivided independently. Model input rain intensity is distributed over a catchment-wide grid using a one minute time step. The catchment is spatially disaggregated into different terrain types according to hydrologically relevant surface characteristics representing the sub-units, to parameterize runoff generation. Mapping relied on air photograph analysis together with a thorough ground-truthing. Parameters of initial loss and initial/final infiltration rate describe infiltration. Using a standardized response function, runoff concentration is described in (on average) 1.6 km^2 sub-tributaries delineated according to topography. Inside the channel network the Muskingum–Cunge technique is used for streamflow routing accounting for channel dimensions and roughness. For each channel segment a constant infiltration rate is applied for transmission losses and discontinued when the wetting front reaches the bottom of the available alluvial storage. The spatial disaggregation for this model routine, i.e. the subdivision of the drainage network into channel segments delimited by channel nodes, is predefined by the sub-tributaries used to parameterize runoff concentration.

THE TWO HIGH-MAGNITUDE EVENTS

In October 1991 a huge single raincell entered the southern margins of Nahal Zin. Subsequently a curved squall line developed, crossing almost the entire catchment from south to north (Greenbaum *et al.*, 1998). Into this main convective rain system inner core cells were embedded with maximum intensities exceeding 200 mm h^{-1}. Every five minutes the catchment-wide rainfall distribution was recorded by rainfall radar calibrated by six ground-based rain recorders. However, no completely gauged hydrographs were available, since all gauging stations went out of operation during this high magnitude flood. Hence the non-calibrated model could only be validated by reconstructed peak discharges using the palaeoflood technique (Greenbaum *et al.*, 1998). A complete model run yielded hydrographs falling inside the uncertainty range of the field peaks (Lange *et al.*, 1999a).

In October 1979 one rainfall station located in the upper catchment recorded the highest rain intensity (224 mm h^{-1}) ever measured by a ground station in the Negev. While the rainfall radar had not yet been installed, gauged hydrographs were available from three consecutive hydrometric stations along the main channel (Fig. 1). Flood peaks and volumes constantly decreased from station to station due to channel transmission losses: Mapal: 324 $m^3 s^{-1}$, 2.04×10^6 m^3; Massos: 210 m^3 s^{-1}, 1.60×10^6 m^3; Aqrabim: 42 $m^3 s^{-1}$, $0.95 \times 10^6 m^3$. Hence runoff generation only took place in the uppermost Zin headwaters and the flood travelled for a long distance on dry channels with no measurable tributary input. For a complete model run, information from only one point was insufficient to represent the spatial distribution of the rainfall input. Hence the model was used as a "runoff–rainfall model" to reconstruct the spatial pattern of the input. A moving circular raincell represented the two-dimensional rainfall field with the necessary parameters (cell trajectory and lifetime) obtained by a comparison of simulated and gauged hydrographs (Lange *et al.*, 1999b).

UNCERTAINTY EVALUATIONS

During parameter determination using measured field characteristics, maximum uncertainty ranges were assessed for each of the 12 model parameters. Within sensitivity runs one parameter was varied over its maximum range of uncertainty, while the others were kept constant. For October 1979 the reconstructed rainfall served as model input, while for October 1991 the adjusted rainfall radar was used. The effects on the simulated flood, i.e. deviations in peak, volume and timing, were analysed and compared. For both events the uncertainty in timing (i.e. the simulated peak arrival) was dominated by channel routing parameters. However, flood magnitude (i.e. the simulated peak and volume) was highly event-dependent. During October 1991 the sensitivity of runoff generation and transmission loss parameters was balanced, while during October 1979 transmission loss parameters made up more than two thirds of overall model uncertainty. In a worst-case scenario, all parameters were

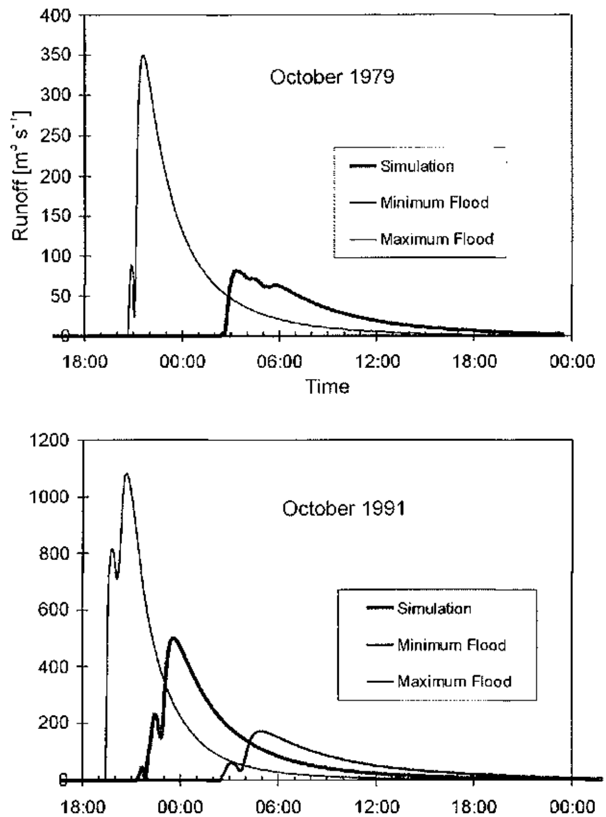

Fig. 2 Worst case scenarios.

set to the boundary values of their maximum uncertainty range yielding possible maximum and minimum floods (Fig. 2). During October 1979 the maximum flood rushed 5.8 h (+51%) ahead and peaked at 268 $m^3 s^{-1}$ (328%), higher than the simulated one; the flow volume was $2.1 \times 10^6 m^3$ (109%) higher. The minimum flood totally infiltrated into the channel alluvium. During October 1991, both "worst-case floods" arrived. The maximum uncertainty ranges were smaller than during October 1979 but still considerable; ±455 $m^3 s^{-1}$ (±91%) for the peak, $\pm 4.0 \times 10^6 m^3$ (±48%) for the volume, and ±4.1 h (±59%) for the peak arrival.

APPLICATION 1: A FIELD-BASED SCENARIO OF AN EXTREME FLOOD

The 55 km^2 tributary Nahal Hazera is known to produce large floods. The channels are characterized by steep slopes and only negligible alluvium, while the catchment has an almost circular shape. Located in the lower Zin catchment, large floods of Nahal Hazera may reach the alluvial fan of Nahal Zin with only minor attenuation due to transmission losses. To illustrate this fact, the circular raincell used to simulate the October 1979 event (15 km diameter, 224 mm h^{-1} maximum rain intensity), was transferred to the centre of the Hazera catchment. Again it travelled for 24 min in a

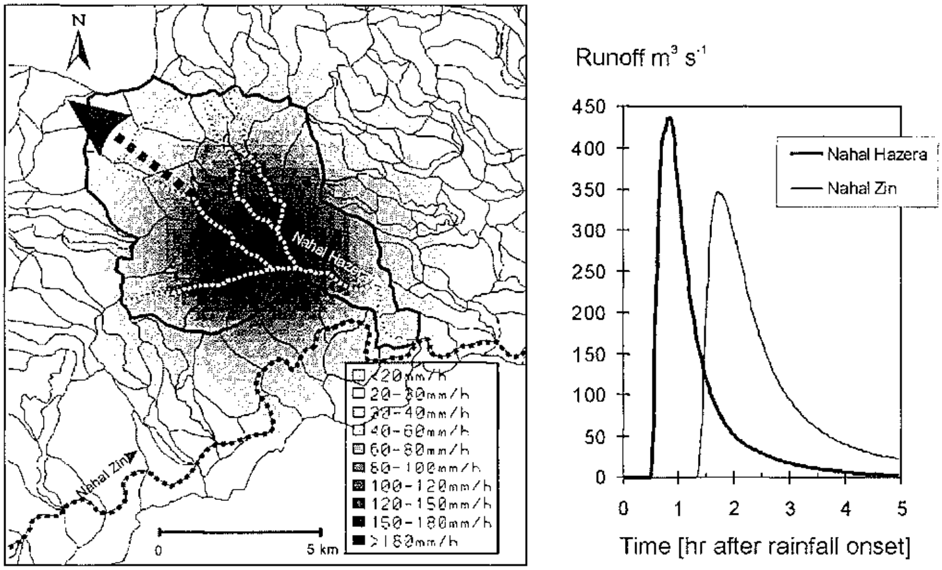

Fig. 3 Nahal Hazera flood scenario.

north-western direction. Only 30 min after rainfall onset, a large flash flood was simulated at the mouth of Nahal Hazera peaking to 440 $m^3 s^{-1}$. At the outlet of the Zin catchment the flood peak still reached 345 $m^3 s^{-1}$ (Fig. 3).

APPLICATION 2: INTERNAL CATCHMENT PROCESSES

The spatially distributed structure of the non-calibrated model provided insights into processes active during the high magnitude flood of October 1991. Hydrographs obtained upstream and downstream of confluences were compared to assess the role different major tributaries played for flood generation. Results indicated that the tributaries acted differently (Fig. 4). The most upstream tributary Nahal Avdat (A) produced a large flood arriving simultaneously with the peak in the main channel. Downstream of the confluence, the peak was significantly sharpened. Nahal Aqev (C) and Nahal Hava (B) and Nahal Hatira (D) responded quicker and generated flood peaks arriving long before the main one. Downstream of the confluence they travelled as preceding peaks in front of the main flood wave. A spatial analysis of runoff onset revealed that the westernmost parts of the Zin catchment, which contain the Nahal Avdat tributary, generated runoff only after 18:00 (Fig. 4). The reason was evident in the radar data. An isolated storm cell had touched the western margins of the Zin catchment by the time the main storm had already left the catchment.

DISCUSSION AND CONCLUSIONS

Overall the maximum ranges of model uncertainty, as illustrated by the worst-case scenarios (Fig. 2), must be regarded as uppermost boundaries. It is very unlikely that,

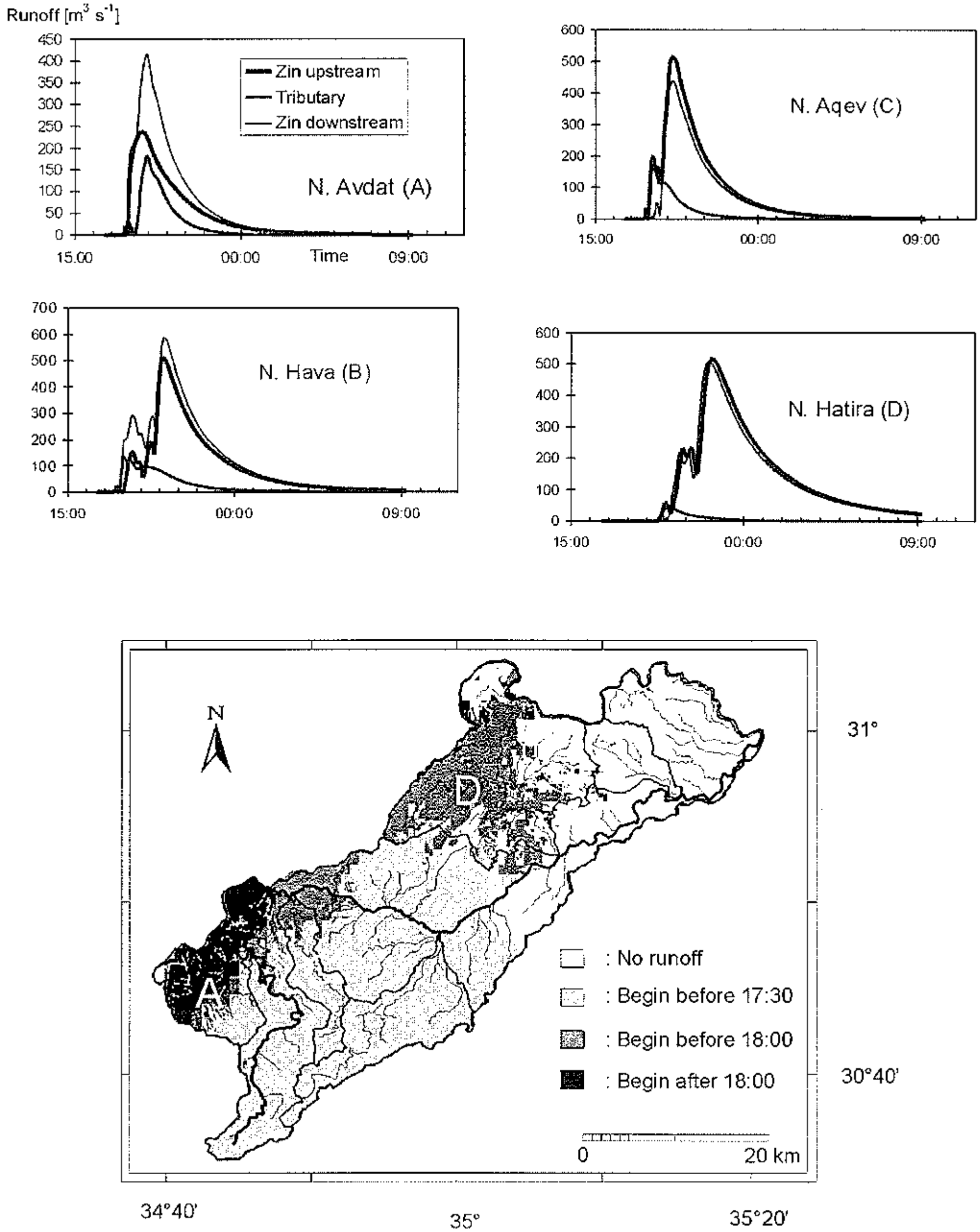

Fig. 4 Tributary response and spatial distribution of runoff onset, October 1991.

in a particular model run, all parameters are at the boundary of their uncertainty range at the same time. Also, most parameters were assessed independently for different elements of spatial subdivision (terrain types, sub-tributaries, channel segments). Thus single mistakes in the data input tend to cancel each other out and, despite a considerable maximum model uncertainty, meaningful applications of the present approach may be found.

The first model application, the field-based flood scenario inside Nahal Hazera, has implications for maximum possible floods and flood control. It establishes that the same rainstorm (in the present example a single raincell) may produce high magnitude floods as well as minor ones, dependent on its location over the catchment. The long travel distance on dry channels during October 1979 buffered most of the flow, while the almost circular tributary Nahal Hazera generated an extreme flash flood with only minor attenuation on its way downstream. The high Hazera flood peak is very close to the envelope line of Yanovich *et al.* (1996) describing the maximum discharges ever observed in the Negev and in the Sinai. It may be assumed that the destructive discharges on this line originate from a fatal combination of catchment morphology and rain intensity. Hence the present model correctly translated favourable catchment characteristics of Nahal Hazera (the almost circular shape of the catchment, the accentuated relief and the limited extent of the channel alluvium) into a quick and accentuated flood generation. It proved to be an appropriate tool to estimate high magnitude floods from ungauged arid catchments and may be regarded more reliable than transferring extrapolated runoff data from distant gauging stations.

In the second model application, internal catchment processes responsible for the generation of the high magnitude flood of October 1991 were analysed. The model provided insights into temporal and spatial tributary responses. It was shown that an isolated raincell, reaching the catchment 1.5 h after the main rain system, had a decisive effect on the flood magnitude of the October 1991 flood. It postponed runoff response of the western headwaters to the time of high flow in the main channel and almost doubled the peak discharge. The influence of the remaining tributaries was indirect. They wetted or even saturated the channel alluvium before the main peak arrived. Then the flood wave rushed over a wet channel and was not further reduced on its way downstream.

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