Modelling high magnitude events in large arid catchments—a field based approach in Nahal Zin, Israel

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Abstract A physically-based distributed rainfall–runoff model was applied to the 1400 km² catchment of Nahal Zin, Israel, to study the major processes governing the development of big floods. Both runoff generation in the headwater surfaces and flow losses along the channel network were studied using spatial distribution. In this way physically-based input parameters can be incorporated into the model and no calibration is needed. The study concentrated on the rocky headwaters of the catchment and on one big flood using a GIS framework to combine map-derived information, images of rainfall radar, air photos and results of an extensive field survey. A modular model structure was chosen to facilitate the stepwise simulation of the dominant hydrological processes. In the upper rocky headwater catchment with its narrow channels simplifying assumptions were possible. The simulation yields results which compare reasonably with measured peak discharges. Multiple peaks by tributaries and the downstream decrease of floods can be described realistically. Sensitivity tests show the outstanding importance of a correctly calibrated rainfall radar as model input.

INTRODUCTION

Arid environments are characterized by the scarceness of water resources. Channel flow controls the hydrological and ecological balance of arid environments in terms of erosion processes and water supply. Due to logistical and financial problems streamflow data are not available for practically all arid catchments. Transferable hydrological models that do not depend on calibration with measured hydrographs may help in the assessment of available water resources. However, an accurate hydrological model must fully include spatial variations of rainfall and surface properties and therefore must be distributed.

Hughes & Sani (1994) introduced a compromise between a complex, physically-based, distributed model and a simple empirical approach. Still calibration was necessary for some of the input parameters. Karnieli et al. (1994) presented a semi-distributed model for a 14.7 km² semiarid catchment. Only after the input parameters were calibrated and optimized was a good model fit reached. Michaud & Sorooshian (1994) applied different types of rainfall–runoff models to the 150 km² semiarid Walnut Gulch catchment. A complex distributed model was more accurate without calibration, than a simple distributed one. After calibration, however, the results of both approaches were comparable. Al-Turbak (1996) used a modelling approach...
based on the GIUH (Rodriguez-Iturbe & Valdes, 1979) in several semiarid and arid catchments of Saudi Arabia. Although the size of the biggest catchment was 600 km$^2$, only four rainfall gauges were used for calibration. Hughes (1997) reviewed the application of different hydrological models within the southern African region. Generally, both monthly and daily time-step models could be applied where good quality data sets for calibration were available. Within the more arid parts of the region problems arose because of inadequate rainfall data and the poor empirical simulation of channel transmission losses.

All approaches mentioned above depend on calibration with measured flow data at one specific location which makes their distributed character blurred. Therefore a rainfall–runoff model for big arid catchments was developed which did not depend on calibration (Lange et al., 1998b). The model restricted itself to a stepwise description of the dominant processes within high magnitude events. A high magnitude flood of October 1991, which had already been analysed in detail (Greenbaum et al., 1998), was chosen for the simulation. The present study focused on the upper rocky headwaters. Inside this part of the catchment channels are confined and the depth of the alluvium is limited.

**STUDY AREA**

Nahal (Wadi) Zin is one of the major arteries draining the mountainous northern Negev Desert in Israel into the Dead Sea (Fig. 1). The upper part of the 1400 km$^2$ arid catchment drains the plateaux of the northern Negev Highlands. Shallow rocky soils dominate the terrain and the valleys are filled with loessial silty sediments. After 45 km the channel passes the Mapal gauging station and goes into a steep waterfall entering the Zin Valley. Here the water flows inside a wide syncline covered by loose sedimentary surfaces. The Massos gauging station is located 28 km

![Fig. 1 Location map and subcatchments of the Nahal (Wadi) Zin model.](image-url)
downstream of the Mapal station. Although the flow of almost half of the catchment (c. 660 km²) is recorded, the hydrological characteristics of arid headwaters still dominate, as channel width and depth of the alluvium are limited. Further on the Nahal Zin enters a section which is covered by thick coarse alluvium. In the last few kilometres before the Dead Sea, the wadi forms a narrow canyon inside hard carbonate rocks and marly sediments. Within the catchment the average annual rainfall amount is between 90 and 60 mm. Localized storms occurring as convective cells are mainly responsible for high magnitude floods (Schick, 1988).

MODEL COMPONENTS AND DATA CAPTURE

Rainfall

In large arid catchments the only tool used to derive an appropriate distributed rainfall input is rainfall radar. However, the rain on the ground is derived measuring the reflectivity within sampling volumes at a certain height above the surface. At long ranges, errors originating from a change in the vertical profile of reflectivity are usually more dominant than those caused by changes in the Z–R relationship due to a varying drop-size distribution (Joss & Waldvogel, 1990). In the present study the distance between radar location and sampling volume over the Nahal Zin catchment was 110 to 150 km long. However, no additional data were available to account for changes in the vertical reflectivity profile or to incorporate a change in the Z–R relationship. Therefore a one-step calibration of reflectivity measurements with station data was made. Data were available from six rainfall recorders located within and close to the study catchment (Greenbaum et al., 1998). A value of 9.8 dBZ was added to the raw reflectivity data resulting in maximum rainfall intensities of 210 mm h⁻¹ inside the Nahal Zin catchment. These values correspond well with extreme rainfall intensities measured elsewhere in the arid zone, e.g. 200 mm h⁻¹ in the Nahal Yael experimental catchment (Schick, 1988). The results of the radar calibration were incorporated as gridded data sets into the GIS ARC/INFO.

Rainfall excess

In arid areas there is almost no vegetation covering the earth surface. Therefore remote sensing (e.g. aerial photography) is a valuable tool for studying hydrologically relevant surface characteristics over large areas. Combining this information with geological maps we mapped 21 different terrain units inside Nahal Zin. Each single unit was studied directly in the field. In a second step, the threshold rainfall required to produce runoff and a time distribution of infiltration was assigned to each terrain unit, allowing existing results of field experiments to be used (e.g. Greenbaum, 1986; Yair et al., 1980; Yair, 1992). In order to apply the results from small runoff plots to larger units, additional processes had to be taken into account and the threshold rainfall increased. On slopes with a colluvial base runoff produced is lost at the interface between the rocky and colluvial part of the slope (Yair, 1992). As the catchment size increases, more and more water disappears flowing on dry
channels (Schick, 1988). Initial losses for the terrain units ranged from 4.5 mm for rocky surfaces with only patchy soil to more than 10 mm for alluvial or sandy sediments. The final rates of infiltration were transferred from the sprinkling experiments ranging from only 5 mm h\(^{-1}\) for rocky terrain to more than 50 mm h\(^{-1}\) for sandy sediments. Within the GIS rain intensity was combined every minute with the depth of infiltration within a 30 x 30 m grid, and a spatial picture of the produced Horton runoff was obtained.

Runoff concentration

The morphology allowed the catchment to be separated into 850 elements representing small subcatchments (Fig. 1). For each element the volume of produced runoff could be calculated within the GIS. These volumes were translated into a hydrograph for tributary inflow using measured field data. A unique time series of rainfall and runoff data was available for the 0.5 km\(^2\) experimental catchment Nahal Yael in Israel (Schick, 1988; Schick & Lekach, 1993). A value of 13 min was calculated for the time lag. To derive the shape of the hydrograph, measured single peak events were standardized and functions of cumulative runoff were calculated. A response function resulted from the mean cumulative runoff.

Channel flow and transmission losses

Different physically-based distributed routing procedures were tested with the data of an artificial flood (Lange et al., 1998a). The Muskingum-Cunge technique (Cunge, 1969) proved to be highly applicable under these circumstances. The variable parameter mode MVPMC3 was used, to account for nonlinearity and wave steepening (Ponce & Chaganti, 1994). The channel was assumed to be rectangular with a constant width. To incorporate infiltration losses at each channel node, a constant infiltration rate and a limited depth of the alluvium were assumed. Inside Nahal Zin the time step used was 1 min. Slope and length of the channel segments were derived from topographical maps. The area of the active alluvium within each channel segment was digitized using aerial photographs. This area was divided by the respective channel length to determine a spatially averaged active channel width. Parameters for the roughness and the infiltration behaviour were estimated dividing the channels into characteristic types. Infiltration rates for the different types were derived from previously existing field experiments (Shanan, 1975; Kuells et al., 1995; Lange et al., 1998a).

RESULTS

Firstly a validation of the routing component within the Nahal Zin was made. A large event, where lateral inflow from tributaries could be excluded and the runoff was gauged at different locations, was chosen for comparison. The event of October 1979 was selected for this purpose (Fig. 2) and the gauged hydrograph at Mapal
station served as input. It can be seen that the physically-based routing quite nicely simulated the shape of the downstream decreasing flood at the Massos runoff gauge. The recession and the volume however were exaggerated. A complete run of all model components in succession for the 13 October 1991 was compared with measured peaks at the two stations of Mapal and Massos (Fig. 3). As the flood completely destroyed the gauging stations, only the rise of the hydrographs could be measured and the accuracy of the derived “field peaks” was limited. Still the simulated hydrographs compared reasonably with the gauged ones. At Massos multiple peaks were created by rocky tributaries. In sensitivity tests the input parameters for the model were varied. The routing parameters (Manning’s $n$, channel width, slope and channel length) had a strong influence on the shape and the timing of the hydrograph. The influence of the transmission loss parameters (infiltration rates and depth of the alluvium) was limited to the first part of the flood and was less obvious. A change in the infiltration characteristics of the terrain elements could also be followed. However, due to the exponential character of the $Z$-$R$ relationship, the parameters of the radar calibration were the most sensitive ones.
DISCUSSION

In the present study only the dominating processes were described and tools appropriate for big catchments (e.g. remote sensing, GIS) were used to derive the necessary input data. To guarantee the transferability and distributed character of the model, the simulations are not calibrated with measured flow data. Inside the upper rocky catchment simulations obtained were satisfactory when compared to the uncertainty inherent with measurements in the arid zone. As the effect of channel transmission loss is less accentuated in these headwaters, the most care must be taken in the estimation of a correct rainfall input. In this respect the use of rainfall radar is the only way to fully incorporate the temporal and spatial variability. Within high magnitude events a critical calibration using rain intensities may limit the uncertainty. During this procedure the maximum occurring rain intensities, which are well documented in arid zones around the world, serve as the upper control limit. Nevertheless, uncertainties still exist and cannot be ignored, especially for long ranges. Therefore the network of rainfall radar in the arid zone should be improved, if more accurate hydrological models are to be guaranteed. In regions without any radar data the use of GIS-driven rainfall models may also be forward-looking.

In arid headwaters channels are narrow and clearly defined and the channel alluvium responsible for transmission losses is of limited extent. Physically-based routing procedures (e.g. the Muskingum–Cunge technique) are applicable for large events. The assumption that the complete width within a rectangular channel is covered by a flood at any time still seems appropriate. Infiltration losses have to be taken into account, although their influence is limited to the first part of a flood. If, further downstream, a channel changes into a wide braided system of sub-channels, transmission losses are much more important. Moreover, modifications applying a stage dependent channel width become necessary (Lange et al., 1998b). Current research is pursuing in the direction of simplifying the model structure systematically. The intention is to create a transferable model, which is as simple as possible without losing too much accuracy, after which guidelines can be given on what kind of input data need the most emphasis for future modelling of ungauged arid catchments.

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