Integrated Methods in Catchment Hydrology—Tracer, Remote Sensing and New Hydrometric Techniques (Proceedings of IUGG 99 Symposium HS4, Birmingham, July 1999). IAHS Publ. no. 258, 1999.

Recent techniques in large arid catchments—ways to overcome model calibration

JENS LANGE, CHRIS LEIBUNDGUT
Institute of Hydrology, University of Freiburg, Fahnenbergplatz, D-79098 Freiburg, Germany
e-mail: jlange@uni-freiburg.de

ASHER P. SCHICK
Department of Geography, The Hebrew University of Jerusalem, 91905 Jerusalem, Israel

Abstract Advanced techniques were applied to determine the spatial distributed parameter values of a non-calibrated rainfall–runoff model in a large arid catchment. Channel dimensions and infiltration characteristics were determined by air-photo analysis and verified by careful fieldwork. A GPS device was used for positioning during field surveys and channel transmission losses were studied by artificial tracers. During one high intensity event (October 1991) rainfall radar yielded the spatial pattern of rainfall intensities, while during another (October 1979) the input rainfall was traced back by the model using a physically-based description of convective arid rainfall. Due to its physical basis, the model could combine different sources of information: basin characteristics determined by field surveys and remote sensing, results of existing experiments, and general scientific experience. Compared with calibrated conceptual models, this resulted in a higher flexibility facilitating applications to basins or events with poor data records, urgently needed for many parts of the arid zone.

INTRODUCTION

Arid ephemeral channels only flow occasionally as a direct response to runoff-generating rainstorms. Convective rain cells of limited spatial extent produce flash floods in which flow may rise from insignificant levels to very high flood peaks within several minutes. Since evaporation is pronounced and time spans between single flood events are usually long, these floods mostly travel on a dry channel bed allowing for significant transmission losses into the channel alluvium (Schick, 1988). Rainfall and runoff gauging stations are rare in arid environments since in most countries financial resources needed for installation and maintenance are short. In Africa, for instance, networks of hydrological observing stations are in decline (Sehmi & Kundzewicz, 1997).

In addition to logistical problems, the characteristics of arid rainfall–runoff events themselves limit the accuracy of hydrological data. Arid precipitation is characterized by a high spatial variability. To accurately measure the space–time distribution of rainfall intensity during a convective storm, dense networks of rainfall recorders are required (Michaud & Sorooshian, 1994b). Otherwise, rain-cell trajectories may move entirely between existing raingauges resulting in huge underestimates of spatial rainfall (Greenbaum *et al.*, 1998). At runoff gauging stations discharge is usually determined using the slope–area method. This method adapts a uniform-flow equation (the Manning equation) using channel characteristics, water-surface profiles, and a roughness coefficient. However, the huge erosive power of high magnitude events may change cross-sectional geometry during a flood event or even destroy existing gauging stations.

Rainfall–runoff models may be used for various purposes, e.g. to analyse the hydrological response of catchments or to complete runoff records. Most existing approaches depend on model calibration with measured streamflow data. As such, they include the uncertainties of measured rainfall and runoff. In humid catchments a great variety of calibrated models has been applied. In low-yielding catchments, where channels are characterized by periodic flows during wet seasons, the information content of the runoff data may be enough to calibrate the parameters of daily or monthly conceptual models (Ye *et al.*, 1997). However, to simulate single events in dry ephemeral channels, adequate data sets only exist in very few basins, e.g. in the semiarid Walnut Gulch experimental basin, Arizona, USA (Michaud & Sorooshian, 1994a) or in the Luni basin, India (Sharma & Murthy, 1998). In other parts of the world arid zone problems usually arise because of inadequate rainfall data and the poor empirical simulation of channel transmission losses (e.g. Hughes, 1997).

To overcome problems with model calibration, a distributed, field-based rainfall–runoff model was developed for the 1400 km^2 catchment of Nahal Zin, Israel (Lange *et al.*, 1998b; Lange *et al.*, in press). The Zin Wadi is the main artery draining the rocky northern Negev desert into the Dead Sea (Fig. 1). Within a GIS framework only the two dominant processes governing the development of large desert floods, generation of Hortonian runoff on the surfaces and flow losses along the channel network, were taken into account. The spatial pattern of the model parameters was determined using previously existing experimental results, measured field data, and information from maps and aerial photographs. No calibration with measured flow data was performed.

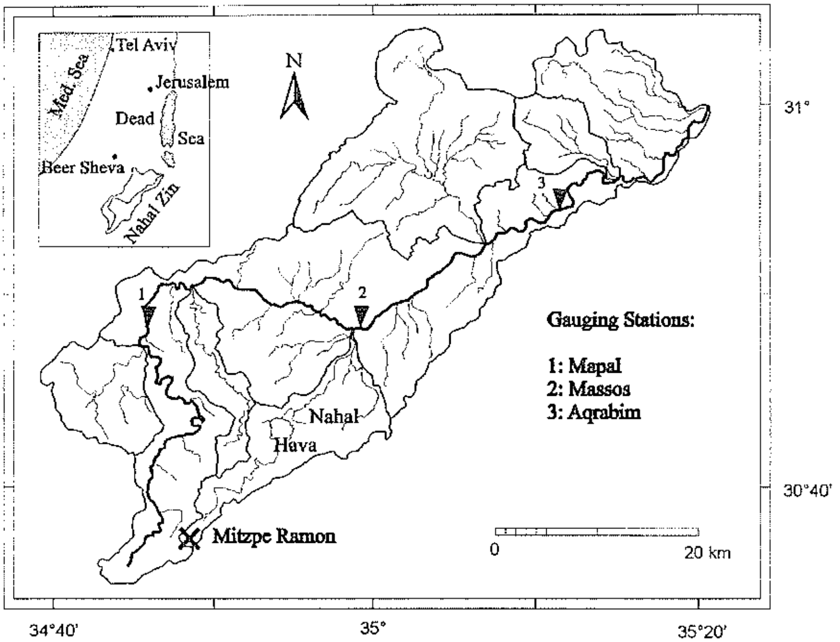

Fig. 1 Location map with gauging stations.

Reconstructed peak discharges of one high intensity rainstorm flood (October 1991) could be successfully simulated. In this paper the recent techniques used to derive and process the spatially distributed model parameters are outlined. Then the flexibility of the non-calibrated distributed hydrological model is shown as it is used to trace back characteristics of another convective arid rainstorm (October 1979).

TECHNIQUES TO DETERMINE MODEL PARAMETERS

Rainfall radar

In large arid basins the only known practical tool to derive an appropriate rainfall input for a distributed hydrological model is rainfall radar. By this technique a large area can be covered in real time from a single point with a relatively high spatial and temporal resolution. Although additional information may be obtained by multi-parameter techniques (e.g. dual polarization radar), only single frequency measurements of the back scattered radiation have been used widely and implemented operationally (Collier, 1996). They require a relationship between radar reflectivity and rainfall intensity (*Z–R* relationship) usually obtained by raingauge adjustment. During the validation event of October 1991, a single frequency radar scan was available every five minutes. Data from six rainfall recorders were used for raingauge adjustment comparing ground and radar-derived maximum rain intensities (Lange *et al.*, in press).

Air-photo interpretation

In arid environments very little vegetation covers the ground surface. Therefore hydrologically relevant surface characteristics may be directly studied using aerial photographs. Channel dimensions may be assessed and the spatial extent of different terrain units mapped. For instance, loose sediments can be distinguished from rocky slopes or plateaus and ages of alluvial deposits may be characterized (Bull, 1991). Within the Zin catchment about 80 air photos were scanned and rectified to determine different channel and terrain characteristics (Fig. 2). More than 20 different terrain types were delineated according to their hydrological response. To provide ground truth each single type was studied in the field. The results of existing studies on runoff generation carried out on plots (e.g. Greenbaum, 1986) and small catchments (e.g. Yair, 1992) were attributed to the different terrain types. As a result, a catchment-wide distribution of infiltration characteristics was determined containing the two parameters initial loss and final infiltration rate. To obtain a spatially averaged channel width for each of the 419 channel reaches, active alluvial area digitized from aerial photographs was divided by flow length.

GPS-guided field survey

With a Global Positioning System (GPS), locations anywhere on earth can be easily determined. Absolute systems yield the position directly by one receiver but are

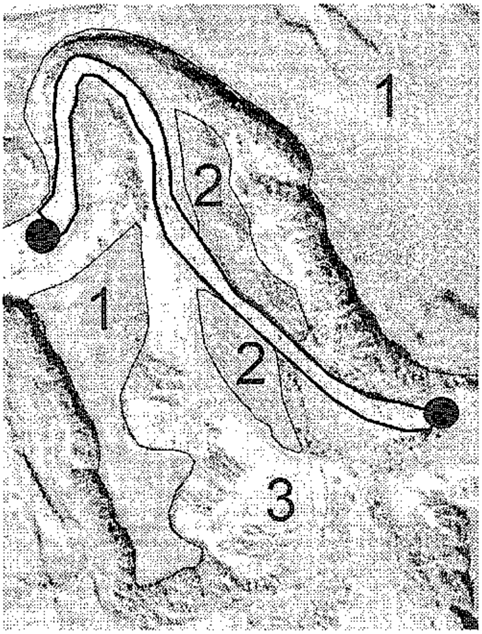

Fig. 2 Detail of an air photo showing two channel nodes, active alluvial area in between and examples of different terrain types; 1: rocky plateau, 2: old terrace, 3: young alluvial/colluvial surface.

limited in accuracy. Differential techniques require two connected receivers yielding much higher accuracy. Since data are robust and easy to process, the cheaper absolute systems are suggested for regional mapping (Cornelius *et al.*, 1994). In the Nahal Zin one GPS receiver proved to be very helpful locating positions of representative channel cross-sections predefined in topographical maps. These cross-sections could be recognized on aerial photographs and helped to assess the extent of active channel alluvium. In the same way, distinct points characterizing extended terrain types were located on aerial photographs and later analysed in the field.

Artificial tracers

In a small ephemeral stream channel in the Eilat Mountains, Israel, a dam-breach-induced flash flood simulation was conducted (Schick *et al.*, 1996). Artificial tracers were used to study transmission losses inside a 250 m long channel reach (Lange *et al.*, 1998a). Fluocapteurs (small samples containing adsorptive charcoal) were placed within the alluvium at different locations and depths. After the flood they were collected and used to obtain a spatial picture of the maximum depth of infiltration and estimate a mean infiltration rate required for the Nahal Zin model. The obtained results compared reasonably with infiltration tests conducted in the lower part of Nahal Zin (Külls *et al.*, 1995). Hence this technique seems promising and may help to overcome the problem of transferring results from "artificial" point scale measurements (infiltration tests) to real floods covering entire channel reaches.

TRACING BACK HISTORIC RAINFALL

The characteristics of convective rainfall have been widely studied using radar techniques. During the developmental stage of a storm, updrafts push moist, unstable air aloft. Rainfall occurs later during both the mature stage and the dissipating stage. Different types of storms exist. *Single cell storms* of limited extent (approximately 5 km diameter) typically do not produce severe weather. Their whole life cycle usually does not exceed 20–30 minutes. *Multicell storms* consist of clusters or lines of single cells moving together, with each cell in a different stage of the storm life cycle. *Supercell storms* develop stable and intense up- and downdrafts that may coexist for relatively long periods of time. They are the largest storms (approximately 15 km diameter) and responsible for the most extreme weather. Often transitional stages between multi- and supercell storms exist. Local studies in the southern Negev and in Sinai recorded both moving stormcells (Schick, 1988) and quasi stationary ones (Schick & Lekach, 1987).

These known features of convective rainfall were accounted for in a physically-based description of the rainfall during the October 1979 storm. Measured data from three runoff gauging stations were available but only one rainfall station located in the upper catchment at Mitzpe Ramon (Fig. 1). The high intensities and long duration recorded indicate a supercell that directly hit the rainfall station (Fig. 3). Following the ideas of Waymire *et al.* (1984) the stormcell was assumed to be circular with an exponential symmetrical decay of rainfall intensity around the cell centre:

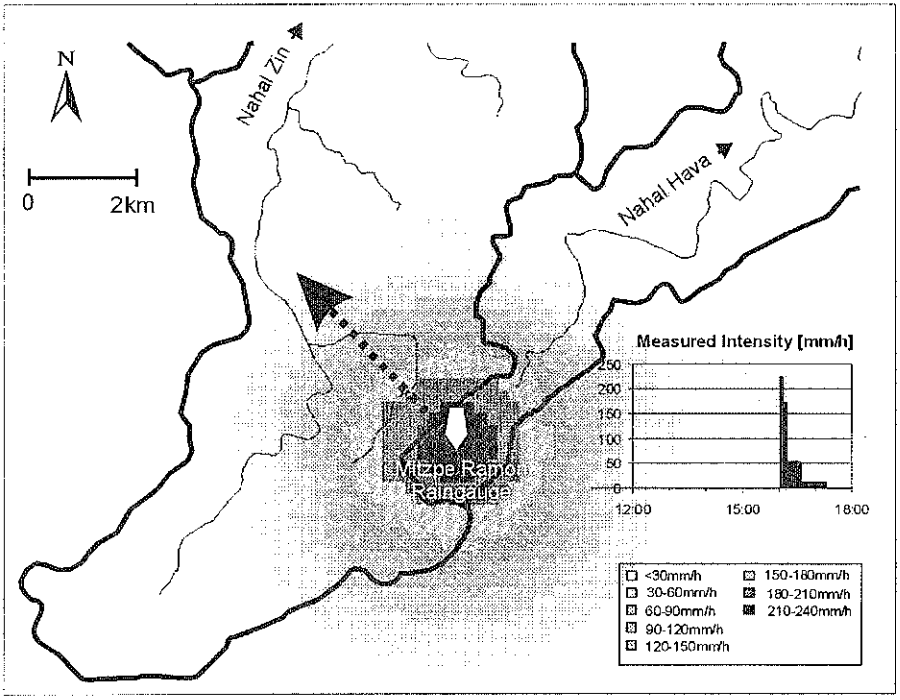

Fig. 3 Spatial representation of the October 1979 rainstorm in the upper catchment. Measured rain intensity at Mitzpe Ramon and assumed rain cell trajectory.

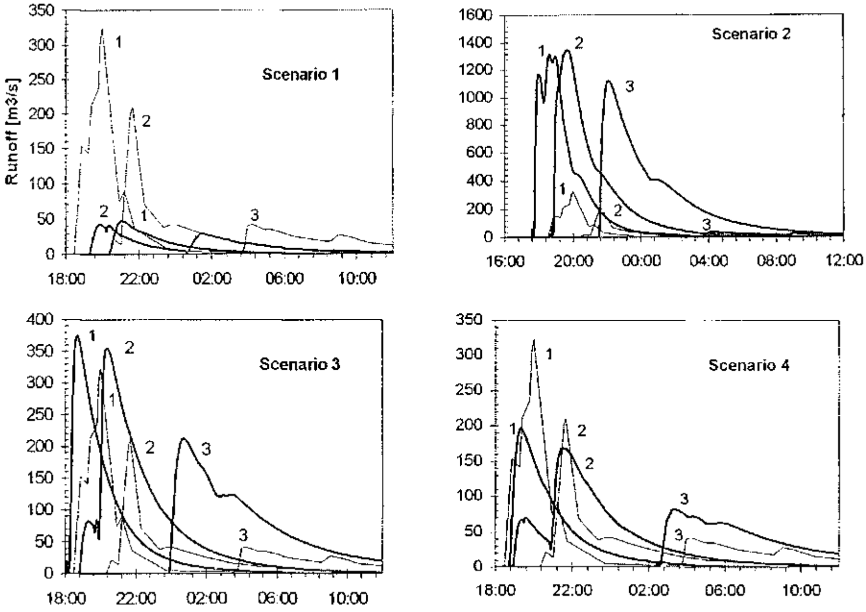

Fig. 4 Different scenarios of the October 1979 flood; *fine line*: gauged hydrographs, *bold line*: simulated hydrographs; 1: Mapal, 2: Massos, 3: Aqrabim.

$$i(r) = i_0 \exp(-r^2/X) \qquad (1)$$

where i_0 is the rainfall intensity at the centre; r is the distance from the centre; and X is a measure of the cell's spatial extent. Assuming a diameter of 15 km in which the intensity dropped from 224 to 1 mm h^{-1}, 10.35 km^2 resulted for X. The results of four different scenarios were compared with measured hydrographs at the gauging stations at Mapal, Massos, and Aqrabim (Fig. 4). All model parameters determined in the field and validated during the October 1991 event remained unchanged.

First, a stationary cell was constructed decaying in time as recorded at the ground station. The resulting flood was too small and totally disappeared at Aqrabim (Scenario 1). Moreover, the hydrograph at Massos arrived earlier than at the uppermost station, Mapal, and was dominated by a preceding peak originating from the fast-responding, steep and rocky tributary Nahal Hava. To improve the simulations it was assumed that the ground-measured intensity decay at Mitzpe Ramon was not caused by a temporal decay, but by a spatial displacement of the stormcell. The moving velocity was determined using equation (1) and the time spans until the intensity dropped from the recorded maximum (224 mm h^{-1}) to the values of 172, 54, and 12 mm h^{-1}. The resulting mean velocity (112 m min^{-1}) indicated a slow moving system. As most high-intensity storms in the Negev originate from the Red Sea Trough in the south (Bar-Lavy *et al.*, 1977), and as Nahal Hava was obviously inactive, the trajectory of the stormcell was set to move from southeast to northwest. Due to its low velocity, the high-intensity stormcell needed 4 h to cross the entire catchment. The resulting hydrographs were much too high (Scenario 2). To improve the results it was further assumed that in addition to the spatial displacement, the cell decayed completely after 34 minutes (Scenario 3). At this point, the measured rainfall intensity at Mitzpe Ramon had dropped to 12 mm h^{-1}. Still, the catchment response was exaggerated. Finally a cell lifetime of 24 minutes reproduced the gauged hydrographs in a correct order of magnitude (Scenario 4). Hence the October 1979 flood was probably produced by a single, slow-moving, and high-intensity cell producing high-intensity rainfall for about half an hour.

DISCUSSION AND CONCLUSIONS

The simulation of the October 1979 event (Scenario 4, Fig. 4) shows that not all details of this specific event could be accurately described. At Mapal the extreme rise was underestimated and the recession overestimated. Further downstream at Massos the main peak arrived in time but the response of Nahal Hava was exaggerated. At Aqrabim the simulated hydrograph arrived too early and was too high. However, it should be recalled that considerable error may also be possible for measured hydrographs, that not a single model parameter was fitted by calibration and that the rainfall input was described applying rather simple geometrical rules. Calibration of the model parameters, e.g. changing the infiltration rate of the alluvium at specific locations, could have produced a perfect fit between measured and simulated hydrographs at all stations. Then these parameters would have been only valid for the present event and the present basin, and the potential to model other basins or events with poor data quality would have been lost.

Due to its field basis, the present model could combine different sources of information: basin characteristics determined by field surveys and remote sensing, results of historic experiments, and general knowledge. Compared with calibrated conceptual models, this resulted in a higher flexibility facilitating applications to basins or events with poor data records, which is urgently needed for many parts of the arid zone. The October 1979 flood may illustrate this fact. Since data from different runoff stations but only one single rainfall station were available, the runoff information was used to trace back the rainfall input. Size and geometry of a moving cell were determined using general knowledge. The recorded rainfall intensity helped to estimate maximum intensity, velocity, and temporal decay. However, information from only one rainfall station was not sufficient to fully describe temporal decay and spatial displacement of a moving stormcell. The missing information was obtained comparing simulated and gauged runoff hydrographs. As a result, the spatial pattern and the quantity of runoff generation could be modelled. If additional information on rainfall characteristics had been available (e.g. eyewitnesses of the event or additional ground measurements), the physically-based description of the convective rainfall might have been used to simulate the catchment response in a completely "non-calibrated way", similar to the validation event of October 1991 when a rainfall radar station had already been in operation.

A major problem in arid zone hydrology is the lack of adequate data sets limiting the application of calibrated rainfall–runoff models to the very few well-instrumented research basins. Model calibration sometimes pretends a high model accuracy, since good model fits may be possible with unrealistic parameter values or process descriptions (e.g. Mein & Brown, 1978; Grayson *et al.*, 1992). Calibrated model parameters depend on the quality of the data sets used for calibration and may rarely be related to physically measurable catchment characteristics. This makes the simulation of catchments with poor data records difficult or even impossible. The non-calibrated model offers an alternative for high magnitude events in large arid basins. Recent techniques appropriate for the arid environment and for a large spatial scale (remote sensing, artificial tracers, GPS, and GIS) made calibration unnecessary. More applications of non-calibrated models in different arid catchments are desirable in the future to prove their general applicability. However, following the observations at Nahal Zin, we anticipate successful applications of this model type in other arid zone basins, especially if local data on infiltration characteristics and operational rainfall radar exist.

Acknowledgements Above all the authors would like to thank N. Greenbaum for his kind help during the field mapping. E. Morin helped to obtain the digital radar data. These data were provided free of charge by Mekorot, Electrical Mechanical Service Ltd. A. Yair provided first-hand information on infiltration properties of different lithologies and A. Margalit shared her experience on arid rainfall. The Israel Hydrological Service and the Meteorological Service both gave us free access to their data files. The Förderverein Hydrologie, Freiburg, provided financial support. Finally the critical review of the draft by S. Uhlenbrook is kindly acknowledged.

REFERENCES

Bar-Lavy, B., Margalit, A. & Sharon, D. (1977) Desert rainfall patterns associated with the Red Sea Trough. *Conf. on Meteorology of Semiarid Zones* (Tel Aviv, Israel).

Bull, W. B. (1991) *Geomorphic Responses to Climatic Change.* Oxford University Press, New York.

Collier, C. G. (1996) Weather radar precipitation data and their use in hydrological modelling. In: *Distributed Hydrological Modelling* (ed. by M. B. Abott & J. C. Refsgaard), 143–163. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Cornelius, S. C., Sear, D. A., Carver, S. J. & Heywood, D. I. (1994) GPS, GIS and geomorphological fieldwork. *Earth Surf. Processes and Landforms* **19**, 777–787.

Grayson, R. B., Moore, I. D. & McMahon, T. A. (1992) Physically based hydrologic modeling. 1. A terrain-based model for investigative purposes. *Wat. Resour. Res.* **28**, 2639 –2658.

Greenbaum, N. (1986) Point runoff in an extremely arid region. Infiltration–runoff tests on small plots in the southern Arava and their hydrological and pedological implications. MSc Thesis, Department of Physical Geography, The Hebrew University of Jerusalem.

Greenbaum, N., Margalit, A., Schick, A. P. & Baker, V. R. (1998) Reconstruction of a high magnitude rainstorm-flood in Nahal Zin—a large hyperarid catchment in the Negev Desert, Israel. *Hydrol. Processes* **12**, 1–23.

Hughes, D. A. (1997) *Southern African "FRIEND"—The Application of Rainfall–Runoff Models in the SADC Region.* WRC Report no. 235/1/97, Grahamstown, South Africa.

Külls, C., Leibundgut, Ch., Schwartz, U. & Schick, A. P. (1995) Channel infiltration study using dye tracers. In: *Application of Tracers in Arid Zone Hydrology* (ed. by E. M. Adar & Ch. Leibundgut) (Proc. Int. Atomic Energy Agency Symp., Vienna, August 1994), 429–436. IAHS Publ. no. 232.

Lange, J., Leibundgut, Ch., Grodek, T., Lekach, J. & Schick, A. P.(1998a) Using artificial tracers to study water losses of ephemeral floods in small arid streams. In: *Karst Hydrology* (ed. by Ch. Leibundgut, J. Gunn & A. Dassargues) (Proc. Rabat Symp., April–May 1997), 31–40. IAHS Publ. no. 247.

Lange, J., Leibundgut, Ch., Greenbaum N. & Schick, A. P. (1998b) Modelling high magnitude events in large arid catchments—a field based approach in Nahal Zin, Israel. In: *Hydrology, Water Resources and Ecology in Headwaters* (ed. by K. Kovar, U. Tappeiner, N. E. Peters & R. G. Craig) (Proc. HeadWater'98 Conf., Merano. April 1998), 561–567. IAHS Publ. no. 248.

Lange, J., Leibundgut, Ch., Greenbaum, N. & Schick, A. P. (in press) A non-calibrated rainfall–runoff model for large arid catchments. *Wat. Resour. Res.*

Mein, R. G. & Brown, B. M. (1978) Sensitivity of optimized parameters in watershed models. *Wat. Resour. Res.* **14**, 299 303.

Michaud, J. & Sorooshian, S. (1994a) Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed. *Wat. Resour. Res.* **30**, 593–605.

Michaud, J. & Sorooshian, S.(1994b) Effect of rainfall-sampling errors on simulations of desert flash floods. *Wat. Resour. Res.* **30**, 2765–2775.

Schick, A. P. (1988) Hydrologic aspects of floods in extreme arid environments. In *Flood Geomorphology* (ed. by V. R. Baker R. C. Kochel & P. C. Patton), 189–203, Wiley, New York.

Schick, A. P., Lekach, J., Grodek, T, Lange, J. & Leibundgut, Ch. (1996) An artificial flash flood in a small arid stream channel, Eilat Mountains, Israel. *AGU Meeting* (November 1996), p. F259.

Schick, A. P. & Lekach, J.(1987) A high magnitude flood in the Sinai desert. In: *Catastrophic Flooding* (ed. by L. Mayer & D. Nash), 381–410. Allen & Unwin, Winchester.

Sehmi N. S. & Kundzewicz Z. W. (1997) Water, drought and desertification in Africa. In: *Sustainability of Water Resources under Increasing Uncertainty* (ed. by D. Rosbjerg, N.-E. Boutayeb, A. Gustard, Z. W. Kundzewicz & P. F. Rasmussen) (Proc. Rabat Symp., Rabat, April–May 1997), 57–65. IAHS Publ. no. 240.

Sharma, K. D. & Murthy, J. S. R. (1998) A practical approach to rainfall–runoff modelling in arid zone drainage basins. *Hydrol. Sci. J.* **43**(3), 331–348.

Waymire, E., Gupta, V. K. & Rodriguez-Iturbe, I. (1984) A spectral theory of rainfall intensity at the meso-β scale. *Wat. Resour. Res.* **20**, 1453–1465.

Yair, A. (1992) The control of headwater area on channel runoff in a small arid watershed. In: *Overland Flow* (ed. by T. Parsons & A. Abrahams), 53–68. University College Press, London.

Ye, W., Bates, B. C., Viney, N. R., Sivapalan, M. & Jakeman, A. J. (1997) Performance of conceptual rainfall–runoff models in low yielding ephemeral catchments. *Wat. Resour. Res.* **33**, 153–166.