Guendouz, A. Michelot, J. L. & Allan, G. (2003) Chlorine–36 in deep groundwaters from north-eastern sahara, Algeria (en préparation).

Moulla, A. S., Guendouz, A. & Reghis, Z. (1995) Qualité chimique et bactériologique des eaux de la nappe phréatique de la région de Oued–Souf. (Sahara nord est septentrional, Algérie). En: *L'eau, une réalité, une urgence, un défi* (Actes du 2ème colloque National Climat–Environnement, Oran, Algérie, décembre 1995).

Moulla, A. S., Guendouz, A. & Reghis, Z. (1997) Hydrochemical and isotopic investigation of rising piezometric levels of saharan phreatic aquifers in the Oued-Souf region (Grand Erg Oriental basin, Algeria). In: *Water in the Mediterranean. Collaborative Euro-Mediterranean Research: State of the Art, Results and Future Priorities* (Proc. Int. conf., Istanbul, Turkey, Novembre 1997).

Sonntag, C., Klitsch, E., Lohnert, E. P. Munich, K. O., Junghans, C., Thorweihe, U., Weistroffer, K. & Swailem, F. M. (1978) Palaeoclimatic information from ^{2}H and ^{18}O, in ^{14}C dated north-saharan groundwater: groundwater formation in the past. In: *Isotope Hydrology 1978* (Proc. Symp. IAEA, Vienna), 569–581. IAEA, Vienna, Austria.

UNESCO (1972) Etude des ressources en eau du sahara septentrional. Projet ERESS, Rapport final, 7 plaquettes, Paris, France.

Yousfi, M. (1984) Étude géochimique et isotopique de l'évaporation et de l'infiltration en zone non saturée sous climat aride: Béni-Abbés, Algérie. Thèse Doctorat 3ème cycle, Univ. Paris–XI, Orsay, France.

Hydrology of the Mediterranean and Semiarid Regions (Proceedings of an international symposium held at Montpellier, April 2003). IAHS Publ. no. 278, 2003.

Large-scale hydrological modelling in the semiarid northeast of Brazil: aspects of model sensitivity and uncertainty

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Abstract For the assessment of water resources under changing environmental conditions, dynamic process-based hydrological models are required. For a semiarid area in northeastern Brazil, rainfall characteristics and lateral redistribution of runoff components are shown to have a considerable influence on runoff simulations. Uncertainties in related data and parameters, and their effects on the simulation results, vary between wet and dry climatic conditions.

Key words climate change; hydrological processes; northeastern Brazil; rainfall–runoff model; uncertainty

INTRODUCTION

Semiarid areas are characterized by limited water resources. The quantitative assessment of water availability is a prerequisite for the development of sustainable measures of water management in view of an increasing water demand and a possibly decreasing availability in future. For this task, hydrological models as one component within an integrated approach, which links various sectors of the complex natural and human system and their feedbacks, are indispensable tools.

A broad set of requirements is usually imposed on hydrological models within such a framework. Similar to the example in this study for semiarid northeastern Brazil (see Gaiser *et al.*, 2003, for an overview) this often includes the applicability of the model for large spatial scales, like river basins, and for long temporal scales, such as decades in the view of climate change impact assessment. The latter objective calls for a physically-based representation of the hydrological processes to capture the influence of climate and land-use change on the water balance. These processes, however, mainly operate at considerably smaller temporal and spatial scales. This, in turn, requires adequate scaling approaches to link the process scales with the final scale of interest of the model application. In semiarid environments, the specific hydroclimatological and physiographic conditions, e.g. high temporal and spatial variability of rainfall, high rainfall intensities, intermittent river runoff, sparse vegetation cover, and large number of dams, lead to a specific set of dominant processes to be represented in the model (see e.g. Beven, 2002). In this study, the focus is on infiltration-excess runoff and lateral water fluxes, including related sensitivities and uncertainties with regard to climate change impact assessment.

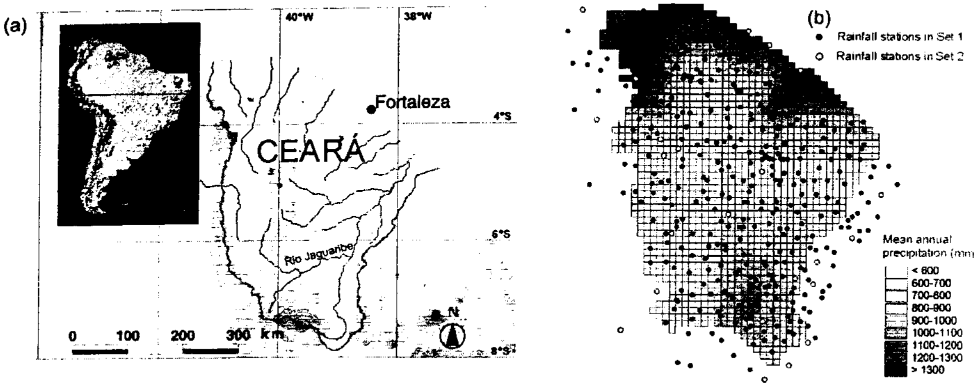

Fig. 1 (a) Location of the study area Ceará in northeastern Brazil. (b) Rainfall stations of Ceará in two different data sets used in this study, and mean annual precipitation interpolated to a 10 × 10 km^2 grid from the station data of Set 1, period 1960–1998.

STUDY AREA

The study area is the Federal State of Ceará (150 000 km^2) in the semiarid tropical northeast of Brazil (Fig. 1(a)). Mean annual precipitation is about 850 mm, falling mainly within a rainy season of about five months. Inter-annual rainfall variability is high, the mean annual rainfall of the 10 driest and 10 wettest years within the period 1960–1998 was 610 and 1370 mm, respectively. The coefficient of variation (C_v) of annual rainfall is 36%. Potential evaporation amounts to about 2100 mm. Being mainly characterized by crystalline bedrock and shallow soils, surface water provides the largest part of the water supply. Mean annual runoff ratios are in the range of 10–20% of annual rainfall. The C_v of annual discharge is generally above 100%. The target units of the model application in this study are sub-basins of about 1 × 10^3 km^2 in size.

MODEL OVERVIEW

Modelling experiments were realized with the hydrological model WASA (Model of Water Availability in Semi-Arid environments) (Güntner & Bronstert, 2003; Güntner, 2002). WASA is a deterministic, spatially distributed model being composed of conceptual, process-based approaches. Water availability (river discharge, storage volumes in reservoirs, soil moisture) is determined with daily resolution. Sub-basins are disaggregated in WASA into smaller modelling units within a multiscale, hierarchical approach. Structured variability of landscape characteristics along toposequences is captured by terrain components which represent areas of a specific topographic position within the toposequence and with similar slope gradients and soil associations. Lateral redistribution processes at the hillslope scale are represented as flow between the terrain components of adjacent topographic position. This includes lateral subsurface flow, based on a simple Darcy-type approach, and re-infiltration of surface runoff, e.g. originating form the slope area and re-infiltrating in the valley bottoms. Additional stochastic variability within terrain components is captured by modelling units which represent the various combinations of different soil and vegetation characteristics. Due to the low resolution of available data, small-scale variability is not represented explicitly with geographic reference, but by the distribution in area of sub-scale units and by statistical transition frequencies for lateral fluxes between these units.

At the smallest level of the hierarchy (soil profiles) vertical processes are represented. Infiltration modelling is based on the Green-Ampt approach. A scaling factor is applied in the infiltration routine to reduce the hydraulic conductivity of the soil surface in order to compensate for underestimated rainfall intensities in the input data. This underestimation is due to: (a) the daily resolution of the rainfall data which does not capture high short-term rainfall intensities of convective precipitation events, and (b) the loss of variance by interpolation from station data to the modelling units, performed by ordinary kriging in this study. The scaling factor is derived as the ratio of mean rainfall intensities of hourly station-based data to those of the daily interpolated time series. Evapotranspiration is described by a modified Penman-Monteith approach, particularly taking into account soil evaporation (Shuttleworth & Wallace, 1985), and the soil water balance is calculated by a multi-layer storage approach. All model parameters of WASA can be derived from the physiographic information about the study area. Thus, model calibration is primarily not required.

RESULTS

Simulations were performed at the scale of the sub-basins of Ceará using two rainfall data sets, one respecting all available information from, on average, 230 rainfall stations in the study area (Set 1 in Fig. 1(b)), and another data set including only those 29 stations with long-term time series which allow the construction of regional climate scenarios (Set 2 in Fig. 1(b)) (Gerstengarbe & Werner, 2003). Large deviations of rainfall volumes at the sub-basin scale resulted for the data set with lower station density (Fig. 2). Differences in simulated annual runoff volumes were larger than the underlying differences in the rainfall input by a factor of about 2.5.

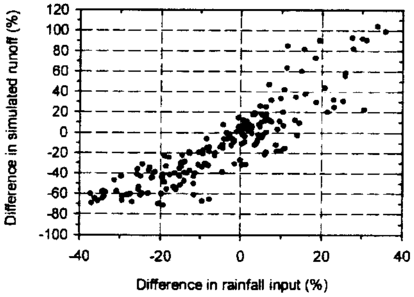

Fig. 2 Effect of differences in rainfall volumes between two data sets on simulated runoff (mean annual values, period 1960–1998, for sub-basins in Ceará).

The simulation with the scaling factor for infiltration modelling resulted in runoff volumes were on average about 25% larger than those of a simulation without the scaling factor (Table 1). This was mainly due to a considerably larger amount of infiltration-excess runoff being generated in the first case. In particular during periods of lower soil moisture, runoff events were correctly represented by the model only if the scaling factor was applied, otherwise they were considerably underestimated (Güntner & Bronstert, 2003).

Respecting the lateral interaction of water fluxes between landscape units led to total runoff volumes at the sub-basin scale being on average 13% lower than for a simulation which did not include any lateral redistribution of runoff (Table 2). The main effect results from re-infiltration of surface runoff into areas of higher infiltration capacity. There, the additional soil moisture is available for evapotranspiration instead of contributing to basin runoff. According to the simulation results, about two thirds of this runoff reduction is due to the effect of stochastic variability between terrain patches with different soil and vegetation characteristics, while the remaining third is due to the effect of structured heterogeneity of the landscape between terrain components along toposequences.

Respecting the lateral redistribution processes in the model increased the inter-annual variability of simulated basin discharge (see C_v in Table 2). Similarly, the relative effect of lateral redistribution on runoff was more apparent in dry years compared with wet years. In dry years, the refillable soil moisture storage in units adjacent to those generating runoff is expected to be larger on average. Thus, a larger fraction of generated local runoff is retained. These results indicate that lateral redistribution effects may provide an important contribution to the nonlinear runoff response of semiarid catchments.

Table 1 Sensitivity of scaling with regard to rainfall intensities on WASA simulations for Ceará, mean annual values, 1960–1998. P: precipitation, E: evapotranspiration, Q: total runoff, Q_i: infiltration-excess surface runoff (mm).

	P (mm)	E (mm)	Q (mm)	Q_i (mm)	Q_i/Q (%)
Simulation without scaling factor	861	724	118	16	14
Simulation with scaling factor	861	696	147	65	44

Table 2 Effect of lateral redistribution processes on runoff for Ceará, mean annual values, 1960–1998, subscript *dry* for the 10 driest years only, subscript *wet* for the 10 wettest years. Q: total runoff, C_v: coefficient of variation of annual runoff.

	Q	C_v	Q_{wet}	Q_{dry}
Simulation without lateral redistribution	169 (mm)	96 (%)	322 (mm)	59 (mm)
Simulation with lateral redistribution	147 (mm)	120 (%)	298 (mm)	41 (mm)
Difference	−13.0 (%)	20.0 (%)	−7.5 (%)	−30.5 (%)

Table 3 Model sensitivity to changes in soil hydraulic conductivity on runoff for Ceará, mean annual values, period 1960–1998. Q: total runoff, Q_i: infiltration-excess surface runoff, Q_{lat}: lateral subsurface flow, f_i, f_{lat}: fraction of both runoff components on total runoff.

Change factor of parameter	0.1	0.5	1.0	5.0	10.0
Q (mm)	181	154	147	142	148
Q_i (mm)	142	86	64	33	23
f_i (%)	78.5	55.8	43.5	23.2	15.5
Q_{lat} (mm)	27	38	42	59	71
f_{lat} (%)	14.9	24.7	28.6	41.5	48.0

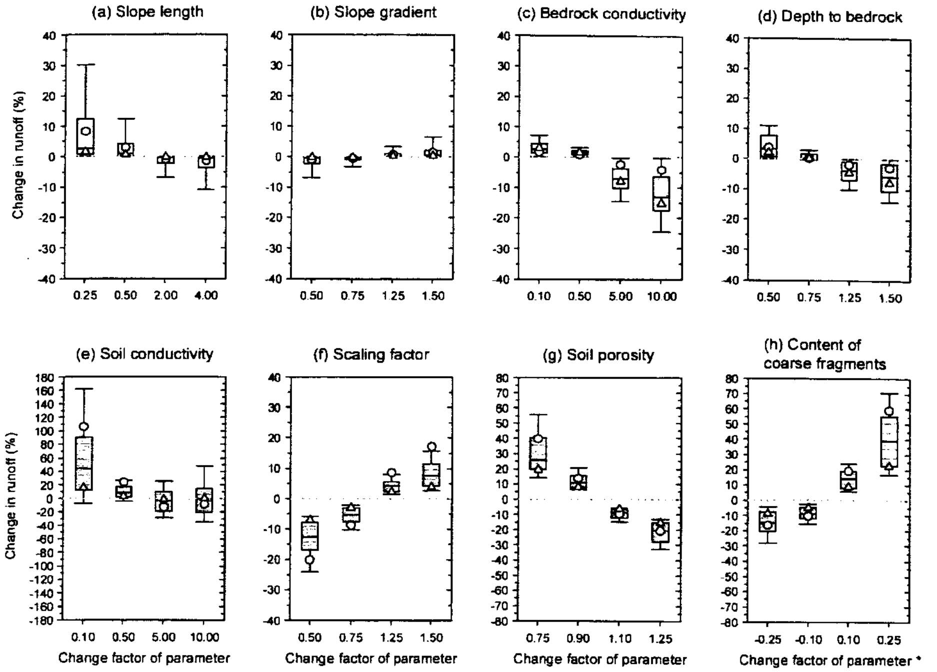

Fig. 3 Sensitivity of soil and terrain parameters of WASA to simulated mean annual runoff, period 1960–1998. x-axis: multiplicative change factor for parameter values; boxes: median, 25th and 75th percentile of change in runoff for 107 sub-basins in Ceará (all years); whiskers: 10th and 90th percentile of runoff change; circles: median runoff change for the 10 driest years only; triangles: median runoff change for the 10 wettest years only.

The sensitivity of model parameters on runoff simulations is presented in Fig. 3 for the example of soil and terrain parameters. Parameter values were changed within an assumed range of uncertainty, depending on the detail and accuracy of the available data. Large sensitivities were found in particular for parameters governing the storage capacity of soils (porosity and content of coarse fragments) and for the saturated hydraulic conductivity of the soil (Fig. 3(e), (g), (h)). A decrease in the soil conductivity values usually led to a marked increase in runoff volumes, as conductivity values are then often in the range of the rainfall intensities, leading to higher volumes of infiltration-excess runoff (Table 3). For an increase of conductivity values, on the other hand, decreasing generation of infiltration-excess runoff was in parts compensated by an increase in lateral subsurface runoff (Table 3), resulting in no net change in runoff at the basin scale on average.

The sensitivity of model parameters on simulation results was of different magnitude for wet or dry climatic boundary conditions. Bedrock parameters, for instance, were more sensitive in wet years because percolation through the soil profile and related lateral subsurface flow processes occur deep enough to be influenced by the bedrock characteristics only for these wet conditions (Fig. 3 (c), (d)). On the contrary, for soil parameters, the model was markedly more sensitive in dry years when infiltration-excess runoff generation and, thus, the near-surface characteristics are dominant (Fig. 3 (e), (g), (h)). A similar study for the vegetation parameters (e.g. canopy height, albedo, stomata resistance) revealed generally a larger sensitivity to runoff for wet as compared to dry years. This is mainly due to the fact that the rate of transpiration losses, being governed by these parameters, is of larger importance for pre-event soil moisture conditions and thus runoff generation in wet years with a more dense sequence of rainfall events.

CONCLUSIONS

The simulation results demonstrate the large sensitivity of the runoff response in semiarid environments to changes in rainfall (see also, e.g. Arnell, 2000). This implies that uncertainties in rainfall input are transferred into considerably larger uncertainties in the simulation of runoff volumes. Beside of rainfall volumes, modelling of runoff generation in this type of environments with a large importance of infiltration-excess runoff is shown to be very sensitive to rainfall time series characteristics. In particular, the need to apply a scaling approach with regard to rainfall intensities is highlighted, as rainfall intensities are underestimated in most large-scale model applications which, for reasons of data availability and model efficiency, use interpolated daily rainfall data. Furthermore, the results demonstrate that processes of lateral redistribution of runoff can have a considerable influence on discharge at the basin scale. It is important to take them into account particularly when the magnitude of the change in runoff for a given change in rainfall in the course of climate change is to be assessed. In addition, due to the different importance of various hydrological processes for different climatic conditions, sensitivity studies on model parameters point out that uncertainties in parameter values may have different implications for the uncertainty of scenario simulations depending on whether an increase or a decrease in rainfall is expected.

REFERENCES

Arnell, N. W. (2000) Thresholds and responses to climate change forcing: the water sector. *Climatic Change* **46**, 305.

Beven, K. J. (2002) Runoff generation in semiarid areas. In: *Dryland Rivers: Hydrology and Geomorphology of Semiarid Channels* (ed. by L. J. Bull & M. J. Kirkby), 57–105. Wiley, Chichester, UK.

Gaiser, T., Krol, M. S., Frischkorn, H. & Araújo, J. C. de (2003) *Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil*. Springer, Berlin, Germany.

Gerstengarbe, F.-W. & Werner, P. C. (2003) Climate analysis and scenarios for Northeast Brazil. In: *Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil* (ed. by T. Gaiser, M. S. Krol, H. Frischkorn & J. C. de Araújo), 137–152. Springer, Berlin, Germany.

Güntner, A. (2002) Large-scale hydrological modelling in the semiarid North-East of Brazil. Dissertation, University of Potsdam, Germany. http://pub.ub.uni-potsdam.de/2002/0018/guentner.pdf.

Güntner, A. & Bronstert, A. (2003) Large-scale hydrological modelling of a semiarid environment: model development, validation and application. In: *Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil* (ed. by T. Gaiser, M. S. Krol, H. Frischkorn & J. C. de Araújo), 217–228. Springer, Berlin, Germany.

Shuttleworth, W. J. & Wallace, J. S. (1985) Evaporation from sparse crops—an energy combination theory. *Quart. J. Roy. Met. Soc.* **111**, 839–855.

Hydrology of the Mediterranean and Semiarid Regions (Proceedings of an international symposium held at Montpellier, April 2003). IAHS Publ. no. 278, 2003.

The limestone aquifers of Malta: their recharge conditions from isotope and chemical surveys

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Abstract The potable water supply in Malta is heavily dependent on groundwater. The two main aquifers, the Perched Aquifer and the Mean Sea Level Aquifer (MSLA), are vertically stacked and separated by impermeable formations. Groundwater is now being threatened by over-pumping and pollution. An isotope and chemical survey was undertaken on rain and groundwater to identify the recharge conditions and set new strategies for exploiting and protecting groundwater. The main results show that: (a) an elevation effect does not appear in rainwater $\delta^{18}O$, so that groundwater cannot be distinguished in either of the aquifers by means of stable isotopes, and (b) groundwater tritium content shows an old recharge of MSLA and a very long residence time. Tritium results look inconsistent with other data, suggesting a present day recharge split into two components: a rapid portion through fractures, and a slow portion through rock porosity which is dominant.

Key words environmental isotopes; groundwater resource; karst; Malta; Mediterranean island hydrogeology; natural tracing; tritium

INTRODUCTION

The Maltese islands obtain their potable water supply from groundwater and seawater desalination in equal proportions. Groundwater is mainly extracted by means of draining galleries in the saturated zones of the two main aquifers found in limestones; the Perched Aquifer (PA) and the Mean Sea Level Aquifer (MSLA). Groundwater is currently endangered by seawater intrusion due to over-pumping from irrigation wells, and by various forms of domestic and agricultural pollution resulting in a significant nitrate contamination of both aquifers.

Various hydrogeological studies have been conducted since the 1950s (Atiga, 1970). BRGM (1991) and Gutierrez (1994) developed two three-dimensional models simulating the MSLA in structure and flow as affected by annual recharge, and abstraction from boreholes and a network of 40 km of sea-level galleries. This model provided an efficient tool for groundwater resources management, but it needs fresh revisions to reflect today's growing number of unmonitored boreholes. Moreover, the degradation of groundwater quality as a result of seawater intrusion and pollution is often interpreted as a result of high aquifer vulnerability in a karst environment (De Ketelaere, 1995, 1996).