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WATER AVAILABILITY, VULNERABILITY OF ECOSYSTEMS AND SOCIETY IN NORTH-EAST BRAZIL

WAVES

Final Report

Working Area: Water Availability and Management
Working Group: Large-Scale Hydrological Modelling

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1. SUMMARY

The main objective of the project 'Large-Scale Hydrological Modelling' within Brazilian-German research programme WAVES (Water Availability and Vulnerability of Ecosystems and Society in the North-East of Brazil) was to develop a hydrological model for the quantification of water availability over a large geographic domain of a semi-arid environment in the Brazilian Federal States of Ceará and Piauí.

The hydrological model WASA (Model of *W*ater *A*vailability in *S*emi-*A*rid Environments) has been developed, which is a deterministic, spatially distributed model being composed of conceptual, process-based approaches that respect specific features of semi-arid hydrology. Water availability (river discharge, storage volumes in reservoirs, soil moisture) is determined with daily resolution. Scaling concepts have been developed and applied to link processes and data across scales. All model parameters of WASA can be derived from physiographic information of the study area. Thus, model calibration is primarily not required. Sub-basins, grid cells or administrative units can be chosen as spatial target units. One version of the model has been provided as a component of the semi-arid integrated model SIM of the WAVES project.

Model applications of WASA for historical time series generally resulted in a good model performance when comparing the simulation results of river discharge and reservoir storage volumes with observed data for river basins of various sizes in the study area. The mean water balance as well as the high interannual and intra-annual variability was in general reasonably represented by the model. Limitations of the modelling concept were most markedly seen for sub-basins with a runoff component from deep groundwater bodies of which the dynamics could not be satisfactorily represented without calibration.

Sensitivity analysis were performed that demonstrated that the simulation results of WASA are characterised by large uncertainties. These are, on the one hand, due to uncertainties of the model structure to adequately represent the relevant hydrological processes. On the other hand, they are due to uncertainties of input data and parameters particularly in view of the low data availability. Of major importance were uncertainties of rainfall data with regard to total volumes and spatial and temporal pattern of time series.

Simulations with WASA for climate scenarios until the year 2050 were run. The results show that a possible future change in precipitation volumes causes a larger percentage change in runoff volumes by a factor of two to three. In the case of a decreasing precipitation trend, the efficiency of new reservoirs for securing water availability tends to decrease in the study area because of the interaction of the large number of reservoirs in retaining the overall decreasing runoff volumes. However, the most important factor of uncertainty for scenarios of water availability in the study area is the uncertainty in the results of global climate models on which the regional climate scenarios are based. Both a marked increase or a decrease in precipitation and thus runoff can be assumed for the given data.

All results of this project were obtained in close co-operation with other German and Brazilian working groups within the WAVES project. The research resulted also in a number of reviewed publications, a PhD thesis and a Diplomarbeit.

2. FRAMEWORK AND OBJECTIVES

The joint Brazilian-German research programme WAVES (Water Availability and Vulnerability of Ecosystems and Society in the North-East of Brazil) (Gaiser et al., 2003; http://www.usf.uni-kassel.de/waves) focussed on the study of the dynamic relationships between climate variability, water availability, agriculture and quality of live in the rural semi-arid north-east of Brazil, taking into account changes in the driving forces of the system, such as climate change or population growth. The region has been struck by recurrent drought periods, which caused fatalities, economic losses and migration. One main objective within WAVES was to develop an integrated model (SIM – Semi-arid Integrated Model, see Krol et al., 2003) which works at the scale of the Brazilian Federal States of Piauí and Ceará, linking modules of water availability and water use, crop yield, agro-economy and demography. The model allows to analyse possible climate change impacts and run scenario simulations as a basis to set up integrated scenarios in order to support sustainable planning of regional development. In this context, a hydrological model for the quantification of water availability was essentially required as one component of the integrated model and as a stand-alone version.

Within this context, the general objective of this WAVES sub-project 'Large-Scale Hydrological Modelling' summarised in the present report was to ***develop a hydrological model for the quantification of water availability over a large geographic domain of a semi-arid environment***. Following the requirements within the framework of WAVES, the main tasks and goals as specified in the research proposal were as follows:

(1) Spatially distributed results on water availability are to be provided by the model for the Federal States of Piauí and Ceará in Brazil with a total area of about 400000 km^2. The spatial distribution primarily refers to sub-basins and administrative units (municipalities) (see also point 7 below).

(2) Water availability is to be assessed in terms of water volumes of river discharge, reservoir storage and soil moisture.

(3) The modelling concept should be applicable to the semi-arid environment of the study area in view of its specific hydro-climatological and physiographic conditions. The relevance of these features for the assessment of water availability is to be assessed.

(4) Temporal and spatial scaling approaches are to be developed to bridge the gap between the scale of interest of model application (e.g., sub-basins at a monthly resolution) and the scale of hydrological processes (e.g., hillslopes with an hourly temporal scale of individual rainfall events).

(5) The model performance of adequately simulating water availability has to be validated by comparison with observed data on, e.g., river discharge or reservoir storage volumes. Uncertainties in the results of model application are to be identified and assessed in the interpretation of the results.

(6) The model should be able to capture the influence of a changing environment on water availability. This primarily refers to the effects of a changing regional climate in the course of global climate change. Other changes include those of land cover and water infrastructure. Scenario simulations of future water availability are to be run with the model for given climate change scenarios or scenarios of reservoir construction.

(7) Beside of being a stand-alone hydrological model, one version of the hydrological model has to serve as a module of the integrated model SIM. Thus, adequate interfaces to adjacent modules are to be provided in terms of input/output variables and their spatial and temporal scale. For example, one important aspect is to provide results at the scale of administrative units (municipalities) which were defined as the common spatial unit of all components in SIM, another aspect is to quantify soil moisture as input of a crop production model for various soil units at smaller spatial scales within municipalities or sub-basins.

3. PROJECT STRUCTURE

3.1 Planning and Progress

The research program comprised the following working steps:

- Literature review on hydrological processes and their modelling in semi-arid environments
- Development of a conceptual model outline
- Collection of secondary data in Brazil and from International Institutions
- Programming of the model code
- Development of scaling techniques
- Preparation of data adequate for the model structure and purpose
- Model parameterization
- Delivery of an adapted model version as a component of the integrated model
- Integration of model components of water use from the integrated model
- Model application for historical time series
- Model validation at different spatial and temporal scales
- Analysis of model sensitivity and uncertainty
- Preparation of scenario data
- Scenario simulations of future water availability
- Discussion of results, presentation to policy makers

The above steps were performed iteratively during the project period. In particular, data collection and preparation took considerably more time than expected and was spread over the entire project period. Reasons were the limited access to data of Brazilian institutions, the lack of centralised data archives, large efforts in digitalizing analogue data collected in Brazil, and the necessarily parallel work of different working groups within the interdisciplinary project which resulted in a comparatively late availability of data and model components that depended on contributions from other working groups (see section on co-operation).

A first prototype version of the hydrological model that was also delivered as a component to the integrated model has been set up at the end of 1999. A distributed model version for the entire study area with most model components was finished in early 2001 and scenario simulations where run with that version. A revised final model version for Ceará, also based on a more detailed rainfall data set which was only available in June 2001, and extended soil, terrain and land use data sets was finished in autumn 2001. For this model version, also a more detailed model validation and sensitivity analysis was performed. The results of the project, primarily the structure and applicability of the hydrological model and the results of scenario simulations for future water availability were presented to and discussed local water authorities and policy makers at the final WAVES-Workshops in 2002.

3.2 Co-operations

3.2.1 Co-operation with German working groups

The project 'Large-Scale Hydrological Modelling' was part of the working area 'Water Availability and Management'. Co-operation was most intense with colleagues of the other working groups in that area, i.e., 'Regional-Scale water use modelling and scenario development' at Kassel University and 'Water management and resources' of Hydroisotop GmbH. A very intense co-operation existed also to the working group 'Integrated modelling' at PIK. These co-operations included common field trips, visits, presentations and data search and collection at Brazilian institutions, exchange and arrangements on ideas of modelling approaches and interfaces between the respective modules, exchange of data and of model components. Close co-operation existed also to the working group 'Climate analysis and modelling' at PIK, mainly concerning data collection and preparation of meteorological variables. Intense work was also done together with the working group 'Soil Sciences' at Hohenheim University concerning the common definition, digitalization and parameterization of the soil and terrain data base with regard to hydrological relevant information and concerning approaches for soil water balance modelling. Common work existed also with the working area 'Landscape Ecology' at the Technical University of München-Weihenstephan in terms of preparation and exchange of spatial data sets of the study area. Common publications resulting from these co-operations are listed in Section 5.6.

3.2.2 Co-operation with Brazilian scientists and institutions

The most important scientific co-operation with Brazilian colleagues existed to the working group of Prof. J.C. de Araújo at the Department of Hydraulic Engineering at Universidade Federal do Ceará (UFC). This co-operation included field excursions, data allocation, preparation and exchange, a summary report on water resources in the study area by Prof. Araújo and discussion of modelling approaches and appropriate ways of linking model components. A publication prepared as a results of this co-operation (Araújo et al., 2003) is listed in Section 5.6. Fruitful contacts including scientific exchange and often supply of literature and data which is highly acknowledged existed to a number of Brazilian institutions: COGERH, FUNCEME, SHR, CPRM, UFC, Universidade Rural, DNPM (all in Fortaleza), DHME (in Teresina), INPE/CPTEC (São Paulo), Fundacão Joaquim Nabuco, DNPM, Universidade Federal de Pernambuco (all in Recife).

4. STATE OF RESEARCH

4.1 Landscape variability and hydrological processes with emphasis on semi-arid environments

River catchments exhibit spatial variability of landscape characteristics such as geology, topography, soils, land cover and vegetation. These characteristics govern the partitioning of precipitation into runoff and evapotranspiration and contribute in defining the spatial distribution of soil moisture within the catchment. Soil moisture patterns, in turn, are a key factor in influencing runoff generation and the hydrological response of a catchment. This interaction of soil moisture and hydrological processes as a function of landscape variability affects both vertical and lateral water fluxes. Vertical fluxes occur by processes such as infiltration, percolation and evapotranspiration. Lateral fluxes are related to redistribution processes of surface runoff including reinfiltration and lateral flow redistribution in the saturated and unsaturated soil zone or in the groundwater. Depending on whether vertical or lateral water fluxes dominated, Grayson et al. (1997) distinguished between local and non-local control on soil moisture patterns. Concerning the variability of landscape characteristics and related processes, a distinction can be made between organised and random variability (Seyfried and Wilcox, 1995; Blöschl and Sivapalan, 1995). In the case of organised variability, a predictable regularity in the spatial distribution of a variable such as soil moisture can be observed, e.g., as a function of topography. Such a catena or toposequence concept of relating landscape characteristics to the topographic location goes back to Milne (1935a,b, cited in Birkeland, 1999). There, a specific variability structure of soils along hillslopes was proposed, where each soil shows a distinct relationship to the soils upslope and downslope for a variety of geomorphologic, pedological and hydrological reasons.

In a semi-arid or Mediterranean type of environment, with often high rainfall intensities and sparse vegetation cover, which may also lead to crusted soil surfaces with a low hydraulic conductivity (e.g., Valentin and Bresson, 1992; Perrolf and Sandström, 1995; Peugeot et al., 1997; Zhu et al., 1997; Bajracharya and Lal, 1999; Puigdefabregas et al., 1999 and an overview in Patrick, 2002), surface runoff generation by an infiltration-excess mechanism is generally considered to be the dominant process at the local (point) scale (Yair & Lavee, 1985). Saturation-excess runoff usually is of less importance. However, it may occur for some specific conditions, e.g., during the rainy period in alluvial valley bottoms (Ceballos and Schnabel, 1998; Giesen et al., 2000) and on soils of relatively high infiltration capacities and low storage capacity, e.g., shallow soils above bedrock of low conductivity (Cadier, 1993; Martinez-Meta et al., 1998; Puigdefabregas et al., 1998). The runoff response at the hillslope or at the catchment scale, however, has frequently been shown to be considerably influenced by the variability of landscape characteristics. An important aspect of patch-scale variability in semi-arid areas is introduced by the neighbourhood of vegetated and bare soil surfaces, as observed in many dryland vegetation types (see summary of examples in Klausmeier, 1999; Reid et al., 1999). This patchiness influences, on the one hand, total evapotranspiration rates of the land surface by the interaction of energy and momentum fluxes from bare and vegetated patches (e.g., Blyth and Harding, 1995; Huntingford et al., 1995; Brenner and Incoll, 1997; Kabat et al., 1997; Boulet et al., 1999; Domingo et al., 1999; Taylor, 2000). On the other hand, the patchiness gives rise to redistribution of runoff and associated sediments and nutrients, with, in general, bare soil surfaces tending to act as source areas of surface runoff and vegetated patches as sink areas, receiving run-on from bare soil surfaces for re-infiltration (Puigdefabregas and Sanchez, 1996; Bromley et al., 1997; Rockström et al., 1998; Reid et al., 1999, Valentin and d'Herbès, 1999). Extending to the scale of hillslopes or small catchments, additional variability of landscape characteristics influences runoff redistribution. Characteristic sequences of surface types in terms of vegetation cover, soils and surface crusts with variable infiltration characteristics were shown for hillslope transects in semi-arid Africa by Perrolf and Sandström (1995), Bromley et al. (1997) and D'Herbes and Valentin (1997) or for semi-arid Spain (Nicolau et al., 1996). For semi-arid north-eastern Brazil, Cadier et al. (1996) illustrated the importance of varying soil types along a hillslope catena where surface runoff generated on soils with low infiltration capacities can directly reinfiltrate in a downslope strip of soils with high infiltration capacity. Decreasing runoff coefficients with increasing slope length due to a large variability of soil characteristics were also observed by Bonell & Williams (1986) and Puigdefabregas et al. (1998) for semi-arid and by Van de Giessen et al. (2000) for sub-humid environments. A distinction between slope segments as runoff source areas and colluvial footslope areas or alluvial deposits in the valley bottoms as sink areas for run-on was highlighted for semi-arid areas by Yair and Lavee (1985), De Boer (1992), Peugeot et al., (1997), Ceballos and Schnabel (1998) and Puigdefabregas et al. (1998). These studies also demonstrate that discontinuities of hydrological pathways can exist between runoff generating areas and the channel network or the catchment outlet particularly for dry conditions (see also Fitzjohn et al. (1998) and Bergkamp (1998)). With increasing catchment area, also the importance of transmission losses of runoff that already became channel flow by reinfiltration into the channel bed increases. This process was referred to as one reason for decreasing runoff coefficients (e.g., Cadier et al., 1996) and an increasing non-linearity of the runoff response (Goodrich et al., 1997) with increasing basin area in small semi-arid catchments. All examples show that runoff at the hillslope or small catchment scale in semi-arid areas is in general considerably less than what can be expected by simply summing up the individual contributions of each soil and vegetation patch. Redistribution processes with re-infiltration of surface runoff between the patches are of high importance.

While the outline so far focused on surface runoff, lateral subsurface flow processes may also be relevant although they are usually not considered in semi-arid environments (see an overview and a critique by Beven, 2002). Lateral subsurface flow is generated for specific conditions, for instance in the presence of soil pipes or other macropores (Torri et al., 1994; Sandström, 1996), during the development of a perched water table in wet periods (Wilcox et al., 1997, Van de Giessen et al., 2000) or during saturation of alluvial zones next to the main channel (Ceballos and Schnabel, 1998).

4.2 Model representation of variability and processes

In hydrological models it is required to account for the spatial variability of landscape characteristics and processes as those mentioned above if the hydrological or any related ecological response of a catchment should be adequately represented. Bronstert and Bardossy (1999), for instance, demonstrated the large influence of using a spatially variable or an average mean soil moisture distribution for modelling surface runoff generation in a small catchment. Flerchinger et al. (1998) showed the need to sub-divide a semi-arid catchment into different landscape units in order to correctly estimate total evapotranspiration particularly under conditions when water is a limiting factor. In particular, a model taking into account spatial variability is required for applications which intend to assess the effect of changing boundary conditions or of disturbances, like land cover or climate change. A lumped catchment model, although it may well capture the overall catchment dynamics in terms of the hydrograph at the outlet (e.g., Chiew et al., 1993; Ye et al., 1997), will hardly be able to incorporate such changes which affect individual processes or parts of the total catchment area only, due to the loss of physical foundation of basin-average model parameters. Additionally, a spatially distributed model representation of the catchment is obviously required where distributed results are to be given as one objective of the model application, e.g., soil moisture patterns which have to be linked to a crop or vegetation model.

Several approaches have been taken to incorporate landscape variability into hydrological models. One is the use of complex fully-distributed models such as SHE (Abbott et al., 1986), IHDM (Beven et al., 1987) or HILLFLOW (Bronstert and Plate, 1997). While capturing landscape variability by using a very detailed sub-division into modelling units and including also explicitly lateral surface and subsurface fluxes and their redistribution, data and computational requirements prevent these models from being applied for larger catchments (e.g., Bronstert, 1999).

An alternative approach is to capture the variability of any essential catchment characteristic by a distribution function, as, for instance, for the soil moisture deficit or infiltration capacity (Beven and Kirkby, 1979; Zhao et al., 1980; Wood et al., 1992). This approach usually gives lumped results at the catchment scale without any explicit spatial assignment of areas of different hydrological characteristics. In TOPMODEL of Beven and Kirkby (1979), in contrary, the resulting distribution of the soil moisture status can be mapped into its spatial pattern in the landscape, based on the distribution of a topographic index. This approach also implicitly takes into account the effect lateral subsurface flow on soil moisture in downslope positions.

Another widely used strategy to capture landscape variability in hydrological models is by defining areas of an assumed similar hydrological response, called hydrological response units (Leavesley et al., 1983) or hydrotopes (Becker and Pfützner, 1987), for instance. The crucial points of this approach lie, first, in the definition of a hydrological quantity of interest according to which this similarity is to be defined. Secondly, they lie in the selection of those landscape characteristics, heterogeneities and related hydrological processes that ensure that the assumption of similarity within one of the accordingly delineated modelling units is valid. This selection can be based on expert knowledge, the perception of the hydrological behaviour of the study area and on comparative studies which evaluate the performance of models for different ways of delineating the hydrotopes (e.g., Becker and Braun, 1999; Woolridge and Kalma, 2001). In most cases, the delineation is done with regard to similarity of vertical hydrological processes, i.e, hydrotopes being similar in terms of infiltration, percolation and evapotranspiration fluxes (e.g., Kite and Kouwen, 1992; Mitchell and DeWalle, 1998; Krysanova et al., 1998; Becker and Braun, 1999; Gurtz et al., 1999; Karvonen et al., 1999; Woolridge and Kalma, 2001). This is usually achieved by intersecting physiographic data such as elevation, soils, vegetation and/or land use. An essential shortcoming of this approach is that interactions between different hydrotopes, e.g., in terms of redistribution of runoff components, are generally not taken into account. One reason is that in the case of irregularly shaped hydrotopes, a routing scheme between them in the sense of upslope-downslope relationships cannot be clearly defined. Particularly in larger-scale models, another reason is that hydrotopes are often too large in size to resolve these hillslope-scale patterns and processes. In both cases, runoff components generated in each hydrotope are simply summed up to give the total basin response, often after passing one or more linear or non-linear conceptual storages. In other words, a problem associated with a two-domain scheme as recommended by Becker and Nemec (1987) with different ways of discretizing the landscape for the domain of vertical processes and lateral processes, respectively, is that it may be difficult to sample patches, once defined with respect to a similar behaviour of vertical water fluxes, to give another type of patches with similarity in lateral function. A different way, presented by Uhlenbrook and Leibundgut (2002), is to structure catchments directly into hydrological functional units as derived from experimental investigations, each with the same dominating runoff generation processes which may also include specific lateral processes, and accordingly each unit with a specific model conceptualisation.

Exceptions of hydrotope-based models where interactions between the modelling units are accounted for are WATBAL (Knudsen et al., 1986), the PRMS-based approach of Flügel (1995) and ARC/EGMO (Becker et al., 2002). In these examples, an additional critieria for the classification of hydrotopes is their location within different topographic zones along hillslopes. By this way, subsurface flow can be routed between storages of different topographic position, for instance, inflow into the groundwater storage in valley bottoms from the slope region. In WATBAL and ARC/EGMO also surface runoff can be redistributed among downslope areas and may reinfiltrate there if sufficient storage capacity exists. A grid-based approach which considers the interaction of lateral flow among cells with different soil-vegetation combinations has been presented by Schumann et al. (2000).

In summary, the number of models which were specifically developed for dryland hydrology is small and models are often restricted to small-scale applications (for an overview see also, e.g., Lange et al. 1999). Large-scale models developed for humid areas often perform less well when applied to semi-arid environments (e.g., Abdulla and Lettenmaier 1997). In addition, the focus of many modelling approaches is on describing vertical hydrological processes. The representation of lateral flow in large scale models is often rather crude and may refer to surface runoff in the river network only. Lateral redistribution processes at the hillslope scale, however, may be of high importance in particular in semi-arid environments. Thus, there is need for further research in this field of hydrology which was seen as the basis for the scientific work of the project reported on here.

5. RESULTS AND PUBLICATIONS

5.1 The Hydrological Model WASA – Structure and Process Description

5.1.1 General features

The hydrological model WASA (Model of Water Availability in Semi-Arid Environments) developed in the project 'Large-Scale Hydrological Modelling' within WAVES is a deterministic model for continuous simulation, composed of process-oriented conceptual approaches. Model formulations are used that basically do not need calibration of their parameters, as the parameters can be derived from physiographic data of the study area or from studies in similar environments. The modelling timestep usually is one day, for small-scale applications an hourly resolution can be used. A detailed description of the model, its parameterization and input data is given in Güntner (2002). In order to capture the influence of the spatially variable landscape characteristics on soil moisture patterns and runoff generation, a hierarchical top-down disaggregation scheme is used in WASA for structuring the landscape into modelling units (Fig. 1). The hierarchy comprises five spatial scale levels. The structure at scales smaller than the sub-basin scale (Levels 2-5 in Fig. 1) is based on the SOTER concept (Soil and Terrain Digital Database) (FAO, 1993), which establishes a way to structure the landscape according to terrain and soil attributes. The SOTER approach has been modified and extended for hydrological purposes in this study in co-operation with the working group 'Soil Sciences' (see Section 3.2.1). The specific features and processes representations at each scale level are described in the following paragraphs.

5.1.2 Sub-basin or municipality

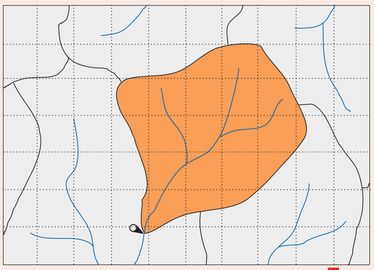
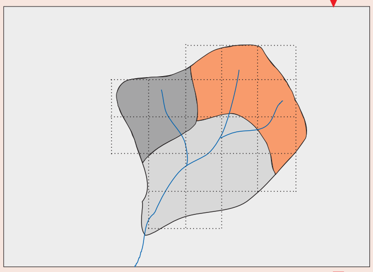
The largest scale (Level 1 in Fig. 1) is made up of the target units for water resources assessment, i.e., sub-basins of in average 10^3 km^2 in size. Their outlet is defined by the location of a discharge gauging station, a large dam or the confluence of major river. Alternatively, grid cells or municipalities (in the case of the model that the model is a component of the integrated model SIM (Krol et al., 2003)) can be used as the largest spatial unit. If more than one grid cell compose a sub-basin of interest, their individual runoff responses are summed up to give the total sub-basin response. At this first level of the hierarchy, the processes of runoff routing in the river network, including runoff retention in reservoirs, reservoir water balance and abstractions by water use, are simulated. The water balance of large reservoirs (with a storage capacity of more than $50 \cdot 10^6$ m^3) is calculated explicitly. Small reservoirs and farm dams which are very frequent in the study area and, thus, cannot be represented individually in a large-scale model, are represented by their distribution among different reservoir classes, classified by their storage capacity. For each class a mean water balance is calculated and runoff is routed between reservoirs of the different classes by a cascade scheme, using simplifying assumptions on the location of the reservoirs in a sub-basin and relative to each other (Güntner, 2002). Runoff routing in the river network is represented by a simple linear response function depending on flow length and average slope of the main river in a sub-basin (Bronstert et al., 1999). Withdrawal water use is based on a model of water use in various sectors (irrigation, livestock, domestic, industrial and tourist water use) (Döll & Hauschild, 2002) and is directly coupled to river flow and reservoir volumes in WASA (see also Bronstert et al., 2000).

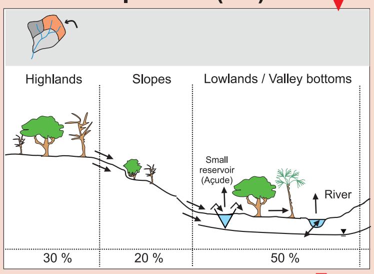
5.1.3 Landscape unit

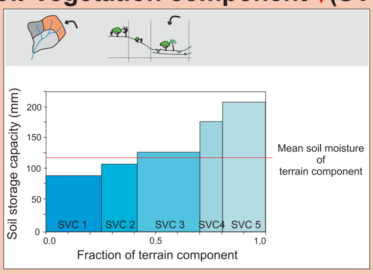
Within sub-basins, so-called landscape units (LUs) (Fig.1, Level 2) are delineated which cover areas that are similar in the underlying lithology and bedrock characteristics and in the general form of the land surface, i.e, the type of dissecation of the landscape by valleys in terms of elevation differences between valley bottoms and hilltops and in terms of the hillslope length. Related to that, LUs are characterised by a typical toposequence, i.e., by a certain sequence of the hillslope topography which may be associated in its different topographic parts with a specific soil and vegetation association (i.e., a group of different soil and land use types). Given these features of similarity, landscape units are considered to be homogeneous in terms of their overall hydrological response at the landscape scale. This implies similarity of lateral hydrological processes (i.e., redistribution of water fluxes along hillslopes and between patches) and similarity in terms of the variability of vertical processes, resulting in a specific pattern of, e.g., soil moisture within a LU. In this sense, landscape units can be called hydrotopes. However, they are not areas of quasi-homogeneous characteristics as in the classical meaning, but they are similar in terms of their sub-scale variability of landscape characteristics and of the hydrological state. The runoff volumes generated in each LU of a sub-basin or grid cell are added up to give the total response of the sub-basin.

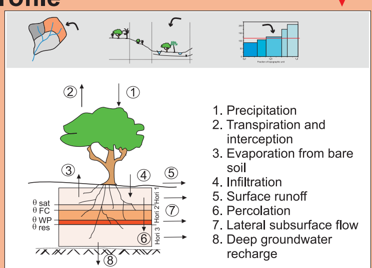
5.1.4 Terrain component

For the description of organised variability of landscape characteristics within LUs, they are sub-divided into terrain components (TCs) at the next smaller scale of the hierarchy (Fig. 1, level 3). Each LU is composed of, at most, three TCs, representing highlands, slopes and valley bottoms, respectively. It is assumed that by using these three zones, the most important differences of terrain, soil and vegetation characteristics among topographic zones along the hillslope can be captured. Each TC is thus characterised by a specific mean slope gradient, its upslope or downslope position relative to other TCs within the toposequence and by the occurrence of a specific soil type or soil association and vegetation class. The number of TCs in a landscape unit can be reduced to two or one if significantly different topographic zones within the LU cannot be distinguished. TCs usually are not represented by their exact geographic location in WASA, but by their fraction of area within the LU only. This is due to limited data availability in large-scale models where the low resolution of terrain data usually does not allow to resolve these hillslope-scale features explicitely.

<table>
<tr><th>Level</th><th>Type and criteria of delimitation</th><th>Function</th></tr>
<tr><td>1 Sub-basin / Municipality / Grid cell
</td><td>– Polygons with geographically referenced location
– Data source of basins: Terrain analysis of 30''-USGS-DEM and digitized topographic maps
– Municipalities: administrative boundaries (municipios)</td><td>▸ Runoff routing, including retention in reservoirs and withdrawal by water use
▸ If grid cells smaller than sub-basin / municipalities are used: Runoff responses of all grid cells pertaining to a sub-basin are added up to give the basin response. Further sub-divison (levels 2-5) starts from the grid cell level.</td></tr>
<tr><td>2 Landscape unit (LU)
</td><td>Polygons with geographically referenced location

Similarity of
– major landform
– general lithology
– soil associations
– toposequences</td><td>▸ Modelling unit with similar characteristics referring to lateral processes and similarity of sub-scale variability in vertical processes
▸ Composed of 1 - 3 terrain components
▸ Runoff responses of all landscape units are added up to give total response of sub-basin / municipality / grid cell</td></tr>
<tr><td>3 Terrain component (TC)

</td><td>Fraction of area of landscape unit (no geographic reference)

Similarity of
– slope gradients
– position within toposequence
– soil associations</td><td>▸ Lateral transfer of surface and subsurface runoff between terrain components of different topographic position by upland-lowland relationships
▸ Reinfiltration and exfiltration (return flow) in component with lower topographic position</td></tr>
<tr><td>4 Soil-Vegetation component (SVC)

</td><td>Fraction of area of terrain component

Characterized by specific combination of
– Soil (sub-)type
– Vegetation / land cover class</td><td>▸ Variability of soil moisture within terrain component
▸ Lateral redistribution of surface and subsurface runoff among soil-vegetation components
▸ Variability of soil moisture storage capacity within soil-vegetation component (partial area approach for saturation-excess surface runoff)</td></tr>
<tr><td>5 Profile

</td><td>Representative profile of soil-vegetation component

– Several soil horizons of variable depth
– Lower limit by depth of root zone or bedrock</td><td>▸ Calculation of water balance in the profile for each soil-vegetation component
▸ Determination of vertical and lateral water fluxes for individual horizons</td></tr>
</table>

Figure 1: Hierarchical multi-scale scheme for structuring the landscape into modelling units in WASA

On the basis of the definition of different TCs, the interaction of surface and subsurface lateral flow components from upslope topographic zones with those at downslope position, including reinfiltration and return flow, is represented in a simplified manner in WASA. The Surface runoff generated in any terrain component is separated into (1) flow entering any downslope terrain component as runon that is available for reinfiltration (reinfiltration of sheet or diffuse surface flow and of flow already concentrated in channels by transmission losses), and into (2) flow going directly into the river (concentrated flow in channels that is not subject to transmission losses). The percentages of the flow separation into the two components are assumed to be a function of the respective areal fractions of TCs within the LU. A TC which makes up a larger fraction of the total area of the LU is assumed to potentially retain a larger fraction of runoff that originates from upslope areas than a TC with a smaller areal fraction. (The actual volume of reinfiltration of runon depends on the soil types and the antecedent moisture content, see Chapter 5.1.5).

In the case of lateral subsurface flow, lateral subsurface runoff leaving on terrain component is completely attributed as inflow to the next downslope TC. Lateral subsurface flow of the lowest TC becomes river runoff. In both cases of surface and subsurface inflow, the total inflow to a TC from upslope areas is separated among the various soil-vegetation components of this TC (Chapter 2.5) weighted by their areal fraction in the TC.

5.1.5 Soil-vegetation component

In order to describe the heterogeneity of soil and vegetation characteristics and, thus, of soil moisture within TCs, they are further sub-divided into soil-vegetation components (SVCs) at the next smaller spatial scale (level 4 in Fig.1). SVCs are modelling units being each characterised by a specific combination of a soil type and a land cover class (similar to the classification used by Schumann et al., 2000). Thus, the number of SVCs in a TC is given by the number of the existing soil-vegetation combinations. SVCs are represented by their fraction of area within the TC without exact geographic reference. The spatial distribution of SVCs within a terrain component and the location of SVCs relative to each other is assumed to be non-organised, i.e., SVCs forming a randomly distributed mosaic of patches. This is also an attribute to the fact that in large-scale model applications the required detailed information to define any organization within TCs is not available. On the basis of this random variability, lateral redistribution of surface and subsurface flow between SVCs is taken into account in WASA. For each SVC, the generated surface runoff is separated into (1) flow to all other SVCs of the same TC and into (2) flow to a TC of lower topographic position or to the river. Similar to the redistribution among TCs (see Chapter 5.1.4), the percentages of the flow separation into the different components (or, in other words, the transition frequencies of water fluxes between the spatial units) are assumed to be a function of the areal fraction of SVCs within the TC. SVCs with a larger areal fraction receive more runon from other SVCs than SVCs with a smaller areal fraction. On the other hand, the percentage of runoff being transferred to a lower TC or to the river without interaction with any other SVC is larger for a SVC with a larger areal fraction.

In the case of surface flow, in receiving SVCs the runon is added as input to the infiltration routine (see Chapter 5.1.6). In the case of subsurface flow, lateral inflow into receiving SVCs is primarily attributed to soil horizons with a similar depth below the terrain surface as the depth of the flow generating horizon in the source area. If a soil profile is too wet or too shallow to absorb all incoming lateral subsurface flow, the remaining flow volume becomes surface runoff (return flow).

In addition, for each SVC a piece-wise linear distribution function distribution approach, being a simplification of Zhao et al. (1980), is used to describe a varying soil water storage capacity within the SVC based on soil profile data of porosity and soil depth (see Chapter 2.6). The distribution defines the fraction of the SVC that is water saturated and can generate saturation-excess surface runoff for a given mean soil moisture of the SVC .

5.1.6 Profile

At the smallest scale of the hierarchy (level 5 in Fig.1), each soil-vegetation component is described by a representative soil profile, combined with vegetation characteristics. The number of soil horizons can be freely chosen and can vary between SVCs in WASA. In practice, it can be set to the number of characteristic horizons for each soil type. The lower boundary of the profile is usually set to the depth of the bedrock. Thus, near-surface groundwater bodies which may develop during the rainy season above a less permeable horizon or above the bedrock can be represented, including their influence when reaching into the root zone or to the soil surface or when generating lateral subsurface flow. If the bedrock is too deep below the terrain surface to influence surface processes, the lower boundary is set to the depth of the root zone. The water balance of the profile is calculated including vertical processes as well as lateral flow components. The incoming fluxes to each horizon are:

- Infiltration, being added to soil moisture in the uppermost horizon or in some cases also to lower horizons if they are tested for infiltration-excess
- Lateral subsurface flow (from TCs of upslope position and from SVCs within the same terrain component
- Percolation from upper horizon

The outgoing fluxes from each horizon are:

- Evaporation at the soil surface, being substracted from soil moisture in the uppermost horizon.
- Transpiration by vegetation. The total transpiration of the canopy is distributed among all horizons in the root zone by a weighting factor which is determined as the fraction of plant-available field capacity in the horizon relative to total available field capacity in the root zone.
- Percolation to the next horizon below
- Lateral subsurface flow (to TC of downslope position or to the river and to adjacent SVCs of the same TC)

Interception by the vegetation cover is modelled in WASA by a simple bucket approach with the interception capacity being a function of the leaf area index (Dickinson, 1984). Evapotranspiration is simulated with the extended Penman-Monteith approach for sparse vegetation cover by Shuttleworth and Wallace (1985), which also accounts for evaporation from bare soil surfaces and its feedback on plant transpiration. An increase in canopy surface resistance to transpiration due to environmental stress factors such as low soil water availability is respected by multiplicative factors as originally proposed by Jarvis (1976) and Stewart (1988).

The Infiltration model is based on the Green-Ampt approach in a formulation given by Schulla (1997), extended in WASA in a simplified form for the infiltration into layered soils.

The total input to the infiltration routine is rainfall minus interception plus surface runoff from other spatial units. Starting with the uppermost horizon, successively deeper horizons are tested until in one with infiltration-excess appears or until the infiltrated volume in all checked horizons equals the amount of rainfall minus interception. A temporal scaling factor is applied when using a low-resolution daily modelling timestep. It reduces the hydraulic conductivity in the infiltration routine in order to compensate for underestimated rainfall intensities (Güntner, 2002).

Percolation from one horizon to the next deeper horizon is assumed to occur if the actual moisture of the upper horizon exceeds soil moisture at field capacity. Following Arnold et al. (1990), a temporal delay factor in percolation (or travel time through the horizon) is applied which is related to the actual unsaturated hydraulic conductivity of the horizon. The final volume of percolation may be constrained by the refillable porosity of the lower horizon or by its saturated hydraulic conductivity. If the lowest horizon of the profile is situated above bedrock, percolation to deep groundwater may be limited by the hydraulic conductivity of the bedrock. For the quantification of lateral subsurface flow leaving a soil horizon, a simple relationship for saturated flow based on the Darcy-equation is applied. Comparable formulations for more complex geometric settings have been used by, e.g., Wigmosta et al. (1994) and Tague and Band (2001). The total lateral subsurface outflow of a profile is the sum of the individual flows from each horizon. It is redistributed among profiles in other SVCs or TCs and river flow according to the descriptions in Chapters 5.1.4 and 5.1.5.

5.2 A scaling approach for disaggregation of rainfall time series

A cascade model for disaggregation of continuous rainfall time series was applied three rainfall stations in the study area of Piauí and Ceará, for which data with hourly resolution were available from the working group 'Climate analysis and modelling'. In the sense used here, a cascade process repeatedly divides the available space of any dimension (here rainfall time series) into smaller regions, while in each step redistributing the quantity of interest to the smaller regions according to rules specified by the so-called cascade generator. In the original approach by Olsson (1998), it is assumed that a dependency exists between the cascade generator and two properties of the time series values to be disaggregated, namely their rainfall volume and their position in the rainfall sequence. The model employed is a multiplicative random cascade of branching number 2 with exact conservation of mass. It was modified and extended here compared to the original version of Olsson (1998) and parameterized and validated for disaggregation of daily to hourly time series. For validation, 100 realisations of disaggregated hourly time series were performed and their mean statistics compared to the observed data (Fig.2). The main results were presented by Güntner et al. (2001).

In summary, the overall high accuracy of disaggregated rainfall data supports the potential usefulness of the cascade model for the semi-arid study area. An advantage of the approach compared to other models is its simplicity and applied nature. The few parameters are directly linked to rainfall time series characteristics and reflect by this way rainfall generation mechanism. This improves the process-related transferability of the model in time and space. The scaling model has been used to disaggregate daily rainfall time series into an hourly resolution for application and validation of the WASA at a small spatial scale in the study area (Chapter 5.3.1).

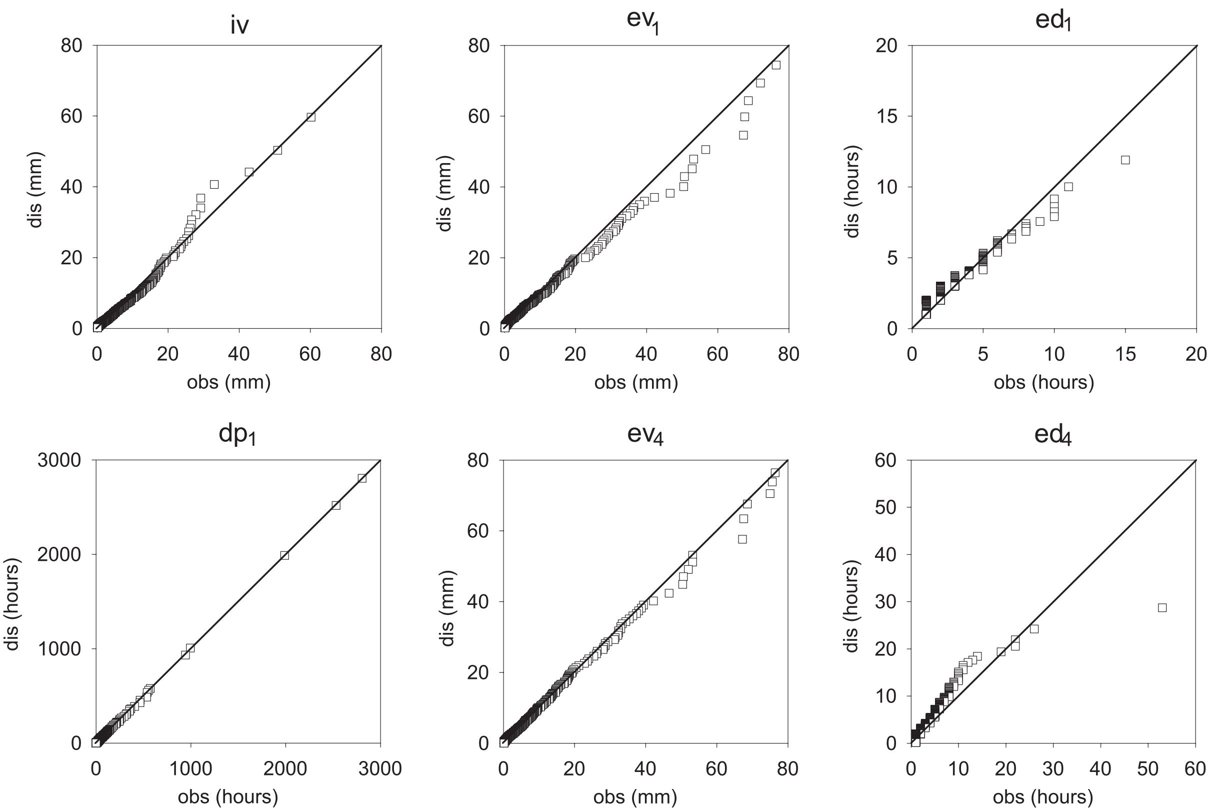


Figure 2: Comparison of the distributions of validation variables for observed (obs) and disaggregated (dis) 1-hour rainfall data, example for station Picos in north-eastern Brazil, period 05/95-03/99 (iv: non-zero 1-hour rainfall volume [mm]; ev: event volume [mm]; ed: event duration [hours]; dp: length of dry period [hours]; subscripts 1 or 4: minimum number of dry hours to separate two independent rainfall events (rainfall intervals separated by a lower number of dry intervals are considered to pertain to the same rainfall event))

5.3 Model validation of WASA

Validating the model with respect to its capability of adequately representing the governing hydrological processes and the target variables of model application is an important prerequisite when subsequently applying the model for impact studies. A number of model validation studies at different temporal and spatial scales have been performed. Simulation results were compared to observed river discharge and reservoir storage data. Other validation data, e.g., soil moisture data, were not available. Details of model validation are given in Güntner (2002).

5.3.1 Small-scale validation

At the smallest spatial scale with available climate and runoff data (Cavalcante et al. 1990), WASA was applied for an 8-year period to the Caldeirão catchment (a headwater basin 0.77 km² in size), in the municipality of Tauá in the upper Jaguaribe basin. This catchment is considered representative for large areas on crystalline bedrock and was not influenced by any water retention in reservoirs, so model performance of WASA with respect to runoff generation could be directly evaluated.

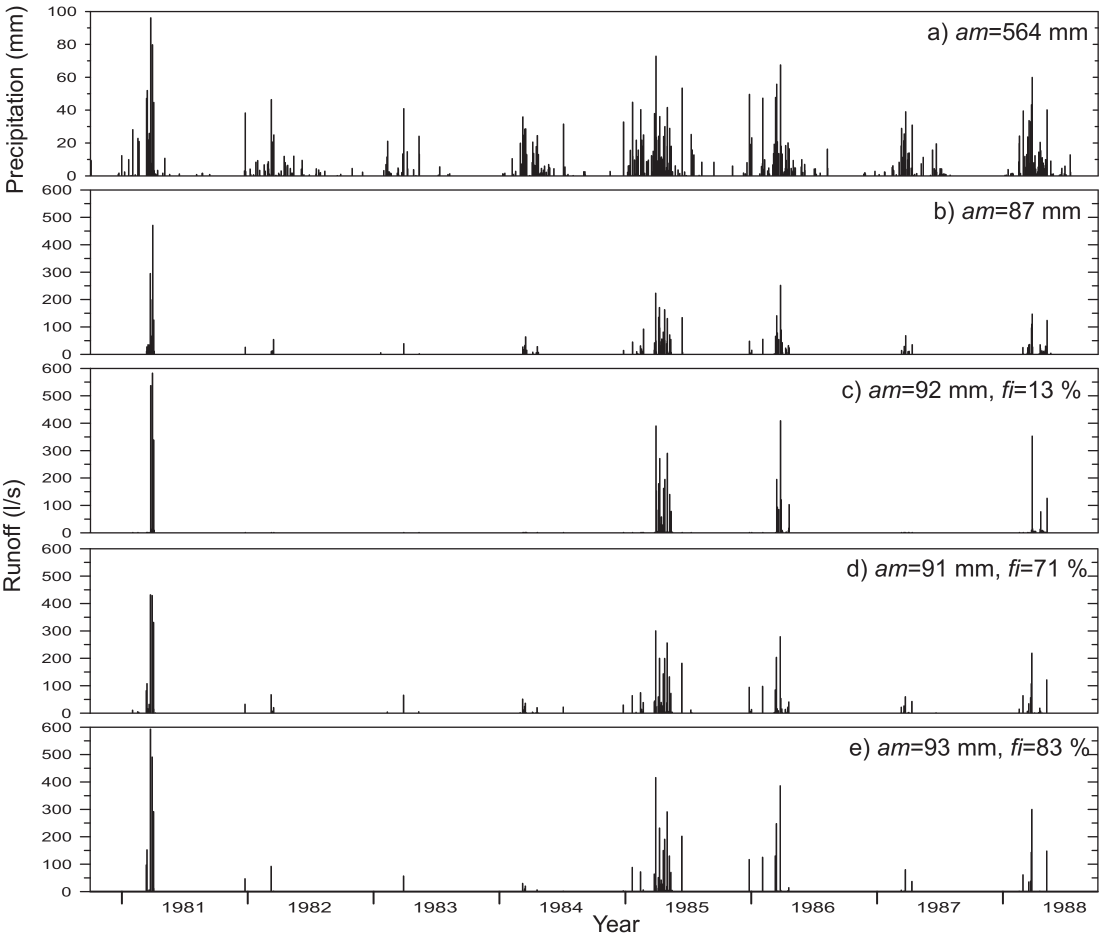


Figure 3: WASA application to the Caldeirão basin (0.77 km^2), period 10/1980-09/1988. (a) Precipitation; (b) observed discharge; simulated discharge for (c) daily model version without scaling factor, (d) hourly model version, (e) daily model version with scaling factor. *am*: annual mean, *fi*: fraction of infiltration-excess runoff on total runoff.

The model application with the usual daily resolution showed that, contrary to the observations, no runoff was simulated for several rainfall events in dry years and before or after the main rainy period (Figure 3b,c). A main reason is that rainfall intensities were underestimated in comparison to the real intensities of short-term tropical rainfall events when running the model with daily resolution. Thus, for pre-storm conditions with low soil moisture where infiltration-excess runoff is the dominant runoff generation mechanism, runoff volumes were underestimated. This was corroborated by an alternative simulation with an hourly resolution, using a disaggregated hourly rainfall time series based on the cascade scaling approach presented in Chapter 5.2. This resulted in a daily distribution of runoff close to the observations and a higher fraction of infiltration-excess runoff (Figure 3d). In view of practical model applications at the regional scale, where only daily data were available, a scaling factor for hydraulic conductivity accordingly was tested (see also Chapter 5.1.6). It was derived as the ratio of rainfall intensities of daily and hourly wet intervals. This resulted in a factor of 6 in this small-scale example. In addition, to compensate for underestimated rainfall intensities at even smaller (sub-hourly) scales, a factor of 2.5 resulted to be reasonable (also applied in the hourly simulation above). The hydraulic conductivity of the soil surface in the infiltration routine of the model application with daily resolution is then divided by the final scaling factor of 15 (the multiplicative combination of both factors).

Simulated runoff is close to both the results with higher temporal resolution and to the observations, both in total volume and inter- and intraannual variability (Figure 3e).

Similar reasonable results were also obtained for an application of WASA at a next larger spatial scale for the basin of Riacho Cipó (194 km²), which comprises also the Caldeirão catchment mentioned above. The observations and simulations showed a considerable decrease in the runoff ratio when going from the headwater scale (15.4% in the Caldeirão basin) to the small-basin scale (7.7% for Riacho Cipó) which could be attributed to discharge losses in reservoirs, on the one hand, and to reinfiltration of runoff due to a different topographic and pedological setting with the occurrence of valley bottoms at the larger scale, on the other hand.

In summary, the small-scale application demonstrated that WASA can well represent the highly variable hydrological response for the given semi-arid conditions, if rainfall time series of high temporal resolution are available. For practical model applications in this study, based on daily data, the introduction of a scaling factor to compensate for underestimated rainfall intensities proves to be a reasonable approximation.

5.3.2 Large-scale validation

Model validation of WASA at the scale of the Federal States was performed by comparison of simulated and observed hydrographs, using different performance criteria, such as the difference between mean observed and simulated annual runoff and the coefficient of efficiency according to Nash & Sutcliffe (1970) for monthly discharge time series (see Güntner, 2002, for details). When interpreting these results, one has to take into account the overall poor quality of observed validation data in accuracy and temporal extent of available time series.

In general, simulated discharge was in reasonable correspondence to observed values for 23 gauging stations available in the State of Ceará (Fig. 4a). Simulated mean annual discharge was generally in the right order of magnitude compared to the observations. The performance varied considerably between the stations. Deviations in the worst cases may be up to around ±50%, in average they were about ±20%. No systematic over- or underestimation could be seen when considering the performance for the entire set of stations throughout the study area of Ceará.

Reasons of primary importance for larger deviations are:

1. Deviations in the estimate of rainfall input, where even small differences may had a considerable effect on simulated runoff (Chapter 5.4.1).
2. Deficits in the simple conceptualization and parameterization of water retention in reservoirs and of withdrawal by water use, causing a discharge reduction of in average 20% at an annual basis according to the simulation results (see Chapter 5.4.4).
3. Deficits in the conceptualization and parameterization of various hydrological processes, such as lateral redistribution of water fluxes, which led to a large (in parts more than 40%) reduction in runoff at the sub-basin scale.
4. Deviations in the estimates of terrain, soil or vegetation parameters, of which some were highly sensitive on mean annual runoff (Chapter 5.4.3).

5. Deviations of basin area in the model from the real-world area, which was about ±10% in average, for smaller sub-basins in maximum up to 30%.

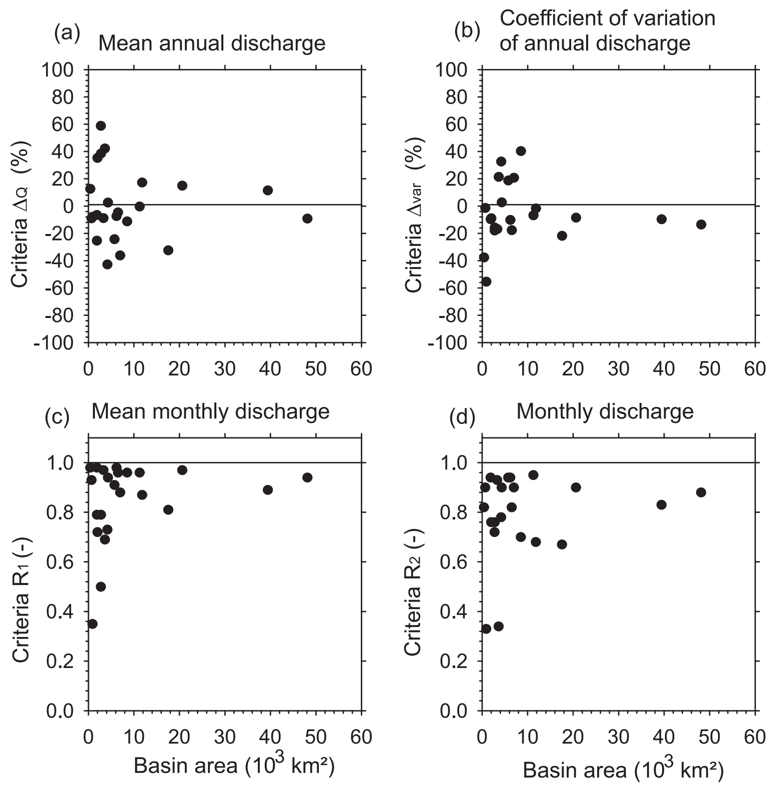


Figure 4: Validation of WASA for 23 gauging stations in Ceará, simulation period 1960-1998, validation period for individual stations is between 6 and 30 years. Deviation of simulations from observations with regard to the (a) mean annual discharge, (b) variation coefficient of annual runoff. Nash-Sutcliffe criteria for (c) mean monthly discharge and (d) continuous monthly discharge time series.

The interannual variability of discharge was generally reasonably represented (Fig. 4b). Discharge was in the right order of magnitude for both dry and wet years, thus reproducing the large differences which occur in the study area between wet and dry years. However, at a closer look, a slight overall underestimation of the interannual variability could be observed, particularly for larger catchments (Fig. 4b). This is mainly due to a tendency of overestimation of discharge in dry years. One main reason may be the lack of a routine for transmission losses by infiltration into the river bed in WASA at the scale of sub-basins. WASA accounts for losses in the river network due to evaporation and water use only, and for transmission losses by infiltration at the smaller scale of landscape units only.

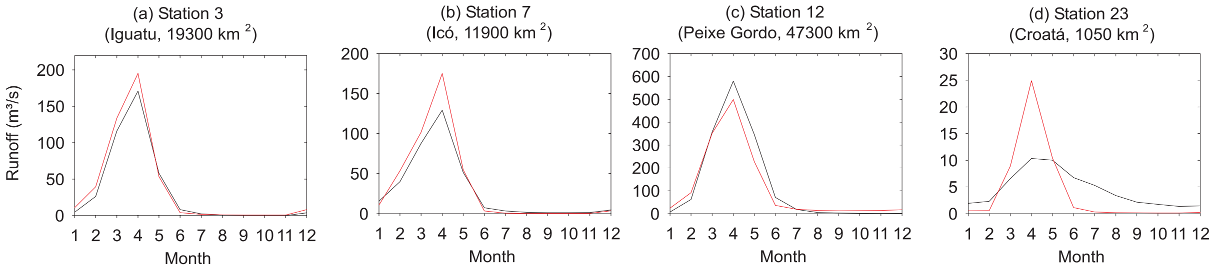


Figure 5: Examples of model validation for mean monthly runoff, black line: observed, red line: simulated. Various stations in Ceará for different validation periods within the years 1960-1998.

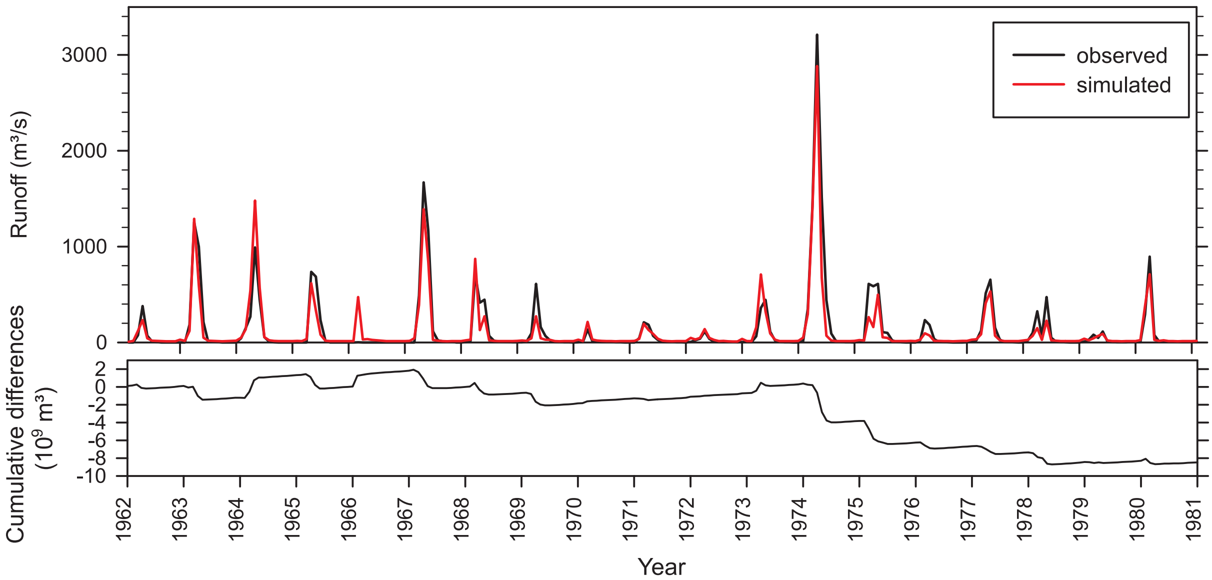


Figure 6: Example of model validation for monthly discharge at station Peixe Gordo, Jaguaribe River, basin area 47300km^2. Upper graph: simulated and observed discharge, lower graph: cumulative difference between simulation and observation.

The mean intra-annual runoff regime was well reproduced by the model for most basins (see Figs. 4c,d, 5 and 6). Even when comparing the continuous monthly observed and simulated time series, the model efficiency with an optimum value of 1.0 was above 0.8 for most studied basins (Fig. 4d). A worse representation of the intra-annual regime was found for sub-basins with a flow contribution from deeper groundwater bodies. This long-lasting outflow, continuing during the dry season, could not be represented with the model without calibration (particularly relevant, for instance, for station 23 in Figure 5d, influenced by baseflow from sedimentary bedrock). For that reason, worse validation results were also obtained for some gauging stations checked in Piauí, where the influence of groundwater in the sedimentary bedrock is often much more important. Another reason for unsatisfactory results of WASA for basins in Piauí was the very poor coverage of that area with available rainfall stations, which caused very high uncertainty in the rainfall input time series provided from the working group 'Climate Analysis and Modelling'.

In general, a tendency of better model performance at stations with a larger basin area was found (Fig. 4), although this statement is limited by the smaller number of larger sub-basins.

It may, however, be reasonable as deviations in discharge from different sub-basins may balance out to some extent when aggregating into larger catchment areas.

Model validation of WASA with regard to reservoir storage volumes showed that model deviations from observations at the end of rainy season are about ±20% in average for the complete set of reservoirs tested (Figure 7). Variations in performance between the reservoirs were large. However, no tendency of a systematic over- or underestimation of the observations was obtained. Beside of the variety of factors which introduce uncertainties in river discharge flowing into the reservoirs, there are additional factors which enhance the uncertainty of the simulation results for reservoirs: (1) Accuracy of the area-volume-relationship and of evaporation rates to determine losses by evaporation, (2) possible percolation to bedrock which is neglected in the model, (3) uncertainty in the simplified operation rules of controlled reservoir outflow used in WASA and of direct withdrawal water use.

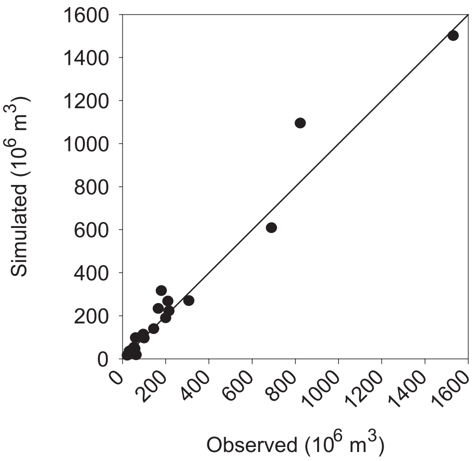


Figure 7: Observed versus simulated mean reservoir storage volume at the end of the rainy period (June) for 22 reservoirs in Ceará, different simulation periods for each reservoirs (depending on data availability) within 1960-1998.

Figure 8 gives examples of storage volume time series for three reservoirs with different model performance. For the largest and most important reservoir of the study area (Açude Orós) very good simulation results were obtained (Fig. 8a). Also for the reservoir in Figure 8b, good results are obtained, with the intra- and interannual dynamics well represented by the model. There is primarily one year (1978), however, where reservoir inflow was underestimated by the model. As a consequence, observed and simulated time series run parallel to each other (separated roughly by the missing inflow volume) until the next complete filling of the reservoir in 1984. Although the dynamics were again well represented, this discrepancy considerably degraded the overall Nash-Sutcliffe-type of quantitative performance criteria for the reservoir. Finally, as an example for a reservoir with bad model performance (Fig. 8c), the time series indicated a too quick emptying of the reservoir in the dry season, but also in a sequence of dry years. This may be a combined effect of an overestimation of evaporation and outflow volumes and, at least in dry years, an underestimated inflow.

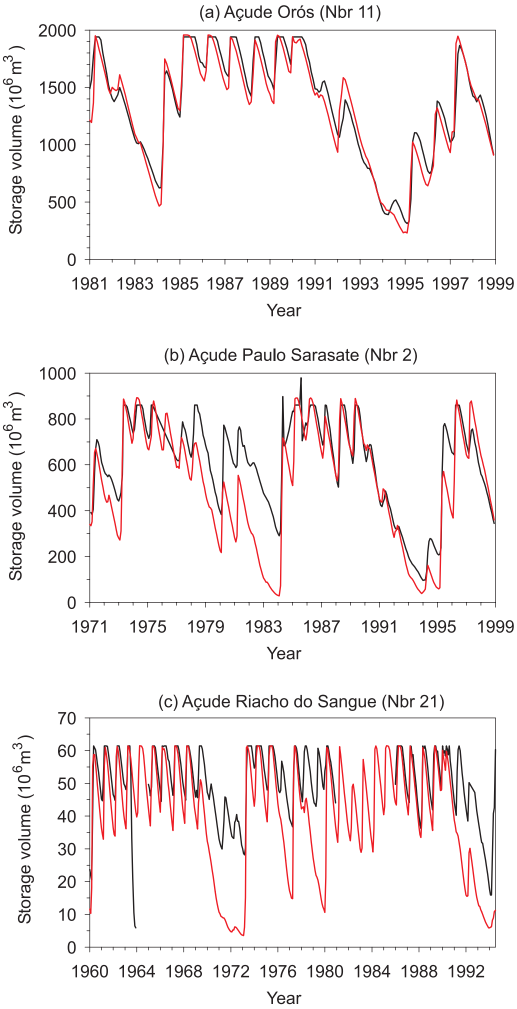


Figure 8: Examples of model validation for monthly storage volumes in large reservoirs in Ceará.

In summary, model performance for reservoir storage volumes was in the same range as discharge simulations when looking at mean annual values. On a monthly scale, deviations tend to be higher because of additional factors of uncertainty are comprised in the modelling of storage volumes. Nevertheless, reasonable values of water availability resulted at the regional scale of the Federal State of Ceará. A validation of reservoir storage volumes could not be performed for basins in Piauí as no reservoir data were available.

5.4 Sensitivity analysis and model uncertainty

A range of sensitivity studies and modelling experiments to assess the uncertainty of results as function of uncertainty in model structure, input data or model parameters were performed for WASA. Details are given in Güntner (2002), some examples were a highly sensitive response at the large-scale of Ceará was found are given below.

5.4.1 Sensitivity to rainfall input (mean rainfall volumes)

Beside of temporal rainfall characteristics (e.g., temporal resolution of input data, Chapter 5.3.1, and spatial rainfall variability), the effect of differences in mean annual rainfall due to the use of different rainfall data sets as input data on simulated runoff volumes with WASA was examined. At the scale of the 184 municipalities in Ceará, two rainfall data sets were used, being based, first, on around 200 stations and, second, on only those 29 stations with time series long enough to be used for construction of regional climate scenarios, as provided by the working group 'Climate Analysis and Modelling' and used in the scenario simulations (Chapter 5.5). Differences between both data sets are in the range of -40% to +40% for annual mean rainfall. Differences in simulated runoff are larger than the underlying changes in precipitation by a factor of about 2 to 3 (Figure 9). Thus, limited availability of rainfall data may considerably influence the runoff simulations and constrain the quality of the model results.

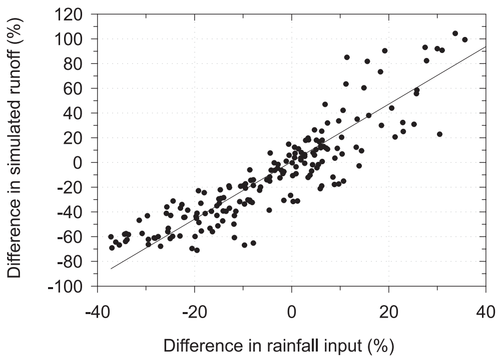


Figure 9: Effect of differences in rainfall input due to different data sets on simulated runoff for the 184 municipalities of Ceará, period 1960-1998.

5.4.2 Sensitivity to model structure

As an example of a sensitivity study concerning the effect of model structure and process formulation of WASA on simulation results, the comparison of two simulations is shown here: Simulation L1 respected lateral fluxes between terrain components and soil-vegetation components as explained in Chapters 5.1.4-5.1.6, simulation L2 did not consider any lateral redistribution and represented basin runoff simply as the sum of the contributions of all individual sub-areas.

Simulation L1 resulted in markedly smaller runoff volumes at the scale of sub-basins than simulation L2 without any lateral redistribution. The decrease of mean annual runoff is 13 % in average for the study area, and more than 40 % for some sub-basins (Table 1, Figure 10). The main effect resulted from reinfiltration of surface runoff into areas of higher infiltration capacity. There, the additional soil moisture was available for evapotranspiration instead of contributing to basin runoff. The spatial pattern at the sub-basin scale showed that the relative effect of lateral redistribution was more pronounced in areas with lower runoff volumes in absolute terms. The effect also increased with the fraction of basin area of soils with high infiltration and storage capacity, as alluvial soils. Additionally, in landscape units with steep topography in the sloping region, the generation of lateral subsurface flow was of higher importance. In simulation L1, this flow component was routed into the terrain component with lowest topographic position, i.e., the valley bottoms, being susceptible to evapotranspiration there. Also in this case, the effect of taking into account lateral fluxes was pronounced in terms of a reduction of total sub-basin discharge.

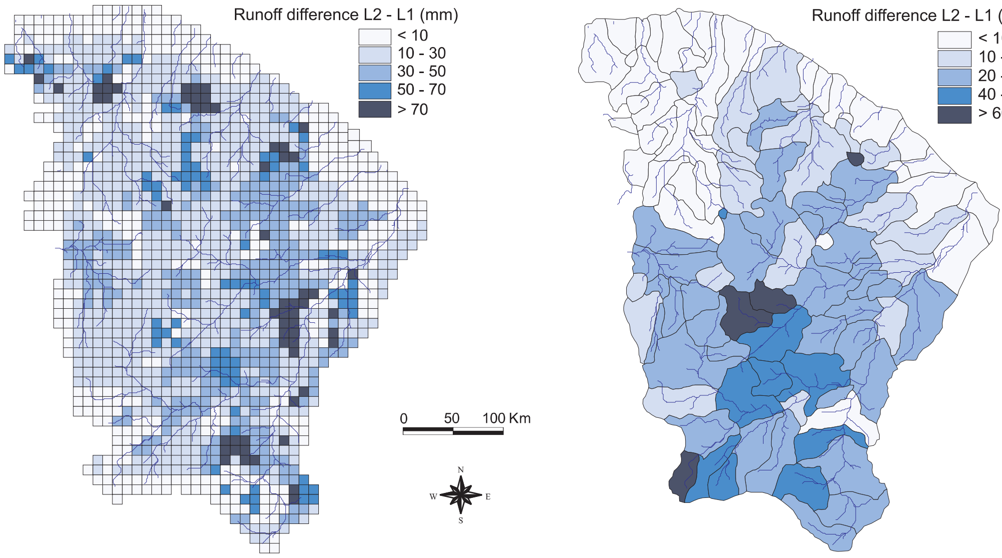


Figure 10: Differences in simulated mean annual runoff between simulations L2 and L1 without and with lateral redistribution, period 1960-1998, (a) at the scale of grid scales in mm, (b) at the scale of sub-basin in Ceará as percentage difference of total runoff.

Table 1: Effect of lateral redistribution on mean annual runoff Q (mm) for different simulations with WASA, averaged for the study area of Ceará, period 1960-1998. Subscript dry indicates results for the 10 driest years only, subscript wet for the 10 wettest years. C_v: coefficient of variation of annual runoff.

	Q	Q_{wet}	Q_{dry}	C_v
Simulation L2	169	322	59	0.96
Simulation L1	147	298	41	1.20
Difference L2-L1 (%)	13.0	7.5	30.5	20.0

The effect of lateral redistribution on runoff was more apparent in dry years as compared to wet years (Table 1). In dry years, the refillable soil moisture storage in units adjacent to those generating runoff was expected to be larger in average. Thus, a larger fraction of generated runoff in soil-vegetation-components and terrain components was retained before reaching the outlet of a landscape unit. Similarly, the comparison of simulations L1 and L2 showed that respecting lateral redistribution processes in the model increases the inter-annual variability of simulated basin discharge (see C_v in Table 1) and may be an important factor for the non-linear runoff response of the semi-arid study area.

5.4.3 Sensitivity to model parameters

A range of sensitivity studies with regard to parameter values were performed for WASA. The sensitivity of model parameters on runoff simulations is presented in Figure 11 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 sensitivites 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. 11e, 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 2). 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 2), resulting in no net change in runoff at the basin scale in average.

Table 2: 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

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 (Figure 11 c, d). For soil parameters, in contrary, the model reacted markedly more sensitive in dry years where infiltration-excess runoff generation and, thus, the near-surface characteristics dominate (Figure 11 e, g, h). A similar study for the vegetation parameters (e.g. canopy height, albedo, stomata resistance) revealed generally a larger sensitivity on runoff for wet as compared to dry years (see Güntner et al., 2002, for details). 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.

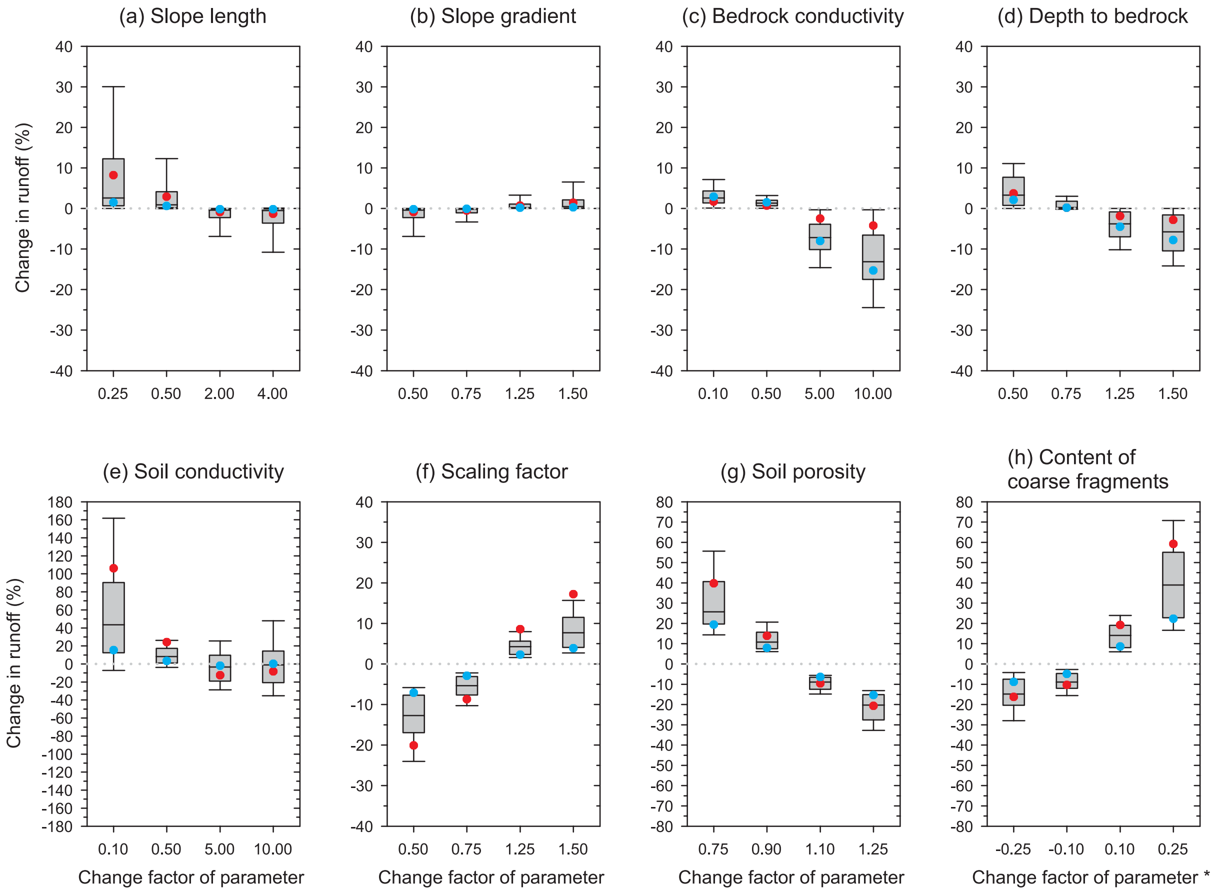


Figure 11: Sensitivity analysis for soil and terrain parameters in WASA. The x-axis indicates the factor by which the parameter is changed multiplicatively (* exception for where the change factor is applied additively); y-axis indicates the percentage change of mean annual runoff (simulation period 1960-98) at the scale of sub-basins as compared to the reference simulation without parameter change; note that the scaling of the y-axis varies between graphs. Box-whisker-plots give the variability of the effect of parameter changes on mean annual runoff among the 107 sub-basins of the study area: Boxes are limited by the 25th and 75th percentiles, black line within box = median, whiskers mark 10th and 90th percentiles. Red points indicate the median change in runoff for all sub-basins for the 10 driest years within 1960-98 only, blue points indicate the median change in runoff for all sub-basins for the 10 wettest years within 1960-98.

5.4.4 Effect of reservoirs and water use

The effect of water storage in reservoirs and of water use on water availability according to the simulation results of WASA is illustrated for Ceará in Figure 12. Water retention in reservoirs and subsequent evaporation reduces markedly the mean annual discharge in downstream sub-basins as compared to naturalised flow (Fig. 12c). In areas of a high reservoir density and storage capacity (see Fig. 12a, b), reduction of downstream discharge is generally up to 20%. If additionally the withdrawal of water from reservoirs and directly from the river is taken into account, downstream discharge reduction often exceeds 20% in the annual mean, in some parts particularly in the Banabuiú basin even more than 30% (Fig. 12 d). Thus, while providing the potential to reduce the intra- and interannual variability of water availability at downstream positions by a managed release from reservoirs during the dry season or during dry years, the total discharge volumes are considerably reduced in most parts of the study area by upstream retention and use. The large influence of water retention and water use has to be taken into account during validation of discharge hydrographs (Chapter 5.3.3).

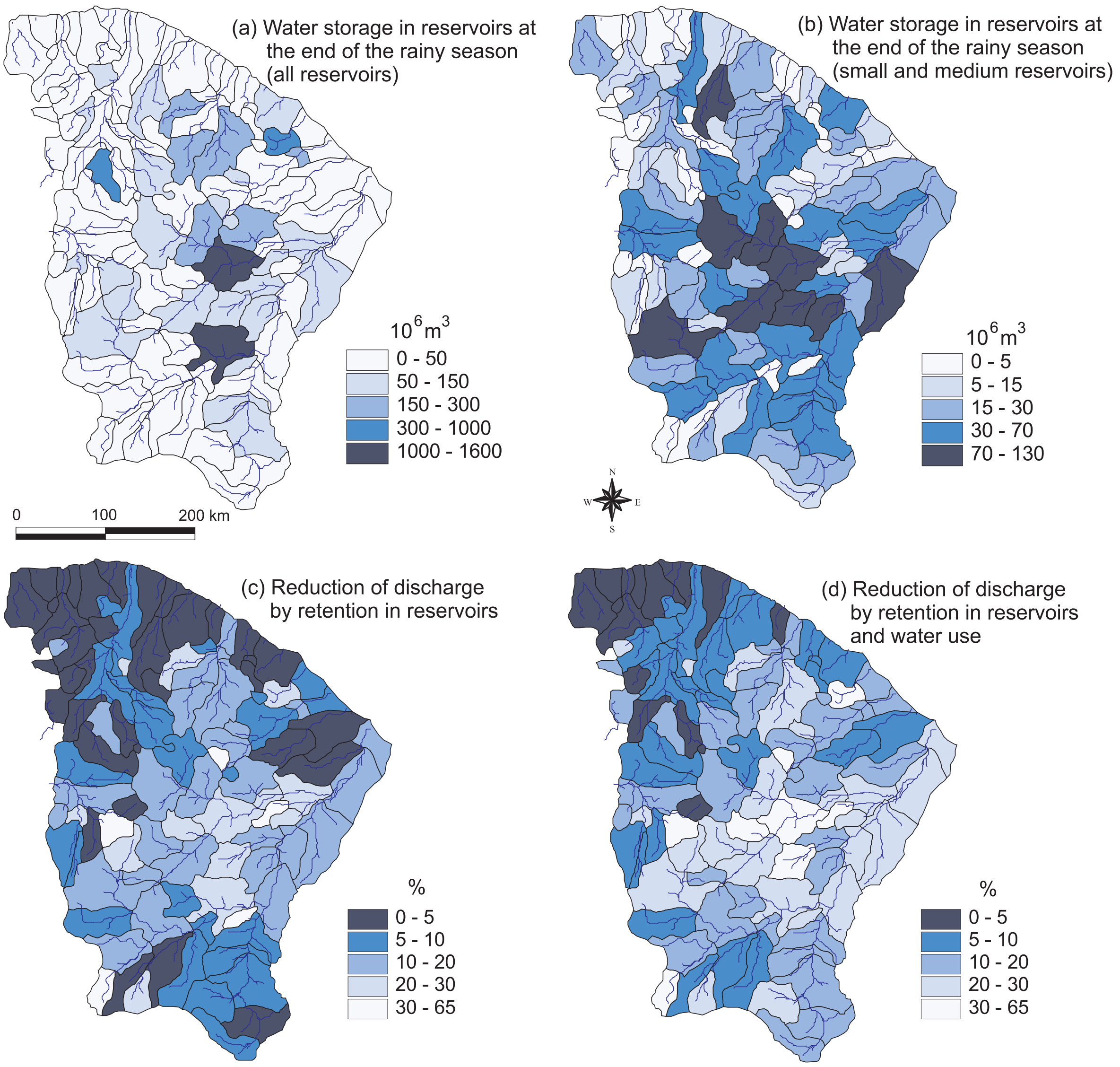


Figure 12: Simulation results for Ceará on the effect of reservoirs and water use on water availability at the sub-basin scale; mean annual values for the period 1960-1998. (a)+(b): Storage in reservoirs at the end of the rainy season (June), in (b) only reservoirs with a storage capacity of $<50 \cdot 10^6 m^3$ are considered. (c)+(d): Reduction of mean annual discharge (as compared to naturalised flow) at the sub-basin outlet by upstream (c) retention in reservoirs and (d) retention in reservoirs and water use.

5.5 Scenario simulations

Scenario calculations with WASA for the period 2001-2050 were run for two climate scenarios, one with an expected decrease of rainfall (based on the General Circulation Model ECHAM4), and one with increasing rainfall in the study area (based on HADCM2). The time series of different climate elements for these scenario runs were provided by the working group ‘Climate Analysis and Modelling’. Except for the climate input, all other boundary conditions of the model (i.e., land cover, vegetation characteristics, number of reservoirs and operation rules) were kept constant throughout the scenario period. Water use was calculated based on the demand at the end of the historical time period but can change as a function of climate variability with regard to irrigation water demand.

Table 3: Impact of climate change scenarios on components of the hydrological cycle in the Federal States of Piauí and Ceará, simulations with WASA, area average trends (%) for the period 2001-2050; climate scenarios based on ECHAM4 and HADCM2 Global Circulation Model results.

	ECHAM4 Piauí	ECHAM4 Ceará	HADCM2 Piauí	HADCM2 Ceará
Precipitation	-22	-26	+9	+11
Potential evaporation	-4	-3	-4	-3
Actual evapotranspiration	-17	-15	+3	+4
Deep groundwater recharge	-36	-37	+40	+23
Runoff	-47	-56	+42	+33

In terms of runoff, the simulations show a highly sensitive response of the study area to the climate change scenarios (Tables 3, 4, Fig. 13). Runoff trends for 2001-2050 are in average by a factor of 2-3 larger than the underlying trends in precipitation for both scenarios. This large amplification factor is in line with the results of the sensitivity analysis for rainfall volumes (see Chapter 5.4.1) and with results of impact analysis in other semi-arid areas. In average for Ceará, runoff is expected to decline by -56% in the case of the ECHAM4 scenario and to increase by +33% for the HADCM2 scenario between 2001 and 2050. For the ECHAM4 scenario, due to lower availability of soil moisture by decreasing rainfall, actual evapotranspiration and groundwater recharge is expected to decrease, too. For the HADCM2 scenario, the slight decreasing trend of potential evaporation prevents in parts a larger increase of actual evapotranspiration in spite of increasing rainfall. Additionally, the length of the rainy period does in average not increase with increasing annual rainfall for this scenario. Thus, more rainfall can be assumed to be quickly transformed into runoff and groundwater recharge instead of being evaporated or transpired. Plant-available soil moisture (above water content at wilting point) in the uppermost meter of the soil horizons is expected to decline in the main vegetation period (February-May) by in average -15% for the ECHAM4 scenario and to increase by 20% for the HADCM2 scenario.

Table 4: Climate scenarios for Ceará and their effects on the water balance (calculated with Wasa). Comparison of a historical time period (column a) and scenario time period (25 years each) (columns b and c), and linear trends for the total scenario period (2001-2050) (columns d and e).

CEARÁ	(a) Historical 1974-1998	(b) ECHAM4 2026-2050		(c) HADCM2 2026-2050		(d) ECHAM4 2001-2050	(e) HADCM2 2001-2050
	Mean	Mean	Change	Mean	Change	Trend	Trend
	mm	mm	%	mm	%	%	%
Precipitation	916	825	-10	1138	+24	-26	+11
Potential evaporation	2062	2042	-1	2028	-2	-3	-3
Actual evapotranspiration	740	669	-10	785	+6	-15	+4
Deep groundwater recharge	15	14	-7	24	+60	-37	+23
Runoff	161	141	-12	329	+104	-56	+33

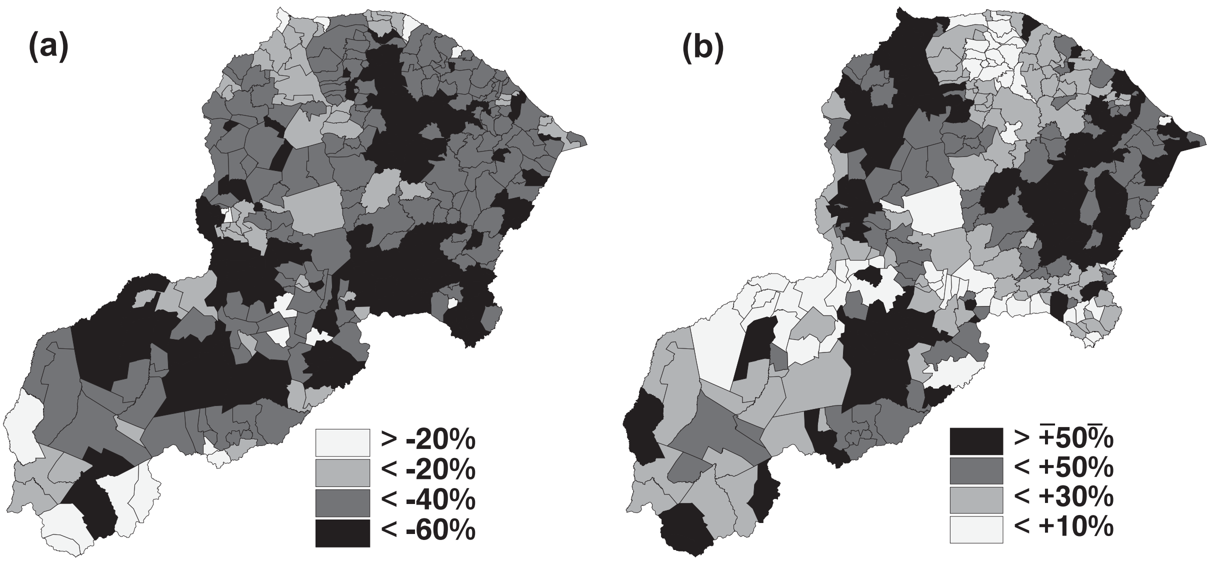


Figure 13: Runoff trends at the scale of municipalities over the period 2001 to 2050, calculated with WASA, based on climate scenarios derived from (a) ECHAM4 and (b) HADCM2

Changes in water availability in terms of river discharge for the climate scenarios were generally more pronounced at the outlet of sub-basins with a larger water storage capacity in reservoirs. For instance, in the case of the ECHAM4 scenario, the percentage of total river discharge being stored in reservoirs and consequently lost by evaporation increases with decreasing annual discharge volumes and this effect was more important in sub-basins with large storage capacity. Similarly, changes in river discharge were in general more severe at more downstream locations in river basins which are exposed to the aggregate effect of all changes in upstream areas.

Further scenario simulations with WASA were performed to assess the effect of the construction of new reservoirs on future water availability. As an example for the State of

Ceará, using the ECHAM4-based climate scenario, the number of reservoirs and thus the storage capacity of smaller reservoirs with capacity $<10 \cdot 10^6 m^3$ was increased for each sub-basin (see also Table 5). For simplicity, this increase was not realised gradually in time during the scenario period, but it was set at once at the beginning of the scenario period.

Table 5: Results of ECHAM4-based scenario runs for Ceará with assumptions on the construction of new reservoirs and an increase of total reservoir storage capacity (V: total storage capacity in reservoirs with $<10 \cdot 10^6 m^3$ storage capacity each; d: change in storage capacity as compared to the basic scenario Echam4-B without new smaller reservoirs; eff: efficiency of new reservoirs (see text).

Scenario	V $10^6 m^3$	d %	eff 2001-2025	eff 2026-2050
ECHAM4-C	4502	+25	0.81	0.57
ECHAM4-D	5403	+50	0.79	0.51
ECHAM4-E	6303	+75	0.75	0.46
ECHAM4-F	7204	+100	0.71	0.42

The results are interpreted in terms of the reservoir efficiency, which is defined as the additional amount of water being stored at the end of the rainy season (June) in all reservoirs of Ceará as compared to scenario ECHAM4-B without new reservoirs, divided by the storage capacity of the new dams. The results (Table 5, Fig. 14) showed in general a substantial increase of water availability in the first part of the scenario period (2001-2030) by in average about 75% of the additional capacity. A full usage of the new reservoirs (efficiency close to 1) was attained only in wet years and for the scenarios ECHAM4-C and ECHAM4-D with a smaller increase of the number of reservoirs. The lower efficiency values for scenarios with a larger number of new reservoirs illustrate the increasingly limiting influence which reservoirs have mutually on each other by the retention of available runoff. Lower storage volumes and efficiencies in dry years as compared to wet years demonstrated that runoff volumes were too low in this case to fill the existing reservoirs. A particularly severe effect occurred in the second half of the scenario period. With the significant decreasing trend in precipitation and runoff, the net effect of additional storage capacity in small upstream reservoirs on total available storage volumes in Ceará declined considerably. The additional water stored in these smaller reservoirs was counteracted by a simultaneous decrease of storage in the large downstream reservoirs as most of the discharge was already retained in upper parts of the basins. This effect was more severe for scenarios with a larger number of new reservoirs, where the efficiency was close to or even below 0 (see, e.g., ECHAM4-F in Fig. 14b). Thus, according to these simulation results, the system of surface water resources in Ceará is in a state where an increase in reservoir storage capacity does not necessarily imply a substantial increase of water availability for the given scenario assumptions with a decreasing precipitation trend.

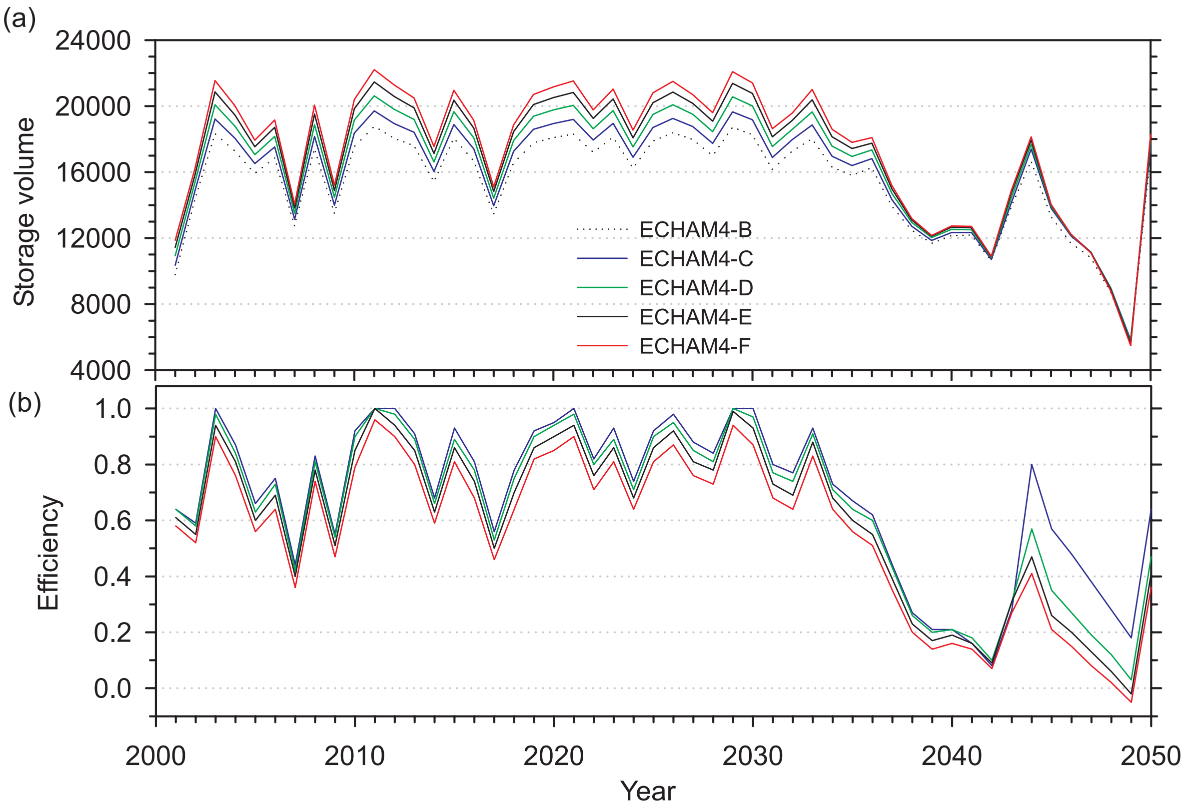


Figure 14: (a) Reservoir storage volumes (in $10^6 m^3$) at the end of the rainy season (June) and (b) efficiency of additional dams, for WASA scenario simulations with additional small reservoirs based on the ECHAM4 climate scenario (see Table 5 and text for scenario assumptions on reservoirs).

The simplicity of the scenario assumptions applied should be taken into account in the interpretation of the results. For instance, changes in water were are a function of the climate variability only, but did not include increasing water demand in the course of, e.g., population growth or industrial development. No land cover changes were taken into account, neither human-induced by regional development nor as a consequence of the adaptation of plant communities to changed climatic conditions. Similarly, the possible effect of increasing atmospheric CO_2 on plant transpiration and thus total evapotranspiration was not considered. Additionally, the availability of only one realisation of each climate scenario for this project enhanced the risk of the results being influenced by some stochastic singularities of the scenario time series.

5.6 Publications resulting from the Project

The following publications were made as a direct result of the research work within the project 'Large-Scale Hydrological Modelling' and as a result of co-operation with other working groups in WAVES:

Bronstert, A., Güntner, A., Jaeger, A., Krol, M., Krywkow, J., 1999. Großräumige hydrologische Parametrisierung und Modellierung als Teil der integrierten Modellierung. In: Fohrer, N., Döll, P. (Eds.): Modellierung des Wasser- und Stofftransports in großen Einzugsgebieten. Kassel University Press, Kassel, Germany, 31-40.

Güntner, A., Bronstert, A., 1999. A large-scale hydrological model for the semi-arid tropics of north-eastern Brazil. In: HiBAm (Ed.): Manaus'99 - Hydrological and Geochemical Processes in Large Scale River Basins, Manaus, Brazil, CD-ROM.

Güntner, A., Bronstert, A., Gaiser, T., 1999. Parameterization of lateral hydrological processes based on geomorphologic units. IUGG 99, XXII General Assembly of the International Union of Geodesy and Geophysics, Birmingham, Workshop HW4 Regionalization of parameters of hydrological and atmospheric land surface models, Book of abstract II, p. B 317.

Bronstert, A., Jaeger, A., Güntner, A., Hauschild, M., Döll, P., Krol, M., 2000. Integrated modelling of water availability and water use in the semi-arid Northeast of Brazil. Physics and Chemistry of the Earth, 25(3), 227-232.

Güntner, A., Olsson, J., Calver, A., Gannon, B., 2001. Cascade-based disaggregation of continuous rainfall time series: the influence of climate. Hydrology and Earth System Sciences, 5(2), 145-164.

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Güntner, A., Bronstert, A., 2001. WAVES - Water Availability, Vulnerability of Ecosystems and Society in the Northeast of Brazil - Sub-project large-scale hydrological modelling. In: M.E. McClain & M. Zalewski (Eds.): Ecohydrology - Hydrological and geochemical processes in large scale river basins. IHP-V, Technical Documents in Hydrology, UNESCO, Paris, p. 26.

Güntner, A., 2002. Large-scale hydrological modelling in the semi-arid North-East of Brazil. PIK-Report No. 77, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 128 pp. (PhD Thesis at the University of Potsdam, available at http://pub.ub.uni-potsdam.de/2002/0018/guentner.pdf).

Güntner, A., Bronstert, A., 2002. Process-based modelling of large-scale water availability in a semi-arid environment: process representation and scaling issues. In: G.H. Schmitz (Editor), Water Resources and Environment Research - Proceedings of ICWRER 2002. Schriftenreihe des Instituts für Abfallwirtschaft und Altlasten. Universität Dresden, Dresden, Germany, pp. 42-46.

Poser, K., 2002. Parametrisierung der Vegetationsdynamik aus Satellitendaten für die hydrologische Modellierung im semi-ariden Nordosten Brasiliens. Dimplarbeit am Institut für Geoökologie der Universität Potsdam.

Güntner, A., Bronstert, A., 2003. Large-scale hydrological modelling of a semi-arid environment: model development, validation and application. In: T. Gaiser, M.S. Krol, H. Frischkorn, J.C. Araújo (Eds.): Global change and regional impacts: Water availability and vulnerability of ecosystems and society in the semi-arid Northeast of Brazil. Springer-Verlag, Berlin, Germany, 217-228.

Araújo, J.C.d., Döll, P., Güntner, A., Krol, M., Abreu, C.B.R., Hauschild, M., Mendiondo, E.M., 2003. Global change scenarios and water scarcity in semiarid Northeastern Brazil. Water International, submitted.

Güntner, A., Bronstert, A., 2003. Large-scale hydrological modelling in the semiarid northeast of Brazil: aspects of model sensitivity and uncertainty, IAHS-Publications, submitted.

Güntner, A., Bronstert, A., 2003. Representation of Landscape Variability and Lateral Redistribution Processes in a Large-Scale Hydrological Model. Jounral of Hydrology, in preparation.

6 CONCLUSIONS AND FURTHER APPLICABILITY OF THE RESULTS

In view of the large heterogeneity of land surface properties, hydrological models should focus on dominant processes and terrain characteristics in order to keep a model structure simple enough to be applicable at a large scale. The novel multi-scale top-down approach applied in the newly developed hydrological model WASA allows to delineate modelling units with respect to the key land surface properties, to the objectives of model application and to the resolution of available data. Hydrological processes can be represented at their relevant scale, while smaller scale features are represent as sub-scale variability. Within this structure, a focus is laid on capturing lateral redistribution of runoff and soil moisture at the hillslope scale, using a simple but efficiently applicable scheme for large areas.

Model applications at different scales generally gave reasonable results in terms of water availability when compared to measured discharge and reservoir storage volumes. The results demonstrate that WASA serves as a tool for practical applications in water resources assessment in the semi-arid study area. However, the limitations and related uncertainties of model applications have to be thoroughly taken into account. Limitations of the applicability of the model in its present form were found in particular in areas with an influence of deeper groundwater bodies. Due to limited data availability and resolution, uncertainty of results is large. Of major importance is:

(1) The uncertainty of rainfall data with regard to their spatial and temporal pattern has, due to the strong non-linear hydrological response, a large impact on the simulation results.

(2) The uncertainty of soil parameters is in general of larger importance on model uncertainty than uncertainty of vegetation or topographic parameters.

(3) The effect of uncertainty of individual model components or parameters is usually different for years with rainfall volumes being above or below the average, because individual hydrological processes are of different relevance in both cases. Thus, the uncer-

tainty of individual model components or parameters is of different importance for the uncertainty of scenario simulations with increasing or decreasing precipitation trends.

(4) The most important factor of uncertainty for scenarios of water availability in the study area is the uncertainty in the results of global climate models on which the regional climate scenarios are based. Both a marked increase or a decrease in precipitation can be assumed for the given data.

No calibration of WASA was carried out for the model application to the large geographic domain in this study. The mentioned uncertainties in model input or model structure (the large but uncertain influence of reservoirs and water use on discharge is another important example) will probably lead to model calibration at the wrong place and, thus, degrade the prognostic capacity of the model to give a process-adequate representation of environmental change impact. For further applications of WASA to individual smaller-scale basins within specific studies on water resources, however, the model should be adjusted to their specific characteristics if additional information is available. Beside of an adequate representation of the spatial and temporal rainfall characteristics, the sensitivity analysis shows that the main focus during a calibration procedure should generally be laid on the highly sensitive soil parameters. If no other validation variables than river discharge are available, the comparison of simulations and observations separately for dry and wet years may help towards a process-related adjustment of parameters with a varying sensitivity due to the predominance of different processes under dry and wet conditions.

Extended possibilities of model validation are an essential prerequisite for future improvements of the hydrological model developed in this project. Multi-criterial validation methods, including several validation variables at various scales, are required to assess model performance more specifically for individual processes, to realise adequate modifications of process formulations and, in this way, to enhance the overall model reliability.

By its model structure, WASA has the potential of being transferred to other semi-arid areas for applications of water resources assessment. The multi-scale spatial concept developed here could also be applied in even larger-scale models, e.g., as sub-grid land surface parameterization in climate models to capture the possible feedbacks of the state of the land surface on the atmosphere. A further model extension, of particular relevance for integrated impact assessment in semi-arid areas, is the incorporation of a module for erosion modelling. Its importance exists not only with regard to the assessment of terrain resources, e.g., for agricultural use, but also directly with regard to the assessment of water resources by changing runoff generation in line with changing characteristics of the erosion surfaces and with regard to the reduction of storage capacity in reservoirs due to subsequent sedimentation of the reservoir volume. With erosion assessment being one basic idea behind the type of data base structure of soil and terrain data as used in WASA, the model WASA has the potential to efficiently include an erosion module within its existing spatial structure.

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