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Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil

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Summary Many semi-arid regions are characterised by water scarcity and vulnerability of natural resources, pronounced climatic variability and social stress. Integrated studies including climatology, hydrology, and socio-economic studies are required both for analysing the dynamic natural conditions and to assess possible strategies to make semi-arid regions less vulnerable to the present and changing climate. The model introduced here dynamically describes the relationships between climate forcing, water availability, agriculture and selected societal processes. The model has been tailored to simulate the rather complex situation in the semi-arid north-eastern Brazil in a quantitative manner including the sensitivity to external forcing, such as climate change.

The selected results presented show the general functioning of the integrated model, with a primary focus on climate change impacts. It becomes evident that due to large differences in regional climate scenarios, it is still impossible to give quantitative values for the most

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probable development, e.g., to assign probabilities to the simulated results. However, it becomes clear that water is a very crucial factor, and that an efficient and ecologically sound water management is a key question for the further development of that semi-arid region. The simulation results show that, independent of the differences in climate change scenarios, rainfed farming is more vulnerable to drought impacts compared to irrigated farming. However, the capacity of irrigation and other water infrastructure systems to enhance resilience in respect to climatic fluctuations is significantly constrained given a significant negative precipitation trend.
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Introduction

Societies in semi-arid areas in developing regions are very vulnerable to variability of climate and water availability and potentially vulnerable to climate change. This vulnerability is caused by the strong constraints on the use of natural resources due to limited water availability, the generally low reliability of water availability and, on the other hand, an often appreciable density of population, strongly depending on these resources with few short-term options to reduce such dependency. Reasonable conditions in the wetter years support the persistence of population in the area; marginal or poor conditions in drier years and under-development hamper significant improvements in the quality of life.

Clearly, the study of environmental change impacts in developing semi-arid regions calls for an integrated approach. The climate impacts are not only an effect of changes in water availability, but emerge from the confrontation of availability and societal demands and the role these demands play in society. Therefore, an appropriate integrated study should include not only the physical understanding of climate on the water balance and on crop yields, but should also include the analysis of water use, agricultural economy and societal impacts. In north-eastern Brazil, one of the most marked societal impacts of droughts is the emigration of population from rural areas in the urban centres and to destinations outside the region.

It is the goal of water resource management in semi-arid regions to reduce vulnerability against water stress and drought and to enhance the resilience of the human—environmental system. At a longer time perspective (over generations) this can only be achieved by aiming for a sustainable use of water resources, which must be an integrating process, encompassing climate, natural resources (water, soil), technology, ecology, economy, and the society (Loucks, 2000). Regional integrated modelling can supply both a conceptual framework and an application tool for integration of such different scientific disciplines.

Regional integrated modelling

The integrated modelling concept

The research area of integrated modelling is developing rapidly in the context of climate and environmental change studies. Originating from natural science models, extended to include climate change impacts, or from macro-economic models, the modelling moves into an area where the integration approach is more central. The relevance of regional factors in global warming impacts is increasingly recognised, considering not only realisations of climate change within the regional climate systems but also accounting for regional characteristics like soil, vegetation, rivers and water management systems. These factors represent the exposure and the sensitivity to climate and environmental change. Next to these, the regional adaptive capacity, depending on geobiophysical as well as socio-economic conditions, is a key factor in the vulnerability of a region to climate change, leading to very regionally specific main concerns with respect to climate and environmental change (McCarthy et al., 2001). One conclusion is that developing regions tend to be more vulnerable to such changes than developed ones. Another conclusion is that the integrative understanding of the natural—social—economic system is not advanced enough to come to firm conclusions on consequences of environmental change and on appropriate mitigation strategies. For instance, knowledge on adaptability relates to climate and hydrologic variability rather than to climate change, where the transferability of findings is an open issue (McCarthy et al., 2001). Such considerations underline the need for integrative regional studies. For water-related issues, this need connects to the international policy rulings and recommendations for integrated water resources management at the catchment scale, as reflected in, e.g., the Water Framework Directive of the European Union (European Commission, 2002) or by the World Water Forum 3 (2003). Nevertheless, modelling at the global or continental scale (e.g., Vörösmarty et al., 2000; Lehner et al., 2001; Döll et al., 2003) is required to identify present and future water-related problems and their world-wide significance, and to represent the feedback of changes in the terrestrial water cycle to the global biogeochemical cycle.

Regional impact assessments need to establish links between different scientific disciplines and to integrate the various discipline-specific methodological approaches. In the past decade a number of regional integrated impact studies have been conducted in different regions of the globe, extending from, e.g., climate change scenarios, hydrological, water management, and agricultural impacts to the representation of interests of various socio-economic sectors. In a study of the McKenzie basin in Canada (Cohen, 1997), climate and hydrology are studied jointly using integrated modelling and stakeholder-specific priorities for climate-change-related issues. In some recent regional studies (Turner et al., 2003a,b), the concept of vulnerability is used as a central vehicle for integration. In a series of integrative catchment studies, various approaches towards integration have been attempted. For example, in a study on the upper Danube (Hennicker et al., 2003), a computer-network-based approach is taken to dynamically link disciplinary modules, which are modelled in a distributed way, with the same grid resolution for each module. In a study on the river Elbe, an integrative framework considers the cycle of problem setting, criteria selection, scenario-definition including policy measures, and multi-criteria multi-stakeholder analysis of alternatives, where impacts are estimated using input—output linkages of chains of disciplinary or partly integrative models (Becker et al., 2001). In a study on the river Volta (van de Giesen et al., 2002), three clusters of integrated dynamic models are defined, with different levels of manageability (atmosphere, land use, water use). The clusters are connected through interfaces, while within the clusters physical models and agent-based approaches are included. Various projects aiming at constructing Decision-Support Systems similarly consider water issues in specific water- or land-use-related policy fields. Often, small-scale spatial representations are included by either static allocation schemes or cellular automata and with a dynamical modelling approach at the aggregated scale (Bathurst et al., 2003; Engelen et al., 2003; de Kok and Wind, 2003).

Integrated modelling of water availability and quality of rural life in a semi-arid region

Integrated modelling mostly starts with a clear definition and a systems analysis of the problem studied. The case study presented below focuses on the assessment of relationships between water availability and quality of life and migration in the rural semi-arid north-eastern Brazil at the meso-/macro-scale in the context of global change, especially climate change. In Fig. 1, a top-down analysis of the overall question ''water availability and migration in a semi-arid region'' is schematized, identifying the basic variables, internal processes, and the external forcing that should be accounted for in the integrated model. The factors of importance influencing the studied system but *not influenced by feedback responses* of the system are termed *external forces*. Such external factors are the overall climatic situation and climate changes, the technological development, the overall demographic development, the soil conditions (natural resources), world-market prices for cash crops, etc. On the other side, the factors and processes which *both do influence and are influenced* by the system under study are termed *internal dynamics*. These internal dynamics can be grouped into some sub-systems, where the most important are the regional hydrological cycle (physical water availability), the water use and its management, agricultural production (both crop and animal production), the employment in the agricultural and other water-dependent sectors and the socio-economic conditions (e.g., expressed as a ''quality-of-life-index'').

In this analysis, the focus is explicitly on internal features which exhibit the most relevant dynamic behaviour rather than on those features which are best understood. The specific challenge is to find a good compromise between the clarity in the representation and the comprehensiveness regarding the main dynamical processes (find 20% of processes that explain 80% of dynamics). Special attention should be paid to cross linkages and feedback processes, which could importantly influence long-term dynamics, for instance the effects of migration on the agricultural sector. It is beyond the scope of this paper to describe the underlying methodology of regional systems analysis and the modelling aspects of sub-system couplings in more detail. More information on these issues is presented in Bronstert et al. (2005).

A particularly interesting feature of the dynamics is the ability of the system to dampen (or enhance) the variability

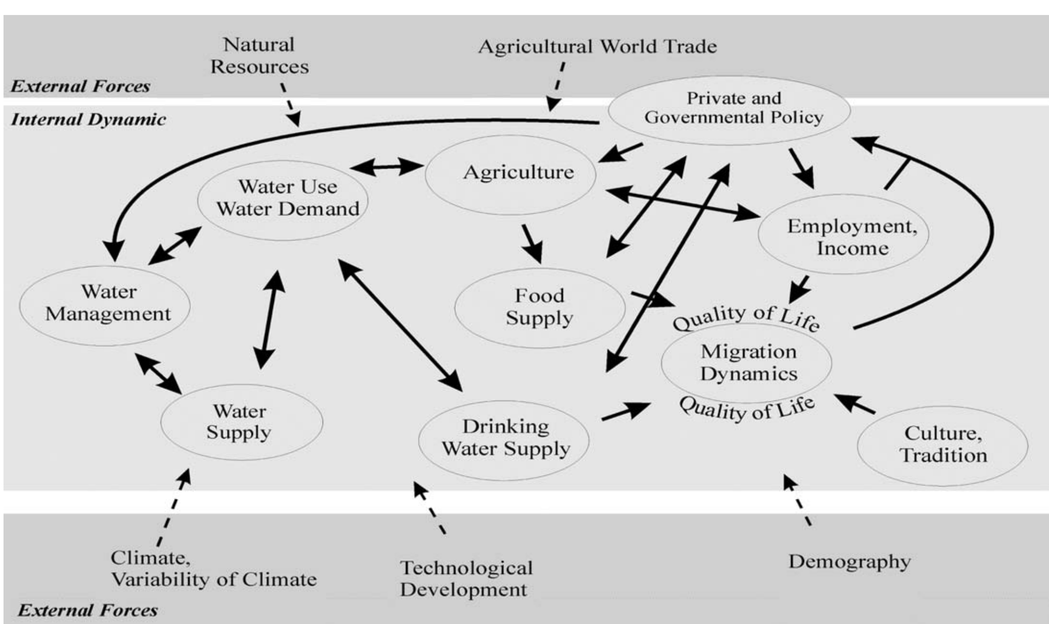

Figure 1 Conceptual model of dynamic relationships between water availability, agriculture and migration in north-eastern Brazil, as influenced by global change.

resulting from the variable climate forcing. For instance, water infrastructure and water policy can reduce the variability of availability of water resources. On the other hand, in the field of agriculture and social dynamics, exceeding threshold values of water availability or income may suddenly trigger strong impacts on crop yield or migration, implying an increase in variability along the causal chain. The usage of adapted crops and rural policy or drought emergency policy may again dampen the variability. The context of global change forces the analysis to consider the long-term behaviour of the system. A reasonable *dynamic* understanding is preferred over an excellent *static* understanding, and processes influencing long-term changes are more in focus than processes just explaining heterogeneity at the micro-scale. Clearly, only (aggregated) process-based models can simulate both the effects of individual influences of global change and policy interventions. In this sense, integrated models generally show a mix of deductive (top-down) and inductive (bottom-up) approaches. Here, the poor availability of data on many themes at the targeted scale also plays a role.

Given these features, the present approach is very well suited to assess possible developments in water stress in the region, as driven by both global processes (especially climate change) and regional development tendencies. Given the large mutual dependencies between water availability and water use, especially under emerging drought conditions, a dynamic coupling representing the feedbacks is a prerequisite for projecting possible developments. Moreover, the integrated model highlights the possible sub-regional locations and magnitudes of impacts, made possible by being spatially explicit. As the level of local detail in the integrated model must be limited, and the representation of small-scale adaptation to water stress or mitigation of water stress impact at the small-scale is coarse, the approach is not suitable for to prioritising specific local policy measures. However, it does allow a qualitative screening of policy directions to be made.

Model description

The Regional Integrated Model for the semi-arid north-east of Brazil (Semi-arid Integrated Model — SIM) is an implementation of the outcome of the systems analysis, which shows schematically in Fig. 1. The model is built up in a modular way, roughly representing the disciplinary contributions from different research groups. Each module has discipline-specific methodological characteristics, i.e., the scientific and technical approaches which are typically applied by the individual discipline determine the structure of each module. Though composed of different modules, the integrated model was constructed in a comprehensive manner, e.g., the model code was assembled within an overall framework and all couplings are executed within this framework. This ''on-line'' coupling mode enables a direct consideration of feedback effects within the integrated model. The code was mainly implemented in FORTRAN, although for a few modules specific software technology was used, such as in the case of the agro-economic model the non-linear optimisation software GAMS (General Algebraic Modelling System).

The SIM model covers different space and time scales, ranging from terrain units (average extent: few tens of km^2) to aggregated administrative units (several 1000 km^2), and from days to tens of years. The modelled region covers the Brazilian Federal States of Ceará and Piauí, an area of almost 400,000 km^2, and the total simulation period is about 20 years for current conditions and 100 years for scenario conditions. The ''common spatial resolution'' for all modules (spatial resolution for information exchange between the modules) is the municipality, an administrative unit with in average about 1200 km^2 in size. The ''common temporal resolution'' is one day. The different scales and resolutions of the individual modules requires aggregation procedures to be applied, such as weighted averaging or catchment-specific assignment, and disaggregation procedures, such as statistical disaggregation or iteration between varying scales. Table 1 summarises the most important features of SIM and the different modules. More comprehensive information is given in Jaeger (2004).

Fig. 2 presents a scheme of the coupled (interacting) modules of SIM. They are summarised in the following paragraphs with focus on the water related components which are of particular interest in this article.

Climate

Climate forcing as input of SIM is by a historical reconstruction of daily time series of temperature, precipitation, air humidity and wind speed for the period 1947—1998, and by scenarios of future climatic conditions resulting from a statistical scenario technique using long-term daily observations in combination with climate trends from Global Circulation Models (Werner and Gerstengarbe, 1997).

Water availability

A large-scale water balance model for semi-arid conditions describes the soil moisture budget, runoff generation, river discharge and water storage in reservoirs. It accounts for vertical and lateral hydrological processes depending on topography, soil and vegetation cover, with a particular focus on lateral processes at the hillslope scale, which is usually not accounted for in large-scale hydrological models (Güntner and Bronstert, 2004). The largest spatial units in the model are sub-basins or municipalities. The latter, administrative units were required within the integrated modelling approach to provide an interface with adjacent modules, e.g., the water use sector, for which data are available only at the level of administrative units. In order to capture the influence of spatially variable land-surface properties on soil moisture patterns and runoff generation, sub-basins or municipalities are sub-divided into smaller modelling units by a hierarchical top-down disaggregation scheme of the landscape. The modelling units at different spatial scales range from landscape units with similar lateral flow characteristics, aggregated terrain components, soil—vegetation components to representative soil profiles (Fig. 3, Güntner and Bronstert, 2004). At the profile scale, vertical processes are represented by process-oriented approaches, e.g., infiltration based on Green-Ampt, evapotranspiration is described by a modified Penman—Monteith approach for sparse vegetation (Shuttleworth and Wallace, 1985), and the soil water balance is calculated by a multi-layer storage

Table 1 Structure of SIM: modules, content covered, methods applied, space and time scales, and scientific institutions responsible for the modules

Module	Scientific approach	Applied methods	Technical realisation	Typical spatial scale/resolution	Typical time scale/resolution	Institution	Reference
Climate	Historic reconstruction of time series and scenarios of future climatic conditions	Statistical—empirical downscaling	FORTRAN; external data bank	State/municipality	10 years/1 day	PIK/FUNCEME	Werner and Gerstengarbe (1997)
Water availability	Large-scale distributed water balance	Process-based, deterministic modelling of the hydrological cycle	FORTRAN; dynamic and distributed model	Municipality/ terrain unit	10 years/1 day (h)	PIK/UFC	Güntner (2002)
Water use	Balancing of water use and management in different sectors	Data driven budgeting	FORTRAN	State/municipality	10 years/10 days	Uni Ks/UFC	Hauschild and Döll (2000)
Soil conditions	Soil description and potential for crop production	Distributed soil data base	External data bank	Terrain unit	—	Uni Ho/UFC/PIK	Gaiser et al. (2003)
Crop yield	Calculation of main crop yield depending on soil fertility and water availability	Empirical functions for different crops limited by stress factors	FORTRAN	State/municipality	10 years/1 day	FAO/PIK	Jaeger (2004)
Agro-economy	Agro-economy	Mathematical optimisation	GAMS-software	State/municipality	10 years/10 years	FH K	Höynck (2003)
Demography	Estimation of birth and mortality rates	Empirical; derived from survey data	FORTRAN	State/municipality	10 years/1 year	UFC/PIK	Jaeger (2004)
Socio-economy and migration	Estimation of migration rates depending on a quality-of-life indicator	Empirical, derived from interviews and published statistical data	FORTRAN	State/municipality	10 years/1 year	Uni Ks/UFC	Fuhr et al. (2003)

PIK: Potsdam-Institute for Climate Impact Research Germany; FUNCEME: Fundação Cearense de Méteorologia e Recursos Hídricos, Fortaleza, Brazil; UFC: Universidade Federal do Ceará, Fortaleza, Brazil; UNI Ks: University of Kassel, Germany; FAO: Food and Agriculture Organization, Italy; UNI Ho: University of Hohenheim, Germany; FH K: University of Applied Sciences Cologne, Germany.

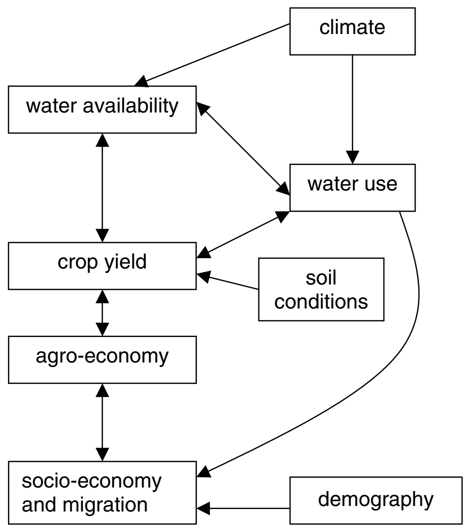

Figure 2 Scheme of the coupled modules of the regional integrated model SIM. A double arrow indicates interactions in both directions (feedback effects) an one-directed arrow indicates an one-way effect.

approach. Further details of this module are given in Güntner (2002).

A very important component of water resources systems in semi-arid areas are surface reservoirs. In the study area, the total number of such reservoirs exceeds 7000, ranging from small ponds used by only one or few families, to very large dams, exceeding 1000×10^6 m^3 storage capacity. For each large reservoir (storage capacity > 50×10^6 m^3) in the study area, the water balance is calculated explicitly in the water availability module. In contrast, the huge number of small reservoirs cannot be taken into account given the scale of model discretization. Instead, small reservoirs are captured by means of their distribution among five storage volume classes, for which the number of reservoirs in each class is known for all municipalities. In each class, the water balance is calculated for one reservoir of average characteristics, which is assumed to be representative for all reservoirs in this class. A simple cascade scheme is applied (Fig. 4), which routes runoff exceeding the storage capacity of one class to the reservoirs of the next larger storage class (Güntner et al., 2004).

Water use

A water use model simulates water withdrawal from groundwater, rivers and reservoirs and consumptive water use in all municipalities, considering five water use sectors, i.e., irrigation, livestock, household, industry and tourism (Fig. 5, Döll and Hauschild, 2002), coupled to the relevant other modules. Each sectoral water use is computed as a function of a water-use intensity (e.g., per capita domestic water use of the specific population group) and a driving force of water use (e.g., associated population). In a scenario of future water use, both the water use intensities and the driving forces might differ from present-day conditions. Although all sectoral water uses are expected to vary to a certain degree with seasonal and inter-annual climate variability and climate change, only the climate dependence of irrigation water use is simulated by this module.

The most relevant link of the water use to the water availability module is performed by a direct coupling of withdrawal and return flow to the reservoirs and rivers. The coupling is performed in both directions, i.e., on the one hand, water use influences the available water resources (e.g., water stored in reservoirs), on the other hand, the available water influences the extent of its use by steering water demand management in periods of water scarcity. This two-way coupling (feedback coupling) proved to be of high importance for simulating the effects of different possible options, such as improving irrigation efficiency, water demand management, or a further extension of water infrastructure (reservoirs, transmission channels, etc.). Details of the coupling are given in Jaeger (2004).

Agriculture

Crop yields (kg/ha) and total agricultural production (kg) for the 14 regionally most important crops (including maize, bean, rice, cashew) are simulated using a scheme for yield response to water and aeration stress (FAO, 1979), including soil quality (nutrient supply, soil layering) (Gaiser et al., 2003) and different management methods (Jaeger, 2004). The module uses evapotranspiration results obtained from the hydrological module. Thus, the water availability, the water use and the soil modules are directly coupled to the crop yield module (Fig. 2). Crop production values are obtained by a simple multiplication of yield values with the corresponding cultivation area. The cultivation area that is potentially usable for the different crops is derived from a suitability assessment of soil characteristics for the specific crop type and from the available permanent and seasonal labour force. The latter information is provided by the socio-economic module. Agro-economy is represented as an optimisation of farm income by varying cropping and husbandry activities, under restrictions of available land, technical and financial opportunities, feed and food requirements, accounting for production costs and prices.

Both irrigated and rain-fed farming are simulated. For scenario simulations, future changes in the area potentially irrigated land are estimated from overall agro-economic projections, i.e., the potentially irrigated land is a boundary condition to the crop yield module and to the agro-economic module. In contrast, the actual irrigated land is calculated as part of the internal system dynamics by accounting for the potentially irrigated land and for the actually available water resources available for irrigation in each municipality.

Socio-economy

Migration between municipalities and to external destinations is preliminarily modelled to occur when gradients in the quality of life exceed migration costs (fixed and distance-dependent). Here, quality of life is a composite indicator, where mean municipal income per head is the dominant influence (Fuhr et al., 2003). Migration is accounted for in a demographic model resolving for age and gender.

As mentioned before, the connection and completion of the disciplinary contributions to the full integrated model required consideration of consistency between disciplines, the information transfer between different space and time scales, and the harmonisation of varying mathematical

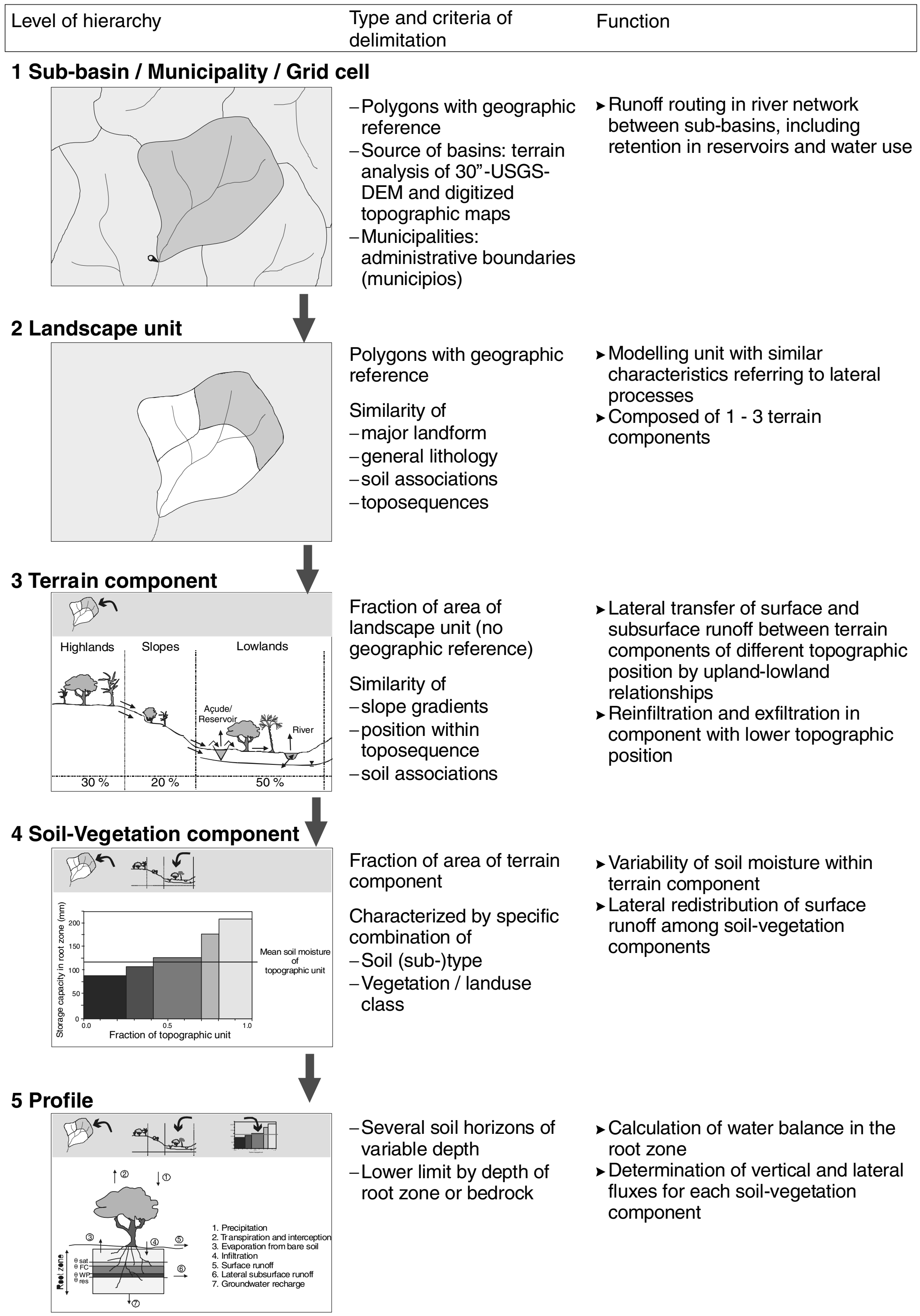

Figure 3 Cascade of scale-specific hydrological modelling units (Güntner and Bronstert, 2004).

approaches. In this regard, the thorough systems analysis proved useful for designing the conceptual model, steering the explicit definition of module interfaces and identifying gaps not accounted for in disciplinary modules, to be found, e.g., how water availability/scarcity influences water consumption.

Case study of north-eastern Brazil

Site description

North-eastern Brazil is seriously affected by the insufficiency and unreliability of precipitation. The adverse

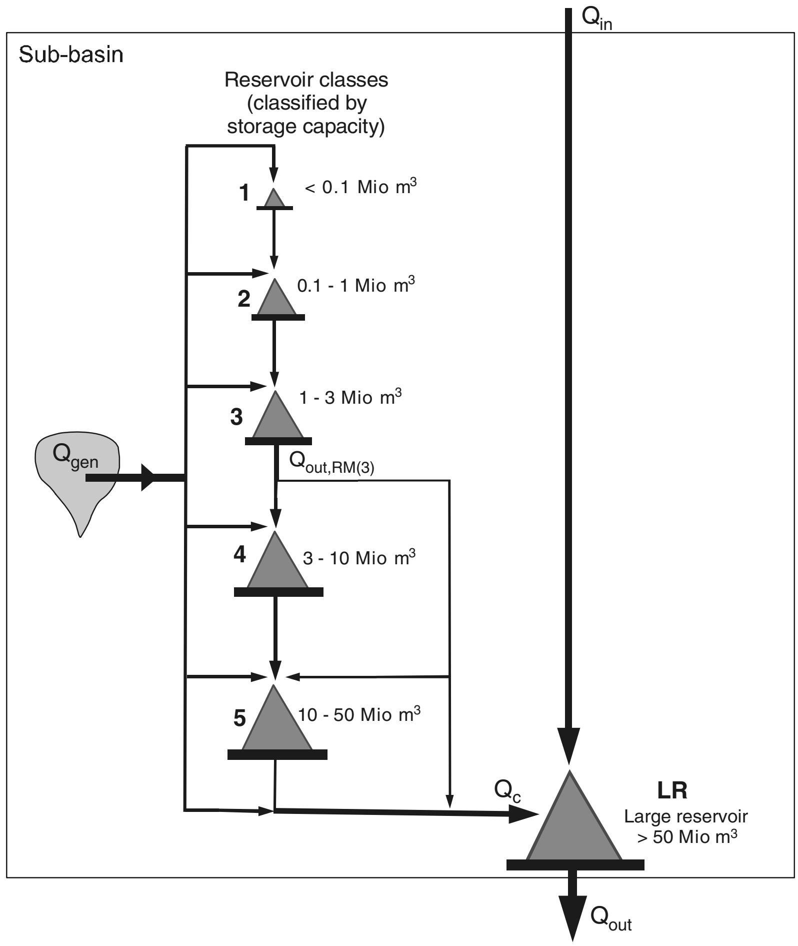

Figure 4 Cascade scheme for reservoir water balance modelling with reservoir classes and runoff redistribution between classes within a sub-basin (for clarity of the figure, only redistribution of outflow from reservoir class 3 ($Q_{out,\ RM(3)}$) among larger reservoirs and the cascade outlet is completely represented by arrows; similar schemes apply for the other reservoir classes). Q_{gen}: runoff generated in the sub-basin, Q_{in}: inflow from upstream sub-basins, Q_c: river flow after the passage of the cascade of small- and medium-sized reservoirs, Q_{out}: total sub-basin outflow (Güntner et al., 2004).

natural conditions and the underdevelopment of the region mean that the rural population cannot support itself in drought years. One of the main characteristics of north-eastern Brazil, where conflict for water use is already a reality, is its vulnerability to recurrent droughts. Within this region there is the so-called *drought polygon*, a semi-arid area of about 940,000 km^2 stretching across nine federal states in Brazil, where droughts occur rather frequently. The study area is largely inside that drought polygon and comprises the Brazilian Federal States of Ceará and Piauí (Fig. 6), together covering 400,000 km^2. Most of this area has a semi-arid climate with precipitation ranging from 500 to 900 mm/year, annual temperature from 23 to 27 °C, annual sunshine up to 2800 h, and relative humidity averaging 50%, resulting in a potential evapotranspiration exceeding 2000 mm/year.

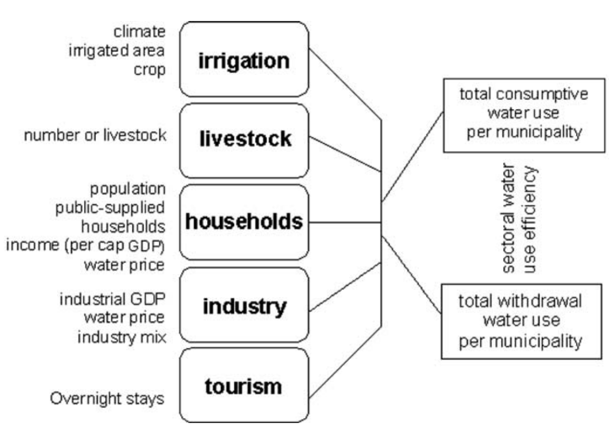

Figure 5 Overview of the regional-scale water use model; on the left-hand side, the driving forces of water use in the five sectors are indicated (Döll and Hauschild, 2002).

Climate shows an annual cycle with a dry period of 6 months; inter-annual rainfall variability is high, related to El Niño, showing irregularly returning of severe droughts. The geological basis in Ceará is mostly crystalline bedrock. Due to these climatic and geological characteristics, all important rivers in the region are intermittent; observed runoff coefficients vary between 7% and 12%. Dam construction, aimed at providing perennial river flow and urban water supply has a tradition of over a century. In rural areas an immense number of small reservoirs succeed in storing water to overcome shortage in the dry season of regular years, but they fail in multi-year drought periods. Groundwater availability in the crystalline interior is scattered and waters often are saline. Major aquifer systems exist only in the coastal region and the downstream area of the Jaguaribe, the main river of Ceará. For both agriculture (irrigation) and municipal water supply the water management and the use of reservoirs is vital. For example, during the dry season, the water supply of the agglomeration of Fortaleza, with more than 2.5 million inhabitants, almost completely relies on a water transfer system consisting of several large reservoirs and transmission canals.

Apart from alluvial soils in the river beds, soils are generally shallow and poor. Land use consists largely of extensive cattle holding and subsistence farming. The main crops are maize, beans, dry rice, cassava and cashew. Distribution of land and income is very uneven, leading to a high vulnerability of small subsistence farmers. Current population is about 11 million, increasing at a rate of 1.4% per year. A steady rural—urban migration compensates the rural birth excess, with migration strongly elevated in drought years. Migration to urban centres in Brazil's South or to land reclamation areas in the Amazon area also is an important demographic factor.

Earlier regional studies on north-eastern Brazil (UNEP study of climate variability and agriculture in the semi-arid tropics, Magalhães et al., 1988) were broad and rich in information but did not arrive at an integrative concept as adopted in this study (Bronstert et al., 2000; Krol et al., 2001).

Selected results

Climate change impacts on water availability and water use

Selected examples of the application of SIM are presented in this section. First, we show the impact of a changing climate on surface hydrology. The starting point for the climate downscaling was the results obtained by two GCMs, ECHAM-4 (Roeckner et al., 1996) and HADCM-2 (Johns et al., 1997). These two models differ strongly in their projections for future precipitation in north-eastern Brazil: For an annual increase of greenhouse gases by 1% per year as of 1990, projections of precipitation changes over that region (2070—2099 compared to 1961—1990) are —50% for ECHAM-4 and +21% for HADCM-2. Fig. 7 shows the precipitation trend until 2050 for the study area of Ceará and Piauí, resulting from the statistical downscaling. The spatial pattern of the precipitation trend reflects the boundaries of the municipalities, which is the common spatial resolution for the integrated model (see above).

Assessing the effects of climate change, simulations for one fixed reference scenario of regional and global developments with three different climate scenarios were compared, referred to as the ECHAM scenario, the HADCM scenario and the Constant scenario (in which no climate change is assumed). The first impact of climate change in the causal chain of processes is the impact on the availability of water resources. Precipitation changes have a direct effect on the water balance, affecting runoff generation, river flow and surface water storage.

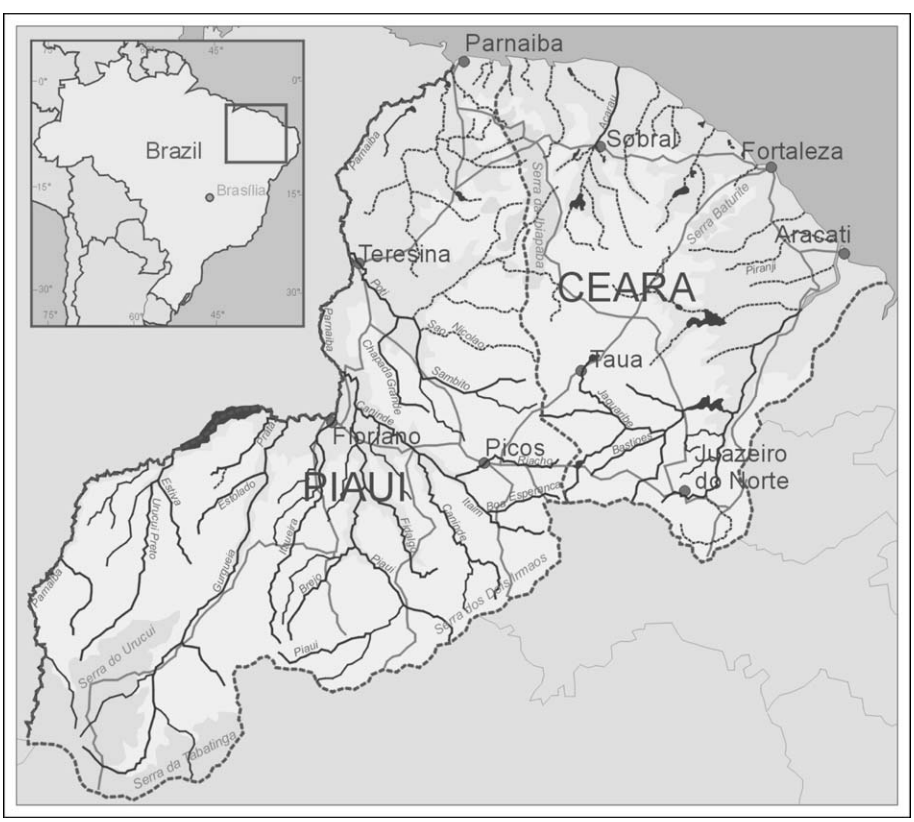

Figure 6 Map of the north-eastern Brazilian states of Ceará and Piauí.

River runoff shows a strong reaction on the precipitation changes (Fig. 8). While runoff approximately until the year 2025 is statistically similar to the historical simulations, a strong decrease in runoff results for the scenario period after 2025 using the ECHAM scenario, and a smaller, statistically insignificant increase for the HADCM scenario.

Similar tendencies appear for the water storage in reservoirs. Dam construction is one of the main regional strategies to reduce water shortages in the dry period (July—November) and to carry water availability from wetter years to later drier years. Derived from the present long-term perspectives of water resources development in that region total water volume stored in large reservoirs with storage capacity $> 50 \times 10^6\ m^3$ at the beginning of the dry season (July 1st) shows a strong increase between 1995 and 2015, see Fig. 9. This is the period where a marked increase in storage capacity occurs due to the estimated construction of additional dams/reservoirs (by an estimated volume of $7000 \times 10^6\ m^3$). Total storage capacity in Ceará and Piauí then reaches almost $22{,}000 \times 10^6\ m^3$, of which $16{,}400 \times 10^6\ m^3$ is installed in Ceará. Afterwards, further dam constructions will be much less because the dam installation potentials will be rather saturated. After 2015, in the HADCM scenario and the scenario with constant climate, the reservoirs show a variable degree of stored water, without a significant trend. For the ECHAM scenario, stored volume in Ceará shows a marked decline (Fig. 9). The general decline in water availability for the ECHAM scenario after 2025 should be seen in connection to the trends in water use. Due to population growth, increased connection to public water supply systems, intensification of industry and, above all, a strong increase in irrigated area, water demand grows strongly in that scenario.

Looking at the water withdrawal from the reservoirs (Fig. 10), one can see an increase from about $1500 \times 10^6\ m^3$/year in 2000 to about $2500 \times 10^6\ m^3$/year 20 years later. This is a result of an increased water demand due to an enlargement of the irrigation area, a growing population, and an improved water infrastructure (increased connection to public water supply). Meeting this increased water demand (resulting in the increase of water withdrawal) is possible through the estimated additional installation of reservoir volume, as explained before. After about 2030, the ECHAM scenario shows a decrease of water withdrawal rates, because the water demand can not be fully met. In other words, the efficiency of the reservoir systems is decreasing significantly, which is a result of the reduced precipitation projected by the ECHAM climate scenario. In contrast, the HADCM scenario does not show a significant decrease of water withdrawal.

Impact of agricultural development on water scarcity (and vice versa)

The yield response module of SIM was validated for the selected crops against available data for yield and production for the period of 1947 until 1998. The simulation results were reasonable for quite a number of crops. In Fig. 11, a less satisfactory example (Fig. 11a) and a rather good one (Fig. 11b) are shown, i.e., the simulated and reported production of maize (Fig. 11a) and tomatoes (Fig. 11b), respectively. In general, the trend of production increase is covered well, and also the decline of production in drought years is simulated in accordance to the reported data. For instance, there is a sharp decline in maize production in 1993, which was a severe drought year. It is worth mentioning that the mismatch between simulated and reported maize production in the first two decades might be due to a different reporting system for crop production before 1970 (Jaeger, 2004).

The model was also spatially validated by considering simulated crop yields for all 332 municipalities in the study area. Being aware that both the data base of the crop production for the different municipalities is weak and that the reliability of data available for water, soil conditions and labour (as input information into the crop yield module) is limited, one cannot expect a strong correlation of simulated and reported crop yield at this spatial resolution. However, the coefficient of correlation of mean annual crop yield at the municipality level varies (for different crops) between 0.90 and 0 (Jaeger, 2004), indicating, that at least for some crops even the spatial differences of the growth conditions are represented rather well. For a higher aggregated regional level results are much better.

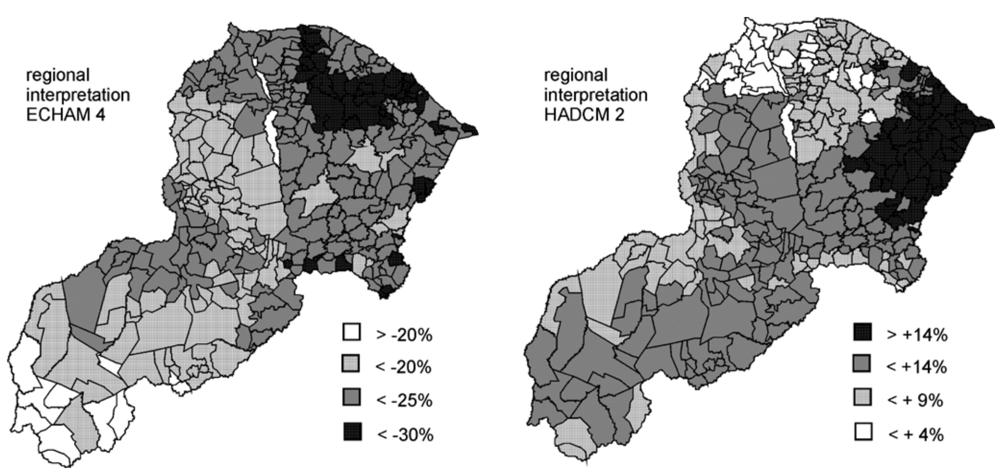

Figure 7 Downscaling of GCM results for precipitation trends in the states of Piauí and Ceará over the period 2001—2050, assuming continued growth of atmospheric greenhouse gas concentrations. The spatial distribution reflects the municipality boundaries.

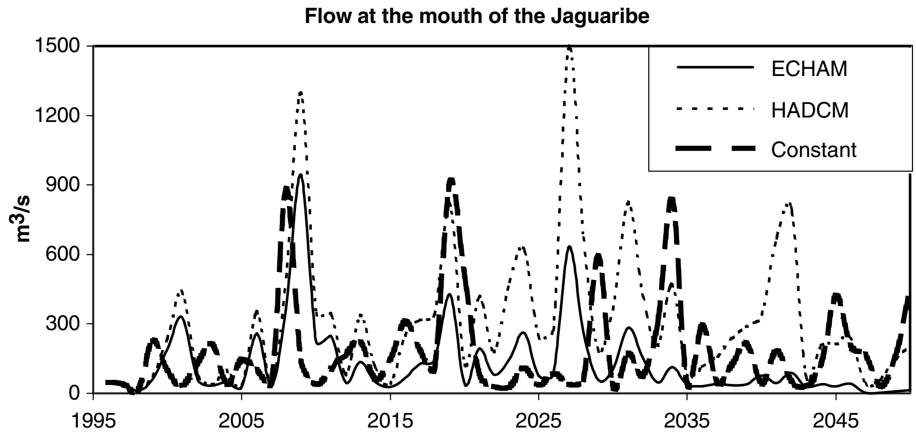

Figure 8 Outflow of the river Jaguaribe, for the three climate scenarios, simulated with SIM.

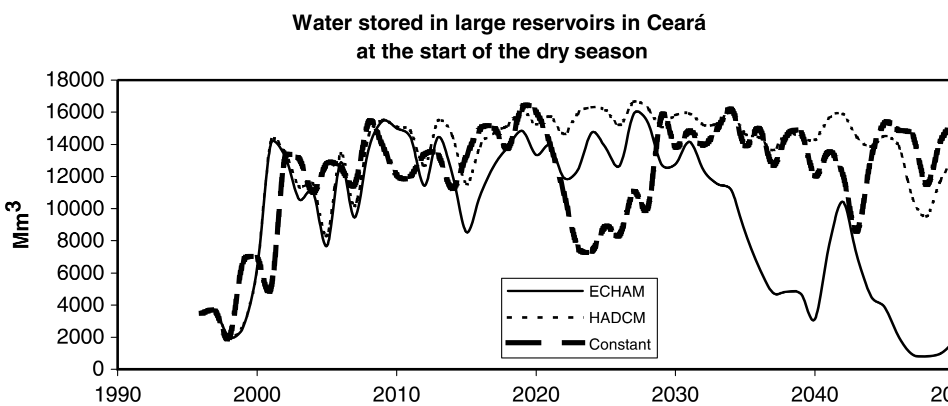

Figure 9 Simulated water storage in large reservoirs in Ceará (>50 m^3), at the beginning of the dry period for regional climate interpretations based on ECHAM, HADCM simulations and on a constant climate scenarios.

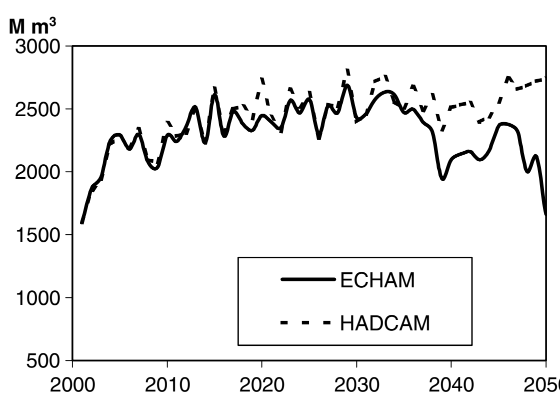

Figure 10 Water withdrawal rates (in $\times 10^6$ m^3/year) for scenarios using climate interpretations based on ECHAM and HADCM simulations.

Applying SIM on integrated scenarios (which combine assumptions of climate change, population increase, water management development, etc.), Table 2 gives an overview over the simulated trends (period 2001—2050) in rain-fed crop yield and crop production of the main crops, for the ECHAM and HADCM scenarios. It is obvious that water stress will strongly influence crop yield, due to climate-triggered limitations of water for irrigation purpose and — to a minor extent — due to changes in actual evapotranspiration. One can also see that the production of irrigated land is less affected by climatic change compared to rain-fed agriculture, which is mainly an effect of the estimated increase in irrigated areas for the coming decades.

Impacts of climatic change are most severe in the case of non-irrigated crop yields. The simulated trend in rain-fed agricultural yields shows a decrease of 12—55% in ECHAM and an increase of 4—23% in HADCM, depending on the crop. Compared to underlying trends in precipitation (—24% in ECHAM and +10% in HADCM), these trends are amplified by a factor of 0.5—2. Throughout the simulation period, positive trends in HADCM are overlapped by the natural variability, whereas the negative trends in ECHAM become clearly visible. As an example of an important crop for basic food supply, Fig. 12 shows the simulated rain-fed yield of beans as an spatial mean for both states. In a spatial perspective, coastal regions are only modestly affected, but rural regions are heavily affected (Jaeger, 2004).

In both scenarios, irrigated crop production is much less vulnerable against climate change compared to rain-fed agriculture. However, climate change may limit the actual benefit of any reclamation of land for irrigation purposes,

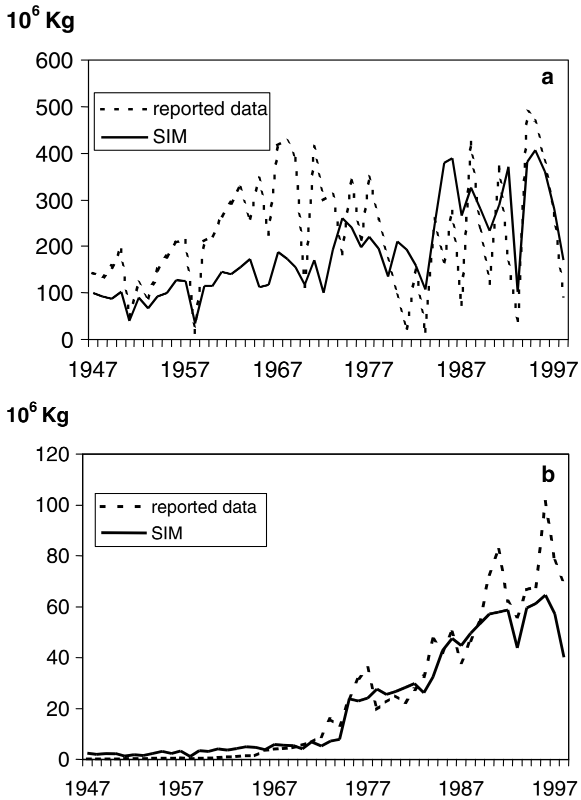

Figure 11 Simulated and reported production of tomatoes (a) and maize (b) for the period 1947 until 1998, state of Ceará.

if the available water resource does not meet the irrigation demand of the newly irrigated land. Fig. 13 shows the proportion of actual irrigated area against potential irrigated area derived from the SIM model results. In both scenarios, irrigated crop production increases until 2025, mainly due to the increase in irrigation area. However, because of the decrease in precipitation, growing water demand cannot be met after about 2025 for the ECHAM-scenario and production thus starts to decline. Irrigated crop yields are influenced by the same factors. Increase of irrigation areas leads to a decrease of yields in the ECHAM scenario, mainly because water demand is not fully met. In contrast in the HADCM scenario, due to the fulfilment of water demand, crop yield is rarely affected.

Outlook: assessment of the linkage between water availability and quality of life by integrated modelling

From the present work and literature it is apparent that integrative approaches, including integrated modelling, offer options to assess how various water-related processes of change generate impact on society. This impact can be represented by considerations of the quality of life, as is done in Fuhr et al. (2003) in projecting drought-induced migration in north-eastern Brazil. Here, it should be noted that ''quality of life'' is by no means a one-dimensional concept. A broad variety of factors can be argued to influence the quality of life, where only some of these factors are quantifiable, and only some of those influenced by water-related processes or other processes are represented in SIM. All these factors can be combined into indices in a variety of ways, for specific purposes. The well-known human development index (HDI) is used to assess differences in development between countries or regions. Fuhr et al. (2003) define an index, specifically for explaining spatial differences in migration, based on the analysis of migration motivation from an interview campaign. They found a one-dimensional index sufficient to represent the basic drivers of migration, deduced from the evidence available. In a more general theoretical framework (Krol et al., 2005), a more general concept of (objective and subjective) quality of life can be used to explain choices of adaptation strategies.

The representation of adaptive capacity is one of the main gaps in understanding global change impacts (McCarthy et al., 2001), and it is to be expected that agent-based modelling will be increasingly attempted to explain behavioural responses of stakeholders to both external driving factors as internal developments (Pahl-Wostl, 2002). For water-related problems, many water management issues should be considered to belong to this category, e.g., the degree of risk-aversion in strategies dealing with drought

Table 2 Overview over the simulated trends (percentage change over the period 2001—2050) in rain-fed and irrigated crop yield and crop production; main crops in Ceará and Piauí, for the ECHAM and HADCM scenarios, respectively (Jaeger, 2004)

Crops	Yield ECHAM		Yield HADCM		Production ECHAM		Production HADCM	
	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated
Bananas	−53	−21	17	−4	−53	−24	17	−1
Cotton	−40	−36	16	−8	−40	−15	16	23
Beans	−22	−10	13	1	−22	2	13	49
Cashew	−53	−19	11	−8	−51	19	10	78
Coconut	−21	−17	4	0	−21	13	4	72
Maize	−30	−12	14	−1	−29	26	14	69
Mango	−55	−34	16	−12	−55	−14	16	17
Manioc	−14	—	12	—	−14	—	12	—
Melons	−12	−19	11	−7	−12	4	11	35
Rice	−33	−7	12	−6	−33	−12	11	8
Tomatoes	−23	−20	23	−10	−23	47	23	20

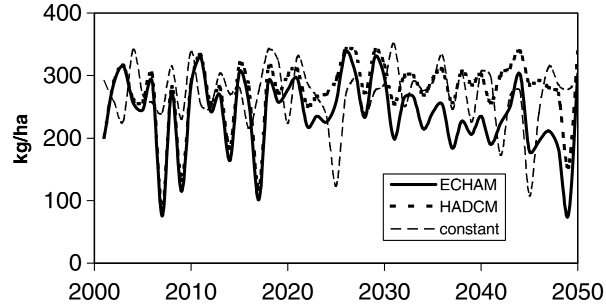

Figure 12 Mean rain-fed yield of beans using climate interpretations based on ECHAM, HADCM simulations and on a constant climate.

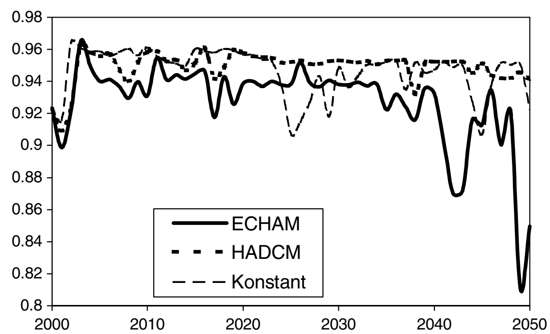

Figure 13 Fraction of the area equipped for irrigation that is actually used for irrigated production, as simulated by the integrated model SIM, based on ECHAM, HADCM simulations and on a constant climate.

or flooding, or the response to uncertain but relevant information like forecasts. The functioning of water management is an essential factor in determining the regional vulnerability to drought and climate change, and it is a great challenge to make projections of this vulnerability using agent-based modelling approaches.

The extent to which water-related behavioural patterns can be represented using modelling is very much an open question, as is the question, to what extent it is desirable. Depending on the research goal, e.g., choices between water management strategies may be an object of discussion between stakeholders and policy-makers, where integrated models represent knowledge to support arguments for specific choices rather than attempting to model how the choice is being made. A well-balanced mix of modelling and scenario analysis is called for. Moreover, doing agent-based modelling is inherently related to communicating with stakeholders, who can be very reluctant to see their actions captured in model representation.

In developing or applying agent-based modelling approaches, a realistic representation of the feedback of (water-related) actions on the environment (and society) is of crucial importance, as this feedback will in its turn drive the actions dynamically. The perceived success of actions of agents is based among other things, on the agent observations of the results of this feedback. Therefore, integrated modelling will play a central role in filling the gap of understanding adaptive capacity and vulnerability; the degree of detail required in representing the feedback needs to be studied. For NE Brazil, many of the relevant environmental indicators can be projected by SIM in an internally consistent way.

Conclusions

The integrated simulations show that this approach provides a tool to assess the dynamics of the rather complex situation in NE Brazil in a quantitative manner including the response to external forcing. It was possible to identify the most relevant cross-links within the system under consideration. Model applications focussed mainly on analysing regional sensitivity to climate change, on scoping pathways of regional development and assessing policy interventions related to dam construction and agricultural alternatives.

The climate scenario data analysed illustrate that current state-of-the-art projections still leave a very wide range of plausible climate developments in north-eastern Brazil, where both dramatic precipitation decreases and significant increases should be considered plausible on the time scale of 50 years. Model results indicate that the impacts of such changes could have effects on water availability of a magnitude that cannot be discounted on the time scale of long-term water policies. This time scale related to, e.g., the lifetime of large water infrastructure, is of at least the same order of magnitude as the time scale of climate change. As an example of the relevance of the coupling of climate, hydrology, surface water storage and water use, it was found that the efficiency of surface water storage in planned new infrastructures may become increasingly more marginal, due to various factors, including climate-driven trends in water availability, regional developments in water demand and the density of the storage network.

The model has also successfully modelled the impact of climatic and other environmental changes on crop yield and agricultural production. The simulated time series of different crops shows reasonable coherence with the reported data of crop production. The scenario analysis showed that water is a very crucial factor, and that an efficient and ecologically sound water management is a key requirement for the further development of this semi-arid region. The simulation results show that independent of the differences between climate change scenarios, rain-fed agriculture is more vulnerable to drought than irrigated farming. This is on the one hand due the fact that the crop production on the presently irrigated area is not restricted by the mean rainfall, whereas the rain-fed agriculture is directly affected by precipitation change. On the other hand irrigated production is influenced inter-twined with impacts on water availability in rivers and reservoirs and with tendencies in water use in other sectors. The vulnerability of irrigated production can significantly change in scenarios where the area equipped for irrigation is expanded beyond the area that can be supported from reliably available water resources; this could occur if a strong expansion of irrigated area were followed by a significant decrease in precipitation. This stresses the importance of an integrated modelling of climate, hydrology, and agricultural production. In regional development plans, expansion of the irrigated area serves to increase the net returns on water resources. But in a risk-averting strategy, expansion will avoid approaching the point where the reliability and sufficiency of water supply can no longer be guaranteed. In this way, strategies concerning the expansion of irrigated production are closely related to water management strategies, again underlining the need for integrated scenario analysis.

The integrated model appears to successfully integrates the state of the art of the understanding of regional processes in such kind of environmental and socio-economic conditions. Even if the system dynamics can never be fully captured by a model understanding, consistent implications of interconnections on the systems dynamics can be shown and the relevant knowledge gaps might be identified. It is important to acknowledge the influence of different spatial and temporal scales applied typically for different disciplines. Hence, the relevance of data transfer between different scales has to be investigated for each relevant process or interaction.

From a science-policy perspective, it is important to note that the integrated modelling approach has enhanced and enforced collaboration of working groups of the project and compatibility of the disciplines involved. In this way, the internal consistency of the overall project accomplishments was supported, strengthening the integrated nature of the results and the applicability in policy support.

In a multi-disciplinary group, integrated modelling is not easily acceptable as a (scientific) objective in itself, but rather serves as a methodological means to accomplish a common overall objective. Here, the individual scientific objective of the mono-disciplinary groups involved play an important role, too. A joint objective of the multi-disciplinary group may include the identification of mutual dependencies or to urge for overall considerations in policy making. The joint construction of scenarios involving both external drivers and internal processes, by the multi-disciplinary research group together with stakeholders, was found to moderate the specification of joint objectives and to bring about a more concrete motivation for furthering the integrated modelling (Döll and Krol, 2002).

The main knowledge gap identified concerns the understanding and representation of water management practices and water management options in modelling scenario alternatives. Water management does have an important role in mitigating drought impact, e.g., through the operation of large reservoirs with strategic storage capacity dedicated to possible upcoming drought conditions (as compared to storage for water supply during the normal dry season). Even more pronounced, geographical and sectoral water allocation procedures in water management play a prominent part in determining where the impacts will occur primarily. In the present integrated modelling, water management is represented in a conceptual way by a small set of simple feedback processes. A serious step forward in this field could be made in future research, including the application of agent-based modelling approaches. Scale issues will be an important topic in representing water management, as water management is very much distributed and located at various organizational levels and many of the explicitly or implicitly defined management strategies are oriented at short time scales (dry season, drought) rather than at long time scales (climate change).

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