Possible climate change impacts on water resources availability in a large semiarid catchment in Northeast Brazil

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Abstract The semiarid region of Northeast Brazil is characterized by water scarcity, vulnerability of natural resources, and pronounced climatic variability. An integrated model has been developed to simulate this complex situation with an emphasis on a large-scale representation of hydrological processes and on the sensitivity to climate change. Regional climate change scenarios were obtained by empirical downscaling with large-scale climate information from different GCMs which differ strongly in their projections for future precipitation. The results show that due to these differences, it is still impossible to give quantitative values of the water availability in a forecast sense, i.e. to assign probabilities to the simulated results. However, it becomes clear that efficient and ecologically sound water management is a key question for further development. The results show that, independent of the climate change, agriculture is more vulnerable to drought impacts in the case of rainfed compared to irrigated farming. However, the capacity of irrigation and water infrastructure to enhance resilience with respect to climatic fluctuations is significantly constrained in the case of a negative precipitation trend.

Key words climate change impacts; large scale hydrological model; Northeast Brazil; semiarid; water scarcity

INTRODUCTION

Societies in semiarid areas in developing regions are most vulnerable to variability of climate and water availability and potentially most vulnerable to changes in climate conditions. This vulnerability is caused by the strong restrictions 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 little short-term options to reduce the dependency. Reasonable conditions in the wetter years support the persistence of the population in the area; marginal or poor conditions in dryer years and arrears in development hamper significant improvements in the quality of life.

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 also the analysis of water use, agricultural economy and societal impacts. In Northeast Brazil (NEB), 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. Regional integrated modelling can supply both a conceptual framework and an application tool for integration of such different scientific disciplines.

Integrated modelling

The case study presented below focuses on the assessment of relationships between climate, water availability, agricultural production, quality of life and migration in the rural semiarid NEB at the meso-/macroscale in the context of climate change. We approached this complex system by the establishment of an integrated modelling system, with the focus on internal features which exhibit the most relevant dynamic system behaviour. Special attention is paid to cross linkages and feedback processes, which could importantly influence long-term dynamics, such as, for instance, the effects of water scarcity on the agricultural sector and *vice versa*. The integrated model further highlights the possible sub-regional locations and magnitudes of impacts, as made possible by being spatially explicit. It is beyond the scope of this article to describe in detail the methodology of regional integrated models and the various coupling aspects, but more information can be found in Bronstert *et al*. (2005).

Model summary

The Regional Integrated Model for the semiarid NEB ("Semiarid Integrated Model" SIM) has been accomplished 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 being 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 direct coupling mode enables a direct consideration of feedback effects within the integrated model.

The SIM 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 climate scenario conditions. The "common spatial resolution" for all modules (spatial resolution for information exchange between the modules) is the municipality, an administrative unit of on

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*
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
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 (hours)	PIK / UFC
Water use	Balancing of water use and management in different sectors	Data driven budgeting	FORTRAN	State/ municipality	10 years/10 days	Uni Ks / UFC
Soil conditions	Soil description and potential for crop production	Distributed soil database	External data bank	Terrain unit	---	Uni Ho / UFC / PIK
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
Agro-economy	Agro-economy	Mathematical optimiza-tion	GAMS-software	State/ municipality	10 years/10 years	FH K
Demography	Estimation of birth and mortality rates	Empirical, derived from survey data	FORTRAN	State/ municipality	10 years/1 year	UFC / PIK
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

* *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 Organisation of the UN, Rome, Italy; *UNI Ho*: University of Hohenheim, Germany; *FH K*: University of Applied Sciences Cologne, Germany.

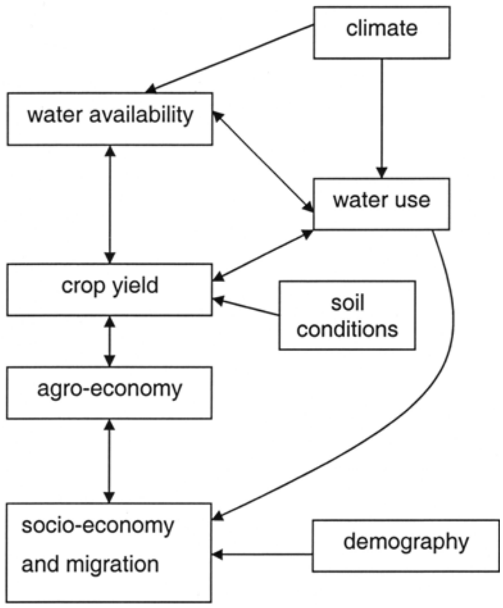

Fig. 1 Scheme of the coupled modules of the regional integrated model SIM. A double-ended arrow indicates interactions in both directions (feedback effects), a single-ended arrow indicates a one-way effect.

average about 1200 km^2 in size. The "common temporal resolution" is one day. The different scales and resolutions require 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 summarizes the most important features of *SIM* and the different modules. More comprehensive information is given by Krol *et al*. (2005b) and in the work of Jaeger (2003). Figure 1 presents a scheme of the coupled (interacting) modules of SIM.

CASE-STUDY FOR NORTH-EASTERN BRAZIL

Site description

NEB is seriously influenced by the insufficiency and unreliability of precipitation. Inside this region there is the so-called "drought polygon", a semiarid area of about 940 000 km^2 stretching over nine federal states in Brazil. The study area is largely within the drought polygon and comprises the States of Ceará and Piauí, together covering 400 000 km^2. The area has a semiarid climate, with precipitation ranging from 500 to 900 mm year^{-1}, annual temperature varies from 23 to 27°C, annual sun-shine reaches 2800 h and relative humidity averages 50%, resulting in a potential evapotranspiration exceeding 2000 mm year^{-1}. Climate shows an annual cycle with a dry period of six months; inter-annual rainfall variability is high, 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, aiming 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 for multi-year drought periods. Groundwater availability is rare and waters are often 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 and reservoir management is most vital, e.g. during the dry season, the water supply of Fortaleza, with more than two 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. Main crops are maize, cassava, beans, dry rice and cashew. Land and income distribution is very uneven, leading to a high vulnerability of small subsistence farmers. The current population is about 10 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 the south of Brazil is also an important demographic factor.

Modelling results

Climate change impacts on water availability and water use The climate downscaling started with 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 NEB. 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. Figure 2 shows the precipitation trend until 2050 for the study area of the region, resulting from the statistical downscaling. The spatial pattern of the precipitation trend reflects the boundaries of the municipalities, which is the common spatial resolution

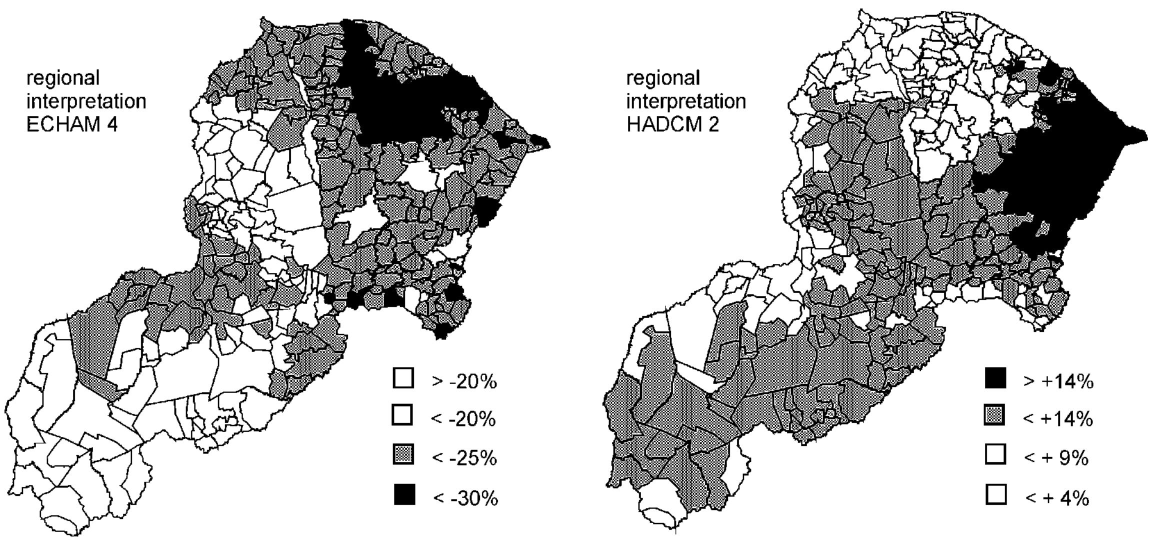

Fig. 2 Downscaling of GCM results for precipitation trends in the States of Piauí and

Ceará over the period 2001–2050, assuming continued growth of atmospheric greenhouse gas concentrations. The spatial distribution reflects the municipality boundaries.

for the integrated model (see above). Assessing the effects of climate change, simulations for one reference scenario of regional and global developments with three different regional climate scenarios (method by Werner & Gerstengarbe, 1997) were compared, referred to as the ECHAM, the HadDCM and the constant scenario, where no climate change is assumed. The most direct impact of climate change is the impact on the availability of water resources, as rainfall changes have a direct effect on the water balance, affecting runoff generation, river flow and water storage.

River runoff shows a strong reaction on the precipitation changes, as shown in Fig. 3 for the mouth of the river Jaguaribe. While runoff until approximately the year 2025 is statistically similar to the historical simulations, a strong decrease in runoff results for the second half of the entire scenario period (until 2050) using the ECHAM scenario, and a smaller, statistically insignificant increase results 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 following dryer years. The total water volume stored in large reservoirs with storage capacity $>50 \times 10^6$ m^3 at

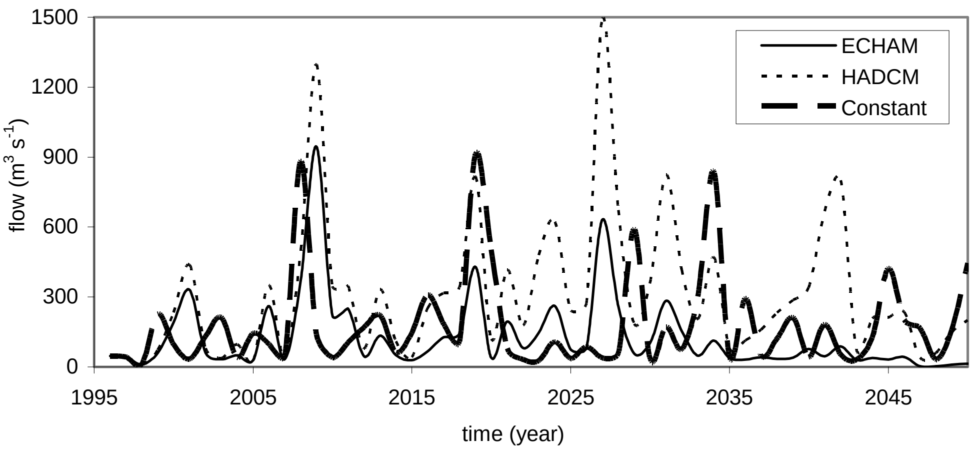

Fig. 3 Outflow of the River Jaguaribe, for the three climate scenarios, simulated with SIM.

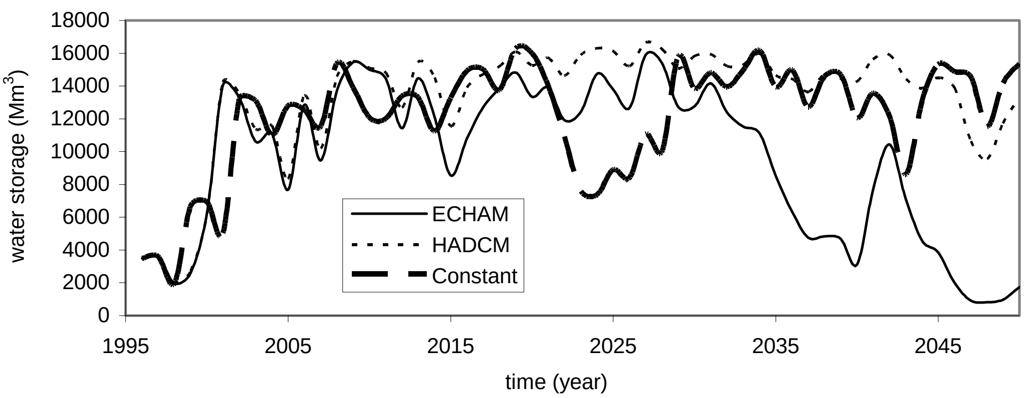

Fig. 4 Simulated water storage in large reservoirs in Ceará (>50 Mm^3), at the

beginning of the dry period for regional climate interpretations based on ECHAM, HadCM simulations and on a constant climate scenarios.

the beginning of the dry season (1 July) shows a strong increase between 1995 and 2015 (see Fig. 4). 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 × 10^6 m^3). Total storage capacity in Ceará and Piauí then reaches almost 22 000 × 10^6 m^3, of which 16 400 × 10^6 m^3 is installed in Ceará. Afterwards, 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. 4) after 2025, which should be seen in connection with 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. 5), one can see an increase from about 1500 × 10^6 m^3 $year^{-1}$ at the turn of the century to about 2500 × 10^6 m^3 $year^{-1}$ 20 years later. This is a result of an increased water demand due to an enlargement of irrigation area, a further growing population number, and an improved water infrastructure (increased connection to public water supply). The fulfilment of this increased water demand (resulting in the increase of water withdrawal) is possible through the estimated additional installation of reservoir volume, as explained before. However, after about 2030, the ECHAM scenario shows a decrease of water withdrawal rates, because the water demand cannot be fulfilled sufficiently. In other words, the efficiency of the reservoir systems is decreasing significantly, due to the reduced precipitation projected by the ECHAM climate scenario. In contrast, the HadCM scenario does not show a significant decrease in 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 1947–1998. The results were reasonable for quite a number of crops (Jaeger, 2003). In Fig. 6, only a moderately satisfactory

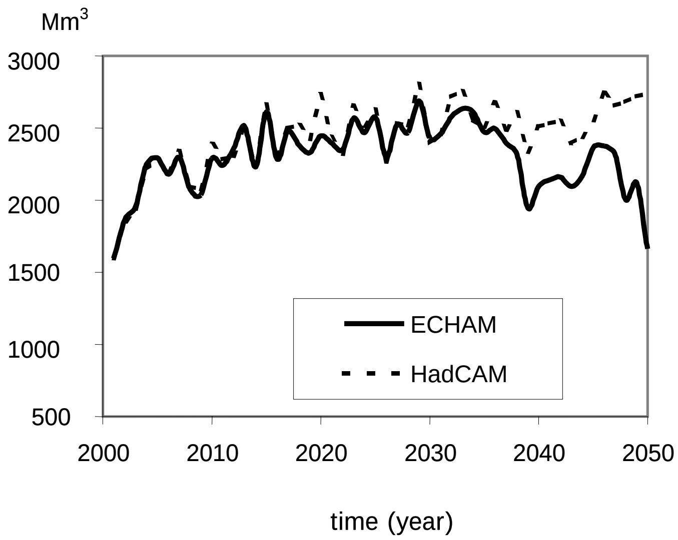

Fig. 5 Water withdrawal rates (in $\times$ 10^6 m^3 $year^{-1}$) for scenarios using climate interpretations based on ECHAM and HadCM simulations.

example is shown, i.e. the simulated and reported production of maize. In general, the trend of production increase is covered well, and also the decline of production in drought years is simulated in accordance with 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 (data from "SEPA" or "PAM", see Jaeger, 2003).

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 rainfed 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 purposes and—to a minor extent—due to changes of the actual evapotranspiration. One can also see that the production of irrigated land is less affected by climatic change compared to rainfed 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 rainfed 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.

In both scenarios, irrigated crop production is much less vulnerable against climate change compared to rainfed agriculture. However, climate change may limit the actual benefit of a potential new reclamation of land for irrigation purposes, if the available

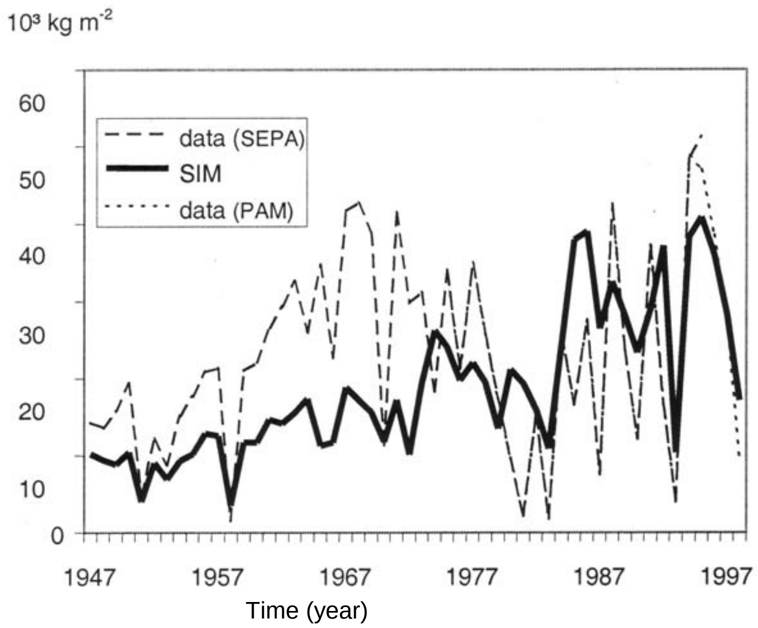

Fig. 6 Simulated and reported production of maize for the period 1947–1998, State of Ceará.

Table 2 Overview over the simulated trends (percentage change over the period 2001–2050) in rainfed and irrigated crop yield and crop production of main crops in Ceará and Piauí, for the ECHAM and HadCM scenarios, respectively (Jaeger, 2003).

Crops	Yield		Yield HadCM		Production ECHAM		Production HadCM	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	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

water resources do not satisfy the irrigation demand of the newly irrigated land (see Krol *et al*. (2005b) for more details).

Outlook: linking water and quality of life by integrated modelling

Integrated models also 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 done by Fuhr *et al*. (2003) in projecting drought-induced migration in NEB. A broad variety of factors can be argued to influence the quality of life, where only some of these factors are quantifiable, and only a part of those influenced by water-related processes. 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*., 2004a), a more general concept of (objective and subjective) quality of life can be used to explain choices of adaptation strategies.

CONCLUSIONS

The climate scenario data analysed illustrate that current state-of-the-art projections still leave a very wide range of plausible climate developments in NEB, where both dramatic precipitation decreases and significant increases should be considered possible on the time scale of 50 years. Model results indicate that the impacts of such changes have effects on water availability of a magnitude that cannot be discarded on the time scale of long-term water policies. The time scale, of, for example 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 infrastructure may be increasingly more marginal, due to diverse factors, including climate-driven trends in water availability, regional developments in water demand and the density of the storage network.

SIM has also successfully modelled the impact of climatic and other environmental changes on crop yield and agricultural production. The scenario analysis made evident 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 semiarid region. The results show that, independent of the differences between climate change scenarios, rainfed agriculture is more vulnerable to drought than irrigated farming. However, the vulnerability of irrigated production can significantly change in scenarios where the area equipped for irrigation is expanded beyond an area that can be supported from reliably available water resources. In many regional 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 levels, at which the reliability of a sufficient water availability cannot be guaranteed.

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