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Water scarcity under scenarios for global climate change and regional development in semiarid Northeastern Brazil

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Abstract: *The State of Ceará, located in semiarid Northeastern Brazil, suffers under irregularly recurring droughts that go along with water scarcity. Structural policies to control and reduce water scarcity, as water supply and demand management, should be seen as long-term planning, and thus have to consider climate change and regional development. To this end, the present research proposes a model-based global change scenario. Water stress is assessed for 184 municipalities in Ceará between 2001 and 2025. For this purpose, four global change scenarios are developed, considering both global climate change and the effects of development policies. Climatic, hydrological and water use models are applied and a proposed index computed for identification of long-term water stress. Application of the methodology in the focus area shows that, if no effective intervention measures are taken, up to almost 60% of the municipalities of the State may suffer under long-term water scarcity by 2025. On average, municipalities in the state of Ceará have a water shortage probability for the next 25 years ranging from 9%yr-1 to 20%yr-1, depending on the scenario. The 10% most stressed municipalities have a probability of over 80%yr-1 of facing water scarcity in the scenario period (25 years). Results also show that a decentralized development policy can compensate for the possible severe effects of climatic trends on future water availability over the scenario period.*

Keywords: *Global change, scenarios, water scarcity, water management, semiarid, Brazil*

Introduction

Global change and its consequences are a major challenge for water resources planners and researchers, especially in regions experiencing water conflicts. Recent publications show concern with the topic in several countries. Cohen et al. (2000) build global change scenarios for the Columbia river basin (US and Canada) for years 2000 and 2050 using global circulation (MPI, GFDL and UKMO) and hydrological models. The authors conclude that there are possible reductions in total annual flow and lower minimum flow, which leads towards lower reliability for power production, fishery and agriculture. Matondo and Msibi (2001) estimate the impact of climate change in Swaziland after analyzing global circulation models (GFDL, UKHI and GISSEK) coupled with the hydrologic model WatBall. According to the results for all global circulation models, runoff reductions are expected for wet, mean and dry conditions in 2075, which demands effective water resources management. Cluis and Laberge (2001) investigate historical hydrological behavior of 78 rivers in the Asia-Pacific region so as to estimate possible climate change effects. The research shows that two thirds of the rivers remained stationary and that changes were due mostly to anthropogenic intervention, so that no evidence supports the assumption of historical runoff changes because of global changes so far. Abu-Taleb (2000) studies the impacts of global changes in Jordan for several scenarios, which consider temperature, sea level, precipitation, evapotranspiration and runoff changes. The author emphasizes the need to consider climate change for planning reasons in arid and semiarid regions and suggests further investigation of more reliable projections of water demand and supply, as well as analysis of further scenarios.

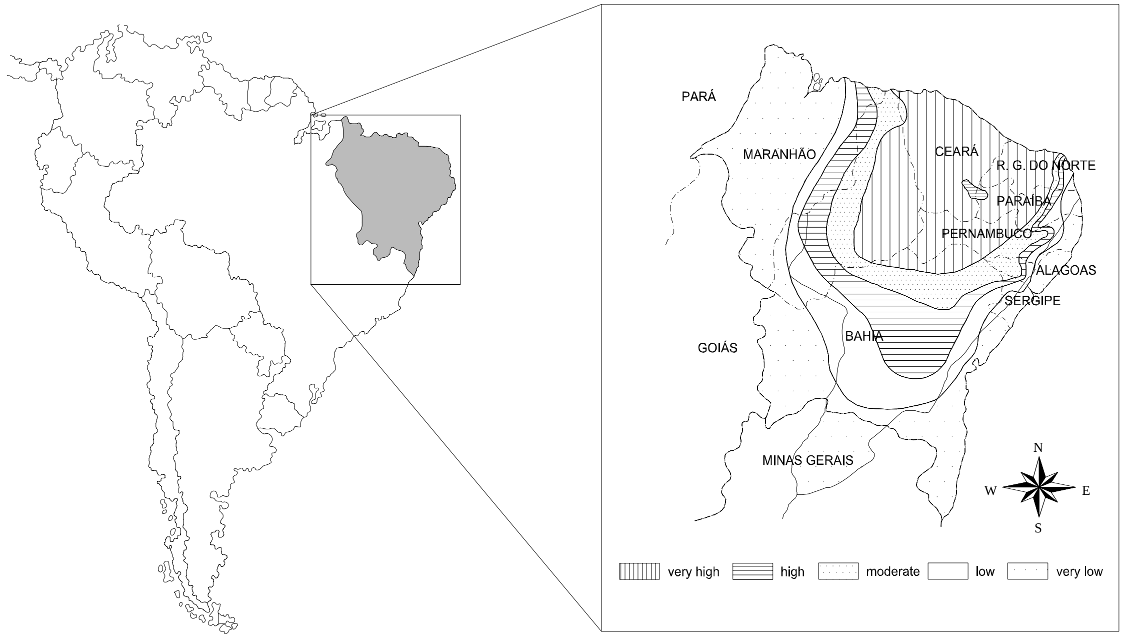


Figure 1. Localization of Brazilian semiarid region and droughts incidence frequency.
[Source: based on Araújo, 1982, p. 15]

This paper proposes a methodology for water scarcity assessment based on global change scenarios approach. The methodology, proposed within the bilateral German – Brazilian program WAVES (Water Availability and Vulnerability of Ecosystems and Society in Northeast Brazil, http://www.usf.uni-kassel.de/waves/), consists of: constructing robust reference scenarios; applying global circulation models for warming assumptions; downscaling the climate change results; applying hydrological model for water availability evaluation; applying water use model for water demand assessment; and computing water stress index in order to analyze water scarcity in the focus area.

A case study is accomplished in Ceará (148,000 km^2), located in the semiarid northeastern region of Brazil and the most vulnerable state in terms of water scarcity (Araújo, 1982). Administrative entities, the so-called municipalities (average area about 800 km^2) are used as spatial units for the integrated analysis of hydrological, agricultural and socio-economic processes. The objective of studying this particular area is to subsidize water planning institutions in the semiarid state by analyzing water scarcity in its 184 municipalities for four global change scenarios in the period 2001 – 2025. In fact, the recommendations made by Abu-Taleb (2000) to consider climate change scenarios for planning reasons in semiarid regions are directly applicable to this investigation.

The study area: semiarid Northeastern Brazil

One of the main characteristics of Northeastern Brazil, where conflict over water use is already a reality, is its vulnerability to the recurrent droughts. Inside this region there is the so-called *drought polygon*, a semiarid area of about 940,000 km2 stretching over nine federal states in Brazil (see Figure 1), where droughts occur rather frequently. Almost 93% of the area of Ceará is located inside the drought polygon. According to Araújo (1982), the semiarid region's annual temperature varies from 23oC to 27oC, annual sunshine reaches 2,800 hours and relative humidity averages 50%. Precipitation is concentrated in a rainy season of about four months (January through April) with extreme interannual variability and an average of about 750 mm.yr-1, whereas the potential evaporation rate is 2,000 mm.yr-1. The geological basis is mostly crystalline bedrock. Due to these characteristics, all important rivers in the region are intermittent, observed runoff ratios vary between 7% and 12% and, according to Campos et al. (1997), the coefficient of variation of annual river discharge ranges from 1.0 to 1.4. Barbosa (2000) states that, although 80% of the state of Ceará is on crystalline bedrock, only 29.5% of the groundwater is provided from its wells, whereas 70.5% of groundwater yield comes from wells in sedimentary environment.

Although the region has suffered from water scarcity for centuries, water resources planning and management only starts in 1909, when the National Department of Works against Droughts (DNOCS) is created. The Department's early policy consists mainly of building strategic infrastructure, most specifically dams, to care for water supply in the dry seasons. A new phase in water resources management in Brazilian semiarid region begins in 1992, when the state of Ceará approves its new Water Law. This Law establishes a water resources state secretariat and the water resources management system, as well as develops the state water management plan and water basin committees. In 1997 the new Brazilian Federal Water Law 9,433 is approved by the Congress, and it establishes the principles, institutional arrangement and instruments of water resources management in the country. In the new context, therefore, the most important objective of a water resources policy is not exclusively to build works anymore, rather to manage the existing resources, concerning both quantitative and qualitative aspects, in a decentralized democratic way.

The general action guideline of Law 9,433 is integrated management and the instruments enabling the implementation are water resources plans, classification of bodies of water into classes according to main uses, the concession of rights to its use, billing for water use and the system of information on water resources. In relation to climate specifically, the article number 15 of the Law 9,433 briefly outlines that the concession of water resources use rights could be suspended in the circumstances of urgent needs due to adverse climate conditions. This gap is one justification to propose methodologies conditioned to global climate change scenarios that could impact the water scarcity in Northeast Brazil as presented in the following sections. Campos and Studart (2000) present a more thorough description on administration of water in Brazil.

Methodology

Methodologically, the research consisted of a three-step approach. First, scenarios are constructed, covering both the consideration of different pathways of regional development and the regional interpretation of global climate change scenarios. Secondly, models are selected as simulation instruments, focusing on regional water availability, and including hydrology, water balances for water infrastructure, and water demand for the various water use sectors. Thirdly, an index for water stress index is proposed, representing imbalances between water demand and water supply.

Scenarios are plausible and consistent images of alternative futures and show different possibilities of how the future might look like. They are not predictions of the future and cannot be qualified by a probability. In general, scenarios are developed to support sustainability-oriented decision-making. So-called "reference scenarios" describe the future without any specific policy intervention. They serve as the baselines to assess the impact of selected policies or interventions on the future state of the system ("intervention scenarios"). The robustness of a certain policy is tested by assessing its impact in different possible future situations, i.e. using reference scenarios.

In the framework of the WAVES program, land use and water related scenarios for the Brazilian semiarid region are derived. Here, the focus is on the development in the state of Ceará only. These scenarios have the potential to support strategic planning by the water and agriculture authorities in Brazil. Two qualitative-quantitative reference scenarios up to the year 2025 are generated by (1) writing storylines (or narratives) of the situation in 2025, (2) quantifying the driving forces and (3) applying simulation models (for a description of the methodology, see Döll, Hauschild and Fuhr, 2001; and Döll, Mendiondo and Alcamo, 2001). This approach has been adapted from the one that the Intergovernmental Panel on Climate Change used to derive global scenarios of greenhouse gas emissions (Nakicenovic and Swart 2000).

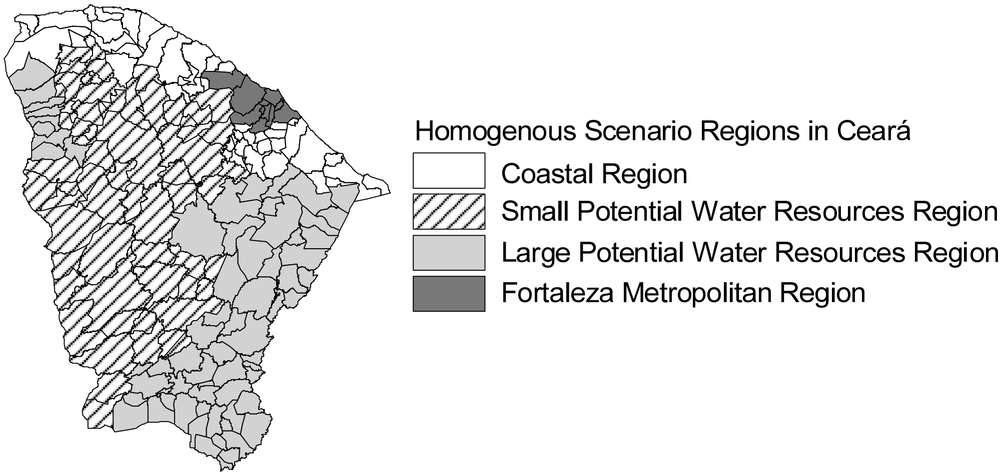


Figure 2. The four scenario regions in Ceará: the smallest spatial units for developing storylines and quantitative assumptions about the development of driving forces. The borders of the municipalities are also shown

For scenario building, three policy workshops in the state of Ceará were held. Members of the state water resources secretariat (SRH), the water resources management company COGERH and of the state planning secretariat SEPLAN joined the German and Brazilian research teams for thorough discussions on scenarios assumptions. Ceará is subdivided into four scenario regions (Figure 2), which are assumed to differ with respect to the future development of the driving forces. Criteria for the configuration of the scenario regions are: similar agro-economic conditions, similar natural conditions (precipitation, position within river basin) and administrative boundaries. For each of the two reference scenarios, a storyline of the situation in every scenario regions in the year 2025 is written, which covers important aspects for rural development and water scarcity problem. The detailed storylines for each of the scenario regions can be found at http://www.usf.uni-kassel.de/waves/szenarien/ reference_scenarios.html. Table 1 provides a concise characterization of reference scenarios A (RS A) and B (RS B). Each reference scenario continues certain existing trends. RS A ("Coastal Boom and Cash Crops") carries on the current trend of increased cash crop production for the Brazilian and external markets; the efforts to promote tourism mainly along the coast; and the rapid economic development in the growing metropolitan area of Fortaleza, the capital of Ceará. RS B ("Decentralization and Integrated Rural Development") takes up the strengthening of regional centers via the establishment of universities and health infrastructure, for example, which has recently begun in the study area.

Table 1. Characteristics of the two reference scenarios

Reference scenario A (RS A) "Coastal Boom and Cash Crops"	Reference scenario B (RS B) "Decentralization and Integrated Rural Development"
• strong economic development (commerce, industry, tourism) in the coastal region • Fortaleza grows very fast • where water is available for irrigation, the production of cash crops by large companies dominates over subsistence farming • Brazilian and global markets for agricultural products dominate • centralized governance prevails	• regional centers prosper (attractive medium-sized towns with improved infrastructure) • regional centers have become the markets for local and regional agricultural products • small-scale agro-industry has extended • local initiatives prevail • Ceará shows autonomy in relation to the Brazilian South • international agencies support sustainable agriculture in crisis-prone regions

The simulation models used to compute the scenarios require information on the quantitative development of their driving forces. The driving forces of water use are shown in Figure 3. The quantification of the driving forces, for each scenario region, is mainly done by an interdisciplinary team, taking into account historical developments and existing global- and country-scale scenarios. Table 2 gives an overview of the development of the main driving forces in RS A and RS B. In the section on water use assessment, some of the driving forces of water use are discussed in more detail.

Table 2. Development of main driving forces in Ceará

Variable	1996/98	2025 Reference Scenario A	2025 Reference Scenario B
population [million]	6.81	8.86[a]	8.63[a]
GDP and industrial GDP	---	+2.7%/year[b]	+2.2%/year[c]
irrigated area [ha]	43,024	116,480	83,175
average precipitation [mm.yr^{-1}]	896 (1969-1998)	859 (2011-40, ECHAM4) 1027 (2011-40, HadCM2)	859 (2011-40, ECHAM4) 1027 (2011-40, HadCM2)

[a] distribution of population among scenario regions changes between 1996/98 and 2025 due to migration

[b] annual increase between 1996/98 and 2025, except in scenario region "Small potential water resources", with +2.5% per year

[c] annual increase between 1996/98 and 2025, except in scenario region "Large potential water resources", with +2.4% per year

Scenarios: regional interpretation of global climate change projections

Complex physically-based climate models (General Circulation Models, GCMs) show an increasing ability to simulate present-day climate as well as historical trends over the last centuries at the global to continental scale. They project significant global climate warming (1.4 to 5.8 degrees Celsius for the period 1990-2100) to take place in the current century, under the assumption of a continuous increase in atmospheric greenhouse gas concentrations, as would be caused by a continued intensive use of fossil fuels.

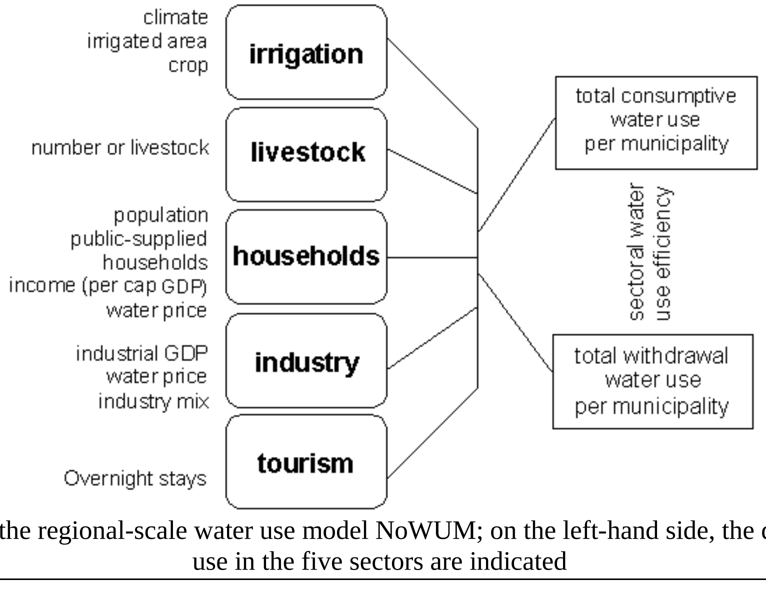


Figure 3. Overview of the regional-scale water use model NoWUM; on the left-hand side, the driving forces of water use in the five sectors are indicated

The skill of GCMs to represent climate at the regional scale of Northeast Brazil is modest. Of seven climate GCMs whose climate change experiments are made available for climate impact assessments by the International Panel on Climate Change (IPCC), only three (see Figure 4) are able to represent in their simulations the semiaridity and strong seasonal cycle, that are characteristic for this region (New et al., 1999). One of these three models has a serious flaw in representing global precipitation, hampering serious interpretation of its results on changes in precipitation. This lack in skill may be caused by the relatively coarse resolution of GCMs, which range from 300 to 900 km so that only 2 to 12 grid cells cover all of Northeastern Brazil. An alternative explanation may be the imperfect representation of regionally important physical processes. In either case, the lack in skill seriously affects the applicability of the model results for impact assessments. As Figure 4 shows one GCM represents Northeast Brazil as hyper-arid, while in three others, climate does not show a marked seasonality (the driest months are too wet). Finally another GCM gives a reasonable representation of regional climate but underestimates precipitation in the driest months by 50%.

The recommended approach by the IPCC to critically review regional performance in selecting model results to be used in assessments is often ignored, for instance in a specific assessment of plausible climate change in Brazil, including a focus on Northeast (Hulme and Sheard, 1999).

The two models which yield a reasonable regional interpretation of their results for Northeast Brazil are ECHAM4 climate model of the Max-Plank-Institute, Hamburg, Germany (Roeckner et al., 1996) and HadCM2 model of the Hadley Centre for Climate Prediction and Research, Bracknell, Great Britain (Johns et al., 1997). Following the recommendations of IPCC-TGCIA, results from these models are selected for analysis.

Assessment of climate change impacts on surface hydrology and agricultural production for the state of Ceará, for example, requires a resolution of climate data at the scale of sub-regions with marked differences in hydro-meteorological or agro-meteorological conditions, the scale of 10-100 km. This seriously hampers the direct grid cell-based regional interpretation of GCM-simulated climate change, whose resolution is much coarser. Indirect methods, using either Local Area Models (LAM) of climate or statistical downscaling of large-scale features to derive regional climate may overcome this problem. The latter method is applied in the WAVES program for the generation of regional climate scenarios (Werner and Gerstengarbe, 1997), as no LAMs are presently operational with sufficient skill for climate studies in the study region (Böhm et al., 2002).

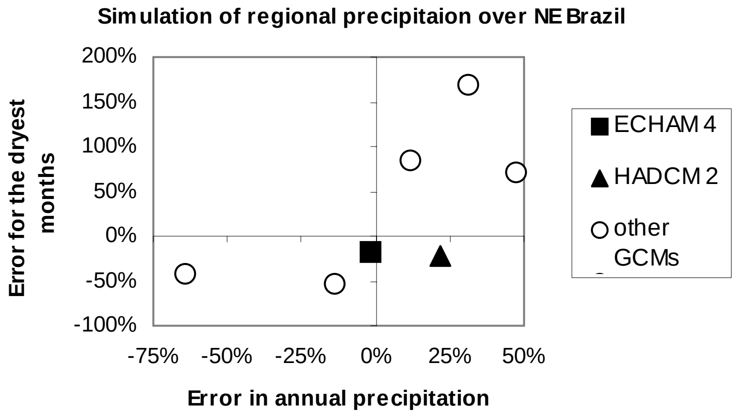


Figure 4. Simulation of regional precipitation over semiarid Northeast Brazil in the period 1961 to 1990 by seven GCMs compared to the observational database (New et al., 1999)

The downscaling method adopted combines observed daily historical climate data at the level of climate stations with long-term climate trends from GCM projections. Here the tendency in annual precipitation at the large scale is taken as the most relevant criteria. Simultaneously observed daily data on precipitation and temperature are used to interpret these tendencies into projections of the variables at the station level. Other meteorological variables such as relative humidity and short-wave radiation are added using regression relations derived from the available daily time series of meteorological variables. This results in climate scenarios at the level of the climate stations. Interpolation routines are used to transform these scenarios into a climate scenario defined at the level of municipalities. For each climate scenario, statistical downscaling results in a realization of the (inherently stochastic) precipitation time series until 2025. Figure 5 shows the precipitation trend over the state of Ceará for period between 2001 and 2050. Results for the two selected GCMs show well-defined spatial patterns of precipitation trends, arising from station-specific correlations between local and large-scale precipitation amounts. The difference between the spatial patterns indicates that this correlation is different for anomalous dry years and for anomalous wet years.

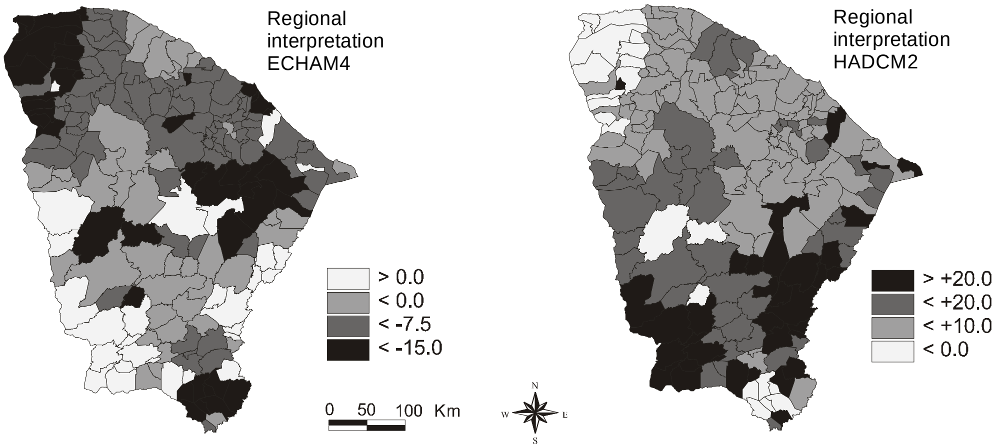


Figure 5. Regional interpretations of GCM results for precipitation trends (%) in Ceará over the period 2001 to 2050, assuming continued growth of atmospheric greenhouse gas concentrations

As a result of combination of two reference scenarios (A and B) and two climate scenarios (ECHAM4 and HadCM2), four composed scenarios are built, i.e., A-ECHAM4, A-HadCM2, B-ECHAM4and B-HadCM2.

Simulation: Hydrological Modeling of Water Availability

For quantification of surface water availability in the study area, the large-scale water balance model WASA (Model of Water Availability in Semiarid environments) has been developed. It is a deterministic model, working with a daily time step and in a spatially distributed mode. The largest spatial units in the model are sub-basins or municipalities. In order to capture the influence of spatially variable land-surface properties on soil moisture patterns and runoff generation, sub-basins or municipalities are subdivided into smaller modeling units. In this respect, the focus in WASA involves taking into account lateral surface and subsurface flow processes at the hillslope scale, which is usually not perceived in large-scale hydrological models. Thus, modeling units are defined as terrain patches with similar characteristics referring to lateral flow processes (Güntner et al., 1999). For including sub-scale variability of water fluxes due to variable surface landform, soil and vegetation characteristics, a hierarchical disaggregation scheme of the landscape based on the SOTER concept - Soil and Terrain Digital Database (FAO, 1993) - is applied. At the smallest level of this hierarchy (i.e., at the scale of representative soil profiles), vertical hydrological processes are represented by conceptual, physically-based approaches. For example, infiltration is based on the Green-Ampt approach (Green and Ampt, 1911), evapotranspiration is described by a modified Penman-Monteith approach, particularly taking into account soil evaporation (Shuttleworth and Wallace, 1985) and the soil water balance is calculated by a multi-layer storage approach.

Simulation of water use

Present and future water use in all 184 municipalities of Ceará is simulated by NoWUM (Nordeste Water Use Model), a regional-scale water use model that has been designed for assessing the impact of global change and of management measures on water use. Döll and Hauschild (2001a) describe the model and present estimates of water use in the states of Piauí and Ceará from 1996 to 1998, with special reference to the impact of climate variability on irrigation water use. Model-based scenarios of water use in both states in 2025 are presented in Döll and Hauschild (2002b).

NoWUM computes withdrawal and consumptive water use in each of the 332 municipalities of Piauí and Ceará. Withdrawal water use is the quantity of water taken from its natural location, while consumptive water use is the quantity consumed by the system during its process. The ratio between consumptive and withdrawal water use is called water use efficiency. NoWUM distinguishes five water use sectors: irrigation, livestock, household, industry and tourism (Figure 3). Each sectoral water use is computed as a function of a water use intensity (e.g. per-capita domestic water use of the self-supplied population) and a driving force of water use (e.g. self-supplied 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 at least to a certain degree with seasonal and interannual climate variability and climate change, only the climate dependence of irrigation water use is simulated by the model.

A time series of withdrawal water use between 2001 and 2025 is computed to enable the computation of water stress on an annual basis. In the case of irrigation water use sector, the irrigated areas per crop are linearly interpolated between the values for the period from 1996 to 1998 and the scenario values for 2025, while the climate time series of 2001 - 2025 is applied. Livestock water use is linearly interpolated between the 1996/98 and 2025 values, while in the case of domestic and industrial water use, the changes are nonlinear due to the effect of price and income elasticity (Hauschild and Döll, 2000).

Water Stress Index

One of the main tasks of this research is to propose a water stress index to help decision makers plan water resources infrastructure intervention in semiarid Northeastern Brazil. The literature provides several index concepts for planning reasons. Merret (1999) proposes a “hydrosocial cycle” approach, and suggests that water balance indices compare total net supply and total water use. The “supply” term, for example, should consider not only classical supply sources, such as surface and groundwater, but also rainwater collection, reuse of surface, groundwater and wastewater, desalinated water and import (or export) of water to (or from) other basins. Ali (1999) studies water scarcity in southern Africa and relies on ratio of total demand to total sustainable supply to draw the conclusions. Bolaane (2000) analyzes water resources planning for scarce water region in Botswana, which suffers under recurrent droughts, as does northeastern Brazil. The author also uses water balance indicators which consider total water supply (although not as completely as suggested by Merret, 1999). Salameh (2000) redefines the “water poverty index” for regions under arid and semiarid conditions, which includes surface and groundwater resources, water use and climate effects.

The water stress index hereafter proposed, which has a strong analogy to the index proposed by Ali (1999), can be defined as the ratio between global demand and global *reliable* supply for each municipality, as in equation (1). The reason for choosing this format is that it is, at the same time, thorough and simple, for it represents directly the balance between the demand and the offer of water.

$$\mathrm{ig(G)} = \frac{\text{Global consumptive water demand}}{\text{Global reliable water supply (G)}} = \frac{Q_D}{Q_s(G)} \tag{1}$$

ig = global stress index; G = water supply annual reliability. For planning reasons, reliability of 90% is used in Brazilian semiarid region. Global consumptive water demand (Q_D) considers water withdrawal (Q_W), consumptive use (Q_C) and water losses in the demand system (dQ_1). Global reliable water supply (Q_S) considers surface (Q_{SW}) and groundwater (Q_{SUB}) yield as well as water losses in the supply system (dQ_2). Figure 6 shows the concept of the terms involved in the index computation.

$$Q_D = Q_C + dQ_1 \tag{2}$$

$$Q_S(G) = Q_{SW}(G) + Q_{SUB}(G) - dQ_2 \tag{3}$$

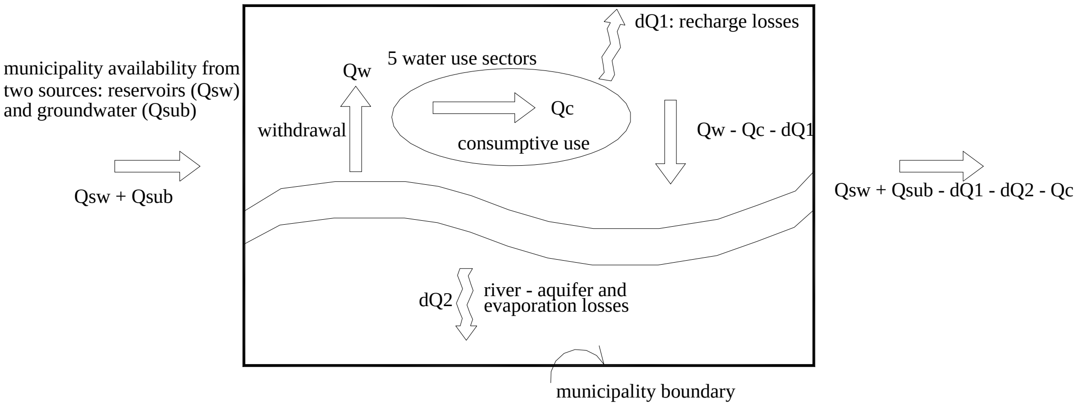


Figure 6. Concept of water scarcity index ig_{90}

The methodology for computing each term is explained as follows.

Global consumptive water demand. As previously mentioned, water withdrawal (Qw) and consumptive use (Qc) for five water use sectors (household, livestock, irrigation, industry and tourism) are calculated for every municipality for the period of 2001 – 2025 by means of the model NoWUM. The water losses in the demand system (dQ1, see Figure 6) occur in the return discharge, after withdrawal and consumptive use. Its main causes are evaporation and infiltration into the fissures of the crystalline bedrock, where interaction with the river rarely occurs. For practical purposes, such losses are assumed to be proportional to the return discharge, i.e.,

$$dQ_1 = X_1 \cdot (Q_W - Q_C) \tag{4}$$

The demand loss factor X_1 is estimated based on Rêgo (2001), and ranges from 0.3 to 0.9 depending on municipality size, geological conditions, climate and possibility of recharge reuse. For example, municipalities on the coast have less opportunity to use their recharge than do upstream municipalities.

Global reliable water supply. The global reliable water supply (QS) indicates water availability in each municipality. In the Brazilian semiarid environment, there are basically two sources of water: the reservoir yield, which supplies 91% of the water demand in Ceará, and, to a lower degree, the groundwater yield, which supplies the remaining 9% in the state (Barbosa, 2000). Direct water pumping from the river is not possible with any reasonable reliability in the study area, since all important rivers are intermittent in the state. The reservoir yield reliability can be calculated by means of stochastic hydrological analysis using Monte Carlo experimental simulation method (Campos, 1996). In order to compute long-term reservoir yield with 90% annual reliability (Q90) in the first simulation year, present-day information is collected. The individual yield Q90 of the 50 largest dams (with a storage capacity greater than 30 million m3) and of 528 smaller dams (with a volume between 1 and 30 million m3) in the state is calculated. The dams are then classified into two categories, either municipal or regional. The total yield Q90 of the municipal dams is allocated to the municipality where they are located, and the yield of regional dams is distributed among the municipalities supplied by the reservoir, in proportion to the respective global demand of each municipality. For the following years until 2025, it is assumed that the rate between reservoir availability Q90 and annual runoff for each municipality remains constant (= Q90/QRUNOFF = constant). For each climate scenario (ECHAM4 and HadCM2), each municipality and each year (t), surface runoff is calculated by the model WASA and the yield computed by equation (5). In this investigation, no intervention scenario is proposed, so that analysis of water scarcity vulnerability consider only present-day infrastructure.

$$Q_{90}(t) = \eta \cdot Q_{RUNOFF}(t) \tag{5}$$

Present-day groundwater yield Q_{SUB} (as obtained by Barbosa (2000) after working out data from 14,000 wells in all municipalities in the state) it is assumed constant for the simulation period, i.e., from 2001 to 2025.

Discharge losses in the supply system (dQ2, mainly river losses) are assumed to be proportional to water supply (Q90 +QSUB), see equation (6). The supply loss factor (X2) can be calculated based on Rêgo (2001), whose research monitored river losses in the Jaguaribe basin, in Ceará. Results showed the average ratio between losses and river discharge to be 0.6%.km-1, as follows: 0.32%.km-1 on crystalline and 1.76%.km-1 on sedimentary areas. Discharge losses dQ2 for the municipalities monitored by Rêgo (2001) represent, on average, 15% of river and groundwater yield in the annual scale $(\overline{X}_2 = 0.15)$.

$$dQ_2 = X_2 \cdot (Q_{90} + Q_{SUB}) \qquad (6)$$

Stress computation. Specific water stress index ig for 90% annual reliability (ig90) can be computed after substituting equations (2) through (6) into equation (1), which leads to

$$ig_{90} = \frac{X_1 \cdot Qw + (1 - X_1) \cdot Qc}{(1 - X_2) \cdot (Q_{90} + Q_{SUB})} \qquad (7)$$

It is assumed that a municipality is considered to be under stress in a certain year when the index ig90 is higher than the complement of a tolerance (reserve) rate *f*. In this research *f* is allowed to be 10%, so the municipality is under stress whenever ig90 > 0.9. The working hypothesis is that all municipalities under water stress in more than one third of the following years in the scenario period (until 2025) need intervention.

Results and discussion of water scarcity analysis

The main result obtained by application of the above-mentioned concepts is an assessment of long-term water scarcity in each of the 184 municipalities of Ceará for four scenarios up to 2025, based on annual estimates.

In terms of climate change, for an annual increase of greenhouse gases by 1% per year as of 1990, projections of precipitation changes over Northeast Brazil (2070-2099 compared to 1961-1990) are –50% for ECHAM4 and +21% for HadCM2. Therefore, while the ECHAM4 model results in a decreasing precipitation trend, the HadCM2 model shows an increasing trend. Figure 7 shows historical precipitation in Ceará (1921 – 1998) as well as precipitation scenarios until 2050 based on ECHAM4 and HadCM2 models.

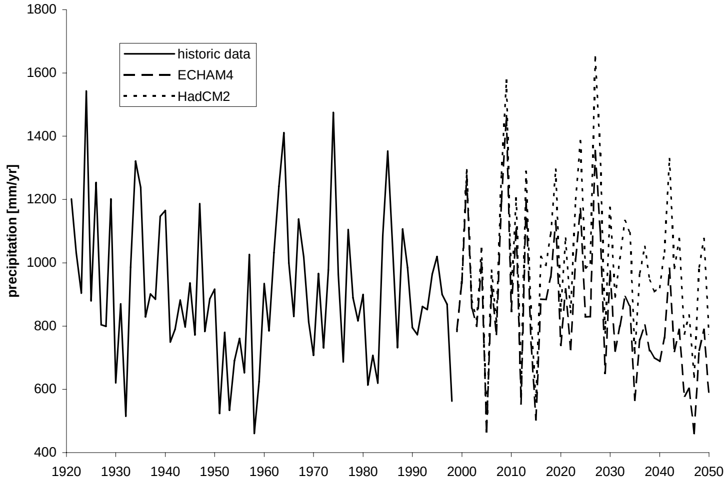


Figure 7. Observed precipitation in Ceará 1921-1998 as well as the two applied precipitation scenarios until 2025 based on ECHAM4 and HadCM2 climate scenarios

Hydrological model deviations in mean annual discharge are on average ±20 % for a set of about 20 gauging stations in Ceará. They tend to be lower for larger catchment areas as uncertainties in parameters and related deviations in discharge may balance out to some extent when aggregating into larger catchment areas. Figure 8 gives an example for the validation of WASA for the most downstream gauging station in the Rio Jaguaribe basin, Ceará, which is the largest and most important basin for water resources of this state. The model satisfactorily represents the inter- and intra-annual runoff variability in most years. Deviations from observed runoff may be mainly attributed to uncertainty of rainfall input and limited information on storage volumes and operating rules of the reservoirs. The slight systematic overestimation of simulated runoff in the dry season can be attributed to transmission losses in the river network by evaporation and water use.

Table 3. Impact of the ECHAM4- and HADCM2-based climate scenarios on components of the hydrological cycle in Ceará (annual values), according to simulations with WASA for the period 2001-2025; Δ denotes changes.

	ECHAM4			HADCM2		
Variable	mean (mm)	Δ (mm)	Δ (%)	mean (mm)	Δ (mm)	Δ (%)
Precipitation	943	-85	-8.6	1059	+108	+10.8
Potential evaporation	2082	-50	-2.4	2066	-50	-2.4
Actual evapotranspiration	700	-38	-5.2	735	+18	+3.0
Groundwater recharge	76	-6	-8.4	96	+28	+34.2
Runoff	163	-15	-14.0	223	+75	+40.1

Applying the climate scenarios and keeping land use and vegetation parameters unchanged, the hydrological simulations result in a trend in runoff of -14% and +40 % for the ECHAM4 and HadCM2 scenarios, respectively, for the state of Ceará can be expected for the period 2001-2025 according to simulations results with WASA (Table 3). On a percentage basis, the change in annual mean runoff is even more pronounced than the expected change in precipitation. The expected changes of other climate elements like temperature and radiation are small, causing only slight changes in the simulated potential evaporation. However, due to the lower availability of soil moisture by decreasing rainfall, actual evapotranspiration is expected to decrease in the case of the ECHAM4 scenario. In the HadCM2 scenario, actual evaporation tends to increase due to higher soil moisture values, however, this increase is dampened by a slight decrease in potential evaporation.

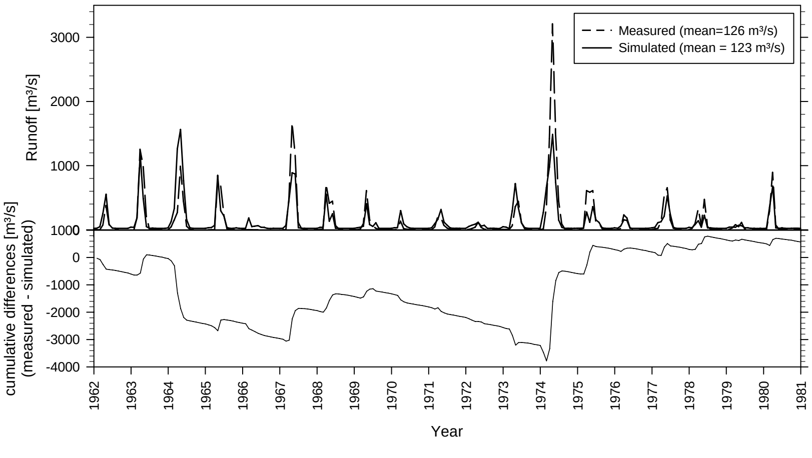


Figure 8. Runoff at station Peixe Gordo (Jaguaribe river, Ceará, Brazil); catchment area: 47500 km²; monthly values, measured and simulated with WASA

Results of simulations of water use are presented in Table 4, listing sectoral water withdrawals in the year 2025 in comparison to the situation in 1996/98. The withdrawals in the four scenario regions of Ceará are shown both for RS A and RS B. Irrigation withdrawals are computed using the climatic time series from 1969 to 1998 in order to represent the 1996/98 values. With climate change according to ECHAM4, which simulates a decrease of precipitation, irrigation water use is computed to be 4% higher in the case of both reference scenarios, while it is 3% less if climate change according to HadCM2 is assumed to occur. Thus, at least until 2025, climate change according to both climate change scenarios is negligible compared to the strong effect of the extension of irrigated areas, which leads to an increase of irrigation water withdrawals of 120% in the case of RS A and 62% in the case of RS B. Besides, the impact of climate change is much smaller than the impact of climate variability under the current climatic conditions (Döll and Hauschild, 2002a).

Table 4. Sectoral water withdrawals in the 4 scenario regions of Ceará in 2025 for both reference scenarios as compared to withdrawals in 1996/98. The impact of climate change is neglected.

Scenario region		Withdrawals [10^6 m^3/yr]					
		Irrigation[a]	Livestock	Domestic	Industry	Tourism	Total
Metropolitan area of Fortaleza	1996/98	8.0	2.6	109.6	32.0	6.7	158.9
	2025 RS A	20.3	4.2	156.0	40.5	33.7	254.7
	2025 RS B	20.3	3.6	123.4	30.4	20.1	197.8
Coastal region	1996/98	155.9	11.0	27.1	6.7	4.4	204.9
	2025 RS A	309.0	18.6	59.0	9.0	22.4	418.0
	2025 RS B	189.9	14.2	37.7	6.0	14.9	262.7
Region with large potential water resources	1996/98	242.9	33.0	56.1	5.5	2.7	340.2
	2025 RS A	566.9	33.7	56.6	4.5	7.3	669.0
	2025 RS B	413.0	40.0	64.4	4.9	7.3	529.6
Region with small potential water resources	1996/98	40.3	34.7	32.8	2.1	0.5	110.5
	2025 RS A	86.8	25.2	25.3	1.2	1.2	139.5
	2025 RS B	103.8	36.1	34.9	1.5	1.2	177.5
Ceará	1996/98	**447.1**	**81.3**	**225.6**	**46.3**	**14.3**	**814.6**
	2025 RS A	**983.0**	**81.7**	**296.9**	**55.2**	**64.6**	**1481.4**
	2025 RS B	**727.0**	**93.9**	**260.4**	**42.8**	**43.5**	**1167.6**

[a] irrigation withdrawals for 1996/98 computed with climate time series 1969-98, for 2025 with climate time series 2011-2040, without climate change.

Total withdrawal water use in 2025 is 82% higher than in 96/98 for RS A, and 43% higher for RS B. In both scenarios, the irrigation sector accounts for 80% of the change in total water withdrawal; irrigation withdrawal as a ratio of total withdrawal increases from 55% in 96/98 to 66% (RS A) and 62% (RS B) in 2025. Consumptive water use in Ceará is 407 million $m^3.yr^{-1}$ in 1996/98, increasing by 119% (RS A) and 73% (RS B) up to 2025. It grows more rapidly than withdrawal water use because the irrigation sector, where consumption is a larger fraction of withdrawal than in the domestic, industrial and tourism sectors, becomes more important, and because it is assumed that irrigation water use efficiency improves from 0.6 today to 0.7 in 2025. The strong increases in irrigation water use mainly reflect the assumed development of irrigated areas (Table 2), while the impact of changed cropping pattern is only locally important. For RS A, it is assumed that the irrigation projects that are planned for Ceará according to Lopes Neto (1998) will be implemented in 2025, and that private irrigation will increase at a rate of $2.0\%.yr^{-1}$ until 2025. For RS B, with its decentralized development based on local initiative, only one fourth of the irrigation project area is assumed to be implemented and private irrigation increases by $2.9\%.yr^{-1}$.

In the second most important sector, the domestic sector, water use rises by 31% in the case of RS A and by 15% in the case of RS B. These values result from a combination of decreased per-capita water use in the households connected to public water supply, an increased fraction of public-supplied households and population change. Per-capita water use in public-supplied households decreases from an average 137 L.d^{-1} to 114 L.d^{-1} (RS A) and to 106 L.d^{-1} (RS B), assuming that water use increases with increasing per-capita Gross Domestic Product (GDP) and decreases with increasing water price (assumed price increase 6%.yr^{-1}, which is below the observed price increase during 1989-98).

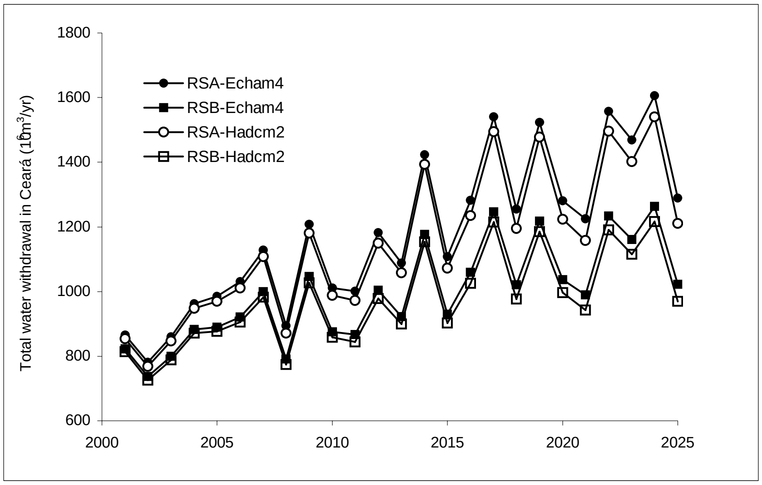


Figure 9. Total water withdrawal in Ceará between 2001 and 2025 as computed by the regional water use model NoWUM for the two reference scenarios RS A and RS B, using climate scenarios based on the climate models ECHAM4 and HadCM2

Of the remaining three water use sectors, tourism shows the most intensive change as overnight stays are assumed to increase significantly in both reference scenarios. The assumed price increase for water leads to lower industrial water withdrawals in 2025 than today in the case of RS B. In the case of RS A (the "Coastal Boom and Cash Crops" scenario), the regions with small potential water resources will have significantly fewer inhabitants than today, due to the migration to the coastal zone. Besides, irrigation increases less than in the case of RS B because there are not many public irrigation projects planned for this region and because private irrigation is assumed to become more extensive there for RS B than for RS A. This region is therefore the only one where total water use is higher in the case of RS B (the "Decentralization and Integrated Rural Development" scenario), than in the case of RS A.

According to one GCM run of ECHAM4 and HadCM2, the temporal development of the total water withdrawal in Ceará between 2001 and 2025 is shown in Figure 9. The differences between the two reference scenarios are much more important than the differences due to the two climate scenarios. If climate changes were neglected, the resulting withdrawals would be between those based on the two climate change scenarios. Thus, the impact of climate change on total water withdrawals appears to be insignificant for the next 25 years in the focus area. The increasing trends are overlain by a strong interannual variability of withdrawals which is due to the impact of interannual climate variability on irrigation water requirements. Climate scenarios just represent one possible realization of the inherently stochastic climate time series such. Thus, one should not conclude from Figure 9 that, for example, water withdrawals in the actual year 2014 will be higher than in the following year.

What concerns the number of municipalities under stress in Ceará, Figure 10 shows that about 40% of the municipalities are not expected to undergo stress more than three years during the simulation period, independently of the scenario. The 10% most stressed municipalities, on the other hand, are expected to suffer water scarcity in more than 16 years until 2025 (with a probability of water scarcity higher than 64%.yr^{-1}). As a median value for scenarios A-ECHAM4 and B-ECHAM4, municipalities have a possibility of 5 years of water shortage (20%.yr^{-1}) until 2025. For scenario A-HadCM2, the median value is 8%.yr^{-1} probability of water scarcity, whereas for scenario B-HadCM2, this probability raises to 10%.yr^{-1}. The temporal evolution of municipalities under long-term water stress in Ceará can be seen in Figure 11, according to which at least 36% of the municipalities in Ceará (and at most 59%) are expected to go under long-term stress within the next 25 years. From Figure 11 one can also learn that a greater number of municipalities will have to deal with water scarcity in RS B than in RS A. A plausible interpretation of this result is that a “coastal boom and cash crops” development policy leads to higher vulnerability than a “decentralization and integrated rural development” policy.

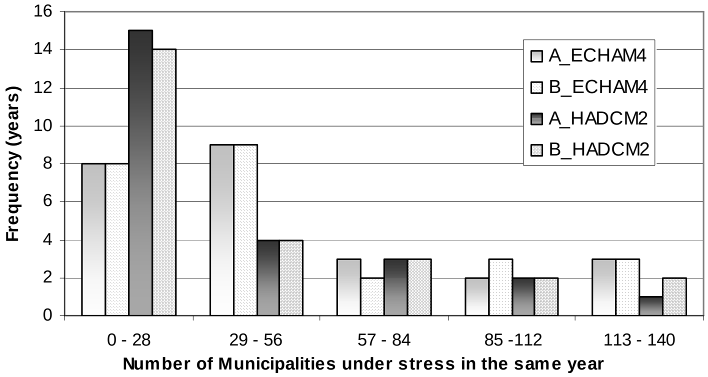


Figure 10. Histogram of municipalities under water stress in Ceará (2001 - 2025) for four scenarios

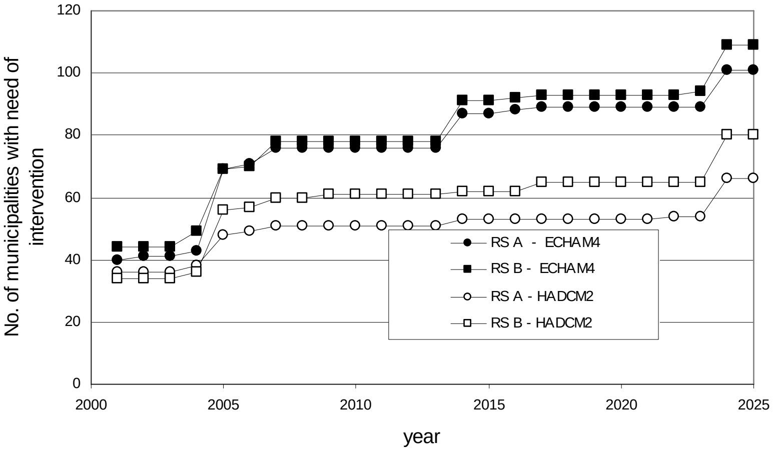
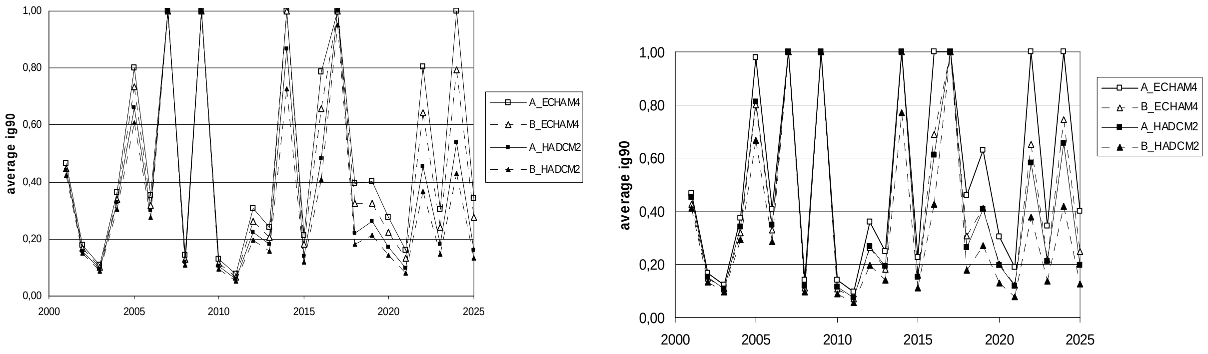


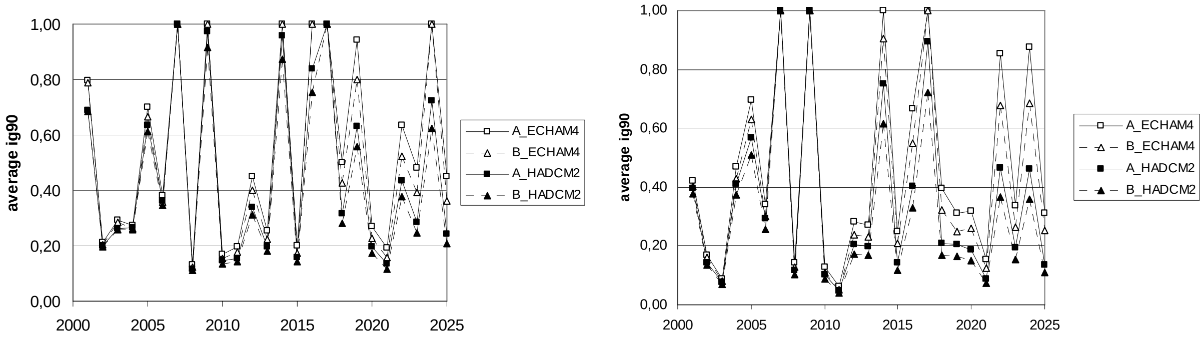
Figure 11. Number of municipalities with need of intervention due to water stress in Ceará for four scenarios in the period 2001 – 2025

Figure 12 shows the time evolution of water stress at the state level for the four scenarios. Figure 12 (a) indicates that scenario A-ECHAM4 is the one that needs a higher level of intervention, since water withdrawal is more intense (see Figure 9) and water yield decreases over time. The least critical scenario is B-HadCM2, due to a better spatial distribution of water demand (RS B) and an expected precipitation increase (HadCM2). Scenarios A-HadCM2 and B-ECHAM4 are qualitatively similar, which means that a decentralizing development policy can partly offset the regional climate effects of global warming. Figures 12b, c and d show that the coast (region 1), the metropolitan area (region 2) and the large potential water resources area (region 3) present the same trend as the entire state. The trend is that scenario A-ECHAM4 is the most critical and B-HadCM2 the least critical, whereas scenarios A-HadCM2 and B-ECHAM4 are closer to each other. It is important to note that ig_{90} in B-ECHAM4 is still higher than in A-HadCM2. Region 4 (low potential water resources) with 62 municipalities, on the other hand (Figure 12 e), has a different trend with reference scenario B leading to more water stress than RS A. The motivation for land use of the small potential water resources region in scenarios B and the lack of water infrastructure explains this result. In terms of regional vulnerability to water scarcity, region 1 (the most vulnerable) presents average probability of water stress of 18%.yr^{-1}; then region 4 with a probability of 17%.yr^{-1}; then region 2 with a probability of 16%.yr^{-1}, and then region 3 (the least vulnerable), with a probability of 11%.yr^{-1}.



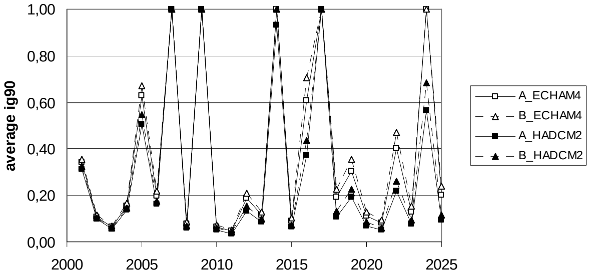
(a) State of Ceará

(b) Region 1 – Coastal area



(c) Region 2 - Metropolitan area of Fortaleza

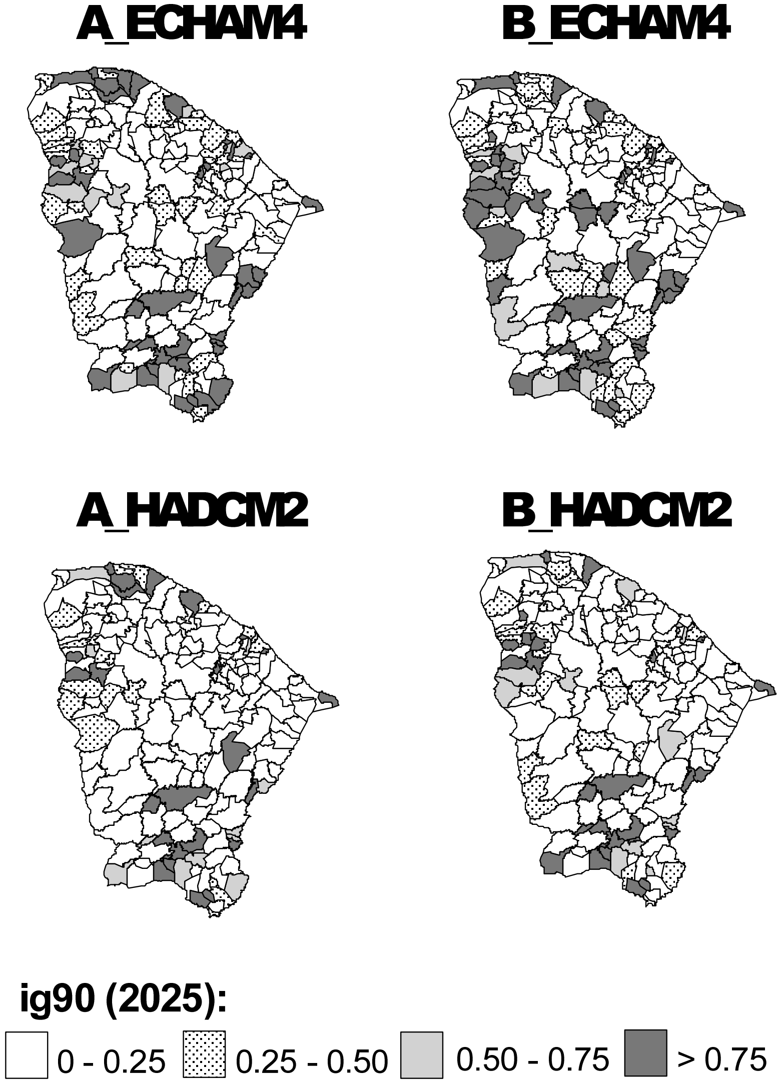
(d) Region 3 – Area with large potential water resources



(e) Region 4 – Area with small potential water resources

Figure 12. Assessment of water stress in four homogeneous regions in Ceará by means of index ig_{90} (2001 – 2025) for four scenarios

Figure 13 shows water stress in all municipalities in Ceará for year 2025 for the four scenarios. The ECHAM4 scenarios tend to present higher stress in most of the municipalities when compared to HadCM2 scenarios, which is due to precipitation decrease expectation all over Ceará for the next decades. It is also important to observe that northwestern and coastal municipalities present lower water stress because of higher water availability, whereas many central municipalities have low stress due to low water demand.


A_ECHAM4

B_ECHAM4

A_HADCM2

B_HADCM2

Figure 13. Water stress (ig90) in all municipalities in Ceará for year 2025 for four scenarios

Conclusions

The research develops a methodology for water scarcity assessment at a regional scale based on global change scenarios. A case study is performed for the state of Ceará, located in semiarid Northeastern Brazil. Long-term water stress is computed for the 184 municipalities of the state between 2001 and 2025 using four scenarios. These include a combination of two climatic scenarios (ECHAM4 and HadCM2) and two macroeconomic reference scenarios (RS A: coastal boom and cash crops; RS B: decentralization and integrated rural development). As a result, vulnerability of each municipality in the state is assessed, so that intervention policy can be planned.

Global circulation models are used to simulate prospective climatic scenarios for hypothesis of continued growth of greenhouse gas concentration. Among seven GCMs available, only two show good agreement with observed climatic data of the Brazilian semiarid region: ECHAM4 (expects precipitation decrease with global heating) and HadCM2 (expects precipitation increase with global heating). The hydrologic model WASA is applied to assess water availability, while the water use model NoWUM assesses water demand (withdrawal and consumptive use for five water sectors) and the stress index ig_{90} is used to compute water scarcity. Results show that the 10% most vulnerable municipalities have an average 82%

yearly expectation of water scarcity until 2025 for the four scenarios. On average, municipalities in the state of Ceará display a probability of water shortage for the next 25 years ranging from 9%yr^{-1} to 20%yr^{-1}, depending on the scenario. According to the research between 36% and 59% of the municipalities will need intervention to prevent long-term water scarcity before 2025. For the low potential water resources region (about a third of the municipalities in the state) RS B is more critical in terms of water scarcity due to expected economic growth, especially the enhancement of small-scale irrigation. On the other hand, for the state of Ceará as a whole, as well as for the coastal, the metropolitan and the large potential water resources regions, the most critical scenario is A-ECHAM4, while B-HadCM2 is the least critical. This is due to expected concentrated urban and industrial development in the coastal and metropolitan regions, and large-scale cash crop irrigation in the large potential water resources region. Scenarios B-ECHAM4 and A-HadCM2 are equivalent, which means that a decentralized development policy (RS B against RS A) can partly compensate a possible decrease of precipitation amounts due to global warming within the next 25 years (ECHAM4 against HadCM2).

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Mathematical Symbols

dQ_1 = water losses in the demand system
dQ_2 = water losses in the supply system
f = tolerance rate, i.e., minimum acceptable reserve rate
G = water supply annual reliability
ig90 = water stress index for 90% annual reliability
Q_C = municipal total water consumptive use
Q_D = global consumptive water demand for a municipality
Q_{RUNOFF} = runoff discharge
Q_S = global reliable water supply for a municipality
Q_{SUB} = groundwater yield
Q_{SW} = surface water yield
Q_W = municipal total water withdrawal
Q_{90} = long-term reservoir water yield with 90% annual reliability
X_1 = demand loss factor
X_2 = supply loss factor
= yield ratio, = Q90/QRUNOFF admitted constant for each municipality