Model-based scenarios of water use in two semi-arid Brazilian states

Petra Döll · Maike Hauschild

Abstract Sustainability-oriented water management calls for scenarios of future water use. Model-based qualitative-quantitative scenarios combine the development of story lines and the quantification of driving forces with the application of a water use model. In order to support regional planning in two semi-arid Brazilian states suffering from water scarcity, the water use model NoWUM was applied to derive two reference scenarios of municipality-specific sectorial water uses (irrigation, livestock, household, industry and tourism), and to assess the impact of certain interventions. Until 2025, the extension of irrigation accounts for almost 80% of the additional water withdrawals and for an even higher fraction of consumptive use in both scenarios. Domestic and industrial use increases in regions with high immigration, but water use intensities can be controlled by appropriate water pricing. A significant improvement of the developed scenarios is only possible if better data on water use and its driving forces become available.

Keywords Regional planning · Scenarios · Water resources · Water demand · Water scarcity · Water management

Introduction

Until recently, water resources managers thought it to be their task to fulfil an ever-increasing demand for water by constructing new physical water infrastructure (reservoirs, wells, pipelines, canals, etc.). They focused on supply-side solutions, and the term "water resources management" was sometimes used synonymously with "optimization of reservoir operation". Now, water resources management is changing for many reasons. The strong human interference with the hydrological cycle has led not only to environmental but also to social problems, often providing water for a few by taking it away from others. Despite an extensive water infrastructure, 1.2 billion people worldwide do not have adequate access to safe drinking water (UNESCO 2001).

Water suppliers and planning agencies are beginning to explore water demand management options which include technological and economic approaches as well as user education (Lallana et al. 2001). (In a few European countries, this development has already begun three decades ago.) They look for ways to achieve water conservation and efficiency improvements and start to facilitate the reallocation of water among users, in order to reduce potential gaps between water supply and demand. Increasingly, demand management is considered to be economically more efficient than supply management (Gleick 2000). Due to the strong human pressure on fresh-water resources, water is now regarded as a scarce resource and an economic good (Lallana et al. 2001). Besides, more attention is given to the basic human needs for drinking water and sanitation. According to Gleick (2000), "[...] these changes [concerning water resources management] have met strong internal opposition. They are still not universally accepted, and they may not be permanent." Therefore, it is important that researchers assist water resources planning agencies in their efforts towards sustainable water management. One possibility to do this is to generate model-based scenarios of future water use (the term "water use" is applied in this paper as a synonym for "water demand"). As intergenerational equity is a core idea of sustainability, scenarios are an important tool for sustainability-oriented regional planning. Scenarios of water use help policy-makers to consider demand-side solutions. If the scenarios are based on a water use model that computes water use as a function of various driving forces, they provide water planners with transparent and reproducible estimates of future water use and allow to identify future scarcity problems. Therefore, such scenarios are to be preferred over simple extrapolations of historic water use increases. In the past, such extrapolations resulted in large overestimations of projected water use (Young 1996).

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P. Döll (✉) · M. Hauschild
Center for Environmental Systems Research,
University of Kassel, 34109 Kassel, Germany
e-mail: doell@usf.uni-kassel.de
Tel.: +49-561-8043913
Fax: +49-561-8043176

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In the framework of the joint German–Brazilian research program WAVES (http://www.usf.uni-kassel.de/waves), land use and water-related scenarios for Piauí and Ceará, two federal states in semi-arid northeastern Brazil (Fig. 1), were derived. Northeastern Brazil, where one third of the Brazilian population lives, is the poorest region of Brazil. For more than one century, many people have migrated, mostly to the more affluent south of Brazil. Due to the strong seasonality of precipitation and El-Niño-related drought years, northeastern Brazil suffers from water scarcity, which negatively influences regional development and the quality of life of the inhabitants.

Qualitative-quantitative scenarios for the year 2025 were generated by (1) writing story lines (or narratives), (2) quantifying the driving forces and (3) applying simulation models (for a description of the methodology, see Döll et al. 2001). This scenario-building approach has been adapted from the methodology that was used by the Intergovernmental Panel on Climate Change (IPCC) to derive global scenarios of greenhouse gas emissions (Nakicenovic and Swart 2000). By applying the regional water use model NoWUM (Hauschild and Döll 2000; Döll and Hauschild 2002), we produced scenarios of water use in all of the municipalities of the study area Piauí and Ceará in the year 2025. Together with scenarios of water availability and agricultural production and income, which were also developed within the WAVES program, these water use scenarios have the potential to support strategic planning by the water and agriculture authorities of the study area.

In this paper, we present two reference scenarios of water use in Piauí and Ceará in the year 2025, and we show, against the background of the reference scenarios, the impact of selected policy measures. First, we describe the regional water use model NoWUM that serves to compute the water use scenarios, summarize the story lines of the two reference scenarios and show the assumed developments to the main driving forces of water use until 2025. Then, the resulting water use for the reference scenarios as well as the impact of policy interventions are presented. We discuss the plausibility of the scenario assumptions and the model uncertainty, and finally draw conclusions.

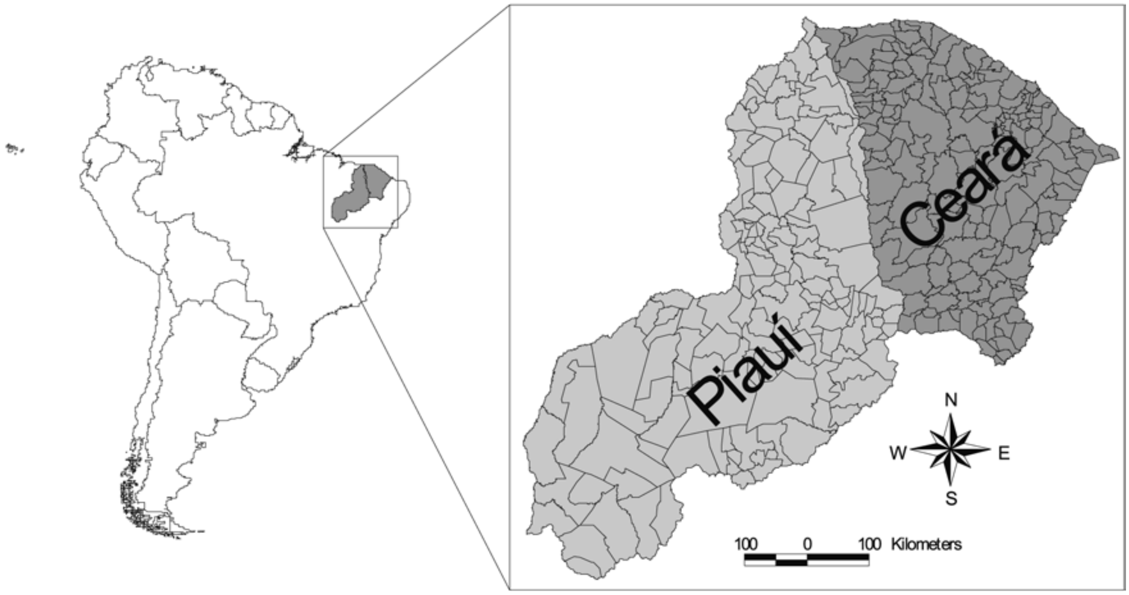

Fig. 1
The study area Ceará and Piauí, two federal states in northeastern Brazil. Borders of the municipalities are also shown. The study area covers approximately 400,000 km^2

Methods

Two methods are combined to generate model-based scenarios of water use, mathematical modeling and scenario development. In this section, the water use model NoWUM is described first. Then, the story lines and driving forces of two reference scenarios are presented. Quantitative assumptions on the future development of these driving forces (and model parameters) are then implemented in NoWUM to compute alternative water use scenarios.

Water use model

NoWUM (Nordeste Water Use Model) is a regional-scale water use model which has been designed in order to assess the impact of global change and of management measures on water use. Hauschild and Döll (2000) and Döll and Hauschild (2002) describe the model and present estimates of water use in Piauí and Ceará around 1996–1998, considering also the impact of climate variability on irrigation water use. In this section, a concise description of NoWUM is provided.

NoWUM computes withdrawal and consumptive water use for each of the 332 municipalities in Piauí and Ceará. Withdrawal water use is the quantity of water taken from its natural location, while consumptive water use is the part of the withdrawn water that is lost by evapotranspiration. The difference between withdrawal and consumptive use is the return flow, the part of the withdrawn water that returns to either the surface water or the groundwater. (In the case of irrigation water use, consumptive use is defined at the field scale, and transport losses to the atmosphere are not included.) The ratio between consumptive and withdrawal water use is called water use efficiency. In-situ water use is not taken into account in NoWUM. The model design is strongly influenced by the availability of data. NoWUM distinguishes five water use sectors: irrigation, livestock, households, industry and tourism (Fig. 2). Each sectorial 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 sectorial water uses are expected to vary at least to a certain degree with climate and the season of the year, only the strong seasonality and climate dependence of irrigation water use is simulated by the model. Water use in all other sectors is assumed to be constant throughout the year, and the impact of climate variability and climate change is not modeled.

Irrigation water use

Consumptive irrigation water use (or net irrigation requirement) is calculated as a function of climate (precipitation and potential evapotranspiration), irrigated area and type of irrigated crop according to the CROPWAT method (FAO 1992), distinguishing nine crop classes and using crop-specific growing periods typical for northeastern Brazil. Due to lack of data, multicropping is not included. Total consumptive irrigation water use in each municipality is computed by taking into account the crop-class-specific irrigated areas. Withdrawal use is calculated from consumptive use applying an irrigation water use efficiency of 0.6 for 1996/1998, based on information on irrigation technology and the respective efficiencies for northeastern Brazil (FAO 2000). Daily values of precipitation and potential evapotranspiration for each of 332 municipalities for the period 1951–1980 were provided by Gerstengarbe and Güntner from the Potsdam Institute for Climate Impact Research (personal communication, 1999), who generated them by spatial interpolation of observed station data. Average net irrigation requirements per unit of irrigated area under present-day conditions are computed by simulating 30 years of irrigation with the climate time series 1951–1980 and the irrigated areas of 1996/1998, and then averaging the resulting annual requirements. Use of long-term average climatic data as input would lead to an underestimation of the long-term average irrigation water requirement, due to the nonlinearity of the CROPWAT equation to compute net irrigation requirements. Estimates of the areas under irrigation in 1996/1998 are very uncertain. Data on irrigated areas from the Brazilian Agricultural Census of 1995/1996 (Instituto Brasileiro de Geografia e Estatística 1998a, 1998b) are generally considered to be unreliable. By combining information from various sources and considering opinions of Brazilian experts, we derived a best estimate of the crop-specific irrigated areas in each municipality. The estimated total irrigated area is 43,000 ha in Ceará (compared to 77,000 ha according to the Agricultural Census; Instituto Brasileiro de Geografia e Estatística 1998a) and 13,000 ha in Piauí (compared to 18,000 ha; Instituto Brasileiro de Geografia e Estatística 1998b). Crop-specific irrigated areas within a municipality are derived from production values of irrigated crops of the Agricultural Census as well as from irrigation licenses of the water ministry of Ceará.

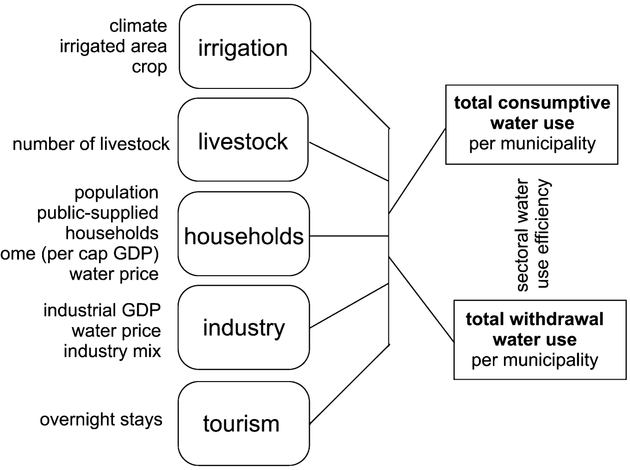

Fig. 2
Overview of the regional-scale water use model NoWUM; *left* the driving forces of water use by the five sectors irrigation, livestock, households, industry and tourism are indicated

Livestock water use

Annual values of livestock water use are calculated from the number of animals per species in each municipality (Instituto Brasileiro de Geografia e Estatística 1998a, 1998b) and a species-specific water use typical for northeastern Brazil. Withdrawal water use is assumed to be equal to consumptive water use.

Domestic water use

Domestic water use includes not only residential water use but also water use by commerce and by public institutions like schools. It is computed as the product of the per-capita water use and the population. The water use in self-supplied households is differentiated from that in households connected to the public water supply, i.e. households with tap water (Fig. 2). The municipality-specific per-capita water use in connected households for the current situation is calculated from municipality-specific data provided by the local water suppliers. No information is available on the per-capita water use in self-supplied households. As a first estimate, we assume a per-capita withdrawal water use of 50 l/day, a value defined by Gleick (1996) as the basic human water requirement, which is equal to approximately half of the per-capita water use of the supplied population. Water use efficiency in the domestic sector is assumed to be 0.2 (Solley et al. 1998). The same efficiency is also used for the industrial and the tourism sectors.

While per-capita water use in self-supplied households is assumed to remain unchanged in the future, per-capita domestic water use in connected households is assumed to depend on water price and income. The econometric concept of elasticities is used to compute per-capita annual withdrawal water use U as a function of water price P per unit volume of water (price elasticity) and income [here per-capita gross domestic product (GDP)] (income elasticity). Price elasticity ϵ_p, which is generally negative, is defined as

$$\varepsilon_p = \frac{\frac{dU}{U}}{\frac{dP}{P}} \tag{1}$$

and income elasticity ϵ_i, which is generally positive, as

$$\varepsilon_i = \frac{\frac{dU}{U}}{\frac{dGDP}{GDP}} \tag{2}$$

Industrial water use

Industrial water use is computed as a function of the industrial GDP (IGDP) of 19 industrial branches in each municipality and the branch-specific water use per IGDP (industrial water use intensity). Branch-specific industrial water use intensities were assumed to be the same as in Germany because no Brazilian data were available. Future industrial water use per industrial output is modeled as a function of water price according to Eq. (1), where U is annual withdrawal water use per IGDP.

Tourism water use

Tourism water use is modeled as a function of the number of tourists in a municipality as well as the average length of stay and the water use per tourist and day, which are regionally differentiated (coast and interior).

Reference scenarios: story lines and driving forces

Scenarios are plausible and consistent images of alternative futures which show different possibilities of how the future might look. They are not predictions of the future and should not be qualified by a probability. In many cases, the aim of scenario development is to support sustainability-oriented decision-making. Scenarios are always interdisciplinary and integrated, at least to a certain extent, because images of the future that are relevant for decision-making by necessity include physical, demographic, economic and technological aspects. Obviously, the planning (or research) aim and scope will determine which parts of the image, i.e. which aspects and processes, are refined and which are only considered in a coarse manner. In order to support regional planning, it is useful to first develop so-called reference scenarios which then serve as the baselines to assess the impact of selected regional planning policies or interventions on the future state of the system. The robustness of a certain policy is tested by determining its impact in different possible future situations, i.e. against all the reference scenarios. While reference scenarios might implicitly include some policy measures related to the topic of interest, e.g. water use, these policy measures continue certain existing policy trends, while the interventions are possible new policies.

In the framework of the WAVES program, story lines of two reference scenarios for the year 2025 were developed; an interdisciplinary team quantified those driving forces that were important not only for water issues but also for the agricultural and socioeconomic development (population, gross domestic product, urbanization, etc., see http://www.usf.uni-kassel.de/waves/szenarien/tabelas_cenario). The other driving forces of water use (see Fig. 2) were quantified by the authors. During three workshops, the scenarios were discussed with members of the Brazilian water authorities. In this section, we present the storylines and the quantification of the driving forces of the reference scenarios. The interventions (and their impacts) are described in the section “Results”.

Story lines

For each of the two reference scenarios, a story line was written that covers aspects important for rural development and the water scarcity problem in the study area. It describes the situation, in the year 2025, in each of eight scenario regions (Fig. 3). The scenario regions are defined based on (1) similar (agro)economic conditions and (2) similar natural conditions (sedimentary vs. crystalline subsurface, location within the river basin, precipitation). Table 1 provides a concise characterization of reference scenario A (RS A), “Coastal boom and cash crops”, and reference scenario B (RS B), “Decentralization – integrated rural development”. The detailed story lines are given in Döll et al. (2000) (in German) and at http://www.usf.uni-kassel.de/waves//szenarien/reference_scenarios.html (in English). Each reference scenario continues certain existing trends. RS A carries on the current trend of increased cash crop production for the Brazilian and external market, the efforts to promote tourism mainly along the coast and the fast economic development in the growing metropolitan area of Fortaleza, the capital of Ceará. RS B takes up the strengthening of regional centers, e.g. by the establishment of universities, which has recently begun in the study area. RS A is consistent with a globalized, economy-driven world as described by IPCC’s global emissions scenario A1, while RS B fits into the less globalized and more sustainability-oriented world of the global scenario B2, where solutions are sought via local initiatives (Nakicenovic and Swart 2000).

Quantification of driving forces and model parameters

The driving forces of each of the five water use sectors are shown in Fig. 2. To derive water use scenarios, the future development of all driving forces must be quantified for each of the eight scenario regions. It is assumed that all municipalities within a scenario region are subject to the same percentage change of a driving force (except for irrigated areas, where planned irrigation projects are implemented in individual municipalities). In addition, a few parameters like the price and income elasticities must be defined. In the next paragraphs, the quantification of the

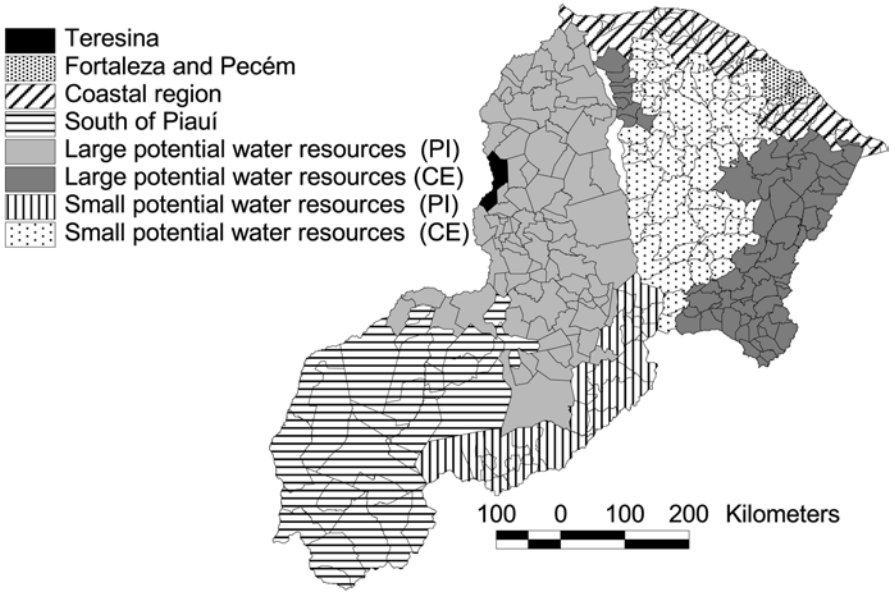

Fig. 3
The eight scenario regions: the smallest spatial units for developing storylines and quantitative assumptions about development of driving forces. Teresina is the capital of Piauí and Fortaleza is the capital of Ceará. *White areas* between Piauí and Ceará are disputed between both states and are almost uninhabited

driving forces (and model parameters) is presented in the order shown in Fig. 2.

Irrigation water use

Climate Within the WAVES program, a climate change scenario for the years 2000–2050 (daily values) was derived statistically by taking into account precipitation change in northeastern Brazil as computed by the ECHAM4 climate model of the Max-Plank-Institute, Hamburg, Germany, for a 1% yearly increase of greenhouse gas concentrations, and historic station data for 1921–1980 (Werner and Gerstengarbe 1997). Irrigation water use in 2025 is computed by applying the climate time series from 2011–2040; subsequently, the results are averaged over this 30-year period.

Irrigated area In Brazil, irrigated areas were extended at a rate of 7%/year in the 1970s, by 5%/year in the 1980s but by only 1.2%/year between 1990 and 1998 (FAO 2000). This decreasing trend is observed in most countries and is due to restricted water and land resources. Brazil is one of only three countries for which the business-as-usual scenario of the global World Water Vision exercise assumes an extension of irrigated area until 2025 (Alcamo et al. 2000). In Piauí and Ceará, rural development is considered to be strongly linked to irrigated agriculture. Therefore, large increases of irrigated area are foreseen in both reference scenarios, with an average over the study area of 3.8%/year in RS A and 2.5%/year in RS B. For RS A, all public irrigation projects planned in 1998 according to Lopes Neto (1998) are assumed to be implemented, while private irrigation, which accounts for approximately half of the current irrigated areas, increases by 2%/year from 1996/1998 to 2025. The 2% increase represents the average for the study area Piauí and Ceará and differs among the scenario regions. These assumptions lead to an increase of irrigated areas in the study area from 56,000 ha in 1996/1998 to 161,000 ha in 2025, with 84,000 ha in new public projects and 21,000 as new private irrigation. For RS B, with its decentralized development based on small-scale local initiatives, it is assumed that only a fourth of the area in each of the planned public irrigation projects is implemented up to 2025, but that private irrigated areas increase by 2.9%/year. Irrigated area in 2025, for RS B, is 112,000 ha (new projects: 21,000 ha, new private irriga-

Table 1
Characteristics of the two reference scenarios

Reference scenario A (RS A) "Coastal boom and cash crops"	Reference scenario B (RS B) "Decentralization – integrated rural development"
Highly globalized world	More regionalized world as compared with RS A, but not as compared with today
Strong economic development (commerce, industry, tourism) in the coastal regions of Piauí[a] and Ceará	Piauí and Ceará show a high degree of autonomy in relation to the Brazilian south
Fortaleza with typical problems of fast-growing cities	Regional centers dominate, i.e. attractive medium-sized towns with improved infrastructure which become the markets for local and regional agricultural products
Where water is available for irrigation, the production of cash crops by large companies dominates over subsistence farming	Small-scale agro-industry
Centralized governance prevails	Local initiatives prevail

[a] The small coastal region in Piauí consists of only two municipalities

tion: 35,000 ha). In both scenarios, the additional private irrigated areas of a scenario region are distributed among the municipalities according to the following rule: 50% of the additional areas is distributed homogeneously over all municipalities, and 50% in proportion to the 1996/1998 irrigated area.

Crops It is expected that in the future the percentage of banana, fruit trees, vegetable and cotton will rise, the percentage of beans, maize and grass will remain the same and the percentage of rice and sugar cane will decrease. In both reference scenarios, 50% of the 2025 irrigated area in each municipality has the same crop mix as in 1996/1998, while the other 50% is planted with a state-specific crop mix that reflects the changing preferences.

Irrigation water use efficiency In northeastern Brazil, the need to improve irrigation efficiency is often mentioned, and it is planned that new irrigation will be mostly microsprinkler and drip irrigation. Therefore, irrigation water use efficiency is assumed to increase from the already high value of 0.6 today (which is equal to the value for the western United States in 1995; Brown 2000) to 0.7 in 2025. This efficiency increase is in line with the assumptions for the global business-as-usual scenario of the World Water Vision (Alcamo et al. 2000).

Livestock water use

The number of livestock in each municipality is assumed to change in proportion to the human population (see below).

Domestic water use

Population For RS A and RS B, two different population scenarios were derived. They differ with respect to the distribution of population among scenario regions (Table 2), but total population growth in the study area is assumed to be the same in both scenarios. In RS A, the fraction of the population living along the coast and in the two capitals increases strongly, while in RS B, the current trend of migration from the hinterland to the coast weakens. The historical population development of the study area is strongly influenced by migration towards the economic centers in the south of Brazil. The fertility has been higher than the Brazilian average but with a decreasing trend. Using a simple cohort population model (Fuhr et al. 2001), the total population scenario was derived by analyzing fertility, mortality and migration rates of Piauí and Ceará in 1991 and 1996, comparing them with the respective values for the whole of Brazil, and by taking into account IPCC population scenarios (Nakicenovic and Swart 2000) and a population scenario for Brazil (Instituto Brasileiro de Geografia e Estatística 1997). It is assumed that fertility and mortality continue to decrease in the future, and that the more recent trend of decreasing net migration continues. By 2025, both the fertility rate and the net migration will have dropped to approximately 65% of the 1996 value, and the mortality rate to approximately 85%. The resulting fertility and mortality rates of 2025 are still higher than the values for the Brazilian average as predicted by the Brazilian population scenario for 2020. According to the population model, the number of inhabitants of the study area increases from 9.48 million inhabitants in 1996 to 11.94 million in 2025.

Households connected to the public water supply Presently, only some of the urban households and virtually none of the rural households are connected to the public water supply. There are plans to extend the number of connected urban households as well as first efforts to supply the rural population. Table 3 lists the fraction of the public-supplied population in each scenario region, in 1997 and in 2025 for RS A and B. For the scenario development, we took into account the urbanization scenarios that were derived in the framework of WAVES. Please note that a slight increase in the fraction of the urban public-supplied population may require a very high number of additional house connections.

Income (per-capita GDP) and income elasticity In NoWUM, an increase in per-capita GDP leads to an increase in domestic water use, proportional to the income elasticity. Per-capita GDP in the study area is approximately one half of the Brazilian average, and the average growth rate since 1970 has been somewhat higher than the Brazilian value. The global IPCC scenario A1 (to which RS A fits) shows a much higher growth rate of per-capita GDP than the global scenario B2 (RS B) (Nakicenovic and Swart 2000). In the case of both IPCC scenarios, the growth rates for the global scenario region to which Brazil belongs are much higher than the average historical growth rates from 1950–1990. We think that this type of GDP growth assumption, with an average of 4.7%/year until 2025, is not plausible for our scenarios for Piauí and Ceará; per-capita GDP growth is likely to be smaller, and more similar in RS A and RS B. Therefore, we assume a value of 2.7%/year from 1996–2025 in RS A (except in Teresina and the regions with small potential water resources, with 2.5%/

Table 2
Spatial distribution of population: historical data and scenarios. *PI* Piauí; *CE* Ceará

Scenario region	Fraction of total population of Ceará and Piauí in each scenario region (%)			
	1991	1996	2025 RS A	2025 RS B
Teresina	6.7	6.9	8.1	7.3
Metropolitan area of Fortaleza and Pecem	26.1	27.6	35.4	30.6
Coastal region	12.7	12.8	17.4	13.3
Southern part of Piauí	3.1	2.9	2.4	2.9
Regions with large potential water resources (PI)	14.5	13.9	11.4	13.5
Regions with large potential water resources (CE)	19.4	19.0	15.5	18.4
Regions with small potential water resources (PI)	2.9	2.7	1.6	2.3
Regions with small potential water resources (CE)	14.7	14.1	8.2	11.7

Table 3
Population connected to public water supply: historical data and scenarios. *RS* Reference scenario; *IS* intervention scenario; *PI* Piauí; *CE* Ceará

Scenario region	Fraction of population connected to public water supply (%) (% of urban population)				
	1997	2025 RS A	2025 RS B	2025 IS A	2025 IS B
Teresina	94 (100)	95 (98)	95 (98)	97	97
Metropolitan area of Fortaleza and Pecem	69 (70)	80 (82)	80 (82)	98	98
Coastal region	31 (57)	60 (80)	45 (64)	79	75
South of Piauí	42 (97)	50 (100)	50 (82)	58	66
Regions with large potential water resources (PI)	42 (87)	55 (92)	55 (79)	66	75
Regions with large potential water resources (CE)	37 (68)	50 (77)	50 (67)	70	79
Regions with small potential water resources (PI)	22 (76)	30 (81)	30 (71)	46	51
Regions with small potential water resources (CE)	34 (69)	40 (73)	40 (67)	62	66

year), and 2.2%/year in RS B (except in regions with large potential water resources, with 2.4%/year).

Gómez (1987) lists an income elasticity for Brazil of 0.78, which was derived by the Inter-American Development Bank from a survey of 400 families in a Brazilian city with approximately 1.5 million inhabitants. Compared to income elasticities determined in nine other Latin American countries (Gómez 1987), Brazil has the highest value. For NoWUM, we decrease the income elasticity to 0.7, also because new connections to public water supply, which lead to a higher water use, are explicitly included in the scenarios.

Water price and price elasticity To define a water price scenario, the water tariffs of the public water supply company of Ceará, which is responsible for most of the water supply in the state, were analyzed (CAGECE 1998, unpublished data). From 1989–1998, the fixed fee component of the tariff (for the first 10 m^3/month) increased by an average of 11%/year (adjusted for inflation) and the marginal price for 11–20 m^3/month by 8%/year. In 1998, the water price covered operation and maintenance costs, which had not been the case before. We therefore do not expect such a high increase for the future, but as operation and maintenance costs are expected to rise, we assume a yearly water price increase of 6%, which is well above the income growth.

According to BNB/PBLM (1997), a typical value of price elasticity in the domestic sector in northeastern Brazil is –0.55. Gómez (1987) provides a value of –0.60 for the Brazilian city in his study. A value of –0.3 is a more common for European and North American countries if indoor use prevails (Young 1996). We assume that the price elasticity of domestic water use changes linearly from –0.55 in 1996 to –0.3 in 2025.

Industrial water use

Industrial GDP and industry mix With respect to sectoral GDP, the general trend world-wide is a strengthening of the service sector and a weakening of the agricultural sector, while the industrial sector will remain approximately constant. Therefore, we assume that the IGDP as a ratio of the total GDP, which is now on average 25%, remains constant such that IGDP increase is equal to the per-capita GDP increase times the population change in each municipality. The industry mix is kept constant.

Water price and price elasticity Due to the lack of specific information about water prices for industry, we assume the same price increase as for domestic water use, 6%/year. According to BNB/PBLM (1997), price elasticity for industrial withdrawals is –0.74 in northeastern Brazil, while a value of –0.4 is common in European and North American countries (Renzetti 1993). We assume that the price elasticity of industrial withdrawal water use decreases linearly from –0.74 in 1996 to –0.4 in 2025.

Tourism water use

Tourism water use includes both water use by pilgrims (there are four municipalities in Ceará which attract more than 2.5 million pilgrims each year) and water use by tourists. The number of overnight stay of pilgrims is assumed to remain constant. In RS A (the coastal boom scenario), the overnight stays of tourists increase by a factor of 5 in the coastal region and in the metropolitan area of Fortaleza until 2025, and by a factor of 3 in the municipalities of the hinterland. In RS B, the overnight stays in all municipalities increase by a factor of 3 everywhere. Water use per overnight stay does not change.

Results

The impact of climate change on irrigation water use can be neglected until 2025. Till then, the climate change scenario results in a non-significant decrease of irrigation requirements in the study area by about 4% (climate time series 2011–2040 as compared to 1951–1980). The impact of climate change is much smaller than the impact of climate variability under the current climatic conditions (Döll and Hauschild 2002). Therefore, the following results were obtained without taking into account the impact of climate change.

Reference scenarios

Table 4 presents sectorial withdrawal water uses in the scenario regions of the study area in 1996/1998, and in 2025 for RS A and RS B (without climate change impact). Total withdrawal water use in 2025 is 71% higher than in 1996/1998 for RS A, and 39% higher for RS B. The irrigation sector accounts for 75–80% of the change in total

Table 4
Sectorial water withdrawals in the eight scenario regions in 2025 for both reference scenarios as compared to withdrawals in 1996/1998. *PI* Piauí; *CE* Ceará

Scenario region (Population 1996, in millions)		Withdrawals (10^6 m^3/year)					
		Irrigation	Livestock	Domestic	Industry	Tourism	Total
Teresina	1996/1998	11.8	0.8	52.1	1.9	0.7	67.2
(0.66)	2025 RS A	14.9	1.2	61.8	2.0	2.0	81.9
	2025 RS B	16.6	1.1	52.5	1.7	2.0	73.8
Metropolitan area of Fortaleza	1996/1998	5.8	2.6	109.6	32.0	6.7	156.7
(2.62)	2025 RS A	14.9	4.2	156.0	40.5	33.7	249.3
	2025 RS B	14.9	3.6	123.4	30.4	20.1	192.4
Coastal region	1996/1998	120.8	12.0	36.7	7.0	5.4	181.8
(1.21)	2025 RS A	239.8	20.4	70.2	9.5	27.7	367.5
	2025 RS B	146.7	15.6	44.6	6.3	16.1	229.4
Southern Piauí	1996/1998	10.2	14.0	10.1	0.3	0.0	34.7
(0.28)	2025 RS A	45.7	14.2	10.0	0.3	0.0	70.3
	2025 RS B	61.5	17.6	11.2	0.3	0.0	90.7
Regions with large pot. water res. (PI)	1996/1998	103.0	38.1	45.2	1.4	0.3	188.1
(1.32)	2025 RS A	213.3	39.0	42.7	1.2	0.9	297.1
	2025 RS B	126.6	46.2	48.5	1.3	0.9	223.5
Regions with large pot. water res. (CE)	1996/1998	167.7	33.0	56.1	5.5	2.7	265.0
(1.80)	2025 RS A	417.6	33.7	56.6	4.5	7.3	519.7
	2025 RS B	304.4	40.0	64.4	4.9	7.3	421.0
Regions with small pot. water res. (PI)	1996/1998	0.8	11.1	6.6	0.1	0.1	18.7
(0.26)	2025 RS A	3.3	8.1	4.6	0.1	0.2	16.2
	2025 RS B	2.5	11.6	6.4	0.1	0.2	20.7
Regions with small pot. water res. (CE)	1996/1998	31.2	34.7	32.8	2.1	0.5	101.4
(1.34)	2025 RS A	75.0	25.2	25.3	1.2	1.2	127.9
	2025 RS B	83.8	36.1	34.9	1.5	1.2	157.6
Piauí and Ceará	1996/1998	451.4	146.3	349.1	50.3	16.4	1013.6
(9.48)	2025 RS A	1024.5	146.1	427.1	59.2	73.0	1729.9
	2025 RS B	757.0	171.8	386.0	46.5	47.8	1409.0

water withdrawals; irrigation withdrawals as a ratio of total withdrawals increase from 45% in 1996/1998 to 59% (RS A) and 54% (RS B) in 2025. Consumptive water use in the study area is 500 million m^3/year in 1996/1998 and increases by 104% (RS A) and 67% (RS B) until 2025. It grows more strongly 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. Irrigation consumptive use as a ratio of total consumption increases from 54% in 1996/1998 to 70% (RS A) and 63% (RS B) in 2025. While irrigation withdrawals increase by 127% in the case of RS A, consumptive use in irrigation rises by 165%. As consumptive use represents the amount of water that certainly cannot be reused (while the return flow part of the withdrawn water has the potential to be reused if water quality is sufficient), its future development is of particular interest.

Water use in the second most important water use sector, the domestic sector, rises by 22% in the case of RS A and by 11% in the case of RS B. These values result from a combination of decreased per-capita water use in the households connected to the public water supply, an increased fraction of public-supplied households and the population change. Per-capita water use in public-supplied households decreases, on average, by 17% in the case of RS A and by 22% in the case of RS B, from 139 l/day in 1996/1998. Even though the higher incomes in 2025 as compared to 1996/1998 potentially lead to raised per-capita water use, this effect is outweighed by the reducing effect of the assumed water price increase.

Of the remaining three water use sectors, tourism shows the strongest increase as overnight stays are assumed to increase significantly in both reference scenarios. Industrial and livestock water uses do not change much. The assumed price increase for water even leads to less industrial water withdrawals in 2025 than today in the case of RS B. More than half of the total industrial water use occurs in the metropolitan area of Fortaleza, and this fraction will remain the same in RS B, but increases in RS A. Livestock water use remains constant in the case of RS A, as livestock is assumed to develop proportionally to the human population, and in this scenario, inhabitants of the hinterland, where livestock numbers are high, migrate towards the coast. In 2025, the hinterland (scenario regions “South of Piauí”, “Regions with small potential water resources”, “Regions with large potential water resources”) has 7% less inhabitants (see Table 2).

Increase of water use between today and 2025 is strongest in the “Coastal region” in the case of RS A, due to a doubling of both irrigation and domestic water use. Irrigation and tourism water use rise in each scenario region and for both scenarios. In the case of RS A, livestock, domestic and industrial water use in the hinterland decrease (or only show a small increase). Industrial water use shows a similar pattern as domestic water use because IGDP in a municipality is assumed to be related to the population development (the development of the per-capita IGDP is prescribed). Nevertheless, in the hinterland

"Regions with large potential water resources", irrigation water use is assumed to increase much more strongly in RS A than in RS B, due to irrigated cash crops such that also in this region, RS A has a higher water use than RS B. Thus, total water use in the case of RS A is higher than in the case of RS B in five scenario regions. In the three other scenario regions ("Regions with small potential water resources", both in Piauí and in Ceará, and "South of Piauí"), the higher water use in the case of the decentralization scenario RS B is caused by higher population (less migration to the coastal region) and the stronger extension of private irrigated areas, where products for the regional markets are grown.

The spatial distribution of water withdrawals in the study area can be observed in Fig. 4. Currently, the highest total withdrawal water use takes place along the coast, along the Jaguaribe in the western part of Ceará, in the Sierra de Ibiapaba (eastern part of the scenario region "Regions with large potential water resources in Ceará"; see Fig. 3) and particularly in Teresina and Fortaleza (Fig. 4a). Irrigation water use dominates total water use in many municipalities (Fig. 4d). In RS A, total water withdrawals will decrease until 2025 in those municipalities of the "Regions with low potential water resources" where no new irrigation projects are planned. This decreases the amount by more than 10% of the current withdrawals. Along the coast, water use increases by more than 100% in many municipalities. Increases are particularly strong in municipalities with new irrigation projects (compare Fig. 4b and e). In RS B, the changes in water use are spatially much more homogeneous than in RS A (Fig. 4c). This is due to the relatively strong development of the hinterland in RS B, the "Decentralization – integrated rural development" scenario as compared to RS A, the "Coastal boom and cash crops" scenario. In particular, additional irrigation is assumed to be based on private, local initiative, and therefore more dispersed and not concentrated in a few large irrigation projects (Fig. 4f). In particular, the municipalities in the water-scarce region of Ceará and in the south of Piauí show significant increases of irrigation water requirements in RS B, but not in RS A. There are only very few municipalities with a decrease of water use. In these municipalities, perennial crops like sugar cane are grown today, while for the future, a crop mix that also includes crops with a growing period of less than 1 year is assumed to be produced (compare section "Quantification of driving forces and model parameters").

Interventions

Even though the irrigation sector is the dominant water use sector, here we only assess the impact of interventions in the domestic and industrial water use sectors. Possible interventions in the irrigation sector are either too case-specific (e.g. implementing or not a certain public irrigation project) or too difficult to model (e.g. the introduction of bulk water pricing for irrigation, the impact of which highly depends on market prices for the produced crops).

Extension of public water supply

In 1996/1998, only about 50% of the households in the study area were connected to the public water supply. In the reference scenarios, an increase to 66% (RS A) and 58% (RS B) of the population in 2025 is assumed. A possible intervention is to improve the water supply situation in 2025 by extending public water supply more strongly than in the reference scenarios. However, average per-capita withdrawal for public-supplied households is more than double the value assumed for self-supplied households (50 l/day). Therefore, an extension of public water supply leads to a higher domestic water use, and the desirable supply of safe drinking water might put an additional pressure on the scarce water resources of Piauí and Ceará. If 83% of the population had access to public-supplied tap water in the case of RS A, instead of only 66%, domestic withdrawals in the study area would increase by 12%, and total withdrawals by less than 3%. In the case of RS B, if the connection rate is 79% instead of 58%, domestic withdrawals would rise by 14% and total withdrawals by less than 4%. Thus we conclude that an extended public water supply would not put a high additional stress on water resources.

Pricing of domestic water supply

Water pricing should be aimed at promoting sustainable water use. This requires full cost recovery for water services, including environmental damage (Avis et al. 2000; World Water Commission for the 21st Century 2000). At the same time, any pricing policy, in particular in developing countries, should help to improve the access to safe drinking water of the poorest inhabitants. The current water prices in the study region only cover operation and maintenance costs, and not investment costs, e.g. for an extension of water supply, or environmental costs. Strong price increases are likely to be necessary to achieve a full cost recovery for water services. Currently, 1% of the average per-capita GDP in the study area is spent on (public) water supply, which is comparable to the situation in Germany, with a tenfold per-capita GDP and the same per-capita water use. Here, we explore the effect of different changes of the water price on water use. The increase assumed for both reference scenarios (6%/year) from 1996/1998 to 2025 (compare section on "Quantification of driving forces and model parameters") is smaller than the actual price increases in Ceará during the last decade.

A price increase of only 2.5%/year results in an approximately constant fraction of the total income that is spent on water, and it is unlikely that with such a price development, investment costs could be covered. A price increase of 11%/year (the price increase of the fixed fee component of the water tariff in Ceará during the last decade) leads, on average, to a water price that, with the same per-capita water use, amounts to about 10% of the per-capita GDP. Such a pricing policy has the potential of full cost recovery. Besides, prices per volume of fresh water will effectively double when households get connected to the sewage system (in 1996/1998, only about 10% of the

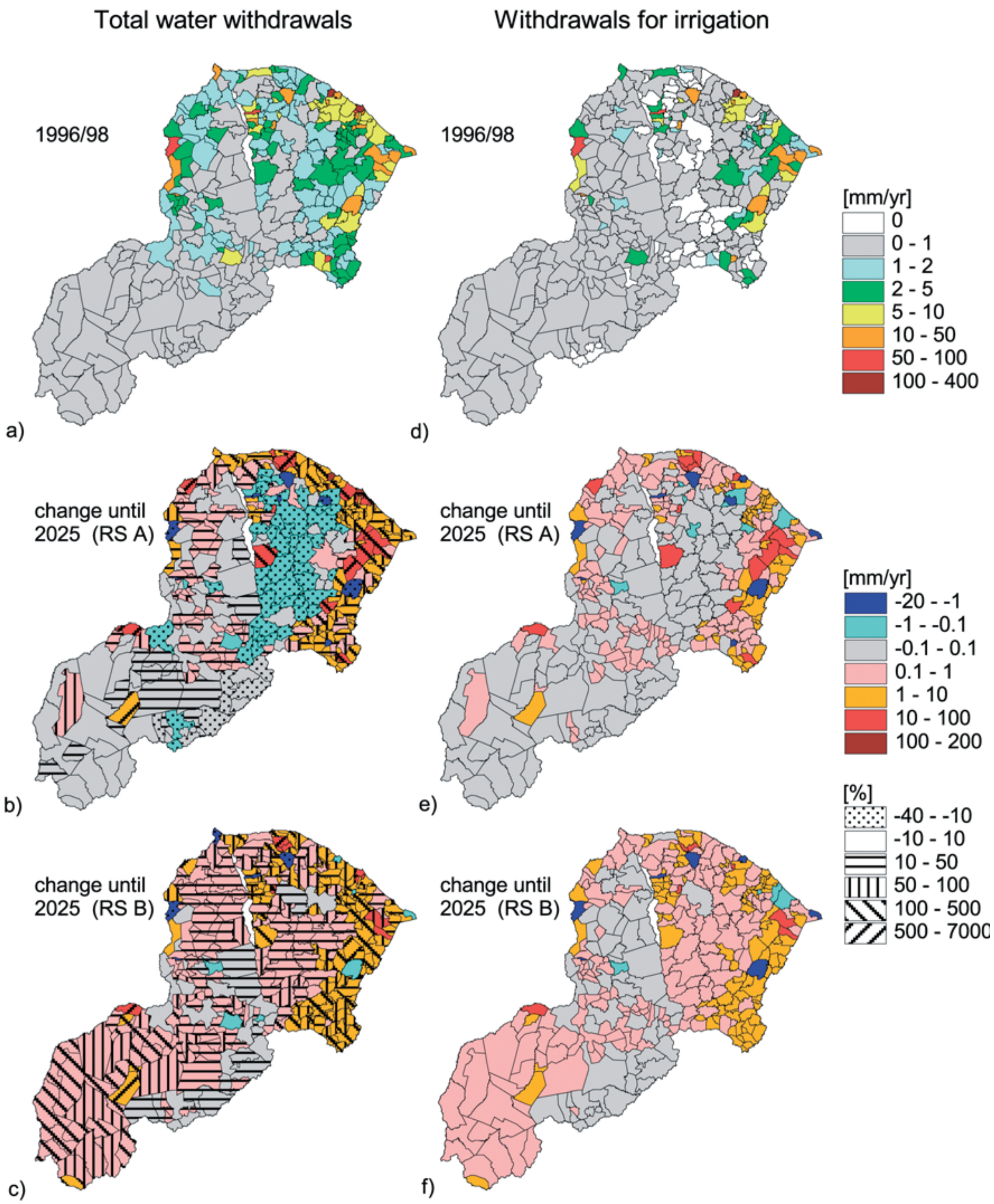

Fig. 4
Withdrawal water use in the 332 municipalities of Piauí and Ceará (in mm/year): **a** total withdrawals 1996/1998; **b** change of total withdrawals until 2025, RS A; **c** change of total withdrawals until 2025, RS B; **d** withdrawals for irrigation 1996/1998; **e** change of total irrigation withdrawals until 2025, RS A; **f** change of total irrigation withdrawals until 2025, RS B. The change of total withdrawals is also expressed in percent of the 1996/1998 values (parts **b** and **c**)

urban withdrawals are discharged into a sewage system). With a 2.5%/year water price increase, total domestic water use (including self-supply) increases by about 40% as compared to the reference scenarios (where 6%/year was assumed), while with 11%/year, total domestic water use decreases by approximately 45%.

Pricing of industrial water supply

Industrial water use intensity (withdrawal water use divided by industrial GDP) is related to price as 0.4:1:1.8 in the cases of 11, 6 and 2.5% water price increase per year. By 2025, the water use intensity will have decreased to 16, 37 and 66% of the present value. Consequently, industrial water use in the study area decreases by 58% in the case of 11%/year and increases by 80% in the case of 2.5%/year as compared to the reference scenarios. According to NoWUM, industrial water use is more responsive to water price than domestic water use because (1) industrial price elasticity is higher and (2) there are no self-supplied industries that are not affected by the pricing scheme of the public water suppliers (whereas self-supplied households are taken into account in NoWUM). In reality, however, the responsiveness is likely to be lower as an unknown fraction of industry is self-supplied.

Discussion

The model-based scenarios of water use in Piauí and Ceará indicate that water use will significantly increase until 2025. These scenarios can form the basis for assessing the extent and cost of additional water supply infrastructure that is necessary to fulfil the increasing demand. Besides, in particular the interventions show the effects of water demand management. They indicate where water use conflicts among water use sectors might occur, e.g. between urban water demand in Fortaleza and irrigation water demand in the upstream Jaguaribe basin (part of the "Region with large potential water resources, Ceará"). Besides, by comparing water use with water availability, the scenarios can be used to assess the problem of water scarcity.

In order to facilitate the application of the model-based water use scenarios for regional planning, it is necessary to discuss both the plausibility of the scenario assumptions and the model uncertainty. As the increase in water use is mainly due to increased irrigation, the question is whether the assumed expansion of irrigated areas is plausible. The implementation on 84,000 ha of public irrigation projects until 2025 in the case of RS A appears to be possible, as their construction has been planned for a much shorter time horizon (even though in the past not all of the planned projects were ever realized). In Piauí, with an estimated irrigated area of 13,000 ha in 1996/1998, irrigated areas are assumed to be extended to 45,000 ha in RS A and 29,000 ha in RS B. According to Paulo Iran from the Ministry of Agriculture of Piauí (personal communication, 2000), Piauí's irrigation covered about 30,000 ha in the mid-1980s (mainly rice), but then the area dropped to less than 10,000 ha at the beginning of the 1990s, due to the low market price for rice. These fast historic changes make it appear plausible that irrigated area could triple or double by 2025, as assumed in RS A and B, respectively. With respect to livestock water use, it is assumed that the number of livestock in a municipality changes with the human population. This is a very simple scenario assumption which could be improved if more information on livestock production, in particular its economics, was available. The tourism scenario is also very simple and requires refinements. The scenarios of industrial water use would become more relevant if a change of the industry mix could be included. However, much-improved statistics of present-day industrial water use (including self-supply) are required to make better assessments of future water use.

The different population distributions in RS A and RS B are, together with the assumed irrigated areas, the main reason for the different water use. For example, migration of people to a municipality with a relatively high per-capita water use (like Fortaleza) will increase domestic water use, as it is assumed that the new inhabitants have the municipality-specific water use. However, the population scenarios also affect livestock and industrial water use.

Finally, the approach to derive future domestic and industrial water use intensities by the econometric concept of elasticities needs to be discussed. It can be argued that the econometric approach is not suitable for long-term scenarios. An alternative approach is the concept of structural and technological change (STC), which has widely been used to generate energy use scenarios and was applied for global-scale modeling of water use by Alcamo et al. (2000). How are the driving forces structural and technological change related to the driving forces income and price? In STC, structural change in the domestic sector stands for changing household appliances that require water (such as washing machines or swimming pools), and it is generally assumed to be related to per-capita GDP. Therefore, it is comparable to income elasticity as applied in NoWUM. Structural change in the industrial sector stems from a changing industry mix, which can be taken into account explicitly by NoWUM. Technological change refers to endogenous water savings due to technological improvements, and as technological improvement are likely to be motivated by the cost of water, technological change and water price can be regarded as comparable driving forces. For NoWUM, we decided to use the econometric approach, because for the STC approach, the available information is even less reliable than for the econometric approach.

The computed domestic and industrial water use is highly dependent on the applied elasticities. With a price elasticity of –0.4, industrial water use intensity would have decreased to 49% of the 1996/1998 value, while with the decreasing price elasticities of NoWUM (–0.74 to –0.4), it decreases to 37%. Table 5 shows the sensitivity of domestic water use to price elasticity, providing both the total and per-capita domestic water use including the statistical distribution among the municipalities. With a price elasticity of –0.3, total domestic water use is computed to be about 18% higher than with a price elasticity that changes from –0.55 to –0.3. With a price elasticity of –0.55, most of the municipalities would have reached the lower limit of per-capita water withdrawals of 50 l/day by 2025 (not shown in the table).

In the case of RS A, average per-capita withdrawals for public-supplied households remain constant over time, and the potential increase due to increased income is balanced by the potential decrease due to increased prices. According to an analysis of domestic water use in selected municipalities of Ceará between 1989 and 1998 (data provided by CAGECE), water use per connected household has remained more or less constant. Unfortunately, the data are too uncertain and disparate to derive income and price elasticities.

Table 5
Total domestic water withdrawals and statistics of per-capita withdrawals for public-supplied households in the municipalities of Piauí and Ceará in 1997 and 2025 as a function of assumed price elasticities

	Decreasing price elasticity (from 1997 to 2025: –0.55 to –0.30)				Constant price elasticity (from 1997 to 2025: –0.30)			
	Total withdrawal (10^6 m^3/year)	Per-capita withdrawal (l/day)			Total withdrawal (10^6 m^3/year)	Per-capita withdrawal (l/day)		
		Average[a]	Minimum[b]	Maximum		Average[a]	Minimum[b]	Maximum
1997	349	139±45	50	399				
2025 RS A	427	115±37	50	334	506	140±45	51	409
2025 RS B	386	108±34	50	315	454	132±42	50	386

[a] Average and standard deviation for 332 municipalities
[b] For 2025, there is a minimum value of 50 l/day per person

Conclusions

If irrigation is strongly extended either by the implementation of the planned public irrigation projects (RS A) or by more disperse private irrigation (RS B), the pressure on scarce water resources will increase significantly in Piauí and Ceará, even if the irrigation water use efficiency is improved. Domestic and industrial water use will increase in regions with high immigration, but water use intensities can be controlled by an appropriate water pricing. Extending public water supply to more households than assumed in the reference scenarios will not increase considerably the pressure on the scarce resource water. The quantitative-qualitative scenario method, which combines narratives and models, appears to be an appropriate methodology to support strategic water management. Model-based scenarios of water use are a good basis for exploring water demand management measures; they are transparent and reproducible and can be easily adapted. First experiences have shown that Brazilian water authorities accept scenarios as a tool for supporting strategic water management. Within one year, three workshops took place in Ceará where representatives of the planning ministry and water agencies cooperated with German and Brazilian scientists of the WAVES program on the refinement of the scenarios. In the future, however, it would be desirable to involve policy-makers more intensively in the scenario development process.

A significant improvement of the developed water use scenarios is only possible if more reliable data on water use today and on its driving forces become available. This could be achieved if sectorial water use data in each municipality were acquired regularly, e.g. by adapting the approach taken in the USA (Solley et al. 1998). Then, the water use model could be refined (e.g. with respect to domestic water use by the self-supplied population), and its reliability could be improved. Furthermore, scenario construction could be enhanced by integrated modeling; a coupled modeling of agricultural economics, water use and water availability would lead to improved scenarios of irrigated areas and crops. Finally, for the generation of regional-scale scenarios of water use it is desirable to model water-use-related decision-making in smaller-scale units, e.g. river basin committees.

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