International Water Resources Association
Water International, Volume 27, Number 3, Pages 310–320, September 2002

Model-based Regional Assessment of Water Use
An Example for Semi-arid Northeastern Brazil

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Abstract: *Water use assessments are a necessary prerequisite for sustainable water resources management and planning in river basins, federal states, or countries. For reasons of transparency, flexibility, ease of update, and the possibility to generate scenarios of future water use, such assessments are best carried out by applying a water use model. To support water resources planning in two federal states of semi-arid Northeastern Brazil, Ceará and Piauí, the regional-scale water use model NoWUM was developed. It computes withdrawal and consumptive water use for each of 332 municipalities, distinguishing five water use sectors: irrigation, livestock, households, industry, and tourism. The model is suited to simulate the impact of global change and of management measures on water demand. Using NoWUM, the present-day water use situation in Ceará and Piauí is assessed. In addition, the impact of inter-annual climate variability and long-term climate change on irrigation requirements is considered. Scarce and uncertain input data lead to a high level of uncertainty in the model results. It is likely that water use in the most important sector, irrigation, is underestimated, while industrial water use is possibly overestimated. With some modifications, NoWUM has the potential to be applied for water use assessments in other data-poor regions of the globe.*

Keywords: *Water demand, water use, water resources planning, irrigation, households, industry, model.*

Introduction

One of the challenges of sustainable water resources management is to match water use with the availability of the resource. Even though it is widely recognized that this can no longer be achieved by only increasing water supply but that supply-oriented measures need to be combined with water demand management, less effort is generally put into assessing and managing water use than into assessing and managing water availability. Information on water availability, in the form of monitored river discharges and groundwater levels, is much more likely to be collected and made available than information on water use. Water use in the globally most important water use sector, irrigation, is typically not even measured (as irrigation water is generally not charged by volume). Existing information on domestic and industrial water use is very difficult to access because it is rarely collected at a central location, such that for a regional water use assessment, it is necessary to request data from each local water supplier and from each owner of private wells (which are not required to share the data).

To the authors' knowledge, the only country in which water use is assessed in a detailed and consistent manner is the USA, where consistent information on sectoral water uses in each county is compiled every five years and later made available to the public (Solley et al., 1998). Sustainable water resources management and planning in other countries would greatly profit from the introduction of such a water use survey. However, we propose to perform regional water use assessments that are based on water use models. A model-based assessment goes beyond the compilation of estimates of present water use that can be obtained without a model. It is likely to be more transparent and flexible, and it can easily be updated when new information becomes available. In particular, the climate-dependent irrigation water requirements can only be estimated by a model. With respect to water resources planning, the biggest advantage of a model-based assessment is that scenarios of future water use can be derived. In combination with scenarios on future water availability, such water use scenarios help to assess sustainability in the water resources sector under the impact of global and regional change (with respect to population, economy, climate, etc.) and water management measures.

While there is a wide range of hydrological (rainfall-runoff) models to estimate water availability in drainage basins and how it is affected by climate and land use change or water supply management measures, very few models exist that estimate the water use in a region and how it is affected by global change and water demand management measures. There are some data-intensive models for municipal water use in individual urban areas (e.g. USBR, 1991; Clarke et al., 1997; Mimi and Smith, 2000) and many models to compute irrigation requirements (e.g. FAO, 1992). IWR-MAIN (2000) is a commercial water use forecasting system that can cover all water use sectors and has been widely applied to cities and river basins in the USA (for a critique of IWR-MAIN, refer to Parker et al., 1995).

In this paper, we present a new regional-scale water use model which computes water use in the five sectors: irrigation, livestock, households, industry, and tourism (the term “water use” is applied in this paper as a synonym for “water demand”). It was designed to support water resources planning in two federal states of semi-arid Northeastern Brazil, Ceará and Piauí (Figure 1), and simulates water use in each of the 332 municipalities of the two states. Ceará and Piauí cover an area of 400,000 km^2 and, in 1996, had a population of 9.5 million. They are among the poorer states of Brazil; the 1996 per-capita Gross Domestic Product (GDP) was only 46 percent (Ceará) and 29 percent (Piauí) of the average value for Brazil (1996 US$ 4800), respectively (http://www.ibge.gov.br, http://www.iadb.org). Scarcity of water is a major constraint for development in the region, which suffers from a strong seasonality of rainfall as well as from recurrent drought years related to the El Niño phenomenon. The major part of the subsurface in Ceará is crystalline bedrock, which does not represent an important aquifer, and water availability in the dry season is provided by about 8,000 very small to large surface impoundments for seasonal and inter-annual storage of water. In Piauí, there are extensive sedimentary aquifers that can be used for water supply, but due to the low groundwater recharge rate, their exploitation is prone to become unsustainable. In the El Niño drought year 1998, for example, the situation of rural population became so desperate that shops were looted. Many reservoirs fell dry such that in some towns tap water was no longer available. Consequently, water resources planning is a particularly important component of regional planning in the study area. In 1999, the state of Ceará spent approximately US$50 million, or 0.5 percent of its GDP, on water resources planning and management (J.C. de Araújo, 2000, personal communication).

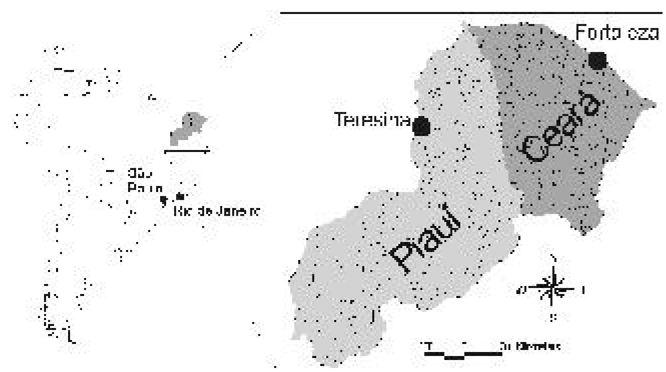

Figure 1. The study region Ceará and Piauí, two federal states in Northeastern Brazil (400,000 km^2). The outline of the municipalities is also shown.

In Ceará and Piauí, irrigation is an important water use sector, and it is hoped that an extended production of irrigated fruits for export will improve the economic situation of the rural population. Different from most other areas of the globe, water use by livestock cannot be neglected, as in the drier parts of the study area, livestock numbers can exceed the human population. With respect to domestic water use, the situation differs strongly between rural and urban areas. Public water supply is almost everywhere restricted to urban areas, where the waterworks have difficulties serving the ever increasing number of urban dwellers (who, given the convenience of tap water, consume relatively high amounts of water). This is particularly true in the metropolitan area of Fortaleza, the capital of Ceará, where population has grown from less than 1 million in 1970 to 2.6 million in 1996, and where only 68 percent of the inhabitants have tap water in their houses. Rural households are, in general, self-supplied. In total, about half the population of Ceará and Piauí is connected to public water supply. Most of the unconnected households rely on more than one source of water (public water points, private shallow wells, rivers, reservoirs, cisterns, water trucks) which vary with the type of end use and the season of the year. For many of these households, access to safe drinking water is difficult, and becomes even more difficult during droughts. Water use by industry and tourism is presently only relevant in a few municipalities, but these sectors are expected to gain importance in the future. Given the above described water resources situation in Ceará and Piauí, it is particularly important to manage both water supply and water demand. While the construction and proper management of water infrastructure is the necessary basis for a secure water supply, a concurrent program of water demand management is essential for a sustainable economic and social development of the region.

The research work presented in this paper contributed to the German-Brazilian research cooperation program WAVES (http://www.usf.uni-kassel.de/waves). This program also lead to the development of a hydrological model of the study area (Bronstert et al., 2000). Both the water use model and the hydrological model are applied conjunctively to compute discharge in rivers and water scarcity indicators. While they are designed to support planning at the state level, they can also be used to assist decision-making by river basin committees, which are being established according to the recent Brazilian water law.

In the following sections, the model-based assessment of municipality-specific water use in Ceará and Piauí is presented. First, the regional-scale water use model, NoWUM (Nordeste Water Use Model), is described. Then, the computed present-day water use (approximately for the period 1996 to 1998) is shown, including the impact of inter-annual climate variability on irrigation water requirements. In addition, the potential impact of global climate change on irrigation water requirements is explored. Finally, the uncertainty of the model results is discussed and conclusions with respect to model-based water use assessments are drawn.

Model Description

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, which is 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 return flow can be reused downstream, but only if the quality of water has not been significantly deteriorated by its use or during transport. The ratio between consumptive and withdrawal water use is called water use efficiency. In-situ water use (e.g. for navigation) is not taken into account in NoWUM.

NoWUM distinguishes five water use sectors: irrigation, livestock, households, industry, and tourism (Figure 2). Each sectoral water use is computed as a function of water use intensity (e.g. per-capita domestic water use of 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 climate and the season of the year, only the strong seasonality and climate dependence of irrigation water use is simulated by the model. Model design was strongly influenced by the availability of data. NoWUM was not calibrated; due to the lack of independent data, the model could be validated only to a very limited extent (see the discussion of model uncertainties below). In the next sections, the modeling approach for the five water use sectors is described; a detailed model documentation is provided in Hauschild and Döll (2000).

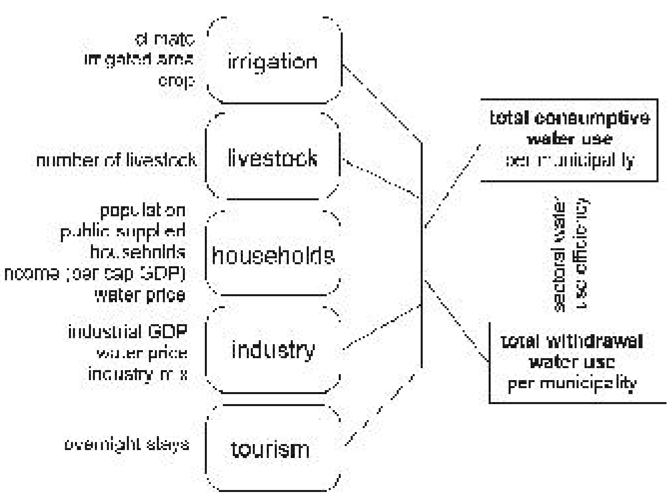

Figure 2. Overview of the regional-scale water use model NoWUM showing the driving forces which determine the water use for irrigation, livestock, households, industry, and tourism.

Irrigation Water Use

Irrigation water use is calculated as a function of climate, irrigated area, and type of irrigated crop. Consumptive water use, or net irrigation requirement, is defined as the amount of water that must be added to the soil such that the crop can evapotranspirate at the optimal (potential) rate. Crop-specific consumptive water use per unit irrigated area during the growing period, I_c, is computed according to the CROPWAT methodology (FAO, 1992) as

$$I_c = \sum_{i=1}^{n} K_{c,i} E_{p,i} - P_{eff,i} \qquad (1)$$

where i is a10-day-period; n is the number of 10-day-periods within the growing period (crop-specific); K_c is crop coefficient (crop-specific) (-); E_p is potential evapotranspiration (mm/10-days); and P_{eff} is effective precipitation (mm/10-days).

Usage of effective precipitation P_{eff} instead of total precipitation P takes into account the part of the rain that is not available for the crops because it runs off or is transported below the root zone. According to the USDA Soil Conservation Service Method (as given in FAO, 1992)

$P_{eff} = P(41.7 - 0.2\ P) / 41.7$ for $P < 83$ mm/10-days
$P_{eff} = 41.7 + 0.1\ P$ for $P \geq 83$ mm/10-days

The total consumptive irrigation water use of each municipality is computed by taking into account the crop-class-specific irrigated areas. Withdrawal water use is calculated by dividing consumptive use by the irrigation water use efficiency, which, following Brazilian expert knowledge, is assumed to be 0.6 in the whole region.

Irrigated Areas in 1996 to 1998

The Brazilian Agricultural Census of 1995 to 1996 (IBGE, 1998a; 1998b) provides crop-specific harvested areas of different irrigated crops and the total irrigated area for all municipalities in Ceará and Piauí. However, Brazilian experts agree that the total irrigated areas are strongly overestimated by the census. Besides, the harvested areas and the total irrigated area often seem to be inconsistent. Therefore, we derived a best estimate of the crop-specific irrigated areas in each municipality by taking into account, for Ceará: (1) information on crop-specific irrigation licenses 1998 in the most important irrigation areas from the Water Resources Ministry in Ceará; (2) information from the Agricultural Census for 23 municipalities; and (3) estimates of Brazilian experts for eight municipalities, and for Piauí: (1) information from the Agricultural Census, and (2) estimates of Brazilian experts. The estimated total irrigated area is 43,000 ha in Ceará (compared to 77,000 ha according to the Agricultural Census), and 13,000 ha in Piauí (compared to 18,000 ha).

Crops

Based on the Brazilian Agricultural Census of 1995/96 (IBGE, 1998a; 1998b), nine irrigated crop classes are distinguished which cover almost all crops irrigated in Ceará and Piauí: banana, beans, cotton, fruit trees, grass, maize, rice, sugar cane, and vegetables. Crop-coefficients and growing season length of each crop class were taken from FAO (1992) (for fruit trees and vegetables, respectively, the FAO values for citrus trees and tomato were used), while crop-class-specific planting dates were defined based on a variety of local sources. Due to the lack of information on multicropping and the uncertainty with respect to the irrigated areas, each crop class was assigned to have only one growing season per year.

Climate Data

Daily values of precipitation and (Penman-Monteith) potential evapotranspiration in each municipality were generated for the period 1921 to 1980 by spatial interpolation of daily data from 30 measurement stations (Gerstengarbe and Güntner, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 1999, personal communication). Average net irrigation requirements per unit irrigated area under present-day conditions were computed by first simulating 30 years of irrigation with the climate of 1951 to 1980 and the irrigated areas of 1996 to 1998, and then averaging the resulting annual requirements. This procedure is more appropriate for the computation than the use of long-term average climatic data as model input, which, due to the nonlinearity of Equation 1, would lead to an underestimation of the long-term average irrigation water requirement.

Two climate change scenarios for the years 2000 to 2050 (daily values) were derived by a statistical downscaling method, taking into account precipitation change in Northeastern Brazil as computed by global climate models for a one percent yearly increase of greenhouse gas concentrations, and historic station data for 1921 to 1980 (Werner and Gerstengarbe, 1997). Here the tendency in annual precipitation as computed by the climate models was taken as the regionally most relevant climate trend. Simultaneously observed daily data on precipitation and temperature were used to interpret these tendencies into projections of these variables at the station level. Other meteorological variables like relative humidity and short-wave radiation were added using regression relations derived from the few available daily time series of a more complete set of meteorological variables. This resulted in climate scenarios at the level of the climate stations, which were then interpolated to municipalities. To estimate the impact of climate change on irrigation requirements, the forecast 2011 to 2040 time series was used. The applied climate models were the ECHAM4 climate model of the Max-Plank-Institute, Hamburg, Germany (Röckner et al., 1996) and the HadCM2 model of the Hadley Centre for Climate Prediction and Research, Bracknell, Great Britain (Johns et al., 1997). Of all state-of-the-art climate models, these two models show the best correspondence of modeled historic climate to observed historic climate in Northeastern Brazil (Krol et al., 2003). Both models result in quite different precipitation developments in the study area. However, the major changes with respect to today as well as a pronounced difference between the two scenarios only appear after 2025. The average precipitation over the study area for the period 2011 to 2040 is 864 mm/yr according to ECHAM4 and 1,053 mm/yr according to HadCM2, compared to 897 mm/yr for 1951 to 1980. Climate variability certainly dominates climate change. Please note that the downscaling method which is based on precipitation trends appears to result in implausible scenarios of potential evapotranspiration; the downscaled average potential evapotranspiration for the period 2011 to 2040 is 2,057 mm/yr according to ECHAM4 and 2,064 mm/yr according to HadCM2, compared to 2,098 mm/yr for 1951 to 1980 even though, according to the climate models, temperature increases.

Livestock Water Use

Annual values of livestock water use are calculated from the number of animals per species in each municipality (IBGE, 1998a; 1998b) and a species-specific water use typical for Northeastern Brazil (EMBRPA-CPATSA/SUDENE, 1984). Eleven species were differentiated. Withdrawal water use is assumed to be equal to consumptive water use, as livestock husbrandry is mainly extensive and the used water evapotranspirates on the grasslands.

Domestic Water Use

Domestic water use includes the 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 households connected to public water supply (i.e., with tap water) is differentiated from that of self-supplied households. The municipality-specific per-capita water use in connected households for the current situation was calculated from municipality-specific data provided by the local water suppliers, which, for 1997, include the number of connected households and the volume of water that was charged to the customers, i.e., the billed volume. This amount is, however, not equal to the actual water use, because each household is charged a minimum of 10 m^3/month even if it does not use that much water, and because many households without a water meter are only charged for 10 m^3/month even though they might use much more. Information on the volume of water withdrawn from its source is not available for all municipalities. However, where information is available, the withdrawn volume is higher than the charged volume by up to a factor of two. Future per-capita domestic water use of connected households is assumed to be a function of income and water price (Döll and Hauschild, 2002). The economic concept of elasticities is used to compute the decreasing per-capita water use in case of increasing water price (price elasticity) and the increasing per capita water use in case of increasing incomes (income elasticity).

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/d, a value defined by Gleick (1996) as the basic human water requirement. Water use efficiency in the domestic sector is assumed to be 0.2, based on data for domestic water use in the USA (Solley et al., 1998). The same efficiency is also used for the industrial and the tourism sectors.

Industrial Water Use

Industrial water use is computed as a function of the industrial GDP (IGDP) of 19 industries (paper, textile, etc.) in each municipality and the branch-specific water use per IGDP (industrial water use intensity). However, no information on either GDP, total IGDP or branch-specific IGDP is available for the municipalities of Piauí. Only the GDP and total IGDP of the whole state is known. We used information on the number of companies in each industrial branch and municipality in Piauí to derive a best estimate of the branch-specific IGDPs, assuming, in the first step, that for a given branch a company in Piauí has the same average IGDP as a company in Ceará. In a second step, the values were corrected proportionally such that they summed up to the state's IGDP value. The branch-specific water use per IGDP was assumed to be the same as in Germany, as derived from annual data of the industrial gross domestic product (IGDP) per branch and the water used in each industrial branch (Statistisches Bundesamt, 1998; 1999), because no Brazilian data were available (please refer to the discussion on uncertainty of computed industrial water use in the Discussion section). Future industrial water use per industrial output is simulated to be influenced by the water price (Döll and Hauschild, 2002).

Tourism Water Use

Tourism water use is modeled as a function of the number of tourists, the average length of stay and the water use per tourist and day. The number of tourists in each municipality and their average length of stay were estimated from a variety of regional studies on tourism. According to Stephenson (1998), the per-capita withdrawal water use in hotels varies between 300 and 500 l/d. In NoWUM, a per-capita value of 500 l/d is assumed for coastal municipalities reflecting the better hotel infrastructure (swimming pools, irrigation of gardens) and activities of tourists (several baths per day). In all other municipalities a per-capita water use of 300 l/d is used.

Results

Table 1 provides an overview of the annual sectoral and total water uses in Ceará and Piauí as computed by NoWUM for the period 1996 to 1998. In both states, irrigation is the most important water user, accounting for 44 percent of the total withdrawal water use in Ceará and Piauí, and for even 54 percent of the total consumptive use; the higher percentage is due to the higher fraction of the withdrawn water that evapotranspirates during irrigation. Households form the second most important sectoral water use sector, followed by the livestock sector. Compared to most other regions of the world, the fraction of livestock water use is exceptionally high. Water use by industry and tourism is small, particularly in Piauí. Total water use in Ceará is more than twice the water use in Piauí, which is mostly due to the driving forces of water use: there are more irrigated areas, a higher human and livestock population, more industry, and more tourism in this state (Table 2). Due to the seasonality of irrigation water use, the total monthly withdrawal water uses vary between 29 and 92 million m^3/month in Ceará (annual average 59 million m^3/month) and between 10 and 41 million m^3/month in Piauí (annual average 27 million m^3/month).

The average values of per-capita withdrawals by persons in households connected to the public water supply are 137 l/d in Ceará and 144 l/d in Piauí. The average per-capita domestic withdrawal water use in public-supplied and self-supplied households is estimated to be 92 l/d in

Table 1. Withdrawal and Consumptive Water Use Per Sector in 1996 to 1998 as Modeled with NoWUM

	Ceará		*Piauí*	
Water Use Sector	*Withdrawal Use ($10^6m^3/yr$)*	*Consumptive Use ($10^6m^3/yr$)*	*Withdrawal Use ($10^6m^3/yr$)*	*Consumptive Use ($10^6m^3/yr$)*
Irrigation[a]	324.0	194.4	127.5	76.5
Livestock	81.2	81.2	65.1	65.1
Households	225.5	45.1	123.6	24.7
Industry	46.2	9.2	4.1	0.8
Tourism	16.7	3.3	2.1	0.4
Total	694.0	333.2	322.4	167.6

[a] average of 30 years of irrigation requirements (climate time series 1951 to 1980) for irrigated areas of 1996 to 1998. Due to the randomness of climate, the irrigation requirements under long-term average conditions are more meaningful than the irrigation requirements under the actual climate in 1996 to 1998.

Table 2. Main Driving Forces of Sectoral Water Uses in Ceará and Piauí 1996 to 1998

	Ceará	*Piauí*
Irrigated area (ha)	43,024	13,170
Cows / pigs / sheep (10^6)	2.4 / 1.1 / 1.6	1.7 / 1.4 / 1.3
Population (10^6)	6.7	2.7
Industrial gross domestic product (10^6 1995-US$/yr)	2,843	363
Touristic overnight stays (10^6/yr)	36.3	3.8

Ceará and 125 l/d in Piauí. The differences reflect the higher percentage of public-supplied population in Piauí (54 percent) as compared to Ceará (46 percent). Per capita total withdrawals are 283 l/d in Ceará and 327 l/d in Piauí.

For management and planning purposes, it is not sufficient to consider state averages only. Spatially resolved information is necessary to identify critical areas and to determine appropriate policy measures taken at the river basin and the state levels. Estimated sectoral water uses in each municipality, as computed by NoWUM, was delivered to the regional planning authorities of Ceará and Piauí, where the assessment will serve as a basis for water resources planning. Figure 3 shows the annual withdrawal water use for 1996 to 98 in each of the 332 municipalities for the two most important sectors, irrigation and households, and the sum of all sectors. Water use is expressed in mm/yr, i.e. it is normalized with respect to the area of the municipality, such that it is directly comparable to runoff (water availability). The spatial pattern of irrigation water use (Figure 3a) is explained by: (a) the fraction of the area of the municipality that is irrigated; (b) the percentage of perennial crops (banana, fruit trees, grass, sugar cane); and (c) the precipitation (more precipitation at the coast and in a few mountainous areas). In Piauí, extensive irrigation takes place around the urban centers of Teresina, Parnaiba, and Picos, and in Ceará along the Jaguaribe river (eastern part of the state), in the Cariri region, in the Curu valley, and in the Serra de Ibiapaba. The highest domestic water uses in Piauí occur in the above-mentioned urban centers, and in Ceará in the metropolitan area of Fortaleza, in Sobral, in the Serra de Ibiapaba and in the Cariri (Figure 3b). The municipal averages of per-capita domestic withdrawal water use in public-supplied households differ strongly and range from 73 to 399 l/d in Ceará and from 50 to 294 l/d in Piauí. The spatial pattern of total withdrawal water use (Figure 3c) is dominated by the irrigation and domestic sectors. Significant contributions from the other three water use sectors are found in: (1) the dry Sertão region of central Ceará, from the livestock sector, due to the high cattle density; (2) the urban centers particularly of Ceará, from the industrial sector; and (3) the most attractive coastal municipalities including the metropolitan area of Fortaleza and in two places of pilgrimage

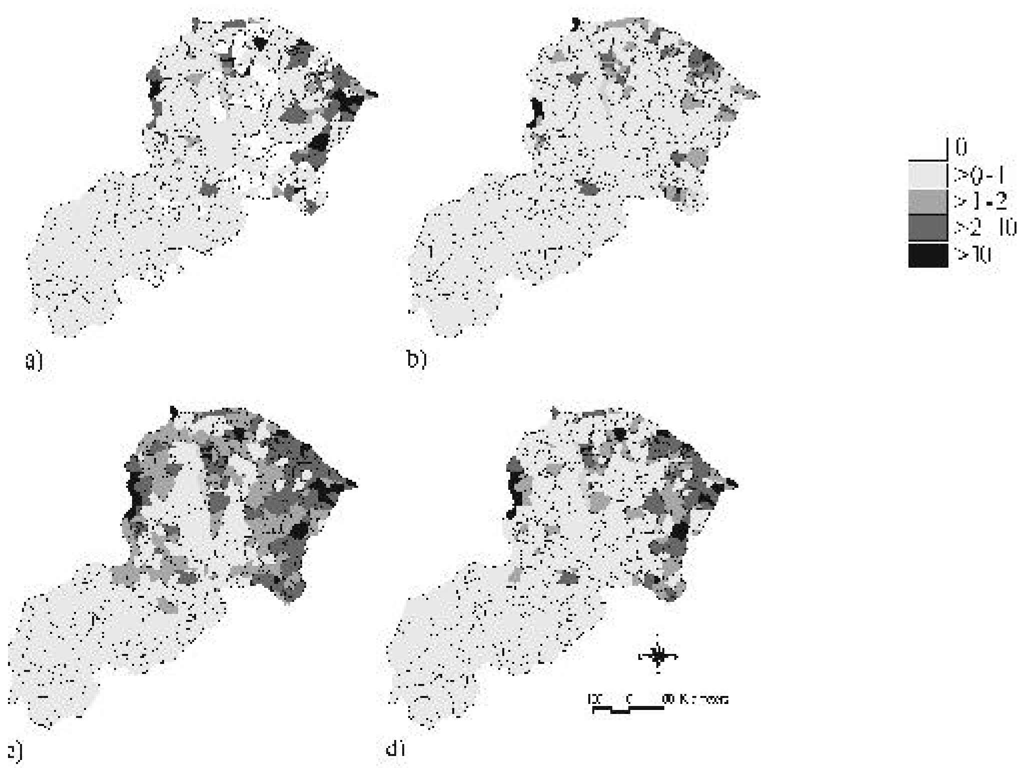

Figure 3. Water use 1996 to 1998 (in mm/yr averaged over the municipal area) as calculated with NoWUM for each municipality of Ceará and Piauí: (a) irrigation withdrawal water use; (b) domestic withdrawal water use; (c) total withdrawal water use; and (d) total consumptive water use.

in Ceará, from the tourism sector.

In the above assessment of present-day water use, irrigation requirements under long-term average climate conditions are taken into account and not the requirements under the climatic conditions of the period 1996 to 1998. Due to the randomness of climate, the actual optimal water use in a certain year is not a useful quantity for planning purposes. It is more meaningful to look at: (1) the irrigation requirements under long-term average climatic conditions, and (2) the requirements under the climatic conditions of typical dry and wet years. In years with below-average precipitation and thus below-average water availability, irrigation requirements are likely to be higher than normal, unless only the precipitation outside the growing season is reduced. This correlation exacerbates any water scarcity problem. For an assessment of water scarcity it is, therefore, useful to look at the situation in dry years, and not at average climatic conditions. Figure 4a shows that irrigation requirements under the climatic conditions of the year 1970, the year with the lowest precipitation during 1951 to 1980 (average over the study region), increase in 67 percent of the 269 municipalities with irrigation by more than 0.01 mm/yr, averaged over the total area of the municipality, as compared to long-term average climatic conditions (1951 to 1980). In 15 percent, irrigation requirements even increase by 25 to 100 percent (up to 3.5 mm/year).

Potential impacts of long-term climatic change on irrigation requirements are determined by comparing the irrigation requirements of the crops irrigated in 1996 to 1998 with the 1951 to 1980 climate and the 2011 to 2040 climate scenarios (derived by downscaling of the ECHAM4 and HadCM2 climate model results). Even though the precipitation averaged over the study area slightly decreases in the case of ECHAM4, the future climate scenario results in significantly reduced requirements in 48 percent of all municipalities with irrigation (up to 6.5 mm/yr reduction) and in increased requirements in only 4 percent (less than 0.3 mm/yr) (Figure 4b). This is due to the spatial and seasonal distribution of precipitation and the (questionable) decrease of potential evapotranspiration in the downscaled climate data set. With HadCM2, the reductions of irrigation requirements are even somewhat higher.

Discussion

Using the regional-scale water use model NoWUM, the first consistent and comprehensive assessment of water use in all municipalities of Ceará and Piauí was achieved. Previous studies on water use in Ceará and Piauí either did not provide results that were consistent for all municipalities (SRH, 1992, for Ceará) or only provided water use estimates in a few river basins but not in municipalities (Marwell Filho, 1995, for Piauí). In both studies, the domestic water use of the urban population is estimated by assuming typical per-capita values that depend on the size of the town, while standard (neither climate-dependent nor crop-specific) withdrawal values are adopted to compute irrigation water use. In NoWUM, municipality-specific information on domestic water supply and the number of connected households is included, and the dependence of irrigation water use on irrigated crops and climate is taken into account. More importantly, NoWUM is an operational model that can be applied to generate scenarios of future water use in a flexible and consistent manner (Döll and Hauschild, 2002). In addition, it provides information on consumptive water use that is necessary to compute water availability using common hydrological models, as the natural discharge is reduced by consumptive water use. In river basins with significant consumptive water use, the observed discharge is smaller than the natural one. NoWUM results can be used to assess water availability and water scarcity in river basins by aggregating the municipal values along the drainage directions in the basin.

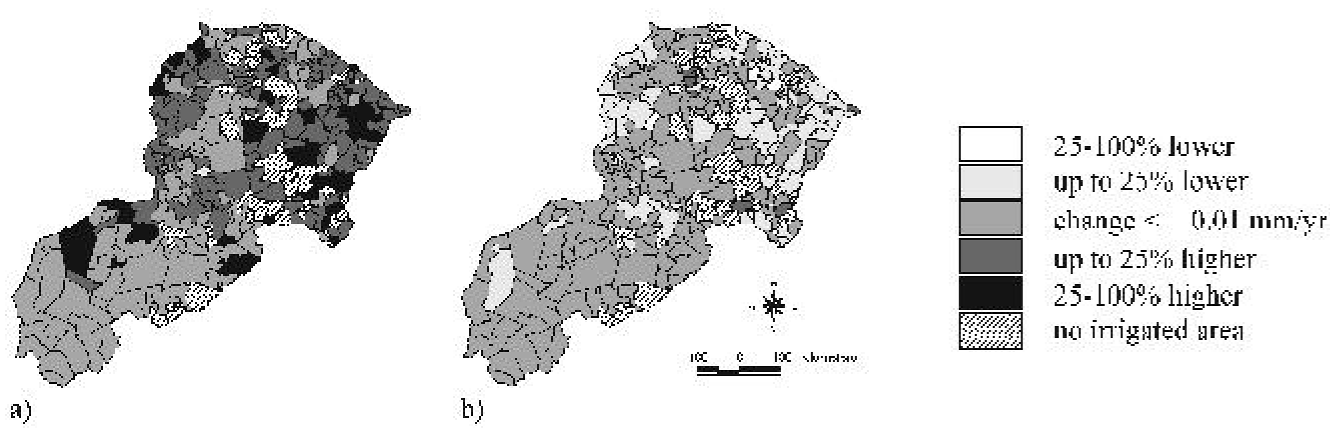

Figure 4. a) Irrigation requirement per unit irriated area in the dry year 1970 as compared to the requirement under long-term average climatic conditions (1951 to 1980); b) irrigation requirement under a changed climate (approx. 2025, i.e. average 2011 to 2040) as compared to the requirement under long-term average climate conditions (1951 to 1980).

Application of NoWUM for water resources planning requires that the uncertainty of the NoWUM model results is known at least approximately. We can only strive for a qualitative uncertainty analysis, as neither quantitative estimates of the uncertainty of important input data nor independent observations to which our model results could be compared are available. In the following, only the uncertainty of the computed present-day water use is discussed. The uncertainties related to the impact of climate change on irrigation requirements are very large, which is due to the low degree of reliability of the precipitation that is computed by climate models (IPCC, 2001) and due to the downscaling.

Uncertainty of Irrigation Water Use

In NoWUM, the optimal irrigation water use, the irrigation requirement, is computed and not the actual one, which in a certain year may be lower due to, for example, reduced water availability. The computed irrigation requirement is strongly dependent on the assumed municipality-specific precipitation and potential evapotranspiration. As only 30 measurement stations with long time series of daily data existed, the (high) spatial variability of precipitation is not represented well. While the spatial variability of potential evapotranspiration is much lower than that of precipitation, its absolute value is rather uncertain, due to the uncertainty of radiation, humidity, and wind measurements and the uncertainty related to the different possible algorithms that can be used to compute potential evapotranspiration.

The irrigated area is another highly uncertain input to the model. SRH (1992) assumed that the total irrigated area in Céara was 108,000 ha in 1990, while COGERH (1998) considered a value of 60,000 ha in 1997, IBGE (1998a) a value of 77,000 ha in 1996 and our study a value of 43,000 ha in 1996 to 1998. For Piauí, Marwell Filho (1995) adopted an irrigated area of 12,000 ha in 1994, IBGE (1998b) a value of 18,000 ha in 1996, and our study a value of 13,000 ha. Obviously, part of the discrepancy can be linked to an inter-annual variability of the actually irrigated area (a fraction of the areas that are equipped for irrigation), which is mainly due to rapidly changing market prices and public subsidies. Besides, in dry years with low water availability and high per unit area irrigation water use, not enough water is available to irrigate the whole area that is equipped for irrigation. The main reason for the discrepancy is that generally only information on public irrigation projects but not on private irrigation is available. In some areas of Ceará, a licensing of irrigation has been recently introduced; this licensing information was included in NoWUM. Due to the high uncertainty of irrigated areas and to the very limited information on multi-cropping, we decided not to model multi-cropping in NoWUM.

The irrigation requirements per unit irrigated area are compared to the irrigation recommendations given by agricultural advisors for Northeastern Brazil (Table 3). The recommended values lie in the range of the municipality-specific values as computed by NoWUM for banana, cotton, fruit trees, and vegetables. For beans, maize and rice, NoWUM withdrawals are smaller than the recommended ones. For beans and maize, there are two possible explanations for the discrepancy: (1) if beans and maize form part of a multi-cropping scheme, they are often planted as the second crop in the growing season and not as the first crop, i.e., at the beginning of the rainy season. Therefore, precipitation during the actual growing season might be much lower than considered by NoWUM; and (2) beans and maize, as cheap subsistence crops, are not irrigated with such advanced water-saving technologies (e.g., micro-sprinkler) as, for example, fruit trees, and thus the water use efficiency for these crops is possibly much lower than 0.6, e.g., only 0.3, a typical value for surface irrigation. Then, the computed withdrawals would be twice the values listed in Table 3 and thus better fit the recommended values. For rice, which is mainly grown under inundated conditions, the water use efficiency might even be lower than 0.3 due to the higher leakage losses and the evaporation from the surface water table, which would also lead to a better fit between computed and recommended values. Therefore, in future calculations, crop-specific irrigation water use efficiencies will be used. Please note how the irrigation requirements vary among municipalities (Table 3); this roughly reflects the climatic differences between the relatively wet coastal zone and the dry hinterland.

NoWUM computes irrigation withdrawals of 324 million m^3/year for Ceará, which is smaller than the COGERH (1998) value of 561 million m^3/year (with 40 percent more irrigated area and 24 percent higher irrigation requirement

Table 3. Comparison of Crop-specific Gross Irrigation Requirements Per Unit Irrigated Area: Withdrawals Recommended by Agricultural Advisors for Northeastern Brazil Compared to the Climate-dependent and thus Municipality-specific Values Computed by NoWUM

		Withdrawals per Growing Period Computed with NoWUM[b] (mm)	
Crop	*Recommended Withdrawal Per Growing Period[a] (mm)*	*Average ± Standard Deviation*	*Range of Values in Different Municipalities*
Banana	2000	1559 ± 212	1069-2093
Beans	500	132 ± 53	41-288
Cotton	800	513 ± 153	292-911
Fruit trees	1000-1200	1267 ± 166	950-1742
Grass	no information	1966 ± 251	1481-2638
Maize	600	201 ± 88	61-474
Rice	800	290 ± 78	128-508
Sugar cane	no information	1846 ± 237	1390-2487
Vegetables	600	835 ± 147	444-1123

[a] BNB (1997)
[b]calculated for 1951 to 1980 climatic conditions and with a water use efficiency of 0.6.

per unit irrigated area than NoWUM), and much smaller than the SRH (1992) value of 942 million m^3/year (with 150 percent more irrigated area and 15 percent higher irrigation requirement per unit irrigated area). The NoWUM withdrawals in Piauí add up to 128 million m^3/year, a somewhat lower value than the 148 million m^3/year in the study of Marwell Filho (1995) (with 8 percent less irrigated area and 15 percent higher irrigation requirement per unit irrigated area than NoWUM).

Uncertainty of Livestock Water Use

The state averages of livestock water use estimated by SRH (1992) and Marwell Filho (1995) are very close to NoWUM results shown in Table 1. This does not necessarily indicate a low uncertainty, as the agreement might be due to the fact that the livestock-specific water use values of all studies are from the same source.

Uncertainty of Domestic Water Use

The largest uncertainty in the computed domestic water use estimates is the per-capita water use in self-supplied households. With 50 l/d, water use might be underestimated if households have their own wells, but might be overestimated if the water source is distant or drinking water must be bought at a considerable price. Marwell Filho (1995), for example, assumes a value of 70 l/d. Table 4 shows the results of a sensitivity analysis of domestic water use with respect to the per-capita withdrawal water use of the self-supplied population. If the per-capita withdrawal water use is only 20 l/d instead of 50 l/d, the total domestic water use decreases by 18 percent in Ceará, and by 10 percent in Piauí. If it is 100 l/d, the total domestic water use increases by 29 percent in Ceará, and by 17 percent in Piauí. The total domestic water use computed

Table 4. Range of Computed Total Domestic Water Use 1996 to 1998 (10^6 m^3) in Ceará and Piauí for Different Assumptions on Per Capita Water Use of the Self-supplied Population

	Total Domestic Water Use 1996 to 1998 (10^6 m^3/yr) Assuming a Per Capita Withdrawal Water Use in Self-supplied Households of			
	20 l/d	50 l/d	70 l/d	100 l/d
Ceará	186	226	252	292
Piauí	111	124	133	145

by NoWUM for Ceará is 18 percent lower than listed in SRH(1992) and COGERH (1998), while the NoWUM value for Piauí is 23 percent higher than the estimate of Marwell Filho (1995).

Uncertainty of Industrial Water Use

As described above, industrial water use is computed as a function of the branch-specific water withdrawals per IGDP for German industry. This could lead to either an over- or underestimation of industrial water use. On the one hand, water is scarce in the study region (except in the municipalities along the main-stem Parnaiba, which include the capital of Piauí, Teresina), and industries might have adapted to the scarcity of water. On the other hand, industrial water use in Germany has strongly decreased since the 1980s due to the introduction of water-saving technology that might not yet be used in the study region. Therefore, we tried an alternative method for deriving present-day industrial water use and compared the results (Table 5). We gathered information on the fraction of water from the public water supply that is used by industry (not available for all municipalities) and the amount of raw water public-supplied to industry by COGERH in Ceará, mainly in the metropolitan area of Fortaleza. A large but unknown part of the industry is self-supplied. The only information available to us was gathered by Marwell Filho (1995), who derived values of self-supplied industrial water use from telephone interviews with industrial companies for the river basins of Piauí. Averaged over Piauí, the self-supplied industrial water use is reported to be 1.57 times higher than the public-supplied industrial water use. Marwell Filho remarked that his values of the self-supplied industrial water use are probably too low as not all the companies were interviewed. Lacking any information on industrial self-supply in Ceará, we simply assumed that in each munipality, the self-supplied water use is 1.57 times the public-supplied industrial water use. In some municipalities with industry, public-supplied industrial water use according to the waterworks is zero. In these municipalities, the water use as computed from branch-specific values was corrected by the ratio between the water use as computed with the alternative method and the water use as computed with our standard method (average over all municipalities with data). With the alternative method, industrial withdrawal water use in Ceará is reduced from 46.2 to 25.6x10^6 m^3/year in Ceará, and from 4.1 to 0.9x10^6 m^3/yr in Piauí. The percent differences of municipality-specific values can even be higher.

Table 5. Industrial Water Use in 1996 to 1998 as Modeled with NoWUM using Two Different Methods

	Ceará		*Piauí*	
	Withdrawal Use (10^6 m^3/yr)	*Consumptive Use (10^6 m^3/yr)*	*Withdrawal Use (10^6 m^3/yr)*	*ConsumpiveUse (10^6 m^3/yr)*
Standard method[a]	46.2	9.2	4.1	0.8
Alternative method[b]	25.6	5.1	0.9	0.2

[a] Calculated from IGDP per industrial branch and German branch-specific water use efficiencies.
[b] Based on incomplete data from water suppliers and an assumed self-supplied industrial water use, derived from Marwell Filho (1995).

Uncertainty of Tourism Water Use

No comparison to other estimates or data is possible for tourism water use. A difficulty in computing tourism water use, in addition to domestic water use, is that tourism water use is already included in the domestic water use. The reason for including tourism water use in NoWUM was not to improve the assessment of the present water use situation but to be able to generate relevant scenarios, as future water use particularly in coastal municipalities is likely to be strongly influenced by the development of tourism.

Conclusions

There is a growing need to assess water use at the regional scale, e.g. for developing strategies for a sustainable river basin management or for supporting sustainability-oriented regional planning. To carry out a regional water use assessment, it is advantageous to develop or apply a water use model. A model-based assessment makes the best use of the available data, and it is cost-efficient because it can easily be updated. In addition, the model can be used to perform a scenario analysis which shows the impact of global and regional change as well as the impact of management measures.

The presented case study for two Brazilian states shows a type of water use modeling approach which is appropriate in the data-poor situation that is quite common in many regions of the world. It gives insight into the limitations of the approach and the uncertainties of the model results. The regional water use model NoWUM provides the first consistent and comprehensive assessment of present-day sectoral water use in all municipalities of Ceará and Piauí. In addition, it can simulate the impact of climatic variability and global climate change on irrigation requirements. NoWUM integrates scarce and uncertain data related to water use; therefore, its output is uncertain, too. It possibly underestimates irrigation water use due to a conservative estimate of irrigated areas, the neglecting of multicropping, and a high value of the irrigation water use efficiency (not relevant for the computed consumptive water use). It possibly overestimates industrial water due to assuming industrial water use intensities typical for humid Germany (where, however, water-saving technologies are widely applied in industry). The domestic water use estimate in municipalities with a large self-supplied population is uncertain due to the lack of quantitative information on water use in households that are not connected to the public water supply. Despite these uncertainties, the modeling results help to assess the problem of water scarcity in Ceará and Piauí and to develop appropriate water management strategies.

Water use estimates for the municipalities of Ceará and Piauí can only be improved if water use is monitored more extensively or information related to water use (e.g., on irrigated areas) becomes more reliable. In addition, the availability of existing data should be improved, e.g., by setting up a water use data base in each state. The public water suppliers, for example, should measure the volume of withdrawn water as well as the volume of water that actually reaches the households. This would also allow to estimate the leakage losses in the water pipe system. Besides, metering the actual household water use is likely to result in a more rational use of water. To estimate the water use in self-supplied households, to learn about their vulnerability to drought and to improve water supply, surveys of the type of water supply (own well, cisterns, ponds, ...) and of used water quantities should be conducted. Irrigators as well as self-supplied industries should be encouraged to meter and document their water withdrawals, and a water register containing water use permits should be established. In Ceará, first steps towards irrigation water use permits and measurement have already been taken (Campos and Studard, 2000).

There are many regions world-wide where a comprehensive water use assessment is lacking and where the situation with respect to the availability of water-use-related data is similar to the situation in our study region. With some modifications, NoWUM has the potential to be applied for water use assessments in such data-poor regions. There, the uncertainties as well as the strategies to reduce the uncertainties that are discussed in this paper are likely to apply, too. The computer code of NoWUM is available from the first author.

Acknowledgments

We thank our partners in the WAVES project, in particular F.W. Gerstengarbe and A. Güntner of the Potsdam Institute for Climate Impact Research, Potsdam, Germany for providing climate input for NoWUM, and J.C. de Araújo, Federal University of Ceará, Fortaleza, Brazil, for sharing his expert knowledge about Ceará and Piauí. We are grateful to the waterworks and water ministries of Ceará and Piauí for providing us with data.The research was funded by the German Federal Ministry of Education and Research (01 LK 9705).

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Discussions open until March 1, 2003.

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