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Modeling of Present and Future Water Use in Two Semi-Arid Brazilian States as a Basis for Water Resources Planning

Petra Döll[a], Jose Carlos Araújo[b] and Mario Mendiondo[a]

[a]Center for Environmental Systems Research, University of Kassel, Kurt-Wolters-Str. 3, D- 34109 Kassel, Germany. E-mail: doell@usf.uni-kassel.de
[b]Department of Hydraulic and Environmental Engineering, Federal University of Ceará, Fortaleza, Brazil

Abstract. Sustainability-oriented water management requires an assessment of present and future water uses. The regional water use model NoWUM was developed to support regional planning in two federal states of the semi-arid Northeast of Brazil. It computes withdrawal and consumptive water use for each of the 332 municipalities of Piauí and Ceará, distinguishing five water use sectors: irrigation, livestock, households, industry and tourism. NoWUM was applied to estimate present-day water use and to derive scenarios of water use in the year 2025. Besides, the cost of supplying the required bulk water was calculated.

1 INTRODUCTION

For a long time, the goal of water resources management had been to fulfil the existing (and ever increasing) demand for water, e.g. by constructing new physical water infrastructure. Now, water is generally regarded as a scarce resource which must be put to its socially and economically best use. Therefore, water suppliers and planning agencies have begun to explore water demand management options which include technological and economic approaches as well as user education (Lallana et al., 2001). Still, 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 mostly 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).

As a basis for water demand management at the regional scale, we propose to perform model-based regional water use assessments which include estimates present and scenarios of future water uses. A model-based assessment goes beyond the compilation of estimates of present water use that can be obtained without a model. It is potentially 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, and that the impact of certain demand management measures can be quantitatively assessed. 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 (i.e. demographic, economic, climatic and other changes) and water management measures.

While there is a wide range of models to estimate water availability in drainage basin 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. 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 for US-American cities and river basins (for a critique of IWR-MAIN, please refer to Parker et al., 1995).

To support water resources planning in two federal states in Northeastern Brazil, Piauí and Ceará (size 400,000 km^2), we developed the regional-scale water use model NoWUM as well as the water cost data base VALOR which contains information on the cost of bulk water (only for Ceará). In semi-arid Northeastern Brazil, scarcity of water is a major constraint for development, as the region suffers from a strong seasonality of precipitation as well as from recurrent drought years related mainly to the El Niño phenomenon. NOWUM and VALOR were applied 1) to assess the current situation in the study region, 2) to generate scenarios of water use in 2025 and 3) to estimate which costs are related to the increased water use in 2025 as compared to today. The work was performed in the framework of the joint German-Brazilian Research Program WAVES (http://www.usf.uni-kassel.de/waves).

2 METHODOLOGY

Two methods were combined to perform a regional water use assessment for the two Brazilian states, mathematical modeling and scenario development. In this section, the water use model NoWUM and the water cost data base are described first. Then, the storylines 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.

2.1 The Regional Water Use Model NoWUM

The regional water use model NoWUM computes withdrawal and consumptive water use for each of the 332 municipalities of Piauí and Ceará, distinguishing five water use sectors: irrigation, livestock, households, industry and tourism. 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 considered in NoWUM.

Figure 1 gives an overview of the regional water use model NoWUM and the driving forces of the computed sectoral water uses. A detailed model description can be found in Hauschild and Döll (2000). While the strong seasonality and climate dependence of irrigation water use is modeled by NoWUM based on daily or monthly climate variables, water use in all other sectors is assumed to be constant throughout the year, and the impact of climate variability and change is not modeled. Due to the inclusion of the relevant driving forces of water use, NoWUM is capable of producing meaningful scenarios of future water use, which for example, take into account the impact of climate change on irrigation water requirement, or the impact of water pricing on domestic water use. The model design has been strongly influenced by the availability of data and can be considered to be appropriate for regional-scale water use modeling in data-poor areas of the world.

2.2 The Water Cost Data Base VALOR

The water cost data base VALOR contains the average per volume cost of supplied bulk (raw, untreated) water in the state of Ceará, distinguishing eleven drainage basins, and within each drainage basin, three different water sources: surface water (reservoirs), groundwater from crystalline aquifers and groundwater from sedimentary aquifers. Investment cost are provided separately from operation and maintenance costs. In order to estimate the cost of surface water, only the construction and maintenance costs of dams are considered, as all the rivers in Ceará would be intermittent without man-made reservoirs and could thus not provide a reliable water supply. A detailed description of the bulk water cost assessment is provided by Araújo et al. (2002).

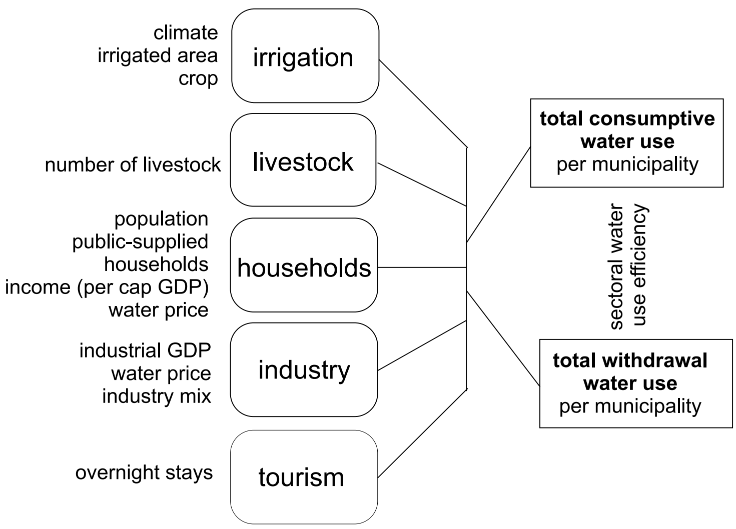

Figure 1. Overview of the regional water use model, showing the driving forces of the water use sectors irrigation, livestock, households, industry and tourism.

In order to compute the cost of bulk water supply in each municipality, a table was generated which defines what fraction of the sectoral water uses (irrigation, livestock, self-supplied households, public-supplied households, industry, tourism) is taken from which of the three sources surface water, sedimentary groundwater, crystalline groundwater. As a first approximation, it is assumed that the source attribution and the per volume costs are the same under current conditions (1996/98) and in 2025.

2.3 Scenario Development

Scenarios are plausible and consistent images of alternative futures which show different possibilities of how the future might look like. They are 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. So-called "reference scenarios" describe futures without any specific policy intervention. They serve as the baselines to assess the impact of selected regional planning policies or interventions on the future state of the system ("intervention scenarios"). The robustness of a certain policy is tested by assessing its impact in different possible future situations, i.e. against the reference scenarios. Qualitative-quantitative scenarios combine the development of storylines and the quantification of driving forces with impact analyses that are performed using mathematical models.

In the framework of WAVES, and in cooperation with Brazilian regional planning authorities, model-based qualitative-quantitative scenarios until the year 2025 were derived for the study region Piauí and Ceará. These scenarios focused on the relationship among climate variability and change, water availability, water use, agricultural production and income and migration. The respective mathematical models were coupled into an integrated model, which then helped to generate integrated scenarios (Döll et al., 2002). Eight scenario regions were distinguished within the study region (four in each of the two states), which differ with respect to the development in population, income, irrigated area and other driving forces. Two reference scenarios (RS A: "Coastal Boom and Cash Crops", RS B "Decentralization — Integrated Rural Development") were generated, and serve as the background for assessing the impact of certain interventions (Table 1). In this paper, we only present the scenarios of water use in 2025 as modeled by the regional water use model NoWUM. Following the storylines of the two reference scenarios, the development of all the driving forces of water use shown in Figure 1 was quantitatively defined for each municipality until the year 2025. Then, NoWUM was applied to compute the respective water use in 2025.

3 RESULTS

The study area suffers from strong interannual climate variability, and the impact of climate variability on irrigation water requirements is computed to be much larger than the impact of climate change until 2025 (as assumed based on two different global climate models, comp. Döll et al., 2002). Therefore, the impact of climate change is not taken into account in the following results. Table 2 presents the computed sectoral water withdrawals for 1996/98 and for both 2025 reference scenarios (climate is assumed to remain constant). Total withdrawal water use in the study area Piauí and Ceará in 2025 is 71% higher than in 96/98 for RS A, and 39% higher for RS B. The total cost of bulk water supply in Ceará, which is calculated to have been 42 million 1996-US$ in 1996/98 (83% of which are investment costs), increases approximately proportionally to the water withdrawals in the case of RS A. This is due to the simplifying assumption that the fraction of the three types of water sources (surface water, crystalline groundwater and sedimentary groundwater) remain the same until 2025. In RS B, the per unit cost increases somewhat because of the expensive reservoir construction in the scenario region "Low potential water resources".

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"
• strong economic development (commerce, industry, tourism) in the coastal regions of Piauí and Ceará • Fortaleza grows very fast • where water is available for irrigation, the production of cash crops by large companies dominates over subsistence farming • Brazilian and global markets for agricultural products dominate • centralized governance prevails	• regional centers prosper (attractive medium-sized towns with improved infrastructure) • regional centers have become the markets for local and regional agricultural products • small-scale agro-industry has extended • local initiatives prevail • Piauí and Ceará show a high degree of autonomy in relation to the Brazilian South • international agencies support sustainable agriculture in crisis-prone regions

Table 2. Sectoral water withdrawals in Piauí and Ceará in 2025 for both reference scenarios as compared to withdrawals in 96/98 (climate change is neglected), as well as the total cost of bulk water supply in Ceará.

		Withdrawals, in 10^6 m^3/yr						Cost of bulk water supply, in in 10^6 1996-US$/yr
(Population 1996, in million)		Irrigation (irrig. area, in 1000 ha)	Livestock	Domestic	Industry	Tourism	Total	Total
Piauí	1996/98	127.4 (13)	65.1	123.6	4.1	2.1	322.4	
(2.7)	2025 RS A	279.5 (45)	64.3	130.3	4.0	8.3	486.5	
	2025 RS B	209.3 (29)	77.8	125,6	3.7	6.2	422.6	
Ceará	1996/98	323.9((43)	81.3	225.6	46.3	14.3	691.3	42
(6.7)	2025 RS A	745.0 (116)	81.7	296.9	55.2	64.6	1243.5	74
	2025 RS B	547.7 (83)	93.9	260.4	42.8	43.5	986.6	61

The irrigation sector accounts for 75-80% of the change in total water withdrawals; irrigation withdrawals as a ratio of total withdrawals increase from 45% in 96/98 to 59% (RS A) and 54% (RS B) in 2025. In Northeastern Brazil, 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%/yr in RS A and 2.5%/yr in RS B (between 1990 and 1998, irrigated areas in Brazil only increased by 1.2%/yr). Water withdrawals in the second most important 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 (due to the higher water price), 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 case of RS A and by 22% in case of RS B, from 139 l/d in 96/98.

The future development of consumptive water use is of particular interest, as it 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). Consumptive use in the study area is 500 million m^3/year in 96/98, 49% of the withdrawals, 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 other sectors (except livestock), is extended, and because it is assumed that irrigation water use efficiency improves from 0.6 to 0.7. Irrigation consumptive use as a ratio of total consumption increases from 54% in 96/98 to 70% (RS A) and 63% (RS B) in 2025.

While the modeled state values of water use in RS A are larger than in RS B (Table 1), the opposite is true for many scenario regions and municipalities. For example, irrigation and domestic water use in the scenario region "Low potential water resources" are higher in RS B than in RS A due to the higher population (less migration to the coastal region) and the stronger extension of private irrigated areas, where products for the regional markets are produced. In the case of RS A, all public irrigation projects planned in 1998 are assumed to be implemented, but only one fourth of the project area in RS B; however, private irrigation based on local initiative (which is distributed more equally over the study area) expands more strongly in RS B than in RS A.

Based on the results for the two reference scenarios, the impact of water demand measures can be assessed. As an example, the influence of pricing of public-supplied water on domestic water use is analyzed. There is wide recognition that an appropriate prizing of water helps 1) to achieve the economically most efficient use of water, 2) to protect the environment and 3) to generate monies to improve water supply and demand management. The water prices of the main public water supplier of Ceará only cover operation and maintenance costs, but not investment costs, e.g. for an extension of water supply, or environmental costs. Between 1989 and 1998, water prices increased by approximately 10%/yr (adjusted for inflation). Currently, 1% of the average per-capita GDP in the study area is spent for (public) water supply, similar as in Germany. In both references scenarios, a constant price increase of 6%/yr is assumed to take place from 96/98 to 2025. A price increase of only 2.5%/yr results in an almost 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%/yr leads to a water price that, with the same per-capita water use, amounts to about 10% of the per-capita GDP. With a 2.5%/yr water price increase, total domestic water use (including self-supply) increases by about 40% as compared to the reference scenarios, while with 11%/yr, total domestic water use decreases by approximately 45%. Please note, however, that these results strongly depend on the assumed income elasticity (0.7 according to Gómez, 1987, determined for a Brazilian city of 1.5 million inhabitants) and price elasticity (linear decrease from –0.55 in 1996 to –0.3 in 2025; -0.55 is a typical value for Northeastern Brazil according to BNB/PBLM 1997, -0.3 a typical value for Europe and North America). Besides, prices per volume of freshwater will effectively double when households get connected to the sewage system (in 96/98, only about 10% of the urban withdrawals are discharged into a sewage system), and the impact of this additional price increase is difficult to predict.

4 DISCUSSION AND CONCLUSIONS

The newly developed regional-scale water use model NoWUM is an instrument that is suitable for regional water resources planning. With some modifications, it is suited for application in other data-scarce regions of the globe. With NoWUM, the first consistent and comprehensive assessment of the current sectoral water uses in all municipalities of Ceará and Piauí was achieved. However, scarce and highly uncertain input data (e.g. irrigated areas, climate, information from water suppliers) lead to a rather high uncertainty of the modelled water use. A significant improvement of the water use scenarios is only possible if more reliable data on water use and its driving forces become available. This could be achieved if sectoral water use data in each municipality were acquired regularly, e.g. by adapting the approach taken in the USA (Solley et al., 1998), and if studies were performed on water use behavior. The coupling of water withdrawals with their costs is innovative at the regional scale, but the cost scenarios suffer from the simplifying assumptions (section 2.2) that had to be made.

With respect to the future situation in Piauí and Ceará, the pressure on scarce water resources will increase significantly, if irrigation is strongly extended either by the implementation of the planned public irrigation projects or by more disperse private irrigation — 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. Even though the total water withdrawals will be larger in the case of RS A than in the case of RS B, in the latter scenario, which assumes a stronger development in the dry hinterland, water stress situations are likely to occur in more municipalities than in RS A. This indicates that water scarcity limits the agricultural development potential of the hinterland, and a continued migration to the coastal zone might be appropriate.

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