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Infrastructure sufficiency in meeting water demand under climate-induced socio-hydrological transition in the urbanizing Capibaribe River Basin – Brazil

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Abstract

Water availability for a range of human uses will increasingly be affected by climate change especially in the arid and semi-arid tropics. This paper aims to evaluate the ability of reservoirs and related infrastructure to meet targets for water supply in the Capibaribe River Basin (CRB), in the state of Pernambuco, Brazil. The basin has experienced spatial and sectoral (agriculture-urban) reconfiguration of water demands. Human settlements that were once dispersed, relying on intermittent sources of surface water, are now increasingly experiencing water-scarcity effects. As a result, rural populations in the CRB are concentrating around infrastructural water supplies in a socio-hydrological transition process that results from (a) hydroclimatic variability, (b) investment and assistance programs that may enhance but can also supplant local adaptive capacity, and (c) demographic trends driving urbanization of the state capital, Recife, which mirror urban growth across Brazil. In the CRB, demands are currently composed of 69.1 % urban potable water, 14.3 % industrial, 16.6 % irrigation (with ecosystem-service demands met by residual flow). Based on the application of linked hydrologic and water-resources models using precipitation and temperature projections of the IPCC SRES A1B scenario, a reduction in rainfall of 31.8 % translated to streamflow reduction of 67.4 % under present reservoir operations rules. The increasing demand due to population was also taken into account. This would entail severe water supply reductions for human consumption (−45.3 %) and irrigation (−78.0 %) by the end of the 21st century. This study demonstrates the vulnerabilities of the infrastructure system during socio-hydrological transition in response to hydroclimatic and demand variabilities in the CRB and also indicates the differential spatial impacts and vulnerability of multiple uses of water to changes over time. The paper concludes with a discussion of the broader implications of climate change, urbanization, and industrialization for water supply under socio-hydrological conditions of scarcity.

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1 Introduction: socio-hydrological transition

One of the most important impacts of climate change occurs in water resources availability (Milly et al., 2008). Surface water and groundwater recharge may be directly affected by change in rainfall and increase in air temperature that causes higher evapotranspiration rates. A direct consequence of changes in streamflow regime is the impact on water supplies. This is expected to lead to decreased water quantity available for different uses, especially to guarantee food supply for population in the arid and semi-arid tropics (Bates et al., 2008). Climate change may also affect the function and operation of existing water infrastructure as well as water management practices (Kundzewicz et al., 2007). Conversely, adaptive water management through forward-looking planning and operation of infrastructure coupled with flexible demand management represent important strategies to face climate change and variability (Short et al., 2012).

It is essential to assess supply-demand imbalances, particularly if they are projected to get progressively worse or if supply targets are not met for prolonged periods of time, causing economic, social, and environmental damage. The most appropriate method to estimate impacts is the use of scenarios run through Global Circulation Models (GCM). The GCM outputs are used as input in hydrological models, which calculate the streamflow in the basin. The combined use of mathematical models makes possible the estimate of the possible impact of streamflow reduction in water allocation as can be seen in Condappa et al. (2009) and Vaze et al. (2011). Integration of the GCM/hydrological models has been accomplished using different types of models such as VIC (Variable Infiltration Capacity) (Liu et al., 2010), Large Basin Hydrological Model (MGB-IPH) (Nóbrega et al., 2011) and DiCaSM (Montenegro and Ragab, 2012) among others. A similar strategy involves the use of Regional Climate Models (RCM) nested within GCMs to improve the spatial resolution and to permit hydrological simulation in smaller basins (Akhtar et al., 2009; Driessen et al., 2010). The vulnerability of water resources systems – understood here as the inability to meet demand targets

– can also be evaluated using coupled or sequentially run models, e.g., GCM, rainfall–runoff model, and simulation model (Cha et al., 2012; Matonse et al., 2013; Hall and Murphy, 2010), and using different indexes for estimating the robustness of the systems: resilience, reliability, vulnerability (Matonse et al., 2013); and water use to resource ratio (Hall and Murphy, 2010).

This paper considers semiarid Northeast Brazil, which is experiencing a reduction of water availability due to changes in the climate (Kundzewicz et al., 2007) as well as increase in human water demand for urban supply, irrigation, and other purposes. As such, this region is broadly representative of water-scarce regions globally that are facing increasing threats to water security (Scott et al., 2013). The Capibaribe River is a basin with typical characteristics of Brazil's semiarid Northeast and it has experienced spatial and sectoral (agriculture-to-urban) reconfiguration of water demands. The economic growth in the interior of the basin combined with urbanization has stressed water security in terms of availability and quality. The domestic and industrial wastewater release in the river and land use affect the water cycle in the basin, as evidence of growing human influence on water availability (Thompson et al., 2013; Savenije et al., 2014). On the other hand, dispersed human settlements in the CRB it must be taken into account. Small communities are increasingly concentrating around infrastructural water supplies (groundwater, where available, but increasingly tanker-truck supplies during drier months and over extended drought periods). These constitute a socio-hydrological transition process that results from (a) hydroclimatic variability, (b) investment and assistance programs that may enhance but can also supplant local adaptive capacity, and (c) demographic trends that are already pronounced in Brazil.

Support programs are crucial to maintaining rural populations from migrating to cities. Such programs include crop insurance (*Garantia Safra*) and credit schemes (*PRONAF*) at the federal level and *Chapeu de Palha* and *PRORURAL* run by the Pernambuco state government. During the recent drought between 2011 and 2013, Pernambuco supported farmers and ranchers with subsidized inputs. The strengthening of the water infrastructure in Northeast of Brazil, including Pernambuco State, in the last decades has increased the resilience of the water supply systems to face drought events and reduce the vulnerability to climate variability. The infrastructure projects involve construction of reservoirs, pipelines and canals. Such solutions have been implemented in the Capibaribe River Basin (CRB) and Recife the capital of Pernambuco State. Other projects are also planned to support water supply systems in Pernambuco. The water transfer project of the São Francisco River will take water to five States in Northeast of Brazil, including regions that today are supplied by CRB. The implications of these developments must be assessed in tandem with climate-change impacts.

In Brazil, the integration of different models has been used in streamflow forecasting for water allocation in semiarid areas (Block et al., 2009). The results of the Intergovernmental Panel on Climate Change (IPCC) GCM ensemble do not agree on the trends of projected change of the rainfall and air temperature in large parts of Brazil. The Assessment Report Four (AR4) indicates that less than 12 models using the A1B scenario agree with the sign of change of the precipitation between the periods 1980–1990 and 2090–2099 for Northeast, Central-West, Southwest and North. Only the East Amazonia and the South of the country have areas where the agreement of the IPCC GCMs is greater than 66 % (Pachauri and Reisinger, 2007).

The current analysis has been accomplished using three types of models: (1) climate model outputs of rainfall and air temperature for the IPCC emissions scenarios; (2) a hydrological model to estimate the discharge in the river; and (3) a network flow model for simulating the balance between water supply and water demand. The main objective of this study is to evaluate the infrastructure sufficiency in meeting water demand under climate-induced socio-hydrological transition in the Capibaribe River Basin (CRB). The evaluation may be useful for planning and developing actions aiming to diminish the impact on the population and economic activities in the basin. At the same time, analyzing the flexibility of the water resources system for different parts of the basin may support the Secretaria de Recursos Hídricos e Energéticos (SRHE), the principal state agency responsible for planning and management of water and energy infrastructure. Two of the authors have served in operational capacity with SRHE. In particular, the assessment presented here supports the Hydro-Environmental Master Plan of Capibaribe River – further details are provided below.

2 Methods

2.1 Study area

The Capibaribe River Basin (CRB) (7454 km^2) located in state of Pernambuco in the Northeast of Brazil has a west-east direction with its headwaters in a semiarid region and its outlet section on the Atlantic Ocean coast (Fig. 1). For this reason, there are different types of soil, vegetation cover, climate and relief along its extension. The uplands are characterized by shallow soils, Caatinga vegetation (thornscrub, cactus, and bunch grasses), and a semiarid climate with 550 mm year^{-1} of rainfall and mean air temperatures between 20 and 22 °C. The lowlands are characterized by deeper soils, Atlantic Forest vegetation and humid/sub-humid climate, with 2400 mm year^{-1} of rainfall and mean air temperature between 25–26 °C. The altitude in the basin varies from 0 m at the outlet section to 1199 m in the uplands. The main course of the Capibaribe River is 280 km long.

There are 42 municipalities completely or partially inside the basin and 26 cities in the interior of the basin, including Recife the capital of Pernambuco. The total population in the basin is 1.71 million, of which 0.76 million reside in Recife. The main water uses are human, industrial and irrigation totaling 7.272 m^3 s^{-1} of demand. The spatial distribution of the demand is influenced by the water availability, i.e., the greatest volumes withdrawn from the basin correspond to places closest to the lower Capibaribe River. There are two points in the basin with infrastructure for water transfer. In the central portion of the basin, there is a pipeline that takes water to cities of the Ipojuca

River basin ($0.609\,m^3\,s^{-1}$). In the lower part, the water supply system of the Recife Metropolitan Region receives water from a reservoir outside of the CRB ($0.455\,m^3\,s^{-1}$).

The CRB has eight reservoirs with storage capacities greater than 10 million cubic meters (MCM) each. The total capacity of the reservoirs is about 800 MCM. All the reservoirs are used for water supply and four of them are also used for flood control (Jucazinho, Carpina, Tapacurá and Goitá). Table 1 shows the characteristics of each reservoir.

The Hydro-Environmental Master Plan of Capibaribe River (Pernambuco, 2010) encompasses a diagnosis with hydrological, environmental and social-economic studies. Two scenarios have been analyzed: "Business as Usual" and "Sustainable". The results aided the set up of investment plans to the basin. The basin has been divided in four regions (Analysis Units – AU) according to their climatological, hydrological and social-economic characteristics. Figure 2 shows the boundaries of each AU and the reservoirs indicated in Table 1.

The temporal variation of water demand is influenced by the growth of the population and the economy in the municipalities of the basin. During the 2000s the average annual water demand growth rate (4.34 %) followed social and economic factors such as the annual growth rate of the Gross Domestic Product (12.36 %), annual population growth (1.38 %), agriculture area growth (6.58 %), human development index improvement (1.00 %) and pollutant load released in the river (5.47 %). These factors are strongly influenced by the development of textile, sugar and ethanol industries.

During the same period the increase rate in the water availability due to improvement of the water infrastructure was not the same. At the same time, the groundwater availability is significant only in AU4. The basin overlies crystalline-rock aquifers over virtually its entire area, but only AU4 presents a sedimentary aquifer as well. The groundwater availability in AU1, AU2 and AU3 corresponds to 3.73 % of the groundwater availability in the AU4 ($1.257\,m^3\,s^{-1}$).

In Northeast of Brazil, many families live in the interior without access to water for drinking, cooking and hygiene. These families live far from the systems of water supply. According to Pernambuco (2010), there are, approximately, 111 796 people in such conditions in the CRB (6.55 % of the total population). During periods of severe droughts, as the Northeast has faced in 2011–2013, this population is supplied with water by tanker trucks and, in some cases, collecting water from springs and small reservoirs in daily journeys, generally made by women and children. In addition to this, wells and cisterns are the more common water collection and storage systems in the region. Non-governmental organizations supported by the federal government have installed about 500 000 cisterns in Northeast of Brazil since 2003. The cisterns in Northeast have storage capacities varying between 7 and 15 m^3, representing an availability of 50 L per day during 140–300 days, if they are considered full of water at the end of the rainy season.

The precipitation in the AUs reduces from east to west, hence the potential evapotranspiration increases in the same direction (Table 2). These characteristics contribute to the low runoff in the AU1, AU2 and AU3 and high runoff in the AU4. The soil type and geology in the basin also contributes to the spatial variability of runoff. The basin is predominantly over the crystalline basement (shallow soil and rock near the surface). The exception is the presence of sedimentary areas in the AU4. The little storage capacity of the soil hinders the stabilization of the flow, resulting in intermittent rivers in the uplands of the basin.

2.2 Data

The mean rainfall in the basin has been calculated using data from 85 rain gauges of the hydrometeorological network of National Water Agency (ANA) and Institute of Technology of Pernambuco (ITEP). The rainfall measured was used to assess the rainfall of the climate model as well as used in the calibration of the parameters of the hydrological model. Scenarios under climate change are derived from Chou et al. (2012), who used the output data of the GCM HadCM3 (UK Met Office Hadley

Centre) as the boundary condition in simulations of the Regional Climate Model ETA-CPTEC. Using ETA-CPTEC/HadCM3 models, Chou et al. (2012) simulated rainfall, air temperature, relative humidity and other climatological variables for 1960–1990, 2010–2040, 2040–2070 and 2070–2100. The CO_2 concentration in the base condition (1960–1990) is 330 ppm, whereas the future projections use the IPCC SRES A1B scenario. Chou et al. (2012) used four members of the HadCM3 Perturbed Physics Ensemble (PPE), in which a single model structure is used and perturbations are introduced to the physical parameterization schemes in the model. The first member is the standard model structure and the other ones are perturbations of the physical parameterization schemes used to produce variants of the same model. In our study, the analysis used the first member.

The calibration of our hydrological model takes into account the stream gauge discharges. The ANA hydrometeorological network has three streamgauges in the stem of the Capibaribe River (shown in Fig. 1). The air temperature for calculation of potential evapotranspiration (PET) is measured in the climatological station at Surubim (also shown in Fig. 1). The PET has been estimated using the Thornthwaite method. This method uses only air temperature in its formulation, besides a factor that varies according to month and local latitude.

The Hydro-Environmental Master Plan of Capibaribe River (Pernambuco, 2010) exhibits the water uses, the volumes withdrawn from the reservoirs and the characteristics of the reservoirs. This information is used in the network flow model.

2.3 Modeling infrastructure vulnerability

2.3.1 Hydrological model

Rainfall and air temperature may be used to determine the discharge in the Capibaribe River in the future using a hydrological model. MODHAC (the Portuguese acronym for “Self Calibrated Hydrological Model”) is a rainfall–runoff lumped model, whose input variables are mean rainfall, potential evapotranspiration and streamflow (Lanna, 1997). Three reservoirs represent the main processes responsible for rainfall–runoff transformation: interception, evapotranspiration and runoff generation, i.e., determination of the volume of water that will either be infiltrated into the soil or flow on the surface. The model has 14 parameters that can be calibrated automatically using four options of objective functions. MODHAC has performed hydrological simulations well in several basins located in the semiarid lands in Northeast Brazil (Lanna, 1997). In addition, MODHAC can run monthly time step simulations (suitable for this study) and it needs few input data (rainfall, PET and streamflow).

2.3.2 Network flow model

A network flow model may be used for optimal basin-wide water allocation. This ensures that water is allocated according to physical, hydrological, demands and institutional aspects of river basin management. Network flow models represent the water resources system using nodes and links. The nodes represent point elements such as reservoirs, demands, inter-basin exchange and confluences, whereas links between two nodes represent river branch, pipelines, canals and other similar elements. Each node has a cost per flow unit that influences the volume of water that will pass through it. The model algorithm seeks to minimize the total cost of the network using optimization techniques such as linear programming.

One of the most widely used network flow models is MODSIM (Labadie, 1995) developed at Colorado State University. MODSIM has been applied to a number of complex river basin systems such as the Sirvan basin in Iran (Shourian et al., 2008). The water allocation in this study was done using the Acquanet model (Porto et al., 2003). This model was essentially constructed based on the structure of MODSIM. Acquanet has an interface of communication with the user and a database to store the information of the network flow.

The network model needs information of volume of water demand, operation rules and priority of demand. These information were obtained from the Hydro-Environmental Master Plan of the Capibaribe River Basin (Pernambuco, 2010). The order of priorities of demands is human, industry and irrigation. In addition, the input discharge entering in each reservoir is calculated with MODHAC and the evaporation in the reservoirs is calculated using air temperature estimated by ETA-CPTEC/HadCM3. The projection of water demand has been considered according to population growth. The Brazilian Institute of Geography and Statistics (IBGE) projects that Brazilian population will achieve the maximum in 2042 (228.4 million) and in 2060 will be 218.2 million inhabitants. In 2100, according to Department of Economic and Social Affairs (United Nations), the Brazilian population will be 194.5 million inhabitants. We have taken into account a proportional relation between population and water demand growth in this study. The environmental flow exhibited in the Hydro-Environmental Master Plan of Capibaribe River was used in the network flow simulation. This discharge is considered only in UA4 because it is the perennial reach of the river. The reservoirs, demands, channels and water facilities are represented in the Acquanet using links and nodes as can be seen in Fig. 3.

3 Results

3.1 Hydrological simulation

MODHAC has been calibrated by using monthly time step in the three stream gauges shown in Fig. 1. The evaluation of the model calibration considers Nash–Sutcliffe coefficient (NS) and volume error (ΔV). Table 3 exhibits the periods used in calibration, the drainage area and values of the criteria (Nash–Sutcliffe and volume). The different periods of time are owing to the construction of reservoirs along the CRB from the mid-1980s onwards. For the same reason, each sub-basin has been simulated in the corresponding incremental area instead of the whole drainage area. Figure 4 shows the streamflow simulated and measured in three stream gauges.

It was necessary to evaluate the performance of the MODHAC model using rainfall and air temperature calculated with the ETA-CPTEC/HadCM3. Figure 5 shows the long-term mean monthly streamflow for the whole basin considering two simulations with MODHAC. The first simulation uses observed rainfall and air temperature. The second one uses rainfall and air temperature from ETA-CPTEC/HadCM3.

Applying the set of MODHAC parameters using the rainfall and air temperature for the different time-slices, it is possible to observe the impact on the streamflow at the outlet section of Capibaribe River. The scenarios exhibited mean annual streamflow of 20.98 $\mathrm{m^3\,s^{-1}}$ (1960–1990), 22.22 $\mathrm{m^3\,s^{-1}}$ (2010–2040), 10.30 $\mathrm{m^3\,s^{-1}}$ (2040–2070) and 6.84 $\mathrm{m^3\,s^{-1}}$ (2070–2100). The streamflow slightly increased in the first period and diminished in the second and third periods. The concept of elasticity is a good way of evaluating the sensitivity of long-term streamflow to changes in long-term rainfall. According to Chiew (2006), the rainfall elasticity of streamflow is defined as the proportional change in mean annual streamflow divided by the proportional change in mean annual rainfall. Considering the present day (1960–1990) as the reference baseline, the elasticity of Capibaribe River can be estimated for the time-slices: 1.67 (2010–2040), 4.06 (2040–2070) and 2.12 (2070–2100). The second period exhibits the range of streamflow most sensitive to changes of rainfall.

3.2 Network flow simulation

There were four simulations with Acquanet: one for the present time and three simulations for the future scenarios. The present period simulation corresponds to a volume of water supply equal to 6.59 $\mathrm{m^3\,s^{-1}}$. The first scenario (2010–2040) did not exhibit any change because the streamflow in the basin fluctuated slightly upward. The following periods presented changes. The volume of water supply decreased to 5.84 $\mathrm{m^3\,s^{-1}}$ and 4.83 $\mathrm{m^3\,s^{-1}}$, respectively, for the periods 2040–2070 and 2070–2010. The criterion for reduction of demands was the same as the order of priorities. Unless there was a physical impossibility, such as the absence of water conveyance pipelines between the reservoir and the location of use, the volume for irrigation was the first to be reduced, after that, supply to industry, and, finally, the volume for human use. For example, the human demands UA4_1 and UA4_2 take water from just a site each one, whilst the demand Industry_UA4 takes water from four different sites (see Fig. 3). Figure 6 shows the supply sufficiency in percentages for the entire basin and the Fig. 7 shows the variation for each AU in terms of discharge ($m^3 s^{-1}$). In Fig. 7, it is possible to verify that, despite the prioritization of supplying firstly the human use, industry is completely met due to the low value of this demand: AU1 ($0.003\,m^3 s^{-1}$), AU2 ($0.015\,m^3 s^{-1}$) and AU3 ($0.019\,m^3 s^{-1}$).

4 Discussion

The IPCC SRES scenario has been used to evaluate the impact of climate change on the water supply in the CRB. The results indicate that the mean streamflow of the Capibaribe River decreases significantly in the time slices 2040–2070 and 2070–2100. The reduction of rainfall and mean streamflow has also been verified in other basins of Northeast Brazil located in semiarid regions, using the same IPCC SRES scenarios. Milly et al. (2005), for example, found a reduction of −20 % in runoff for the Northeast of Brazil, using an ensemble of 12 climate models. Montenegro and Ragab (2012) have simulated the Tapacurá river basin, a tributary of Capibaribe River, using the low emission (B1) scenario and found a reduction of −20 % in surface flow for the time span 2070–2100. Marengo et al. (2009) also identified a reduction of rainfall in the Northeast of Brazil using three RCM nested within theHadAM3P global model. Fung et al. (2011) verified the change in runoff in a world 2 °C and 4 °C warmer. Ensembles of GCMs runs for SRES A1B scenario from 1930 to 2079 were used. According to Fung et al. (2011), the ensemble-average changes in mean annual runoff in the Northeast of Brazil will reach −40 % (+2 °C) and −80 % (+4 °C). The air temperature change estimated in CRB is +3 °C with a corresponding runoff reduction of −67 %.

The elasticity of the CRB exhibited values that indicate high sensitivity to changes in the rainfall: 1.67 (2010–2040), 4.06 (2040–2070) and 2.12 (2070–2100). In other words, small changes in rainfall may mean a high reduction in streamflow. The elasticity found by Chiew (2006) in catchments of Australia is about 2.0–3.5 (observed in about

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70 % of the 219 catchments analyzed). These values are similar to the elasticity presented by the CRB in the time-slices of climatic scenarios. Chiew (2006) observed that streamflow is more sensitive to rainfall in drier catchments, which partially is in accordance with CRB. Scenarios of either reduction of rainfall or even change in the time distribution of rainfall can make an impact on the water supply in the CRB.

The consequence of the decreasing of the streamflow is the reduction of water supply for human (−45.3 %), industry (−92.4 %) and irrigation (−78.0 %) uses up to the end of the 21st century. The major reduction in the water supply occurs in the part of the basin closest to Recife, capital of Pernambuco. The actual configuration of the water supply system, in some cases, does not permit prioritization of human use in a scenario of reduced streamflow. There are human uses that are connected to only one source of water (as can be seen in Fig. 2), whereas industrial use is connected to many sources.

The reduction of water supply on the climate scenario has also been verified by Vaze et al. (2011) in Australia using 15 IPCC AR4 GCMs. Two hydrological models and a river system model were used to estimate water availability for historical (1895–2006) and future (2030) rainfall. The change of the diversion for irrigation varies between −27 and +21 % depending on the GCM and hydrological model (the median value is about −6 %). By the end of the 21st century, the change could meet the values obtained in CRB.

Using the network flow model, it was possible to estimate the impact along the basin according to its division in four Analysis Unit. The reduction of human and irrigation supply had the same proportion in AU1. The AU2 exhibited high impact on human supply. This unit has the reservoir (Jucazinho) responsible by the water transfer for other basin. In the region AU3, there was a slight reduction of the human water supply in the time slice 2070–2100 and the impossibility to allocate water for irrigation from 2040 on. The AU4 exhibited no change in the water supply for irrigation use. On the other hand, the human use has been reduced from 3.1 to 1.6 $m^3 s^{-1}$ and industry use from 1.1 to 0.07 $m^3 s^{-1}$.

5 Conclusions

The integration of three models made possible to evaluate the impact of streamflow reduction in the Capibaribe River Basin water supply due to possible climate change scenarios. The ETA-CPTEC/HadCM3 coupled climate models were used to estimate rainfall and air temperature in the CRB. Rainfall and air temperature exhibited values underestimated when compared to the observed data. The methods used for bias correction presented results appropriate for hydrological simulation. The MODHAC hydrological model accurately represented the streamflow in the CRB, which has been used to represent the inflow discharge in each reservoir that comprises the water supply system in the basin. The use of a RCM instead of a GCM is more appropriate to represent the rainfall–runoff transformation in a basin with the dimensions of the CRB.

The results indicate high reduction of rainfall and, hence, reduction in mean streamflow and in the volume of water supplied for the different users in the CRB. By the end of the 21st century, the reduction may reach −45.3 % (human supply), −78.0 % (irrigation supply) and −92.4 % (industry supply). Two factors can explain the sensitivity of CRB to IPCC scenarios. First, part of CRB is located in a semiarid land, which is expected to suffer more severe impact than other regions. On the other hand, the high population density and the water demand have as a consequence higher pressure on the water availability.

The system simulated in the CRB exhibited some vulnerability and low flexibility to face climate changes. According to the simulations, the water supply for human use is the most vulnerable owing to the high values of demand, mainly in AU4 next to Recife city. The actual water supply system in the CRB is not connected to other systems that could complement the supply in water-scarcity periods. Investments have been made to improve infrastructure with the objective to connect the CRB's supply system to other systems. One pipeline will connect the Jucazinho reservoir to the canal of the water transfer project of the São Francisco River. The pipeline will take water to eight municipalities that nowadays are supplied by reservoirs of the CRB. The new infrastructure will integrate the AU1 and AU2 in a system that will allow the exchange of water among basins in Pernambuco State. This type of measure can reduce the vulnerability of the water supply systems in the CRB. Originally the project has not been planned to be an adaptive strategy to face climate change impacts. Nevertheless, it may be considered a no-regret strategy that will help to face the climate variability in the region despite the climate change scenarios will become true or not.

Hydroclimatic impacts on water resource systems' ability to meet multiple demands is of growing concern globally with climate change and variability coupled with fluctuating demands. Adaptation measures to ensure water supply in a world under change require demand-side as well as supply-side strategies (Bates et al., 2008). Supply-side strategies involve increases in storage capacity, abstraction from water courses and water transfers. The investment in water facilities, for example, is one of the strategies adopted by China to develop effective adaptation to climate change, natural disasters and food security (Li, 2012). Demand management improves water-use efficiency, water rights, effective regulation enforcement, and pollution control (Cheng and Hu, 2012). Until the 1990's, the Northeast of Brazil had a history of inappropriate policies based on the construction of small reservoirs and drilling wells in the crystalline rock. Additionally, there was a lack of effective water management policies. In the late 1990's, a new philosophy has been implemented by Brazilian states with support of Federal Government and the law 9433/1997 that establishes the National Water Resources Policy. The States were able to develop actions for water use control (permits and water abstraction charges), water resources master plan for the basins and States, creation of an institutional framework for water management and programs for water facilities construction.

The combination of infrastructure development and improvement of water management policies that anticipate hydroclimatic impacts, such as those modeled in this paper, may result in effective climate-change adaptation measures. Similar processes have been described for Australia by Short et al. (2012) and for developing countries by Mujumdar (2013). Hydrological and water resources models are tools able to simulate both the effectiveness of infrastructures and the adoption of water management policies in a basin impacted by the climate change.

On the other hand, the socio-hydrological transition underway shifts water demand in ways that can be considered another drive forcing in the process of increasing the water deficit. At the same time, the sustainable economic growth in the basin will demand an increasing volume of water. Thus, both climate change and water demand may lead to a water stress condition in CRB. In a scenario with lower water availability, actions to overcome deficits into the water balance will be necessary. The adaptation for this condition requires a combination of diverse solutions in an integrated manner: construction and use of cisterns for human supply in dispersed population and desalination of water drawn from wells; family agriculture with short harvesting cycle, to take advantage of the water of surface reservoirs before losses by evaporation; construction and use of reservoirs with lower water surface; and even underground dams; integration of large water sources using large main water systems to supply the cities and for development of irrigated agriculture; use of water saving technologies in agriculture, industry and domestic use; and reuse of wastewater.

Uncertainties are inherent in analyses involving impact on climate change. In order to diminish the uncertainties related to the GCM output, it is important to use other models with performances as good as HadCM3 for the simulation of base conditions. The reliability of the results may be related to the number of GCMs used in the analysis and it is also possible to associate a confidence interval to the rainfall change. This must be done in the next steps of the research. Despite the necessity of improving the reliability of the results, we can conclude that the combined use of mathematical models is able to indicate the vulnerabilities of the system, such as the elasticity of Capibaribe River, and also show which parts of the basin are more vulnerable to changes.

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Table 1. Characteristics of the reservoirs.

Name	Capacity (10^6 m^3)	Drainage area (km^2)
Poço Fundo	27.75	926.00
Eng. Gercino Pontes	13.60	384.00
Jucazinho	327.04	4772.00
Carpina	270.00	6000.00
Cursaí	13.00	57.00
Goitá	52.00	450.00
Tapacurá	94.20	360.00
Várzea do Una	11.57	38.00

Table 2. Climatological characteristics of the Analysis Units (AU).

Unit	Precipitation ($\mathrm{mm\,year^{-1}}$)	Potential Evapotranspiration ($\mathrm{mm\,year^{-1}}$)
AU1	579.1	1700–1850
AU2	621.5	1650–1900
AU3	842.2	1550–1800
AU4	1228.1	1500–1700

Table 3. Model calibration at the stream gauges.

Name	Incremental area (km^2)	Period	NS	ΔV (%)	Q_{mean} (m^3 s^{-1})	
					Observed	MODHAC
Toritama	2458.45	1973–1982	0.8518	−4.6	4.45	4.65
Limoeiro	3138.47	1983–1990	0.8058	−9.1	5.86	5.32
S.L. da Mata	1328.97	1990–1996	0.3821	−26.2	13.18	9.72

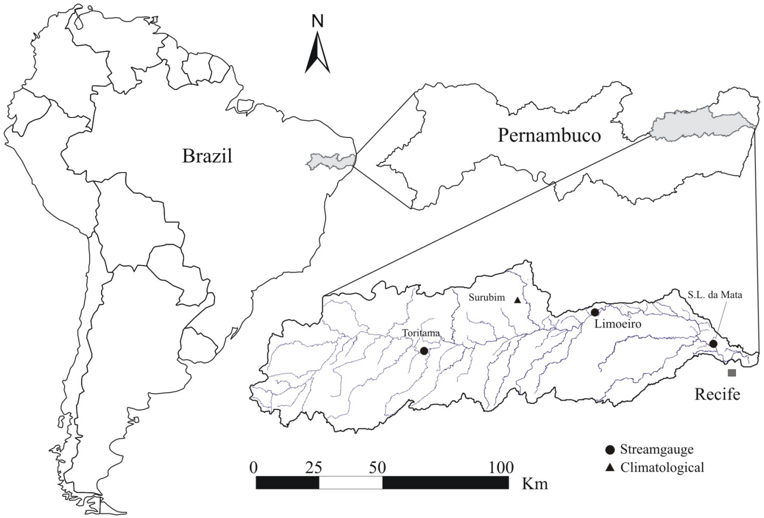

Fig. 1. Capibaribe River Basin.

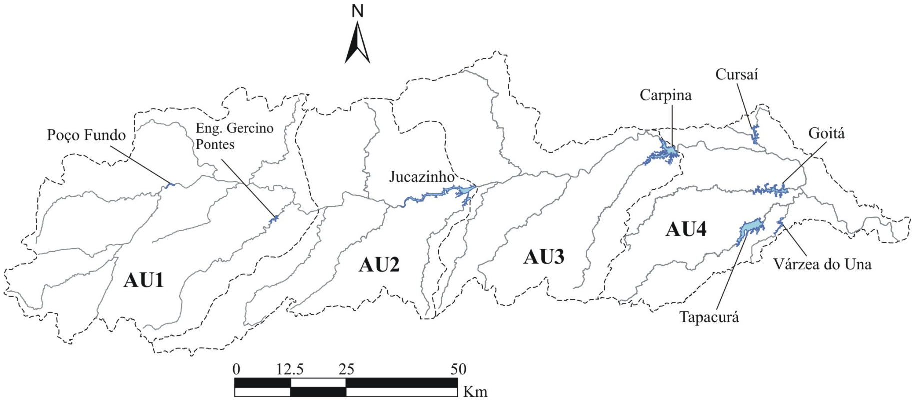

Fig. 2. Reservoir locations and Analysis Units.

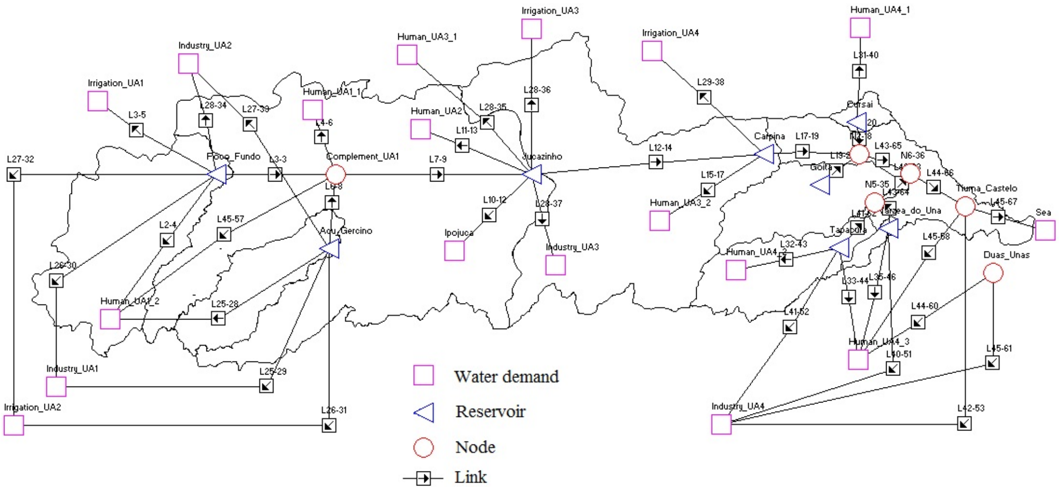

Fig. 3. System representation in Acquanet.

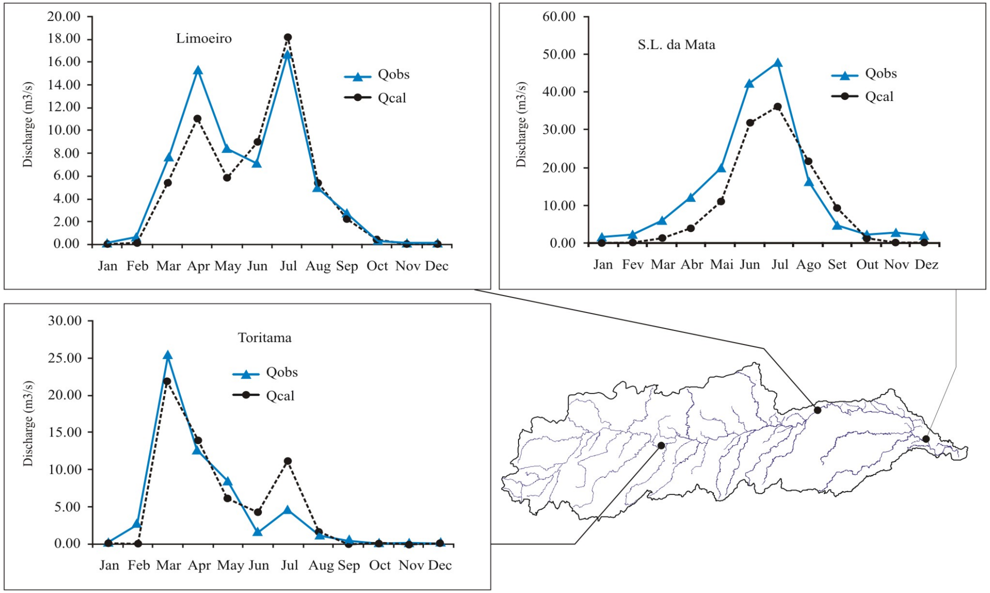

Fig. 4. Streamflow measured and simulated in the incremental drainage area of three stream gauges.

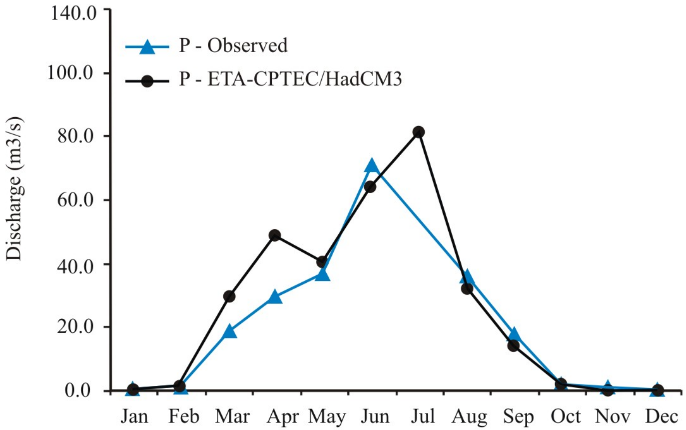

Fig. 5. Streamflow at the outlet section of Capibaribe River calculated with MODHAC using observed precipitation (triangles) and ETA-CPTEC/HadCM3 precipitation (circles).

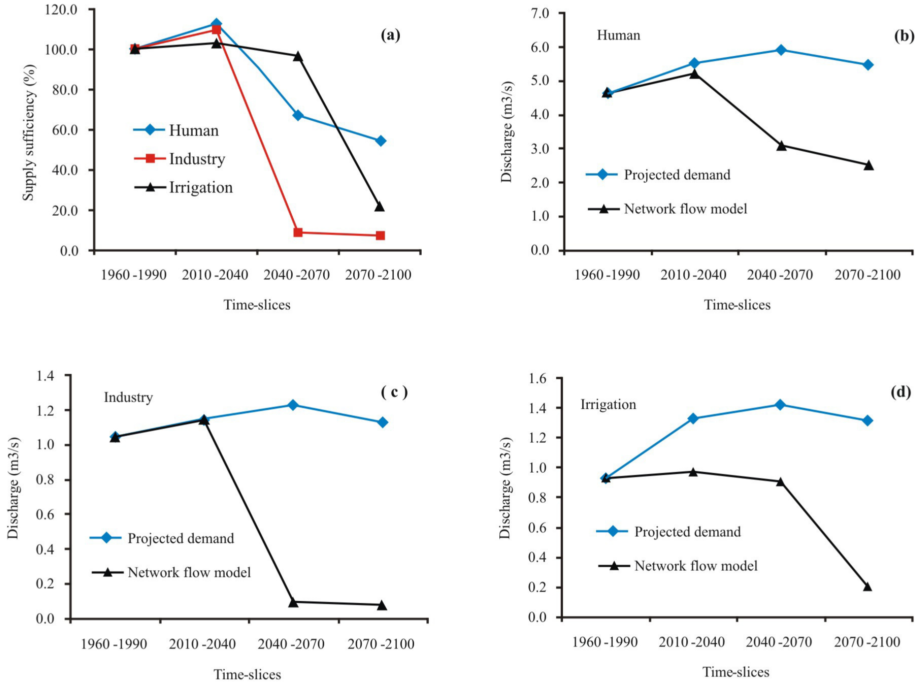

Fig. 6. Simulation scenario: supply sufficiency for different time slices for the entire basin (100 % means no reduction in demand supply) **(a)**, projected demand and network flow model for human **(b)**, industry **(c)** and irrigation **(d)**.

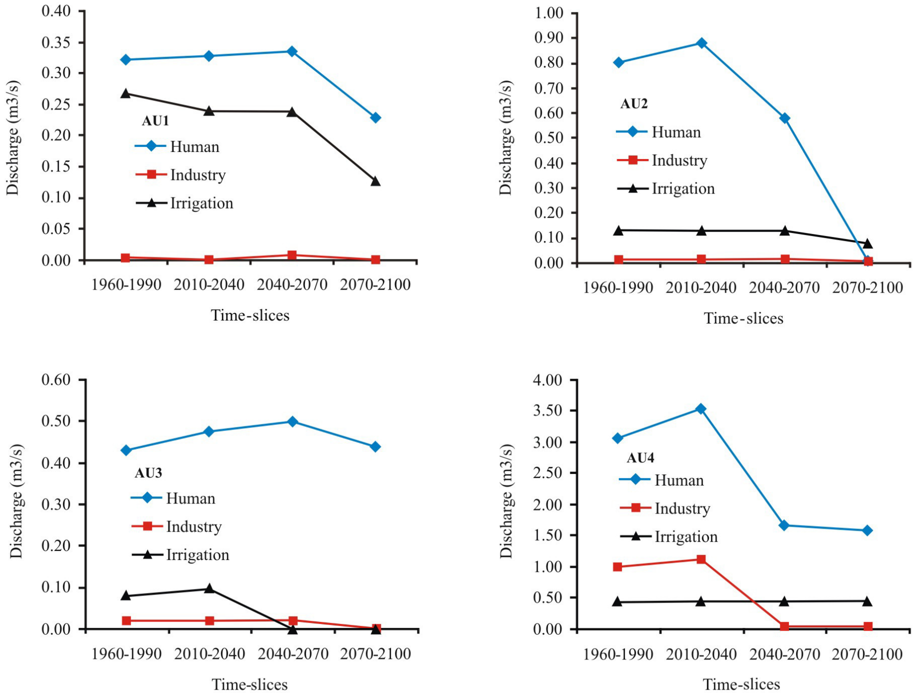

Fig. 7. Simulation scenario: reduction of the different supplies for different time slices for each Analysis Unit.