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Climate, stream flow prediction and water management in northeast Brazil: societal trends and forecast value

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Abstract We assess the potential benefits from innovative forecasts of the stream flows that replenish reservoirs in the semi-arid state of Ceará, Brazil. Such forecasts have many potential applications. In Ceará, they matter for both water-allocation and participatory-governance issues that echo global debates. Our qualitative analysis, based upon extensive fieldwork with farmers, agencies, politicians and other key actors in the water sector, stresses that forecast value changes as a society shifts. In the case of Ceará, current constraints on the use of these forecasts are likely to be reduced by shifts in water demand, water allocation in the agricultural Jaguaribe Valley, participatory processes for water allocation between this valley and the capital city of Fortaleza, and risk perception. Such changes in the water sector can also have major distributional impacts.

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1 Introduction

This paper assesses the potential gains from an advance in climate-based forecasting for Ceará, one of nine states in Brazil's semi-arid Northeast. From aggregate and multi-actor perspectives, we consider the potential for benefits and for losses from using one-season-ahead, climate-based stream-flow forecasts to adjust rates of water release from the reservoirs in the Jaguaribe Valley, the state's largest agricultural region. Based upon over 2 years of field observation of the local participatory water allocation process and of private and public decisions about water allocation, we identify key current constraints on benefits from forecasts. We then analyze the implications for those constraints, and thus also for forecast value, of current and potential policies in Ceará.

Ceará's rural population of 2.1 million, about a third of its population, is mostly agricultural (79%) and poor even by local standards (76%).[1] Recurring drought has long been identified as a critical factor in the state's economy, ecology, culture and politics (Girão 1986; Prado Júnior 1989; Parente 2000, 2002; Neves 2002; Magalhaes 2002). Persistent poverty, rudimentary agriculture and drought have created ongoing vulnerability. Actions to reduce it have focused on reservoirs, canals and irrigation schemes. The reservoirs are central to rural life but also supply the capital city, Fortaleza, home to another third of the people. Thus, improved management of this water system could affect many. Recently, climate-based forecasts have become available as a tool to improve the efficiency and reliability of water investments. This motivates our analysis.

Recent changes in water management relevant for our analysis include major institutional shifts such as the creation of COGERH (the Company for Management of Water Resources in Ceará), i.e. a specialized agency, and the increased importance of the meteorological agency, FUNCEME (Ceará's Meteorological and Water Resources Research Foundation), that provides forecasts to inform choices concerning agricultural planning (e.g. seed distribution schemes), water management, health programs (e.g. dengue control efforts) and drought relief (see Fig. 1 for bulk water consumption). Further, local allocation of water now involves multi-stakeholder participatory water committees, one for each sub-basin of the Jaguaribe River and each of the other river basins, which were functioning by the late 1990s. These committees choose the seasonal rates of water release from the main reservoirs in the (sub-) basins, selecting from a small set of scenarios prepared by COGERH.

Much is written about climate and water in this region. Some recent work has assessed the potential gains from forecast use for rainfed agriculturalists not directly affected by reservoirs (Lemos et al. 1999; Finan 2001; Finan and Nelson 2001). Drought early warning might aid this group in principle but evidence suggests that the constraints under which these households operate would limit the benefits. Further, Lemos et al. (2002) and Lemos (2003) identified state bureaucracy and politics as a strong influence on any process of generating benefits for citizens through climate information. The models of adaptation of Gaiser et al. (2003) to climate are relevant background but are not focused on forecasts at a seasonal time scale. Complementary to these prior studies, our focus is the use of seasonal climate-based forecasts by those who depend upon the reservoir system and, in particular, by irrigated agriculturalists, a relatively poor and vulnerable group.

As is true for many new technologies, whether forecasts are adopted in water management is influenced by the features of the decision setting. The details of local

[1] In 1999, for instance, the average monthly income per person within the rural population of the state was R $ 75.40 (around US$ 35). This is less than half of the national minimum wage (IPLANCE 2002b, p. 136).

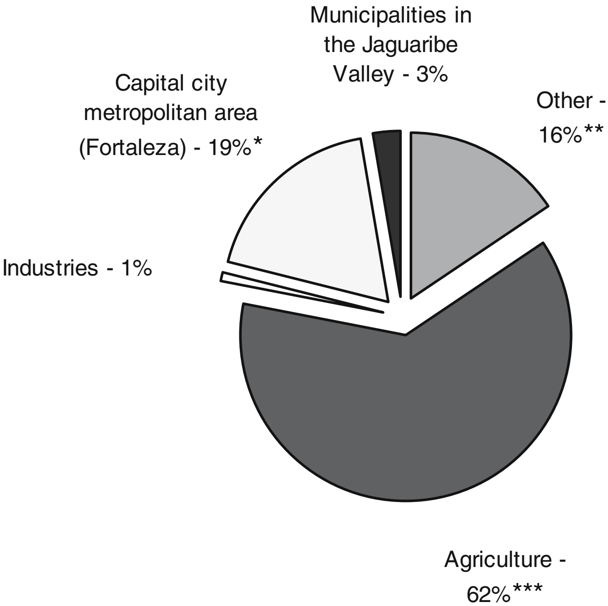

Fig. 1 Estimated bulk water consumption per sector 2003. Sources: COGERH and CAGECE.
* Includes the municipal water distribution system and water consumption by the service sector.
** This is a rough estimate of the amount of water that is classified as "lost in transit," i.e. lost to evaporation, percolation, and non-accounted uses along the valley. It does not account for evaporation in reservoirs.
*** Includes small, medium and large scale irrigated agriculture

involvement have received much attention. It is claimed that provision of services will suffer if communities are not closely involved in both decisions and their implementation.[2] Within the water sector in Brazil, the push towards local participation in water governance has also been hailed in terms of democratization (Garjulli 2001a,b; Garjulli et al. 2002; Johnsson and Kemper 2005). Yet what "participation" is most effective has not been demonstrated for water or in general. Cases where the participatory-process effect is shown are relatively few and careful empirical examination of participation or decentralization remains relatively rare (Kemper et al. 2005; Bardhan 2002).

We examine key economic and institutional constraints on the benefits of forecast use for relevant groups. Then we consider how ongoing as well as debated possible changes in Ceará could affect those constraints and thus also affect the benefits from forecasts. Forward-looking assessment of changing constraints, and their implications for forecast value, is simply illustrated by a reconsideration of the results in Sankarasubramanian et al. (2003). They argue that increased reservoir capacity in the Jaguaribe Valley, which addresses concerns with drought and interest in high-value irrigated agriculture as well as plans for new industrial urban centers, raised significantly the ratio of storage to demand and thereby reduced the value of season-ahead supply forecasts. However, as we explain in greater detail below, because rising water demand will catch up with current storage investments, the value of forecasts will rise again. Thus now is an opportune time to think about how water allocation decisions can be made contingent upon forecast information.

[2]See for instance the World Bank's (1996) *Participation Sourcebook*. Also, from a purely theoretical perspective, Tiebout (1956) shows that local provision can be more efficient than central whether the local provider is public or private. Oates (1972) and Klibanoff and Morduch (1995) suggest that a central agency can take into account spillovers across localities while local providers may have better information about local needs and preferences. Yet a local entity may not have the best technical information and know-how (Bird 1995). From another point of view, some suggest that whether decentralization leads to better outcomes depends upon who has control over local and central decision making (see, e.g., Bardhan and Mookherjee 2000a,b; Besley and Coate 2000; Seabright 1996; Johnsson and Kemper 2005; Kemper et al. 2005).

Although it is well known that various shifts in setting affect forecast value, including in the water sector (Hilton 1981; Glantz 1982; Changnon and Vonnhame 1986; Adiku and Stone 1995; Katz and Murphy 1997; Callahan et al. 1999; Chiew et al. 2000; Pagano et al. 2001; Rayner et al. 2005), this point is rarely made through an evaluation of which socioeconomic constraints will in fact change. We do exactly that, for four types of changes: (1) in water demand; (2) in water allocation within the agricultural Jaguaribe Valley; (3) in the participatory water process, with a specific focus on water allocation between the Jaguaribe Valley and the capital city of Fortaleza; and (4) in risk perception of the individuals, both farmers and water managers. For all four areas, we identify changes that we think will affect the forecasts' value.

Our analysis blends disparate research methodologies, including those from anthropology and hydroclimatology, while incorporating economics in their application. The quantitative assessment of stream-flow forecasts within reservoir release decisions is hydrology previously developed by our team (Sankarasubramanian et al. 2003) and summarized here. Yet as Sankarasubramanian and Lall (2004) emphasized, that was not designed to reflect how groups within a society vary in their influence on forecast use and in the impacts they experience from changed water management. Our field methodologies place these hypothetical aggregate potential net benefits of forecast use into a broader context that emphasizes the range of relevant actors and the specific key institutions.

Our findings rely most heavily upon: archival research; extensive participant and field observations from 2002 to 2005; structured and semi-structured interviews with policy makers, academics and civil society leaders; and a database analysis of over 4,000 records concerning land plots in the Jaguaribe Valley which helped delineate a typology of stakeholders and their positions in the hydrosystem (Taddei et al. 2006 more completely describes the relevant groups). This research has been done in collaboration with members of relevant Ceará agencies, with groups of water users and with organizations of civil society involved in water allocation.

In this article, we are commenting upon the implications of changes that we perceive to be occurring or to have significant potential to occur. We are not in any way, though, advocating for or against any of those changes. In Ceará, each change will or will not occur for many reasons. Our comments focus on the implications for forecast value. We stress that in thinking about value, it is important to think not only in terms of aggregates but also about distributions of the impacts across types of water use, hydrosystem locations, and any other relevant dimensions.

Our discussion puts additional focus on equity in the distribution of benefits from natural resources along intra-rural and urban–rural dimensions. Note that the most vulnerable are farmers in non-irrigated areas. They might eventually benefit from forecasts but the general development required for that is beyond our scope (Lemos et al. 1999; Nelson and Finan 2000; Finan and Nelson 2001; Höynck 2003). Those on the water system, though, vary tremendously in wealth and in expected net benefits from water transfers. If concerned not only with forecasts, which can affect transfers, but also with equity per se, one should look closely at all water transfers.

Below, we describe the history of water management in Ceará, the current policy landscape (Section 2) and the innovative forecast-based reservoir optimization being considered in Ceará (Section 3). We then identify key current constraints upon forecast value and suggest four areas in which the constraints are likely to change, including regarding water transfers (Section 4). We end with a broader discussion of water allocation considerations (Section 5).

2 Water management in Ceará

2.1 History

The state of Ceará in Brazil's relatively highly populated[3] and relatively undeveloped semi-arid Northeast region has over 7.4 million inhabitants[4] [Fundação Instituto de Pesquisa e Informação do Ceará (IPLANCE) 2002b]. Ceará's GDP has grown in the last 15 years but, for most, the productivity of agriculture has been low. The fraction of gross domestic product (GDP) from agriculture has dropped from 30% in the 1950s to 7% (industry and services in Fortaleza are now responsible for 85%), while the fraction of the population still working in agriculture as a main source of livelihood remains above 30%. Rural illiteracy was 56% in 1999 (Governo do Estado do Ceará 2000). Small holdings (under 10 ha) represent 70% of agricultural holdings but only 5.4% of area.

Low productivity has been attributed to drought, poor soil, land distribution, a broad lack of education, poverty, and limited physical and social infrastructure (Costa et al. 1997, p. 138). Climate variability in particular permeates life, linked to: cyclical migration (Montenegro 2001; Neves 2002); religion (Villa 2000; Della Cava 1970; Couper-Johnston 2000); economic and demographic instability (Della Cava 1970; Parente 2000; Greenfield 2001); the relations of the State with its poorer inhabitants (Neves 1995, 1998, 2003); and ties among elites in public office (Faoro 1984; Parente 2000) who gained from "the drought industry" linked to federal drought assistance (Callado 1960; Cunniff 1975; Coelho 1985; Medeiros Filho and De Souza 1988; Kenny 2002; Albuquerque Junior 2004). These constraints and relationships affect incentives to respond to any crisis through seasonal or longer-term investments. They also affect the use of information.

The Great Drought between 1877 and 1879, alleged to have killed over 500,000 people (see Neves 2000; Greenfield 1986, 1992, 2001; Davis 2001),[5] and hence transformed climate variability from a private to a public matter (Villa 2000). The imperial (later federal[6]) government sent its best technicians to fight drought through the application of science, with a focus on water storage (though in later periods, migration to other parts of the country was also used to limited extent[7]). The construction of massive reservoirs began under Emperor Pedro II in 1886 and was continued by the federal Inspetoria de Obras Contra a Seca (IOCS – Inspectorate of Works Against the Drought) starting in 1909.[8] The IOCS later became DNOCS (Departamento Nacional de Obras Contras as Secas), whose responsibilities are mainly research on infrastructure and operations of the reservoirs and whose history is enmeshed with the history of the state. DNOCS' past actions have been linked to the state's politically 'clientilistic' relationships with the elite and the poorer classes. For instance,

[3]Ceará's population density is about 50 per square kilometer (IPLANCE 2002b), high for semi-area areas globally.

[4]In 1970, the population of the state was 4.35 million, and in 1980 it was 5.3 million (Carvalho 1988).

[5]Carvalho (1988) proposes 150,000 as a more realistic count. There is evidence that in the height of the crisis, Fortaleza was the site of 1,000 deaths per day due to starvation and illnesses (Neves 2000; Villa 2000).

[6]Brazil became independent from Portugal on September 7, 1822, but remained a monarchy until November 15, 1889, when a military coup initiated the country's republican era.

[7]Later, cloud seeding was also tried (see Finan (1998) for a review of the uses of science to "combat" drought).

[8]Brazil's first public reservoir (Cedro, in Quixadá, Ceará) was started in 1886 and its construction took 20 years.

documentation exists that some of DNOCS' infrastructural investments were made to benefit local elite groups (Coelho 1985; Villa 2000; Albuquerque Junior 2004).

In 1986, official institutions were shifted when the longstanding rural oligarchy lost the state elections to a new group of young businessmen focused on industry. Development became the policy focus and incentives were created to promote economic progress. The State Secretariat for Water Resources [Secretaria de Recursos Hídricos do Ceará (SRH)] was created in 1987 and FUNCEME and COGERH were placed in it (FUNCEME, which was created in 1972, was later moved out again). COGERH later incorporated some management responsibilities previously resident at DNOCS. Its responsibilities include oversight of the debate over reservoir releases within the new participatory water management process being created within the same reform.

In 1992, Ceará's state law 11.996 created a state system for management of water resources calling for water planning and management to be integrated, decentralized, and participative. The management was to include licensing of and charging for water, plus permits for infrastructure development, but these have been minimally enforced. Regarding participation, a formal partial decentralization of water management was effected. Conselho Estadual de Recursos Hídricos (CONERH) or the State Council for Water Resources was given the ability to arbitrate water conflicts, although oversight remained with the state's judiciary. Also a mandate was given for one water committee to exist for each of the 11 river basins (or sub-basins in the case of the Jaguaribe, due to its length). These were intended to have the power to decide on the allocation of water inside of their (sub-) basins, although all are still under the power of the state council.

In 1994, as the state was about to experience a crisis in water supply, a participatory water allocation group was created in the Jaguaribe Valley. It would evolve into codified watershed committees though its task was only to allocate water to reduce political conflict from impending water shortage. In 1995, the first watershed commission was formed in a small basin called Curú.

Eight of the 11 river basins now have water committees that decide on water allocation. Usually a committee allocates the water of the largest and most important reservoirs of the basin. Diverse stakeholders meet each January and June and choose from scenarios (from COGERH) showing the fall over time in reservoir water storage for each of a set of reservoir release rates over the upcoming 6 months. Basin committee composition is roughly: 30% local water users; 30% civil society; 20% municipal government; and 20% from the state and federal governments.

In 2000, a national water agency (ANA-Agência National de Águas) was created to modernize water management with a focus on transboundary watersheds.[9] Despite the recent efforts to modernize the local institutional landscape, the turnover within the political cycles in Brazil poses challenges for water management. The heads of even the most technical agencies are often replaced after state elections and the highest offices are filled with an eye to party lines.

After the 2002 elections, for instance, political changes with implications for the organization of the state water system occurred at both the national and the state level.[10]

[9]According to Brazilian law (Decreto 24643/1934), all rivers that are located entirely inside the borders of one state are under the jurisdiction of that state, while those rivers that cross state frontiers are under federal jurisdiction.

[10]Brazil's President, Mr. Luis Inácio Lula da Silva, initiated a restructuring of DNOCS by appointing a new head and new directors. In Ceará, FUNCEME, the meteorological agency, has been shifted across secretariats. The heads of SRH and COGERH were replaced even though the party of the previous governor remained in power.

The responsibility for organizing the water committees was firmly centralized, within the state, at the SRH. In terms of local reflections of national debates, within Ceará revenue generation to cover the water system's costs became an explicit policy priority (Lemos and Oliveira 2004; Taddei 2005).

2.2 The Jaguaribe–Metropolitana region

Our research focus is the Jaguaribe-Metropolitana (JM) area.[11] The Jaguaribe River system (Fig. 2) is the source of water for over 45 municipalities. All of the most important economic centers of the Jaguaribe Valley are among them. The valley occupies about half of the area of the state and is home to just over half of the state's interior (non-Fortaleza) population. Its occupants range from rainfed agriculturalists to large agribusiness enterprises to urban dwellers.

The JM hydrological system is dominated by reservoirs and pumping stations operated by COGERH (Fig. 3). Water demands include: human consumption in Fortaleza and in the small towns in the hinterland; growing agribusiness; small family farmers; shrimp aquaculture (which has large environmental impacts of growing concern); marginalized riverbed farmers using sump pumps; and poor fishermen who require specific reservoir levels to be productive (for additional information on stakeholder typologies, see Taddei et al. 2006).

The organization of water stakeholders has been in large part dominated by their locations. Communities located upstream of the reservoir tend to disagree with those downstream, as the former tend to oppose water releases while the latter tend to favor them. Organization concerning water issues also occurs along occupational lines, e.g. by unions, cooperatives and associations.

The water allocation commission of the Jaguaribe River has 153 members, from four of its sub-basins (Alto Jaguaribe, Médio Jaguaribe, Baixo Jaguaribe, and Banabuiú[12]). Of the 30% from civil society, 40% are from the rural workers unions. As noted, roughly 30% are local water users, for instance companies providing water for human use and producers in public and private irrigation areas. Also 40% are from local government and state/federal institutions, e.g. DNOCS, COGERH, the Empresa de Assistência Técnica e Extensão Rural do Ceará, the Secretaria de Agricultura Irrigada do Ceará, and the Companhia Hidrelétrica do São Francisco. Across sub-basins, Baixo Jaguaribe has the most representatives (36%). It produces more fruit and shrimp and bigger, more organized producers using more sophisticated irrigation technologies (Fig. 4).

Two stories are commonly offered to explain the limited representation of actual water users. First, all of civil society indirectly uses water and directly produces water pollution. Second, and as suggested by government and agency roles, COGERH and others in government feared shifts in the control of the water allocation process to non-governmental stakeholders (Taddei 2005).

[11] Average population is about 24 thousand inhabitants per municipality in the hinterland. Average urbanization rate is 53% (IPLANCE 2002a; without Salgado sub-basin, due to its relative independence from the rest of the valley).

[12] The Salgado sub-basin, though part of the Jaguaribe Valley, is not directly connected to the network of reservoirs that "perennialized" the river, and therefore it was left out of the commission that allocates the reservoir waters.

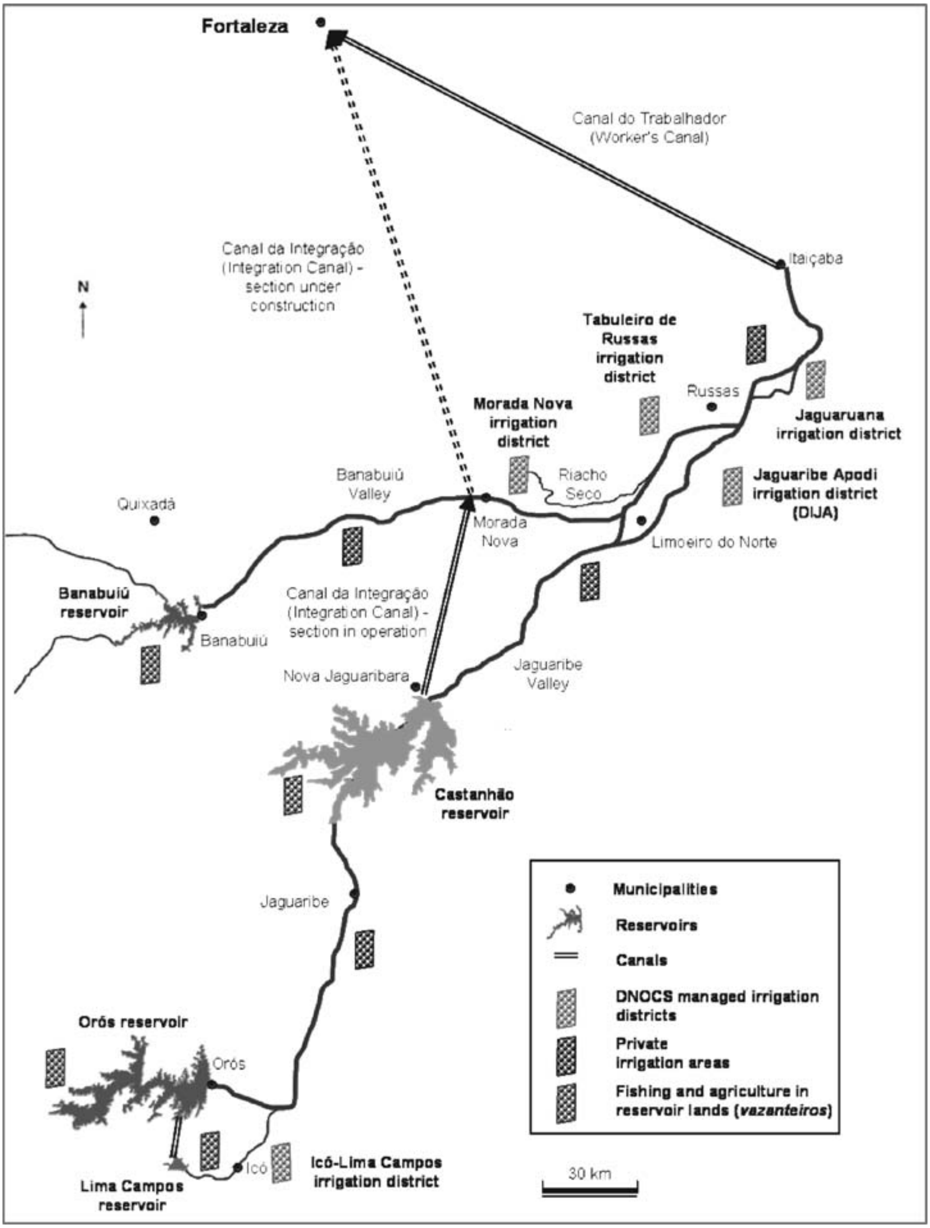

Fig. 2 Jaguaribe Valley River & irrigation system

3 Climate-based stream flow forecasts in reservoir management

The development of Fortaleza's industrial and service sectors depends on the provision of water from around the state, with the Jaguaribe River being most important. As there are no naturally perennial rivers in the state, the official and private investments in infrastructure throughout the twentieth century were "to make water" (in the local phraseology) by

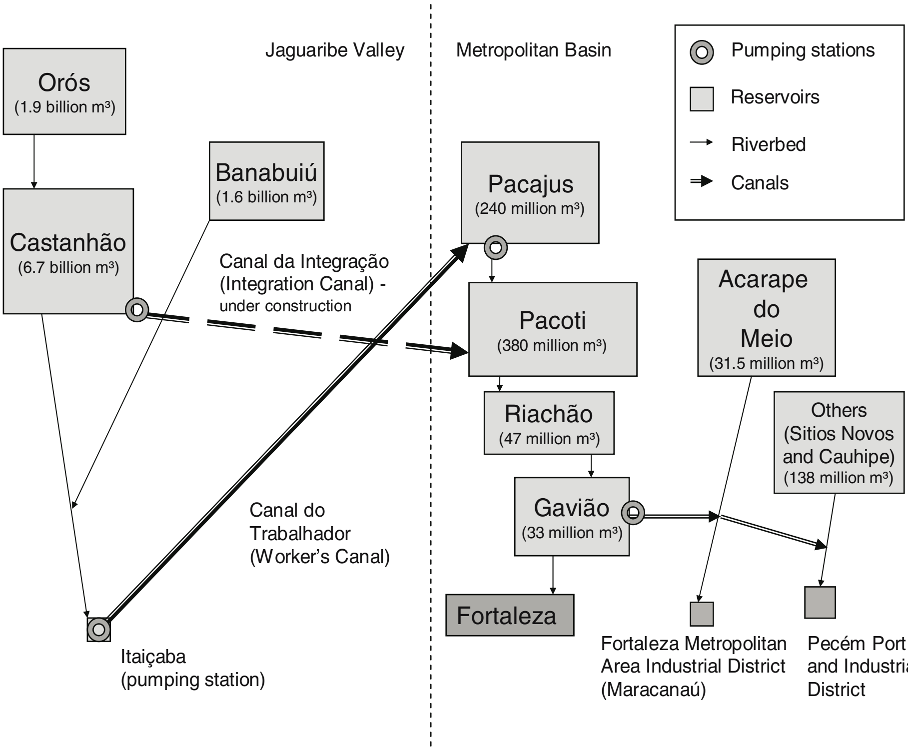

Fig. 3 Jaguaribe Valley and Metropolitan Hydrological System overview. Numbers below reservoir names reflect their storage capacity. Adapted from Guidotti (2003)

accumulating large amounts of water during the rainy season (January–June) for use in irrigation during July–December.

Given these reservoir and canal investments, which themselves have reduced vulnerability, one recent idea is that the use of forecasts can help to better manage this water system.[13] There is now some ability to predict general patterns of climate variability, which for this case means the ability to predict stream flows. Having a sense prior to the dry season (i.e., July–December) of how much water will flow into the reservoir in the next rainy season (January–June) should in principle permit beneficial adjustments to reservoir releases that trade off short- and long-term water use (Fig. 5) taking into account intertemporal factors such as high evaporation rates.

Ceará's current reservoir operation assumes zero inflows into reservoirs from future rainfall. Its policies specify a volume of water in a reservoir at a given date and the prioritized releases for specific uses, including for drinking in Fortaleza when Jaguaribe water is needed to meet those demands (see Fig. 1 for state bulk water allocation and Fig. 6 for Jaguaribe water users).

Recently, it has been shown that remote climatic conditions such as tropical sea-surface-temperature anomalies can be linked to hydroclimatology to yield predicted stream flows (i.e., the

[13] In this article we do not address local climate prediction efforts that are dominated by individual 'profetas' – rain prophets. Widespread attention is paid to these forecasts that are widely disseminated via the media (for details see Finan 1998; Taddei 2005, 2006).

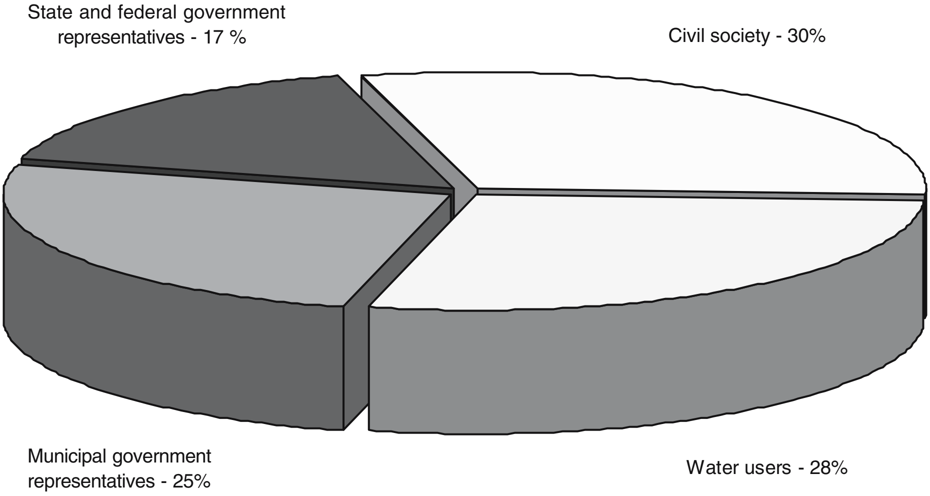

Fig. 4 Types of participants in the water allocation meetings (Year of reference: 2003). Source: COGERH

inputs to reservoirs) at seasonal and longer lead times, (Hamlet and Lettenmaier 1999; Sharma 2000a; Piechota et al. 2001;Souza Filho and Lall 2003). This could benefit water management (Dracup and Kahya 1994; Cayan et al. 1999; Sharma 2000b; Goddard et al. 2001). However, few have investigated the potential benefits that could be obtained in water systems management by utilizing such forecasts of streamflow (Yao and Georgakakos 2001; Hamlet et al. 2002; Arumugam et al. 2003). For Ceará, the question is whether the gains from using estimates of future inflows are sufficient to drop the conservative zero-inflow assumption.

To address this question, Arumugam et al. (2003) model the state water system to analyze the potential for gains in reservoir performance from the use of forecasts of stream flows, i.e. inputs to reservoirs. Forecasts derive from exogenous climatic indices of slowly varying anomalies in sea-surface temperatures over different parts of the globe that influence the moisture transport into a region on a seasonal or long-lead basis. Forecasts can be dynamical but those used here are purely statistical, following the forecasting methodology given in Souza Filho and Lall (2003).[14]

To study the Orós reservoir, a multivariate, semi-parametric conditional resampling strategy was employed for forecasting annual and monthly inflows into six reservoirs in Ceará using the Nino 3.4 index (an indicator of El Niño and Southern Oscillation) and a North Atlantic Dipole index. Souza Filho and Lall's (2003) streamflow forecasts correlate well with observed flows into those reservoirs. A forecast is issued in July for the monthly flows from January through June of the next year. The reservoir system is then simulated from July through June, to determine the potential to meet the irrigation demands

[14]The alternative, a dynamical model, typically sequentially couples a hydrological model to a Regional Climate Model (RCM) simulation preserving boundary conditions specified by the General Circulation Model (GCM) (Leung et al. 1999; Nijssen et al. 2001; Yu et al. 2003). Biases in forecast rainfall fields are typically substantial, and require statistical correction. Further, only a smaller number of ensemble members are typically simulated and hence it is difficult to accurately assess the probability distribution of the forecast rainfall from a GCM and consequently the seasonal streamflow. Uncertainty propagation from the sequential coupling of GCM-RCM-hydrologic model (Kyriakidis et al. 2001) may further call into question the adoption of the forecasts for short-term water management. Consequently, statistical models using either ocean observations, other proxies, or GCM forecast fields (Hamlet and Lettenmaier 1999; Piechota et al. 2001; Souza Filho and Lall 2003) may be more effective at this point.

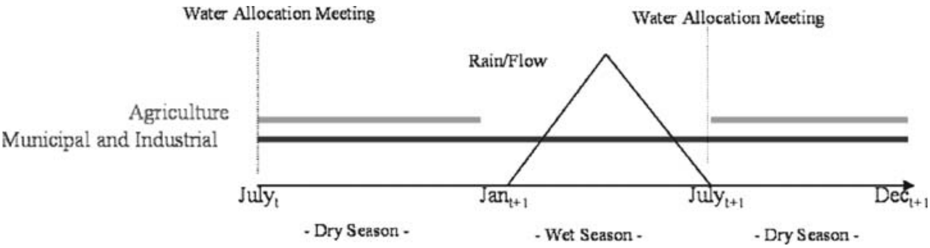

Fig. 5 Seasonal rainfall and water system demands. Water allocation decision timeline

predominantly during July–December as well as the approximately constant municipal and industrial demands. The model is similar to both Lall and Miller (1988) and Lall et al. (1996), modified with an end-of-year storage constraint as well as an annually varying yield at a specified target reliability for each use category. This yield could be promised to specific users with compensation for non-delivery depending on assigned reliability.

Sankarasubramanian et al. (2003) compare the use of four different inflow forecasts for the period 1950–1996. The first is Souza Filho and Lall (2003)'s. The second is "climatology," i.e. historical years from 1950 to 1996 are drawn with replacement with equal probability to form an ensemble (assuming no skill in forecasting). The third forecast is zero inflow for the ensuing year at all reservoir locations, as currently done. Near-zero flows were experienced in only 1% of past years but the probability distribution is strongly skewed towards small annual inflows with a few dramatically larger flows. The fourth method is a perfect forecast, i.e. using observed inflows.

The model sets end-of-year target storage and both minimum and maximum releases by use. The optimization model then generates yields that maximize a weighted combination of uses, with weights presumed to reflect marginal utilities (Hamlet et al. 2002; Yao and Georgakakos 2001; Faber and Stedinger 2001). In addition, Arumugam et al. (2003) assess performance in terms of reservoir 'reliability,' 'resilience,' and 'vulnerability' shortfalls relative to demand (Hashimoto et al. 1982), and spill events for a range of years. Simulations show that as forecast skill increases, yield rises at any level of reliability, while reliability rises at any level of yield. The K-nearest

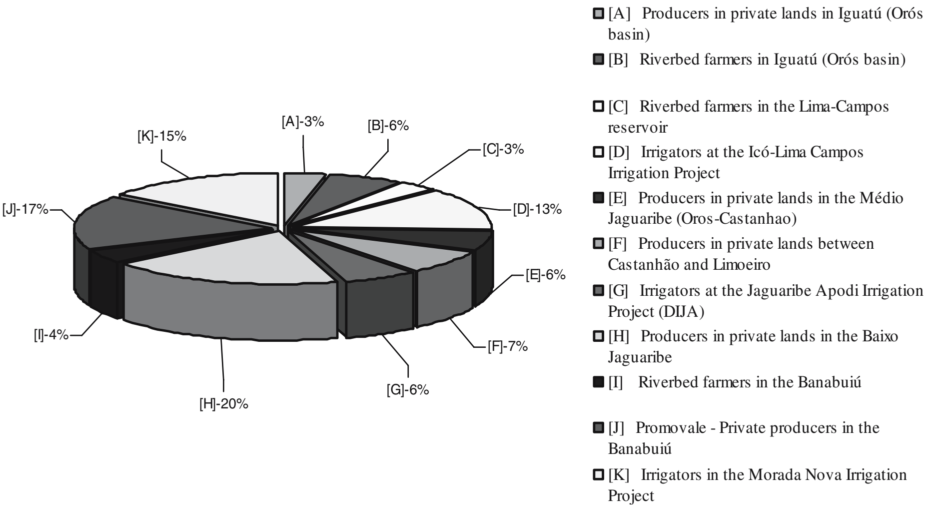

Fig. 6 Demography in irrigated agriculture in Jaguaribe Valley-survey sampling. Sources: DNOCS, SEAGRI, municipal governments, rural workers unions and COGERH database

neighbor forecasts used for Cearà have considerable skill and the improvement in yield (again that must be considered for a given reliability level) using 'K-nn' forecasts is found without a reduction in the other performance measures considered, resilience and vulnerability.

4 Societal shifts and the value of climate-based forecasts

The forecast innovation described above moves beyond generating climate-based forecasts to modeling their potential use by the operator of a reservoir and evaluating the effects of such forecast use on societal outcomes. Such modeling efforts can quantify the value of forecasts once an objective is specified, i.e. once it is specified both what matters to whom and, looking across some broad groups, who matters how much.

Such modeling also shows explicitly that multiple factors influence the value of forecast use for *any* given objective. The sub-sections below identify changes that are either ongoing or under consideration and would affect the net benefits from using climate-based forecasts of stream flows. The societal shifts we examine are: changes in water demand; changes in water allocation within the Jaguaribe Valley; changes in the participatory water-management process, specifically focused on allocation between the Jaguaribe Valley and the capital city of Fortaleza; and changes in effective risk perception by key individuals, both farmers and water managers. For all four of these areas, the changes we identify point to an increase over time in the value of a forecast.

4.1 Changing water demand: catching up with storage

Recall that Sankarasubramanian et al. (2003) find that recent increases in reservoir storage limit the value of stream flow forecasts in Ceará at the current time.[15] This is one indication that the investments in lowering vulnerability to drought have had a significant impact. There are two reasons why those infrastructure investments also lowered the value of forecasts. First, one reason to release more water from reservoirs when the forecast of rain is higher is the possibility of water spilling over the top of the dam and simply being wasted. For any amount of current reservoir storage, the likelihood of spillage is clearly lower when reservoirs are larger. Second, one reason to release less water from reservoirs when the forecast of rain is lower is the chance of the reservoir running dry. As the storage-to-annual-demand ratio rises, e.g. if a half-full reservoir holds enough to meet critical needs for a year, or 2 years, that is less of an issue.

Yet as noted in Section 1, demographic and economic trends suggest that demand will catch up with storage, raising forecast value. While the major infrastructure (i.e., the reservoirs) and thus the water supply are likely to hold constant,[16] already major investments in the new port of Pecém are creating significant increases in the demand for water outside of agriculture. The industrial expansion in Ceará is taking place at a rate

[15]This is a good conceptual point and one that best applies to the Castanhao reservoir, the newest and by far biggest within Ceará. Within smaller reservoirs that essentially create isolated sub-hydro-systems, it does not always apply.

[16]In terms of potential new supply, the debate about shifting water from the Rio Sao Francisco north to Ceará must be noted. In principle, sufficient water could be diverted from the state of Bahia that even if demand increased considerably in Ceará, as it will, supply could at least keep pace. However, as can easily be imagined, the potential loss of so much water has generated enormous opposition in those states and this may never happen. Another important detail is that, due to the required high amount of pumping the cost of transference of the water will be very high, although there are no official numbers yet.

almost twice the GDP growth of the state. The 2004 data show that the economic growth of the state was 4.4%, a little under the national growth (5%). However there was a much larger rise in industry (7%), a more modest rise in the services area (3.9%), and a decline in agriculture (Governo do Estado do Ceará 2006). Though statistics for 2005 have not been released, all indicators point toward a continuation of this trend.

As part of this industrial development trend, the state's official development plan explicitly aims to bring many or most of the 40% of the population who are currently employed in rainfed agriculture, i.e. those who are not currently drawing on the water system, into new urban areas specifically built around strategic locations within the existing hydrosystem (Governo do Estado do Ceará 2002). The trend and plan are transparent. A government billboard in front of the port Pecém states: "One new industry every 6 days. Industries for Ceará, jobs for Ceará's people."

Looking at the trends in human demand for drinking water, Fortaleza is one of the fastest growing cities in Brazil. It is about to become the fourth most populated metropolitan area in the country, having grown at an average annual geometric rate of 2.4% during the 1990s, the highest among metropolitan areas in Brazil. Estimates projected that 3.3 million people would be living in the metropolitan area in 2005, indicating 39% growth in the last 15 years (IPECE 2006).

Turning to supply, the Jaguaribe Valley has now exhausted its possibilities for large water accumulation infrastructure (Ministério da Integração Nacional 2004). One looming possibility that points in the other direction is the potential diversion of the San Francisco River to Ceará. On the other hand, that this highly controversial and uncertain project is being discussed clearly indicates that growth and water demand (and so forecast value) are expected to continue to rise.

4.2 Changing water allocation in the Jaguaribe Valley

One gain from the use of forecasts is more water for society to use. As mentioned above, benefits from forecast use can include lower reservoir overflow and lower evaporation if, in anticipation of rain, withdrawals can be planned. Thus, forecasts provide not only socio-political value, if they help to reduce allocation conflicts, but also economic value, tied to economic water uses.

From an economic point of view, currently water goes to a mix of low- and high-valued uses. Formal water rights are virtually non-existent and misgivings about formal water trading are very publicly expressed by actors concerned with the potential inequities in the distribution of water[17] (Fig. 7) despite the existence of some small scale, spontaneous, and informal water trading.

4.2.1 State & national allocation policies

Important actors in both federal and state governmental agencies support the idea of trading water across sectors within a state as one form of macro-water-allocation mechanism. A

[17]Local commentary about a potential water market in Ceará includes strong negative reactions by left-wing groups in Ceará (anti-market and anti-water-commodification have recently become a frequent discourse among parties such as the *Partido Socialista Brasileiro* [PSB or Brazilian Socialist Party)] or *Partido Comunista do Brazil* (Communist Party). For example, in April 2003, the PSB had a TV commercial alerting the population against neo-liberal pro-water-market efforts in the country, without explicitly mentioning any group. Many university students and professors and government employees (including at COGERH) oppose a market approach to allocation. Ideological aversion to the commodification of water is exemplified in campaign slogans and graffiti around the state against water-market concepts.

Fig. 7 Public expression of concern about the distribution of water

policy experiment in 2001 named *Aguas do Vale* (Waters of the Valley), designed by the national water agency (ANA) and COGERH, paid rice growers about $25/hectare to not produce.[18] Water they did not use went to perennial cultures and shrimp production. Given water scarcity, this appears to have headed off conflict while raising the economic value of the water and thus also forecasts.

While this program of implicit water rights and compensated transfers did temporarily re-allocate water, it did not achieve its other stated goal of permanent shifts out of rice production.[19] It is also worth noting that not much consideration appears to have been given, at least explicitly, to the distribution of the surplus generated by shifting water to uses with higher economic value.

Difficulties existed in collecting payment from those who received water (only 21% paid[20]). This presages administrative challenges for new water institutions that link water transfers to payment. It may also signal to others that higher-value water users get preferential treatment. That this experiment occurred, however, suggests significant institutional interest in such programs.

ANA is the actor most often cited for support of water licenses (*outorgas*), which are natural precursors of trading as well as of tariffs, although there has also been activity in the state and the national legislatures regarding the reform of water laws to allow for licenses and billing.[21] Since it is not easy to shift the regime for allocation of such a fundamental resource, national signals matter. Water laws recently enacted in Ceará allow for transference of *outorgas* among users, but there is little public discussion of this point and our observations indicate the public is generally unaware of that (note it may

[18]COGERH data indicates that rice production consumes about half the water used in the Jaguaribe Valley.

[19]This shift did not occur as hoped for, despite some efforts to train farmers and provide credit (though the later suffered from the lack of collection of funds from those receiving water). Low capacity to invest and low literacy are also significant constraints.

[20]The 21% refers to the payments by the date stipulated by COGERH. The Secretariat for Water Resources of Ceará and COGERH took further action in order to get water bills paid, with mixed degrees of success, for the following four years after the Águas do Vale program.

[21]In 2001, at the national level, a resolution of the National Council for Water Resources (resolution 16/2001) created legal space for the transfer of water licenses between users. In 2004 the Ceará Legislative Assembly (Assembléia Legislativa) passed a new water law that allows transfers of licenses (*outorgas*) between users.

understandably not be stressed by lawmakers, given the fierce political debate concerning the linking of water allocation to a free market system).[22]

Signals to the public in Ceará since the 2002 election have also been in the direction of effective payment for water (something the 1992 water law prescribed but that could not be implemented for lack of infrastructure and resistance of local populations). Rationales include that payments bring about more rational consumption and "cost recovery" (e.g., balancing of COGERH's budget). In any case, Ceará's SRH takes the idea seriously enough to have hired local private consultancy company (Consórcio Tahal 2000 JP Meio Ambiente/ SRH-CE) and the Ceará Federal University (UFC) researchers to study the ability of the farmers within the Jaguaribe Valley to pay for their water.

SRH also promotes the water licenses, e.g. as preconditions for Banco do Nordeste do Brasil (Northeast Brazilian Bank) loans as well as for environmental licenses from SEMACE, the state environmental secretariat. If having an *outorga* is necessary to use water, when the system gets implemented then Ceará will be close to having water rights or claims (contingent claims, since the government could not guarantee delivery), i.e. an institutional prerequisite for water trading.

Current discussions in local academic circles focus on issues like inter-sectorial vs. intra-sectorial trading, the optimal level of coordination by agencies, prices as allocation mechanism, and which users should be integrated into or outside of any trading (for instance distinguishing high- from low-payment-capacity stakeholders) and how that would affect impacts on equity. Summarizing, much effort and attention goes into shifting of water to higher economic value.

4.2.2 Local water trading

Such generalized discussion about the pros and cons of water trading has not reached broader audiences in Ceará. However, there are examples of such behavior taking place within the state independent of broad policy discussions, i.e. simply as a result of decisions made by producers.

A regional decree from the Cariri area in southern Ceará (and more specifically within the Batateiras Valley) that became effective from 1870 to 1880 gave control of water to owners of the lands containing the water sources, to their benefit. These rights shift only with the sale of land and can fairly be said to have derived from the interests of at least a subset of the local producers. Since then, inhabitants have been selling their water to each other and to local municipalities (Kemper et al. 1999; Campos and Simpson 2001; Garjulli et al. 2002). Despite the fact that this practice violates both state and federal legislation, there appears to be no official enforcement. Water claims are defended through various types of pressure common in traditional practices.

In addition, within a publicly managed irrigation area inside the Jaguaribe-Apodi perimeter, during water scarcity in 2001 growers of perennial cultures (mostly fruits) negotiated with bean, soy and corn growers to rent their lands and thereby obtain the use of the water the latter used. Thus informal water trading (through trading land rights) seems to have appeared spontaneously.

[22] It is noteworthy that the *outorga* and tariff system became law in 1992 and is still not fully implemented. It is not unusual in Brazil that laws are made but then not put into practice due to societal resistance. See Taddei (2004) for discussion of this point.

4.3 Changing scope of participation and intra-state allocation

The economic value of providing forecasts to inform Water Allocation Committees' (WAC) decisions depends on the potential economic value from the re-allocations WACs consider (of course, WACs can also provide value by decreasing conflict). Thus the scope–in terms of spatial scale of WAC decisions – constrains value. This point also holds for whatever other decision making bodies (WAC analogs) that may arise to make such choices.

Watersheds are being hydrologically connected now and group decisions include more actors (e.g., the number of voting members in WACs rose from 107 to over 150 in the last 2 years). Also, COGERH technicians continue to educate stakeholders about the inter-connectedness of the watersheds, where decisions about one point affects other areas. More generally, we believe that the trend is toward a larger spatial scope for allocation and, thus, forecasts having higher value.

Reservoir Release Scenarios Presented to Water Allocation Committee

OPERATION SIMULATION FOR THE ORÓS RESERVOIR

FROM JULY 1st, 2002 TO JANUARY 1st, 2003

MAXIMUM LEVEL:	199,50 m	VALVE LEVEL:	169,00 m
CAPACITY:	1.940,00 hm3	DEAD VOLUME:	16,87 hm^3

SIMULATION AT 5,0 m^3/s*

Date	Level (m)	Volume (hm^3)	Volume (%)	Evaporation area (m)	**Released flow (m^3/s)**	Released volume (hm^3)**	Evaporated volume (hm^3)	Level variation (m)	Volume variation (hm^3)
07/01/02	186,36	420,091	21,7%	0,19	**5,000**	13,39	10,30	-0,44	-23,70
08/01/02	185,92	396,447	20,4%	0,22	**5,000**	13,39	10,68	-0,49	-24,07
09/01/02	185,43	372,417	19,2%	0,22	**5,000**	12,96	10,73	-0,48	-23,69
10/01/02	184,95	349,137	18,0%	0,24	**5,000**	13,39	10,38	-0,54	-23,77
11/01/02	184,41	325,459	16,8%	0,21	**5,000**	12,96	9,42	-0,52	-22,38
12/01/02	183,89	303,167	15,6%	0,21	**5,000**	13,39	8,34	-0,55	-21,74
01/01/03	**183,34**	**281,601**	**14,5%**	**1,29**		**79,48**	**59,85**	**-3,02**	**-139,35**

Source: COGERH. * This table is just a sample of the type of data presented to water commission members. Usually around six different scenarios like the one above are presented to the commission, each with different released flow rates. For the period illustrated above (dry season, 2002), the approved release rate was 5 to 6 m^3/s. ** Release volumes are different due to the fact that some months have more days than others.

Fig. 8 Copy of reservoir release scenarios presented to water allocation committee

WAC history helps to understand the current limited scope of the participatory water process. That WAC scope is limited is demonstrated by the small differences among the release scenarios generated by COGERH for committees to consider (see Fig. 8 for COGERH scenarios). This does not mean that in principle the WACs, or analogous groups, could not have a greater say in water allocation. Yet the current process constrains the value of any forecasts provided to them.

Many discuss WACs (in Ceará and elsewhere in Brazil) in terms of democratic decentralized water decision making, yet their limited scope may be better understood if it is recognized that in Ceará their existence appears to be due in part to a desire to dispel and to manage potential rural anger about water re-allocation. The Ceará WACs were created just after significant discontent was expressed concerning water transfers to Fortaleza during a 1993 drought, especially in the Jaguaribe Valley. Many agricultural water uses were prohibited in the Valley at that time, with enforcement by military police (Garjulli et al. 2002). Meeting urban water needs in this fashion was, not surprisingly, unpopular in the Valley. Thus the state felt that something had to be done.

Describing a WAC in this way, i.e. as an instrument for management of discontent, is at odds with the point that any popular institution is a break from longstanding paternalistic relationships between the state and marginalized rural inhabitants. Yet despite this, there does not appear to have been a clear break from "business as usual" in water. That is most clearly manifested in three ways: first, the decisions of the WACs can be overturned by CONERH, a water council controlled by the government; second, WACs include many non-water-using actors including from government; and third, the WACs must choose from the scenarios generated by COGERH. In short, forecasts provided to WACs are informing highly constrained choice.

Such constraints on the scope of WACs' choices have strong implications for not only how democratic water allocation is, but also the value of the forecasts. For greater value, forecasts would have to influence the larger-scale decision about urban versus agricultural use of water, either within a 'WAC with greater scope' or within an agency taking such decisions.[23]

Such an 'expanded mandate WAC,' or other analogous institution, may actually come into being relatively soon in Ceará, brought on by the construction of the *Canal de Integração* ("Integration Canal") from the Jaguaribe Valley to Fortaleza and to the new port in Pecém. Completion will make feasible a larger scale of water transfer, necessitating a focus on a new set of transfer choices. In the areas to be connected, participatory committees are already in place (the Jaguaribe WAC, the Metropolitan Water Committee, and the Canal da Integração multi-participatory group). Informed actors believe they likely will merge when construction is done, drawing members from the valley and the city.[24] For their new transfer choices, forecasts about stream flows in the Valley will remain relevant and the greater scale will raise forecast value.

[23] In this context, it may actually be important to embed analysis of forecast use within COGERH, particularly if COGERH has the interest or capacity to manage sectoral/user group annual reliable contracts, associated transactions and potentially secure insurance to backstop their annual reliability guarantees.

[24] For example, COGERH technicians working passionately for the WACs are not independent of their bosses. Our fieldwork finds that there have been discussions among some agency heads concerning a more equitable manner to decide on bulk rural–urban water transfers in the future, something perhaps along the lines of a larger-scale WAC.

4.4 Changing risk perception of water users

Ethnographic data show that risk aversion leads some important local stakeholders to prefer not using forecasts in making decisions. This is a fundamental constraint on forecast value, as risk aversion is not likely to vanish and non-use of a forecast of course eliminates its potential gains.

At the household level, we have observed 'defensive' or 'hedging' behavior in the decisions by the more vulnerable populations to invest, or not, in fruits or advanced irrigation equipment.[25] Those who lack resources neither easily survive a weather-related loss of output nor are capable of taking full advantage of a good weather shock to increase production (Lemos et al. 2002).

However, the way in which risk affects water decisions varies across stakeholders. For instance, not only do households typically vary in preference for risk but also COGERH may be much more averse to risk than the water committees. Generally, then, shifts in who makes water decisions can shift the level of risk aversion which is brought to bear on the decisions that forecasts could inform.

For instance, irrigators located downstream from the reservoir, in irrigation projects or along the riverbed, use accumulation and sales of assets (e.g. cows and vehicles) to cope with climate variation, in addition to hedging within seed and crop choice and occupational multiplicity (Comitas 1973).[26] Therefore, irrigators tend towards maximization of current harvest to generate sales and thus assets. This large group tends to press for the release of as much water as possible and would be more likely than others to rely on forecasts of high future rain to release more now.

In contrast, the technicians from COGERH (and, to some extent, DNOCS) appear to feel a significant political pressure and assume *zero* future rain in the upcoming season in generating reservoir-release scenarios. These water managers feel they will not be rewarded for having a bit more water for production but will be punished if they come up short relative to basic needs. In fact, while the participatory water allocation decision has often been to release on the high end of the COGERH scenarios, COGERH has often actually released less water than was decided. This is publicly justified by COGERH as due to the high rate of climate variability of the region. Yet many local agents, and some technicians from COGERH and DNOCS[27], suggest that the next step in the participatory process is the inclusion of agricultural producers in creation of scenarios.

Even without that shift, the risk perceptions relevant for water and forecast use are likely to shift if water re-allocation to increase water's economic value occurs. It is believed that aversion to risk decreases with wealth and in Ceará the producers of higher-economic-value outputs are relatively wealthy. This holds in the Jaguaribe Valley and also if water is transferred to industry. Thus, water trading to higher-valued uses can effectively lower aversion to risk in average water use. This should make the use of forecasts more likely, increasing the value of the forecasting.

[25] We are currently surveying households concerning their investments and adjustments to water levels.

[26] That said, it is possible that these forecasts *lower* the variance of the information that farmers commonly receive. During strong El Nino years, the media often publicizes many quite general – and at times conflicting – forecasts about the expected rainy season. A stream flow forecast that is more relevant to user activities and takes into account additional variables can send a clearer signal on supply expectations and thus reduce the public confusion, although whether this is the outcome would depend strongly upon public trust in the forecast supplier.

[27] One of them is João Lúcio de Oliveira, a former COGERH technician and currently high rank manager of DNOCS.

Further, re-allocation based on forecasts could help those who do not wish to face the risk of uncertain rainfall (this point follows Small et al. 2005; and a related policy suggestion in Brown and Lall 2005). A forecast of low rain, for instance, could provide a useful early signal of water scarcity that helps people to make decisions. [28] Relevant choices include the decision not to plant but instead rent your land to a neighbor and pursue less risky temporary urban employment. That follows the *Águas do Vale* idea of transfers during a dry year and it could be based on forecasts.

Another institutional step or tool that may address concern with risk is the use of insurance.[29] Being able to count on compensation when agricultural production is undermined by a drought could make farmers less risk averse in making investments that would raise their average output. Concerning this paper's focus, also the value that we have suggested that forecasts could create would be more likely to be realized, since the effective risk from their use would be reduced.[30]

5 Discussion

This paper emphasized the influence of societal setting upon the value of innovative forecasts of streamflows. Both 'top-down' and 'bottom-up' changes occurring and being considered in Ceará will affect what the use of these forecasts can contribute to overall welfare and who will benefit.

We noted four types of societal shifts (in water demand, in two types of water allocation, and in risk perception) that we believe will occur in Ceará and which will increase the value of forecasts. Summarizing, water is likely to be in increasing demand for high-economic-value activities, such as in new industries, and to be re-allocated to higher-economic-value activities over time. This increases the economic value of water-saving forecasts and makes them more likely to be used.

Understanding when forecasts are useful, and for whom, facilitates both public and private assessments concerning forecast generation and dissemination (Broad et al. 2002). One should compare forecasts' net benefits with gains from other actions such as incentives for relocation, job sector retraining, subsidies for non-water-intensive activities, and the promotion of water-conserving technologies.

In addition, forecast suppliers can target their efforts based upon the trends in forecast value. We focused here on the use of stream flow forecasts on a seasonal-to-interannual timescale. We have observed, though, that ongoing planning for certain medium- to long-term development and infrastructure initiatives (e.g., for new reservoirs of uncertain size)

[28] It should be noted that even without forecasts, i.e. with the average forecast every year, a market in such places in the water line could coordinate water investments and demand. However, the more information about water supply is available, the more relevant the demand signal. For instance, when water is low, we want the demands for water or greater or lesser certainty to be revealed. Forecasts help this market do that.

[29] Without going too far into the details here, as the most important hurdles at this point are probably the political and institutional issues, distinguishing water and crop insurance is worthwhile. Conceptually, insurance for crop failure faces 'moral hazard' concerns about farmers' unobserved levels of effort. Insurance for delivery of water does not have a role for farmer effort. Payouts for no water are triggered by rain and the release decisions.

[30] While insurance may be priced solely from the entire historical record, it may be that insurers more happily enter the market when year-to-year signals of scarcity exist. It is also possible that cutting-edge analysis of climatic regimes, i.e. forecasts of how temporal averages will shift, would assist insurers.

could benefit from improved forecasts of multi-year droughts. This distinct climate-forecast output is not currently developed.

Finally, we stress two points about equity, which cannot be overlooked in any discussion of the water sector in Northeast Brazil. The evolution of water demand and water policy will affect not only forecast value but also, without question, the absolute and relative welfare of millions. The effects of these trends upon a forecast's value and its optimal production, dissemination and use are second-order relative to the direct impacts of water allocation on average welfare and equity. Those will be first-order issues with forecasts or not and the equity effects deserve real attention.

That said, the very same point about the centrality of the water sector to life within Ceará implies that the details of forecast use matter not only for average gains but also for distribution. At the individual level, as a general rule the better-off actors may use forecasts to greater effect. But the less well off could benefit and within public decisions such as about reservoirs' releases the use of forecasts in decision processes may not clearly a priori favor one group over another. Yet specific institutional settings may change that, as some may see the likely outcome as harm. For instance, if forecast use tends to raise releases, upstream–downstream conflict may be raised. This not only matters per se but also may give groups reasons to contest the use of the forecasts.

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References

Adiku SGK, Stone RC (1995) Using the southern oscillation index for improving rainfall prediction and agricultural water management in Ghana. Agric Water Manag 29(1):85–100

Albuquerque Junior de DM (2004) Weaving traditions: the invention of the Brazilian Northeast. Lat Am Perspect 31(135):42–61

Arumugam S, Sharma A, Lall U (2003) Water allocation for multiple uses based on probabilistic reservoir inflow forecasts. In IAHS-IUGG Proceedings, Soppore, Japan

Bardhan P (2002) Decentralization of governance and development. J Econ Perspect 16(4):185–205

Bardhan P, Mookherjee D (2000a) Corruption and decentralization of infrastructure delivery in developing countries. Working Paper, University of California, Berkeley

Bardhan P, Mookherjee D (2000b) Decentralizing anti-poverty program delivery in developing countries. Working Paper, University of California, Berkeley

Besley T, Coate S (2000) Centralized versus decentralized provision of local public goods: a political economy analysis. J Public Econ 87(12):2611–2637

Bird RM (1995) Decentralizing infrastructure: for good or for ill? In: Estache A (ed) Decentralizing infrastructure: advantages and limitations. World Bank Discussion Papers 290 22–51

Broad K, Pfaff AP, Glantz MH (2002) Effective & equitable dissemination of seasonal-to-interannual climate forecasts: policy implications from the Peruvian fishery during El Niño 1997–98. Clim Change 54 (4):415–438

Brown C, Lall U (2005) Water allocation and management in a changing world: assessing strategies for reliable and equitable water use responsive to dynamic risk assessment. Mimeo Columbia University, New York

Callado A (1960) Os Industriais da Seca e os "Galileus" de Pernambuco. Civilização Brasileira, Rio de Janeiro

Callahan B, Miles E, Fluharty D (1999) Policy implications of climate forecasts for water resources management in the Pacific Northwest. Policy Sci 32:269–293

Campos N, Simpson L (2001) Mercado de Água. In: Campos N, Studart T (eds) Gestão de Águas: princípios e práticas. ABRH, Porto Alegre
Carvalho O De (1988) A Economia Política do Nordeste – Seca, Irrigação e Desenvolvimento. Associação Brasileira de Irrigação e Drenagem. Campus Brasília, Rio de Janeiro
Cayan DR, Redmond KT, Riddle LG (1999) ENSO and hydrologic extremes in the western United States. J Climate 12(9):2881–2893
Changnon SA, Vonnhame DR (1986) Use of climate predictions to decide a water management problem. Water Resour Bull 22:649–652
Chiew F, McMahon TA, Zhou S-L, Piechota TC (2000) Streamflow variability, seasonal forecasting and water resources systems. In: Hammer GL, Nicholls N, Mitchell C (eds) Applications of seasonal climate forecasting in agricultural and natural ecosystems: the Australian experience. Kluwer, Dordrecht, pp 409–428
Coelho J (1985) As Secas do Nordeste e a Indústria das Secas. Vozes, Petrópolis
Comitas L (1973) Occupational multiplicity in rural Jamaica. In: Comitas L, Lowenthal D (eds) Work and family life – West Indian perspectives. Anchor Books, New York
Consórcio Tahal (2000) JP Meio Ambiente/SRH
Costa ACG, Kottak CP, Prado RM (1997) The sociopolitical context of participatory development in Northeastern Brazil. Human Organ 56(2):138–146
Couper-Johnston R (2000) El Niño – the weather phenomenon that changed the world. Hodder & Stoughton (Coronet), London, p 354
Cunniff R (1975) The birth of the drought industry: imperial and provincial responses to the great drought in Northeast Brazil (1877–1880). Revista de Ciências Humanas, VI
Davis M (2001) Late Victorian holocausts: El Niño famines and the making of the third world. Verso, New York
Della Cava R (1970) Miracle at Joaseiro. Columbia University Press, New York
Dracup JA, Kahya E (1994) The relationships between United-States streamflow and La-Nina events. Water Resour Res 30(7):2133–2141
Faber BA, Stedinger JR (2001) Reservoir optimization using sampling SDP with Ensemble Streamflow Prediction (ESP) forecasts. J Hydrol 249:113–133
Faoro R (1984) Os donos do poder: formação do patronato politico brasileiro. Globo, Rio de Janeiro
Finan TJ (1998) Birds nests, donkey balls, and El Niño: the psychology of drought In Ceará, Northeast Brazil. Paper presented at the annual meeting of the American Anthropological Association, Philadelphia
Finan TJ (2001) Drought and demagoguery: A political ecology of climate variability in Northeast Brazil. paper prepared for the workshop Public Philosophy, Environment, and Social Justice, Carnegie Council on Ethics and International Affairs, New York, NY
Finan TJ, Nelson DR (2001) Making rain, making roads, making do: public and private adaptations to drought in Ceará, Northeast Brazil. Clim Res 19:97–108
Gaiser T, Krol MS, Frischkorn H, de Araújo J (eds) (2003) Global change and regional impacts: water availability and vulnerability of ecosystems and society in the semi-arid Northeast of Brazil, Springer, Berlin
Garjulli R (2001a) Experiência de Gestão Participativa de Recursos Hídricos: a Caso do Ceará. In: Alves RFF, de Carvalho GBB (eds) Experiências de Gestão dos Recursos Hídricos. MMA/ANA, Brasília
Garjulli R (2001b) Oficina Temática: Gestão participative dos recursos hídricos-Relatório Final. PROÁGUA/ANA, Aracajú
Garjulli R, de Oliveira JLF, da Cunha MAL, de Souza ER, Folhes MT (2002) Projeto Marca D'Água, Relatórios Preliminares. A Bacia do Rio Jaguaribe, Ceará-2001. Núcleo de Pesquisa em Políticas Públicas/Projeto Marca D'Água, Brasília
Girão R (1986) A Marcha do Povoamento do Vale do Jaguaribe (1600–1700). SUDENE/GEVJ, Fortaleza
Glantz MH (1982) Consequences and responsibilities in drought forecasting: the case of Yakima, 1977. Water Resour Res 18:3–13
Goddard L, Mason SJ, Zebiak SE, Ropelewski CF, Basher R, Cane MA (2001) Current approaches to seasonal-to-interannual climate predictions. Int J Climatol 21(9):1111–1152
Governo do Estado do Ceará (2000) Ceará-Indicadores Sociais e Demográficos-PNAD 1999. Secretaria de Planejamento e Coordenação / Fundação IPLANCE, Fortaleza
Governo do Estado do Ceara (2002) A Reestruturação Espacial como Componente da Estratégia de Combate à Pobreza Rural. Fortaleza, Edições Iplance
Governo do Estado Do Ceará (2006) PIB Cearense Apresenta Crescimento. Portal De Serviços E Informações. February 28, 2006
Greenfield GM (1986) Migrant behavior and elite attitudes: Brazil's Great Drought, 1877–1879. Americas 43(1):69–85
Greenfield GM (1992) The great drought and elite discourse in Brazil. Hisp Am Hist Rev 72(3):375–400
Greenfield GM (2001) The realities of images: imperial Brazil and the Great Drought. American Philosophical Society, Philadelphia
Guidotti G (2003) Utility of Climate Information Based Reservoir Inflow forecasts for Bulk Sector water allocation. Master Thesis, Earth and Environmental Engineering Department. Columbia University, New York, p 6

Hamlet AF, Lettenmaier DP (1999) Columbia River streamflow forecasting based on ENSO and PDO climate signals. J Water Res Plan Man-Asce 125(6):333–341
Hamlet AF, Huppert D, Lettenmaier DP (2002) Economic value of long-lead streamflow forecasts for Columbia River hydropower. J Water Res Plan Man-Asce 128(2):91–101
Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency, and vulnerability criteria for water-resource system performance evaluation. Water Resour Res 18(1):14–20
Hilton RW (1981) The determinants of information value: synthesizing some general results. Manage Sci 27 (1):57–64
Höynck S (2003) Structure and possible development of the agricultural sector of Ceará and Piauí. In: Gaiser T, Krol M, Frischkorn H, de Araújo JC (eds) Global change and regional impacts – water availability and vulnerability of ecosystems and society in the semiarid northeast of Brazil. Springer, Berlin
IPECE-Instituto de Pesquisa e Estratégia Econômica do Ceará (2006). Ceará em Números 2005. Edições IPECE, Fortaleza
IPLANCE-Fundação Instituto de Pesquisa e Informação do Ceará (2002a) Índice de Desenvolvimento Municipal 2000. Edições Iplance, Fortaleza
IPLANCE-Fundação Instituto de Pesquisa e Informação do Ceará (2002b) Diagnóstico Social do Ceará. Edições Iplance, Fortaleza
Johnsson RMG, Kemper KE (2005) Institutional and policy analysis of river basin management – the Jaguaribe River Basin, Ceará, Brazil. World Bank Policy Research Working Paper 3649, June 2005, Washington, DC
Katz RW, Murphy AH (eds) (1997) Economic value of weather and climate forecasts. Cambridge University Press, New York
Kemper K, Gonçalves JYB, Bezerra FWB (1999) Water allocation and trading in the Cariri region–Ceará, Brazil. World Bank Technical Paper **no.** 427, Washington, DC
Kemper K, Dinar A, Blomquist W (2005) Institutional and policy analysis of river basin decentralization. The principle of managing water resources at the lowest appropriate level – when and why does it (not) work in practice?. The World Bank, Washington DC
Kenny ML (2002) Drought, clientalism, fatalism and fear in Northeast Brazil. Ethics Place Environ 5(2):123–134
Klibanoff P, Morduch J (1995) Decentralization, externalities and efficiency. Rev Econ Stud 62(2):223–247
Kyriakidis PC, Miller NL, Kim J (2001) Uncertainty propagation of regional climate model precipitation forecasts to hydrologic impact assessment. J Hydrometeorol 2(2):140–160
Lall U, Miller CW (1988) An optimization model for screening multipurpose reservoir systems. Water Resour Res 24:953–968
Lall U, Sangoyomi T, Barbanel HDI (1996) Nonlinear dynamics of the Great Salt Lake: nonparametric short-term forecasting. Water Resour Res 32(4):975–985
Lemos MC (2003) A tale of two polices: climate forecasting and drought relief in Ceará, Brazil. Policy Sci 36:101–123
Lemos MC, Oliveira JLF (2004) Can water reform survive politics? Institutional change and river basin management in Ceará, Northeast Brazil. World Dev 32(12):2121–2137
Lemos MC, Nelsom D, Finan T, Fox R, Mayorga D, Mayorga I (1999) The social and policy implications of seasonal forecasting: a case study of Ceará. Northeast Brazil. NOAA Final Report, Award no. NA76GPO385
Lemos MC, Finan T, Fox R, Nelson D, Tucker J (2002) The use of seasonal climate forecasting in policymaking: lessons from Northeast Brazil. Clim Change 55:479–507
Leung LR, Hamlet AF, Lettenmaier DP, Kumar A (1999) Simulations of the ENSO hydroclimate signals in the Pacific Northwest Columbia River basin. Bull Am Meteorol Soc 80:2313–2329
Magalhaes AR (2002) Climate, society and public policy: How climate affects society, how society and government respond to climate impacts presented at Climate Affairs in Latin America: Climate Issues and Policy Responses, Institute of Latin American Studies. Columbia University. New York, NY
Medeiros Filho J, De Souza I (1988) A Seca do Nordeste: Um Falso Problema – A política de combate às secas antes e depois da SUDENE. Vozes, Petrópolis
ministério Da Integração Nacional (2004) Relatório De Impacto Ambiental-Projeto De Integração Do Rio São Francisco Com As Bacias Hidrográficas Do Nordeste Setentrional. Brasília, MIN
Montenegro AF (2001) Interpretação do Ceará, Casa de José de Alencar / Programa Editorial, Fortaleza
Nelson DR, Finan T (2000) The emergence of a climate anthropology in Northeast Brazil. Pract Anthropol 22:6–10
Neves FC (1995) Curral dos Bárbaros: os campos de concentração no Ceará (1915 e 1932). Rev Bras Hist 15:93–122
Neves FC (1998) Economia moral versus moral economia (Ou: O que é economicamente correto para os pobres?). Proj Hist 16:39–57
Neves FC (2000) A Multidão e a História. Relume Dumará, Rio de Janeiro
Neves FC (2002) A seca na história do Ceará. In: Souza S de (ed) Uma Nova História do Ceará. Edições Demócrito Rocha, Fortaleza

Neves FC (2003) Seca, Estado e Controle Social: as políticas públicas de combate às secas no Ceará In: Braga EMF (ed) América Latina: transformações econômicas e políticas. Editora UFC, Fortaleza
Nijssen B, O'Donnel GM, Hamlet AF, Lettenmaier DP (2001) Hydrologic sensitivity of global rivers to climate change. Clim Change 50:143–175
Oates W (1972) Fiscal federalism. Harcourt Brace Jovanovich, New York
Pagano TC, Hartmann HC, Sorooshian S (2001) Using climate forecasts for water management: Arizona and the 1997–1998 El Nino. J Am Water Resour Assoc 37:1139–1153
Parente FJC (2000) A Fé e a Razão na Política. Conservadorismo e Modernidade das Elites Cearenses. Universidade Federal do Ceará, Fortaleza
Parente FJC (2002). O Ceará dos "coronéis" (1945 a 1986). In: Souza de S (ed) Uma nova história do Ceará. Edições Demócrito Rocha, Fortaleza
Piechota TC, Chiew FHS, Dracup JA, McMahon TA (2001) Development of exceedance probability streamflow forecast. J Hydrol Eng 6:20–28
Prado Júnior C (1989) Formação do Brasil Contemporâneo. Brasiliense, São Paulo
Rayner S et al (2005) Weather forecasts are for wimps; Why water resource managers do not use climate forecasts. Clim Change 69:197–227
Sankarasubramanian A, Lall U (2004) Dynamic water allocation framework for multiple uses: utility of climate forecasts towards short-term water management, presented at Climate Change: a challenge or a threat for water management, Amsterdam
Sankarasubramanian A, Lall U, Sharma A, Guidotti G (2003) Utility of climate information based reservoir inflow forecasts in annual water allocation – Ceará Case Study, NOAA workshop on Insights and Tools for Adaptation: learning from Climate Variability, November 2003, Washington, DC
Seabright P (1996) Accountability and decentralization in government: an incomplete contracts model. Eur Econ Rev 40:61–89
Sharma A (2000a) Seasonal to interannual rainfall probabilistic forecasts for improved water supply management: part 1-A strategy for system predictor identification. J Hydrol 239:232–239
Sharma A (2000b) Seasonal to interannual rainfall probabilistic forecasts for improved water supply management: part 3 – A nonparametric probabilistic forecast model. J Hydrol 239:249–258
Small AA, Pfaff A, Osgood D (2005) Allocation of an uncertain renewable natural resource: missing markets, quantity options and climate-based forecasts. Mimeo Columbia University, New York
Souza Filho F, Lall U (2003) Seasonal to interannual ensemble streamflow forecasts for Ceara, Brazil: applications of a multivariate, semi-parametric algorithm. Water Resour Res 39:1307–1325
Taddei R (2004) Os usos da lei e a vida social da legislação hídrica. Notas e reflexões sobre o caso do Ceará. Teor Pesqui 45:273–286
Taddei R (2005) Of clouds and streams, prophets and profits: the political semiotics of climate and water in the Brazilian Northeast. PhD dissertation, Teachers College, Columbia University, New York
Taddei R (2006) Oráculos da Chuva em Tempos Modernos: Mídia, Desenvolvimento Econômico, e as Transformações na Identidade Social dos Profetas do Sertão. In: Martins, Karla (org.), Os Profetas da Natureza. Fortaleza: Editora Tempo d´Imagem
Taddei R, Broad K, Pfaff A (2006) Integrating climate and water management in Ceará: historical background, social and legal structures and implications. Climate, water and society. In: Francisco de Assis de Souza Filho, Upmanu Lall, and Renzo Taddei (eds) New York: IRI
Tiebout CM (1956) A pure theory of local expenditures. J Polit Econ 64:416–424
Villa MA (2000) Vida e Morte no Sertão. Ática / Instituto Teotônio Vilela, São Paulo
Yao H, Georgakakos A (2001) Assessment of Folsom Lake response to historical and potential future climate scenarios; 2. Reservoir management. J Hydrol 249:176–196
Yu L, Weller RA, Liu WT (2003) Case analysis of a role of ENSO in regulating the generation of westerly wind bursts in the Western Equatorial Pacific. J Geophys Res 108:doi:10.1029/2002JC001498
World Bank (1996) The world bank participation sourcebook. Washington, DC