Water Resour Manage (2010) 24:3731–3756
DOI 10.1007/s11269-010-9630-z

Sustainable, Just, Equal, and Optimal Groundwater Management Strategies to Cope with Climate Change: Insights from Brazil

Fabio Zagonari

Received: 5 March 2009 / Accepted: 4 March 2010 /

Abstract This paper applies optimal-control theory to develop groundwater exploitation strategies that account for potential climate change patterns in Brazil. Numerical experiments showed that whether climate change only affects groundwater quantity or whether it affects both groundwater quantity and quality, Brazilian water institutions will be able to implement optimal, equitable groundwater management strategies. However, they may be unable to achieve justice between current generations, while the economic, social, and environmental sustainability is likely to be favoured by a large regional groundwater availability. Institutional sustainability is ensured by the principles and institutions established by Brazil's 1988 Constitution and by Law 9.433/97. Some sources of misunderstandings between managers and the research community are dealt with by suggesting directly applicable management strategies that accommodate stakeholder perceptions and desires. Some potential water policies based on the modelling results are discussed, with water conservation and water subsidies turning out to be beneficial for current and detrimental for future generations, respectively; in contrast, current generations paying for water at its social opportunity cost and being more concerned for future generations would benefit current generations.

Keywords Groundwater • Climate change • Optimal-control models •
Resource management strategies

1 Introduction

Groundwater management can be defined as the ongoing performance of coordinated actions related to the replenishment and withdrawal of water to achieve

---

F. Zagonari (✉)
Dipartimento di Scienze Economiche, Facoltà di Economia (sede di Rimini),
Università di Bologna, via Angherà 22, 47900 Rimini, Italy
e-mail: fabio.zagonari@unibo.it

long-term sustainability of the resource without detrimental effects on other resources, where sustainability mainly refers to meeting demands that arise from both population and economic growth (Loaiciga 2003).

Climate change will affect groundwater quantity by directly and indirectly affecting multiple factors. First, it affects the replenishment rate directly, since the groundwater recharge rate decreases with decreased amount, and increased intensity, of precipitation, and with increased evapotranspiration resulting from increased temperature. The quantity also decreases indirectly as a result of decreased infiltration and increased overland flows that result from soil degradation. The quantity directly decreases due to increased withdrawal, since groundwater withdrawal increases with decreasing amount and increasing instability of surface water supplies, with decreasing precipitation, and with increasing evapotranspiration due to an increase in temperature. The groundwater quantity might decrease indirectly because of additional water demands caused by new cropping patterns. Climate change will also directly and indirectly affect groundwater quality: rising sea levels and coastal flooding will directly increase aquifer salinity, whereas lower precipitation, higher evapotranspiration, and higher temperature will directly increase the depth of the water table. As well, natural phenomena that result from climate change, such as drier summers and wetter winters or drought and flooding episodes, might indirectly increase aquifer pollution. In addition, human responses to climate change, such as increased crop production or a decreased drainage base, might indirectly lower the water table. Note that groundwater replenishment and withdrawal imbalances, as well as recharge and discharge at large rates, can also affect groundwater quality (Tanaka et al. 2006).

For these reasons, aquifer exploitation strategies should account for climate change patterns. However, managers of groundwater tend to disregard this issue because the potential impacts of climate change are perceived as being too uncertain and too far in the future to be important in comparison with myriad other factors that influence their present decisions (Purkey et al. 2007). Moreover, climate change is neglected by both hydrologic and economic researchers who study groundwater because of the lack of good-quality data that could be used to develop a meaningful model that integrates economic and hydrologic issues, or that could be used to rigorously evaluate the impact of future climate scenarios on future hydrological conditions (Ivey et al. 2004). Finally, this issue is disregarded because discussions between groundwater managers and researchers have led to misunderstandings about the transferability of models from the sites where they were developed to new sites; additional problems arise from the need for social participation in water management decisions, a lack of confidence in model-based tools, and insufficient development of user interfaces that would improve the usability of such models (Borowski and Hare 2007).

The purpose of the present study is to develop a model that can be used to develop economically, socially, environmentally, and institutionally sustainable groundwater management strategies that would be just, egalitarian, and optimal and that would be able to cope with the impacts of climate change on aquifers in Brazil. Here, optimality (efficiency) refers to both economic and institutional aspects, equity and justice pertain to both economic and social aspects, and sustainability refers to economic, social, environmental, and institutional aspects.

This purpose might seem to be quite ambitious. However, I will deal with the problems that water managers confront by suggesting simple management strategies (rather than specific decisions or actions) obtained from numerical solutions of a dynamic optimal-control problem, in which both the groundwater stock and groundwater exploitation are considered. Moreover, I will account for the uncertainties faced by hydrologic and economic researchers by considering a wide range of potential climate change impacts on groundwater as a *variable*, with all direct and indirect effects of climate change on groundwater quantity depicted in terms of changes in the recharge rate and in human withdrawal. In addition, I will represent all direct and indirect impacts of climate change on groundwater quality in terms of the costs required to avoid them and by including the dynamics of both economic and social water demands and welfare implications as parameters. Finally, I will apply the efficiency, equity, justice, and sustainability criteria by obtaining numerical solutions for management strategies moulded around the well-defined institutional context for groundwater in Brazil, where the relative importance of stakeholders in water decision-making at a basin level is specified by the 1988 Constitution and by Law 9.433/1997.

Research on groundwater management in the context of the impacts of climate change are rare, and this required a wide survey of the literature, including papers that were sometimes clearly close to and sometimes clearly distant from this issue. To accomplish this, I emphasised the technical aspects, since the Brazilian institutional context was taken as a given. The resulting approach was to check whether Brazilian water institutions could achieve efficiency, equity, and justice while coping with climate change impacts, rather than seeking reforms that would allow Brazil to achieve these goals.

The Brazilian institutional context led to the development of a model with variables and parameters that were defined at a basin level, although a lack of detailed information made it necessary to calibrate these variables and parameters using average data at the national level. However, normalisation of the hydrological variables with respect to the groundwater recharge rate, together with the assumption of a plausible difference in concern for the environment between the economic and social sectors, made it possible to obtain general results that would support the development of water management strategies and that would be capable of assessing the efficiency, equity, and justice of these strategies. More specific data at the basin level would be required to assess sustainability in practice. In other words, the suggested management strategies represent an efficient response to climate change, on average, with an increase in groundwater use in dry years and a decrease in wet years to be expected (Tanaka et al. 2006).

The main results produced by the present analysis can be summarised as follows: Efficiency implies that if climate change affects only the *quantity* of groundwater, then the ratio of water rights for the social sector to those for the economic sector (which is larger with smaller concern for future generations) should be changed in favour of the social sector in response to increasing impacts of climate change. At the same time, the groundwater stock (which is larger with larger concern about future generations) should be decreased with increasing impacts of climate change. In comparison, if climate change affects both the *quantity* and the *quality* of groundwater, the groundwater stock should be increased at all discount rates, the ratio of water rights in the social sector to those in the economic sector should be adjusted in favour of the economic sector in response to increasing impacts of climate change, but extraction rates should not be significantly modified. The present numerical experiments suggest that Brazilian water institutions show little concern for future generations, with current groundwater extraction rates and stocks consistent with a discount rate of 20%. Moreover, a given percentage reduction in the recharge rate would require a similar percentage reduction in groundwater withdrawals by both sectors and in groundwater stocks, regardless of the prevailing concern for future generations, whether climate change affects quantity alone or affects both quantity and quality. Although all statements about sustainability crucially depend on the prevailing conditions for each aquifer, recent studies suggest that this might not be an urgent issue in Brazil, with the exception of the northeastern regions (Rosenzweig et al. 2004; Krol et al. 2006). Finally, a smaller concern for future generations leads to groundwater management strategies that ensure a more equal distribution of the impacts of climate change between the current economic and social sectors, although the strategies might not be fair if *unexpected* increases occur in either economic or social groundwater needs.

Therefore, *Brazilian* water institutions seem able to implement optimal groundwater management strategies that will ensure equity, but that might not achieve justice, between current generations, where the economic, social, and environmental sustainability is likely to be favoured by a large regional groundwater availability. The institutional sustainability is ensured by the principles and institutions established by Brazil's 1988 Constitution and Law 9.433/97.

2 A Survey of the Literature

The study goals described in Section 1 led to the inclusion of the following keywords in my literature review: groundwater, management, climate change, strategies (i.e., best responses to changing conditions), economic (i.e., economic indicators and dynamics), social (i.e., social indicators and dynamics), environmental (i.e., environmental indicators and dynamics), institutional (a reference to institutional structures), sustainability (a reference to dynamic models), optimality (an analysis of technical models), and justice and equity (a reference to distributional theories and measures).

I found no work that embodied all these features simultaneously. In order to obtain suitable insights, I will separate the literature on groundwater and climate change (Section 2.1) from the literature on groundwater and management (Section 2.2). Next, I will divide the existing literature into papers that focus on quantity and quality issues, and will analyze the latter literature according to the following criteria: two main research fields, namely the hydrologic and the economic literature, and the technical and institutional aspects of both. I will omit the other features of my study (social, environmental, sustainable, justice, equity, and strategies) as potential aspects to further differentiate the relevant contributions in the research literature.

Note that Iglesias et al. (2007) would combine aspects of both groundwater management and climate change. They provided an interesting summary of a planning framework for risk management for water scarcity due to climate change, among other factors, based on the current adaptation strategies used in Mediterranean countries to minimize drought impacts. However, no simple management strategies were presented.

2.1 The Literature on Groundwater Resources and Climate Change

Several downscaling approaches have been adopted in climate change research: global, regional, or land-use models (Holman et al. 2009). I will disregard this issue by considering a wide range of potential climate change impacts on groundwater at basin level, since water decision-making is at basin level in Brazil. Alternative institutional forms (e.g., community-organised, centralised, or private property regimes) could affect the impacts of climate change on groundwater (Emel and Roberts 1995). However, I will disregard this issue here, since the Brazilian institutional context is taken as given.

In terms of groundwater quantity, climate change affects groundwater systems through both direct and indirect changes both in the aquifer recharge rate (rr) and in the human net withdrawal (hw) (Candela et al. 2009), with hw being positive to show extraction or negative to show artificial recharge. However, the impacts of climate change on groundwater are slower than the impacts on surface water (Holman 2005), although both temporal changes and spatial variability are likely to be observed (Jyrkama and Sykes 2007). Formally, the change in groundwater storage during a given period (GW') can be represented as $GW' = rr - hw$. In this paper, I will assume an annual basis for calculations of GW'.

Note that groundwater recharge is determined by groundwater conditions as well as by the surface-water and the vadose-zone hydrologic balances: in order to discern the effects of climate change on groundwater recharge, one should consider the factors that affect the surface water storage (SW'): changes in precipitation (pr), evapotranspiration (et), overland flows (of), and infiltration (in). One should also include factors that affect the vadose-zone ($VW\prime$) storage: in, rr, and interflow (if). Formally, $SW' = pr - et - of - in$, and $VW' = in - rr - if$ (Loaiciga 2003, p. 34). However, if steady-state conditions are considered ($SW' = 0$ and $VW' = 0$), these dynamic equations reduce to $GW' = rr - hw$, with $rr = pr - et - of - if$. I will consider climate change impacts on all these parameters.

In terms of the direct effects of climate change on rr, three main facts can be observed. First, a decreased amount and increased intensity of pr reduces the recharge rate (Vicuna et al. 2007). Second, a warmer future climate, with drier summers and wetter winters, will increase the length of the growing season, so that soils return to field capacity later in the autumn and start drying out sooner in the spring; this reduces the length of the recharge period, and consequently, the magnitude of the recharge, even though annual rainfall increases (Hanson and Dettinger 2005). Third, increased et due to increased temperatures will reduce rr (Vicuna et al. 2007).

In terms of the direct effects of climate change on hw, two main phenomena could arise. First, a reduced amount and an increased instability of surface water would lead to a greater reliance on groundwater resources (Hsu et al. 2007). Second, increased et due to global warming would require a greater proportion of total water resources to be reserved to sustain the water environment, and would again imply an increased reliance on groundwater resources (Quinn et al. 2004).

The impacts of temperature changes will be negligible compared with those of the changes in precipitation amount and intensity (Kovalevskii 2007; Woldeamlak et al. 2007).

In terms of the indirect effects of climate change on *rr*, an increase in temperature and a decrease in precipitation might lead to soil degradation and then to decreased *in* and increased *of*, as well as to longer growing periods; this might increase the need for machinery or livestock to access land during the wettest seasons, which might imply soil degradation, increased runoff, and decreased recharge (Holman 2005). In terms of the indirect effects of climate change on *hw*, an increase in temperature and a decrease in precipitation might lead to new cropping patterns (e.g., cultivation of sunflower, grain, or forage maize); this might increase the need for groundwater withdrawals (Ranjan et al. 2006b).

Other factors might affect *rr*, including urbanisation pressure, which restricts the recharge volume because surface water that would previously have entered the ground is instead diverted into the sewer system (White and Howe 2004). Moreover, the extraction of peat soils overlying aquifers or located in aquifer discharge zones will reduce the base flow (Holman 2005). Finally, the infrastructure used to transport and distribute water supplies exacerbates the reduction in the groundwater recharge, although it may partially compensate for this loss as a result of high leakage rates (White and Howe 2004). Other factors might affect *hw*, including population or economic growth, and changes in housing density and household size (Ojima et al. 1999).

Note that the magnitude of the effects of climate change on the water supply would be comparable to the changes in the population-driven demand.

In terms of the impacts of climate change on groundwater quality, climate change directly affects salinity, since increases in sea level and coastal flooding might result in saline intrusion into coastal aquifers (Ranjan et al. 2006a). Climate change directly affects this process because the water table is likely to descend due to lower *pr*, higher *et*, and higher temperatures (Scibek and Allen 2006).

Note that variations in water recharge and groundwater levels will have a similar fluctuation pattern, with a time delay and with recharge rates depending on the precipitation quantity and intensity (Chen et al. 2002).

Climate change also has indirect effects on aquifer pollution, since drier summers and wetter winters imply a larger pollution load in summer and increased probability of flooding in winter; drought episodes might lead to overuse of aquifers, and habitat conservation and agricultural production often have conflicting and irreconcilable interests. Floods might produce sewer overflows and increased hydraulic loads in sewers, depending on the capacity of the urban drainage system (Semadeni-Davies 2004). Again, climate change shows indirect effects on the level of these impacts because of increased crop production, the implementation of drainage systems, and lowering of the drainage base.

Other factors might affect *rr*, including excessive pumping that exceeds the average natural recharge, return flows from irrigated agriculture that includes intensive use of pesticides and fertilisers (Khan et al. 2008), and leakage from urban areas (Morehouse 2000). Leakage from land fills, septic tanks, sewers, and mine tailings, combined with drought episodes, might also contribute to the degradation of groundwater quality as a result of the overuse of aquifers. Other factors might cause the water table to descend, including increased crop production, the implementation of drainage systems, lowering of the drainage base, and increased groundwater extraction, although the drainage base (i.e. river water level) would limit the impacts of these changes (Krysanova et al. 2006).

2.2 The Literature on Groundwater Management

The complexity of the issues surrounding groundwater management is due to the many idiosyncratic characteristics of groundwater (which is a multifaceted good in terms of time, space, and consumer preferences), to the tough competition among users for access to this resource, and to the intersection between historical rights and modern requirements; all these issues must be considered to avoid misallocation of the resource (FAO 2003). Here, I will consider as many features as possible.

There is a huge and well-established hydrologic literature on optimisation models for groundwater management. In particular, the research has aimed at maximising groundwater withdrawal or at minimising the capital and operating costs for a given level of demand, both subject to constraints on the hydraulic head and pumping capacity; that is, the objectives have been hydrologic or economic in nature, and the constraints have been hydrologic or environmental in nature. See, for example, Wang and Zheng (1996) and Jha et al. (2009). Moreover, these studies have predicted the best withdrawal at all production wells in order to meet the yearly demand while avoiding land subsidence; that is, the objectives have a hydrologic nature, whereas the constraints have an economic or environmental nature (for example, see Don et al. 2006). Finally, these studies have aimed at maximising the net benefits from groundwater recharge; that is, the objectives were economic in nature, and no constraints were considered. See, for example, Al-Sabbry et al. (2002).

Lobo Ferreira et al. (2007) modelled the best location of wells in order to minimise the well installation, protection, and operating costs, as well as the cost of the pipes needed to convey the flow from the wells to a tourist hotel. In the present study, I will disregard spatial issues by performing the analysis at a basin level. In practice, in order to permit economically and socially efficient groundwater management, the objectives must be both economic and social in nature, but the constraints must be environmental.

In terms of methodologies, the above mentioned research has used both static and dynamic optimisation models with a range of solution algorithms, including dynamic programming and control theory, genetic algorithms, simulated annealing, and neural networks. In practice, to obtain management strategies, objectives must be dynamic in nature.

Batabyal (1996) applied queuing theory to determine how much water to supply and at what rate in the context of uncertain and dynamic demand and supply. Here, I will disregard uncertainty issues by considering a wide range of possible impacts of climate change. Khan et al. (2008) predicted the optimal mix of land uses at a farm scale by integrating agronomic, climatic, hydro-geologic, and economic aspects of irrigated agriculture. I will not explicitly show the effects of changing cropping patterns and crop rotations, or of urbanisation extension and types, but will instead refer to the dynamics of human withdrawals by considering a wide range of possible impacts of climate change: further research to identify optimal land use in order to minimise the impacts of climate change on groundwater quantity and quality would be of great interest; see Qureshi et al. (2008) for some methodological insights. Finally, Holman (2005) showed that the physical properties of a landscape, such as soil bulk density, water retention, and hydraulic conductivity could change due to the changing conditions in temperate soils. I will disregard soil property issues by considering a wide range of possible impacts of climate change.

There is also a significant recent hydrologic literature on institutions for groundwater management. In particular, researchers have suggested how to set up water institutions to achieve quantitative objectives, as in the case of Martín de Santa Olalla et al. (2005) for groundwater overexploitation, or qualitative objectives, as in the case of Henriksen et al. (2007) for groundwater contamination. Moreover, researchers have provided criteria to assess existing water institutions; for example, Ananda et al. (2006) suggested clearly defined boundaries, proportional equivalence between benefits and costs, collective choice arrangements, monitoring, graduated sanctions, conflict resolution mechanisms, external recognition of the rights to organise, and nested or federated organisations, and referred to the principle of long-standing, self-organised irrigation systems identified by Ostrom. Finally, some researchers have suggested how to modernise water institutions in order to increase their efficiency; for example, Kretsinger Grabert and Narasimhan (2006) stressed the required coordination of the scientific and political communities. Others have stressed the need for flexibility; for example, Lopez-Gunn and Cortina (2005) highlighted salience, common understanding, trust and reciprocity, autonomy, prior organisational experience, and local leadership as the attributes characterising high-level water authorities.

However, the present study aimed neither at setting up new Brazilian water institutions, nor at assessing their effectiveness *per se*, nor at changing them: the goal was solely to assess the existing institutions in terms of the groundwater management strategies they could implement to cope with the impacts of climate change.

The economic literature on optimisation models for groundwater management consists of several studies (Provencher and Burt 1993, 1994; Roseta-Palma 2002; Zeitouni 2004). In general, these researchers have applied differential games to explore use strategies by highlighting their efficiency and sustainability, but have not referred to non-cooperative bargaining models to depict water allocation processes among competing users. In particular, Roseta-Palma (2002) developed a dynamic model to analyse the optimal aquifer exploitation patterns and the optimal groundwater stock under steady-state conditions by combining both groundwater quantity and quality aspects, in which firms have an increasing and concave revenue function as dependent on the amount of water pumped, and groundwater dynamics depend on a constant recharge rate and on the total water pumped by the firms.

Although the general framework is consistent with the purposes of the present work (i.e., objectives are defined in welfare or economic or utility terms, and constraints in environmental terms), the research in these papers must be further developed to provide simple management strategies that are suitable for empirical validation; some unrealistic simplifying assumptions, such as the assumption that all water uses are alike, must be avoided, and specific institutional conditions must be introduced.

The economic literature on institutional models for groundwater management can be divided into two main groups, as in the recent review by Carraro et al. (2005): positive and normative works.

The positive papers aim at predicting negotiation outcomes given specific institutional characteristics, or at moulding institutions to achieve some beneficial negotiation outcomes or to avoid some detrimental outcomes (Becu et al. 2003; Barreteau et al. 2003; Thiesse et al. 1998; Hämäläinen et al. 2001). However, in the present study, the purpose is neither to predict negotiation outcomes nor to suggest interventions in negotiation processes.

Apart from the Gisser-Sanchez effect, i.e. no management, competitive dynamic solution of GW exploitation is almost identical, in terms of derived social welfare, to the efficient management optimal solution (see Koundouri 2004 for a recent discussion of its robustness), the normative papers aim at identifying sustainable water governance solutions by explicitly modelling the negotiation processes and by making outcomes depend on the relative political influence, preferences, and internal structures of the stakeholders (Adams et al. 1996). In particular, some research (Thoyer et al. 2001) has applied a multi-person, multi-issue negotiation model developed by Rausser and Simon and depicted a sub-game perfect equilibrium, but this required several simplifying assumptions, including that unanimity is required to reach an agreement and that all players prefer any negotiated agreement to the default policy. Other work (Salazar et al. 2007) applied alternative solution concepts (the non-symmetric Nash, Kalai-Smorodinsky, area monotonic, and equal loss solutions) to identify the groundwater withdrawals that would maximise economic benefits and minimise the negative environmental consequences, but confronted only two attributes (economic and environmental categories) rather than more than two stakeholders. However, all these studies applied static models for the control variables.

3 Methodology

The results of the literature review described in Section 2.1 can be summarised as follows. Several direct and indirect effects of climate change on groundwater quantity can be predicted, but they can all be described in terms of their impacts on the recharge rate (rr) and on human withdrawals (hw). Next, two main direct and indirect effects of climate change on groundwater quality can be anticipated, namely the effects on water quality (e.g., salinity or pollution) and on the water quantity (e.g., water table level). I will describe both factors by applying the replacement-cost approach (i.e., by introducing the desalinisation or treatment costs and the pumping costs that must be borne to avoid these effects).

The results of the literature review described in Section 2.2 can be summarised as follows. It is necessary to develop a dynamic optimal-control model with continuous variables, with objectives defined in welfare or economic or utility terms, and with constraints defined in environmental terms, by introducing realistic assumptions about Brazilian economic and social conditions and water institutions. In addition, the solution concepts for Brazilian aquifers must refer to differential games to depict the strategic interactions between stakeholders, must identify the groundwater withdrawals that will maximise economic and social benefits, and minimise the negative environmental consequences.

Section 2.1 and 2.2 emphasized that no research has focused on technical or institutional groundwater management in response to the impacts of climate change.

Recent contributions to the technical literature on surface water management could represent a starting point to obtain a model with all the features described in Section 1. Although Kerachian and Karamouz (2007) and Ganji et al. (2007b) introduced a final time horizon (t) for their models, they used a penalty function and focused only on quality issues, while disregarding social impacts and quantities, and they assumed asymmetric information, they applied the Nash bargaining model for a case with four stakeholders. Similarly, although Ganji et al. (2007a) did not focus on preservation, they compared the reliability values of alternative models, assumed an exogenous safe storage, and did not present groundwater management strategies, they evaluated stakeholder preferences.

Note that the focus on national aquifers in these studies allows us to disregard trans-national issues in this analysis.

In terms of institutional issues, ANA (2007) specified that Brazil's 1988 Constitution stated that [italics added for emphasis] "all have the right to an ecologically balanced environment, which is an asset of common use and essential to healthy quality of life, and both the Government and the community shall have *the duty to defend and preserve it for present and future generations*". Moreover, ANA (2007) specified that Law 9.433/97, which was based on the principles and obligations established by the 1988 Constitution, prescribed the following fundamental premises [italics added for emphasis]: water is a public good; water is a limited resource, with an economic value; *priority for human consumption and watering livestock*; multiple use of water; *river basins as the planning and management units*; and decentralised and participative management. Emel and Brooks (1988) discuss alternative forms of property rights for groundwater preservation. Finally, ANA (2007) specified that the National Water Resources Management System, introduced by Law 9.433/97, rests on the following institutions:

- The Natural Water Resources Council, which is the political body of the National Water Resources Management System, is presided over by the Ministry of Environment, and consists of 57 representatives, of which 29 are representatives of the Federal Government, 10 are representatives of the State Councils, 12 are representatives of water use sectors, and 6 are representatives of civil-society organisations. The Council has the responsibility of providing general guidelines and policies, approving the establishment of Basin Committees, arbitrating in case of disputes between Basin Committees and State Water Resources Councils, and approving general criteria for the granting of licenses for the use of water and the setting of water use fees.
- The Basin Committees, which are regional deliberative bodies of various sizes, consist of up to 40% representatives of public authorities, up to 40% representatives of water user sectors, and at least 20% representatives of civil society.
- The National Water Agency is not considered here, but functions as an executive and regulatory agency at the national level.
- The Water Agencies and the Basin Agencies are disregarded here, though they serve as the executive bodies of the respective Basin Committees.

On this basis, I will focus on the Basin Committee as the relevant institution in accordance with Law 9.433/97, and I will use the Nash (1950) bargaining solution with perfect and symmetric information as the most suitable model to represent the bargaining process for water allocation, since all decisions are made in committee meetings based on shared knowledge. This makes it possible to transform the collective choice problem into a problem defined as the maximisation of a single objective function with respect to threat points once the physical water system and the economic and political structures are described. Moreover, I will apply the generalisation by Harsanyi (1963) to the three-person case in order to depict the three stakeholders (the government, the economic sector, and the social sector) involved in Basin Committees. The relative importance of these sectors will be established according to their proportional representation in this deliberative body. Finally, I will use a constant elasticity of substitution utility function for the government preferences, in which the weights represent the priority for human consumption and watering livestock, according to Law 9.433/97, and its exponents will represent the duty to defend and preserve [the resource] for present and future generations, as stated by the 1988 Constitution.

4 Development of the Model

In this analysis, I will use lower-case letters for parameters, and capital letters for state and control variables. Thus, if *GW* is the stock of groundwater (million cubic metres, MCM), *HE* is the withdrawal by the economic sector (MCM per year), and *HS* is the withdrawal by the social sector (MCM per year), the analysis developed in Section 3 can be summarised by the following social utility function (*SUF*):

$$SUF = UG^{\gamma g}\, UE^{\gamma e}\, US^{\gamma s} \tag{1}$$

with

$$UG = \left[\delta_f\; GW^{(1-\varepsilon)} + \delta_e\; HE^{(1-\varepsilon)} + \delta_s\; HS^{(1-\varepsilon)}\right]^{(1/[1-\varepsilon])} \tag{2}$$

where *UG*, *UE*, and *US* depict utilities for the government (g), the economic sector (e), and the social sector (s), respectively; γ_g, γ_e, and γ_s represent the relative representation of these sectors within the Basin Committee; δ_f, δ_e, and δ_s depict the relative importance of future generations (f) and the current economic (e) and social (s) sectors, as defined by Law 9.433/97; and ε (Atkinson's inequality index) represents the duty to preserve groundwater for future generations, as stated in the 1988 Constitution.

Since decision-makers in the economic sectors could be interested in future groundwater availability, *GW* is also taken into account by transforming a production function into the utility function. Moreover, the water needs required to meet sectoral growth will be represented by each sector's utility at the disagreement point (UE_0). Finally, the production sectors will be charged for water rights, with t_e representing the water price per MCM. Thus, *UE* becomes:

$$UE_0 = GW^{\alpha e} HE^{\beta e} - t_e HE - UE_0 \tag{3}$$

Where α_e and β_e represent the preferences of the economic representatives for future groundwater availability and for current withdrawal, respectively. Similarly, since decision-makers in the social sectors could be interested in future groundwater availability, the *GW* is also considered by transforming a single-argument utility function into a two-arguments utility function. Moreover, the water required to sustain population growth will be represented by the household utility at the disagreement point (US_0). Finally, the social sectors will be charged for water rights, with t_s representing the water price per MCM. Thus, US becomes:

$$US = GW^{\alpha s} HS^{\beta s} - t_s HS - US_0 \tag{4}$$

where α_s and β_s represent the preferences of the social representatives for future groundwater availability and for current withdrawal, respectively.

Note that the model can be closed by assuming that water charges are invested for artificial recharge in the river basin where water is collected, as suggested by Law 9.433/97; for the sake of simplicity, I have assumed that water is charged according to its social opportunity cost.

In terms of environmental issues, changes in GW during one year (GW') are represented by $GW' = rr - HE - HS$, where rr is the natural recharge rate. To characterize the impacts of climate change on groundwater quantity, I will explicitly show the direct and indirect impacts on rr by introducing a positive or negative change in groundwater recharge (cc), but I will implicitly represent direct and indirect impacts on human withdrawals by modifying UE_0 and US_0: $GW' = rr - HE - HS - cc$. For the impacts of climate change on groundwater quality, I will represent the direct and indirect impacts on water salinity or pollution and on the water table level by applying the replacement-cost approach; that is, I will charge both the economic and the social sectors for desalinisation or purification costs and for pumping costs that must be paid to avoid these effects. Thus UE and US become:

$$UE = GW^{\alpha e} HE^{\beta e} - t_e HE - tc_e HE - UE_0 \tag{5}$$

$$US = GW^{\alpha s} HS^{\beta s} - t_s HS - tc_s HS - US_0 \tag{6}$$

where tc_e and tc_s are the unit treatment costs per *tonne* of discharged pollution. See Randhir and Genge (2005) for a discussion of groundwater quality policies.

Note that one could also show the effects of the negotiation process between stakeholders on water quality; for the sake of simplicity, I have assumed that all sectoral representatives support the "polluter pays" principle, so that the replacement-cost approach is appropriate.

In terms of optimality issues, I applied the optimal-control theory:

$$Max_{\,HE,HS}\; UG^{\gamma g}\, UE^{\gamma e}\, US^{\gamma s} - \lambda\,(rr - HE - HS - cc) \tag{7}$$

$$\text{s.t } GW' = rr - HE - HS - cc \tag{8}$$

with

$$UG = \left[\delta_f GW^{(1-\varepsilon)} + \delta_e HE^{(1-\varepsilon)} + \delta_s HS^{(1-\varepsilon)}\right]^{(1/[1-\varepsilon])} \tag{9}$$

$$UE = GW^{\alpha e} HE^{\beta e} - t_e HE - tc_e HE - UE_0 \tag{10}$$

$$US = GW^{\alpha s} HS^{\beta s} - t_s HS - tc_s HS - US_0 \tag{11}$$

where λ is the co-state variable attached to the groundwater stock (GW).

In terms of sustainability issues, I will only discuss steady-state solutions, in which $\lambda' = 0$ and $GW' = 0$. For management strategies, I will solve for the optimal water rights to be issued to the economic and social sectors as a continuous function of the impacts of climate change; that is, $HE^*(cc)$ and $HS^*(cc)$. These management strategies will then be evaluated according to the equity and justice criteria specified below.

Note that some potential water policies could be considered. All water policies that affect the quantity of groundwater, such as water conservation in agriculture or the industrial sector, and re-use of agricultural water, would decrease overall water needs (i.e., decrease UE_0); similarly, all water policies that affect water quality, such as watershed-level treatment facilities and environmental measures to reduce the use of fertilizers or pesticides in agriculture, would increase the economic costs of treatment (i.e., increase tc_e) charged to the polluting sector.

5 Estimation of the Model Parameters

Four main sets of parameters can be identified for the model developed in Section 4: hydrological, institutional, economic and social, and water system parameters.

For the hydrological parameters (Eq. 8), I have normalized the recharge rate (rr) to 1 so that all solutions for water flows (HE and HS) and water stocks (GW such that $GW' = 0$) can be expressed as a proportion of rr, and so that a wide range of potential climate change impacts can be considered (from −20% to +40% of rr) in order to deal with uncertainties in these parameters.

For the institutional parameters (γ_g, γ_e, γ_s, δ_f, δ_e, δ_s, ε; Eqs. 7 and 9), the 1988 Constitution suggests setting the relative weights in the government utility function at $\delta_f = 0.2$, $\delta_e = 0.4$, and $\delta_s = 0.4$ for future generations, the economic sector, and the social sector, respectively, with ε being fixed at 0.5. Law 9.433/97 describes the relative importance of the government, the economic sector, and the social sector within the Basin Committee such that $\gamma_g = 0.4$, $\gamma_e = 0.4$, and $\gamma_s = 0.2$, respectively.

For the parameters of the economic and social sectors (Eqs. 10 and 11), the choice-modelling methodology seems to be the most appropriate of the stated-preference approaches to estimate the stakeholder utility functions as a function of the groundwater stock and withdrawal levels. The choice-modelling methodology investigates individual behaviour and estimates the value of goods (or projects) by asking people to choose among scenarios whose differences result from systematic combinations of levels of diverse attributes or characteristics. Hanley et al. (2001) and Bennet and Blamey (2001) have provided recent contributions to the literature on this method. This methodology consists of three main steps: identification of the main characteristics (attributes) of the good or project to be evaluated, which can assume different values (levels); a decision by each respondent among alternative hypothetical scenarios characterised by different combinations of the attribute levels; and econometric analysis of their answers to permit estimation of the relative importance of the various attributes and, if a monetary factor or price is included as an attribute, the willingness to pay for different levels. However, although the number of experimental choices is consistent with the choice-modelling approach (e.g. one could use three groundwater stocks (low, medium, large) and three water withdrawal levels (low, medium, large), with a total of nine choices that result from all possible combinations of them), the number of potential interviewees (i.e., members of the Basin Committee) would not allow us to obtain meaningful econometric estimates. Thus, a simple fitting procedure based on minimised squares seems to be more appropriate. An example of the questionnaire that would be submitted to the stakeholders is available, on request. For the numerical simulation, I assumed that concern for the environment (i.e., for groundwater stocks) was smaller for the economic sector (due to the larger discount rate that characterises this sector) than for the social sector, and I therefore used the following parameter values: $\alpha_e = 0.2$, $\beta_e = 0.8$, $\alpha_s = 0.3$, and $\beta_s = 0.7$.

Next, I estimated UE_0 and US_0 based on the average water rights issued and the GDP growth rates observed during the last 5 years for Brazil's economic sector, as well as based on the average water rights issued and the population growth rates observed during this period for the social sector. However, I normalised these values to 0.1 to avoid potential distortions that would result from different measures of sectoral utility.

For the water system parameters (t_e, t_s, tc_e, and tc_s), official documents on water opportunity costs ($/MCM), on the artificial recharge costs, and on water treatment costs ($/t) and the groundwater pumping costs, suggest setting them at $t_e = t_s = 0.5$ and $tc_e = tc_s = 0.25$.

Therefore, the dynamic problem developed in Section 3 and modelled in Section 4 consists of two state variables (GW and λ), two choice variables (HE and HS), and two parameters (cc and the discount rate, ρ).

6 Development of Management Strategies

Two main impacts of climate change on groundwater were highlighted in Section 2: the impacts on water quantity and quality. Section 6.1 will develop a set of management strategies (optimal HE and HS) at different values of the discount rate (ρ) by setting the parameters related to water quality to 0 so that only water quantity is considered; that is, $tc_e = tc_s = 0$. In contrast, sub-Section 6.2 will develop a set of management strategies (optimal HE and HS) at different values of the discount rate on the assumption that water quantity and quality are both important by setting $tc_e = tc_s = 0.25$.

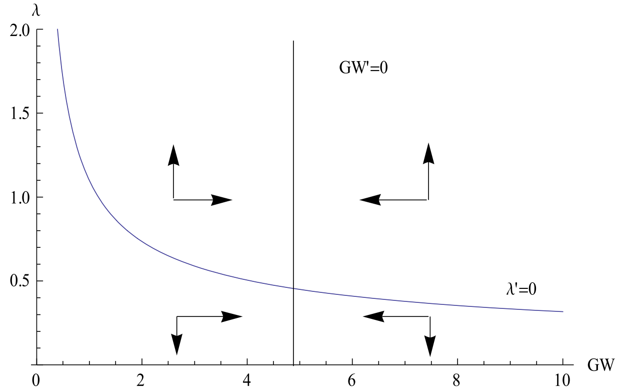
Note that the solution of the dynamic problem developed in Section 3 is a saddle. The graphical representation of the solution for $cc = 0.2$, $\rho = 0.1$, and $tc_e = tc_s = 0$ is given in Fig. 1.

6.1 Quantity Issues

The impacts of climate change on groundwater quantity are represented by a larger or a smaller recharge rate. Figures 2, 3, and 4 represent optimal groundwater withdrawals (HE^* and HS^*) and groundwater stocks (GW^*) at different levels of climate change impacts, with cc ranging from -0.2 (a 20% increase in recharge) to 0.4 (a 40% decrease in recharge).

Figure 2 suggests that extraction rates for both the economic and social sectors should be proportionally reduced with increasing impacts of climate change on the

Fig. 1 Steady-state conditions for the state variable groundwater stock (*GW*) and the co-state variable attached to the groundwater stock (λ). The solution is provided for an impact of climate change on groundwater recharge $cc = 0.2$, a discount rate $\rho = 0.1$, and treatment costs of $tc_e = tc_s = 0$



recharge rate, regardless of the prevailing level of concern for future generations (i.e., for all discount rates).

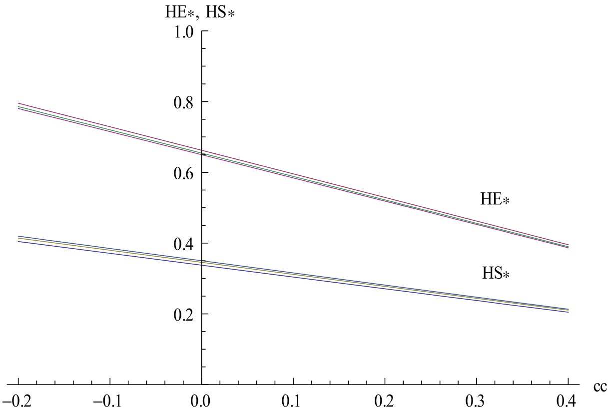
However, Fig. 3 shows that the ratio of water rights for the social sector to water rights for the economic sector (larger with a smaller level of concern for future generations) should be changed in favour of the social sector in response to increasing impacts of climate change.

Note that a ratio of around 0.5 is consistent with the average water rights issued to Brazilian sectors at a basin level (ANA 2007), although a lack of detailed data makes it difficult to specify the relevant discount rate in practice.

The average national data on the groundwater extraction and groundwater potential of Brazilian aquifers (ANA 2007), together with Fig. 4 evaluated at $cc = 0$, suggests that the discount rate prevailing in the Brazilian context is around 0.2. Note that the groundwater stock (larger with a larger concern for future generations) should be linearly reduced with increasing impacts of climate change.

Also note that numerical simulations carried out with $US_0 = 0.2$ and $UE_0 = 0.1$ show that an expected increase in population larger than the expected increase in GDP implies an increase in HS^* and a decrease in HE^*, consistent with the results of Adams et al. (1996), with a larger impact of the discount rate on the

Fig. 2 Optimal management strategies with the discount rate (ρ) set at 0.05, 0.1 and 0.2. HE^* and HS^* (higher with larger discount rate levels, although they are too close together to appear as separate lines) are the withdrawals by the economic and social sectors, respectively; *cc* is the impact of climate change on groundwater recharge



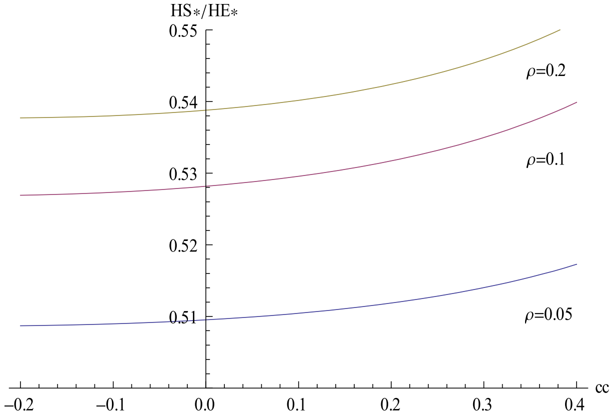


Fig. 3 Optimal management strategies ratio (*HS**/*HE**) with the discount rate (ρ) set at 0.05, 0.1 and 0.2. *HE* and *HS* are the withdrawals by the economic and social sectors, respectively; *cc* is the impact of climate change on groundwater recharge

optimal extractions and a constant *GW**: the economic, but not the environmental, sustainability might be at risk.

6.2 Quality Issues

The impacts of climate change on groundwater quality are represented by the treatment cost that must be borne to cope with the increased water salinity or pollution and with the decreased water table level. Considering several independent impacts on groundwater quality would require a consideration of several treatment costs; however, without loss of generality, it is possible to consider only a single dimension that reflects the mean treatment cost, and that is the approach I have chosen. Thus, Figs. 5, 6, and 7 represent optimal groundwater withdrawals (*HE** and *HS**) and groundwater stocks (*GW**) as a function of the impacts of climate change only on quality, if evaluated at $cc = 0$, and at different impacts of climate change on both quantity and quality, with *cc* ranging from −0.2 (a 20% increase in recharge) to 0.4 (a 40% decrease in recharge).

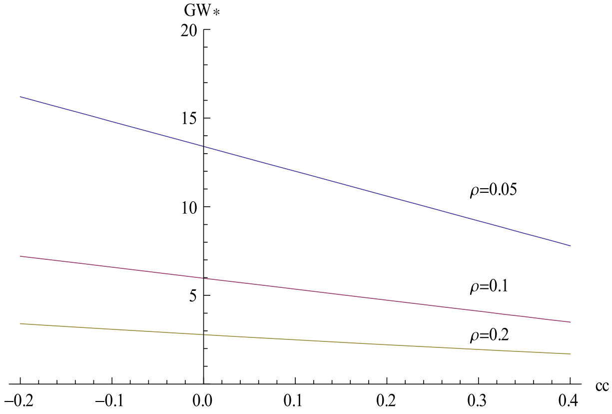


Fig. 4 Optimal groundwater stock (*GW**) with the discount rate (ρ) set at 0.05, 0.1, and 0.2; *cc* is the impact of climate change on groundwater recharge

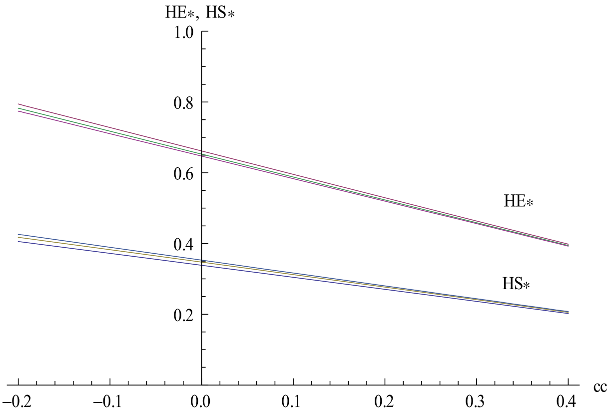


Fig. 5 Optimal management strategies with the discount rate (ρ) set at 0.05, 0.1, and 0.2. *HE** and *HS** (higher with larger discount rate levels, although they are too close together to appear as separate lines) are the withdrawals by the economic and social sectors, respectively; *cc* is the impact of climate change on groundwater recharge

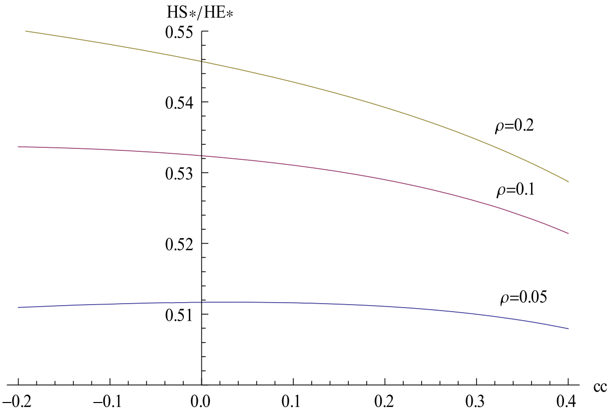


Fig. 6 Optimal management strategies ratio (*HS**/*HE**) with the discount rate (ρ) set at 0.05, 0.1, and 0.2. *HE* and *HS* are the withdrawals by the economic and social sectors, respectively; *cc* is the impact of climate change on groundwater recharge

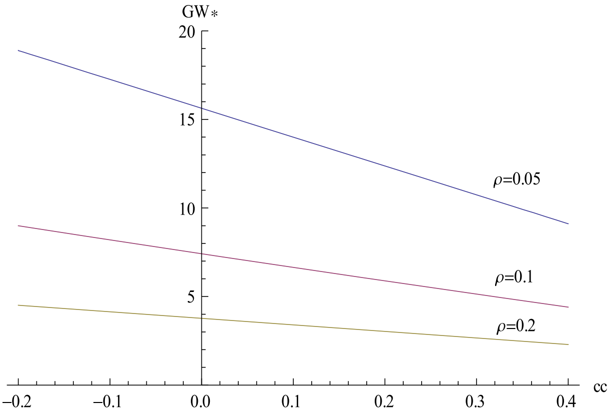


Fig. 7 Optimal groundwater stock (*GW**) with the discount rate (ρ) set at 0.05, 0.1, and 0.2; *cc* is the impact of climate change on groundwater recharge

Comparing the results in Figs. 5, 6, and 7 with the results in Figures 2, 3, and 4 suggests that when the impacts on quality and quantity are combined, the groundwater stock should be increased at all discount rates, and the ratio of water rights in the social sector to those in the economic sector should be changed in favour of the economic sector in response to increasing impacts of climate change, whereas extraction rates should be significantly modified in favour of the social sector with small impacts of climate change.

Note that the numerical simulations carried out with $t_e = 0.05$ and $t_s = 0.5$ show that the introduction of water subsidies for the economic sector implies a small impact on the optimal extraction rates (HE^* and HS^*), but a significant reduction in GW^*: the environmental, but not the social, sustainability might therefore be at risk.

7 Assessment of Management Strategies

Section 6 identified the optimal management strategies under a range of conditions. In this section, I will assess the strategies in terms of their economic, social, institutional, and environmental sustainability in Section 7.1, and in terms of their efficiency, equity, and justice in Section 7.2.

7.1 Economic, Social, Institutional, and Environmental Sustainability

In this analysis, I assumed that institutional sustainability exists, since the management strategies under consideration represent a Nash bargaining solution.

Figure 8 suggests that a given percentage reduction in the recharge rate leads to a similar percentage reduction in groundwater withdrawals by the economic and social sectors and in groundwater stocks, regardless of the prevailing concern

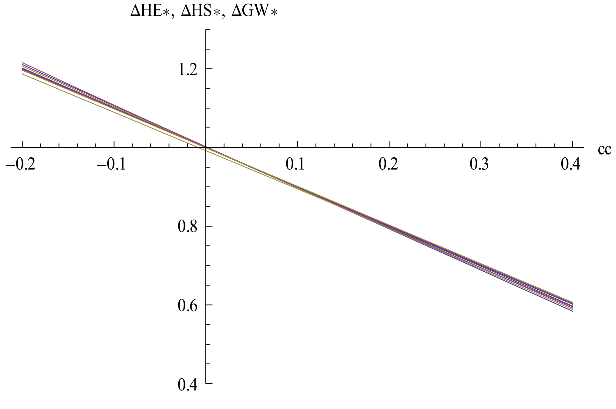


Fig. 8 Percentage reductions in the optimal withdrawals (HS^*, HE^*) and optimal groundwater stock (GW^*) in terms of optimal values without climate change impacts, in both cases of impacts on water quantity and quality, with the discount rate (ρ) set at 0.05, 0.1 and 0.2: curves are too close together to appear as separate lines. HE^* and HS^* are the withdrawals by the economic and social sectors, respectively; GW^* is the groundwater stock; the *asterisk* represents the optimal level; *cc* is the impact of climate change on groundwater recharge

for future generations (i.e., for all discount rates), whether climate change affects only the quantity of groundwater or affects both quantity and quality. Thus, for economic sustainability, it's necessary to consider whether the suggested HE^* is above the groundwater requirements consistent with the expected economic growth. For social sustainability, it's necessary to confirm whether the suggested HS^* is above the groundwater requirements consistent with the expected population growth. For environmental sustainability, it's necessary to confirm whether the suggested GW^* is above the water requirements consistent with the aquifer being at mining risk within a given period (e.g., 100 years).

Note that the results presented in this section were obtained by normalising the recharge rate (rr) to 1, so that it was possible to state that ΔHS^* and ΔHE^* are proportional to rr and ΔGW^* is proportional to rr, so that ΔHS^* and ΔHE^* are proportional to ΔGW^*. Thus, a proportional reduction in the optimal extraction levels (with respect to the recharge rate) and in optimal groundwater stocks (again, with respect to the recharge rate) suggests that there is an optimal balance between groundwater withdrawal and groundwater preservation, with an increase in extraction (due to population or economic growth) requiring a corresponding increase in groundwater preservation.

Therefore, all statements about sustainability depend crucially on the conditions prevailing in each aquifer, and detailed data at the basin level (rather than the national averages used in the present study) will be required to discuss sustainability in practice. However, Rosenzweig et al. (2004) and Krol et al. (2006) suggest that groundwater sustainability is not an urgent issue in Brazil, except for the northeastern regions.

7.2 Efficiency, Equity, and Justice

Efficiency can be assumed in this analysis, since the management strategies under consideration are obtained by solving a dynamic optimal-control problem. However, if agricultural and industrial data are available at the basin level, as are the corresponding sectoral GDP values and water rights, a comparison of the agriculture GDP over water rights issued to agriculture and the industry GDP over water rights issued to industry would make it possible to assess the efficiency of water allocation between the two economic sectors. Next, if data are available at the basin level for rural and urban incomes as well as for rural and urban water rights, comparing the average rural income over water rights issued to rural households and the average urban income over water rights issued to urban households would make it possible to assess the efficiency of water allocation between these social sectors.

For equity, the impacts of climate change should be equally distributed between the economic and social sectors. Formally, this would amount to a 45° straight line in the plane ($\Delta US^* = US^*/US_0$, $\Delta UE^* = UE^*/UE_0$), in which the relative utility achievements with respect to the disagreement points are used to avoid intersectoral comparisons of utility. For justice, the impacts of climate change should not force the economic or social sectors to consume less groundwater than their estimated basic needs. Formally, this would amount to a point above 1 ($US^*/US_0 = 1$, $UE^*/UE_0 = 1$) in the plane (ΔUS^*, ΔUE^*), where US_0 and UE_0 represent the groundwater requirements consistent with the expected economic and social growth rates, respectively.

Note that Neufeld (2000) suggested alternative assessment criteria for groundwater management strategies by applying the specific attributes of an ecosystem approach to groundwater protection.

Figure 9 suggests that a large concern for future generations (a discount rate at 0.05) indicates that the justice criterion will be met for current generations (both utility levels are higher than the estimated basic groundwater needs), although it shows a small bias in favour of the social sector with respect to the equity criterion: this is due to the combination of a large groundwater stock coupled with a larger preference for groundwater preservation in the social sector than in the economic sector. Next, the presence of quality issues, and the consequently larger groundwater stock, suggests greater utility for both sectors, with the utility greater for smaller impacts of climate change; this suggests that making current generations pay for groundwater at its social opportunity cost protects the utility of future generations by preserving more groundwater, and it forces current generations to satisfy their preferences for the groundwater stock that would be otherwise disregarded in the bargaining process as being less important than their preferences for groundwater withdrawals.

Figure 10 shows that an intermediate level of concern for future generations (a discount rate at 0.1) indicates an unequal distribution of the impacts of climate change, in favour of the economic sector (again, due to a smaller groundwater stock and to smaller preferences for groundwater preservation in this sector). Moreover, utility is smaller for both sectors than in Fig. 9, with larger differences if the impacts on both quantity and quality rather than only the impact on quantity are relevant; this is due to the larger withdrawals, and consequently the larger desalinisation or purification costs and larger pumping costs that must be borne by both sectors. Finally, the justice criterion might be challenged by an unexpected increase in the social groundwater needs only (only ΔUS^* is close to 1 with $cc = 0.4$).

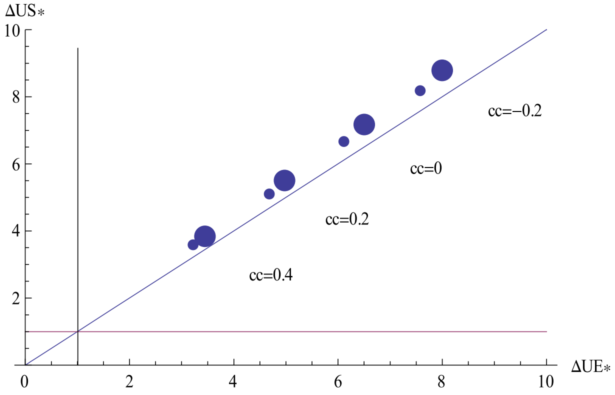


Fig. 9 Relative utility achievements (US^* and UE^* in terms of US_0 and UE_0), with cc at −0.2, 0, 0.2, and 0.4, in both quantity (small points: $\Delta US^* = 0.1841 + 1.0457\,\Delta UE^* + 0.0018\,\Delta UE^{*2}$) and quality (large points: $\Delta US^* = -0.0417 + 1.1264\,\Delta UE^* - 0.0028\,\Delta UE^{*2}$) cases, with the discount rate (ρ) set at 0.05. US^* and UE^* are social and economic utilities, respectively; The *asterisk* depicts the optimal level; the subscript 0 represents the disagreement point; cc is the impact of climate change on groundwater recharge

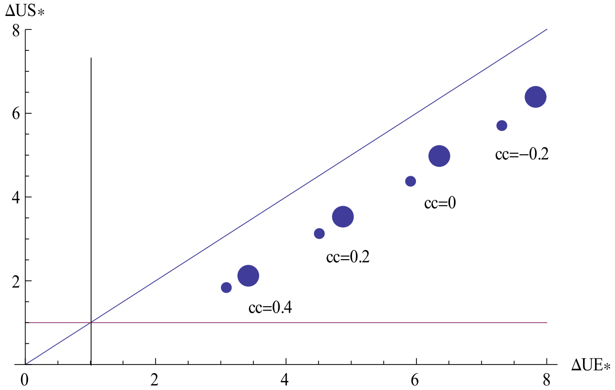


Fig. 10 Relative utility achievements (*US** and *UE** in terms of US_0 and UE_0), with *cc* at −0.2, 0, 0.2, and 0.4, in both quantity (small points: $\Delta US^{*} = -0.9326 + 0.8867\,\Delta UE^{*} - 0.0251\,\Delta UE^{*2}$) and quality (large points: $\Delta US^{*} = -1.2149 + 0.9830\,\Delta UE^{*} - 0.0148\,\Delta UE^{*2}$) cases, with the discount rate (ρ) set at 0.1. *US** and *UE** are social and economic utilities, respectively; the *asterisk* depicts the optimal level; the subscript 0 represents the disagreement point; *cc is* the impact of climate change on groundwater recharge

Figure 11 suggests that a small concern for future generations (a discount rate at 0.2) indicates an equal distribution of all impacts of climate change; this is due to the crucial importance of groundwater withdrawals for both sectors and, consequently, to the insignificant differences between their preferences for the groundwater stock in the bargaining process. Moreover, utility is smaller for both sectors than in Figs. 9 and 10 (again, due to a smaller groundwater stock), with larger differences if the impacts on both quantity and quality rather than only the impacts on quantity are relevant (again, due to larger desalinisation or purification costs and pumping costs

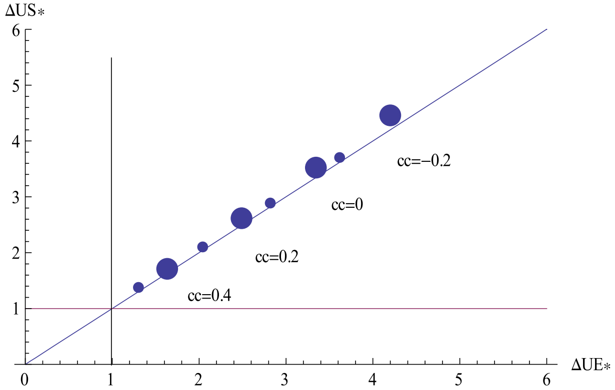


Fig. 11 Relative utility achievements (*US** and *UE** in terms of US_0 and UE_0), with *cc* at −0.2, 0, 0.2, and 0.4, in both quantity (small points: $\Delta US^{*} = 0.1033 + 9676\,\Delta UE^{*} + 0.0080\,\Delta UE^{*2}$) and quality (large points: $\Delta US^{*} = 0.0451 + 1.0679\,\Delta UE^{*} - 0.0001\,\Delta UE^{*2}$) cases, with the discount rate (ρ) set at 0.2. *US** and *UE** are social and economic utilities, respectively; the *asterisk* depicts the optimal level; the subscript 0 represents the disagreement point; *cc* is the impact of climate change on groundwater recharge

that must be borne by both sectors). Finally, the justice criterion might be challenged by unexpected increases in either social or economic groundwater needs (both ΔUS^* and ΔUE^* are close to 1 with $cc = 0.4$).

Note that calculating water charges based on per capita income or water rights in rural and urban areas would make it possible to assess the equity within the social sector. Next, calculating the ratio of water rights to basic needs in rural and urban areas would make it possible to assess the degree of justice within the social sector. However, data at the basin level would be required for these calculations.

To summarise, a smaller concern about future generations leads to groundwater management strategies that ensure more equal distributions of the impacts of climate change among the current economic and social sectors, although the distributions might not meet the justice criterion when unexpected increases in either economic or social groundwater needs occur. Therefore, the discount rate deduced from data on current groundwater management (discussed in Section 6.1), together with the potential groundwater management strategies obtained in Section 7.2, suggest that Brazilian water-management institutions will be able to achieve efficiency and equity while coping with the impacts of climate change, at the risk of injustice if unpredicted increases in social or economic groundwater requirements occur.

8 Discussion

Four main policy suggestions can be identified based on the results presented in Section 7:

- Water conservation should be implemented in the economic sector (i.e., a smaller UE_0), since this will increase water availability for the social sector for a given optimal level of the groundwater stock.
- Water subsidies should not be adopted for the economic sector (i.e., a smaller t_e), since this would significantly reduce the groundwater stock by marginally affecting the groundwater management strategies for both the economic sector and the social sector.
- The current generation should pay for groundwater at its social opportunity cost (i.e., including economic costs for water quality), since this will protect the utility of future generations by better preserving groundwater, and since it will force current generations to satisfy their preferences for the groundwater stock that would otherwise be disregarded in the bargaining process, because conservation would be less important than their preferences for groundwater withdrawals.
- Current generations should show greater concern for future generations (i.e., by reducing the discount rate), since this will significantly improve justice, although it will marginally worsen equity between the current economic and social sectors.

Two main assumptions about the calibration of parameters might affect the accuracy of the present results: the relative magnitudes of the environmental concerns of the economic and social sectors, and the disagreement points for the two sectors. However, the normalisations applied in the present study are theoretically robust, and suggest that the present study's methodologies are realistic and can be applied in other contexts.

9 Conclusions

The development of management strategies Section 6 and the assessment of management strategies (Section 7) stress that the model developed in this paper can identify management strategies that satisfy all the criteria emphasized in Section 1. However, Borowski and Hare (2007) stress that water researchers must improve their understanding of water management processes, since the main sources of misunderstandings between managers and the research community revolve around the following issues: the transferability of models developed for one site to new sites; social participation in water management decisions; a lack of confidence in model-based tools; and the development of improved user interfaces to make the modelling tools more usable to non-researchers. The lack of confidence can be mitigated by analyses such as the one in the present study, because the results suggest the kinds of directly applicable management strategies that water managers are comfortable with. In terms of social participation, the model includes a questionnaire that can be submitted to stakeholders to define their perceptions and desires, which can then be used to define the management strategies. Thus, the present model implements some of the recommendations proposed by Borowski and Hare (2007). Additional research will be required to improve its ability to respond to their recommendations. For example, the transferability of the model could be tested by applying it to different target basins by changing only the model parameters if the institutional context is the same, or by developing a new model using the same methodology if not. In terms of making the model more usable, it should be presented to managers as software with a user interface that meets their needs, thereby combining scientific validity with the ability to satisfy the requirements of potential users of the model.

The model is deterministic (although it considers several scenarios), it assumes perfect and symmetric information, and it does not distinguish between rural and urban households or between the agricultural and industrial sectors because of lack of suitable information. Further efforts to confirm the information assumptions and improve the ability to discriminate between groups within a given sector would be of great interest.

References

Adams G, Rausser G, Simon L (1996) Modelling multilateral negotiations: an application to California water policy. J Econ Behav Organ 30:97–111

Al-Sabbry MM, Harris DV, Fox R (2002) An economic assessment of groundwater recharge in the Tucson basin. J Am Water Resour Assoc 38:119–131

ANA (2007) GEO Brazil water resources. National Water Agency, Brazil

Ananda J, Crase L, Pagan PG (2006) A preliminary assessment of water institutions in India: an institutional design perspective. Rev Policy Res 23:927–953

Barreteau O, Garin P, Dumontier A, Abrami G, Cernesson F (2003) Agent based facilitation of water allocation: case study in the Drome River Valley. Group Decis Negot 12:441–461

Batabyal AA (1996) The queuing theoretic approach to groundwater management. Ecol Model 85:219–227

Becu N, Perez P, Walker A, Barreteau O, Page CL (2003) Agent based simulation of a small catchment water river management in northern Thailand: description of the CATCHSCAPE. Ecol Model 170:319–331

Bennet J, Blamey R (eds) (2001) The choice modelling approach to environmental evaluation. Edward Edgar, Cheltenham

Borowski I, Hare M (2007) Exploring the gap between water managers and researchers: difficulties of model-based tools to support practical water management. Water Resour Manage 21:1049–1074

Candela L, von Igel W, Elorza FJ, Aronica G (2009) Impact assessment of combined climate and management scenarios on groundwater resources and associated wetland (Majorca, Spain). J Hydrol 376:510–527

Carraro C, Marchiori C, Sgobbi A (2005) Applications of negotiation theory to water issues. Res Work Pap 47:1–47

Chen Z, Grasby SE, Osadetz KG (2002) Predicting average annual groundwater levels from climatic variables: an empirical model. J Hydrol 260:102–117

Don NC, Hang NTMH, Araki H, Yamanishi H, Koga K (2006) Groundwater resource management under environmental constraints in Shiroishi of Saga plain, Japan. Environ Geol 49:601–609

Emel J, Brooks E (1988) Changes in form and function of property rights institutions under threatened resource scarcity. Ann Assoc Am Geogr 78:241–252

Emel J, Roberts R (1995) Institutional form and its effect on environmental change: the case of groundwater in the Southern High Plans. Ann Assoc Am Geogr 85:664–683

FAO (2003) Groundwater management: the search for practical approaches. Water Reports, 25, Rome

Ganji A, Karamouz M, Khalili D (2007a) Development of stochastic dynamic Nash game model for reservoir operation I. The symmetric stochastic model with perfect information. Adv Water Resour 30:528–542

Ganji A, Khalili D, Karamouz M (2007b) Development of stochastic dynamic Nash game model for reservoir operation II. The value of players' information availability and cooperative behaviours. Adv Water Resour 30:157–168

Hämäläinen R, Kettunen E, Marttunen M, Ehtamo H (2001) Evaluating a framework for multi-stakeholder decision support in water resource management. Group Decis Negot 10:331–353

Hanley N, Mourato S, Wright RE (2001) Choice modelling approaches: a superior alternative for environmental valuation? J Econ Surv 15:435–462

Hanson RT, Dettinger MD (2005) Groundwater/surface water responses to global climate simulations, Santa Clara—Calleguas Basin, Ventura, California. J Am Water Resour Assoc 44:517–536

Harsanyi JC (1963) A simplified bargaining model for n-person cooperative game. Int Econ Rev 4:194–220

Henriksen HJ, Rasmussen P, Brandt G, von Bülow D, Jensen FV (2007) Public participation modelling using Bayesian networks in management of groundwater contamination. Environ Model Softw 22:1101–1113

Holman IP (2005) Climate change impacts on groundwater recharge—uncertainty, shortcomings, and the way forward? Hydrogeol J 14:637–647

Holman IP, Tascone D, Hess TM (2009) A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management. Hydrogeol J 17:1629–1641

Hsu K-C, Wang C-H, Chen K-C, Chen C-T, Ma K-W (2007) Climate-induced hydrological impacts on the groundwater system of the Pingtung Plain, Taiwan. Hydrogeol J 15:903–913

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manage 21:775–788

Ivey JL, Smithers J, de Loë RC, Kreutzwiser RD (2004) Community capacity for adaptation to climate-induced water shortages: linking institutional complexity and local actors. Environ Brief 33:36–47

Jha MK, Kamii Y, Chikamori K (2009) Cost-effective approaches for sustainable groundwater management in alluvial aquifer systems. Water Resour Manage 23:219–233

Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). J Hydrol 338:237–250

Kerachian R, Karamouz M (2007) A stochastic conflict resolution model for water quality management in reservoir-river systems. Adv Water Resour 30:866–882

Khan S, O'Connell N, Rana T, Xevi E (2008) Hydrologic-economic model for managing irrigation intensity in irrigation areas under water-table and soil salinity targets. Environ Model Assess 13:115–120

Koundouri P (2004) Current issues in the economics of groundwater resource management. J Econ Surv 18:703–740

Kovalevskii VS (2007) Effects of climate change on groundwater. Water Resour 34:140–152

Kretsinger Grabert V, Narasimhan TN (2006) California's evolution toward integrated regional water management: a long term view. Hydrogeol J 14:407–423

Krol M, Jaeger A, Bronstert A, Güntner A (2006) Integrated modelling of climate, water, soil, agricultural and socio-economic processes: a general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. J Hydrol 328:417–431

Krysanova V, Kundzewicz ZW, Pińskwar I, Habeck A (2006) Regional socio-economic and environmental changes and their impacts on water resources on example of Odra and Elbe Basin. Water Resour Manage 20:607–641

Loaiciga HA (2003) Climate change and groundwater. Ann Assoc Am Geogr 93:30–41

Lobo Ferreira J, Conceição Cunha M, Chachadi A, Nagel K, Diamantino C, Oliveira M (2007) Aquifer development planning to supply a seaside resort: a case study in Goa, India. Hydrogeol J 15:1147–1155

Lopez-Gunn E, Cortina LM (2005) Is self-regulation a myth? Case study on Spanish groundwater uses associations and the role of higher-level authorities. Hydrogeol J 14:361–379

Martín de Santa Olalla FJ, Domínguez A, Artigao A, Fabeiro C, Ortega JF (2005) Integrated water resources management of the hydro-geological unit "Eastern Mancha" using Bayesian Belief Networks. Agric Water Manag 77:21–36

Morehouse BJ (2000) Climate impacts on urban water resources in the Southwest: the importance of context. J Am Water Resour Assoc 36:265–277

Nash JF (1950) The bargaining problem. Econometrica 18:155–162

Neufeld DA (2000) An ecosystem approach to planning groundwater: the case of Waterloo region, Ontario, Canada. Hydrogeol J 8:239–250

Ojima D, Garcia L, Elgaali E, Miller K, Kittel TGF, Lackett J (1999) Potential climate change impacts on water resources in the Great Plains. J Am Water Resour Assoc 35:1143–1454

Provencher B, Burt O (1993) The externalities associated with the common property exploitation of groundwater. J Environ Econ Manage 24:139–158

Provencher B, Burt O (1994) A private property rights regime for the commons: the case of groundwater. Land Econ 69:325–340

Purkey DR, Huber-Lee A, Yates DN, Hanemann M, Herrod-Julius S (2007) Integrating a climate change assessment tool into stakeholder-driven water management decision-making process in California. Water Resour Manage 21:315–329

Quinn NWT, Brekke LD, Miller NL, Heinzer T, Hidalgo H, Dracup JA (2004) Model integration for assessing future hydro-climate impacts on water resources, agricultural production and environmental quality in the San Joaquin Basin, California. Environ Model Softw 19:305–316

Qureshi ME, Qureshi SE, Bajracharya K, Kirby M (2008) Integrated biophysical and economic modelling framework to assess impacts of alternative groundwater management options. Water Resour Manage 22:321–341

Randhir T, Genge C (2005) Watershed based, institutional approach to developing clean water resources. J Am Water Resour Assoc 4:413–424

Ranjan SP, Kazama S, Sawamoto M (2006a) Effects of climate change on coastal fresh groundwater resources. Glob Environ Change 16:388–399

Ranjan SP, Kazama S, Sawamoto M (2006b) Effects of climate and land use changes on groundwater resources in coastal aquifers. J Environ Manag 80:25–35

Rosenzweig C, Strzepek KM, Major DC, Iglesias A, Yates DN, McCluskey A, Hillel D (2004) Water resources for agriculture in a changing climate: international case studies. Glob Environ Change 14:345–360

Roseta-Palma C (2002) Groundwater management when water quality is endogenous. J Environ Econ Manage 44:93–105

Salazar R, Szidarovszky F, Coppola EJ, Rojano A (2007) Application of game theory for a groundwater conflict in Mexico. J Environ Manag 84:560–571

Scibek J, Allen DM (2006) Modelled impacts of predicted climate change on recharge and groundwater levels. Water Resour Res 42:W11405. doi:10.1029/2005WR004742

Semadeni-Davies A (2004) Urban water management vs. climate change: impacts on cold region waste water inflows. Clim Change 64:103–126

Tanaka SK, Tingju Z, Lund JR, Howitt RE, Jenkins MW, Pulido MA, Tauber M, Ritzema RS, Ferreira IC (2006) Climate warming and water management adaptation for California. Clim Change 76:361–387

Thiesse E, Loucks D, Stedinger J (1998) Computer assisted negotiation of water resource conflicts. Group Decis Negot 7:109–129

Thoyer S, Morardet S, Rio P, Simon L, Goodhue R, Rausser G (2001) A bargaining model to simulate negotiations between water users. JASSS 4(2). http://www.soc.surrey.ac.uk/JASSS/4/2/6.html

Vicuna S, Maurer EP, Joyce B, Dracup JA, Purkey D (2007) The sensitivity of California water resources to climate change scenarios. J Am Water Resour Assoc 43:482–498

Wang M, Zheng C (1996) Groundwater management optimisation using genetic algorithms and simulated annealing: formulation and comparison. J Am Water Resour Assoc 34:519–530

White I, Howe J (2004) The mismanagement of surface water. Appl Geogr 24:261–280

Woldeamlak ST, Batelaan O, De Smedt F (2007) Effects of climate change on the groundwater system in the Grote–Nete catchment, Belgium. Hydrogeol J 15:891–901

Zeitouni N (2004) Optimal extraction from a renewable groundwater aquifer with stochastic recharge. Water Resour Res 40:W06S19. http://www.agu.org. doi:10.1029/2003WR002162