

Simulations of multipurpose water availability in a semi-arid catchment under different management strategies

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ABSTRACT

In the semi-arid Brazilian Northeast, the exploitation of alluvial aquifers for irrigation and domestic supply to rural communities over the last 10 years has upset the traditional mechanisms of water resources management. In the Forquilha watershed (221 km²; 5°17'S, 39°30'W), the two main water resources are reservoirs (with a capacity exceeding 0.9–6.7 × 10⁶ m³), used for domestic water supply only, and an alluvial aquifer (2.3 × 10⁶ m³), used for irrigation and domestic water supply. From 1998 to 2006, the irrigated area with alluvial groundwater increased from 0 to 75 ha, and the fraction of population supplied through domestic water networks, using reservoirs and the aquifer, increased from 1% to 70%. Based on physical and socioeconomic issues, three main water territories have been defined ("Aquifer", "Reservoirs", and "Disperse Habitat"). Considering the next 30 years with a realistic population growth, three hypotheses regarding irrigated area (i.e., 0, 75, or 150 ha), and several possible water-management scenarios, hydrological balance models were built and used to simulate the different impacts on water resource availability and salinity. Simulation results showed that, in all cases, releases from the upstream main reservoir are necessary to keep reservoir salinity below 0.7 g L⁻¹ and for guaranteeing domestic needs in the whole watershed. As a consequence, a management approach that takes into account the interrelations among the three territories is necessary. Moreover, the simulations showed that the area of irrigated fields cannot exceed the current extent (75 ha), or serious restrictions on water availability and salinity will take place. Moreover, important socioeconomic problems are expected, including a high cost of palliative water supply with tank trucks from external sources.

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1. Introduction

The Brazilian Northeast (750,000 km², 51 million inhabitants) is a semi-arid region with a rainfall of less than 700 mm yr⁻¹ and potential evapo-transpiration (ETP) greater than 2000 mm yr⁻¹. The high annual rainfall deficit is accentuated by a short rainy season (3 months) and strong irregularity in rainfall distribution. The spatial and temporal heterogeneity of precipitation combined with shallow soils overlying crystalline rocks, and high evaporation lead to intermittent river flow with a mean duration of less than 3 months (Cadier, 1993, 1996).

In order to adapt to this restricted water availability, the inland colonization of the Northeast, which started in the 1650s, has been guided by the river systems that constitute open paths and allow water access to the riverbed itself or to the related alluvial aquifer.

Indeed, during the dry season, open dug wells provided the cattle and human water supply (Molle, 1994). The land tenure of the small watersheds in Ceará State was, as a consequence, generally organized into narrow bands perpendicular to the river, allowing every landowner access to the riverbed.

The Forquilha catchment illustrates this pattern, with some fields as narrow as 50 m along the river and as long as 6 km perpendicular to it (Fig. 1). Since 1998, the drilling of wells has resulted in the extraction of groundwater from the alluvial aquifer for irrigated crops, whose surface area has increased by 75 ha from 1998 to 2007. Even if this figure is small when compared to the 1000 ha of traditional rain-fed agriculture (beans, maize, and forage crops in the region in general; IBGE, 2004), it still has had an important impact on water requirements.

The pressure on water resources is indeed increasing and whether or not water availability can be sustainable is an open question. Support policies for participative water resources management are lacking. This results in strong individualism (Molle, 1994) and in a lack of social links among the different water territories within the same watershed (Tonneau and Caron, 2006).

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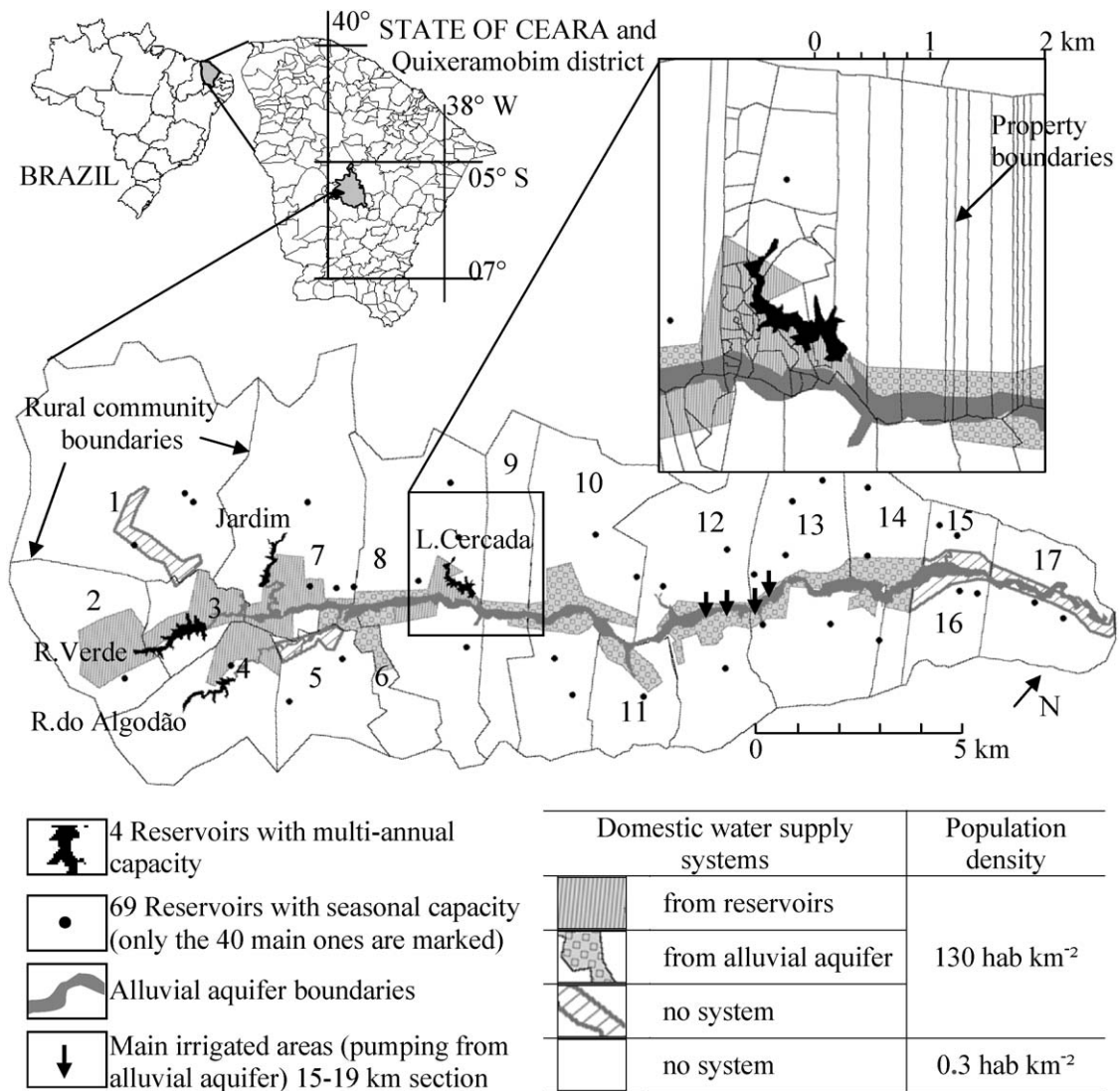


Fig. 1. Forquilha Watershed (CEARÁ-BRAZIL) location and characteristics: main water resources (reservoirs and alluvial aquifer); irrigated areas, boundaries of the 17 rural communities; population density and respective type of domestic water supply system. Area near L. Cercada is framed to show the land structure with very narrow properties allowing water access in river.

Finally, because of the inter-annual climatic variability, during droughts, the rural population is highly dependent on local authorities to provide domestic water by tank trucks.

To provide stakeholders and local authorities with the elements of discussion on the possible options for managing the Forquilha valley water resources, different scenarios have been built using socioeconomic and hydrological data. Taking into account these two aspects is a growing trend for helping to discuss and assess water allocation in watersheds (Jakeman and Letcher, 2003; Liu et al., 2007; Mainuddin et al., 2007).

In the Forquilha case, the main factors considered in building such scenarios are (1) socio-political and economic factors; (2) hydrological factors (seasonal dynamics of the alluvial aquifer, salinity, sensitivity to anthropogenic actions, and relations between upstream reservoirs and downstream aquifer); and (3) interference from multiple uses on the different resources.

The objective of the present study was to evaluate water availability for different users and different uses within the whole Forquilha watershed (221 km²) for the next 30 years, according to different possible future evolutions of irrigated crops (the main water consumers). The study has three specific constituents. First is the characterization of the different water resources (amount,

salinity, and variability) and the development of the related hydrological models, the different uses and users, and the main constraints (physical, socio-political, and economic) on water resources management. Second is the development of evolution scenarios for the next 30 years, assuming growing domestic water supply needs (SRH, 1992) and different assumptions about the evolution of the irrigated field area. Also, taken into consideration are possible water transfers among different regions within the watershed (e.g., release from the upstream reservoirs to the river that may feed the downstream aquifer). Third is the simulation, based on a 30-year rainfall series, of the impacts of the above scenarios on how well needs are met for water resources availability and reservoir quality (volume and salinity) and in aquifer volume for main user categories, taking into account a realistic climatic variability.

2. Study area and historical evolution of the water resources

The Forquilha catchment is occupied by 17 villages and their community territory (Fig. 1). During the period 1998–2007, the annual flow duration ranged from 0 to 7 months (average: 3 months).

Table 1

Present types of water resources in Forquilha watershed.

Name	Max capacity (m ³)	Annual usable volume of water (m ³)	Surface area (m ²)	Salinity range (g L ⁻¹)	Location (Fig. 1)
Four multiyear reservoirs					
R. Verde	67 × 10 ⁵	5.7 × 10 ⁵	8 × 10 ⁵	0.14–0.38	2 and 3
R. Algodão	8.7 × 10 ⁵	2.1 × 10 ⁵	1.6 × 10 ⁵	0.09–0.25	4
Jardim	9.7 × 10 ⁵	2.1 × 10 ⁵	1.8 × 10 ⁵	0.09–0.28	7
L. Cercada	13 × 10 ⁵	1.3 × 10 ⁵	3.1 × 10 ⁵	0.07–0.35	8
69 annual reservoirs	<10 × 10 ⁵	–	<1 × 10 ⁵	>0.05	1–17
90 Cisterns	9 × 10 ²	9 × 10 ²	–	0.05–0.15	1–17
Alluvial aquifer	2.3 × 10 ⁶	1 × 10 ⁶	6 × 10 ⁶	0.1–2 Mean value 0.7	Mainly in 12 and 13
Tank trucks		30 L day ⁻¹ capita ⁻¹			1–17

At present, there are four types of water resources used for domestic and economic uses. Three are internal: reservoirs, an alluvial aquifer (storing runoff water) and cisterns (collecting rainfall water from the house roofs); and one is external: water brought from other catchments by tank trucks provided by the state authorities in case of necessity for domestic uses during severe droughts.

There are many reservoirs in the Forquilha catchment. There are sixty-nine annual reservoirs that are well distributed over the 17 communities (see dot points in Fig. 1; Table 1); they fill and empty every year; capacity of each ranges from 0.05 × 10⁶ to 0.3 × 10⁶ m³ for a total capacity approaching less than 10⁶ m³. There are four over-year reservoirs with a total capacity of about 10 × 10⁶ m³ (Table 1), the biggest one is the Riacho Verde Reservoir (6.7 × 10⁶ m³). They are located in the upper part of the catchment (Fig. 1). Salinity is often less than 0.4 g L⁻¹; however, the impact of evaporation may strongly increase this value up to 3 g L⁻¹ during the dry season. Upstream populations preferentially use these four main reservoirs. Cisterns provide very low-salinity water and are an auxiliary resource for domestic use for 5–45% of the families, depending on the community.

The alluvial aquifer covers about 6 km² (23 km by 250 m) with a mean depth of alluviums of 6.8 m. At the end of the rainy season, the water table lies about 2.8 m below the soil surface and with a saturated height of 4 m. The groundwater volume is about 2.3 × 10⁶ m³. The main inflow to the aquifer originates from the intermittent river (Burte et al., 2005). Alluvial aquifer groundwater is essentially used in the downstream part of the watershed, traditionally by riparian landholders for forage crops with roots that use water directly and for cattle and domestic uses by digging holes in the riverbed (Ribeyre, 2006; Fabre and Burte, 2007). It has a higher salinity (mean value of 0.7 g L⁻¹, Table 1) than the river water. This difference testifies to other inputs of saline water: a permanent input from the saline basement hard-rock aquifer, and an occasional input from the flush back of water from the unsaturated zone, where salt is accumulated by evaporation close to the soil surface (Coudrain et al., 2001; Burte, 2008). A great number of wells (180) have been drilled since 1998, allowing

Table 2

Present types of needs of water resources in Forquilha watershed.

Name	Mean annual water requirement (m ³)	Max salinity (g L ⁻¹)	Location (Fig. 1)
"Reservoirs" territory			
Domestic water	57 × 10 ³	<0.7	2, 3, 4,7,8
Cattle water	13 × 10 ³	<5	
"Aquifer" territory			
Domestic water	43 × 10 ³	<0.7	
Cattle water	22 × 10 ³	<5	5,6,7, 9–14
irrigated fields (75 ha)	1 × 10 ⁶	<1.2	
"Disperse habitat" territory			
Domestic water	13 × 10 ³	<0.7	1–17
Cattle water	23 × 10 ³	<5	1–17

intensive water-related activities during both dry and rainy seasons. Crop irrigation utilized 95% of the water withdrawal between 2000 and 2007, which benefited 5% of the families in the watershed. The remaining 5% of the available water was used for domestic water supply, which benefited 70% of the families in the watershed (Ribeyre, 2006). Intense pumping leads to progressive, locally accentuated depression of the water table (reaching about 2 m) and influences alluvial groundwater salinity dynamics, making it locally unsuitable for traditional uses or irrigation. This outcome leads farmers to limit and sometimes even to stop irrigation at the end of the dry season when the water table is too low and/or the water salinity too high.

Therefore, the crucial question is as follows: Is it possible to satisfy pumping requirements for irrigation, restricted to few farmers (landholders), while securing water access to the riverbed for poor landholders and landless farmers without pumping facilities, while guaranteeing a continuous domestic supply (Table 2)?

3. Data and methods

3.1. Hydrological characterization of Forquilha watershed

For this study, monthly rainfall data were needed for the simulations over 30 years. The data used were the mean values from the two closest rain gauges of the Brazilian monitoring network with the longest time in operation (1977–2007). They are located in Manituba and São Miguel, 8 km northeast and 5 km southwest of the study area, respectively.

SPOT5 images with 10 m resolution (10/2002 and 07/2003) were used to map the watershed and the alluvial sediment boundaries and to estimate the surface area of the reservoirs. Water level and electric conductivity were monitored in the four over-year reservoirs (03/2003 to 06/2007) and in 20 piezometers located along the alluvial aquifer (09/2000 to 06/2007). Discharge rate and flow routing in the river were monitored during three events of release from the R. Verde reservoir in 2003, 2004, and 2005. These data have been used to calibrate the models.

3.2. Characterization of uses, users, and water-management constraints

A water resources typology was undertaken in two steps. The first step was based on interviews and semi-directive surveys carried out in 15 of the 17 watershed communities, from July to September 2005 (Ribeyre, 2006). These investigations identified the main groups of water users, types of uses, perceptions about water resources, and criteria for using and managing water resources. The results were compared with qualitative and quantitative socioeconomic data, collected over a two-month period from July to August 1998 with a questionnaire covering 1024 households (99% of the population). The second step was conducted in six communities (no. 3, 7, 10, 12, 13, and 17 in Fig. 1). Multiple-choice questionnaires, records, and analysis grids were

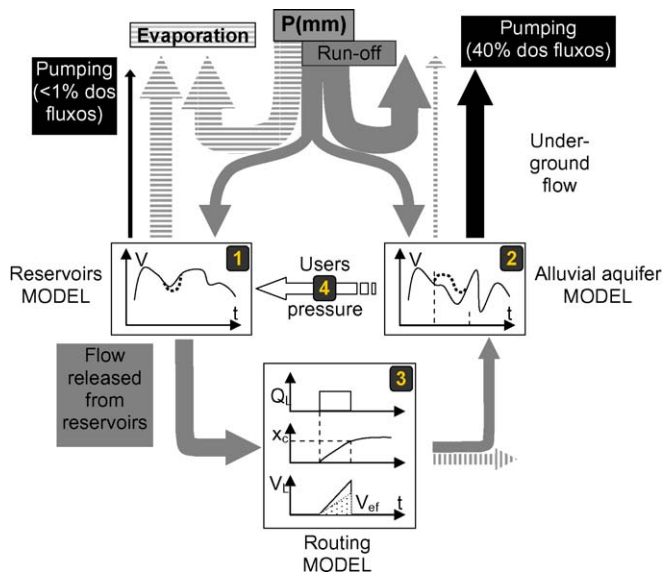


Fig. 2. Hydrological models built and used in the study with monthly time step to simulate the time evolution of the water content and water salinity (1) of the reservoirs, (2) of the alluvial aquifer and (3) of the released discharge routing. Constraints due to social pressure are taken into account (4) in the flow released from reservoirs.

used in order to highlight and quantify the individual and collective water-management modes.

Finally, these data were completed by observations and data collected since 1998 through discussions with internal and external stakeholders, including politicians. From these data, satisfaction criteria and constraints on resources exploitation were defined and are further used to discuss scenario impacts on resource availability and uses/user satisfaction.

3.3. Scenario building

Selected scenarios should be both technically sound and socially useful so that they can be used to discuss the different management options with relevant stakeholders (Srdjevic et al., 2004; Mermet, 2005; Treyer, 2005). Here, the objective was to provide, through different simulations, some insight into the availability of the resources in terms of quantity and quality for the next 30 years, taking into account the assumption of a growing population and an unknown increase in the irrigated field area. Because variations in irrigated areas affect water availability much more than variations in population, three contrasted values were selected for irrigation level:

1. **Irrigated area = 0 ha**, corresponding to what prevailed before 1998. The water resources are only dedicated to domestic and cattle water supply, and all crops are rain fed.

2. **Irrigated area = 75 ha**, corresponding to the 2007 situation; pumping from the aquifer is necessary in communities 12 and 13 (Fig. 1) to ensure agricultural production and to assure survival of tree crops like guava.
3. **Irrigated area = 150 ha**, corresponding to a doubling of the 2007 irrigated area.

The simulations were based on the rainfall data for the 1977–2007 period that includes some multiyear droughts leading to water supply collapse. In such situations, tank trucks provide a palliative domestic supply, using as reference a need of $30 \text{ L day}^{-1} \text{ capita}^{-1}$. The cost, $5.4 \text{ US\$ m}^{-3}$, is covered by the state (Araujo et al., 2005).

It is now widely accepted that climate is changing worldwide (IPCC, 2007); however, in the studied area, the effects on local rainfall are still being debated (Christensen et al., 2007; Krol and Bronstert, 2007; Salazar et al., 2007). Thus, the results of the simulations presented below must be used knowing that the aridity could increase and aggravate the water needs in the Brazilian Northeast.

3.4. Modelling approach

To take into account the rainfall seasonality, a time step of one month was chosen. At each step, the needs of the population, cattle, and irrigation have to be computed. At each step, the water availability and salinity of the different water bodies—reservoirs, cisterns, and aquifer also have to be computed.

Three models were built to simulate the dynamics of the main hydrological resources (Fig. 2): (1) a hydrological balance (water and salt) model for reservoirs, in which evaporation is very high; (2) a hydrological model for the alluvial aquifer (Burte et al., 2005) with main recharge from stream flow in the minor riverbed (corresponding to flood and released discharged events from the R. Verde reservoir), which takes into account pumping and groundwater flow; and (3) a downstream discharge routing model for water release into the river from the R. Verde reservoir, allowing evaluation of its impact on alluvial aquifer recharge.

4. Results

4.1. Typology of water resources users and uses

From the analysis of the spatial variations of water resources, users, and uses, three different water territories were defined (Fig. 3) in conformity with “thoughts and actions are structured by water” (Tonneau and Caron, 2006). The “territories” as set up in this study conform closely to those perceived by the local people. Evident tensions exist among people in these territories about water transfer from one territory to another.

The “Reservoir” territory (40% of whole population) covers the area of the communities located upstream around the four main

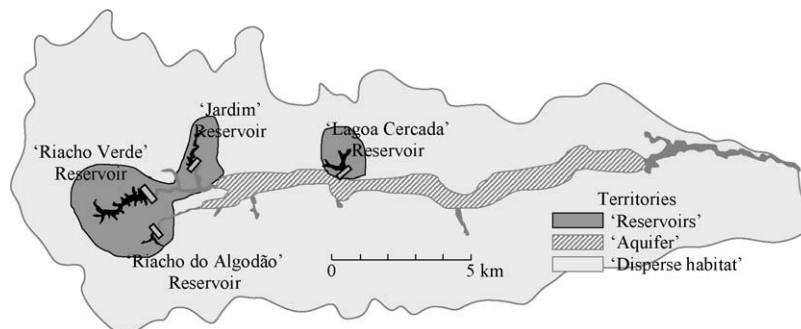


Fig. 3. Main water territories with 40%, 30% and 30% of the population respectively in “Reservoirs”, “Aquifer” and “Disperse Habitat” territories.

reservoirs of the catchment. All uses (drinking water, domestic water, cattle water) are supplied by community systems fed by these reservoirs. There is no local water supply alternative. These populations are poor, established on steep slope areas that are not very suitable either for agriculture or for cattle breeding.

The “Aquifer” territory (30% of whole population) accounts for downstream communities that meet water requirements (domestic water supply systems, irrigation, and cattle) by pumping from the alluvial aquifer. Irrigation exists only in this territory, and has been developed since 1998. The irrigated zones are located almost exclusively in the 15–19 km section downstream from the R. Verde reservoir (Fig. 1). Water from small reservoirs and cisterns is used only as drinking water.

The “Disperse Habitat” territory (30% of whole population) covers the area where the habitat is dispersed and small local resources (cisterns or small reservoirs) provide the water supply. The recharge of these cisterns or reservoirs occurs during the rainy season but is irregular: families must adapt their strategy for water supply throughout the year according to the available resources. During droughts, the access to water is recurrently problematic; water needs to be transported from remote resources such as over-year reservoirs or the alluvial aquifer, which is accessed through holes excavated in the riverbed. In this context, daily consumption in “Disperse Habitat” territory is only 30 L day⁻¹ capita⁻¹, whereas it is around 100 L day⁻¹ capita⁻¹ in the other two territories.

The water transfers between these “conceptual” territories are either natural or under control. The “natural flow” is the upstream–downstream flow related to flood events. The control transfers are related to the opening of the gates of the R. Verde. During the dry season, aquifer users put pressure on politicians to force upstream communities to accept water release from the R. Verde reservoir. This seasonal strain situation can degenerate into social conflicts. The upstream communities want to preserve “their” resources and do not accept releasing water unless the water level in the reservoir is quite high.

4.2. Hydrological models

4.2.1. Hydrological balance model of reservoirs

The hydrological balance model of reservoirs was developed at monthly time intervals taking into account main outflows (evaporation; seepage losses; released discharge; and pumping), and inflows (precipitation over the reservoir and runoff from upstream watersheds during the rainy season).

The water level–surface–volume relationships, described by $VR = K \times HR^\alpha$ and $SR = \alpha \times K \times HR^{\alpha-1}$, were used to characterize each reservoir, where HR is water level, SR is water surface, VR is water volume, and K and α are two parameters related to depth–area–volume relationship of each reservoir obtained from a regional model (Molle and Cadier, 1992; Cadier, 1993). Data used to calibrate parameters was highest value of HR (measured in situ), HR and SR on 17/07/2003 (HR was measured and SR was obtained from the 10 m resolution SPOT5 image).

In the semi-arid Northeast, runoff is the main recharge mechanism for reservoirs (Dubreuil, 1966; Dubreuil et al., 1968); it also generates the river flood events that are the main inflow into the alluvial aquifers (Burte et al., 2005). Because runoff data are needed in the simulations and they are not available for this watershed, runoff was evaluated from the Sudene/Orstom annual rainfall–runoff regional model (Molle and Cadier, 1992; Cadier, 1993) developed on the base of a regional study carried out on 165 small watersheds (Cadier, 1993). For every watershed, a characteristic runoff depth (RD₆₀₀) has been calculated according to geomorphologic, vegetation, and soil parameters for 600 mm annual rainfall. Next, for any annual rainfall P, runoff depth RD is estimated by $RD = RD_{600} \times 1.4^{(P-600)/100}$.

Volume losses by seepage have been neglected except for the L. Cercada reservoir, where seepage rates are known to be higher because they result in superficial flow downstream from the dam. They have been measured and vary from 15 to 30 L s⁻¹ depending on the water level in the reservoir.

Evaporation of reservoir water, E (mm), is linearly related to evapo-transpiration, ETP (mm), through a coefficient β , with $E = \beta \times ETP$ (Cadier et al., 1992; Molle & Cadier, 1992; Cadier, 1993). The β coefficient has been calibrated from level curves observed in dry seasons over the 2003–2007 period ($\beta = 1.14$).

Verification of the reservoir model has been based on the simulation of the evolution of water salinity. Computed values were compared to observed values during the dry seasons of the 2003–2007 period. The R² was 0.91 for runoff for the Cercada reservoir and 0.96 for the R. Verde reservoir.

4.2.2. Hydrological balance model of alluvial aquifer

The hydrological balance model of the aquifer is detailed in Burte et al., 2005. Simulations of flow and salt transport on a 1.5 km alluvial aquifer section have been carried out with the spatial, physically based model Feflow (WASY, 2005). Results corroborate that the main water inflow into the aquifer is related to flood events.

4.2.3. Hydrological balance model for released flow in riverbed

Recharge of the alluvial aquifer by water release from the reservoir is expected to be of major impact 15–19 km downstream from the R. Verde reservoir where irrigation is the most developed. A released flow routing model along the river was built to compute the time of release necessary to recharge the aquifer 15–19 km downstream from the R. Verde reservoir. Simulations were carried out for different discharge rates and pumping scenarios. Initial condition is the water level of the alluvial aquifer before recharge (z_0). Part of released volume is consumed by pumping and by evaporation and does not contribute to raising the water table. Evaporated volume and pumping volume can be viewed as a function of distance from R. Verde reservoir (DIST). Evaporating rate in the riverbed is assumed to be 8 mm day⁻¹.

Then, during a time step Δt , the released volume V_R can be divided into three components: evaporated volume, pumping volume and “effective” volume (V_{EF}). Only V_{EF} contributes to water table rising (Δz) and flood progression in the river from DIST to $DIST + \Delta_{DIST}$ (Fig. 4), as follows:

$$V_{EF} = \ell \times \rho \times \Delta_{DIST} \times \Delta z + h_0 \times \Delta_{DIST} \times [l_R + \rho \times (\ell - l_R)].$$

where ℓ is aquifer width, ρ is the aquifer porosity, Δz is the difference between the water level before recharge and the river bed level, l_R is river width, and h_0 is a parameter calibrated using three monitored release events occurring in 2003, 2004, and 2005 (Fig. 5).

4.3. Evolution scenarios over 30 years

The objective of the scenarios is to project ahead for 30 years from 2007 (2007–2037) to discuss the availability of water resources. Because this availability depends on the rainfall scenario, we used an observed time series (1977–2007), which integrates a realistic distribution of dry and rainy spells. → decrier là un minimum durée “over-year sécheresse ... comme c’est utilise après.

Different hypotheses can be considered for the evolution of population. We chose the “growing” hypothesis following the observed 1998–2006 period trend (Fig. 6). Nevertheless, as already noticed since 2002 (Fig. 6), we chose a linearly decreasing growth rate of the number of families from 3% to 0% between 2007 and 2037. This may correspond to realistic conditions with land and pedo-climatic constraints. In any case, the growth rate is not

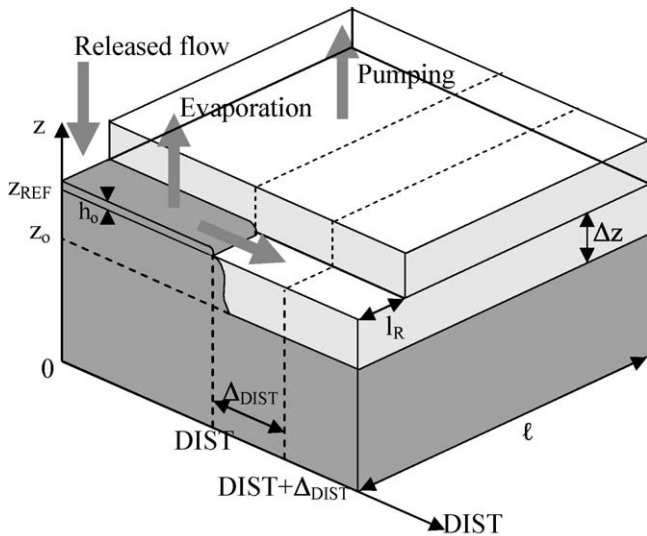


Fig. 4. Alluvial aquifer and river bed diagram, with main fluxes of hydrological balance during time Δt (released flow, evaporation, pumping), resulting in aquifer recharge along distance Δ_{DIST} . l is aquifer width, I_R is river width, Δz is the difference between the water level before recharge (z_0) and the river bed level (z_{REF}).

expected to have a significant influence on the results of the simulations, since only a small portion of the resources is used for domestic supply (Table 2).

In all of the simulations, population evolution is the same one (Fig. 6), growing from 974 to 1400 families (i.e., from 3500 to 5600 people) in 30 years and with increasing proportion of population having access to domestic supply (Fig. 6).

In the simulations, the domestic and drinking water requirements are met with priority at each time step. The “Reservoir” territory is supplied by pumping from the four main over-year reservoirs, while the “Aquifer” territory is supplied by pumping from the alluvial aquifer. For the “Disperse Habitat” territory, the families supply themselves from high renewal rate resources or, when necessary, from the alluvial aquifer. In “Disperse Habitat” territory, because all water resources are small and used until exhaustion, management cannot improve water availability.

Simulations of release events have been carried out for the four over-year reservoirs. Results show that only the R. Verde reservoir can yield volumes and discharges sufficient to affect the alluvial

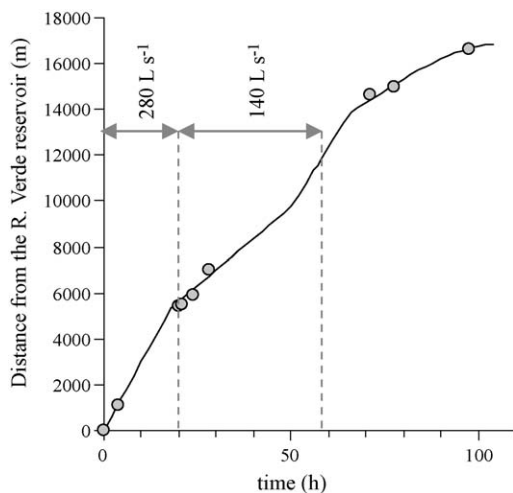


Fig. 5. Simulated (solid line) and observed (circles) flood routing downstream from the R. Verde reservoir for a discharge event of 57 h (280 L s^{-1} during the first 20 h, then 140 L s^{-1}) occurred in 2004.

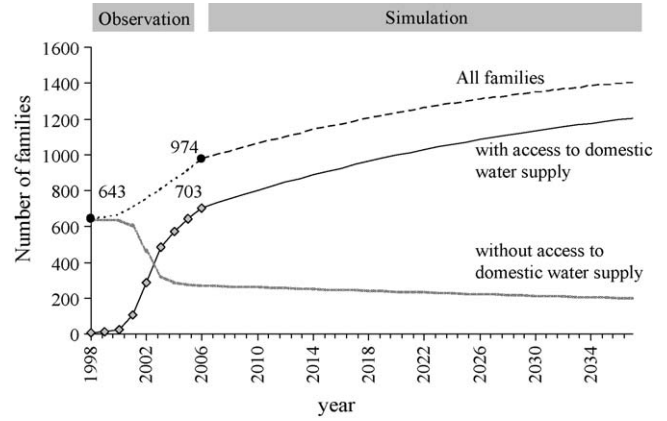


Fig. 6. Number of families vs time: during the observation period 1998–2006 the growth rate decreased from 6% to 3% and during the simulation period 2007–2037 the growth rate used decreases from 3% to 0%.

aquifer. Therefore, the simulations presented here refer only to releases from the R. Verde reservoir.

For all simulations, the following constraint was taken into account: pumping from reservoirs for domestic water supply systems is not possible if the volume is less than 15% of the reservoir capacity (a critical volume reserved for safeguarding the aquatic ecosystem and for acceptance for communities) and is not possible if water salinity is greater than 1.5 g L^{-1} .

In aquifer simulations, inflow into the aquifer, corresponding to results from the reservoir release simulations was taken into account. And, the following constraint was taken into account: pumping from the aquifer is possible for domestic supply and irrigation as long as the water height is higher than 2 m. This is in respect to the fact that when the aquifer water level drops, farmers stop pumping if the water level is deeper than 2.8 m below soil surface.

Families of the “Disperse Habitat” territory use annual reservoirs and sometimes the aquifer for all uses as long as the water level is less than 1.8 m below the soil surface.

4.4. Simulation results

In the “Reservoir” territory, monthly pumping from the reservoirs for domestic water supply ranges 0.4–1.2% of outflows for the R. Verde reservoir, and 0.8–2% of the R. Algodão reservoir. Therefore, the pumping has a negligible influence on the

Table 3 Minimum continuous discharge rate (L s^{-1}) for river flows reach 15–19 km downstream.

Initial filling of alluvial aquifer (%)	Scenario/Irrigated area (ha)		
	0	75	150
100%	30	50	70
75%	55	80	90

Table 4 Minimum discharge time (day) necessary to reach 15–19 km downstream in case of 75% initial water-filling of alluvial aquifer, for different scenarios and discharge rates.

Discharge rate (L s^{-1})	Scenario/Irrigated area (ha)		
	0	75	150
80	90	120	^a
130	50	62	66
280	22	23	24

^a Released flood did not reach the 15–19 km downstream.

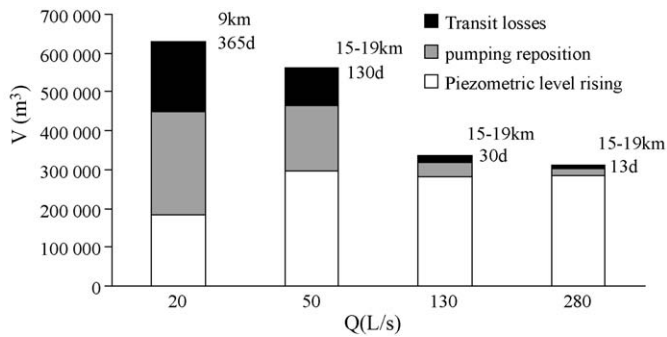


Fig. 7. Scenario 'present/75 ha': results of four simulations for discharge rates from 20 to 280 L s⁻¹, with duration of release and distance reached by flow downstream from R. Verde reservoir. For the case of 20 L s⁻¹, even after 365 days of release, the computed flow only reaches 9 km downstream from the reservoir.

hydrological balance and dynamics of the reservoirs. For instance, mean pumping in the R. Verde reservoir is $1.3 \times 10^3 \text{ m}^3 \text{ month}^{-1}$ and represents, per family, a mean water consumption of $10 \text{ m}^3 \text{ month}^{-1}$. Evaporated volumes correspond to the main term of outflow from reservoirs, computed values range from 80×10^3 to $250 \times 10^3 \text{ m}^3 \text{ month}^{-1}$.

Release discharge simulations from the R. Verde reservoir have been carried out (see Tables 3 and 4) for up to 280 L s⁻¹ (maximum discharge allowed by valve). The aim was to determine the release

characteristics (flow, duration and date in the year) necessary to recharge the alluvial aquifer down to the main pumping areas (section 15–19 km downstream R. Verde). Two hypotheses have been tested: (1) the release starts at the beginning of the dry period (i.e., highest levels of water in the alluvial aquifer) and ends with the onset of the rainy season; and (2) the release begins when water level drops below 3.8 m below soil surface, that is to say 1–3 months after the onset of the dry season. Results of the simulations show that if the release is continuous and starts when the alluvial aquifer is full, discharge rates of 50 L s⁻¹, and of 70 L s⁻¹ are required to meet sufficient water to maintain continuous water flow in the river to 19 km from the water source and irrigation of 19 km downstream. Discharge rates in the range 0–280 L s⁻¹ have been simulated for release starting when the aquifer is 75% full to evaluate the duration of release necessary to recharge the alluvial aquifer as far as 19 km downstream (Table 3). For the scenario "Present/75 ha", a continuous 80 L s⁻¹ discharge during 120 days is necessary to recharge 19 km of alluvial aquifer downstream. Simulations show that the higher the discharge rate, the lower the transit losses and the faster the water level rise (Fig. 7).

Discharge rates higher than 130 L s⁻¹ lead to flooding of parts of upstream fields, which is not allowed by landowners. Hence, simulations for 2007–2037 have been limited to the 0–130 L s⁻¹ range for the discharge.

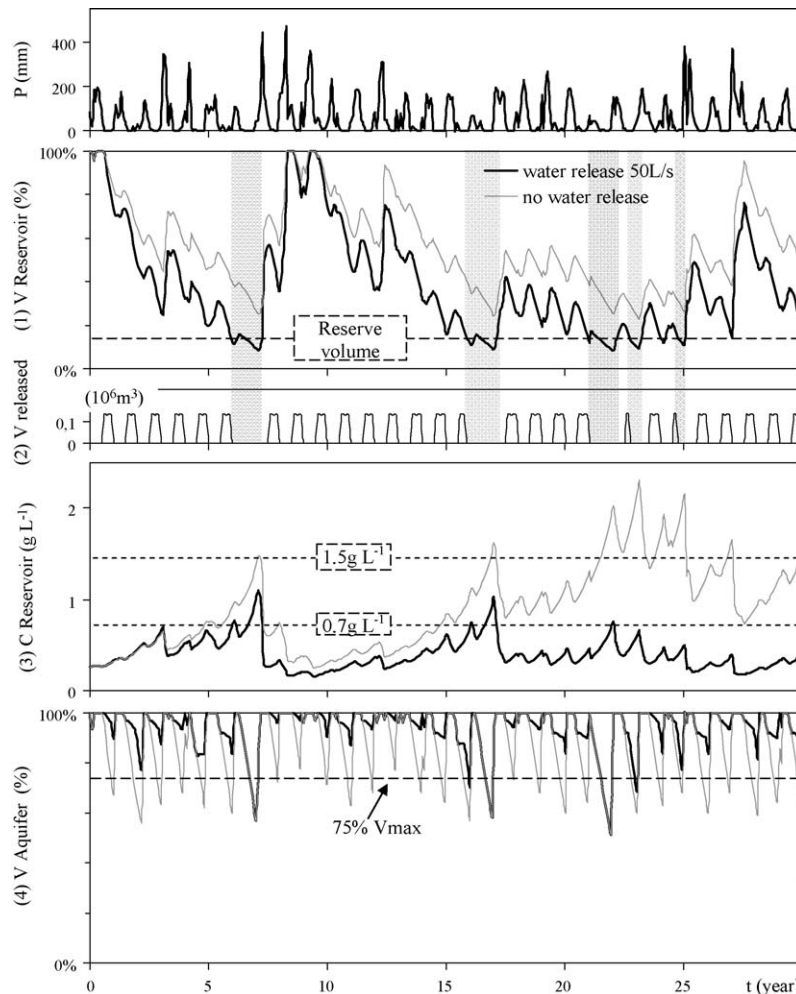


Fig. 8. Scenario "75 ha". Precipitations (30 years series) and results from 2 simulations (in black, with release of 50 L s⁻¹ during 5 months; in grey, without release) (1) R. Verde (RV) volume of water (%); (2) released volumes (10^6 m^3) from RV; (3) RV salt concentration (g L^{-1}) and (4) volume of water in the alluvial aquifer (%). Horizontal dotted lines and outlined grey areas indicate critical values and periods.

4.4.1. Scenario “Present/75 ha” (Fig. 8)

During the 1989–1998 period, the populations of the “Reservoir” territory did not allow releases from reservoirs in order to guarantee the availability of “their” water resource. With the hypothesis of “no release”, simulations for 2007–2037 (Fig. 8) show that the reservoir volume always remains higher than the critical volume. They also show that salinity reaches the threshold of 0.7 g L^{-1} in 6 out of 10 years for drinking water and irrigation and the threshold of 1.5 g L^{-1} in 1 out of 6 years for domestic water. During over-year drought, the recharge to the R. Verde reservoir is insufficient during several consecutive years, leading to high value of water salinity. In this 30-year time series simulation, the quality of water remains poor for human consumption half of the time. The threshold of 1.5 g L^{-1} is exceeded during two long periods (23 and 15 months) during which water supply to the R. Verde communities would require tank truck supply at an annual cost of 3000 US\$. Water volume and salinity of the smaller reservoirs (R. Algodão and Jardim) never exceed the limits for domestic uses because they have a higher renewal rate.

The alluvial aquifer has a seasonal dynamic and is entirely recharged in 9 out of 10 years. Nevertheless, without releases, water level decreases in 9 out of 10 years by more than 25%, leading farmers to adapt to the situation by decreasing the irrigated area at the end of the dry season. Moreover, water access to the alluvial aquifer is difficult for families in “Aquifer” and “Disperse Habitat” territories and for cattle. However, the domestic water supply

system is secure. In 1 out of 30 years, the water level decreases more than 50%. Consequently, irrigation stops and domestic uses are strongly limited. In contrast to the “Reservoir” territory, restrictions on supply are temporary (less than 3 consecutive months), so that there would be a limited duration for tank truck water supply by the State.

In the case of a management with releases from the R. Verde reservoir, two simulations have been made (Fig. 8), with discharge hypotheses of 50 L s^{-1} during 5 months in the dry season, and of 130 L s^{-1} during one month when the alluvial groundwater level drops below 4.8 m below soil surface. There is no release if the volume of the R. Verde reservoir is lower than the critical level (15%).

With both discharge hypotheses, the volume of R. Verde drops below critical volume in 1 out of 3 years and 15% of the time. Salinity is lower than 0.7 g L^{-1} , 95% and 91% of the time for the 50 and 130 L s^{-1} hypotheses, respectively. The reservoir volume is insufficient to release water in 1 out of 10 years. The longest continuous period with an R. Verde volume below 15% is 11 consecutive months. Domestic water supply through tank trucks, leads to annual costs of 3.5×10^3 US\$. For both discharge hypotheses, in 8 out of 10 years, the aquifer water resource is sufficient to satisfy domestic and agricultural requirements and is easily accessible, without pumping, for cattle and families of the “Disperse Habitat” territory. In 1 out of 10 years, quantitative restrictions appear for irrigation but not for domestic water supply.

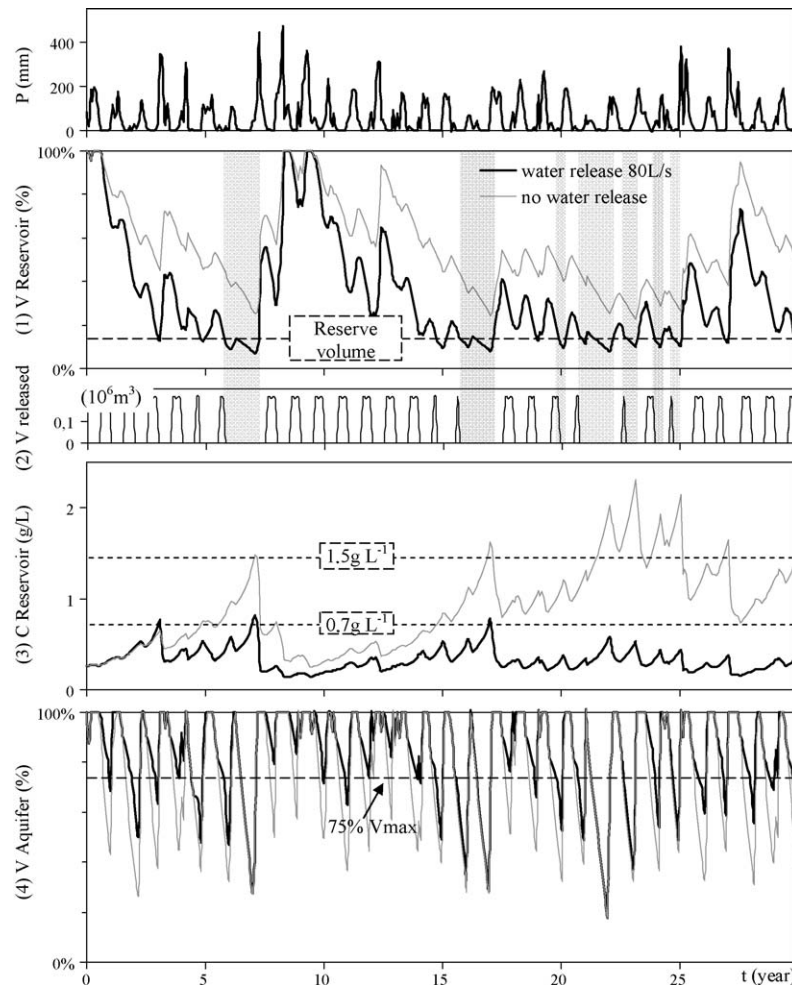


Fig. 9. Scenario “150 ha”. Precipitations (30 years series) and results from 2 simulations (in black, with release of 80 L s^{-1} during 5 months; in grey, without release) (1) R. Verde (RV) volume of water (%); (2) released volumes (10^6 m^3) from RV; (3) RV salt concentration (g L^{-1}) and (4) volume of water in the alluvial aquifer (%). Horizontal dotted lines and outlined grey areas indicate critical values and periods.

In the case of severe over-year drought (once in 30 years), release from R. Verde is not possible because the water level is too low; consequently, the alluvial aquifer water volume decreases to less than 50%.

Seasonal release with 50 or 130 L s⁻¹ discharge rates for 5 months or 2 months, respectively, strongly improves the guarantee of water availability for irrigated areas of the territory “Aquifer” and maintains a low water salinity of R. Verde. However, the critical volume of the R. Verde reservoir is reached in one of three years, which can cause supply interruption to the reservoir communities.

4.4.2. Scenario “no irrigation/0 ha”

The main result from this simulation is that the seasonal decrease of alluvial aquifer volume is only 10–20%, guaranteeing all uses in the “Aquifer” territory, even without release.

However, discharge from R. Verde is necessary to maintain low salinity in this water body. With 30 L s⁻¹ seasonal discharge during 5 months, simulation shows that there is no seasonal reduction of the alluvial aquifer volume 99% of the time, which is particularly favourable for traditional agricultural uses (breeding, forage crops on the river banks) and domestic uses by the poorest populations (direct access to the aquifer in the riverbed). Resource availability (reservoirs or aquifer) for domestic supply is guaranteed 100% of the time for the aquifer and 98% of the time for the R. Verde reservoir.

4.4.3. Scenario “irrigation doubled/150 ha” (Fig. 9)

If the irrigated area is 150 ha and if there is no release from the R. Verde reservoir, the alluvial aquifer level decreases to less than 50% of the maximum value 9 out of 10 years (Fig. 9). As a consequence, farmers would have to stop pumping for agricultural uses, and restrictions would strongly affect domestic uses in the territory “Aquifer”. Thus, according to the simulations, this scenario should be rejected.

In case of a management with release from R. Verde, only discharge rates higher than 80 L s⁻¹ during 5 months will recharge the alluvial aquifer 19 km downstream, where the main irrigation area is located. With this mode of management, the R. Verde reservoir volume decreases below 15% in 1 out of 2 years and 25% of the months. Water salinity stays below 0.7 g L⁻¹ 99% of the time. The reservoir volume is insufficient to release enough water to recharge the aquifer in 2 of 10 years. The longest continuous period with an R. Verde volume below 15% is 17 consecutive months. Domestic water supply through tank trucks in this situation leads to annual costs of 17.5 × 10³ US\$. Aquifer volume drops below 50% once in five years, restricting irrigation. Water access for the population of the “Disperse Habitat” territory and for cattle is very

difficult. The aquifer volume drops below 75% in two out of three years, requiring domestic water supply to “Aquifer” territory population through tank trucks at an annual cost of 12 × 10³ US\$.

5. Conclusions

Characterization of the physical environment was carried out in parallel to a study of uses and resource users in the Forquilha catchment. This approach allowed the design of relevant management scenarios for water resources exploitation and the construction of simple hydrological models to simulate the impacts of those scenarios.

From the experience gained with the Forquilha watershed, the use of available formulas for small catchments of the semi-arid Northeast (Cadier, 1993) seems sufficient to characterize surface water resources within the framework of our modelling strategy. The minimum hydrological data necessary to our approach have to be provided; the monitoring of water level and salinity of main water resources during one year is necessary to characterize the dynamics (quality and quantity) of the alluvial aquifer and of reservoirs and to allow calibration of “Reservoir” and “Aquifer” models. One release event resulting in full alluvial aquifer recharge must also be monitored to calibrate the routing model.

The main result from the simulations is that seasonal releases from a large upstream reservoir (of a capacity of 6.7 × 10⁶ m³) are effective in maintaining reservoir salinity at a level compatible with a domestic water supply. Depending on discharge rates from the upstream reservoir and on scenarios, it is possible to recharge the alluvial aquifer downstream. Releases from small reservoirs (<1 × 10⁶ m³) would not have any significant impact on alluvial aquifer recharge far downstream from the reservoir.

The other main result concerns the computed results on the water resources availability as a function of the scenario of “irrigation”.

For the “No irrigation” scenario, resource availability for domestic uses and cattle is maximum: 100% of the time for the “Aquifer” and “Disperse Habitat” territories and 98–100% of the time for the “Reservoir” territory (Table 5).

With the simulations of “Present/75 ha” scenario, current management practice effects are evaluated. In case of released discharge of 50 L s⁻¹ during the dry season, water availability for domestic uses is guaranteed 99% of the time for the territory “Aquifer” and 90–100% of the time for the “Reservoir” territory. For irrigation, water supply is guaranteed in 8 out of 10 years. Without release, irrigation in the territory “Aquifer” would be guaranteed only in 1 of 10 years: during the dry season, restrictions on irrigation would be imposed in 9 out of 10 years. This result emphasizes that the present situation with 75 ha irrigated cannot

Table 5

Results from simulations for 30 years (population increasing from 3900 to 5600 persons).

Conditions of simulations:	Results of simulations (in bold when highly beneath desired):				
Surface of irrigated fields	Mean annual cost for tank trucks (US\$)	% time of satisfaction for domestic needs (% yrs)	% time of satisfaction of the irrigation needs (% yrs)	% time with volume of Verde > 15% of its capacity (% yrs)	% time with salinity of R. Verde < 0.7 g L ⁻¹ (% months)
Irrigated fields: 0 ha					
0 L s ⁻¹		88%	–	100%	40%
30 L s ⁻¹ during 5 months		98%	–	100%	86%
Irrigated fields: 75 ha					
0 L s ⁻¹	3000	40%	10%	100%	40%
50 L s ⁻¹ during 5 months	3500	70%	90%	70%	95%
130 L s ⁻¹ during 2 months	3500	70%	90%	70%	95%
Irrigated fields: 150 ha					
0 L s ⁻¹	0	10%	10%	100%	40%
80 L s ⁻¹ during 5 months	17500	30%	30%	50%	99%

be sustainable without negotiations on the discharge issue among the different communities and users.

Results from the simulation with the scenario “Irrigation doubled/150 ha” show that such irrigation growth is incompatible with priority uses, especially domestic uses. The consequence is that free extension of irrigated crops, as is currently observed and even encouraged by authorities, is unsustainable. To avoid future conflicts, irrigation extension should be restricted through negotiations between communities and irrigating farmers.

A participatory water management, integrating main related water resources, would be hydrologically effective and socially desirable; communities of both “Reservoir” and “Aquifer” territories would benefit from it. To identify the best release strategy would allow maximization of resources availability for users, taking into account evaporated volumes from R. Verde, the need to recharge the alluvial aquifer, and the maintenance of good reservoir water quality and the guarantee of water quantity in R. Verde. However, this approach may result in a high social cost of conciliation work to guarantee acceptance by all categories of users.

The results from the different scenarios presented in this paper, showing clearly the risks if no coordination is put in place, are a basis for promoting discussions that include the different stakeholders. The forms to be adopted for such coordination, the installation of an official catchment committee, informal negotiations, and political mediation, will have to be defined with cooperation of the different stakeholders, but its necessity is clear.

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References

- Araujo, J.C.d., Molinas, P.A., Lamartine Leão Joca, E., Pacheco Barbosa, C., Souza Bemfeito, C.J.d., Carmo Belo, P.s.d., 2005. Custo de Disponibilização e Distribuição da Água por Diversas Fontes no Ceará. *Revista Econômica do Nordeste* 36, 281–307.
- Burte, J., 2008. les petits aquifères alluviaux dans les zones cristallines semi-arides: fonctionnement et stratégies de gestion. Etude de cas dans le nordeste brésilien. Université Montpellier II et Universidade Federal do Ceará, Montpellier (France) and Fortaleza (Brasil), pp. 193.
- Burte, J., Coudrain, A., Frischkorn, H., Chaffaut, I., Kosuth, P., 2005. Human impacts on components of hydrological balance in an alluvial aquifer in the semiarid Northeast, Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 50, 95–110.
- Cadier, E., 1993. Hydrologie des petits bassins du Nordeste brésilien semi-aride. Transposition à des bassins non étudiés. PhD Thesis. Université Montpellier 2, pp. 404.
- Cadier, E., 1996. Hydrologie des petits bassins du Nordeste Brésilien semi-aride: typologie des bassins et transposition écoulements annuels Small watershed hydrology in semi-arid north-eastern Brazil: basin typology and transposition of annual runoff data. *Journal of Hydrology* 182, 117–141.
- Cadier, E., Molle, F., Albuquerque, C.H.C.d., Doherty, F.R., Montgaillard, M., 1992. Dimensionnement de petits barrages dans le Nordeste brésilien semi-aride. In: ORSTOM (Ed.), pp. 28.
- Christensen, J.H., Hewitson, B., Busuico, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., T. M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University, Cambridge, United Kingdom and New York, NY, USA, p. 94.
- Coudrain, A., Talbi, A., Ledoux, E., Loubet, M., Vacher, J., Ramirez, E., 2001. Subsurface transfer of chloride after a lake retreat in the central Andes. *Ground Water* 39, 751–759.
- Dubreuil, P., 1966. L'étude pluvio-hydrologique du bassin de Jaguaribe. *Terres et eaux* 19, 11.
- Dubreuil, P., Girard, G., Herbaud, J., 1968. Monographie hydrologique du bassin du Jaguaribe (Ceara-Brésil). ORSTOM, pp. 397.
- Fabre, N., Burte, J., 2007. In: UFRGS (Eds.), *Efeitos da interação entre políticas públicas e dinâmicas locais sobre a agricultura familiar: Estudo de caso da bacia do Riacho Forquilha – Quixeramobim/CEARÁ. Agricultura familiar: Interação entre políticas públicas e dinâmicas locais, Rio Grande do Sul*, pp. 221–248.
- IBGE, 2004. *Uso da terra no Brasil Indicadores de desenvolvimento sustentável*. Brasília, pp. 42.
- IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 996.
- Jakeman, A.J., Letcher, R.A., 2003. Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling & Software* 18, 491–501.
- Krol, M.S., Bronstert, A., 2007. Regional integrated modelling of climate change impacts on natural resources and resource usage in semi-arid Northeast Brazil. *Environmental Modelling & Software* 22, 259–268.
- Liu, Y., Guo, H.C., Zhang, Z.X., Wang, L.J., Dai, Y.L., Y.Y., F., 2007. An optimization method based on scenario analysis for watershed management under uncertainty. *Environmental Management* 39, 678–690.
- Mainuddin, M., Kirby, M., Qureshi, M.E., 2007. Integrated hydrologic-economic modelling for analyzing water acquisition strategies in the Murray River Basin. *Agricultural Water Management* 93, 123–135.
- Mermet, L., 2005. *Etudier des écologies futures: un chantier ouvert pour les recherches prospectives environnementales*. PIE Peter Lang, Bruxelles.
- Molle, F., 1994. *Politique de l'eau, irrigation et société - le cas du Nordeste brésilien*. Les cahiers de la Recherche Développement 37, 18–32.
- Molle, F., Cadier, E., 1992. *Manual do pequeno açude*, pp. 528.
- Ribeyre, D., 2006. La vallée du Forquilha: multi-usages et stratégies de gestion de l'eau dans le Nordeste semi-aride (Ceara - Brésil). CNEARC (Montpellier-France), pp. 145.
- Salazar, L.F., Nobre, C.A., Oyama, M.D., 2007. Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters* 34, L09708.
- Srdjevic, B., Medeiros, Y.D.P., Faria, A.S., 2004. An objective multi-criteria evaluation of water management scenarios. *Water Resources Management* 18, 35–54.
- SRH, 1992. *Política Estadual de Recursos Hídricos*. Secretaria de Recursos Hídricos - Governo do Estado do Ceara, pp. 1–18.
- Tonneau, J.-P., Caron, P., 2006. *Sécheresse et développement territorial. Colloque eau et territoires*, Lyon, pp. 1–9.
- Treyer, S., 2005. L'adaptation sur le long terme à la limitation des ressources en eau. Une prospective par scénarios pour la région de Sfax, en Tunisie. *Etudier des écologies futures. Un chantier ouvert pour les recherches prospectives environnementales*. Bruxelles 325–341.
- WASY, 2005. *Feflow - Finite element Subsurface Flow & Transport Simulation System*. Berlin. www.wasy.de.