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The impact of upstream water abstractions on reservoir yield: the case of the Orós Reservoir in Brazil

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Abstract Water abstraction for irrigation upstream of a reservoir and its impact on reservoir yield and reliability are studied. Water demand and availability are strongly related in semi-arid environments where the irrigation sector is responsible for a large part of consumptive water use. Variations in water abstractions for irrigation depend on irrigation requirements per hectare and the size of the irrigated area. The Orós Reservoir in semi-arid Northeast Brazil has been taken as a case study. The results show that water abstract-tion for irrigation is of significant importance for reservoir yield and reliability. Yield–reliability simulations for the study area show that taking into account upstream water abstraction for a reservoir yield of 20.0 m^3/s results in a water-scarcity probability of 10% on an annual basis (90% reliability). This is only 5% if upstream abstraction for irrigation is ignored. This study shows that observed land-use changes in the study area do have a significant impact on reservoir yield reliability. The variability of upstream water abstraction was found to be of low importance for reservoir yield and reliability.

Key words reservoir yield; reliability; water availability; irrigation; semi-arid; Orós; Brazil

Impact de prélèvements d'eau en amont sur le rendement d'un réservoir: cas du réservoir d'Orós au Brésil

Résumé Le prélèvement d'eau pour l'irrigation à l'amont d'un barrage réservoir et son impact sur le rendement et la confiance associée sont étudiés. La demande et la disponibilité en eau sont fortement corrélées en contextes semi-arides où l'irrigation représente une grande part de la consommation en eau. Les variations dans les prélèvements d'eau pour l'irrigation dépendent des besoins en irrigation par hectare et de la taille de la zone irriguée. Le réservoir d'Orós a été choisi comme cas d'étude dans le nord-est semi-aride du Brésil. Les résultats montrent que le prélèvement d'eau pour l'irrigation est d'une importance significative vis-à-vis du rendement et de la confiance du réservoir. Des simulations de la relation rendement–confiance pour la zone d'étude montrent que la prise en compte du prélèvement d'eau en amont, pour un rendement de 20.0 m^3/s, conduit à une probabilité de pénurie de 10% sur une base annuelle (confiance de 90%). Elle tombe à 5% si le prélèvement d'eau en amont est ignoré. Cette étude montre que les changements d'occupation du sol observés dans la zone d'étude ont un impact significatif sur la confiance associée au rendement du réservoir. La variabilité du prélèvement d'eau en amont apparaît être de faible importance vis à vis du rendement et de la confiance.

Mots clefs rendement de réservoir; confiance; disponibilité en eau; irrigation; semi-aride; Orós; Brésil

INTRODUCTION

Decreases in rainfall reduce inflow into surface water bodies, while at the same time they increase the requirement for irrigation water. Periods with low flows are generally also those with the highest irrigation water requirement. This could result in even lower inflows into reservoirs when these are located downstream of irrigation water abstraction sites. Upstream rainfall variability and flow abstraction for irrigation are key parameters in understanding low flows in rivers (Smakhtin, 2001; Smakhtin *et al.*, 2006). Several studies address the impact of land use on low flows. Eheart & Tornil (1999) show the effect of water abstraction for irrigation in response to changes in rainfall on the occurrence of low flow in streams in Illinois and other states in the midwest USA. They take into account both groundwater and river water abstraction. Wilk & Hughes (2002) studied a catchment in south India. They observed an increase in runoff as a result of land-use changes from indigenous forest and savannah to agriculture. This resulted in increased reservoir inflow and reservoir yield. They concluded that likely changes will have a negligible impact on reservoir yield alone. Simulation results for a river basin in south central Ethiopia (Legesse *et al.*,

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2003) show an 8% decrease in discharge after converting cultivated/grazing land into woodland. Studies such as Wilk & Hughes (2002) and Legresse *et al.* (2003) create the impression that increasing agricultural activities will tend to increase river discharge. However, these studies did not include large-scale increases in irrigated land use, with related abstraction. Obviously, decreasing reservoir inflow may reduce reservoir yield or its associated reliability (McMahon & Mein, 1986; Vogel & Stedinger, 1987; Campos, 1996; Loucks & Van Beek, 2005).

The effects of upstream water abstraction on the inflow volume and on the variability of inflow volume in downstream reservoirs are the focus of this study, as well as the effects of changed reservoir inflow patterns on reservoir yield and reliability of yield. The study takes into account the fact that upstream water use depends on upstream water availability. It includes the effect of rainfall variability on water availability and water abstraction for irrigation, and the effect of such abstraction on reservoir inflow, yield and reliability.

According to Campos (1996), for the purpose of deriving reservoir yield, the water balance of reservoirs in a semi-arid environment is well approximated by:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = Q_{\mathrm{in}} - Q_{\mathrm{E,d}} - Q_{\mathrm{S}} - Q_{\mathrm{out}} \qquad (1)$$

where V is the water storage volume in the reservoir; t represents time (with steps of one year); Q_{in} the inflow from the river network into the reservoir; $Q_{\mathrm{E,d}}$ the water loss due to evaporation in the dry season; Q_{S} the reservoir outflow over the spillway; and Q_{out} the regulated outflow from the reservoir in the dry season (all variables are in m^3/year). According to Campos (1996), water input by rainfall directly on the reservoir surface, together with groundwater discharge to the reservoir, are roughly compensated for by wet season evaporation and loss due to seepage, and can therefore be neglected for deriving reservoir yield in semi-arid environments such as the Jaguaribe basin. In this study, Q_{in} depends on the amount of water abstracted for irrigation. The impact of current upstream irrigation-water abstraction is compared to that of decreasing reservoir capacity, increasing irrigation efficiency and increasing irrigation area.

STUDY AREA

The Jaguaribe basin is located within the institutional borders of the State of Ceará in semi-arid Northeast Brazil (Fig. 1). The basin covers approximately 74 000 km^2. Annual precipitation ranges from 400 to 2000 mm, most of which falls in the period January–June. Temporal rainfall variability is highly significant on a suite of scales: inter-annual variability, seasonal variability and variability at the time scale of a week (Uvo *et al.*, 1998; Enfield *et al.*, 1999; Smith & Sardeshmukh, 2000; Gaiser *et al.*, 2003). Seventy-five percent of the basin's reservoir capacity is provided by three public service reservoirs, which have transformed about 470 km of the rivers in the middle and lower part of the basin into perennial waterways. One of these reservoirs is the Orós Reservoir, subject of this study, which was constructed in 1961 and has a capacity of $1.940 \times 10^6\ \mathrm{m}^3$.

Irrigation is intensively practiced (~26 000 ha in the Jaguaribe basin) and discussed in Ceará because of its high pressure on water reserves in strategic reservoirs (COGERH, 2001, 2003; Johnsson & Kemper, 2005). Still, many additional irrigation projects are planned. So far, little research has been done on the impact of upstream abstraction for irrigation on the water availability in downstream reservoirs.

Within the study area, there are three different irrigation zones (Fig. 1), each having a different sort of rainfall dependency: in the river zone, water is pumped from the river or from the alluvial aquifer; in the natural lakes zone, irrigated area is limited by water availability and by inundation, both dependent on local rainfall; in the flood-plain zone, irrigated area depends on inundation of the reservoir bed and plains alongside the reservoir. Inundation may limit irrigation in the direct surroundings of that reservoir.

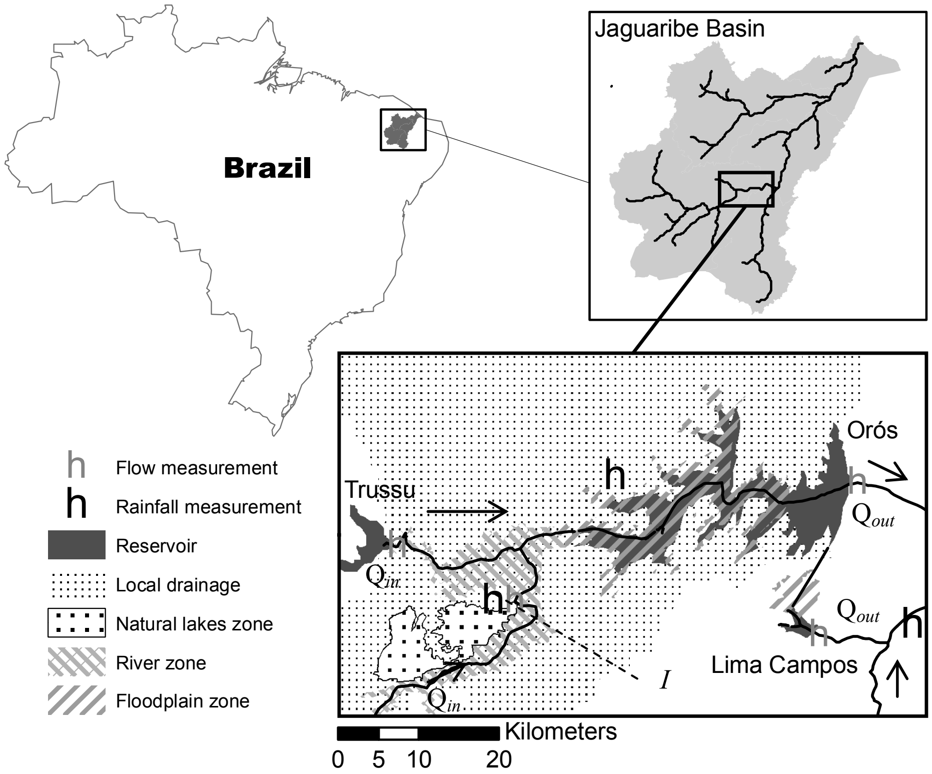

Fig. 1 Study area: the Jaguaribe basin and the direct surroundings of the Orós Reservoir, indicating irrigation zones, reservoirs, local drainage and locations of measurement stations.

METHOD

The research method consists of three steps:

1. The relationship between rainfall and water abstraction for irrigation was explored, using an empirical data set for the period 2000–2005, yielding parameterizations of irrigation area and water use.
2. The results of the first step were validated by establishing a water balance of the Orós Reservoir for the same period.
3. Reservoir yield was assessed at various reliability levels, under the influence of changing irrigation-water abstraction. This was done by running simulations using a synthetic 10 000-year series (Loucks & Van Beek, 2005) based on rainfall and discharge data.

Two assumptions were made for irrigation-water abstraction:

(a) The amount of abstracted water per hectare is rainfall-dependent.
(b) The size of irrigated area in the vicinity of natural lakes and reservoirs is influenced by land availability, which depends on water levels in these water bodies.

Step 1: Establishment of the relationship between rainfall and water abstraction

Variations in water abstraction for irrigation are based on the following relationships, established using empirical data for the period 2000–2005:

Relationship between rainfall and irrigation Irrigation requirements for every season (total of 12) were determined using the CropWat model (FAO, 1998), based on the Penman-Monteith equation. The model takes into account area-specific climatic parameters, including daily rainfall data from measurement stations, indicated in Fig. 2. The model output includes irrigation requirements per crop. Linear regression of the results yields relationships between rainfall and irrigation

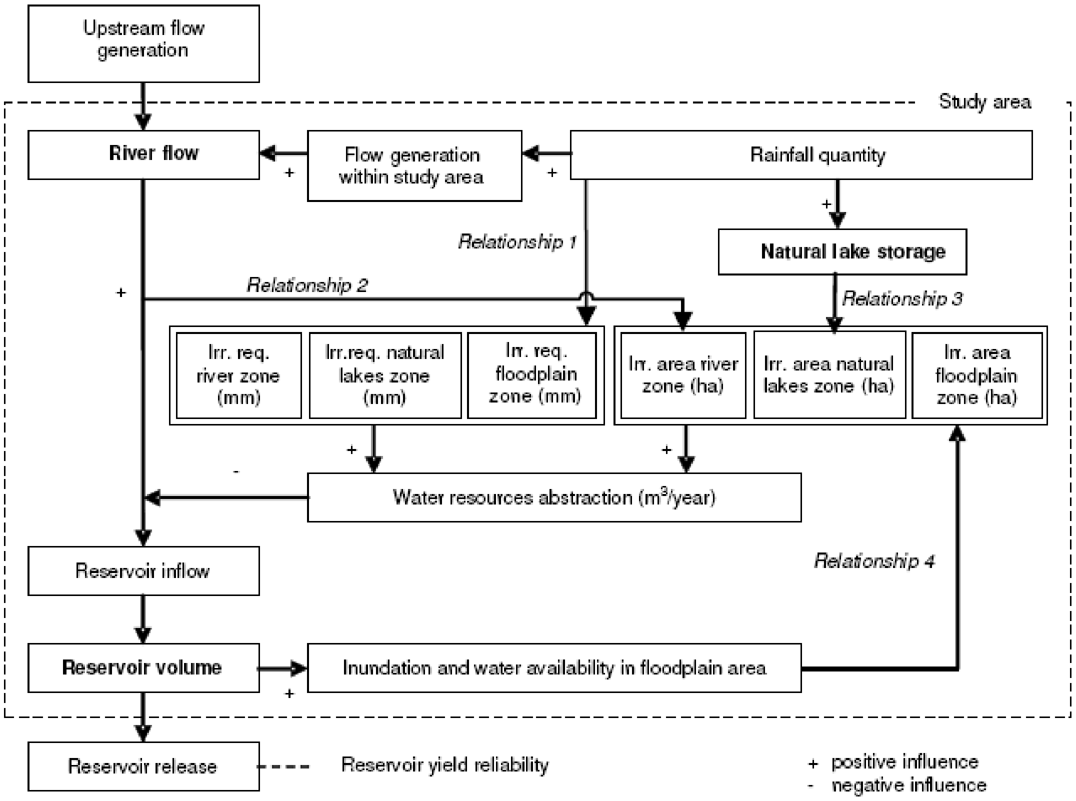

Fig. 2 The relationship between rainfall, irrigation requirement (Irr. req.), reservoir inflow and reservoir yield for the study area.

requirement, to be used for simulation, using a time step of one season (6 months). The irrigation water requirements were taken as estimates for water abstraction. Rice and banana are the most relevant and most water-consuming irrigated crops in the area. No other crop was taken into account.

Relationship between rainfall/river flow and irrigated area in the river zone The irrigated area in the river zone was tested to see whether it was dependent on local rainfall and river flow.

Relationship between local rainfall, inundation and irrigated area in three neighbouring natural lakes, supplied with local rainfall and runoff The irrigated area in the natural lakes zone was tested to see whether it was dependent on local rainfall.

Relationship between reservoir volume and irrigated area in the flood-plain zone The surface area of the reservoir is dependent on the amount of rainfall upstream. The time scale for this dependency is inter-annual rather than intra-annual. The relationship between reservoir volume (instead of rainfall) and irrigated area is therefore explored. The following data were used:

- Rainfall data for three rainfall stations (FUNCEME, 2006) (Fig. 1).
- Land use based on yearly agricultural production data for the period 1990–2005 (IBGE, 2006); seasonal agricultural production data for the period 2003–2005 from the Iguatu Office of the Agricultural Institute for the State of Ceará, EMATERCE; and land-use classifications using remotely sensed imagery for the dry season: Landsat TM, (path–row) 217–64 (25 October 2000, 13 November 2001, 31 October 2002); CB2CCD (path–row) 150–107 (22 November 2003, 29 September 2004, 24 October 2005); and CB2CCD (path–row) 151–107 (19 November 2003, 26 September 2004, 21 October 2005).
- A volume–surface relationship of the Orós Reservoir (COGERH, 2006).

Step 2: Establishment of the water balance of the Orós Reservoir

The explored relationships are implemented in our simulation approach to calculate the season-by-season development of the volume of the Orós Reservoir, using a 6-month time step. A water balance of the area around the Orós Reservoir (Fig. 1) was made for the period 2000–2005. To determine this water balance, the following data were used in addition to the data used for Step 1: reservoir releases and river flow based on data for three reservoirs: Orós, Lima Campos and Trussu (COGERH, 2006), and flow data at Iguatu (ANA, 2006).

Equation (1), after the method of Campos (1996), separates reservoir water balance parameters for the dry and the wet season. Introducing water abstraction in this method, the separation is made more explicit, by splitting equation (1) into two equations, one for the wet season (2) and one for the dry season (3):

$$V_{(t)\mathrm{wet}} = V_{(t-1)\mathrm{dry}} + Q_{\mathrm{in}} - Q_{\mathrm{UseWet}(t)} - Q_{\mathrm{UseDry}(t-1)} - Q_{\mathrm{S}} \tag{2}$$

$$V_{(t)\mathrm{dry}} = V_{(t)\mathrm{wet}} - Q_{\mathrm{E,d}} - Q_{\mathrm{out}} \tag{3}$$

where V_t (m^3) represents volume in the end of the season in year t; $V_{t(\mathrm{wet})}$ and $V_{t(\mathrm{dry})}$ for the wet season and the dry season, respectively; Q_{in} (m^3) is inflow before abstraction in the study area; $Q_{\mathrm{UseWet}(t)}$ (m^3) is water abstraction for irrigation during the wet season; $Q_{\mathrm{UseDry}(t\text{-}1)}$ (m^3) is water abstraction for irrigation during the previous dry season (since irrigation during the dry season is established largely by pumping water from the alluvial aquifer, reservoir inflow in the following wet season is reduced because of recharging by river water); Q_{S} (m^3) is the reservoir outflow over the spillway; $Q_{\mathrm{E,d}}$ (m^3) is the dry season evaporation from the reservoir; and Q_{out} (m^3) is the regulated water withdrawal.

The parameter Q_{in} is based on daily data from flow measurement at two inflow points, while Q_{out} is based on daily reservoir release data from measurements at the two dams in the east of the study area. Both Q_{out} and Q_{in} are converted into seasonal values. The parameters Q_{UseDry} and Q_{UseWet} are based on the land-use data and irrigation requirements as described in Step 1.

Step 3: Simulation of the relationship between upstream water abstraction and downstream reservoir yield and reliability

Equations (2) and (3) are used for stochastic simulation, applying a 10 000-year synthetic series of annual rainfall and discharge. This synthetic series is based on statistical characteristics of rainfall data for the period 1974–2005 (FUNCEME, 2006) and discharge data for the period 1982–2005 (ANA, 2006). It reproduces historical mean and the coefficient of variation, cross-correlations and autocorrelations of both annual rainfall and inflow, using a multivariate model with a lag of one year, as described in Loucks & Van Beek (2005).

To determine Q_{UseWet} and Q_{UseDry} in each time step, the established empirical relationships from Step 1 are used. If Q_{out} is less than the target water yield, the year is considered unsuccessful. The reliability level G for that target yield is given by $G = 1 - (N_{\mathrm{U}}/N)$ where N_{U} is the number of unsuccessful years and N is the total number of years in the simulation. The result is compared to the result of applying equation (1). In this way the impact of varying and changing water abstraction on reservoir yield-reliability is assessed.

Finally the effect of water abstraction is compared to the impact of decreasing reservoir capacity due to sedimentation.

RESULTS

The dependency of net irrigation requirement on seasonal rainfall rates can be approximated by a linear relationship (Fig. 3). Net irrigation requirement in the wet season varied roughly between 100 and 400 mm for rice and between 300 and 600 mm for banana. In the dry season net irrigation requirement was relatively constant, since rainfall quantities in the dry season were relatively small.

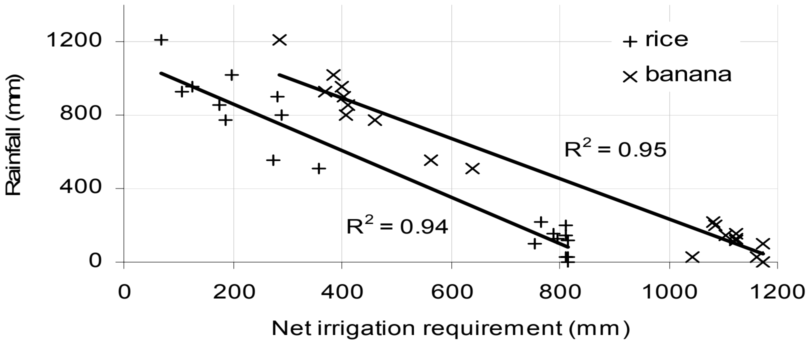

Fig. 3 Relationship between seasonal rainfall and irrigation requirement derived from CropWat calculations. Rainfall data for the period 1996–2005 were used.

Table 1 Observed and simulated variability of land-use and upstream water abstractions.

		Coefficient of variation: River zone	Natural lakes zone	Flood-plain zone	Total
Observed 2000–2005	Irrigated area	0.28	0.65	0.12	0.19
	Water abstractions	0.28	0.59	0.16	0.19
2000–2005, simulated with land-use rules	Irrigated area	0.00	0.90	0.08	0.08
	Water abstractions	0.11	0.83	0.11	0.10
Synthetic 10 000-year simulation, Q_{90}: 19.96 m^3/s	Irrigated area	0.00	0.71	0.12	0.11
	Water abstractions	0.09	0.66	0.12	0.09

Irrigated area in the river zone was found to be relatively independent of rainfall and river flow. This is because water from the alluvial aquifer is available, originating from, but hardly constrained, by river flow. Research in a nearby sub-basin in the Jaguaribe basin (Burte *et al.*, 2005) concludes that the river is the most important source for recharging the aquifer following withdrawal of water directly from the alluvial aquifer. This water is available all year round, providing a relatively stable water supply. The relatively high coefficient of variation for irrigated area (Table 1) is explained by a steadily increasing area of irrigated land for fruit production, as a result of government policy (COGERH, 2001, 2003; SEAGRI, 2004, 2005), rather than by inter-annual variability. As this trend does not represent an effect of rainfall variability, it is not considered in the determination of reservoir yield.

The extent of irrigated area in the natural lakes zone depends on local rainfall since the latter is directly responsible both for water availability and for inundation of arable land by water from natural lakes. The temporal extent of influence exceeds annual rainfall rates, since storage capacity is larger than what is consumed and evaporated each year. Therefore the rainfall quantity from the previous year is also taken into account. From the remotely sensed imagery data, one may observe that inundation forces farmers to move their irrigation activities frequently. The irrigated area generally increases with increasing rainfall amount, but decreases when high rainfall inundates a potential irrigation area. In this study, a relationship representing this observed qualitative behaviour was established (Fig. 4). This takes into account rainfall in year t and in year $t - 1$. A quadratic relationship is found to give a reasonable representation of the data for the period 2000–2005 ($R^2 = 0.73$).

The amount of irrigated area in the flood-plain zone appears to depend on the size of the area inundated by the Orós Reservoir and the accessibility of water from local streams and groundwater. Figure 5 shows the empirical data and quadratic relationship between the stored volume in the Orós Reservoir at the end of the wet season and the area cultivated with irrigated crops in the consecutive dry season. The relationship gives a fair representation of the data for the period 2000–2005 ($R^2 = 0.70$). To illustrate changes in land use, a simplified land-use classification for

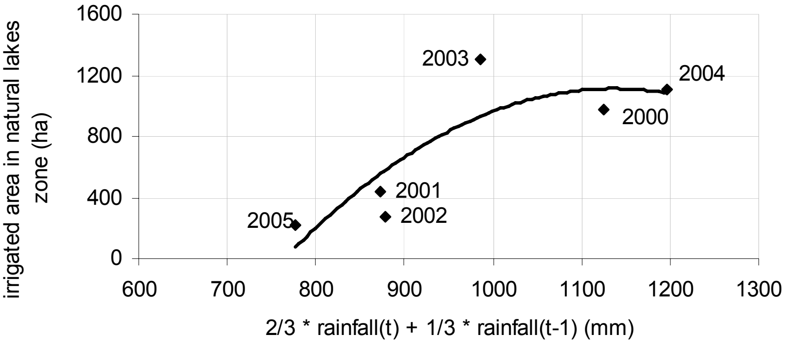

Fig. 4 Relationship between rainfall and area of irrigated crops in the natural lakes zone.

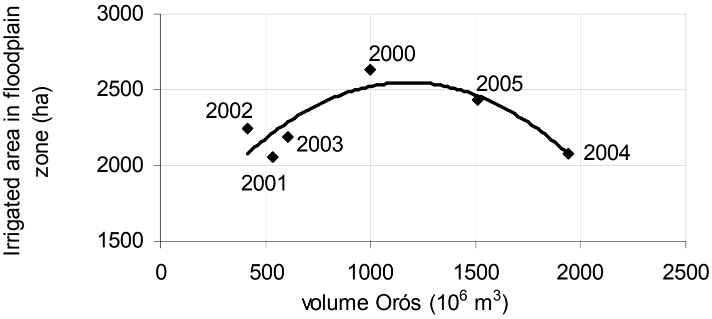

Fig. 5 Relationship between reservoir volume and irrigated land in the flood-plain zone near the Orós Reservoir.

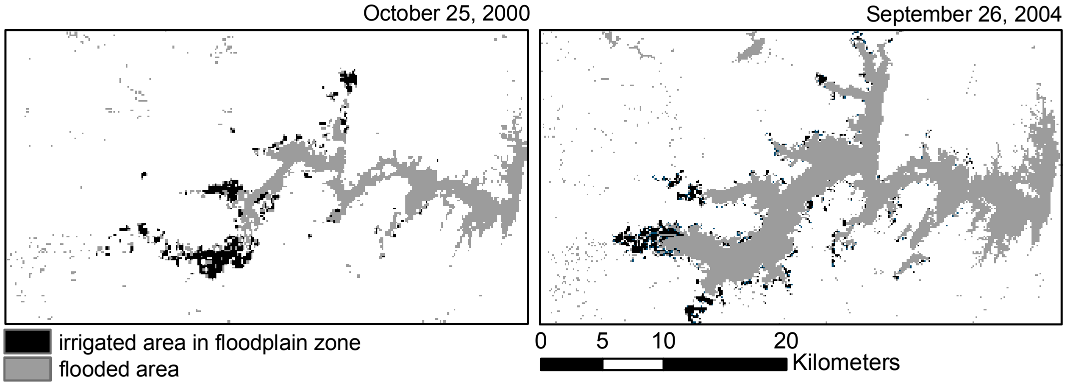

Fig. 6 Simplified land-use classification for images of 2000 and 2004 for part of the study area.

images of 2000 and 2004 is shown for part of the study area (Fig. 6), making clear that inundation shifts and limits irrigation.

Applying the empirical rules for the three zones in the water balance equation for the period 2000–2005 results in a simulated evolution of reservoir volume that approximates the observed data much better than the Campos method of not accounting for upstream water abstraction (Fig. 7). So, this new method with empirical rules is able to represent the water balance under highly variable conditions.

Applying our method for determining yield-reliability simulations shows that upstream water abstraction for irrigation results in a decrease in the reservoir yield, with a reliability level of 90% (Q_{90}), from 24.4 m^3/s (Campos method) to 20.0 m^3/s (our approach) (Fig. 8). According to the results of the Campos method, the water-scarcity probability for a 20.0 m^3/s yield, for instance, is

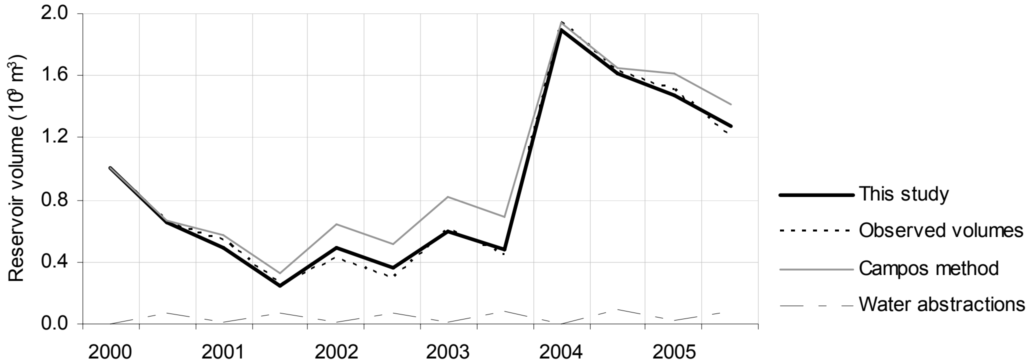

Fig. 7 Reservoir volume simulation taking into account upstream abstractions for irrigation.

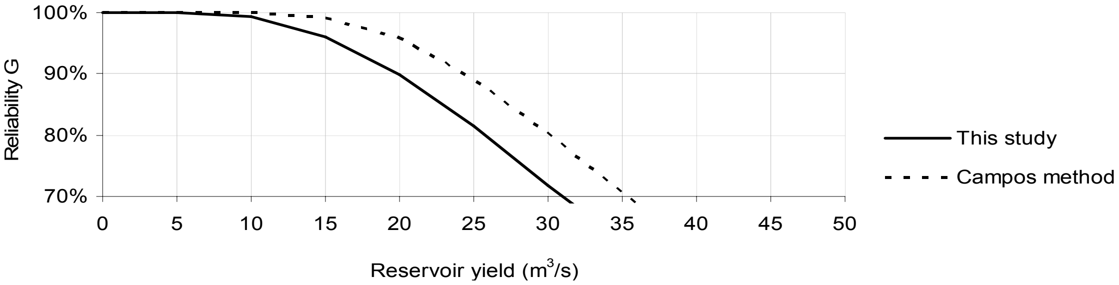

Fig. 8 Results of yield reliability simulations using the Campos method (without upstream water abstraction) and using our method (with abstraction).

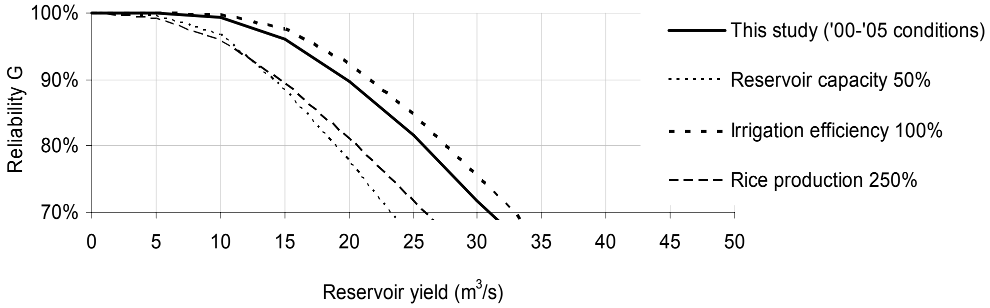

Fig. 9 Results of yield-reliability simulations with: reservoir capacity reduced by 50%; 100% irrigation efficiency; and rice area increase by a factor 2.5 (corresponding to the 1993 situation).

close to 5% every year (95% yearly reliability) whereas, according to this study, it is as high as 10%. This difference is very relevant for water allocation purposes.

The results of this study show that major impacts of variations in land use on yield reliability should not be expected. Simulations that include the established relationships for land-use variation in the different zones result in a yield that is 0.4% higher in comparison to simulations with constant land use based on the period 2000–2005.

The developed simulation method was also applied to assess the impact of possible changes on reservoir yield reliability. The current impact of upstream water abstraction for irrigation was compared to that of decreasing reservoir capacity, increasing irrigation efficiency and increasing irrigation area. In Fig. 9 the impacts of "possible" future developments are compared to the outcomes of our results based on the empirical data for the period 2000–2005. Developments considered are: an increase in irrigation efficiency to 100% due to technological improvements; an increase n irrigation area for rice production to a level that was previously reached in 1993; and a 50% reduction in reservoir capacity due to long-term sedimentation.

The results show that shifts in upstream water abstraction may seriously affect reservoir yield. When abstraction was increased to levels reached in the recent past (1993), the impact on reservoir yield was of the same order of significance as a 50% reduction in reservoir capacity due to sedimentation. However, sedimentation causes gradual changes, whereas changes in water abstraction could happen relatively fast. It would take decades for a 50% capacity reduction to develop in effect of sedimentation. For an impact assessment of sediment deposition on reservoir yield in semi-arid Brazil, see De Araújo *et al.* (2006).

DISCUSSION

Some comments on the method applied in this study are justified. Firstly, a relatively short time series of data was used to determine variations in water abstractions. Remotely sensed imagery for dry seasons in six consecutive years was used. This implies that information on the variability of irrigated area is limited to the margins of events that occurred in the period 2000–2005. With respect to recent historical data on average yearly rainfall in area upstream of the reservoir, the year 2004 was relatively wet; however, 1985 and 1989 had higher rainfall rates. Also, 2001 was relatively dry, yet 1983, 1993 and 1998 had lower rainfall rates. The effect of rainfall extremes beyond these margins is therefore uncertain. Secondly, longer series of consecutive dry or wet years that did occur historically were not represented in the empirical data set. Therefore, the effect of such series on water use could not be evaluated. Thirdly, variations in the timing of the growing season in different years has not been taken into account.

The variability of irrigated land and water abstractions for the empirical data set and the simulated series does not match perfectly (Table 1). The applied rules do not reproduce empirical variability completely, since they are based on regression relationships. Moreover, the observed variance in the river zone is explained, not so much by variability as by a trend towards more fruit production in the period 2000–2005, which, in our view, is not particularly related to rainfall variability. For the natural lakes zone, it was observed that the variability of irrigated area is higher than that of water abstraction. This is explained by the observed increase in irrigated area with the decrease in net irrigation requirement per hectare. In the flood-plain zone, water use was observed to be more variable than irrigated area. This is explained by a larger irrigated area in years of low precipitation and a smaller irrigated area in years with high precipitation for the period 2000–2005. This is largely a coincidence and is not resembled as such in the simulations using a 10 000-year synthetic time series.

Inter-annual variations in water abstraction, such as were observed for the period 2000–2005, influence downstream reservoir reliability to a limited extent. The variability of water abstraction is small in comparison to variability of inflow. Furthermore, abstraction in the natural lakes zone and the flood-plain zone generally decreases in times with low water availability. Applying our simulation approach for Q_{90} (irrigation efficiency 60% and regulated dry season release being 20 m^3/s), the coefficient of variation for yearly water abstraction is 0.09. With a fixed irrigated area (average 2000–2005), the coefficient of variation for water abstraction is 0.07. The coefficient of variation for the inflow is 1.485 when applying our simulation approach, and 1.484 in the case of a fixed irrigated area. The difference for reliability levels is accordingly negligible.

The simulations in this study show that the variation in river flow upstream of the study area is of high importance to yield reliability. The variation in river flow into the area is quite large (coefficient of variation: 1.46). In the case of all variation being fully compensated for, e.g. by upstream reservoirs, reservoir yield at Q_{90} could be increased by over 100%. However, a serious increase in flow stability would come at the cost of increasing evaporative losses and would probably also lead to an increase in upstream water abstraction.

The local rainfall variability affects irrigation requirement, but does not dramatically influence reservoir yield reliability. Most of the water for irrigation is abstracted during the dry season, when rainfall rates are too low to seriously reduce irrigation requirement per hectare.

The volume of abstracted water due to long-term changes is more important to yield reliability than rainfall-dependent variations from year to year. This volume depends on many more factors than inflow and rainfall variability alone. In the early 1990s, for example, irrigation for rice production in the study area was much higher (an additional 150% on top of the 2000–2005 level) than in the period 2000–2005. Because of changes and variations in the market, and technological improvements in the irrigation sector, shifts in water abstraction are very possible. It is hard to say what developments in water abstraction will take place in the future. However, it is possible to determine the effect of such developments on reservoir reliability. Our results show that such effects can be serious.

In our simulation method, a fixed target yield is coupled to a reliability level. In reality, a target yield neither is nor should be applied for reservoir operation in semi-arid Northeast Brazil. Water demand is variable due to rainfall variations. This makes it inefficient to apply a fixed release volume. Moreover, with the introduction of institutionalized participative water allocation management in the study area, originating from late 1993, the decision-making process for water allocation is no longer solely based on water engineering decisions (Lemos & de Oliveira, 2004; Johnsson & Kemper, 2005; Taddei, 2005). Besides individual preferences of different stakeholders participating in decision-making, actual reservoir reserves and increasingly also rainfall predictions are taken into account for decision making on reservoir releases. In reality, reservoir operation rules are far more difficult than represented in the reliability concept applied here. However, for the purpose of this study it served well.

Climate change was not taken into account in this study. According to the IPCC, climate change may substantially affect irrigation withdrawals: “Higher temperatures, hence crop evaporative demand, would mean that the general tendency would be toward an increase in irrigation demands” (IPCC, 2001, p.31). Obviously, changes in evaporation and rainfall regimes would influence reservoir yield reliability.

CONCLUSION

The reliability level of reservoir yield is sensitive to upstream abstraction for irrigation. Methods to determine reservoir yield can conveniently be adapted to account for the effect of abstraction and their variability. Yield-reliability simulations for the study area show that taking into account upstream water abstraction for a reservoir yield of 20.0 m^3/s results in a water-scarcity probability of 10% on an annual basis (90% reliability). This is only 5% if upstream abstraction for irrigation is ignored. Changes in water abstraction seriously influence reservoir yield and reliability.

The results show that inter-annual variability of upstream water abstraction as a result of rainfall-dependent variability of irrigated area and irrigation water requirement is of low importance for reservoir yield and reliability. Rather, governance with respect to irrigation programmes and construction and operation of upstream storage reservoirs has a strong impact on reservoir yield and reliability of reservoirs located downstream. This study shows that observed land-use changes in semi-arid regions can have an impact on reservoir yield reliability that is more serious than estimated long-term effects of sedimentation.

For the case studied, average upstream inflow is much greater than average water abstraction. Therefore, the influence of the variability of water abstraction on reservoir inflow is small. However, if average inflow were to decrease (e.g. as a result of increasing average water abstraction), the impact of variability of water abstraction would increase accordingly. In cases where inflow is lower, relative to abstraction, the impact of variability of water abstraction could also be higher.

In the study area as a whole, variations in irrigated area compensate for, rather than amplify, variations in irrigation water requirements. This implies that self-regulation is taking place, rather than increased scarcity. In parts of the study area, this self-regulation is not taking place. This implies that in other regions this self-regulation may not occur either.

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REFERENCES

ANA (Agência Nacional de Águas) (2006) HidroWeb, www.hidroweb.ana.gov.br,.Brazil.

Burte, J., Coudrain, A., Frischkorn, H., Chaffaut, I. & Kosuth, P. (2005) Human impacts on components of hydrological balance in an alluvial aquifer in the semi-arid Northeast, Brazil. *Hydrol. Sci. J.* **50**(1), 95–110.

Campos, J. N. B. (1996) Dimensionamento de Reservatórios. Federal University of Ceará, Fortaleza, Brazil.

COGERH (Companhia de Gestão dos Recursos Hídricos) (2001) Plano de use racional de água para irrigação nos vales do Jaguaribe e Banabuiú. Governo do estado do Ceará, Secretaria dos Recursos Hídricos Fortaleza, Brazil.

COGERH (Companhia de Gestão dos Recursos Hídricos) (2003) Relatório do plano de uso racional das águas para irrigação nos vales dos rios Jaguaribe e Banabuiú Convêncio no. 002/2001.SRH/COGERH. Governo do estado do Ceará. Secretaria dos Recursos Hídricos, Fortaleza, Brazil.

COGERH (Companhia de Gestão dos Recursos Hídricos) (2006) Monitored reservoir releases database, www.cogerh.com.br. Governo do estado do Ceará, Secretaria dos Recursos Hídricos Fortaleza, Brazil.

De Araújo, J. C., Güntner, A. & Bronstert, A. (2006) Loss of reservoir volume by sediment deposition and its impact on water availability in semi-arid Brazil. *Hydrol. Sci. J.* **51**(1), 157–170.

Eheart, J. W. & Tornil, D. W. (1999) Low-flow frequency exacerbation by irrigation withdrawals in the agricultural midwest under various climate change scenarios. *Water Resour. Res.* **35**, 2237–2246.

Enfield, D. B., Mestas, A. M., Mayer, D. A. & Cid-Serrano, L. (1999) How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures? *J. Geophys.. Res. - Oceans* **104**, 7841–7848.

FAO (1998) *CropWat 4 Windows Version 4.3* (ed. by M. Smith). FAO, Rome, Italy.

FUNCEME (Fundação Cearense de Meteorologia e Recursos Hídricos) (2006) Arquivos com dados pluviométricos, www.funceme.br. Fortaleza, Brazil.

Gaiser, T., Krol, M., Frischkorn, H. & Araújo, J. C. (eds) (2003) *Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semi-arid Northeast of Brazil.* Springer-Verlag, Berlin, Germany.

IBGE (Instituto Brasileiro de Geografia e Estatística) (2006) SIDRA - Produção Agrícola Municipal, www.sidra.ibge.gov.br. Brasilia, Brazil.

IPCC (Intergovernmental Panel on Climate Change) (2001) *Climate Change 2001, Impacts, Adaption & Vulnerability*, Contribution of Working Group II to the Third Assessment Report of the IPCC. (ed. by J .J. McCarthy, O. Canziani, N. A. Leary, D. J. Dokken & K. S. White), 31. Cambridge University Press, Cambridge, UK.

Johnsson, R. M. F. & Kemper, K. E. (2005) Institutional and policy analysis of river basin management. Report no. WPS3649. World Bank, New York, USA.

Legesse, D., Vallet-Coulomb, C. & Gasse, F. (2003) Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *J. Hydrol.* **275**, 67.

Lemos, M. C. & de Oliveira, J. L. F. (2004) Can water reform survive politics? Institutional change and river basin management in Ceará, Northeast Brazil. *World Development* **32**, 2121–2137.

Loucks, D. P. & Van Beek, E. (2005) *Water Resources Systems Planning and Management: AnIntroduction to Methods, Models and Applications.* UNESCO Publishing, Paris, France.

McMahon, T. A. & Mein, R. G. (1986) *River and Reservoir Yield.* Water Resources Publications, Littleton, Colorado, USA.

SEAGRI (Secretaria do Desenvolvimento Agrário) (2004) Projeto frutas do Ceará, www.seagri.ce.gov.br. Fortaleza, Brazil.

SEAGRI (Secretaria do Desenvolvimento Agrário) (2005) Fruticultura irrigada grande potencial do Ceará, www.seagri.ce.gov.br. Fortaleza, Brazil.

Smakhtin, V. U. (2001) Low flow hydrology: a review. *J. Hydrol.* **240**, 147–186.

Smakhtin, V. U., Shilpakar, R. L. & Hughes, D. A. (2006) Hydrology-based assessment of environmental flows: an example from Nepal. *Hydrol. Sci. J.* **51**(2), 207–222.

Smith, C. A. & Sardeshmukh, P. (2000) The effect of ENSO on the intraseasonal variance of surface temperature in winter. *Int. J. Climatol.* **20**, 1543–1557.

Taddei, R. (2005) Of clouds and streams, prophets and profits: the political semiotics of climate and water in the Brazilian northeast. Columbia University, New York, USA.

Uvo, C. B., Repelli, C. A., Zebiak, S. E. & Kushnir, Y. (1998) The relationships between tropical Pacific and Atlantic SST and Northeast Brazil monthly precipitation. *J. Climate* **11**, 551–562.

Vogel, R. M. & Stedinger, J. R. (1987) Generalized storage reliability yield relationships. *J. Hydrol.* **89**, 303–327.

Wilk, J. & Hughes, D. A. (2002) Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. *Hydrol. Sci. J.* **47**(1), 19–30.

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