Simple water balance modelling of surface reservoir systems in a large data-scarce semiarid region

ANDREAS GÜNTNER[1], MAARTEN S. KROL[2], JOSÉ CARLOS DE ARAÚJO[3] & AXEL BRONSTERT[4,5]

1 *GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany*
guentner@gfz-potsdam.de

2 *Discipline Group Water Engineering and Management, Faculty of Engineering Technology, University of Twente, PO Box 217, NL-7500 AE Enschede, Netherlands*

3 *Department of Hydraulic and Environmental Engineering, Federal University of Ceará, Campus do Pici, bl.713, 60.451-970, Fortaleza, Brazil*

4 *Institute for Geo-ecology, University of Potsdam, PO Box 601553, D-14415 Potsdam, Germany*

5 *Potsdam Institute for Climate Impact Research, PO Box 601203, D-14412 Potsdam, Germany*

Abstract Water resources in dryland areas are often provided by numerous surface reservoirs. As a basis for securing future water supply, the dynamics of reservoir systems need to be simulated for large river basins, accounting for environmental change and an increasing water demand. For the State of Ceará in semiarid Northeast Brazil, with several thousands of reservoirs, a simple deterministic water balance model is presented. Within a cascade-type approach, the reservoirs are grouped into six classes according to storage capacity, rules for flow routing between reservoirs of different size are defined, and water withdrawal and return flow due to human water use is accounted for. While large uncertainties in model applications exist, particularly in terms of reservoir operation rules, model validation against observed reservoir storage volumes shows that the approach is a reasonable simplification to assess surface water availability in large river basins. The results demonstrate the large impact of reservoir storage on downstream flow and stress the need for a coupled simulation of runoff generation, network redistribution and water use.

Key words water balance model; surface reservoir; water availability; semiarid regions; water use; Northeast Brazil

Modélisation simple du bilan hydrologique de systèmes de réservoirs de surface dans une grande région semi-aride pauvre en données

Résumé Les ressources en eau de régions sèches sont souvent fournies par de nombreux réservoirs de surface. Comme base pour garantir l'approvisionnement en eau à l'avenir, la dynamique des systèmes de réservoirs doit être simulée pour de grands bassins versants, en tenant compte des changements environnementaux et d'une demande en eau croissante. Un modèle déterministe simple du bilan hydrologique est présenté pour l'Etat de Ceará dans le Nord-Est semi-aride du Brésil, qui dispose de plusieurs milliers de réservoirs. Dans le cadre d'une approche en cascade, les réservoirs sont groupés en six classes selon leur capacité de stockage; des règles de transfert d'eau entre réservoirs de tailles différentes sont établies; et les prélèvements d'eau et les rejets dans les cours d'eau après usages anthropiques sont considérés. Malgré de grandes incertitudes dans l'application du modèle, en particulier en termes de règles de gestion des réservoirs, la validation du modèle par confrontation avec des volumes de stockage observés montre que l'approche est une simplification raisonnable pour estimer la disponibilité en eau de surface dans les grands bassins versants. Les résultats montrent l'impact important du stockage dans les réservoirs sur l'écoulement en aval et soulignent la nécessité d'une simulation couplée de la génération d'écoulement, de la redistribution en réseau et des usages de l'eau.

Mots clefs modèle de bilan hydrologique; réservoir de surface; disponibilité en eau; régions semi-aride; usage de l'eau; Nord-Est du Brésil

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INTRODUCTION

In many semiarid regions of the world, surface water provides a major source of water supply. River runoff occurring during the rainy season is stored in surface reservoirs to sustain human, agricultural and industrial water use during the dry season. Dryland areas such as Northeast Brazil are often characterized by a huge number of reservoirs ranging from large impoundments for over-year storage and water supply for agglomerations and large irrigation districts to small farm dams in rural areas for short-term local use. The reservoirs are interconnected via the river network, mutually influencing their inflow and outflow volumes.

Recognizing the scarcity of water resources in semiarid regions due to the large variability of climate and an increasing water demand by changing climatic, environmental and socioeconomic conditions (e.g. Gaiser *et al*., 2003), adapted integrated measures of water management are required to secure water availability from reservoirs in the future. In this regard, optimization models to derive adequate design and operating strategies of multi-reservoir systems are applied (for recent examples, see, e.g. Dahe & Srivastava, 2002; Loáiciga, 2002; Mousavi & Ramamurthy, 2002). To assess the long-term dynamics of the hydrological response in an environmental change context, deterministic process-based models are used which need to represent both runoff generation processes and the influence of water use, including feedback mechanisms between water availability and water consumption, for instance (Krol *et al*., 2003). The assessment usually has to cover a large geographical domain, because any impact will affect all downstream locations in a river basin (e.g. Barbier, 2003). However, particularly at large spatial scales, difficulties in the above approach arise: first, in representing adequately the climate and landscape variability and related processes of runoff generation (see Güntner & Bronstert, 2004, for an overview with focus on semiarid environments). Second, in view of the large number of reservoirs that may amount to some hundreds or thousands in a river basin, it is not feasible to describe each reservoir individually in a large-scale model. In addition, available information on reservoir characteristics such as the exact location in the river network, reservoir geometry, and operation rules, is often scarce. To the authors' knowledge, there are only few studies which report on deterministic modelling approaches for dense reservoir networks in large dryland areas. For the dry zone of Sri Lanka, Jayatilaka *et al.* (2003) recently presented a small-scale model for cascades of the order of 10 interconnected reservoirs.

The objective of this paper is to describe a simple water balance modelling scheme for representing water availability in a large number of surface reservoirs in a macroscale dryland area. To be of practical relevance, the complexity of the approach should respect the scarce data availability while retaining enough detail to capture the most important aspects of reservoir dynamics, such as interactions and varying storage behaviour as a function of size and of water use. Thus, the focus is not on an utterly exact representation of the singular reservoir behaviour, but rather on an appropriate aggregated modelling of reservoir systems at the regional scale. For the application to a large area in semiarid northeastern Brazil, the performance of the approach is discussed in terms of the prediction of storage volumes, which, contrary to river discharge, is a variable rarely considered when validating hydrological models.

STUDY AREA AND DATA

The study area is the Federal State of Ceará (148000 km^2) in the semi-arid tropical Northeast of Brazil (Fig. 1). Details on the natural and socio-economic conditions of the area are given in Gaiser *et al.* (2003). The state of Ceará has recurrently been affected by droughts which caused serious economic losses and social impacts such as migration from the rural regions (Magalhães *et al.*, 1988). Mean annual precipitation is about 850 mm, with less than 550 mm in the dry interior (Sertão) and with high inter-annual variability. Rainfall is concentrated in a rainy season of about five months (January–May). Potential evaporation is about 2100 mm. About 80% of the study area is characterized by crystalline bedrock and usually shallow soils with a xerophytic woodland as the dominant natural vegetation type. Agricultural land use is dominated by extensive cattle farming and subsistence farming of mainly beans and maize. Irrigation is applied in Ceará to an area of about 1100 km^3 which is 2.4% of the area used for agriculture and animal husbandry. Mean annual runoff ratios in the study area are in the range of 10–20% of annual rainfall. River flow is intermittent for natural conditions, but has been transformed into perennial flow in the downstream sections of large reservoirs. About 7000 reservoirs (individual storage capacity V_{max} up to 1.9×10^9 m^3) exist in the study area, with a total storage capacity of about 12.5×10^9 m^3, of which 83% is attributed to the 113 largest dams (Frischkorn *et al.*, 2003). In some regions, the water surfaces of reservoirs cover 5% of the total land area in the rainy season (Cadier, 1996). Surface water from the reservoirs provides 91% of the water supply in Ceará (Araújo *et al.*, 2004). Small reservoirs often dry out within a few months during the dry season, whereas middle-sized and large reservoirs ($V_{max} > 1.0 \times 10^7$ m^3) are usually designed to retain water at least in two consecutive drought years (Frischkorn *et al.*, 2003).

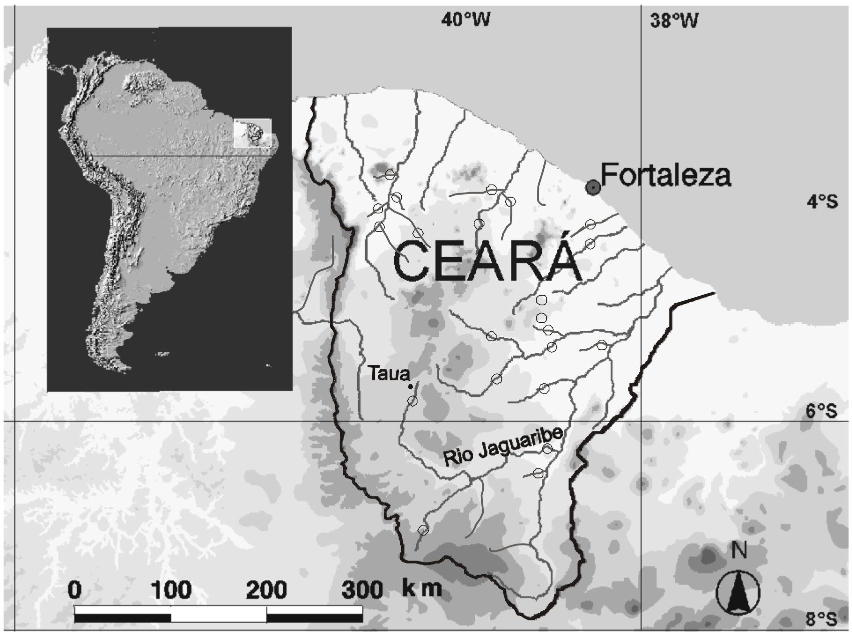

Fig. 1 Study area Ceará in Northeast Brazil, with main river network and location of large reservoirs with observed time series of storage volumes for model validation.

Table 1 Number of reservoirs in the study area of Ceará, classified by storage capacity.

Reservoir class	1	2	3	4	5	Large reservoir
Storage capacity (10^6 m^3)	<0.1	0.1–1.0	1.0–3.0	3.0–10.0	10.0–50.0	>50.0
State of Ceará (148 000 km^2)						
Number of reservoirs	2669	3518	431	130	54	36
Reservoirs with observed storage volume time series	4	2	0	0	0	22
Tauá basin (194 km^2)						
Number of reservoirs	14	6	1	0	0	0
Reservoirs with observed storage volume time series	4	2	0	0	0	0

For this study, climate data time series with daily resolution covered the period 1960–1998 on a 10 km × 10 km grid (Gerstengarbe & Werner, 2003, Güntner & Bronstert, 2004). Monthly time series with variable length in the period 1960–1998 (7–34 years) were available for, first, river discharge at 23 gauging stations (basin area 400–38 500 km^2) (partly provided by the Global Runoff Data Centre, GRDC, Koblenz, Germany) and, second, for storage volumes for 22 large reservoirs ($V_{max} > 50 \times 10^6$ m^3, Fig. 1). Individual reservoir characteristics, such as the relationships between water level, surface area and storage volume, as well as values on regulated outflow volumes, were known only for the 36 largest reservoirs with $V_{max} > 50 \times 10^6$ m^3. All reservoir data were provided by the local water agencies. For all smaller reservoirs, only their number in five different classes, classified according to V_{max}, was known for the year 1992 at the level of administrative units (municipalities) with an average size of about 1000 km^2 (Ceará, 1992). In total, 6838 reservoirs were listed by the survey for Ceará and taken into account in the model (Table 1).

Time series of observed storage volumes for small reservoirs were available only in the small research basin Tauá (gauging station Pirangi, basin area 194 km^2, Fig. 1). For this catchment, which is considered to be representative for large parts of Ceará, Cavalcante *et al.* (1989) listed 21 reservoirs with individual V_{max} in the range of 0.02–1.0 × 10^6 m^3 and about 4.5 × 10^6 m^3 in total, six of them with observed storage volumes time series (Table 1). Climate and runoff time series were measured for a 10-year period (1978–1988) (Cavalcante *et al.*, 1989).

METHODS

Overview

The water balance model for reservoirs presented here is part of the hydrological model WASA (Model of Water Availability in Semi-Arid Environments), a process-oriented distributed model which was specifically developed to simulate runoff generation and water availability in large catchments with semiarid environmental conditions (Güntner, 2002; Güntner & Bronstert, 2004). The modelling time step of WASA is one day. The largest spatial modelling units are sub-basins of 1000 km^2 in size, on average. A hierarchical top-down scheme for landscape discretization is used to define modelling units at different smaller-scale levels and to capture landscape variability. In the present study, which focuses on reservoir modelling, the runoff generation part of the WASA model was applied as described in Güntner & Bronstert (2004). The WASA model, in turn, is part of the Semiarid Integrated Model SIM (Krol *et al.*, 2001; Jaeger, 2004), which integrates in a modular way component models of water availability, water use, agricultural production, agro-economy and socio-economy to assess impacts of global change on the semiarid Northeast of Brazil. Within this framework, the coupling of the modules of water availability (WASA) and water use (NOWUM, Döll & Hauschild, 2002) is of particular relevance for the present study (see also Bronstert *et al.*, 2000). The basic concept of reservoir modelling presented here is to group the large number of reservoirs into different classes according to their size, i.e. storage capacity V_{max}. The reservoir classes are arranged in a cascade-type routing scheme to represent water flow between them. A major difference is made between large reservoirs ($V_{max} > 50 \times 10^6$ m^3) and small and medium-sized reservoirs ($V_{max} < 50 \times 10^6$ m^3) (for an overview, see Fig. 2; for details, see the following sections).

Large reservoirs

Among the 6838 reservoirs in the study area, the water balance for the 36 largest reservoirs with $V_{max} > 50 \times 10^6$ m^3 is represented explicitly in the model, first, because of their great importance for water supply, and, second, because they were the only reservoirs for which specific data on reservoir characteristics were available. The location of their dams was one criterion among others for subdividing the entire study area into 137 sub-basins, linked via the river network (Güntner & Bronstert, 2004).

The water balance of a large reservoir, *RL*, was calculated on a daily basis according to (see also Fig. 2):

$$V_t = V_{t-1} + Q_c + Q_{in} - Q_{out} - U_{RL} + (P - E) \cdot A_{RL} \quad (1)$$

where V_t is the reservoir storage volume (m^3) at day t, Q_c is the daily inflow from the sub-basin area adjacent to the reservoir after the passage of the cascade of small and medium-sized reservoirs in this sub-basin, Q_{in} is the inflow from all other upstream sub-basins via the river network, delayed by a simple streamflow routing scheme (Bronstert *et al.*, 1999), Q_{out} is the outflow from the large reservoir, U_{RL} is water withdrawal (all variables in m^3), P and E (m) are precipitation to and evaporation from the reservoir water surface, A_{RL} (m^2) (see Fig. 2). The value of E was calculated with the Penman approach (Shuttleworth, 1992). Losses by seepage into the bedrock were not accounted for, because no information on their magnitude was available. The outflow, Q_{out}, is composed of (a) uncontrolled outflow over the spillway if V_{max} is exceeded by storage plus inflow and (b) controlled outflow by reservoir operation, $Q_{control}$. Exact operation rules for reservoir outflow as a function of actual storage volume and water demand were not available. Instead, simple rules summarizing common practice of reservoir management in the study area were applied:

(a) $Q_{control}$ is a fraction f_Q of Q_{90}, the annual yield (m^3) of a reservoir, i.e. the volume of regulated outflow which can be provided with a probability of 90% (in 90% of the years). The value of Q_{90} was given for the large reservoirs based on simple hydrological modelling from the state water authorities (SRH, 1992; COGERH, 2000). By rule of thumb, Q_{90} is of the order of 25–50% of mean annual reservoir inflow in the study area.

(b) The value of f_Q was set at 0.8 for so-called strategic reservoirs (i.e. reservoirs with $V_{max} > 300 \times 10^6$ m^3 and reservoirs important for water supply of the metropolitan area of the city of Fortaleza); f_Q was set at 0.9 for all the other large reservoirs. The water volume $f_Q \cdot Q_{90}$ was distributed equally to daily volumes of $Q_{control}$ among all days of the year; seasonal variations were not taken into account due to the lack of detailed information.

(c) If V_t fell below a reservoir-specific alert volume, V_{alert}, $Q_{control}$ was reduced by a factor, f_{alert}, defined as:

$$f_{alert} = \frac{V_t - V_{min}}{V_{alert} - V_{min}} \tag{2}$$

where V_{min} is the dead volume of reservoir below which $Q_{control} = 0$; V_{alert} is 15–35% of storage capacity for most large reservoirs in the study area according to the data given by the state water authorities.

The water surface area, A_{RL}, was calculated as a function of the actual storage volume:

$$A_{RL} = c_{RL} \cdot (V_t)^{d_{RL}} \tag{3}$$

where c_{RL} and d_{RL} are reservoir-specific constants depending on its geometry (see data section).

Small and medium-sized reservoirs

The several thousands of small and medium-sized reservoirs ($V_{max} < 50 \times 10^6$ m^3) are represented in the model in an aggregated way by grouping them into r_{max} classes depending on their V_{max} (Fig. 2). In this study, the class limits were set equal to those given in the reservoir survey for the study area (SRH, 1992, see also data section and Table 1); r_{max} was accordingly set to 5. Based on the survey, the number, n_r, of reservoirs in each class, r, was known for each of the 137 sub-basins of the study area after an area-weighted regrouping of the data from administrative units to the natural sub-basin units. To account for the construction of new reservoirs during the simulation period, the actual number of reservoirs in each sub-basin is gradually increased with time in the model, based on a relationship between time and number of reservoirs which was derived from a detailed survey in one municipality (Bazin, 1993).

For each reservoir class, r, the water balance was calculated for one hypothetical representative reservoir, *RM*, with mean characteristics for that reservoir class, i.e. with its storage capacity being equal to the mean value of the respective class. The water balance of *RM* was calculated with a daily time step according to:

$$V_{RMr,t} = V_{RMr,t-1} + \frac{(Q_{in,r} - U_r)}{n_r} - Q_{out,RMr} + (P - E) \cdot A_{RMr} - S_{RMr} \tag{4}$$

where $V_{RMr,t}$ is the storage volume of the hypothetical mean reservoir *RM* in reservoir class r at day t, $Q_{in,r}$ is the daily inflow to reservoir class r, U_r is water withdrawal from

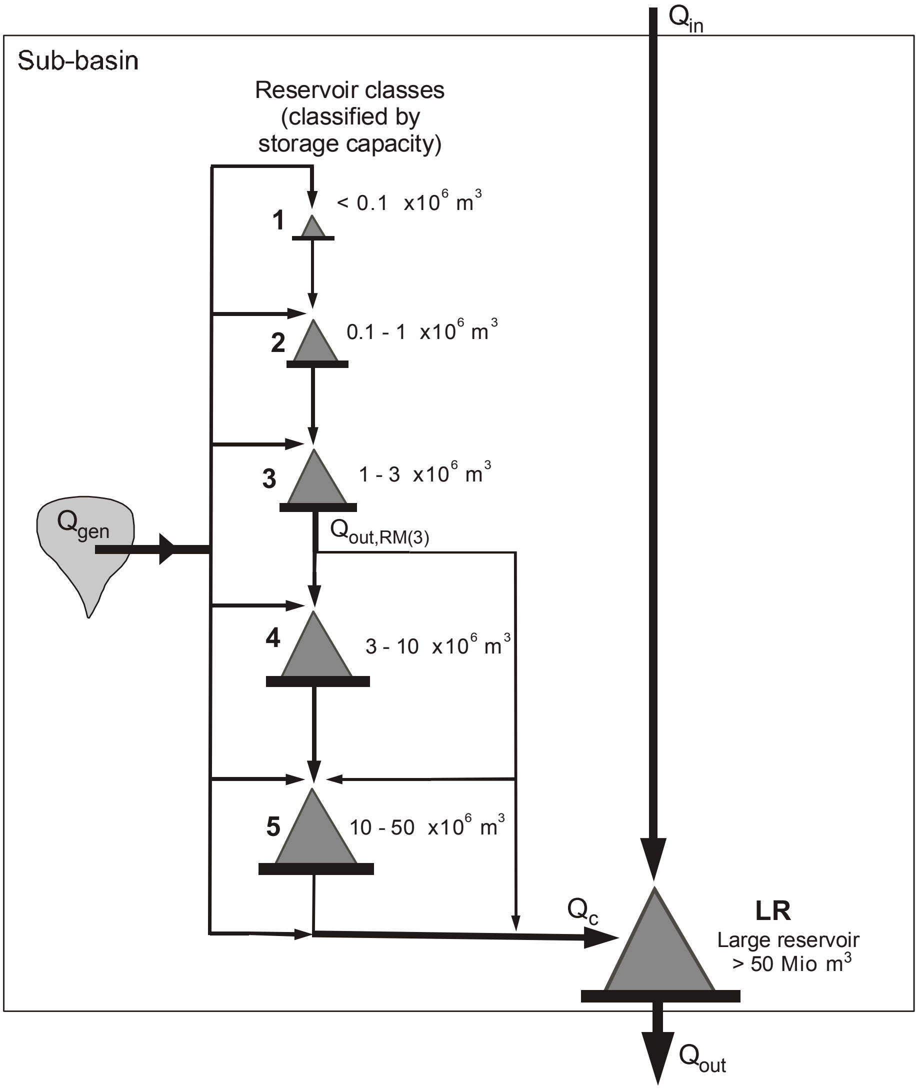

Fig. 2 Cascade scheme for reservoir water balance modelling in WASA, with reservoir classes and runoff redistribution between classes within a sub-basin (for clarity of the figure, only redistribution of outflow from reservoir class 3 ($Q_{\text{out},RM(3)}$) among larger reservoirs and the cascade outlet is completely represented by arrows; similar schemes apply for the other reservoir classes, see text). (Q_{gen}: runoff generated in the sub-basin, Q_{in}: inflow from upstream sub-basins, Q_c: river flow after the passage of the cascade of small and medium-sized reservoirs, Q_{out}: total sub-basin outflow).

reservoir class r, n_r is the number of reservoirs in class r, $Q_{\text{out},RMr}$ is the daily outflow from reservoir RM (all in m^3), A_{RMr} is the water surface area of reservoir RM (m^2), and S_{RMr} is the seepage loss of reservoir RM due to infiltration into the bedrock and lateral seepage below the dam (m^3).

The total actual storage volume $V_{r,t}$ of reservoir class r is then obtained by:

$$V_{r,t} = V_{RMr,t} \cdot n_r \tag{5}$$

A cascade scheme was developed as an approximate description of the upstream–downstream position of the reservoir classes relative to each other within the sub-basin and, thus, to describe the redistribution of runoff among the reservoir classes. In view of the lack of detailed information on the location of reservoirs, the aim was to set up a scheme that could be considered to be a plausible average approach for most sub-basins in the study area. Therefore, based on experience in the study area and qualitative reasoning from topographic maps, the following simplifying assumptions were made for the cascade scheme (Fig. 2):

(a) The small and medium-sized reservoirs are located along tributaries to the main river that flows through the sub-basin. Thus, the inflow to any small or medium reservoir class, $Q_{in,r}$, is composed only of runoff being generated within the sub-basin itself. There is no runoff contribution to $Q_{in,r}$ from upstream sub-basins. (The latter was attributed only to large reservoirs of the main river, Q_{in}, equation (1).)

(b) The total sub-basin area is equally distributed as runoff contributing area among the five reservoir classes. This implies that a fraction $1/(r_{max} + 1)$ of the total sub-basin runoff, Q_{gen}, generated in a time step (see Güntner & Bronstert, 2004, for a description of runoff generation modelling in WASA) was attributed as direct inflow to each reservoir class without previous storage in any other reservoir class (equation (6)). For another $1/(r_{max} + 1)$ part of Q_{gen} (i.e. one-sixth of Q_{gen} in this study), no retention by any small or medium-sized reservoir was assumed. This fraction of generated runoff was directly added to runoff, Q_c, after the passage of the reservoir cascade (equation (7)).

$$Q_{in,\,r} = \frac{Q_{gen}}{r_{max}+1} + \sum_{x=1}^{r-1} \frac{Q_{out,\,XM} \cdot n_x}{(r_{max}+1)-x} \tag{6}$$

(c) Smaller reservoirs are located upstream of larger reservoirs. Thus, additional inflow to a reservoir class r was provided by the outflow, $Q_{out,XM}$, of all reservoir classes, x, with smaller representative mean storage capacity (i.e. where $x < r$). Similarly to Q_{gen}, $Q_{out,XM}$ was equally distributed among all larger reservoir classes and among non-stored runoff Q_c (equations (6) and (7)). This assumption accounts for the fact that a reservoir can be upstream of any larger reservoir (not necessarily a reservoir of the next larger class), or can have no other small or medium-sized reservoir in the downstream direction. In combination with assumption (b) above, this implies that the effective contributing area of the five reservoir classes, including contributions from areas that previously drained into smaller reservoir classes, is 1/6, 1/5, 1/4, 1/3 and 1/2 of the total sub-basin area, respectively. Furthermore, the assumption implies that these areal fractions are independent of the actual number of reservoirs in a class. Outflow from one reservoir class is attributed to any larger reservoir class within the sub-basin in the same time step. For daily time steps, this was assumed to be a reasonable approximation in view of the travel times that occur in the river network, given an average sub-basin size of about 1000 km^2 in this study.

Outflow from the small and medium-sized reservoirs, Q_{out}, was assumed to occur only if the storage capacity is exceeded. This is valid in particular for small reservoirs that are mainly simple earth dams without devices for outflow regulation. For simplicity, and due to the lack of information on outflow regulation, this assumption was also applied to the medium-sized reservoirs. Total runoff, Q_c, of a sub-basin after the passage of the reservoir cascade is given by:

$$Q_c = \frac{Q_{gen}}{r_{max}+1} + \sum_{r=1}^{r_{max}} \frac{Q_{out,\,RM} \cdot n_r}{(r_{max}+1)-r} \tag{7}$$

Reservoir surface area, A_{RM} (equation (4)), was estimated as a function of the actual storage volume, $V_{RM,t}$, by a relationship similar to equation (3), with average parameters derived for several small reservoirs in the study areas by Molle (1989). Seepage losses, S_{RM}, for the three smallest reservoir classes ($V_{\max} < 3 \times 10^6$ m^3) were set at 34% of evaporation losses according to an average value found by Molle (1989) in an investigation of small reservoirs. With increasing size of the reservoir, a decreasing relative importance of seepage losses on the total water balance of a reservoir can be assumed, because lateral outflow in the alluvial material below the dam was a major reason for the losses estimated by Molle (1989). As no further information on S_{RM} was available, for the medium-sized reservoirs (classes 4 and 5) S_{RM} was set at 0 in this study, as proposed by Campos (1996).

Water use

Water use in the study area (required in the water balance model in terms of U_{RL} and U_r in equations (1) and (4)) was determined by a data survey-based assessment at the scale of municipalities in five water-use sectors (irrigation, livestock, domestic, industrial and tourist water use) (NOWUM model, Döll & Hauschild, 2002). For each sector, the water-use intensity (specific water demand) and the activity level (irrigated area, number of animals, population, industrial activity, number of tourist overnights) were combined to determine water demand. The water use intensity was computed as a function of climate and crop type in the case of irrigation agriculture, and assumed to depend on water pricing in the case of domestic and industrial demand. Calculations of water use were done as follows (for details, see Jaeger, 2004): first, water use was computed as withdrawal water use, i.e. the quantity of water taken from its source location (80% from reservoirs, 15% from rivers and 5% from groundwater for irrigation, while 70% from reservoirs, 20% from rivers, and 10% from groundwater for the other sectors). Total water extraction from reservoirs was evenly distributed among the reservoir classes. However, due to the varying number of reservoirs in each class, the volume which is withdrawn from each individual reservoir is different between the reservoir classes. Whenever individual water sources could not supply the allocated demand, the excess demand was re-allocated. When water demand approached the actual water availability in dry years or the dry season, and available water would only guarantee supply for a limited number of days, withdrawal volumes were reduced. The threshold number of days was taken dependent on the sector according to priorities in water supply, with a long time horizon (30 days), i.e. a more rapid reduction, for irrigation water demand, intermediate horizon (20 days) for industrial and animal water demand, and a short time horizon for domestic water demand (2 days for public water supply). Second, the amount of consumptive water use was calculated by applying water use efficiency coefficients for each sector. The difference between withdrawal and consumptive use was assumed to be partially lost to local evapo-transpiration, and to partially return into the river and reservoir system. The return ratio was taken to be sector-specific, i.e. 50% for publicly supplied domestic demand as well as irrigation, industrial and tourist demand, and 0% for non-publicly supplied domestic demand and animal demand. Return flow was added to Q_c and Q_{in} in equations (1) and (4). Water use per sub-basin is recalculated from the data given primarily at the scale of administrative units by simple area-weighting.

Model validation—performance criteria

There is no standard criterion to evaluate the performance of hydrological models in terms of simulated versus observed reservoir storage, such as the Nash-Sutcliffe model efficiency for evaluating runoff simulations. As the storage volume in reservoirs at the end of the rainy season is a key variable of water availability in semi-arid areas, the mean annual difference between simulated and observed storage volume in the month of June (d_V) was used in this study as a long-term performance criterion. In addition, to evaluate model performance in simulating the temporal behaviour of storage volumes, the Nash-Sutcliffe coefficient of efficiency, e_V, based on monthly observed and simulated reservoir storage volumes ($V_{\text{obs},t}$, $V_{\text{sim},t}$) was computed for the large reservoirs (with $\overline{V_{\text{obs}}}$ being the mean observed monthly storage volume):

$$e_V = 1 - \frac{\sum_t \left(V_{\text{obs},\,t} - V_{\text{sim},\,t}\right)^2}{\sum_t \left(V_{\text{obs},\,t} - \overline{V_{\text{obs}}}\right)^2} \tag{8}$$

In the case of river discharge, the model efficiency, e_Q, is computed by using monthly discharge, Q, in equation (8) instead of V. The term d_Q is the difference between simulated and observed mean annual discharge at each gauging station.

For the small reservoirs in the Tauá basin, the observed monthly storage volume time series were first divided by the storage capacity of the respective reservoir. From the resulting individual time series of relative storage volumes, an average time series for each reservoir class was then calculated by averaging among all observed reservoirs that pertain to a specific class (see Table 1 for the number of reservoirs in each class). For model validation, the obtained averaged time series were compared to the simulated series of the mean reservoir *RM* of the respective class.

RESULTS AND DISCUSSION

Small-scale application

As a small-scale example, WASA was applied to the Tauá basin (194 km^2) for a 10-year period (October 1978–September 1988, mean annual rainfall 547 mm). The overall basin water balance was reasonably well represented (mean annual discharge, $\overline{Q}$, was 40 and 42 mm for the observation and simulation, respectively (Güntner, 2002)). According to the model results, runoff retention in the reservoirs and subsequent evaporation and seepage losses reduce $\overline{Q}$ by about 20% in this basin (naturalized $\overline{Q}$, i.e. simulated without any reservoir retention: 52 mm). Figure 3 illustrates the different reservoir storage dynamics as a function of reservoir size. Smaller reservoirs, i.e. those of lower storage capacity, show a stronger variability in their storage volumes, falling to very low levels or drying out completely during each dry season. Larger reservoirs generally exhibit a smoother behaviour. In particular, the frequency of drying out is lower than for smaller reservoirs. This different behaviour is mainly a consequence of the volume–surface area relationship of reservoirs which in general favours larger evaporation losses relative to storage volume in the case of smaller

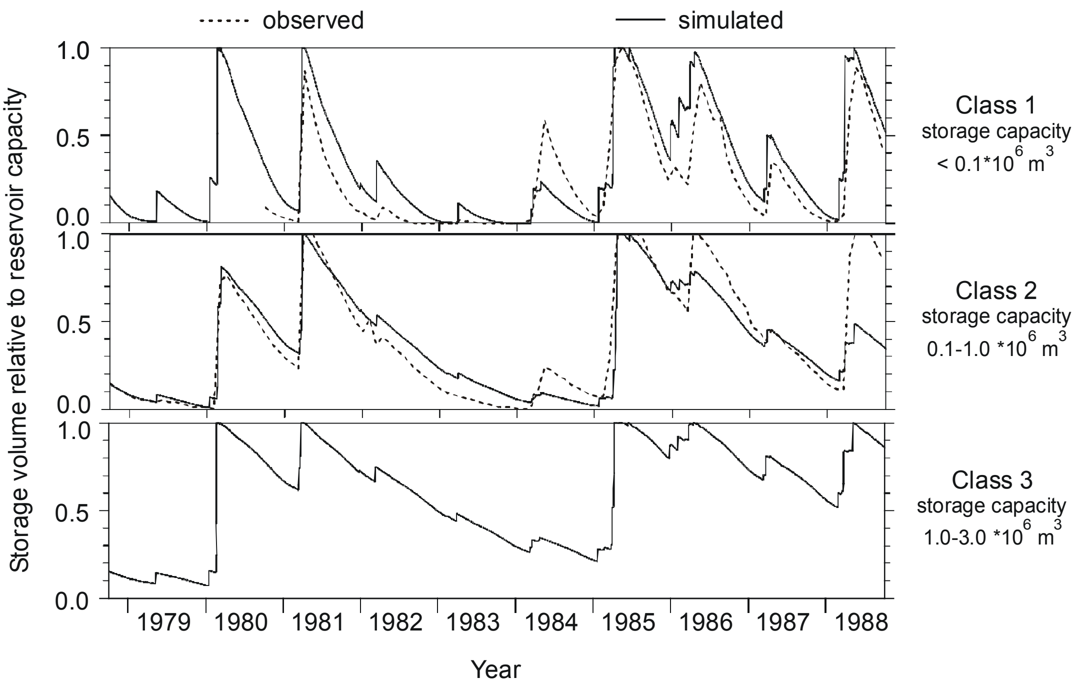

Fig. 3 Storage volumes relative to storage capacity of the reservoirs in three reservoir classes, Tauá basin (Ceará, Brazil), comparison of observations with simulation results.

Table 2 Simulated storage behaviour of three reservoirs classes in the Tauá basin and comparison with observed storage volumes (classes 1 and 2) for the period October 1979–September 1988 (storage volumes are normalized by storage capacity); c_V: coefficient of variation of storage volumes, e_V and d_V are defined in the main text.

	Class 1	Class 2	Class 3
Mean storage, simulated	0.34	0.41	0.66
Mean storage, observed	0.25	0.44	-
c_V, simulated	0.92	0.66	0.36
c_V, observed	1.14	0.78	-
Model efficiency e_V (-)	0.69	0.80	-
Model performance d_V (%)	10.1	–16.9	-

reservoirs. The simulation results were widely confirmed by the measurements which also exhibited the stronger intra-annual variability of storage volumes and on average lower storage volume for the smaller reservoir class (Fig. 3, Table 2). The observed variability between years with a tendency of reservoir volumes to reach the storage capacity in the years 1981, 1985, 1986 and 1988, was also well represented by the model. It should be noted, however, that the power of validation was limited in this example due to the low number of monitored reservoirs (cf. Table 1). Thus, discrepancies between observations and simulations may be attributed to the particularities of the observed reservoirs in their geometry, catchment characteristics, or contributing basin area, that differ from the average characteristics assumed in WASA for the respective reservoir class. Nevertheless, the validation results demonstrate that the simplified water balance modelling approach is a reasonable approximation to represent reservoir dynamics at the small basin scale as a sound basis for its application to large river basins.

Large-scale application

For the non-calibrated application of WASA to the entire area of Ceará (period 1960–1998), differences between simulated and observed mean annual river discharge (d_Q) were in the range of ±40% (Fig. 4(a)), being in general <20% for basins of more than 10 000 km^2 in size. The large intra- and interannual variability of discharge was reasonably represented by the model, with monthly efficiency e_Q above 0.7 at most gauging stations (Fig. 4(c)) (see Güntner & Bronstert, 2004, for details on model validation with respect to discharge). In terms of water storage volumes of large reservoirs, model deviations from the observations at the end of the rainy season (d_V) were about ±20% on average (Fig. 4(b)). There was no tendency of a systematic over- or underestimation and reasonable model results of average water availability in large reservoirs at the regional scale were obtained (Fig. 5). However, variations in model performance between individual reservoirs were large. This could also be seen in terms of e_V (Fig. 4(d)), which was about 0.4 on average, i.e. a fair representation of monthly reservoir dynamics, but dropped to values <0 for several reservoirs, indicating that the simulated variability performed worse in representing the observed time series than the assumption of a constant mean value. Clearly, the performance of modelling storage volumes is limited by the accuracy of the runoff simulations which are used as reservoir inflow (reservoir performance is equal to or worse than discharge performance in Fig. 4). There are, however, several additional factors which may enhance the uncertainty of the simulation results for reservoirs: (a) inaccuracies of the area–volume relationship and of evaporation rates when determining evaporation losses; (b) possible percolation to bedrock which is neglected by the model for large reservoirs, and (c) inappropriateness of the simplified operation rules of controlled reservoir outflow used in the model and uncertainties in withdrawal water use volumes. Local experience in the study area suggests that uncertainties in human withdrawal rates from the reservoir storage add the largest uncertainty to reservoir

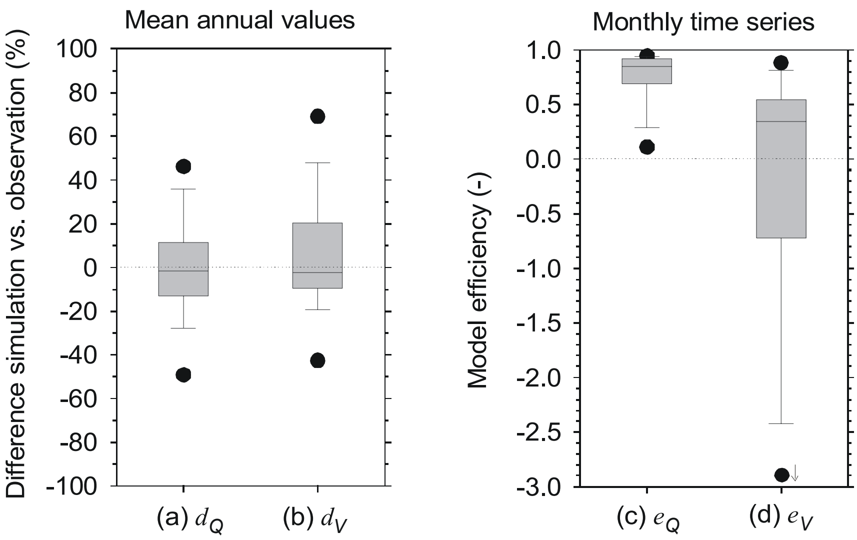

Fig. 4 Performance of WASA in simulating runoff (*Q*) and reservoir storage volume (*V*), period 1960–1998. The box-whisker-plots give the distributions of the performance criteria among the 23 gauging stations and 22 large reservoirs in the study area of Ceará (see text for the definition of the performance criteria *d* and *e*).

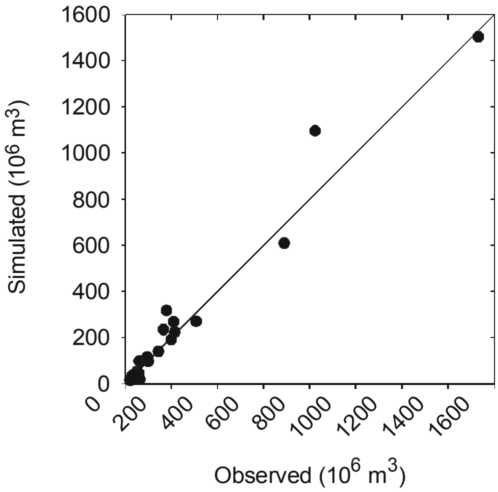

Fig. 5 Observed versus simulated mean annual reservoir storage at the end of the rainy season (June) for 22 large reservoirs in Ceará (simulation period 1960–1998, validation period differs among reservoirs depending on reservoir inauguration and data availability).

water balance calculations due to their strong variability and the lack of reliable historical data.

To illustrate the meaning of the numerical performance criteria, Fig. 6 gives examples of storage volume time series for three large reservoirs with different performances. Very good simulation results were obtained, both visually and in terms of the performance criteria, for one of the largest and most important reservoirs of Ceará (Açude Orós), (Fig. 6(a)). One main reason is that errors in runoff volumes used as reservoir input were comparatively small in this example due to the large basin area where smaller-scale deviations tend to average out. Good results were also obtained for the reservoir in Fig. 6(b). The intra- and interannual dynamics were well represented by the model. There was one year (1978), however, where reservoir inflow was considerably underestimated. As a consequence, the observed and simulated storage time series run roughly parallel to each other during the next years until the complete filling of the reservoir in 1984. This discrepancy seriously degraded the performance criteria. It illustrates the possible long-term persistence of individual modelling errors in subsequent simulation results in the case of reservoir storage. This persistence is usually more pronounced than in the case of runoff simulations. In this sense, it might be advisable to use numerical measures other than e_V, e.g. measures giving weight to deviations between observed and simulated seasonal volume changes, in evaluating which simulations are good, fair or poor (compare, for example, the classification of e_Q by Andersen *et al.* (2001)). Finally, Fig. 6(c) gives an example of a reservoir with $e_V < 0$. In this case, the poor performance was mainly caused by a too pronounced decline in storage volumes during the dry seasons or sequences of dry years. This might be a combined effect of overestimating evaporation and outflow volumes and, at least in dry years, underestimating reservoir inflow. Nevertheless, in contrast to what might be expected from the poor values of the quantitative performance criteria, there were still various characteristic similarities between observed and simulated time series in terms of the intra-annual variability (the strong seasonal pattern of storage volumes) and the interannual variability (the contrast between sequences of years with storage volume

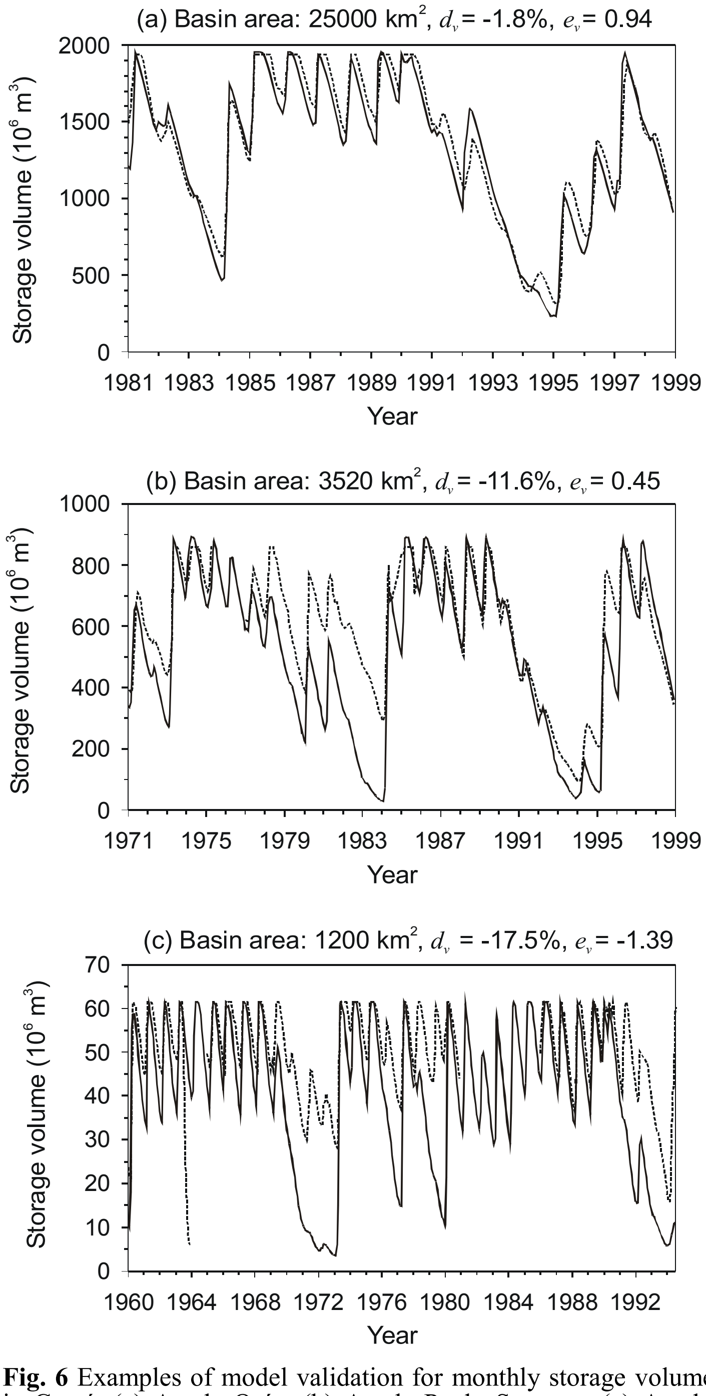

Fig. 6 Examples of model validation for monthly storage volumes in large reservoirs in Ceará, (a) Açude Orós, (b) Açude Paulo Sarasate, (c) Açude Riacho do Sangue. (solid line: simulated, dotted line: observed).

remaining below reservoir capacity in dry periods and sequences with yearly reservoir overflow in wet periods).

Similar to the small Tauá basin, reservoirs showed distinct storage dynamics as a function of size also at the scale of the entire study area. The intra-annual variability in storage volumes was considerably larger in the reservoir classes of small storage capacity according to the simulation results, whereas larger reservoirs in general had a

Table 3 Storage characteristics of the different reservoir classes, total values for the area of Ceará, averages for simulation period 1960–1998. *V*: actual storage volume of all reservoirs in a class, V_{max}: storage capacity, Q_{total}: average monthly reduction of storage volume by evaporation (*E*), seepage losses (*S*), water use and regulated outflow; for all 36 large reservoirs in Ceará (LR_{all}), and for those 22 reservoirs (LR_{22}) for which both simulations and observations were available with shorter time periods.

Reservoir class	1	2	3	4	5	LR_{all}, sim.	LR_{22}, sim.	LR_{22}, obs.
V_{max} of each reservoir within class (10^6 m^3)	<0.1	0.1–1	1–3	3–10	10–50	>50	>50	>50
V June (10^6 m^3)	70	830	469	481	685	5588	5509	5131
V June (% of V_{max})	90.1	79.4	84.7	86.5	80.4	70.9	71.1	66.2
V December (10^6 m^3)	35	490	336	392	580	4223	4165	4050
V December (% of V_{max})	44.5	46.9	60.6	70.5	68.1	53.6	53.7	52.2
V, Intra-annual variability (% of V_{max})	45.6	32.5	24.1	16.0	13.3	17.3	17.4	14.0
Q_{total} (10^6 m^3)	11	65	26	16	17	256	247	-
$(E + S)/Q_{total}$ (%)	78.2	70.7	60.9	50.6	41.9	41.0	40.4	-

more balanced behaviour (Table 3). One aspect of this behaviour is that smaller reservoirs tended to have a higher ratio of actual storage volume relative to capacity at the end of a rainy period than larger reservoirs. This is presumably a consequence of smaller reservoirs being at a more upstream position in the river basins where generated runoff is less affected by prior retention in other upstream reservoirs and total available runoff volumes relative to storage capacity are larger. This corresponds to the general observation that smaller reservoirs tend to have shorter residence times (i.e. storage capacity divided by inflow rates) than larger reservoirs. Furthermore, different dynamics as a function of reservoir size were expressed by an increasing fraction of evaporation and seepage losses relative to human water use with decreasing reservoir size (Table 3). This demonstrates the less effective storage behaviour of smaller reservoirs. The time-variable ratios of actual storage volume relative to capacity were well represented by the model for the large reservoirs, at the end of both the rainy and the dry seasons. For small and medium-sized reservoirs, no validation data were available at the scale of Ceará. Comparatively high ratios were simulated in particular for the medium-sized reservoirs (classes 3–5) at the end of the dry season. These ratios might be considered to be overestimated when compared to the values of both smaller and larger reservoirs. Possible reasons are an overestimation of spill-over flow routed to these reservoirs through the cascade scheme, and the fact that, due to the lack of data, the model disregards any regulated outflow from these reservoirs. Instead, water for human use is extracted directly from the reservoir in the model with its volume corresponding to the actual demand in the sub-basin. This volume can often be expected to be lower than the real regulated outflow, which usually includes additional water volumes for use further downstream.

Due to the evaporation losses, water retention in reservoirs reduced markedly the average downstream discharge (Fig. 7(a)). Mean annual discharge, $\overline{Q}$, at the mouth of Ceará's largest river basin, the Jaguaribe basin, was lower by 15% when comparing simulations of naturalized flow (i.e. WASA was run while disregarding all the reservoirs) ($\overline{Q}$ = 219 m^3 s^{-1}) and simulations with reservoir retention ($\overline{Q}$ = 187 m^3 s^{-1}). Additionally, taking into account consumptive water use, the reduction of downstream discharge usually exceeded 20% in areas with a high reservoir density, for some sub-

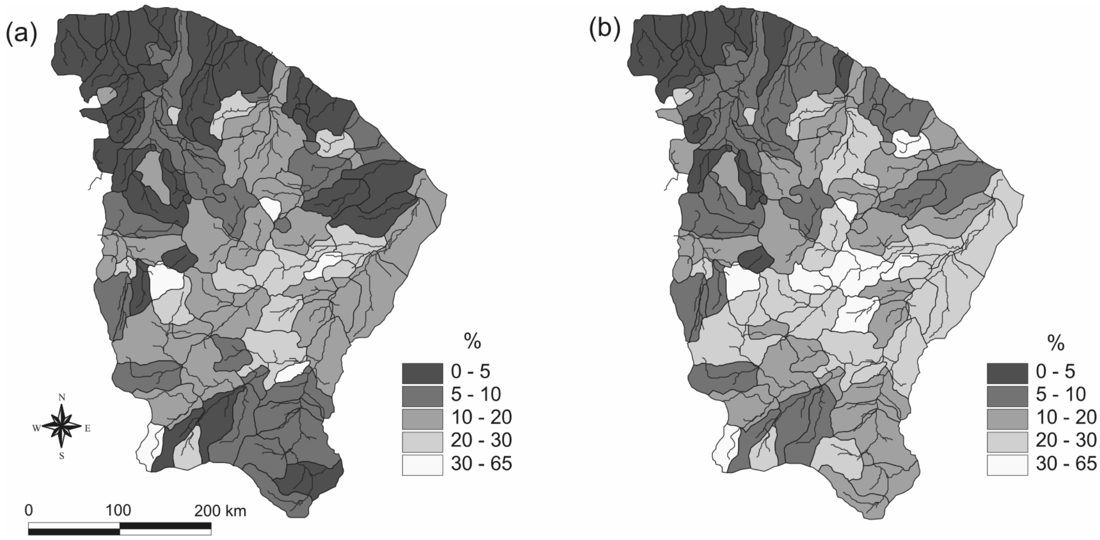

Fig. 7 Effect of reservoir retention and water use on downstream river discharge: Reduction of mean annual discharge as compared to naturalized flow (i.e. disregarding all reservoirs) at the outlet of sub-basins in Ceará due to (a) evaporation losses in reservoirs, and (b) evaporation losses and consumptive water use. Simulations with WASA for the period 1960–1998.

basins more than 30% (Fig. 7(b)) and 21% at the outlet of the Jaguaribe basin ($\overline{Q}$ = 174 $m^3 s^{-1}$). These results indicate that high levels of interference exist among reservoirs in terms of their competition for the available runoff volumes. In accordance with other studies in individual basins, this is a critical issue for the study area where the construction of small dams upstream of large reservoirs is common practice. For instance, Campos *et al*. (2000) showed for one large reservoir in Ceará (Várzea do Boi) that the influence of small upstream reservoirs led to a reduction in its water yield by more than 50%.

CONCLUSIONS

Storage of surface water is a central strategy in guaranteeing water supply in dryland regions. The model results reported here confirm the significant impact of water retention in reservoirs on the water balance of Ceará in Northeast Brazil. They show that the total impact is often considerably greater than the volumes extracted for water use, due to the large amount of losses by evaporation. The latter is the price to be paid by fulfilling water demand from surface-water storage facilities. As a consequence, water balances of reservoirs can only be simulated realistically in direct link with simulations of water use and discharge routing through the river network and the multiple-reservoir systems, including spatially explicit information on runoff generation along the river system. The relevance of a direct coupling becomes obvious for all locations receiving inflow from upstream areas, where this inflow depends on the upstream reservoir water balance.

This study presents a simple water balance model for surface water reservoir systems that can easily be linked to descriptions of surface hydrology, river routing and water use, as it is done within WASA and the integrated model SIM. Grouping the numerous reservoirs into a small number of representative classes according to storage capacity resulted in being an effective simplification at a large spatial scale. Characteristic differences in the storage behaviour of reservoirs of different sizes could thus be represented. Model performance for simulating reservoir storage volumes was in the same range as discharge simulations when looking at mean annual values. On a monthly scale, deviations tend to be higher because additional factors of uncertainty are introduced in the modelling of storage volumes. Nevertheless, the reasonable values of water availability obtained at the scale of the study area confirm the applicability of the approach for large river basins.

Specific choices for the design of the cascade scheme, for the routing of water between reservoirs and for the allocation of water extractions and return flows to surface water bodies are subject to high uncertainty, as there are few data available to validate them. The present description is of an appropriate complexity, being able to represent the basic mechanisms of hydrological processes and water management that influence the water balance, while being flexible enough to allow for inclusions of additional process knowledge or data. Refinements of the model should primarily focus on an improved definition of the basin area fractions that contribute to individual reservoir classes by use of more detailed data on topography and reservoir locations from remote sensing studies. Additionally, a better knowledge of reservoir operation rules promises to significantly improve model performance.

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