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Assessment of observed and simulated low flow indices for a highly managed river basin

Hagen Koch, Stefan Liersch, José Roberto Gonçalves de Azevedo, Ana Lígia Chaves Silva and Fred Fokko Hattermann

ABSTRACT

Droughts and resulting low flows are a threat for society, economy, and ecosystems. Droughts are natural phenomena, but anthropogenic water use can increase the pressure on water resources. To analyze the effects of changing land-use or water management and climate variability/change on water resources, models integrating the most important hydrological processes are needed. These models must account for natural processes and water resources management at different spatial and temporal scales, e.g., reservoir operation, water withdrawals. Low flow indices are analyzed for observed and simulated flows for the highly managed São Francisco river basin in Brazil, showing that during wet, normal, and moderately dry years, the existing reservoir system is able to augment low flows while during strong droughts the system reaches its limits. This effect is also represented in the simulations using the eco-hydrological model SWIM, which was adapted to account for region-specific characteristics of land-use and water management. While good to very good performance was achieved for calibration and validation for most gauges, for some gauges at tributaries only insufficient quantitative criteria are reached. The reasons for the deviation between observations and simulation results are discussed. Overall, the model is able to represent natural discharges and observed, managed discharges.

Key words | hydrology, low flows, São Francisco river basin, SWIM, water resources management

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INTRODUCTION

Droughts are a threat for society, economy, and ecosystems (Tallaksen *et al.* 1997; Fleig *et al.* 2006; Burke & Brown 2008; Stahl *et al.* 2010; Van Lanen *et al.* 2016). Although droughts are natural phenomena ecosystems are adapted to, anthropogenic water use can put the water resources system beyond environmental acceptable limits. Usually, droughts are categorized into four general types (e.g., Fleig *et al.* 2006): (i) meteorological or climatological drought: shortfall of precipitation over a certain period of time; (ii) agricultural drought: links a meteorological drought to agricultural impacts (e.g., soil moisture deficits); (iii) hydrological drought: precipitation shortfalls depleting surface or subsurface waters, often combined with anomalies in other meteorological variables affecting potential evapotranspiration (e.g., temperature, humidity, wind); (iv) socioeconomic drought: imbalance between water demand and supply with economic impacts (e.g., reduced water supply and hydropower generation). Social impacts can be health-related, e.g., shortage of clean potable water. Sometimes numbers (iii) and (iv) are considered as hydrological drought. A better understanding and management of hydrological droughts requires understanding the propagation of water deficits through the hydrological cycle, with consideration of the impacts on natural and socioeconomic systems

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(Van Lanen *et al.* 2016). In arid regions hydrological droughts are normal, while in semi-arid or temperate regions they occur occasionally.

Low flow indices or measures are statistical values used to describe the flow regime of a river. The knowledge on low flow characteristics is important for water resources management and planning, e.g., water supply systems, reservoir storage design, and reservoir operation (Fleig *et al.* 2006; WMO 2008; Stahl *et al.* 2010). The minimum flows can be calculated for every year, but must not be correlated to drought (Smakhtin 2001). Calculating indices for longer time periods, e.g., ten years, is a better indicator for hydrological drought, as it is more probable that a ten-year period includes periods of meteorological drought. There are a number of indices used to describe low flows, e.g., the 7-day ten-year low flow (7Q10: lowest average flows that occur for a consecutive 7-day period at a recurrence interval of ten years, also termed Q7(10) or $Q_{7,10}$), the mean annual 7-day minimum flow (MAM7: lowest average flows that occur for a consecutive 7-day period during a year, also termed AM7) and Q90 or Q95 (discharges exceeded 90% and 95% of the time) (Smakhtin 2001; WMO 2008). In many countries, low flow indices are applied in the granting of water rights, e.g., 7Q10 and Q90 in Brazil (Pereira 2000) and MAM7 in the UK (Smakhtin 2001). Although the calculation of lowest average flows for a consecutive x-day period differs from the calculation of exceedance frequencies, strong correlations are found between these, e.g., 7Q10 is highly correlated to Q95 (Smakhtin 2001).

Due to water resources management, e.g., reservoir operation, water transfers, discharges from waste water treatment plants, observed flow can deviate strongly from natural flow (Thoms & Sheldon 2000; de Wit *et al.* 2007; Lopez-Moreno *et al.* 2009; Xu *et al.* 2013; Omer *et al.* 2017). Deviations can be prominent during hydrological droughts, with reservoir discharges increasing or water withdrawals reducing river flow. Therefore, observed flows in highly managed river basins cannot easily be used to calibrate and validate models, as water resources management is affecting the homogeneity of observed flow records (Jones *et al.* 2006), requiring flow naturalization.

System analysis is necessary before calibrating and validating a hydrological model for highly managed river basins. According to Loucks & van Beek (2005), the system needs to be separated and analyzed for three interdependent subsystems: (i) the natural river subsystem in which physical, chemical and biological processes take place; (ii) the socio-economic subsystem, including human activities related to the use of the natural river subsystem; and (iii) the administrative and institutional subsystem, including legislation and regulation.

To account for human-induced changes in hydrological modeling is difficult (Thoms & Sheldon 2000; de Wit *et al.* 2007), as data and information on water resources management and water use are usually difficult to obtain. Due to these constraints, the effects of human activities are often omitted in low flow studies (e.g., de Wit *et al.* 2007; Huang *et al.* 2013). Lobanova *et al.* (2016) show, using the example of the Tagus River, that a good performance of a hydrological model can be achieved without implementation of water management, mainly storage in reservoirs, by a specific parameterization of the model, e.g., by adjusting infiltration and groundwater return flow processes. This means that water storage does not take place in the artificial surface reservoirs but rather in the aquifers, thereby losing the physical basis of the simulation. The latter is a prerequisite for reliable simulating of the hydrological effects of changing climate or land-use. Dunn & Ferrier (1999) describe the integration of simple management controls into a spatially distributed hydrological model and illustrate how this model can be used to assist in catchment management for the River Carron in central Scotland, draining an area of 187 km^2 and including two reservoirs. They compare simulated natural and managed flow to show the effects of including water management in the simulations. As no naturalized flows are available they cannot evaluate the quality of the simulated natural flow. Creech *et al.* (2015) use observed discharges from reservoirs to include water management; concentrating on simulating the sediment budget for the São Francisco river for the observational period. The use of observed discharges in the simulations leads to high model quality criteria downstream of reservoirs. Including reservoir operation in this way precludes the model for studying changes in climate, land-use, or reservoir operation. Other studies simply neglect the effect of water resources management altogether, arguing that their study merely focuses on climate change impacts on natural discharges, e.g., Ho *et al.* (2016). The simulation of water resources management differs from mere

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hydrological impact studies, where change signals, e.g., due to climate or land-use change, are analyzed. In these studies it is assumed that, even if in the reference period the climate or the hydrological models show a significant bias, the change signal is correct. Non-linearity of effects and thresholds are usually neglected.

If human interventions change the runoff regime significantly, a naturalization of observed flows is required before utilizing for calibration and validation. Naturalized river flows are created by adjusting observed flows to known artificial influences such as reservoir operation, water withdrawals, or return flows. According to Smakhtin (2001), return flows from agricultural irrigation can reach 40% of the water withdrawn; however, besides the absolute value the location and time-lag of return flows are uncertain. Other uncertainties arise from the estimation of evaporation losses and seepage to the groundwater of large reservoirs. According to WMO (2008), for observed flows the error is usually ±5%, while the error for naturalized river flows can reach ±40% (see also description of naturalization applied by *Operador Nacional do Sistema Elétrico* (ONS) in the Methods section).

Calibration and validation periods should contain dry and wet years. For models calibrated over wet years only, it is generally difficult to predict runoff for dry years and vice versa (e.g., Vaze *et al.* 2010; Todorovic & Plavsic 2016). According to Moriasi *et al.* (2007), calibration and validation periods should have durations of three to five years. In some studies, e.g., Huang *et al.* (2013), hydrological models were specifically calibrated to low flows, using the logarithmic Nash–Sutcliffe efficiency (LNSE) as a statistical criterion to magnify the weight of the low flows. Trudel *et al.* (2017) analyze the effects of applying different objective functions in the calibration of two hydrological models for low flow studies. They found the best results in simulating low flows if the LNSE is used as objective function. However, they give no indication on the quality of simulated mean and high flows using the different objective functions.

If beside the natural (low) flows, also water resources management, e.g., reservoir operation, and its effects on flows are of interest, it can be inappropriate to use the LNSE as criterion. While low flows are important for reservoir operation, e.g., augmentation of flow downstream, also mean and high inflows to reservoirs are important, as in these periods the reservoirs are filled. If simulated inflows into the reservoir are inaccurate, the simulation of reservoir operation will not be reliable. The simulated reservoir volumes and/or discharges will either be too low or too high compared to observations. Also, the annual cycle (dry and wet seasons) should be simulated reliably. In the case the long-term mean discharge is simulated well but high flows are over- and low flows underestimated, the reservoir may be filled during the wet or high flow season up to the maximum capacity and water that cannot be stored is spilled. In the dry season, the reservoir may run dry as inflows are too low and the downstream water demands require high reservoir discharges. In order to get a parametrization appropriate for low, mean, and high flows in the calibration and validation of a model the NSE instead of the LNSE should be applied.

This paper describes the calibration and validation of the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova *et al.* 1998, 2000) to the heavily managed São Francisco river basin in Brazil. In contrast to many other studies describing the calibration and validation of hydrological models, naturalized river flows and water resources management issues are considered. A two-step approach is applied, where naturalized flows are used for calibration (1988–1994) and validation (1995–2000) in the first step, and water resources management is included in the second step (1981–2010). The latter requires simulating the natural flows with high accuracy, as non-linear effects and thresholds are effective in the water resources management simulations. In this approach, the paper differs from the study of Creech *et al.* (2015) for the São Francisco river.

Furthermore, the ability of the model to reproduce low flows under natural and managed conditions is tested. To show the long-term development of low flows, first the observed flows between 1931 and 2010 are analyzed; the low flows simulated under natural and managed conditions for the time period 1981 to 2010 are then compared to the observed low flows.

STUDY AREA

The São Francisco river basin in the north-east of Brazil has an area of approximately 640,000 km^2 (Figure 1). According

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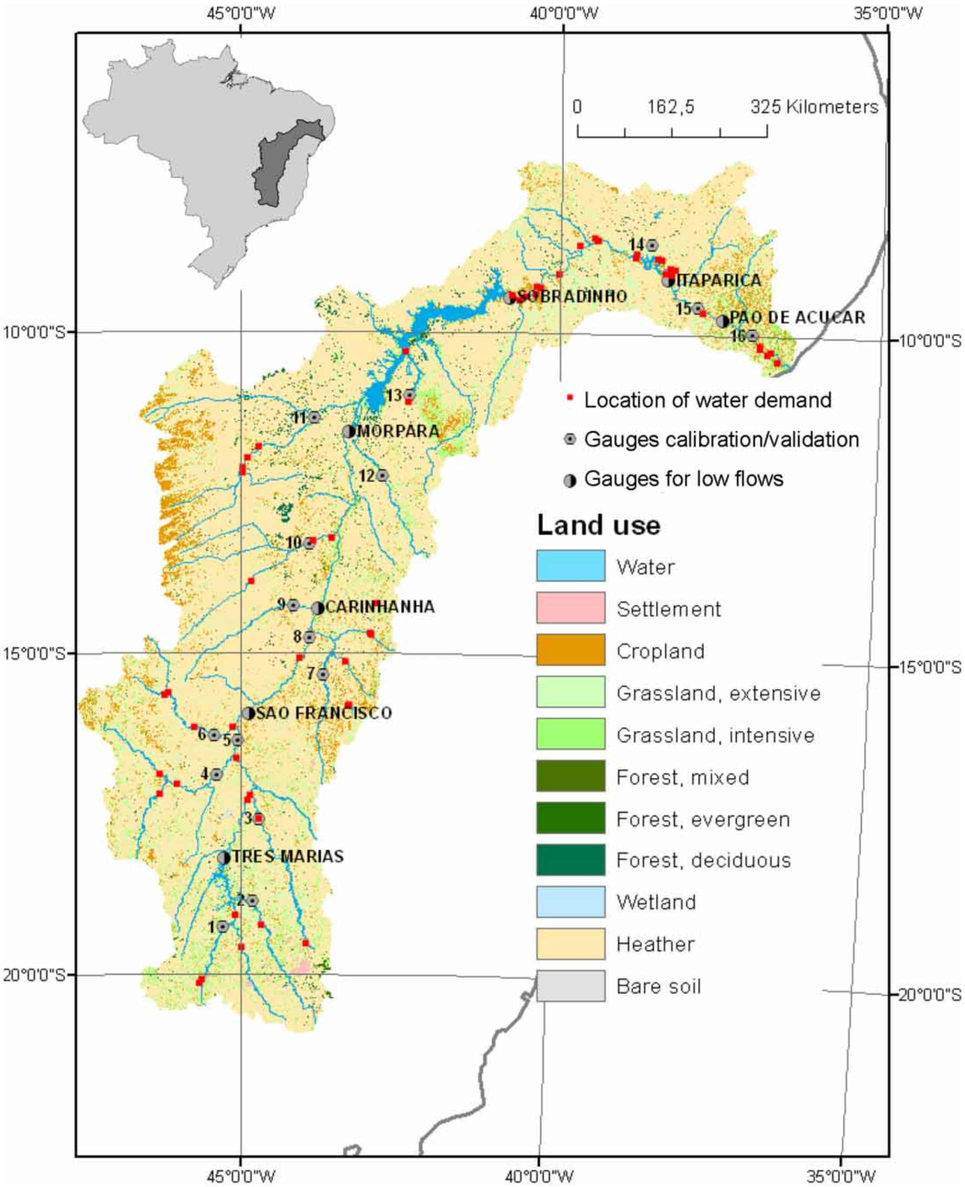

Figure 1 | Overview of São Francisco river basin with locations of demand included in the model, gauges used for calibration and validation, gauges for which low flow analysis is carried out.

to ANA/MMA (2013) the river basin has the lowest mean annual precipitation sum (1,003 mm/a for 1961–2007) of all Brazilian basins. While the mountainous upper part receives annual precipitation sums between 1,000 and 1,750 mm/a (1950–1999), the middle and lower part are characterized by lower values, in some regions only 400 mm/a (ANA/GEF/PNUMA/OEA 2004). The annual potential evaporation in these parts is much higher. According to Neto *et al.* (2007), in the literature on the Sobradinho reservoir (see Figure 1) sums of actual evaporation between 1,529 and 2,538 mm/a are given. Calculations carried out by Neto *et al.* (2007) showed that the lake evaporation varied between 2,041 and 2,291 mm/a in this region. The mean discharge is 2,846 m^3/s and the per capita water availability is 5,183 m^3/a (ANA/MMA 2013, population of 2010). This value is clearly above the threshold of 1,700 m^3/a given as necessary for human consumption by Falkenmark & Widstrand (1992). Despite overall sufficient water availability,

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some sub-basins are seen to be critical regarding the relation between water demand and water availability (ANA/MMA 2013).

According to Cirilo (2008) or De Azevedo (2010), the main problem is not the overall water availability, but the concentration of precipitation within a few months of the year and the high variation between years. In the Sub-Middle São Francisco, the region between reservoirs Sobradinho and Itaparica (see Figure 1), shallow soils and groundwater bodies with little storage capacity are amplifying the problem. Beside these natural factors, the increasing water demand, especially for agricultural irrigation, is seen as a problem (e.g., Medeiros *et al.* 2013; Nunes & Pruski 2015). Between 2006 and 2010, water withdrawals have increased from 180.8 m^3/s to 278.8 m^3/s, with irrigation being the most important user demanding 68% (2006) and 77% (2010) of the withdrawals (ANA/MMA 2013). The river basin is one of the most important sources of water in north-eastern Brazil (Silveira *et al.* 2016). One example for the increasing water demand is the Transposition Project, where water is transferred from the main river to northern regions inside and outside of the basin. The minimum quantity transferred is 26.4 m^3/s, while during high flows the daily maximum is 114.3 m^3/s (ANA 2005).

Due to the climatic characteristics, the first large dam, Três Marias with a total capacity of 19,528 hm^3 (location see Figure 1), was constructed and started its operation in 1961. In the late 1970s Sobradinho reservoir (34,117 hm^3) and in the late 1980s Itaparica reservoir (10,782 hm^3) began operation. The main use is hydropower generation and flood protection. They also deliver water for irrigation and to municipalities, and augment streamflow for navigation. Besides these huge reservoirs, numerous smaller dams were constructed in the basin, mainly to deliver irrigation water. Downstream of Itaparica reservoir a number of large hydropower plants, Apolônio Sales (installed capacity 400 MW), Paulo Afonso 1 (180 MW), Paulo Afonso 2 (445 MW), Paulo Afonso 3 (800 MW), Paulo Afonso 4 (2,460 MW), and Xingó (3,000 MW) are located (ANA/GEF/PNUMA/OEA 2004). These hydropower plants have rather little or no storage capacities. Due to the storage of the reservoirs Três Marias, Sobradinho, and Itaparica, the discharge at the main river has changed dramatically. The natural flow regime with wet and dry seasons no longer exists (Medeiros *et al.* 2013, see Figure S1 in the Supplementary material).

DATA AND METHODS

Data

Observed daily discharge time series for 175 gauges from ANA (2012) were analyzed. *Operador Nacional do Sistema Elétrico* (ONS) provided observed discharge data for selected gauges. Using auto- and cross-correlation, these measurements were checked and their usability was affirmed. Depending on criteria like length of time series (>20 years within the time period 1981 to 2010), catchment area (>500 km^2), only small gaps in time series, and location close to the outlet of a sub-basin, 18 gauges were selected for calibration and validation. Discharges at the gauges 1 to 16 and for Três Marias reservoir and gauge Morpará were used (for locations see Figure 1). These gauges are well distributed over the basin, with the majority concentrated in the southern half, where, due to high precipitation, most of the runoff is generated. For subcatchment 13, two gauges were used, one in the very upstream part of this subcatchment, also used to control the sum of simulated inflows to this subcatchment.

In the calculations of water consumption return flows coefficients depending on water use are applied, e.g., agricultural irrigation 0.2, rural water supply 0.5, urban water supply and industrial use 0.8 (ONS 2005b). The assumed return flow coefficients, the calculation of potential evaporation, assumptions on crop rotation, etc., introduce non-negligible uncertainties in the procedure of naturalization. Especially for huge reservoirs, small volume errors, e.g., resulting from imprecise water level-volume relationship or wind-induced waves at the lake, can lead to large errors in the naturalization according to Equation (2) (Silva *et al.* 2007). For example, at reservoir Sobradinho at high water levels, a difference of 1 cm corresponds to a volume of 40 to 45 hm^3, corresponding to a release of approximately 500 m^3/s, while at low water levels a difference of 1 cm corresponds to a volume of 10 hm^3 and a reservoir release of approximately 115 m^3/s. Despite these uncertainties, naturalized discharges are assumed to be much closer to

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natural flow conditions than the observed, managed discharges (see Figure S1) and be applicable for calibrating and validating the model.

Data of daily storage, inflow, and outflow volumes for the reservoirs Itaparica, Sobradinho, and Três Marias were provided by ONS for the operational periods up to the year 2014. Water level-volume relationships and characteristics of the hydropower plants, e.g., maximum discharge capacity, efficiency of power plant, are available from ONS (2016). Daily climate data (e.g., temperature, precipitation, solar radiation) available from the WATCH-project (http://www.eu-watch.org/, Weedon et al. 2011) for the time period 1979 to 2010 and grid cells of 0.5° (approximately 50 × 50 km at the equator) were used.

Water use data starting in 1998 were downloaded from ANA (2013) and from IGAM (2011). Data about the development of large-scale irrigation projects in the basin, starting in 1968, are available from CODEVASF (2014). Depending on water use the data are mean monthly, e.g., irrigation demand, or mean annual, e.g., potable or industrial water demand. The locations of water demand implemented in the model are shown in Figure 1. The development of water demand from 1979 to 2010, the major part for agricultural irrigation, is shown in Figure S2 (simulation results are discussed in the section 'Results and discussion'). The water demand implemented reaches 204.1 m^3/s in 2010, i.e., 73.2% of the maximal demand of 278.8 m^3/s given in ANA/MMA (2013).

The river network and 1,627 sub-basins for the São Francisco river basin were delineated using the location of gauges and the SRTM-Digital Elevation Model (NASA 2011). Thereafter, hydrotopes were derived using sub-basins, land use (MODIS2001 data set, Friedl et al. 2010, see Figure 1) and soil data. Data for the spatial soil distribution are from EMBRAPA (2013). This map was combined with general soil characteristics according to FAO (FAO 2011) soil classes and adapted to Brazilian data taken from EMBRAPA (2006) and IBGE (2007).

Methods

The Soil and Water Integrated Model is a continuous-time spatially semi-distributed eco-hydrological model. It is process-based, combining physics-based processes and empirical approaches. It was developed from SWAT version '93 (Arnold et al. 1993) and MATSALU models (Krysanova et al. 1989), mainly for climate change and land-use change impact studies. SWIM simulates hydrological processes, vegetation growth, erosion, and nutrient dynamics at the river-basin scale. Hydrotopes or hydrological response units (HRUs) are the core elements of the model. Hydrotopes are generated by overlaying GIS-maps of land-use/cover, soil, and sub-basins, and are considered as units with the same properties regarding bio-physical processes. There is no lateral connection between hydrotopes. All processes at the hydrope level are calculated at the daily time-step. Beside spatial data, SWIM requires temporal input data, e.g., daily climate data including precipitation, air temperature (minimum, maximum, mean), radiation, and humidity.

SWIM has been developed for (central) European climate conditions. For application in the southern hemisphere, a number of adaptations were necessary, e.g., concerning vegetation dynamics. These are temperature driven in (central) Europe, while they are precipitation driven in Brazil. Also, the crop rotation schemes were adjusted to two to four harvests per year. Data on cultivated crops on municipality level from IBGE (2013) were applied to derive crop rotations for different regions of the river basin.

Evapotranspiration is an important part of the water balance, but measurements are generally sparse. Comparing measurements and simulations is therefore of high value to test the validity of a site-specific model set-up. SWIM has been extended and applied to analyze potential evapotranspiration at the plot scale (Silva 2014). Results of two approaches were compared to measurements in north-eastern Brazil. It was shown that the less data demanding approach of Turc–Ivanov (Wendling & Schellin 1986) gives as good results as the data demanding approach of Penman–Monteith (Allen et al. 1998). As a result it was decided to apply the Turc–Ivanov approach.

Time series of daily naturalized discharges for three selected gauges (time period 1931 to 2010) of ONS (2012) were used for calibrating and validating the SWIM model (see Table 1). The procedure of naturalization is described in ONS (2005a), where the effects of reservoir operation and water consumption are considered and briefly described

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Table 1 | Results for calibration (1988–1994) and validation (1995–2000) for gauges

No. (Figure 1)	Code	Name	Drainage area [km^2]	Qmean; obs. (sim.) [m^3/s] 1988–1994	Qmean; obs. (sim.) [m^3/s] 1995–2000	NSE [-] cal.	NSE [-] val.	PBIAS [%]* cal.	PBIAS [%]* val.	Q
1	40100000	Porto Das Andorinhas	13,087	224 (221)	220 (215)	0.83	0.86	1.0	−3.7	obs.
2	40865180	Retiro	11,900	129 (139)	128 (148)	0.69	0.68	7.0	16.0	nat.
-	40990080	UHE Três Marias	50,600	632 (696)	638 (693)	0.80	0.81	13.	8.5	nat.
3	41990000	Varzea Da Palma	25,940	297 (310)	266 (313)	0.61	0.54	4.6	16.6	obs.
4	42980000	Porto Alegre	41,709	511 (538)	351 (349)	0.81	0.70	5.0	−3.2	obs.
5	43200000	São Romão (PCD)	154,100	1,663 (1,688)	1,474 (1,437)	0.74	0.63	3.6	−2.4	obs.
6	43880000	Santo Inacio	23,765	282 (242)	168 (168)	0.70	0.63	−14.0	−2.0	obs.
7	44670000	Colonia Do Jaiba	12,401	16.1 (18.7)	9.4 (10.8)	0.74	0.67	7.0	11.0	obs.
8	44500000	Manga	202,400	1,874 (1,975)	1,705 (1,622)	0.72	0.56	7.5	−5.5	obs.
9	45260000	Juvenilia (PCD)	15,600	150 (129)	125 (87)	0.46	0.49	−14.0	−31.0	obs.
10	45960001	Porto Novo	31,156	223 (217)	195 (172)	0.13	0.31	−4.3	−11.7	obs.
11	46902000	Boqueirão	68,540	289 (338)	282 (308)	0.61	0.54	16.0	8.7	obs.
12	46295000	Ponte BR-242	13,700	6.1 (13.4)	5.2 (14.7)	0.52	0.32	88.0	366	obs.
-	46360000	Morpará	348,074	2,434 (2,382)	2,117 (2,051)	0.73	0.60	−1.4	−10.0	obs.
13	47249000	Rio Verde II	7,470	3.4 (4.3)	1.7 (3.1)	−3.59	−0.09	33.8	23.2	obs.
14	48860000	Floresta	13,240	11.0 (13.3)	4.1 (10.5)	0.52	−0.07	53.0	322	obs.
15	49340080	Xingó	608,693	2,794 (2,895)	2,135 (2,419)	0.64	0.54	4.0	12.0	nat.
16	49660000	Traipú	622,600	2,285 (2,301)	1,889 (1,800)	−0.18	−0.03	2.5	−4.8	obs.

*In observed mean discharges, there can be gaps in the time series, for simulations the mean discharge is calculated from all days within a period, therefore the given Bias (calculated for days with observations only) can deviate from the difference between observed and simulated discharge.
For locations of gauges, see Figure 1.
Gray shading means naturalized discharges from ONS.

here. The naturalized discharges upstream of reservoirs or before the start of reservoir operation are calculated according to Equation (1):

$$Q_{nat} = Q_{obs} + Q_{cons} \quad (1)$$

where: Q_{nat} = natural discharge (m^3/s); Q_{obs} = observed discharge (m^3/s); and Q_{cons} = water consumption of water users (m^3/s), according to Equation (3).

For location of reservoirs (dam) the naturalized discharges are calculated according to Equation (2):

$$Q_{nat} = Q_{out,obs} + Q_{cons} + dVol/0.0864 \quad (2)$$

where: Q_{nat} = natural discharge (m^3/s); $Q_{out,obs}$ = observed discharge from reservoir (m^3/s); Q_{cons} = water consumption of water users at reservoir (m^3/s), according to Equation (3); $dVol$ = change in volume of reservoir (million m^3/d); 0.0864 = constant to transform million m^3/d to m^3/s.

In case there are return flows or water transfers not originating from the upstream region, these need to be subtracted in Equations (1) and (2). The water consumption of water users is calculated according to Equation (3):

$$Q_{cons} = Q_{irr} + Q_{urb} + Q_{rur} + Q_{anim} + Q_{ind} \quad (3)$$

where: Q_{cons} = water consumption of all water users (m^3/s); Q_{irr} = water consumption of irrigation (m^3/s); Q_{urb} = water consumption of urban water supply (m^3/s); Q_{rur} = water consumption of rural water supply (m^3/s); Q_{anim} = water consumption of livestock (animal) water supply (m^3/s); and Q_{ind} = water consumption of industrial water users (m^3/s).

In the calculation of irrigation water consumption the irrigated area, the potential evaporation, a crop-specific

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constant for evaporation, the effective precipitation, the efficiency of irrigation systems, and the return flow coefficient are considered. The main source for information on irrigated agriculture is from IBGE (*Instituto Brasileiro de Geografia e Estatística*), where data from 1960 onward, the time when irrigation started at a larger scale in Brazil, on municipality level are available. The censuses of IBGE are also the main source of information used for the other sectors.

The calculations of water consumption of urban and rural water supply consider the number of inhabitants connected to the water supply system, the per capita water demand, and the return flow coefficients. In the calculation of livestock water consumption the number of animals for each type of livestock, the per capita water demand for each of these, and the return flow coefficient are considered. The calculation of industrial water consumption considers the monetary value of each product produced, the volume of water needed to produce one monetary unit of the product, and the return flow coefficient. The water consumption for all sectors is calculated on municipality level and monthly time scale.

The reservoir module of SWIM, described in Koch *et al.* (2013), was applied. This module is a conceptual representation of storage-release processes based on three management options, to which the reservoirs are assigned: (i) objective is the minimum discharge downstream considering minimum and maximum reservoir volumes for each month, (ii) daily release based on hydropower generation demand considering the minimum and maximum reservoir volumes for each month, other restrictions can be included, e.g., daily minimum or maximum discharges, and (iii) daily release based on the water level of the reservoir.

Using observed daily inflow volumes for the reservoirs Itaparica, Sobradinho, and Três Marias, the parameters for management option (ii) were derived by comparing simulated and observed filling and outflow volumes (observational data provided by ONS). A number of smaller reservoirs are included applying management option (i): Serrinha II, Bico de Pedra, De Cajuru, Estreito, Mandioca, de Miroros, Queimado, and Poco da Cruz.

The water allocation module (WAM) of SWIM is applied to simulate water supply. The WAM options are: (i) water supply from a sub-basin to another sub-basin within the river basin, (ii) water supply from a sub-basin to another river basin or from another river basin to a sub-basin, and (iii) water supply for irrigation, supplied water is assigned as additional precipitation in the recipient sub-basin areas with land-use type agricultural irrigation. The WAM allows assigning minimum flow requirements at the location of withdrawal, and takes efficiency and losses of the water transfer into account. It allows withdrawing water if the minimum flow condition in the reach is secured, i.e., only water volumes above the minimum flow can be withdrawn.

Manual calibration of the SWIM model helped in understanding the hydro-meteorological characteristics and processes of the sub-regions. To estimate the quality of the model, beside annual mean discharges, the goodness of fit using the Nash–Sutcliffe efficiency (NSE) was applied (Nash & Sutcliffe 1970). An NSE equal to 1 represents a perfect fit. The logarithmic Nash–Sutcliffe efficiency magnifying the weight of low flows was not used, because the quality of simulated mean and high flows is important for simulating the filling of the reservoirs properly. Furthermore, percent bias (PBIAS) as statistical criterion and graphical analysis, as suggested by Legates & McCabe (1999), were used to derive calibration parameter sets. For the calibration 17 subcatchments (a conglomerate of sub-basins) were defined and for each subcatchment a parameter set was derived (Figure S3). The most sensitive parameters in the calibration were *ecal* (correction factor for potential evaporation), *roc* parameters (routing coefficients to calculate the storage time constant), *sccor* (correction factor for saturated conductivity), *bff* (baseflow factor), *delay* (groundwater delay), and *abf* (groundwater recession).

The calibration was carried out using naturalized and observed discharges from upstream to downstream gauges. For gauges with naturalized discharges, i.e., Retiro (No. 2 in Figure 1), Três Marias reservoir, and Xingó (No. 15) the parameters during the calibration were changed in order to best fit naturalized discharges. For other gauges at tributaries with water users upstream but without naturalized discharges available, the parameters during the calibration were changed to simulate somewhat higher discharges compared to observed ones. For instance, for gauge Boqueirão (No. 11 in Figure 1) observed discharges from 1977

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onward are available. In the decade 1977 to 1986, flows in the dry season, i.e., May to October, were approximately 10 to 20 m^3/s higher compared to the decade 1988 to 1997, a reduction that can be explained by growing water withdrawals for irrigation during this period (see also Figure S2). This approach was necessary in order to use the naturalized discharges at gauge Xingó in the lower part of the basin during calibration. Only after calibration and validation for gauge Xingó, water management (reservoir operation, water allocation) was included and simulated managed discharges compared to observed discharges.

RESULTS AND DISCUSSION

Observed low flow indices

ONS provided daily observed discharges for selected gauges (years 1931–2014). For these gauges, the 7Q10 was calculated for the decades between 1931 and 2010 (Figure 2, location of gauges see Figure 1). The decades before 1960 represent more or less the natural state. Due to the climatic conditions with sequences of dry and wet years the range for the 7Q10-indices is large.

The Três Marias reservoir, starting its operation in 1961, had small effect on the 7Q10 in the 1960s and 1970s, where little is known about reservoir operation. After the 1970s, the 7Q10 is increasing. The strong effect of Sobradinho reservoir, starting its operation in 1979, is visible with 7Q10-indices higher than in the preceding decades. During the strong drought in 2001 the 7Q10 is low, almost dropping to the level before Sobradinho reservoir began operation. This shows that during wet, normal, and moderately dry years the existing reservoir system is able to augment low flows significantly, during strong droughts the systems reaches its limits. Due to the strong effect of reservoir operation after 1979, it is not possible to estimate effects of land-use or climate change on the 7Q10-indices.

Calibration and validation results for the natural state

The error of observed flows is usually ±5%, while the error associated with flow naturalization can surpass ±40% (WMO 2008). For the Três Marias reservoir, with little water management upstream and the error introduced by flow naturalization being low, the naturalized flow as calculated by ONS is used to assess the quality of the simulations (Figure 3). The water management impact at gauge Xingó is very strong and the uncertainties introduced by flow naturalization are rather high. Therefore, the simulated natural discharge is compared to the naturalized discharge as calculated by ONS including an uncertainty range of ±40% (Figure 4). For the calculation of mean discharge, NSE and PBIAS as given in Table 1, the naturalized discharge

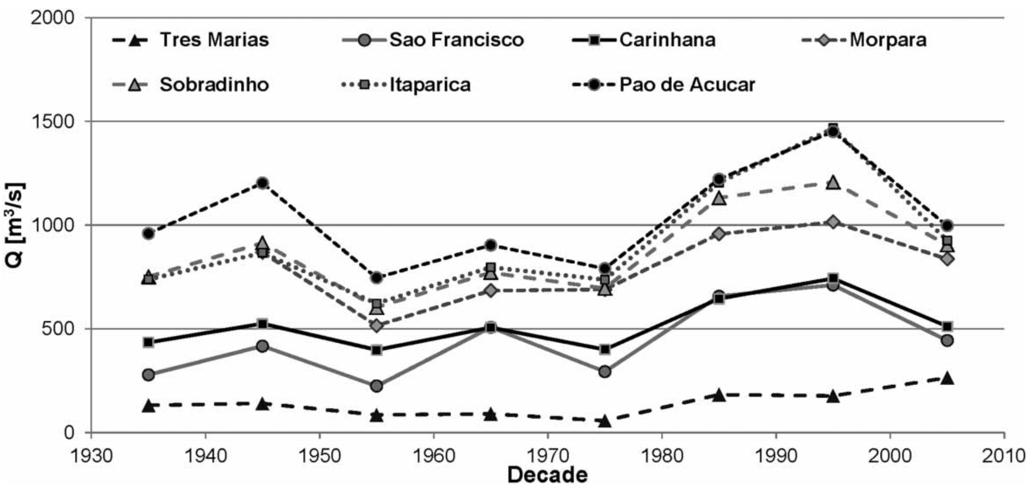

Figure 2 | Development of low flow indices (7Q10) for selected gauges for the decades between 1931 and 2010 (the value placed at year 1935 represents the 7Q10 for the decade 1931–1940, etc.; for location of gauges see Figure 1).

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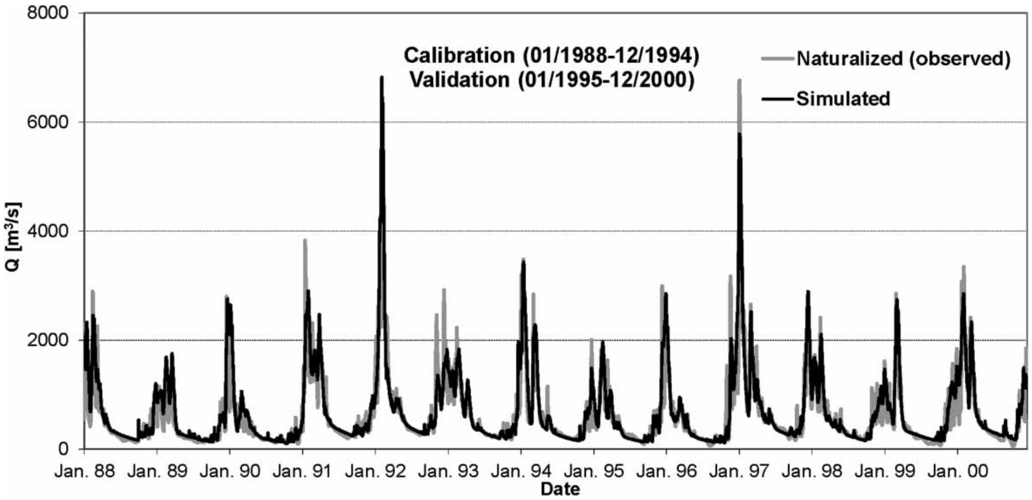

Figure 3 | Naturalized (ONS) and simulated (SWIM) discharges at Três Marias reservoir.

at gauge Xingó is used. Overall, the annual cycle, high, mean, and low discharges are simulated well at both gauges. The values for the most sensitive parameters in the calibration are given in Table S1.

Annual and monthly sums of simulated runoff for the 1,627 SWIM sub-basins are shown in Figure S4 for the years 1981 to 2010; the years 1979 and 1980 are used as warm-up period. The southern and western parts of the basin are generating most of the runoff. Runoff generation is low in the whole river basin in the dry season from May to October.

Simulation results for the managed state

After calibration and validation to naturalized discharges, reservoirs and water withdrawals were included. The locations and quantities of water withdrawals are shown in Figure 1 and Figure S2, respectively. The main characteristics of the largest reservoirs are given in Table S2.

Water resources management simulations usually include long-term operation of reservoirs or water abstraction schemes, while the effective operation is adapted on a short-term basis. For highly managed river basins with

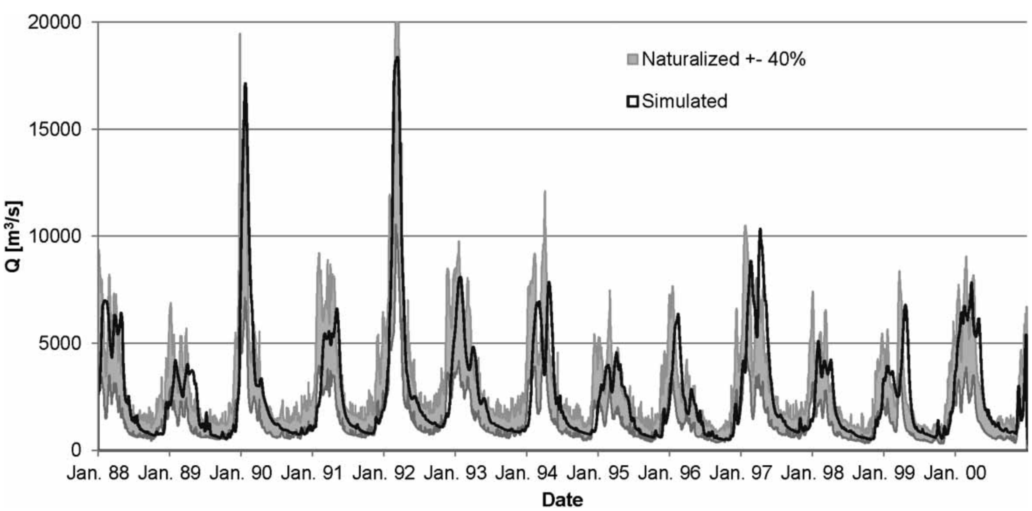

Figure 4 | Naturalized (ONS) and simulated (SWIM) discharges at gauge Xingó (No. 16 in Figure 1).

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many reservoirs, water transfers, and water users it is difficult to obtain good results for calibration and validation (Wang & Xia 2010), as the short-term reservoir operation, e.g., during floods, often is decided at short notice or actual water withdrawals can deviate from planned values, e.g. due to operating failures or withdrawals higher than permitted values. Observed and simulated storage volumes and outflows for Itaparica reservoir for the last decade analyzed are shown as an example in Figure 5. Obviously, the maximum capacity of the reservoir, according to official data 10,782 hm^3 and used as maximum capacity in the simulations, is surpassed frequently during high flows. This is also found for the reservoirs Três Marias and Sobradinho upstream (not shown). Applying the official data for maximum capacity in the simulations leads to deviations between observed and simulated reservoir volumes, and an overestimation of high flows downstream of the dams in the simulations.

The results for calibration and validation are given in Table 1. If reservoir capacities are restricted to official data, the cutting of peak floods is underestimated. For gauges in the main river upstream of Sobradinho reservoir, e.g., Manga or Morpará, applying the scale given in Moriasi et al. (2007), the criteria for the simulations of the managed state are satisfactory to good. Downstream of the reservoirs Sobradinho and Itaparica, i.e., gauge Traipú in Table 1, the NSE for calibration and validation declines markedly, while the PBIAS can be rated as very good. This is due to the fact that the annual cycle is evened out (see observed discharge in Figure S1) and the NSE is a measure to compare observed and simulated dynamics.

Semi-arid regions are known for their unreliable rainfall having a deep impact on the hydrological cycle (Balme et al. 2006). Channels remain dry for most of the year and flow depends almost exclusively on rainfall (Camarasa & Tilford 2002; Bracken et al. 2008). Small deviations in precipitation data can lead to strong differences between observed and simulated flows and the usefulness of using performance indicators like NSE in semi-arid regions has been questioned, e.g., by Costelloe et al. (2005). For such rivers, it seems more appropriate to use the long-term mean discharge as criterion and utilize graphical comparison between precipitation occurrence and volume and simulated runoff occurrence and volume.

The low NSE performance for some gauges in the semi-arid region, e.g., Ponte BR-242, Rio Verde II, and Floresta (No. 12, 13, and 14 in Figure 1 and Table 1), is not surprising and should not be overestimated as these only account for a very small part of discharge in the main river. As discussed above for gauge Boqueirão (No. 11), for a number of gauges at tributaries with no naturalized flows available, the parameterization was done deliberately overestimating the

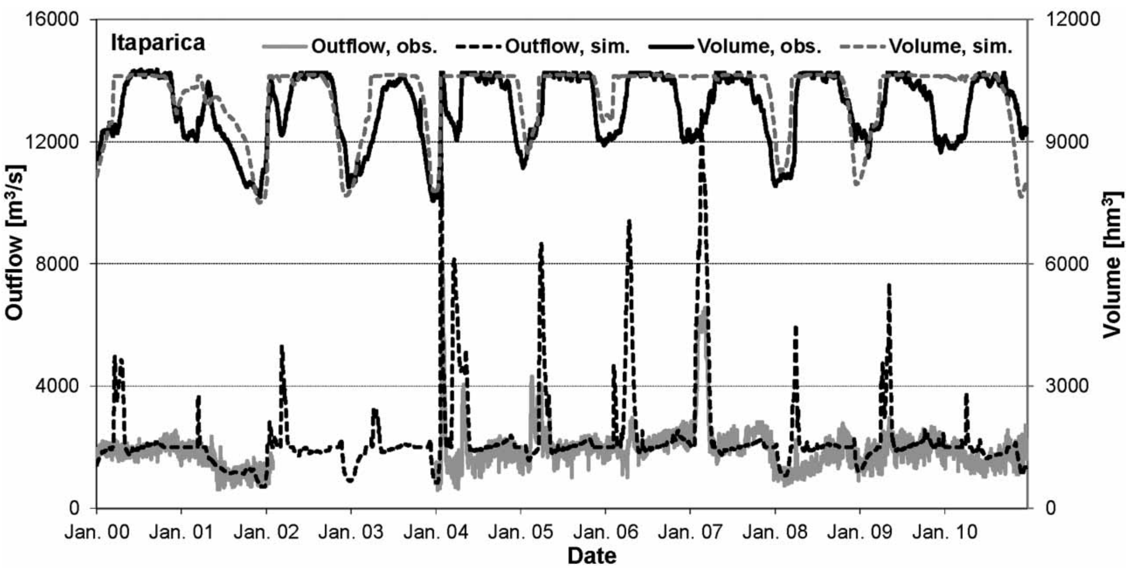

Figure 5 | Observed (ONS) and simulated (SWIM) outflows and volumes for Itaparica reservoir.

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observed discharge. Therefore, the simulated discharges, e.g., at gauge Rio Verde II (No. 10), are much higher than the observed ones, leading to poor results applying NSE and PBIAS as criteria. The results for gauge Traipú (No. 16, managed discharge) are not satisfying applying NSE as criteria, while the results for gauge Xingó (No. 15, natural discharge) are satisfactory to good. On the one hand, as discussed above, the inclusion of water resources management introduces some uncertainties, e.g., due to deviations between long-term management included in the simulations and short-term adaption or even surpassing maximum capacity during high flows (see Figure 5). Furthermore, the PBIAS for gauge Traipú, being less than 5%, can be seen as a very good result. As can be seen in Figure 5 for Itaparica reservoir, the discharge downstream of the dam, where gauge Traipú is located, shows almost no annual cycle while a few short-term peak flows are observed. In the case these peak flows are not simulated or are simulated with some deviation in the occurrence, the NSE will rapidly deteriorate.

Discussing the quality of the simulation, one has to keep in mind that a global climate data set with a resolution of $0.5 \times 0.5^{\circ}$ is used. Some local events, e.g., extreme precipitation events, or local effects, e.g., clouding and global radiation, can be over- or underestimated. Comparing the simulation results with observed data, the general usability of the global climate data set can be deduced. A Brazilian source containing all climate data required for the whole river basin is not known to the authors.

Deviations between observations and simulation results also come from numerous small- to medium-sized reservoirs not included. In Governo do Estado de Pernambuco (1999) for the sub-basin of the river Rio Pajeú, where gauge Floresta (No. 14) is located, a number of approximately 1,380 reservoirs is given, of these 1,338 with a capacity below 500,000 m^3. At the moment only the largest of these reservoirs, Serrinha II with a capacity of 311.1 hm^3, is included.

The simulated water supply shows very low values for the extreme dry year 2001 (Figure S2) and storage volume and outflow for Itaparica reservoir are low (Figure 5). Also in other years simulated water supply is lower than the demand. A number of water users are located on tributaries without huge reservoir storage capacity (Figure 1) and water supply cannot be secured permanently.

Comparison of observed and simulated low flow indices

To analyze observed and simulated low flows, the annual MAM7 index is used. Figure 6(a) shows the annual MAM7 for the natural flow at the reservoirs Três Marias, Sobradinho, and Itaparica. In both the calibration and validation period, annual MAM7 values are simulated very well. Before 1988 the simulations often underestimate the annual MAM7 for Sobradinho and Itaparica, while they overestimated after 2001, also for Três Marias. Reasons for these differences can be land-use changes not included in the simulated natural discharges or missing information on water resources management or errors in the naturalized observed discharges. At Sobradinho reservoir, the 7Q10 of observed naturalized flows for the decade 2001 to 2010 (442 m^3/s) is 38% lower than for the decade of the 1980s (708 m^3/s) and the mean value of the annual MAM7 is 37% lower. Even if land-use change can affect the flow regime, changes of this extent can hardly be explained by land-use change only. At Sobradinho reservoir, the 7Q10 of simulated natural flows for 1981 to 1990 is 625 m^3/s and is about 4% higher than for 2001 to 2010 (602 m^3/s). The mean value of the annual MAM7 (872 m^3/s) is about 10% lower for 2001 to 2010 than for 1981 to 1990. The decline in the simulated flows can be explained by the observed increase in temperature (PBMC 2012), leading to increased evaporation. According to the WATCH data set used for the river basin, the mean temperature for the decades is 24.94 °C (1981–1990), 25.15 °C (1991–2000), and 25.45 °C (2001–2010). For the decade 1981 to 1990, the mean annual precipitation is 970 mm/a (driest year 628 mm/a), for the decade 1991 to 2000 it is 979 mm/a (driest year 631 mm/a), and for the decade 2001 to 2010 it is 989 mm/a (driest year 749 mm/a). Overall, there has been an increase in the mean temperature of 0.5 °C, corresponding to an increase of 2.0%, between 1981 to 1990 and 2001 to 2010, while the mean annual precipitation increased by 19 mm/a (+2.0%) between both decades. The driest year of the decade 2001 to 2010 has an annual precipitation 121 mm (+19%) higher than the driest year of the decade 1981 to 1990. Depending on the temporal and spatial distribution of precipitation, an increase in annual precipitation does not necessarily

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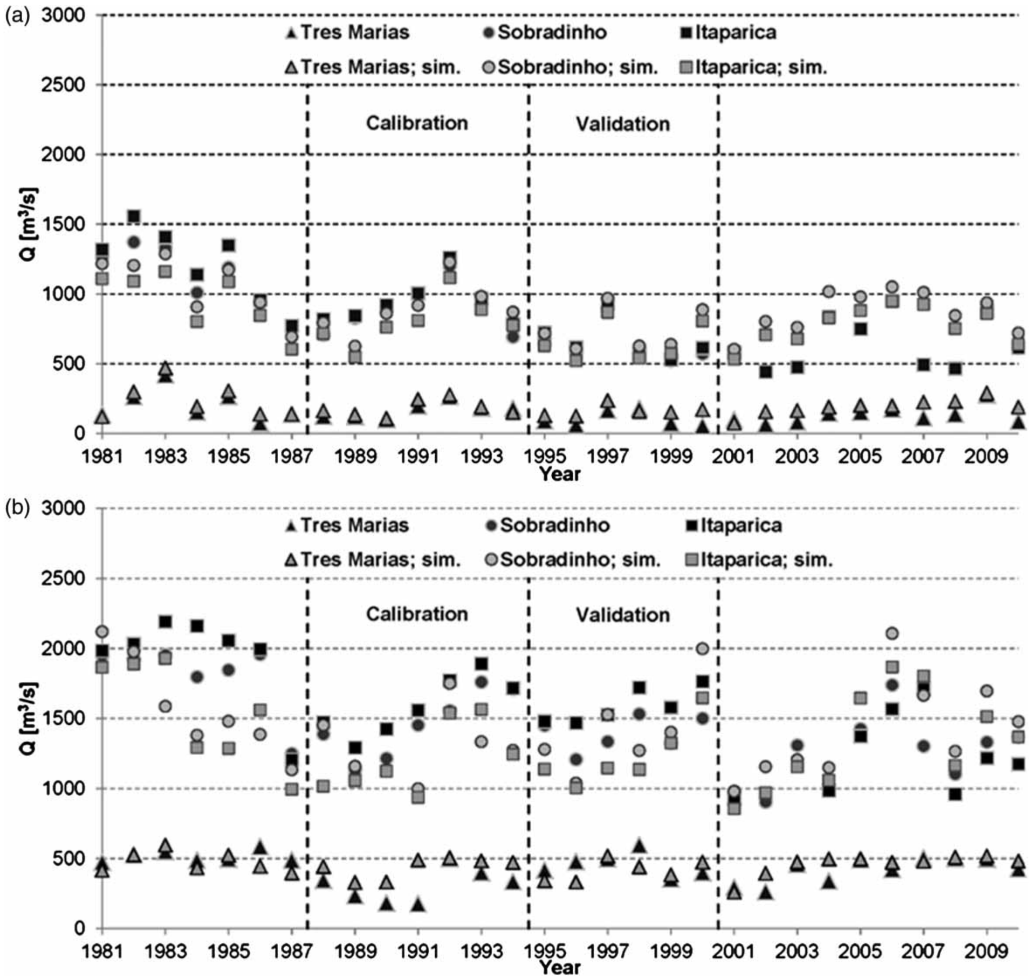

Figure 6 | MAM7-indices for years 1981 to 2010, observed (ONS), and simulated (SWIM) for (a) natural and (b) managed flow.

mean an increase in annual mean discharge or in low flows. Temperatures and annual precipitation sums are only slightly higher in the decade 2001 to 2010 and therefore cannot explain the strong decline for the 7Q10 and the annual MAM7 of observed naturalized flows compared to the decade 1981 to 1990, especially since the driest year in the decade 2001 to 2010 is considerably wetter than in the decade 1981 to 1990.

The annual MAM7 for observed and simulated managed flows are shown in Figure 6(b). The best simulation results are achieved for the decade 2001 to 2010, probably because the operation of reservoirs included in the model represents the most recent state.

Figure S5 shows natural and managed annual MAM7 observed and simulated at reservoirs Três Marias and Sobradinho. Although there are deviations from the 1:1 line, a clear increase in the MAM7 as effect of the reservoir operation, is simulated well.

CONCLUSIONS

Due to reservoir operation, low flow indices calculated for selected gauges in the São Francisco river basin have changed markedly. The analysis of observed low flows shows that during wet, normal, and moderately dry years, the existing system of reservoirs is able to augment low flows. During strong droughts, e.g., year 2001, the water management system reaches its limits. This effect is also represented in the simulations.

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The approach applied to separate the natural from the anthropogenic (managed) subsystem to analyze these discretely and keep this separation in the model by (i) calibration and validation on naturalized discharges and (ii) simulation including water management, is promising. The model developed integrates the most important hydrological processes and can thus be used to assess the impacts of climate change and land-use scenarios on water balance components, including water resources management, e.g., reservoir operation and water supply.

Overall, the data availability for the São Francisco river basin is good. However, for the model set-up, the calibration and validation of a number of global data sets were used, because consistent data from Brazilian sources were not available (e.g., climate, land-use). The eco-hydrological model SWIM, developed for (central) European conditions, was modified to fit South American conditions. A number of problems during the calibration and validation of the model could be solved, while some problems, e.g., the reliability of naturalized discharges, remain. Despite the uncertainties in the naturalization procedure, the naturalized discharges are assumed to be much closer to natural flow conditions than the observed, managed discharges, and can be applied to for the calibration and validation of the model.

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