INNOVATE-Discussion-Paper

Towards a more ecologically-oriented reservoir management: Testing release rules for the sub-middle and lower São Francisco river basin

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Sumário Executivo

A gestão dos recursos hídricos tem um papel importante no abastecimento de água necessário para atender as necessidades dos diferentes usuários. Assim, reservatórios que superam a natureza estocástica dos fluxos dos rios e atendem as demandas de água de vários usuários têm vindo a ser construídos em muitas regiões do mundo. Com a construção e operação de barragens surgiu também a discussão sobre os benefícios e os custos ambientais e sociais destas obras. Hoje em dia sabe-se que a alteração do regime de vazões resultante das escolhas de operação de reservatórios afeta as condições ecológicas da respectiva secção do rio a jusante, por exemplo, pela perda de planícies aluviais, zonas ribeirinhas e zonas úmidas associadas. Como resultado, ao longo das últimas décadas tem-se vindo a debater sobre regimes de fluxo mais ecológicos para as bacias hidrográficas. Existem em todo o mundo mais de 200 métodos para a determinação de vazões ecológicas e que são agrupados em quatro categorias:

i) regras hidrológicas,
ii) métodos de classificação hidráulicos,
iii) métodos de simulação de habitat, e
iv) metodologias holísticas.

Normalmente, o debate se foca em como gerenciar reservatórios de forma a proporcionar vazões ecológicas que mantenham os serviços ecossistêmicos a jusante tendo em consideração as demandas humanas. Os ecossistemas dos próprios reservatórios raramente são incluídos neste debate sobre fluxos ecológicos. Por exemplo, as variações do nível da água podem levar ao deslocamento de linhas costeiras em diferentes escalas de tempo (de curto a longo prazo) e influenciam de várias maneiras os ecossistemas aquáticos. Embora estas variações sejam observadas em lagos naturais, os reservatórios apresentam normalmente variações do nível de água superiores. Esta variação de amplitude é influenciada, principalmente, pela morfometria do reservatório e grau da regulação da descarga antropogênica. Em sistemas como este, as interações aquático-terrestres são fortemente aceleradas devido à inundação periódica e dessecação das margens do reservatório. Estes sistemas mostram também uma alta rotatividade de nutrientes que por sua vez provoca parcialmente processos de eutrofização. Recentemente, hidrogramas ambientais foram desenvolvidos no âmbito do projeto "*Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental*, do Baixo trecho do rio São Francisco - AIHA". Este projeto permitiu definir valores-alvo mensais para vazão do rio (sendo o valor mais baixo 1 100 m³/s, de julho a outubro) para a sub-bacia do médio e baixo rio São Francisco. Participaram na discussão e no

desenvolvimento dos hidrogramas ambientais membros das comunidades locais, bem como membros das autoridades responsáveis pelo setor da água. Os hidrogramas ambientais foram desenvolvidos principalmente considerando as condições do rio e possíveis utilizações da água ao longo do respectivo trecho do rio.

No entanto, para além de se ter em conta as condições do rio e usos da água, também se pode adoptar uma estratégia mais ecológica para a gestão de reservatórios. Tanto para o reservatório de Sobradinho, como para o de Itaparica foram observadas fortes variações diárias no nível da água. A restrição de variações do nível da água pode ajudar a alcançar um estado ecológico mais estável das margens do lago/reservatório. No entanto, uma mudança de gestão do reservatório afetará também a disponibilidade de água para irrigação agrícola e geração de energia hidrelétrica. Neste estudo são discutidas e aplicadas diferentes opções de gestão de reservatórios, com foco em aspectos ambientais.

As quatro opções de gestão de reservatórios que foram analisadas, incluindo três com enfoque em aspectos ecológicos, são as seguintes:

- Estado de Referência: gestão atual (*Reference*),
- Vazão Ecológica (hidrogramas ambientais): fornecimento de vazões mínimas para a sub-bacia do médio e baixo rio São Francisco (*Ecological discharge, Qecol*),
- Capacidade Reduzida: redução de variações do nível da água, reduzindo a capacidade útil de reservatórios (*Reduced Capacity*),
- Nível de Água: as variações do nível da água são reduzidas ao máximo para 0,05 m/dia (*Water level*).

Durante períodos de secas prolongadas nenhuma destas opções de gestão apresentadas pode assegurar as vazões mínimas (hidrogramas ambientais) estabelecidas para anos secos, enquanto que em anos chuvosos ou normais, as vazões mínimas poderão ser atingidas na maioria dos casos. Os volumes efluentes da opção *Vazão Ecológica* definidos para a estação chuvosa resultam em volumes de água nos reservatórios baixos durante todo o ano. E mesmo conduzindo a uma redução da taxa de evaporação, o risco de que as vazões efluentes estipuladas durante a estação seca não sejam alcançadas aumentará. Por conseguinte, a vazão mínima efluente parece ser um valor demasiadamente estático e muito elevado para o sistema em questão. Com a opção *Capacidade Reduzida,* os níveis de água e respectivos volumes armazenados são mais constantes. Neste caso, a taxa de evaporação não muda drasticamente, mas a geração de energia hidrelétrica diminui fortemente. A opção *Nível de Água* leva a volumes armazenados elevados. Em geral, comparando esta opção com as opções mencionadas anteriormente, a taxa de evaporação diminui, enquanto a geração de energia hidrelétrica é mais equilibrada ao longo do ano. Usando a opção de *Capacidade Reduzida*, a variação do nível da água dos reservatórios é menor. Para a opção *Nível de Água,* as variações de nível do reservatório são mais elevadas em comparação com a opção de *Capacidade Reduzida*, mas menor em comparação com as variações das opções *Referência* e *Vazão Ecológica.* Para a opção de *Vazão Ecológica*, as variações do nível da água são maiores. A opção *Nível de Água* parece ser a mais flexível de todas, especialmente durante os períodos mais secos, assegurando maior consideração das funções dos ecossistemas.

Estas opções de operação destinam-se a ser exemplos e com estes resultados é possível ter uma visão inicial sobre as consequências de diferentes tipos de gestão de reservatórios. As restrições precisam ser discutidas com as diferentes partes interessadas da bacia do rio São Francisco (*stakeholder*).

Os hidrogramas ambientais foram desenvolvidos com base nas vazões naturais referentes ao medidor de vazão em Traipu no baixo do rio São Francisco. Em uma série de estudos, os hidrogramas ambientais foram aplicados para todo o sub-médio do rio São Francisco, ou seja, como critério de vazão efluente para o reservatório de Sobradinho. Uma análise das medições das vazões efluentes do reservatório de Sobradinho e avaliação de Traipu mostram que durante a estação chuvosa, entre 5 a 10% da vazão é gerada na própria sub-bacia, no sub-médio do rio São Francisco. Portanto, a vazão efluente do reservatório Sobradinho pode ser reduzida. Esta redução da vazão mínima durante a estação chuvosa pode ajudar a assegurar que as vazões mínimas poderão ser atingidas durante a estação seca.

Executive Summary

Water resource management plays a major role in delivering water required for different users and uses. Reservoirs are built to overcome the stochastic nature of river flows and to make water supply more reliable for users. With the construction and operation of dams a discussion on the benefits and environmental and social costs emerged. The flow regime manipulated by reservoir regulation affects the ecological state of the respective downstream river section, e.g. by loss of floodplains, riparian zones and associated wetlands. As a result, over the last decades there has been a discussion of a more ecologically or environmentally oriented flow regime for river basins. Usually the discussion focusses on how to manage reservoirs in a way that provides ecological flows for sustaining ecosystem services downstream while taking human demands into consideration. Ecosystems of reservoirs themselves are rarely included in these discussions. For example, water level variations lead to the displacement of shorelines and strongly influence the aquatic ecosystem in various ways. The amplitude of water level variations is mainly influenced by reservoir morphometry and the degree of anthropogenic discharge regulation. In these fluctuating systems terrestrial-aquatic interactions are heavily accelerated due to periodical inundation and desiccation of reservoir margins and show high nutrient turnover in respect to eutrophication processes. Recently, environmental hydrograms (*hidrogramas ambientais*) were developed within the project "*Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental, do baixo trecho do rio São Francisco - AIHA*". This project provided monthly target values for river discharges (the lowest value suggested is 1 100 m^3/s from July to October) for the sub-middle and lower São Francisco river basin. In the discussion about and the development of the environmental hydrograms both, local people and water authorities, were involved. The environmental hydrograms were developed mainly considering the river in-stream requirements and water uses along the respective river stretch.

Besides looking on the river's in-stream requirements and water uses, one could also look at reservoirs themselves from a more ecological perspective. In fact, strong daily water level variations were observed at the reservoirs Sobradinho and Itaparica. Restricting water level variations can help to achieve a more ecologically stable state of the lakeside. However, a changed reservoir management will directly affect water availability for agricultural irrigation and hydropower generation.

In this study different management options for reservoirs are discussed and applied, focusing on selected environmental aspects. Four different reservoir management options, including three options focusing on ecological aspects, were analyzed:

- *Reference State:* present management,
- *Ecological discharge* (based on environmental hydrograms): provide minimum discharges for the sub-middle and lower São Francisco river basin,
- *Reduced Capacity:* reduction of water level variations by reducing the live capacity of reservoirs,
- *Water level:* water level fluctuations are reduced to maximum of 0.05 m/day.

During prolonged drought periods none of the management options can safeguard the minimum discharge levels (*hidrogramas ambientais*) established for dry years while in wet or normal years minimum discharge levels can be met in most cases. The outflow volumes set for the wet season in the *Ecological discharge* option lead to low stored reservoir volumes (water levels) year-round. This reduces evaporation rates strongly but increases the risk of failure to meet the requested outflow during the dry season. The minimum discharge seems to be too static and too high for the existing system. The *Reduced Capacity* option leads to more constant stored reservoir volumes and respective water levels. Evaporation rates do not change drastically, but hydropower generation declines strongly. The *Water level* option leads to high stored reservoir volumes and respective water levels. Overall, the evaporation rates are decreasing while the hydropower generation is more balanced over the year compared to the other options. The water level variations for the reservoirs are least for the *Reduced Capacity* option*.* For the *Water level* option the variations are higher compared to the *Reduced Capacity* option, but smaller compared to the options *Reference* and *Ecological discharge*. For the *Ecological discharge* option water level variations are strongest. The *Water level* option seems to be more flexible than the other ones, especially during longer dry periods and leads to enhanced consideration of ecosystem functions.

The restrictions applied in the different management options are intended to be examples and the results presented should give a first insight into the consequences of the changed reservoir management. With these results, we want to initiate and strengthen a discussion about the applied values and optional reservoir management strategies in the São Francisco river basin with the related stakeholders.

1. Introduction

In many regions of the world population growth and economic development are increasing the demand for water, food and energy. Water resource management plays a major role in delivering the water required for this development. One of the most important tasks in the management of water resources is to balance water supply and demand, if these do not coincide spatially and temporally. Reservoirs are built to overcome the stochastic nature of river flows in many regions of the world and to make water supply more reliable for users. In the last century, there was a boom of dam constructions, large and small, as most significant and visible tool for water quantity control (Bird & Wallas, 2001; Bergkamp et al., 2000; WCD, 2000). Today, more than 47 000 large dams and several 100 000 smaller dams around the world regulate rivers for many purposes, such as water supply for agricultural irrigation or households, electricity generation, flood control, recreation as well as many other uses (Richter & Thomas, 2007; Rosenberg et al., 2000; WCD, 2000; Tundisi et al., 1998). With the construction and operation of dams a discussion on the benefits and environmental and social costs emerged (Scudder, 2005; Bergkamp et al., 2000). Main impacts of large dams, due to the damming of the river system and the temporal storage of water, include altered flow regimes, alteration of sediment transport, change of aquatic biodiversity, flooding or falling dry of native vegetation, greenhouse gas emissions, reallocation of water by evaporation and infiltration, resettlement of human population and loss of fertile soils (Anderson et al., 2006; Fearnside, 2002; WCD, 2000).

The water quantity controlled by a reservoir is highly dependent on the water balance of the upstream watershed. Climate, particularly precipitation, air temperature and potential evaporation, and watershed characteristics such as slope, drainage density, water retention capacity in soils and vegetation, groundwater recharge, and water use are major driving factors. With anthropogenic alterations of the watershed the water balance gets modified as well. Land-use, population growth, agricultural and industrial water use, and the reservoir itself, due to evaporation from the surface or seepage, are influencing the water balance significantly. Evaporation has to be considered especially in semi-arid and arid climates. Changes in the named catchment characteristics not only change the long-term water balance but also can change the timing, frequency and magnitude of low and high flows. Additionally, water quality is affected by cultural eutrophication and higher retention times and therewith lower dilution of pollutants from agricultural and urban areas (Smith et al., 2010). Future trends show population growth with enhanced food and energy demand, accompanied by climate change which can affect water resources strongly.

The flow regime manipulated by reservoir regulation affects the ecological state of the respective downstream river section, e.g. by loss of floodplains, riparian zones and associated wetlands (Rosenberg et al., 2000; Pringle et al., 2000). As a result, over the last decades there has been a discussion of a more ecologically or environmentally oriented flow regime for river basins (Porse et al., 2015; Yin et al., 2011). Environmental flows often contain water use aspects, while ecological flows usually consider the ecological state only. Despite this differentiation in the following we will refer to instream flow requirements, ecological flows or environmental flows as “ecological flows”.

Usually the discussion focusses on how to manage reservoirs in a way that provides ecological flows for sustaining ecosystem services downstream while considering human demands, e.g. the provision of potable or irrigation water and the generation of electricity by hydropower plants (e.g. Porse et al., 2015; Richter & Thomas, 2007). For the determination of ecological flows there exist worldwide more than 200 methods that usually are grouped into four categories i) hydrological rules, ii) hydraulic rating methods, iii) habitat simulation methods, and iv) holistic methodologies. For an in-depth discussion of these methods the reader is referred to King et al. (2008) or Arthington et al. (2006).

With regard to ecological flows one has to keep in mind a return to an entirely natural flow regime downstream of reservoirs would mean to give up the primary functions of reservoirs. Therefore, only partial restoration of unaffected flow regime is possible in most cases. For instance the EU-WFD (Water Framework Directive of the EU, 2000) demands to reach “good ecological potential” for artificial water bodies (see Moss, 2008). However, as long as they are managed to supply water and generate hydropower they hardly can reach the state of a natural lake.

Ecosystems of reservoirs themselves are rarely included in the discussions on ecological flows. However, an integration of ecological water management for reservoirs could enhance their ecosystem stability and functions. For example, water level variations lead to the displacement of shorelines in different time scales from short- to long-term and strongly influence the aquatic ecosystem in various ways (Hirsch et al., 2014; Hofmann et al., 2008; Wantzen et al., 2008b; Coops et al., 2003). Although natural lakes show water level variations too, reservoirs show higher amplitudes usually (Hirsch et al., 2014; Selge & Gunkel, 2013). The amplitude of water level variations is mainly influenced by reservoir morphometry and the degree of anthropogenic discharge regulation. Dams are preferably constructed in narrow gauges to reduce dam construction costs and gaining a high head for hydropower generation. When this condition is not complied large areas are getting inundated with rising and desiccated with declining water level. On the one hand areas inundated for longer time periods can be seen as wetlands with its multiple ecosystem functions and high biodiversity. On the other hand, dislocation of sediments by erosion, salinization of margins, zonation of aquatic macrophytes by varying conditions, due to higher water level or suspended matter with rising water table, and nutrient release by rewetted floodplains are disturbing the ecosystem (Wantzen et al., 2008b; Austin et al., 2003; Coops et al., 2003). Especially biodiversity is affected strongly by occurring physico-chemical habitat changes (McCartney et al., 2000). During strong short-term water level variations aquatic and riparian organisms are physically stressed (Hofman et al., 2008). In these fluctuating systems terrestrial-aquatic interactions are heavily accelerated due to periodical inundation and desiccation of reservoir margins and show high nutrient turnover in respect to eutrophication processes.

Different management options for reservoirs, focusing on selected environmental aspects, i.e. the riverine environment or the environment of reservoirs themselves, are discussed and applied in a simulation study.

The study presented was carried out within the Brazilian-German research project “Interplay among multiple uses of water reservoirs via innovative coupling of substance cycles in aquatic and terrestrial ecosystems (INNOVATE)”. The values applied in the different management options are intended to be examples and the results presented should give a first insight into the consequences of the changed reservoir management. The values applied are to be discussed with stakeholders from the São Francisco river basin.

2. Material and methods

2.1 Study area: The São Francisco river basin

The São Francisco river basin in the east of Brazil has an area of approximately 640 000 km^2. The drainage area occupies 8% of Brazil and covers six states: Bahia, Minas Gerais, Pernambuco, Alagoas, Sergipe, Goiás and the Federal District. More than 14.2 million people, equivalent to 7.5 % of the country's population, lived in the region in 2010 (IBGE, 2010). While the mountainous upper part receives high annual precipitation sums between 1 000 and 1 750 mm/a (years 1950-1999), the middle and lower part are characterized by much lower annual precipitation sums, in some regions only 400 mm/a (ANA/GEF/PNUMA/OEA, 2004). The annual potential evaporation in the sub-middle is much higher than annual precipitation. For the Sobradinho reservoir, located in the sub-middle São Francisco river basin, a literature review by Neto et al. (2007) gives annual evaporation sums between 1 529 and 2 538 mm/a. These values were calculated using different approaches and time periods. Calculations carried out by Neto et al. (2007) using different approaches give annual evaporation sums between 2 041 and 2 291 mm/a.

The mean discharge at the mouth of the São Francisco river is 2 846 m^3/s (ANA/MMA, 2013). Overall, the water availability calculated according to Falkenmark & Widstrand (1992) with a per capita water availability of 5 183 m^3/a is sufficient (see Koch et al., 2015). Some sub-basins, e.g. Rio das Velhas, Paraopeba and Rio Grande Verde, are critical regarding the relation between water demand and water availability (ANA/MMA, 2013). According to Azevedo et al. (2010), Cirilo (2008) and Lerner (2006) 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. Shallow groundwater bodies with little storage capacity are amplifying the problem. Beside these natural factors the ever increasing water demand, especially for agricultural irrigation, is seen as problem in the region (e.g. Medeiros et al., 2013; Braga et al., 2008). Between 2006 and 2010 the water withdrawals in the basin 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 overall withdrawals (ANA/MMA, 2013). A future increase in water demand is expected, including the Transposition Project, where water is transferred to northern regions inside and outside of the basin (see, e.g. Lee et al., 2014; Lerner & Carpio, 2006). The secured quantity transferred by the two axes of the transposition is licensed at 26.4 m^3/s, while during high flows temporally up to 127 m^3/s (averaged daily maximum of 114.3 m^3/s) can be transferred.

Due to the climatic characteristics mentioned, in the middle of the last century the first large dam, Três Marias with a total capacity of 19 528 hm^3 (live capacity of 15 278 hm^3), was constructed. In the late 1970ies Sobradinho reservoir (total capacity of 34 117 hm^3, live capacity of 28 669 hm^3) and in the late 1980ies Itaparica reservoir (total capacity of 10 782 hm^3, live capacity of 3 549 hm^3) were constructed. The reservoirs were mainly constructed for hydropower generation and flood control. However, they also deliver water for agricultural irrigation and to municipalities and are used to augment streamflow for navigation. Beside these huge reservoirs, a great number of smaller dams were constructed in the basin, mainly to deliver water for agricultural irrigation, a few including hydropower plants. Downstream of Itaparica reservoir a number of large hydropower plants are located: 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) (ANA/GEF/PNUMA/OEA, 2004). These hydropower plants have no or very little live capacities.

Due to the large reservoirs and their storage effects 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). This can also be seen in Fig. 7, where the inflow to and the outflow of Sobradinho reservoir are shown. Recently, for the sub-middle and lower São Francisco river basin so-called *hidrogramas ambientais* (environmental hydrograms), giving monthly target values for river discharge, have been developed within the project "*Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental, do baixo trecho do rio São Francisco* – AIHA" (see Ferreira, 2014). In the discussion on and the development of the *hidrogramas ambientais* both, local people, e.g. fisherman, and the water authorities, e.g. *Comitê da Bacia Hidrográfica do Rio São Francisco* – CBHSF, were involved. The named *hidrogramas ambientais* was developed mainly considering the rivers in-stream requirements, e.g. live cycles of riparian and aquatic plants and animals, and water uses, e.g. agricultural irrigation, along the respective river stretch.

2.2 Data sources

Daily inflow and outflow time series, and volumes for the reservoirs Sobradinho and Itaparica up to the year 2014 were delivered from *Operador Nacional do Sistema Elétrico* (ONS) to the INNOVATE project. The reservoir module of the eco-hydrological model SWIM developed by Koch et al. (2013) was used in this study. However, in order to exclude deviations between observed and simulated discharges the reservoir module was applied outside of the SWIM model, i.e. the observed daily inflow time series were used as input for the reservoir module.

Daily climate data (T_{max}, T_{mean}, T_{min}, precipitation, wind speed, solar radiation, air pressure, and relative humidity) were available from the WATCH-project (http://www.eu-watch.org/; Weedon et al., 2011). These data were used to calculate the potential evaporation. In a separate study (Silva, 2014), SWIM has been extended and applied to analyze potential evaporation rates at the plot scale comparing different approaches for the calculation of potential evaporation. Results of both approaches were compared to measurements in north-eastern Brazil. It could be shown that the much less data demanding approach of TURC-IVANOV (cf. 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 approach of TURC-IVANOV in the simulations. Using the observed inflow time series, precipitation and the potential evaporation rates calculated by SWIM, the reservoir module can simulate the management of the reservoirs Sobradinho and Itaparica satisfactorily (compare observed and simulated "Reference" in Figs. 4 to 7). Water withdrawals from the reservoirs are included in the simulations.

In Table 1 the monthly values for minimum discharge (*hidrogramas ambientais*) for the sub-middle and lower São Francisco river basin are listed. These values were developed for normal and dry years within the project AIHA and were derived using the Building Block Methodology (see Ferreira, 2014; Medeiros et al., 2013).

Table 1: Monthly values for minimum discharge (*hidrogramas ambientais*) in the sub-middle and lower São Francisco river basin, normal and dry year (from Project AIHA)

month [m³/s]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
normal year	2 754	3 150	3 097	2 685	1 727	1 588	1 448	1 300	1 300	1 300	1 647	2 234
dry year	2 020	2 300	2 100	1 837	1 271	1 218	1 100	1 100	1 100	1 100	1 331	1 740

The relations volume (live capacity) to water surface area and volume to water surface area-volume-coefficients, calculated as water surface area (in km^2) per volume unit (in hm^3), for the Sobradinho and Itaparica reservoirs are shown in Fig. 1. As can be seen the volume to water surface area-volume-coefficient is almost constant for Itaparica reservoir. For Sobradinho reservoir the values for the volume to water surface area-volume-coefficient are higher for lower volumes. That means, for low volumes the respective water surface area is comparably high and evaporation losses per volume unit are increasing with lower volumes.

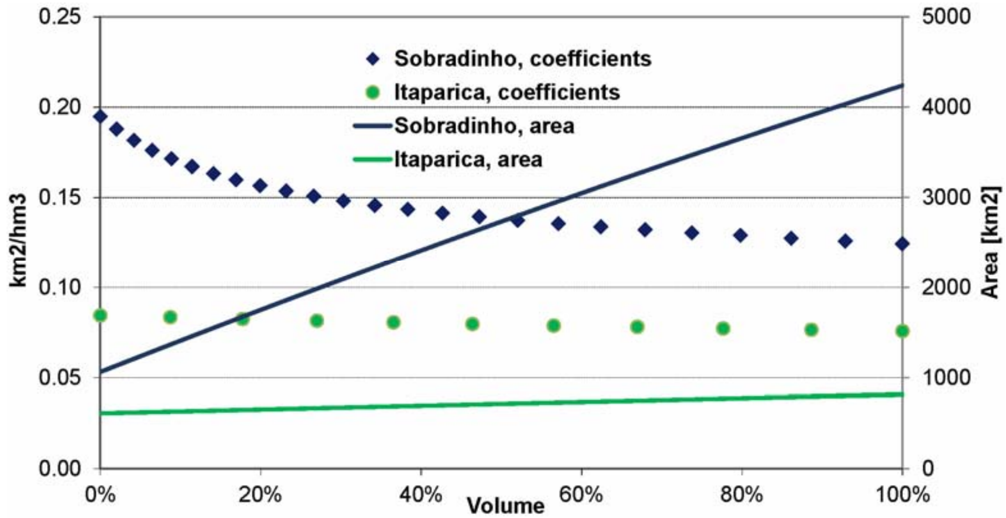

Fig. 1: Relation of volumes (live capacity) to water surface area and to area-volume-coefficient for Sobradinho and Itaparica reservoirs

2.3 Reservoir management options for the sub-middle and lower São Francisco river basin

Besides looking on the river's in-stream requirements and water uses, one could also look at reservoirs themselves from a more ecological perspective. In fact, the daily water level variations at the reservoirs Sobradinho and Itaparica in the past have surpassed 0.25 m/d and 1.00 m/d, respectively. In the course of the year minimum as well as maximum water level can be reached in both reservoirs, i.e. the water level variations for the reservoirs Sobradinho and Itaparica can reach 10 m/a and 5 m/a, respectively. Restricting water level variations of these reservoirs can help to achieve a more ecologically stable state of the lakeside. However, a changed reservoir management will directly affect water availability for agricultural irrigation and hydropower generation.

Today's water management system of the sub-middle and lower São Francisco river basin is in operation since the end of the 1980ies, when the damming of the Itaparica reservoir was completed. The last of the large hydropower plants installed is Xingó, operating since 1994 (ANA/GEF/PNUMA/OEA, 2004). However, due to its low capacity the Xingó dam has very little effect on the discharge. Therefore, all results are presented for the time period 1991 to 2010, enabling a comparison between observations and simulation results. Applying the reservoir module of SWIM the management of the reservoirs can be simulated reliably (see observed and simulated "Reference" in Figs. 4 to 7 in this paper).

An overview on the main objectives of the selected management options is given in Table 2, further information are given in the following sections.

Table 2: Main objectives and steering strategies for management scenarios

Scenario	Main objectives	Steering strategy	Reservoir	Water level [m a.s.l.] minimum	maximum	Live capacity [hm3]
Refe-rence	Hydropower generation, water supply, flood control		Sobra-dinho	380.5	392.5	28 669
			Itapa-rica	299.0	304.0	3 549
Qecol (hidrogr. ambien.)	Instream flow requirements downstream of reservoirs, water supply, flood control	Changing reservoir management to meet minimum flow	Sobra-dinho	380.5	392.5	28 669
			Itapa-rica	299.0	304.0	3,549
Water Level	Ecology in reservoirs and downstream river sections and flood control	Reducing water level fluctuations in reservoirs to 5 cm/d	Sobra-dinho	380.5	390.0	19 479
			Itapa-rica	299.0	304.0	3 549
Reduced Capacity	Ecology in reservoirs, reducing evaporation losses, hydropower generation	Reducing water level fluctuations in reservoirs to 0.5 m/a	Sobra-dinho	388.5	389.0	1 446
			Itapa-rica	303.5	304.0	403

Observation and Simulation of Reference State

Overall, four different reservoir management options, including three options focusing on ecological aspects, were analyzed. The first option simulated corresponds to the present management (“Reference”). In the simulations for higher volumes respective water levels less water is released for hydropower generation, while lower volumes require the release of larger water quantities. However, to prevent a strong decline of the volume or risking the drying out of the reservoirs, for lower volumes restrictions to the released quantities are set (see Fig. 3 for Sobradinho reservoir, “Reference”). These restrictions are set depending on the season. For instance in the month of June, the start of the dry season, the required quantities are only released if the volume is rather high. In the month of October, the end of the dry season, the required quantities can be released at much lower volumes (Fig. 3). Monthly potential evaporation rates, minima, mean and maxima, for the Sobradinho reservoir and the share of mean evaporation on observed mean monthly inflow are shown in Fig. 2.

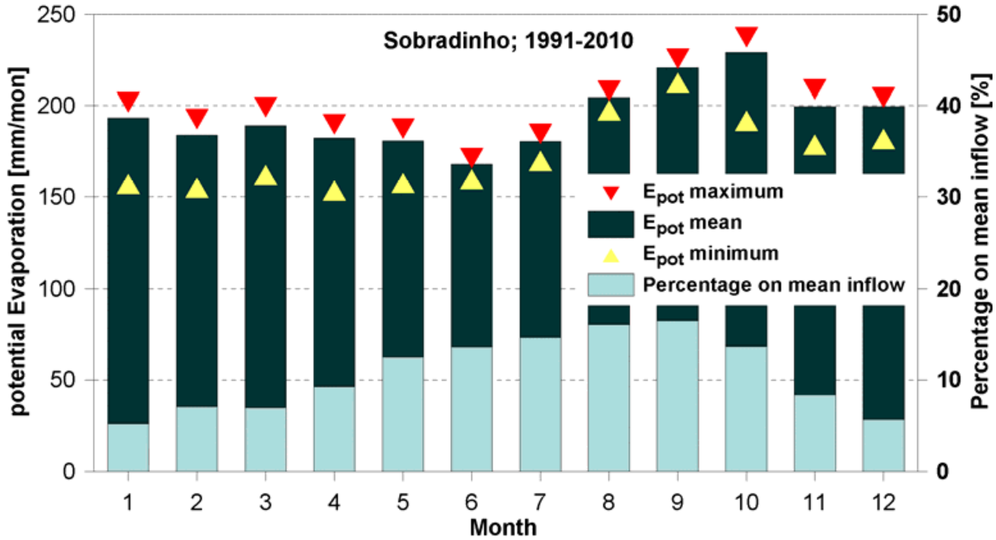

Fig. 2: Minimum, mean and maximum monthly potential evaporation and the share of mean monthly evaporation on observed mean monthly inflow for Sobradinho reservoir

Ecological discharge (*hidrogramas ambientais*)

The second reservoir management option aims at providing minimum discharges (*hidrogramas ambientais*) for the sub-middle and lower São Francisco river basin as given in Table 1 (labelled “Qecol” in Figures and Tables). The values used are according to Ferreira (2014).

Reduced Capacity

The reduction of water level variations over the year can be implemented by reducing the live capacity of a reservoir. A high water level, i.e. high fall height, is desirable because the reservoirs Sobradinho and Itaparica serve for hydropower generation. Therefore, for Itaparica reservoir this management option is implemented in the simulations by restricting water level variations to minimum and maximum values of 303.5 and 304.0 m a.s.l., respectively, i.e. the upmost half meter of the present volume. This setting, i.e. the restriction of water level variations to the upmost half meter, reduces the live capacity to 403 hm^3. For Sobradinho reservoir, however, the derivation of minimum and maximum values is more complicated. Also here a high water level would be desirable for hydropower generation. Due to the very large water surface a high water level would lead to very high evaporation losses over the whole year. Therefore, a low water level would be desirable to reduce evaporation losses. On the other hand, as can be seen in Fig. 1, with lower volume respective water level, the evaporation losses per volume unit are increasing. In the simulations for Sobradinho reservoir water level variations are restricted to minimum and maximum values of 388.5 and 389.0 m a.s.l., respectively, by this reducing the live capacity to 1 446 hm^3. The water surface corresponds to 2 800 and 2 960 km^2 approximately for the minimum and maximum water level, respectively. This is a reduction of approximately one third compared to the maximum water surface of the reference state. Restricting the water level variations to these water levels the evaporation losses can be reduced significantly while not lowering the fall height extremely. The results for this management option are labelled "reduced Capacity". The values applied are intended to be examples and results should give a first insight into the consequences of the changed reservoir management.

Water level

The capacity of Itaparica reservoir is not changed compared to the reference state. For Sobradinho reservoir the water level is restricted to maximum values of 390.0 m a.s.l., reducing the live capacity to 19 479 hm^3. Furthermore, in this option water level variations are reduced by restricting the daily maximum water quantities to be released, reducing water level fluctuations to a maximum of 0.05 m/day. The changed restrictions for the released quantities, depending on the season, are shown Fig. 3 for Sobradinho reservoir ("Water level"). The values applied are intended to be examples and results should give a first insight into the consequences of the changed reservoir management.

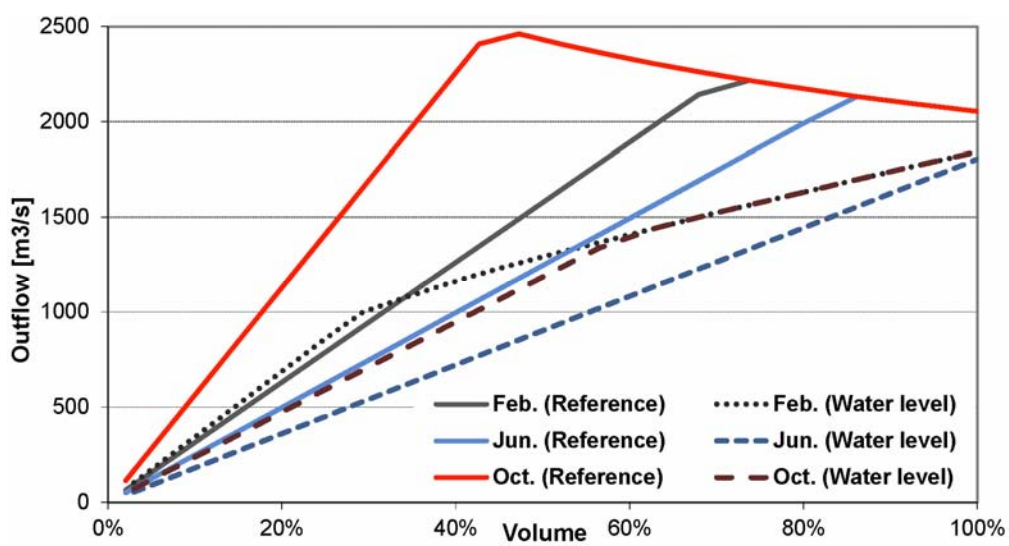

Fig. 3: Rule curves for outflow Sobradinho reservoir, management options Reference (100%= 28 669 hm^3) and Water level (100%= 19 479 hm^3)

3. Results

Mean monthly water levels for the reservoirs Sobradinho and Itaparica are shown in Figs. 4 and 5, respectively. In Figs. 6 and 7 the mean monthly outflow from reservoirs Sobradinho and Itaparica, respectively, is shown. For Sobradinho reservoir also the inflow is displayed in Fig. 6 to show the effect of the reservoir on downstream discharge.

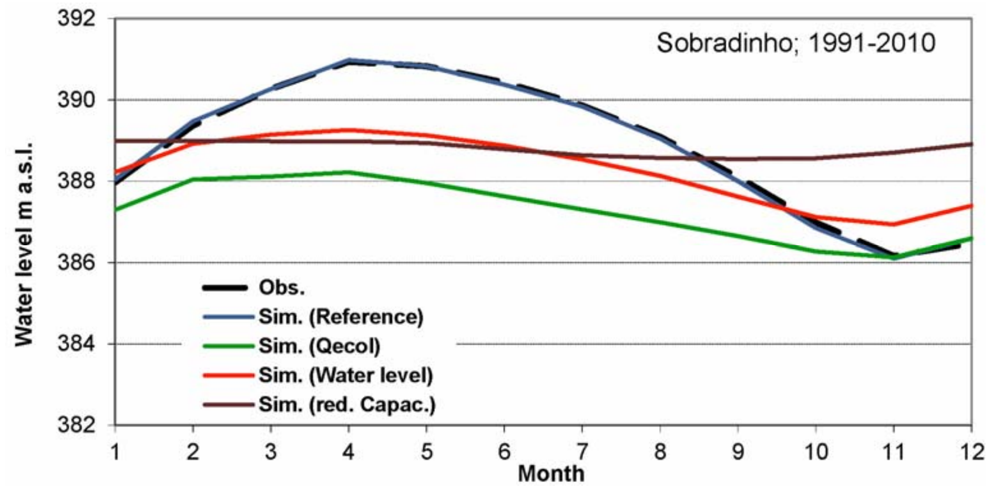

Fig. 4: Mean monthly water levels Sobradinho reservoir

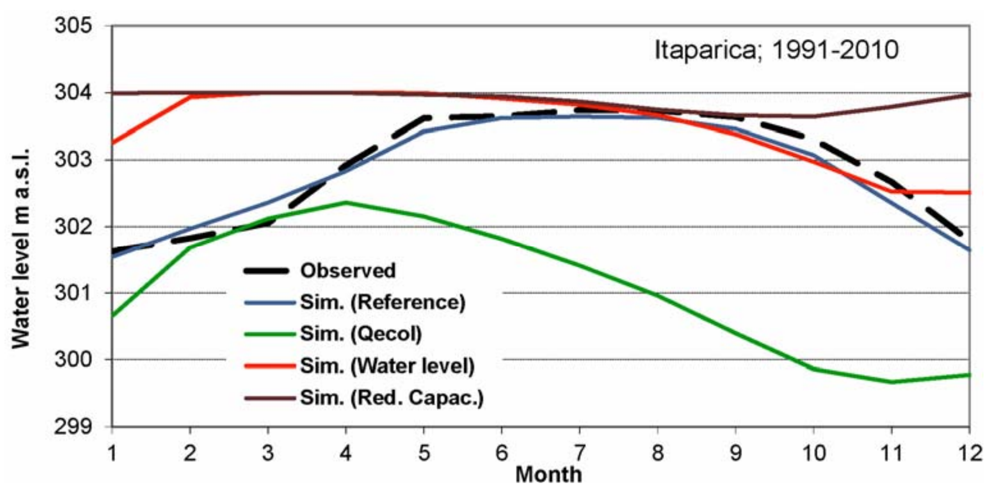

Fig. 5: Mean monthly water levels Itaparica reservoir

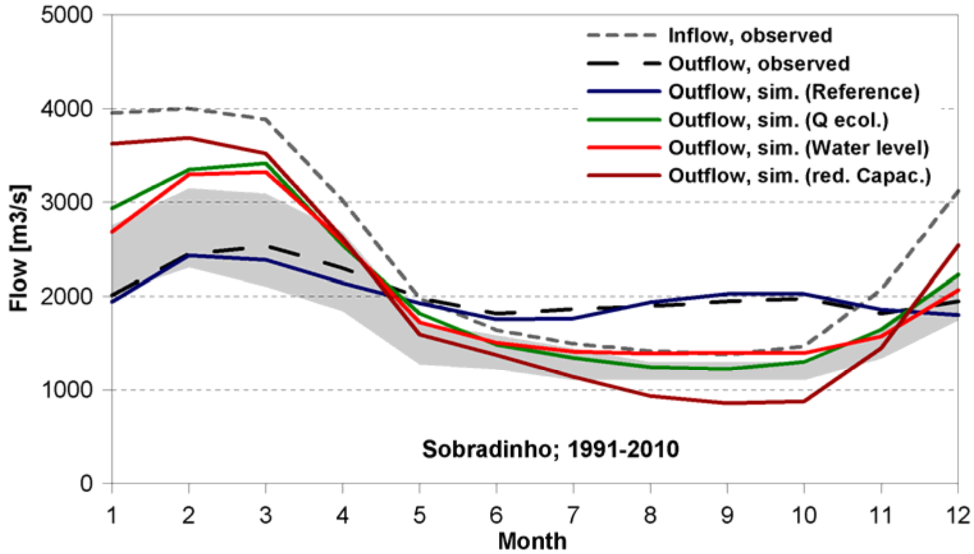

Fig. 6: Mean monthly flows for Sobradinho reservoir; grey shaded area: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA

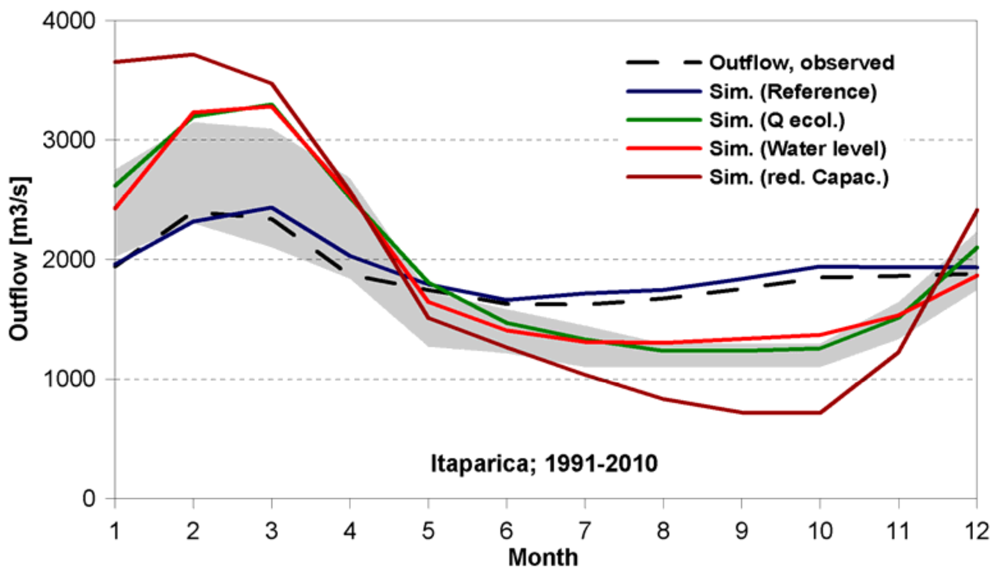

Fig. 7: Mean monthly outflow Itaparica reservoir; grey shaded area: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA

For reasons of better readability in the Figures above mean monthly values are given. As also extremes are of high interest for water resources management, in Figs. 8 to 11 monthly outflows for Sobradinho and Itaparica reservoirs are given. Given are values with probability of exceedance of 50 % (Q50), 75 % (Q75), 90 % (Q90) and 95 % (Q95). The minimum discharges (*hidrogramas ambientais*) for normal and dry years are also given.

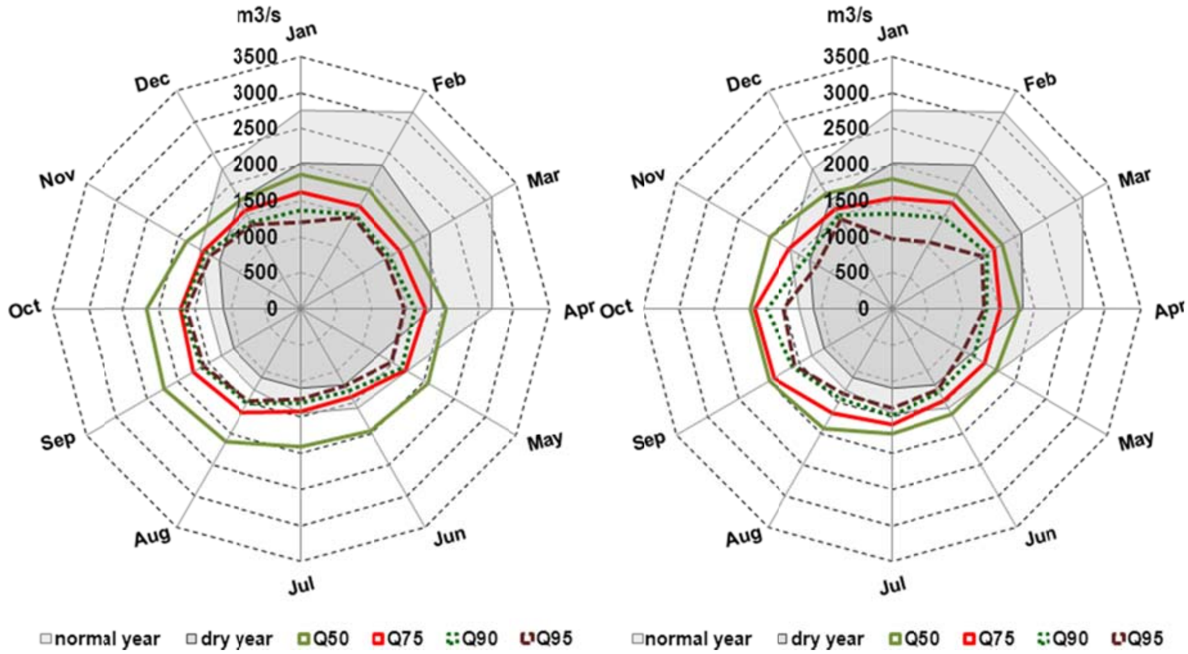

Fig. 8: Monthly outflows (Q50, Q75, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for "Reference"; grey shaded areas: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA, years 1991-2010

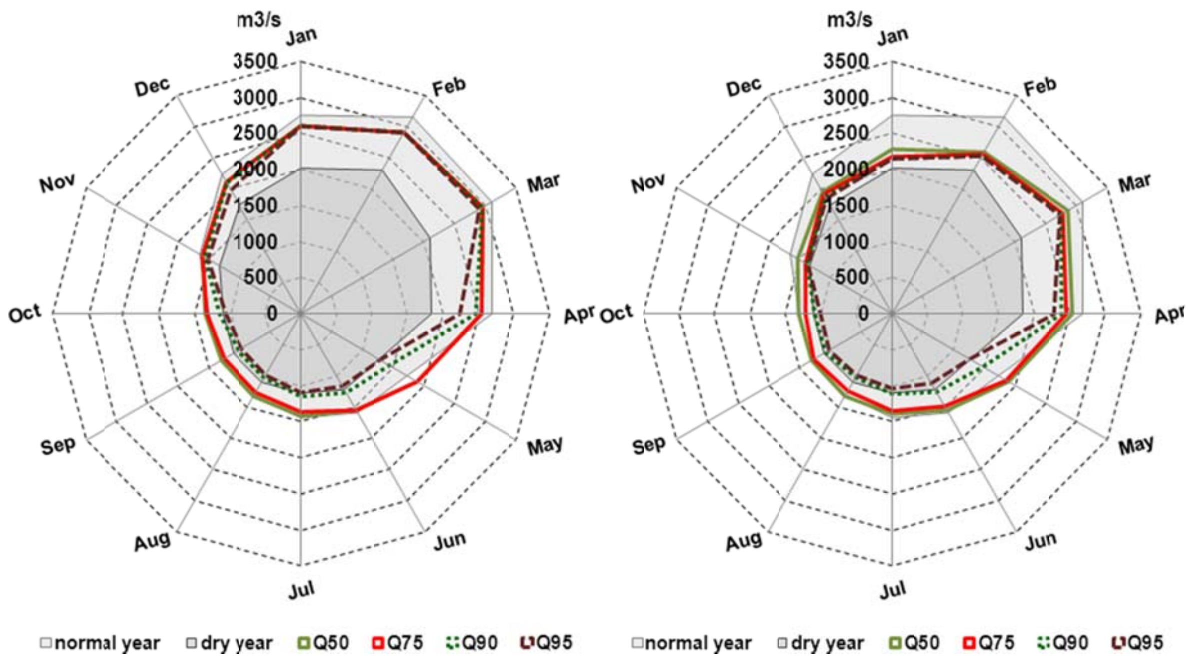

Fig. 9: Monthly outflows (Q50, Q75, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Ecological Discharge"; grey shaded areas: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA, years 1991-2010

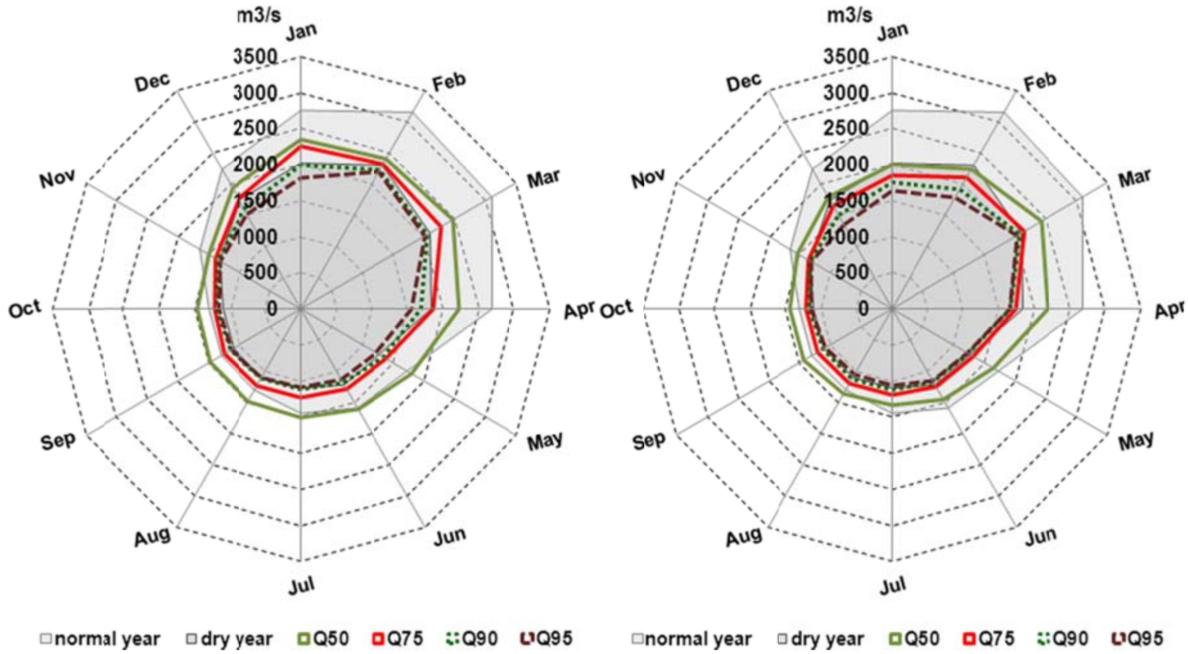

Fig. 10: Monthly outflows (Q50, Q75, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Water level"; grey shaded areas: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA, years 1991-2010

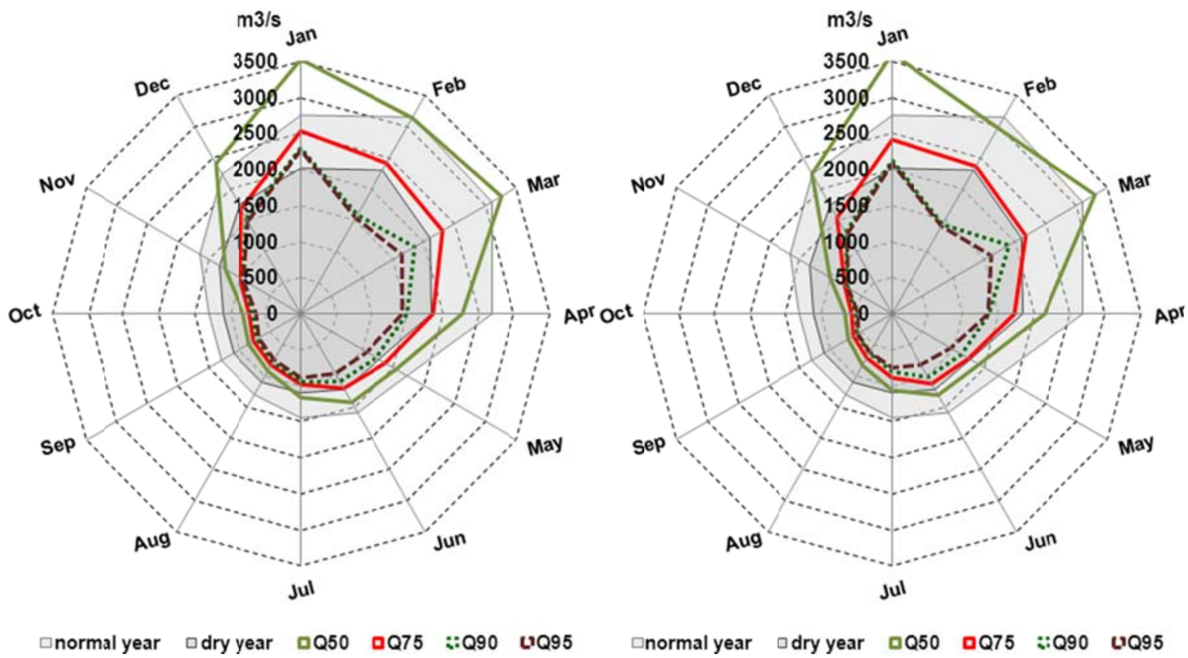

Fig. 11: Monthly outflows (Q50, Q75, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Reduced Capacity"; grey shaded areas: minimum discharge for normal and dry year (*hidrogramas ambientais*) according to project AIHA, years 1991-2010

Monthly water levels for Sobradinho and Itaparica reservoirs are given in Figs. 12 to 15. Given are values with probability of exceedance of 5 % (Q05), 10 % (Q10), 50 % (Q50), 90 % (Q90) and 95 % (Q95).

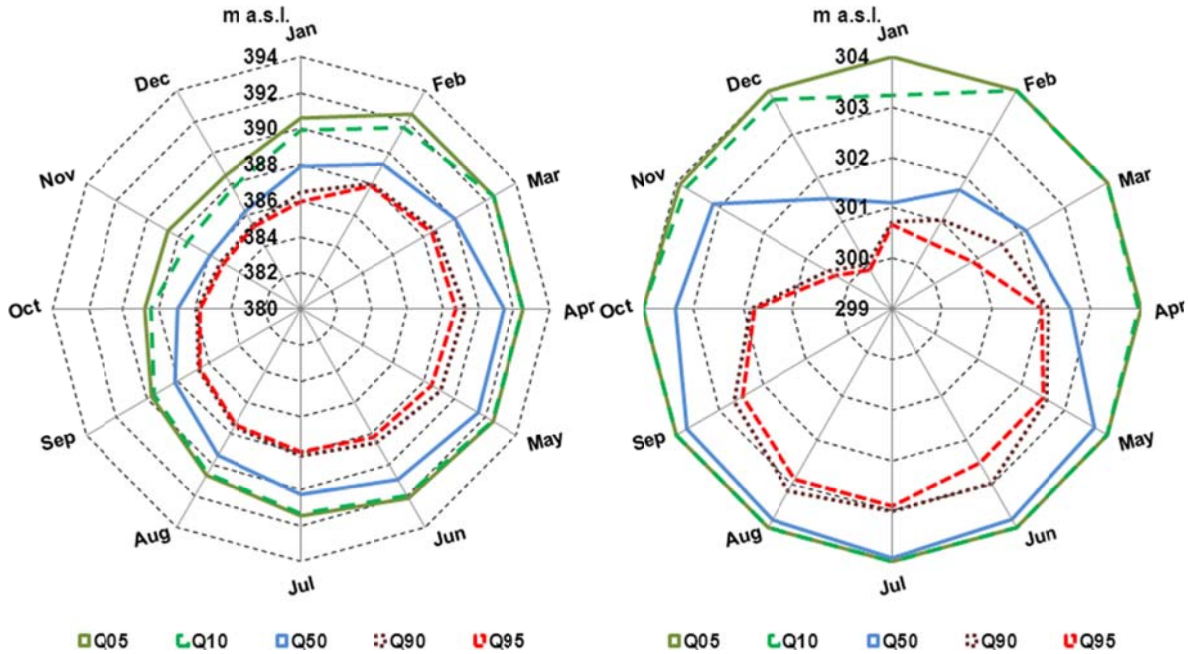

Fig. 12: Monthly water levels (Q05, Q10, Q50, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for "Reference", years 1991-2010

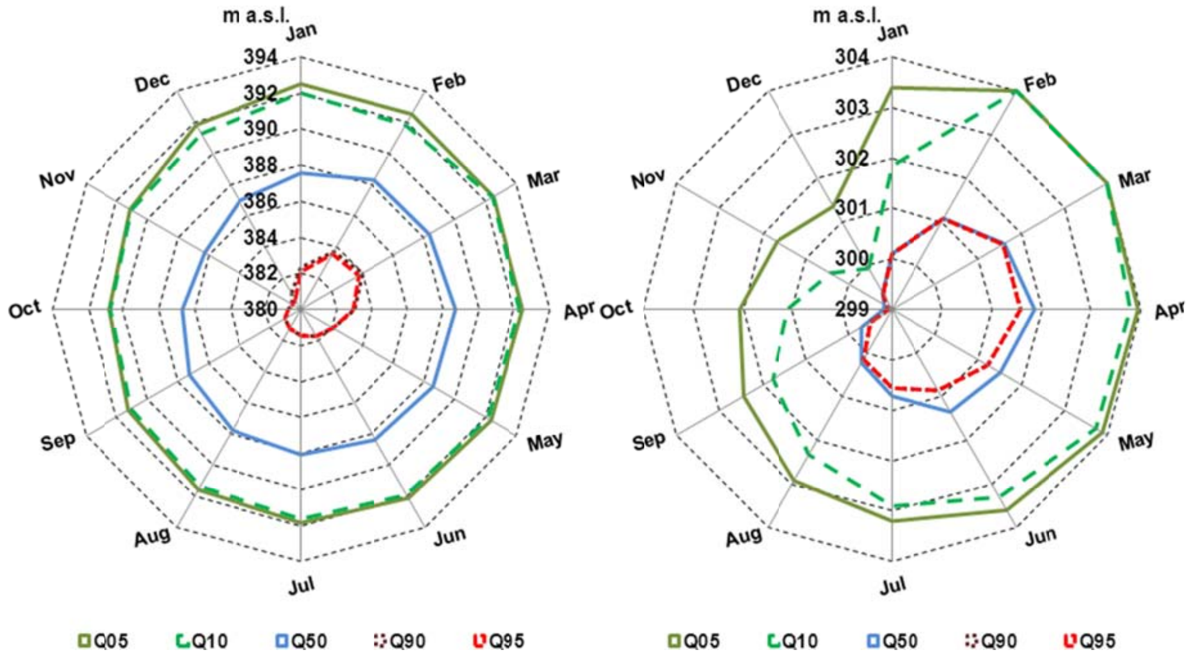

Fig. 13: Monthly water levels (Q05, Q10, Q50, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Ecological Discharge", years 1991-2010

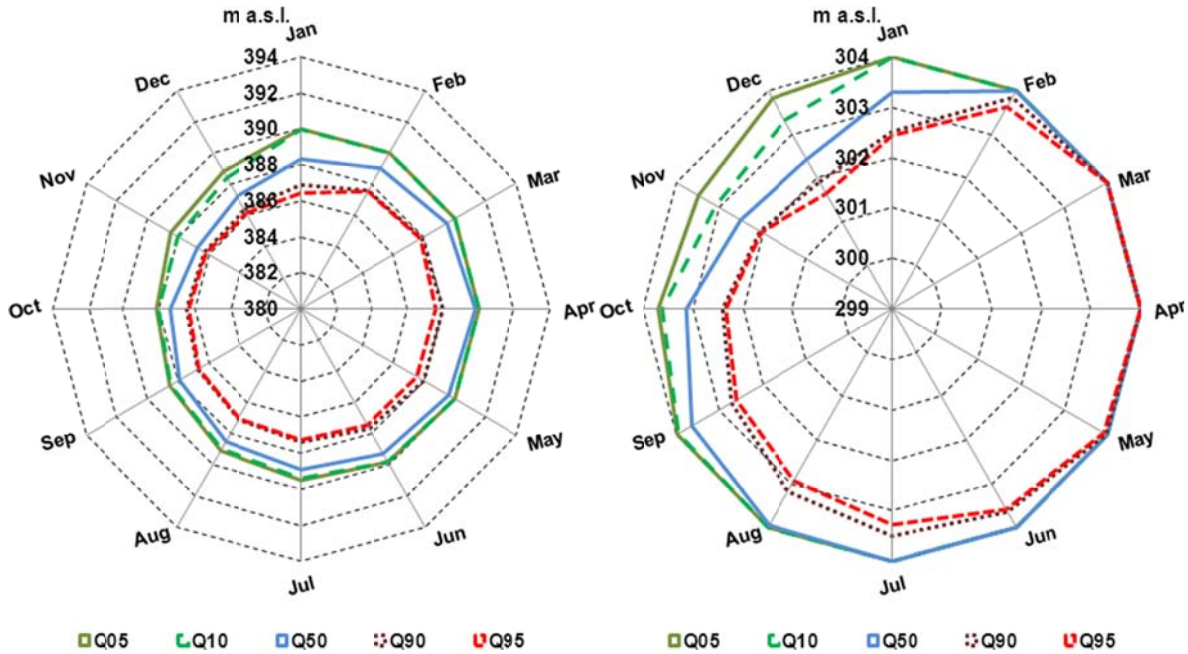

Fig. 14: Monthly water levels (Q05, Q10, Q50, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Water level", years 1991-2010

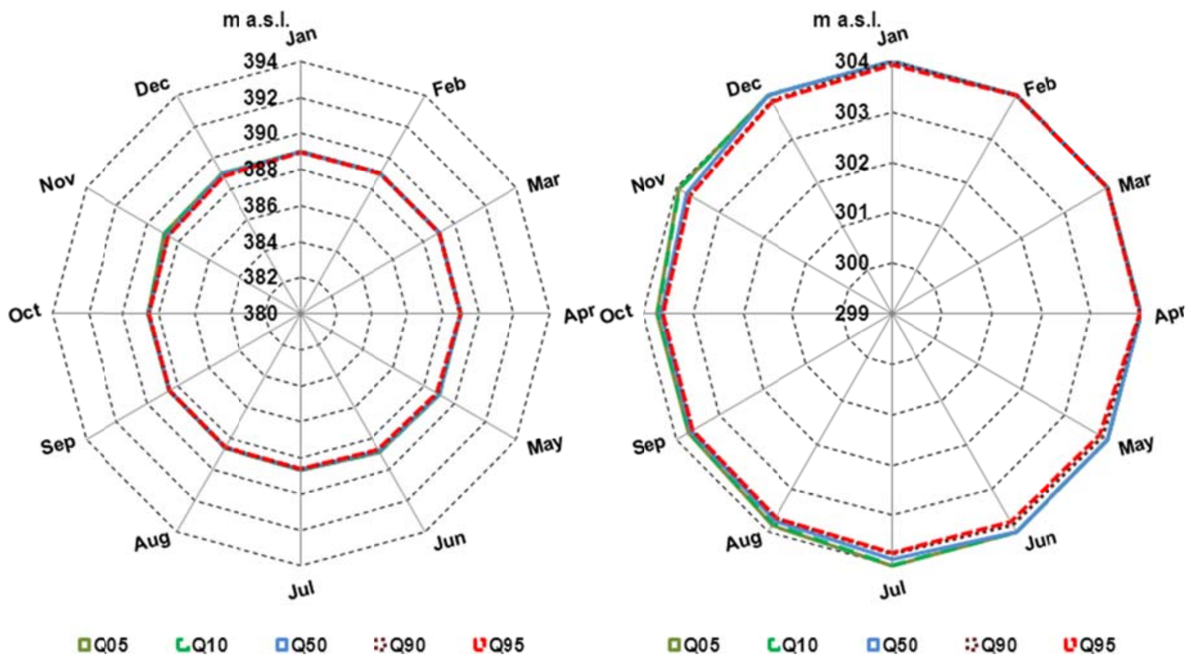

Fig. 15: Monthly water levels (Q05, Q10, Q50, Q90 and Q95) Sobradinho reservoir (left) and Itaparica reservoir (right) for option "Reduced Capacity", years 1991-2010

In Table 2 the mean monthly evaporation rates from reservoirs Sobradinho and Itaparica for the reference are given and differences to the reference for the management options. Mean monthly evaporation rates from the reservoirs Sobradinho and Itaparica are shown in Figs. A1 and A2 (Annex), respectively. For comparison both, flows and potential evaporation rates, are calculated as volume per second (m³/s).

Table 2: Mean monthly and annual sum for evaporation from reservoirs Sobradinho and Itaparica for reference, differences to the reference (years 1991-2010)

	[m3/s]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	mean	Sum [hm3/a]
Refe-rence	Sobrd.	194	236	240	258	245	224	220	229	227	200	165	169	217	6 846
	Itapar.	55	57	54	52	48	44	45	51	61	68	64	61	55	1 733
	sum	249	293	295	309	292	268	265	280	288	268	229	229	272	8 579
Diff. Qecol	Sobrd.	-6	-28	-43	-58	-55	-48	-43	-35	-19	0	14	11	-26	-810
	Itapar.	-3	-1	-1	-1	-3	-4	-5	-7	-10	-12	-10	-6	-5	-166
	sum	-9	-28	-43	-59	-58	-52	-48	-42	-29	-11	5	5	-31	-977
Diff. Water Level	Sobrd.	3	-14	-28	-43	-41	-34	-30	-23	-11	5	16	16	-15	-482
	Itapar.	6	7	5	3	2	1	0	0	0	0	0	3	2	69
	sum	9	-7	-22	-40	-40	-33	-29	-23	-11	5	16	19	-13	-413
Diff. Red. Cap.	Sobrd.	19	-13	-31	-50	-46	-36	-28	-13	12	41	56	49	-3	-106
	Itapar.	8	7	5	3	1	1	1	0	1	2	5	8	4	113
	sum	27	-6	-26	-46	-44	-36	-27	-13	13	43	61	58	0	8

Monthly minimum and maximum values for hydropower generation in the sub-middle and lower the São Francisco river basin are given in Table 3. Also given are the minimum and maximum sums for annual generation. Mean monthly hydropower generation at the reservoirs Sobradinho and Itaparica are shown in Figs. A3 and A4 (Annex), respectively. The hydropower generation for the sub-middle and lower São Francisco river basin, including the reservoirs Sobradinho and Itaparica, and the hydropower plants located downstream: Apolônio Sales, Paulo Afonso 1-4, and Xingó, is shown in Fig. A5. The hydropower generation labelled “observed” in Table 3 and Figs. A3 to A5 is calculated from the observed outflow time series (considering the respective maximum flow capacity of hydropower plants) and volumes (respective water level) for the reservoirs.

Table 3: Results monthly electricity generation Sub-Medio and Lower SF (years 1991-2010)

Hydropower [MW]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum [GWh/a]
Observed, max.	8 685	9 620	9 670	8 189	7 094	6 974	6 363	6 166	6 537	6 909	7 001	9 154	62 411
Observed, min.	3 327	2 798	2 888	3 442	3 431	2 964	2 923	2 808	3 022	3 187	3 080	3 170	33 372
Q ecol., max.	9 708	9 768	9 681	7 807	5 714	4 241	3 889	3 615	3 543	3 674	5 086	9 360	51 744
Q ecol., min.	5 767	6 718	7 228	5 334	3 190	2 638	2 472	2 103	2 116	2 446	3 326	3 980	36 616
Water Level, max.	9 629	9 671	9 601	9 349	6 613	4 576	4 389	4 507	4 348	4 530	5 289	8 212	54 349
Water Level, min.	3 814	4 666	5 301	4 125	3 045	2 816	2 565	2 499	2 378	2 394	2 772	3 529	31 838
Red. Cap., max.	9 632	9 632	9 600	9 328	6 501	4 599	4 056	3 381	2 814	3 418	7 133	9 292	54 895
Red. Cap., min.	4 621	3 488	4 120	3 330	2 463	1 987	1 784	1 210	1 005	1 287	1 965	2 439	24 116

Discussion

Due to high water demand, especially for agricultural irrigation and hydropower generation, a return to an entirely natural flow regime seems to be impossible for the sub-middle and lower São Francisco river basin. On the other hand a more ecological oriented reservoir management is possible. However, the fragmentation of the respective river stretch with its mostly negative effects on ecosystems, e.g. migrating fishes, reduced sediment transport and increased river bed erosion downstream of dams, remains an unsolved question.

The results presented give a wide range of results for the different reservoir management options. However, there are some remarkable points discussed here in more detail.

The data in Figs. 8 to 11 show that during prolonged drought periods none of the management options can safeguard the minimum discharges (*hidrogramas ambientais*) given for dry years. The monthly values for minimum discharge (*hidrogramas ambientais*) as given in Table 1 seem to be too high, even for the management option focusing on these minimum discharges ("Qecol."). During wet or normal years these minimum discharges can be met in most cases (see option "Qecol." in Figs. 6 and 7, 'Q50' and 'Q75' in Fig. 9). However, the high outflow volumes set for the wet season lead to low reservoir volumes respective water levels year-round (see 'Q90' and 'Q95' in Fig. 13), reducing evaporation rates strongly but increasing the risk of failure to meet the requested outflow during the dry season. During prolonged droughts even the minimum discharges given for dry years cannot be met (see 'Q95' in Fig. 9). Therefore, the monthly values for minimum discharge (*hidrogramas ambientais*) seem to be too static and too high for the existing water management and water use system.

The option restricting the annual water level variation to 0.5 m/a by reducing the live capacity (see "red. Capac." in the Figures) leads to more constant reservoir volumes respective water levels (Fig. 15). During the dry season even mean discharges are below the minimum discharges given for dry years (Figs. 6 and 7). Evaporation rates are not changing drastically (see Table 2), but hydropower generation is declining strongly (see Table 3). An increase of the live capacity by restricting the annual water level variation of 0.5 m/a to higher water levels, e.g. minimum and maximum values of 391.5 and 392.0 m a.s.l. instead of 388.5 and 390.0 m a.s.l. for the Sobradinho reservoir, could increase hydropower generation but would increase also evaporation rates.

The coupling of reservoir management to its current volume and restricting water level fluctuations (see “Water level” in the Figures) leads to high reservoir volumes respective water levels. One effect is a decrease in evaporation rates for Sobradinho reservoir (see Table 2 and Fig. A1). For Itaparica reservoir evaporation rates for this management options are increasing (see Table 2 and Fig. A2). Overall the evaporation rates are decreasing (Table 2). The hydropower generation under this management option is more balanced over the year compared to the other options focussing on ecological aspects, especially regarding the minimum values during the dry season (see Table 3).

The water level variations for the reservoirs (see Figs. 12 to 15) are least for the management option “Reduced Capacity”. For management option “Water level” the water level variations are higher compared to option “Reduced Capacity”, but smaller compared to options “Reference“ and “Ecological Discharge”. For the management option “Ecological Discharge” water level variations are strongest.

The restriction of water level variations to maximum values of 0.5 m/a in management option “Reduced Capacity” reduces the live capacity of the reservoirs enormously. This restriction can, especially at Sobradinho reservoir with a rather gentle slope, lead to the development of a littoral zone with its effects on water quality as found at natural lakes. However, even in natural lakes water level variations can reach values of 2 to 3 m (Hirsch et al., 2014; Hofmann et al., 2008). Therefore, water level variations reaching maximum values of 4.0 m and 2.5 m for Sobradinho reservoir and Itaparica reservoir, respectively, for management option “Water level” seem to be acceptable for artificial and managed lakes, especially under semi-arid climate conditions. The rather high volumes of the reservoirs under this option reduce the free volume at the beginning of the rainy season and larger water quantities are simply routed through the reservoir; increasing high flows. Therefore, for reservoirs which also serve for flood protection, a pre-flood emptying to create a larger flood storage capacity can be necessary (see, e.g. Chou & Wu, 2013). This pre-emptying can require overshooting the set maximum daily water level variation, in the case of the management option “Water level” 0.05 m/day.

The management option “Water level” seems to be more flexible than the other options, especially during longer dry periods. Furthermore, high reservoir outflows occur more frequently than in the simulation of option “Ecological Discharge” (see Figs. A7 to A10). A higher variability of maximum discharges is reflecting more the natural flow of the São Francisco river before impoundments. Fluctuating peak discharges implicating a varying erosion potential and therewith morphological structuring processes and influencing biodiversity in the downstream river section. The option “Water level” is also adaptive to changing climate conditions or changed water management and use in the upstream region, although such changes are not included in the simulations yet. Furthermore, in the case of climate change a minimum discharge (*hidrogramas ambientais*) based on past observations is questionable. Also a changed water management or increasing water withdrawals upstream of or from reservoirs, e.g. for increased agricultural irrigation according to plans of the *Companhia de Desenvolvimento dos Vales do São Francisco e Parnaíba* (CODEVASF) or for the Transposition Project, can decrease the inflow volumes to the reservoirs markedly. However, reservoirs serve to reallocate water resources temporally, i.e. storage in time of abundance and release in times of drought or high water demand, but cannot produce water or enhance water availability in general.

With regard to evaporation rates from reservoirs Sobradinho and Itaparica (see Table 2) the management option “Ecological Discharge” shows the highest reduction, because the water levels are lowest and hence water surfaces are smallest. As discussed this leads also to strong decline in hydropower generation. The option “Water level” overall leads to decreased evaporation rates compared to the “Reference”; while the Sobradinho reservoir shows a strong reduction for most of the year evaporation rates from the Itaparica reservoir is increasing for some months while for other months there is no change. For management option “Reduced Capacity” the overall effects on evaporation rates are rather small. The Sobradinho reservoir shows a strong reduction for some months while for other months it is increasing. The selected minimum and maximum values for water level respectively volume for this option lead to a reduction of the annual evaporation sum. As discussed a restriction to higher water levels respectively volumes would increase hydropower generation but also the annual evaporation sum, while lower water levels respectively volumes would decrease hydropower generation even further but lessen the annual evaporation sum. Evaporation rates from the Itaparica reservoir are increasing for almost all months, with the only exception of month August, because the water level is restricted to the upper half meter of the present volume.

The analysis of natural flows by Genz & Luz (2007) was carried out for the gauge Traipu (49660000) at the lowermost part of the sub-middle São Francisco river basin. The *hidrogramas ambientais* for the sub-middle and the lower São Francisco river basin was developed based on these data too. In different studies, e.g. Ferreira (2014) and Silva (2010), the *hidrogramas ambientais* was applied for the entire sub-middle São Francisco, i.e. as outflow criteria for Sobradinho reservoir. In the simulations presented in this study (management option “Qecol”) the high discharge values given in the *hidrogramas ambientais* during the rainy season, in the months from January to April especially, preclude the storage of large volumes in Sobradinho reservoir. Therefore, during the dry season the *hidrogramas ambientais* cannot be met. An analysis of discharge measurements for the outflow of Sobradinho reservoir and gauge Traipu shows that during the rainy season between 5 to 10 % of the flow is runoff generated in the sub-middle São Francisco river basin itself. Therefore, the outflow of Sobradinho reservoir can be reduced accordingly (see Table 4). The reduction of the minimum discharge during the rainy season increases the safety of reaching minimum discharges during the dry season (see Figs. 16 and 17).

Table 4: Monthly values for minimum discharge (*hidrogramas ambientais*) in the sub-middle and lower São Francisco river basin, from project AIHA and for Sobradinho reservoir (adapted), normal year

month [m³/s]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AIHA	2 754	3 150	3 097	2 685	1 727	1 588	1 448	1 300	1 300	1 300	1 647	2 234
Sobradinho	2 750	2 950	2 800	2 500	1 650	1 550	1 448	1 300	1 300	1 300	1 647	2 234

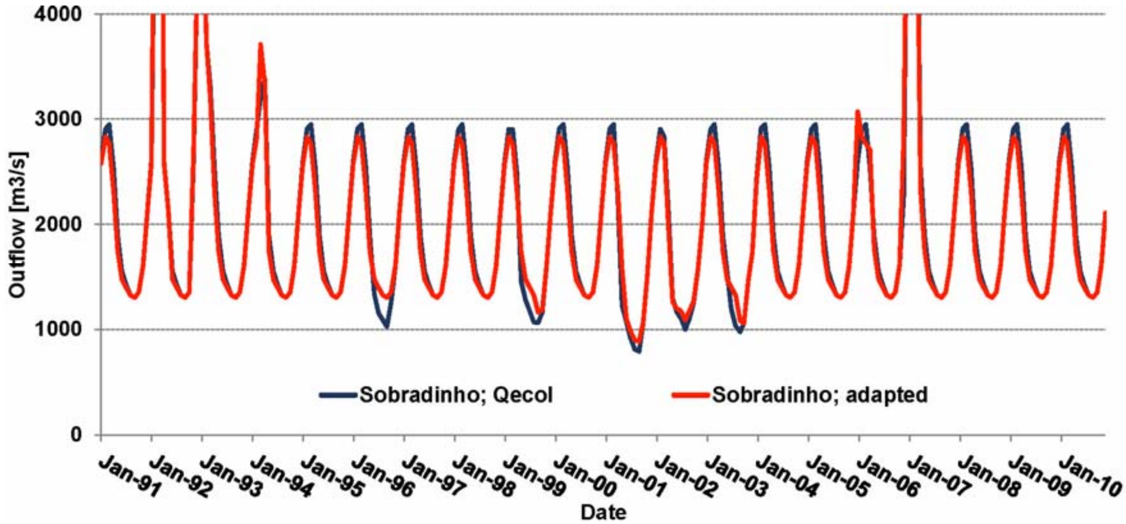

Fig. 16: Monthly outflow from Sobradinho reservoir for option "Qecol." for values according to project AIHA (*hidrogramas ambientais*) and for adapted minimum discharge

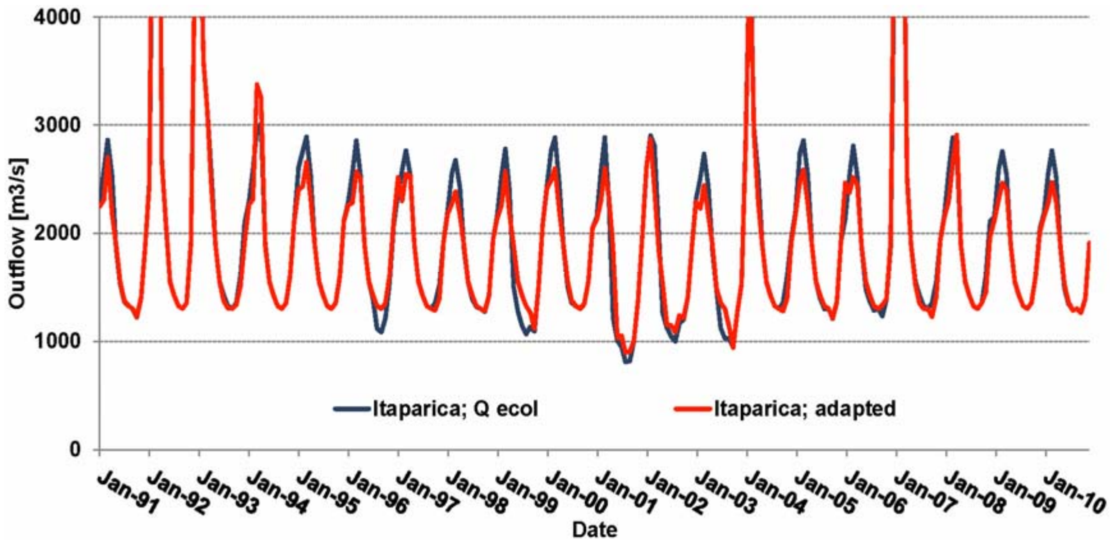

Fig. 18: Monthly outflow from Itaparica reservoir for option "Qecol." for values according to project AIHA (*hidrogramas ambientais*) and for adapted minimum discharge

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Annex

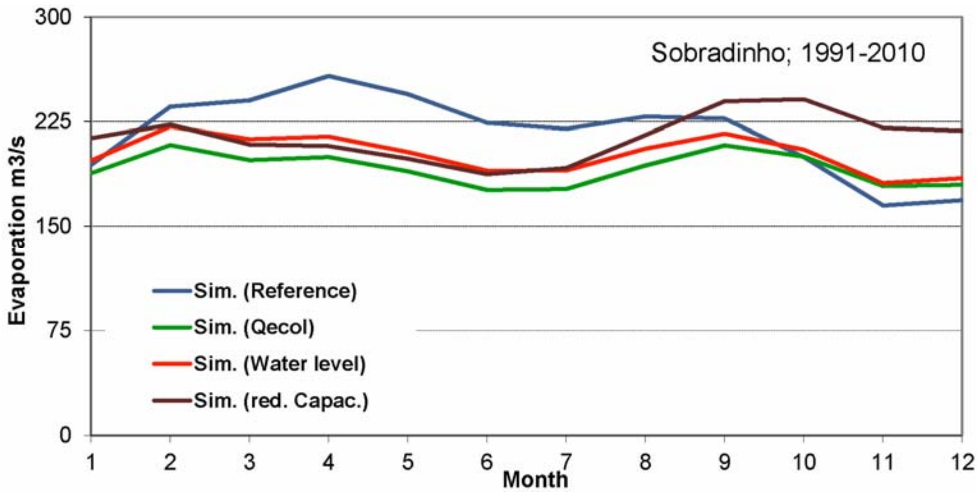

Fig. A1: Mean monthly evaporation rates Sobradinho reservoir

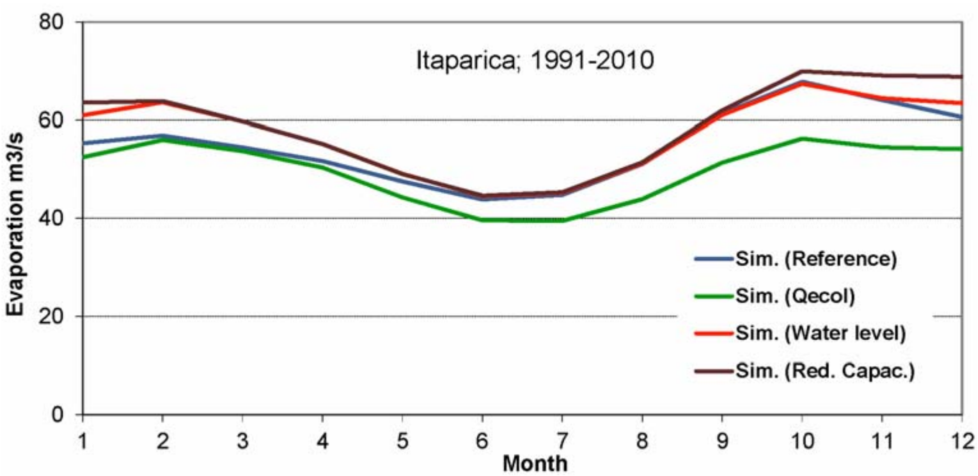

Fig. A2: Mean monthly evaporation rates Itaparica reservoir

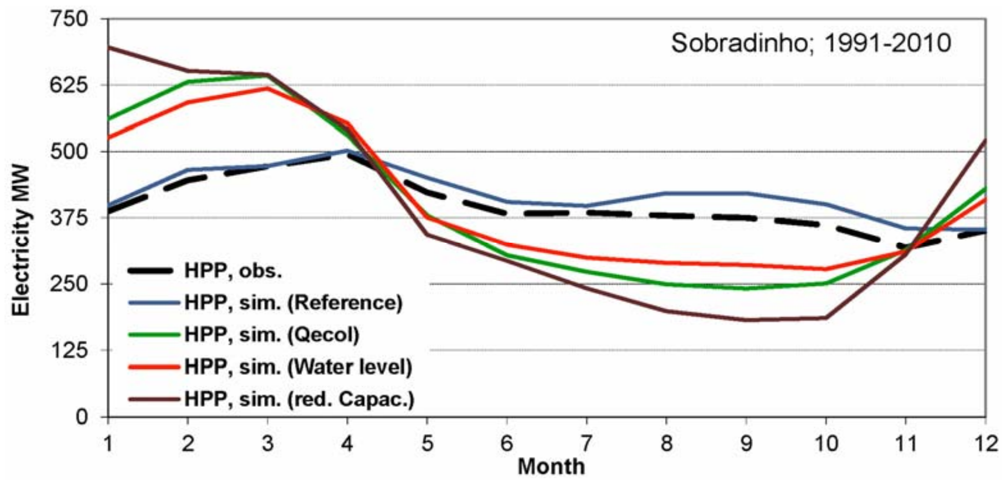

Fig. A3: Mean monthly electricity generation Sobradinho reservoir

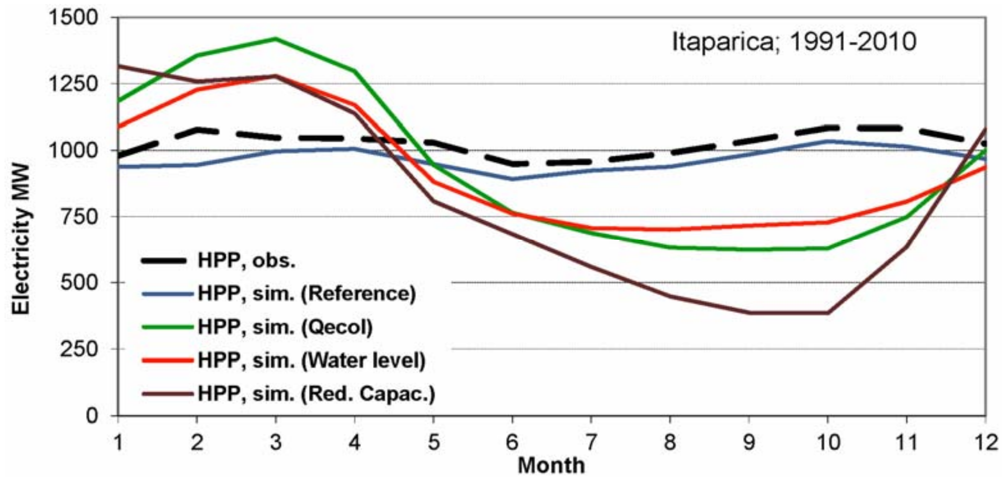

Fig. A4: Mean monthly electricity generation Itaparica reservoir

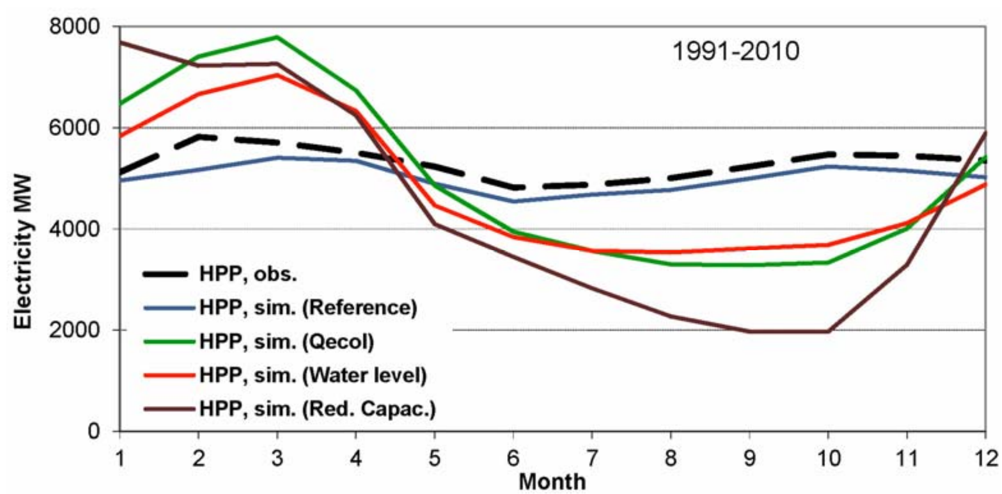

Fig. A5: Mean monthly electricity generation in the sub-middle and lower São Francisco river basin

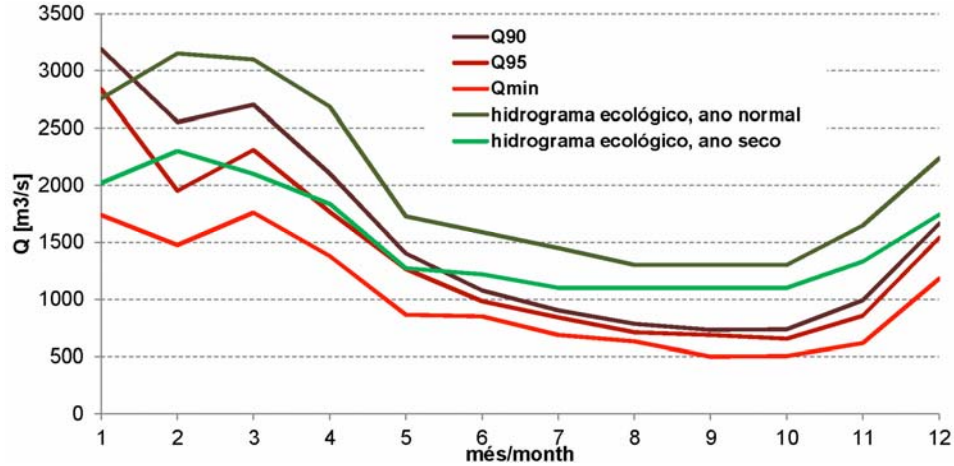

Fig. A6: Discharge at gauge Xingó, naturalized flows according to ONS (1931-2010); minimum discharge for normal and dry year (*hidrogramas ambientais* according to project AIHA)

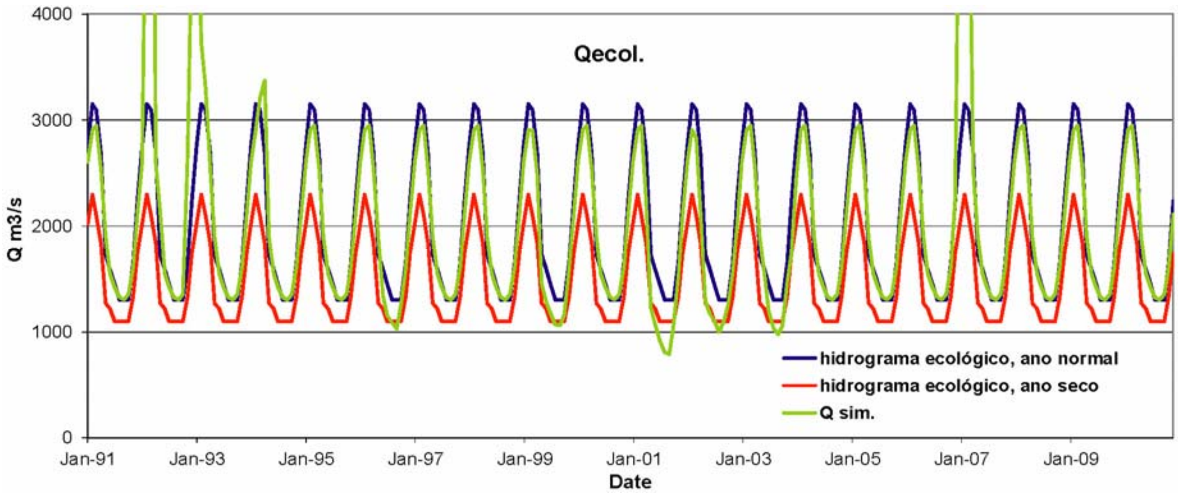

Fig. A7: Monthly outflow Sobradinho reservoir for option "Qecol."; minimum discharge for normal and dry year (*hidrogramas ambientais* according to project AIHA)

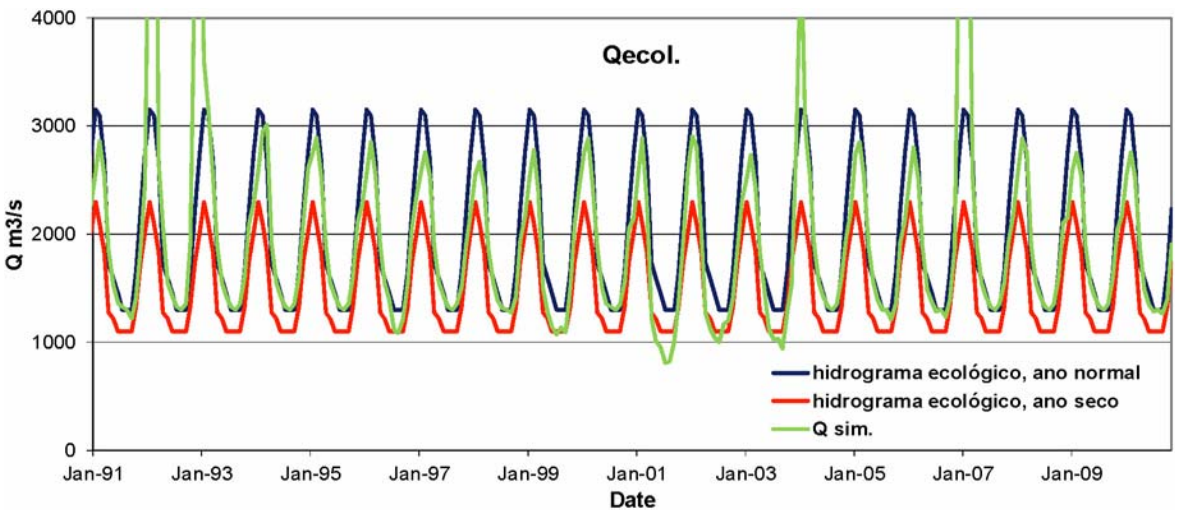

Fig. A8: Monthly outflow Itaparica reservoir for option "Qecol."; minimum discharge for normal and dry year (*hidrogramas ambientais* according to project AIHA)

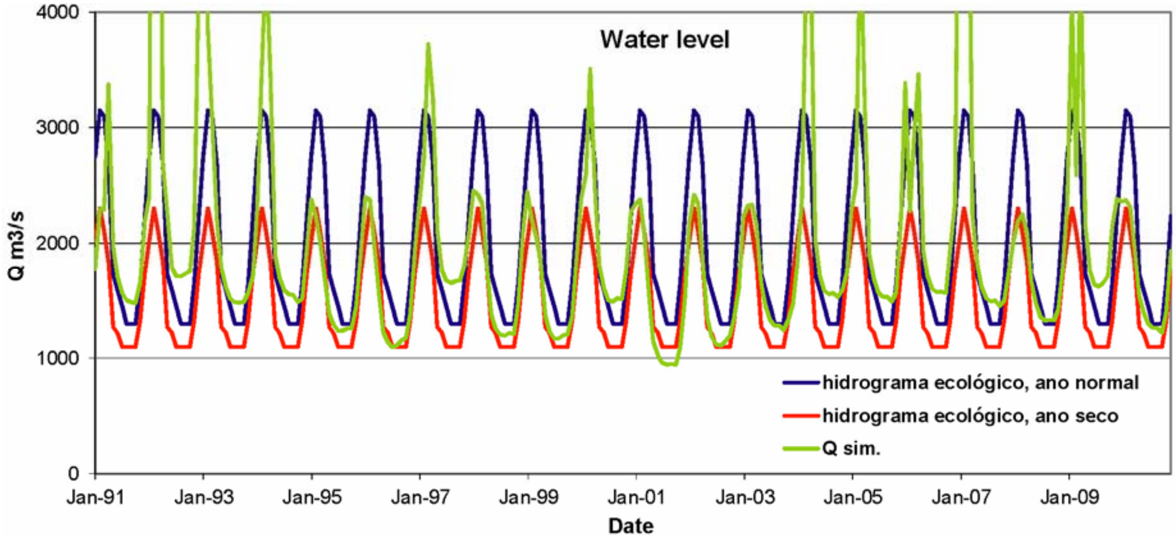

Fig. A9: Monthly outflow Sobradinho reservoir for option "Water level"; minimum discharge for normal and dry year (*hidrogramas ambientais* according to project AIHA)

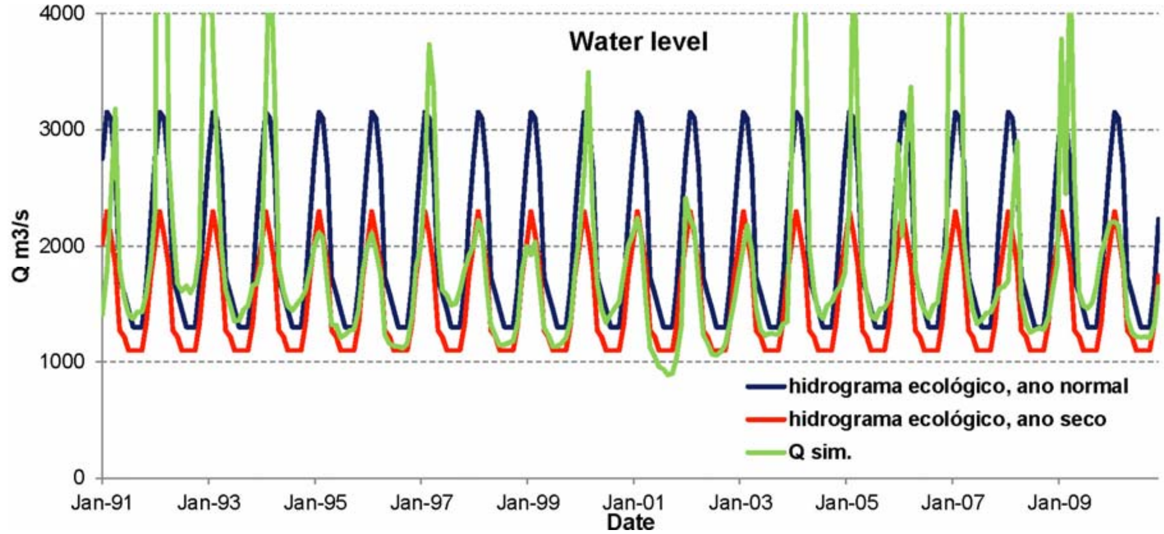

Fig. A10: Monthly outflow Itaparica reservoir for option "Water level"; minimum discharge for normal and dry year (*hidrogramas ambientais* according to project AIHA)