Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-615
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 20 November 2017

Hydrology and Earth System Sciences
Open Access
Discussions

Economic impacts of drought risks for water utilities through Severity-Duration-Frequency framework under climate change scenarios

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Abstract

Climate variability and increasing water demands prioritize the need to implement planning strategies for urban water security in the long and medium term. However, actions to manage the drought risk impacts entail great complexity, such as the calculation of economic losses derived from the combination of severity, duration and frequency under uncertainties in the climate projections. Thus, new approaches of risk aversion are needed, as an integrated framework for resilience gap assessment, for water utilities to cope with droughts, thereby linking drivers of climate, hydrology and human demands. This paper aims to present the economic impacts of risk aversion for water utilities through a framework linking severity, duration and frequency (SDF) of droughts under climate change scenarios. This new model framework addresses the opportunity cost that represent the preparedness for risk aversion to cope with potential future impacts of droughts, involving a set of options for planning of water resources, under different demands and climate projections. The methodology integrates the hydrological simulation procedures, under radiative climate forcing scenarios RCP 4.5 and 8.5, from a regional climate model Eta-INPE, with time horizons of 2007-2040, 2041-2070, and 2071-2099, linked to Water Evaluation and Planning system (WEAP) hydrologic model and under stationary and non-stationary water supply demand assumptions. The model framework is applied to the Cantareira Water Supply System for Sao Paulo Metropolitan Region, Brazil, with severe vulnerability to droughts. By using hydrological simulations with WEAP, driven by Eta-INPE Regional Climatic Model base line scenarios (1962-2005), were characterized the SDF curves. On the one hand, water tariff price associated to calibrated and modelled scenarios constitute supply/demand proxies of the water warranty time delimited by drought duration. Then, profit loss analysis scenarios are assessed for the regional water utility. On the other hand, for drought resilience gap, results show water utility profit losses per period between 1.3% and 10.3% of the regional GDP in 2016. Although future economic impacts vary in a same order, non-stationary demand trends impose larger differences in the drought resilience gap, when the future securitization are linked to regional climate outputs.

Key Words: Climate change, Water Security, Severity-Duration-Frequency curves, Economic profit losses

1. Introduction

Climate change, population growth and uncontrolled urban/industrial development make society more dependent on water (Montanari et al., 2013). The complex interaction between meteorological, terrestrial and socio-economic water distribution schemes are the main factors that define droughts (Lloyd-hughes, 2013; Van Loon et al., 2016a, 2016b; Wada et al., 2013). Thus, to face a prospective drought scenario, with the demand as a determinant anthropogenic factor requires society to rethink the way forward, mainly to reduce its vulnerability by mobilizing more water for its use, by expanding and making use of alternative sources or by regulating its demand (Falkenmark and Lannerstad, 2004; Kunreuther et al., 2013; Wanders and Wada, 2015).

In terms of drought, a hydrological drought is defined as a negative anomaly in surface and subsurface water levels (Van Loon, 2015; Wanders et al., 2017). These negative anomalies on the surface, related to a level of water demand can cause water systems to collapse and trigger strong socioeconomic impacts or the so-called socioeconomic drought (Mehran et al., 2015). Droughts may not be as apparent as floods, but have proven to be one of the most complex risks due to their slow development, strong and long lasting impacts such as broad geographic coverage (Bressers and Bressers, 2016; Frick et al., 1990; Smakhtin and Schipper, 2008; Van Lanen et al., 2013). Furthermore, various studies have shown that more severe and prolonged droughts are expected for the future, leading to greater economic consequences, environmental degradation and loss of human lives (Asadieh and Krakauer, 2017; Balbus, 2017; Berman et al., 2013; Freire-González et al., 2017; Prudhomme et al., 2014; Shi et al., 2015; Stahl et al., 2016; Touma et al., 2015). Therefore, it is essential to create appropriate expectations about their potential impacts, aiming to mitigate catastrophes, reduce the risks of damage and build a more resilient community (Bachmair et al., 2016; Mishra and Singh, 2010; Nam et al., 2015).

The need for a broader perspective in terms of comprehending and managing the impacts of drought requires actions to integrate their states or categories (Hao and Singh, 2015; Van Loon, 2015). This implies in studying droughts, understanding their propagation from meteorological phenomena, underground-surface dynamics and alterations of anthropogenic origin such as storage (Huang et al., 2017; Van Loon et al., 2016b; Wong et al., 2013). However, the most visible impacts on the water supply, energy generation, transport, recreation and water quality are strongly related to hydrological drought and not directly to meteorological drought (Van Lanen et al., 2016). Thus, we in this work addresses hydrological droughts as the main driver of direct economic impacts when water demand exceeds supply (Bressers and Bressers, 2016).

The availability of water supply new sources every day are more scarce, so the demand regulation is a strategy that is being considered by the supply companies to guarantee reliability during the drought (Zeff and Characklis, 2013). Among the demand control strategies are price-based policies ones, these seek to change the user's consumption pattern based on economic penalties or incentives (Millerd, 1984). However, the implementation of these strategies entails a great complexity in their planning and a high risk of utility losses for the water company.

The São Paulo Metropolitan Region (SPMR) located in the south east of Brazil, which has approximately 20 million inhabitants, is an important economic center in Latin America that influences approximately 12% of the Gross Domestic Product (GDP) in Brazil (Haddad and Teixeira, 2015). During the (2013-2015) period, the population of the SPMR experienced a significant reduction in water resources availability and decrease in the water supply (Coutinho et al., 2015; Nobre and Marengo, 2016; Taffarello et al., 2016b). Consequently, the 2013-2015 water deficit had socioeconomic impacts such as widespread social protests, increases in food prices and energy tariffs in homes, industries and commerce (Hanbury, 2015). The Federation of Industries of the State of Sao Paulo (FIESP) estimated that 60,000 establishments, which represent almost 60% of the state's industrial GDP, are affected by a lack of water (Marengo et al., 2015). In addition, from 2014 to 2015, the Sao Paulo State Water Utility Company (SABESP) recorded an average annual liquid net income reduction of approximately 75% compared to 2016, leading to a major financial crisis in the company (GESP, 2016). Thus, as long as there are no systematic and detailed studies on the impact of drought on the regional economy, shaping financial planning policies is a complex and uncertain task that must be reinforced. Based on the severity and duration of the water deficit, this article aims to assess the economic impacts of drought risks for water utilities through integrating a severity-duration-frequency framework under climate change scenarios. Also, this paper describes an academic exercise to manage drought financial planning for the SPMR, considering the perspective of the economic impact on the Sao Paulo Water Utility company.

The sections of this article outline interconnected methods and criteria, explained as follows. In Section 2, the text describes the study area (see Figure 1) and water crisis contextualization. Section 3 outlines the methodological approach starting with the hydrological modeling, characterization of the droughts using the threshold level method, the formulation of the SDF curves of the system and subsequently the links climatic, hydrological and economic aspects of the methodology (Figure 2). In Section 4, the results obtained are shown as financial drought planning scenarios. Finally, in Section 5, the discussion and conclusions are presented regarding the proposed approach.

2. Study area and water crisis contextualization.

The Cantareira Water Supply System, hereafter referred to as the Cantareira System, is located in the South-East of Brazil between the states of Sao Paulo and Minas Gerais (-46.9 to -45.7 longitude and -22.5 -23.5 latitude). The regional climate is classified as subtropical – sub-humid, with a maximum annual average temperature of 25 °C and a minimum annual average of 15 °C (Blain, 2010; Rodríguez-Lado et al., 2007). On the other hand, the rainfall in the Southeast of Brazil presents an annual cycle, with maximum rainfall from December to February (summer) and minimum rainfall from June to August (winter). The rainy season in the Cantareira System generally begins at the end of September and ends in March. In this period, on average 72% of the rainfall in the region is accumulated (Marengo et al., 2015). In hydrological terms, 2265 km^2 of drainage area into the system historically generates an annual mean tributary discharge of 38.74 m^3/s, where the Jaguarí tributary contributes approximately 46%. Structurally, the system consists of the damming and interconnection of five basins with a useful total storage volume of 988.8 hm^3, arranged to transfer water from the Piracicaba River Basin to the Upper Tietê Basin (Fig. 1). Thus, the system had been configured to supply water to about 8.8 million people in the SPMR before the last acute crisis in 2013-2015 (De Andrade, 2016; Marengo et al., 2015; Nobre et al., 2016; Nobre and Marengo, 2016; PCJ/Comitês, 2016, 2006).

Previously in the SPMR, some water shortages were recorded. The first one was during 1953-1954, then from 1962 to 1963 (Nobre et al., 2016), which apparently motivated the construction of the Cantareira system and the latest one was from 2000 to 2001 (Cavalcanti and Kousky, 2001). Thus, the system, designed to supply the increasing demand for water in the SPMR, began its partial operation in 1974 and its construction was completed in 1981 with a 30-year permit to transfer up to 35 m^3/s according to a periodic technical report (Mohor and Mendiondo, 2017; Taffarello et al., 2016a). Cantareira System is currently administered by SABESP, which mainly operates the water network in the SPRM, and with Government of the State of Sao Paulo as its main shareholder.

However, various studies have identified changes in trends in rainfall and temperature extremes, showing an increase in the intensity and frequency of days with heavy rainfall and longer duration of hot dry periods between rainfall events in South America and southeastern Brazil (Chou et al., 2014b; Dufek and Ambrizzi, 2008; Haylock et al., 2006; J. A. Marengo et al., 2009; Jose A. Marengo et al., 2009a, 2009b; Nobre et al., 2011; Zuffo, 2015). Although historically, the SPRM study area is not affected by droughts of the same order of Northeast Brazil, the SPRM is progressively becoming vulnerable to water shortages. Therefore, during the recent period of the acute crisis 2013/2015, SABESP were taken reactive measures, to control the consumption in the SPMR, such as (Marengo et al., 2015): Programmed water cut-offs; Bonuses and penalties to reduce and increase consumption, respectively; Extraordinary increases of water tariff cost; Network pressure reduction; Water use from the reservoirs´ dead volume; Social awareness campaigns to inform people about shortages; Water distributed by tankers in the most critical areas of the city to provide the Basic Water Requirement (BWR) for human needs. Nevertheless, according to SABESP, there is currently a gradual system recovery, which enables the reestablishment of pre-crisis supply levels (SABESP, 2016a).

3. Methodology

The methodology was followed in three modules that are summarized in Figure 2. In the first module, the hydrological simulation was approached by the Water Evaluation and Planning tool (WEAP) (Yates et al., 2005a). The model was calibrated and validated, based on the available historical hydrometeorological information (2004-2015) for the study area. Then, from the calibrated hydrological model and the RCM Eta-INPE historical periods datasets, the base discharge scenarios were estimated. In the second module, in the TLM approach, the "threshold" had to be defined according to stationary and non-stationary assumptions of water demand in the SPMR. Afterwards by analyzing the duration series and extreme deficits through GEV (Generalized Extreme Value) distribution, the Severity-Duration-Frequency

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curves (SDF) were developed (J. H. Sung and Chung, 2014). To complete the second module, the average water price is defined per each cubic meter of deficit, as a function of the supply warranty time during the hydrological drought events, to configure the baseline analysis scenarios. The final module evaluates through the baselines scenarios the Water Utility Company economic profit losses, under the hydrological model WEAP output datasets, driven by the Eta-INPE, RCPs and (2007-2040, 2041-2070, 2071-2099) scenarios, previously processed by the TLM approach. It should be clarified that, for the analysis under the non-stationary assumption, the growth of water consumption is represented in each projection time step, that is, to 2005-2040 correspond 31 m^3/s, to 2041-2070 correspond 38 m^3/s and to the period 2071-2099 correspond 43m^3/s.

The results of the methodology of Figure 2 can be seen as the opportunity cost, which would represent appropriate financial planning, considering the anticipation of drought events by implementing adaptation measures, supported economically by the forecast of the potential impacts. These impacts are shown as a set of potential scenarios involving climate uncertainty, human triggering factors and the prediction of extreme theory (Baumgärtner and Strunz, 2014; Wanders and Wada, 2015). Thus, the approach seeks to provide a planning water-security support analysis in areas highly dependent on surface water resources.

As a complement to Figure 2, the main variables that induce the change scenarios for this study are shown in Table 1.

3.1. Climate and hydrological modeling

Currently the RCM Eta-INPE (Brazilian National Institute for Space Research) plays an important role in providing information for local impact studies in Brazil and other areas in South America (Chou et al., 2014b). In order to assess the uncertainties of climate change impacts, the simulation results of the Eta-INPE model were used in this paper. The model is nested within the GCMs MIROC5 and HADGEM2-ES, forcing by two greenhouse gas concentration scenarios (RCPs) 8.5 and 4.5 [W/m^2] used in AR5 (IPCC 5th Assessment Report); with a horizontal grid size resolution of 20 km x 20 km and up to 38 vertical levels through 30 years of time slices (periods) distributed as follows: 1961-2005 (as the baseline period), 2007-2040, 2041-2070 and 2071-2099 (Chou et al., 2014a, 2014b; Prudhomme et al., 2014). The climate projections of the Eta-INPE model was used to drive the WEAP Rainfall Runoff Model-soil moisture method (World Bank, 2017; Yates et al., 2005a). The WEAP, developed by the Stockholm Environment Institute US Center, is an integrated water resource planning tool used to develop and assess scenarios that explore physical changes (natural or anthropogenic) and has been widely used in various basins throughout the world (Bhave et al., 2014; Esteve et al., 2015; Groves et al., 2008; Howells et al., 2013; Mousavi and Anzab, 2017; Psomas et al., 2016; Purkey et al., 2008; Vicuna and Dracup, 2007; Vicuña et al., 2011; Yates et al., 2005b). Climate-driven models, such as WEAP provide dynamic tools by incorporating hydroclimatological variables to analyze, in this case, a one-dimensional, quasi physical water balance model, which depicts the hydrologic response through the surface runoff, infiltration, evapotranspiration (Penman-Monteith equation), interflow, percolation and base flow processes (Forni et al., 2016).

The hydrological model comprises 16 sub-basins with a spatial resolution ranging from 67 to 272 km^2 (see Table A-1 in supplementary material - section A), which defines the natural discharge produced by the Cantareira System. The observed hydrologic data (discharge and rainfall) were taken from HIDROWEB (the National Water Agency database [ANA]), SABESP and the São Paulo state Water and Electricity Department [DAEE]. A network of 52 rain gauge stations and 11 discharge gauge stations were configured, with inputs and outputs by a monthly time-step. On the other hand, the meteorological data from 14 gauge stations (temperature, relative humidity, wind speed and cloudiness fraction) were taken from the National Institute of Meteorology and Center for Weather Forecasting and Climate Research (CPTEC) databases. For the basin characterization, we adopted the soil map from (De Oliveira et al., 1999) (1:500,000) and the land use map of 2010 from (Molin et al., 2015) (1:60,000).

The WEAP model was calibrated using an automatic PEST tool module (Doherty and Skahill, 2006; Seong et al., 2015; Skahill et al., 2009; Stockholm Environment Institute (SEI), 2016) and manual techniques on a monthly basis. In the modeling process, a two-year warm-up period from 2004 to 2005 was established, for the calibration period from January 2006 to December 2010 and from January 2011 to August 2015 as the validation period. During this process, the following variables were calibrated: Kc (Crop Coefficient), SWC (Soil Water Capacity), DWC (Deep Water Capacity), RZC (Root Zone Conductivity) and PFD (Preferential Flow Direction). The chosen performance criteria, widely used in hydrologic applications, were the Volumetric Error Percent Bias (PBIAS), Standard Deviation Ratio (SDR), Nash-Sutcliffe Efficiency (NSE), NSE of the logarithmic of discharges (NSELog) which is more sensitive to low-flows, Coefficient of determination (R^2) and Volumetric Efficiency (VE) criterion (Muleta, 2012).

The calibration and validation procedure of the hydrological model was carried out from upstream to downstream streams with historical discharge information (refers to the reservoirs inflows) from collected from ANA-HYDROWEB (www.ana.gov.br). Cantareira's reservoirs were set up as a single Equivalent System (ES), where the specific water demands are adapted (ANA and DAEE, 2004; PCJ/Comitês, 2006). This ES can be expressed as follows:

$$ES_{Cantareira} = \sum_i^n QN_i - \sum_i^n WD_i \qquad \text{Equation 1.}$$

where $ES_{Cantareira}$ is the available water for withdrawal from the system, QN is the natural discharge from the reservoir i and WD is the specific water demand in each reservoir (such as the Piracicaba River demand).

It is worth noting the sub-basins areas are smaller than each cell of the adopted climate model (400 km²). Therefore, in order to adjust the dataset, the projections of the Eta-INPE scenarios had to be adapted from/to the original location of the gauge station, and corrected according to the observed historical climate conditions. The climate projections from Eta-HadGEM2-ES and Eta-MIROC5 under RCP 4.5 and 8.5 scenarios were used in the hydrologic model to evaluate the impacts and climate uncertainty in the discharge regime. The results can be seen in supplementary material – section B (Fig. B-1) and are represented as future time slices of 30 years approximately: 2007-2040, 2041-2070 and 2071-2099, under the intermediary (pessimistic in this study) and optimistic RCP scenarios (IPCC, 2014).

3.2. SDF curve development

Following the flowchart of Figure 2, the Threshold Level Method (TLM) is traditionally used to estimate hydrological drought events from continuous discharge time series. TLM was originally called 'Crossing Theory Techniques" and it is also referred to as run-sum analysis (Hisdal et al., 2004; Nordin and Rosbjerg, 1970; Şen, 2015). Usually different values are used to define the threshold in hydrological drought analysis by the TLM approach (Tosunoglu and Kisi, 2016). In this study, two demand scenarios, approached as "threshold levels", were used in the mean daily-monthly discharge data. Initially, a stationary demand of 31 m^3/s was defined as the historical average demand and another non-stationary demand of 31 to 42 m^3/s over time was defined as a hypothesis representative of the population growth in the SPRM (see Figure 3). These water demand values are consistent with the ANA/DAEE, 2004 study, according to the record and projection scenarios of the population growth of the IBGE[1].

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[1] Brazilian Institute of Geography and Statistics: http://www.ibge.gov.br/home/

Based on the time series of "severity" (or deficit, in m^3) and duration (days) in the Cantareira System, obtained from the hydrological modeling of the historical scenarios from the Eta-INPE model (1962-2005), the SDF curves were constructed. To estimate the return periods of drought events of a particular severity and duration, the block maxima GEV frequency analysis distribution was used. In this case, the GEV distribution is useful because it provides an expression that includes all three types of extreme value distributions (Tung et al., 2006).

In various studies addressing SDF curve development, the GEV distribution was consistent with the data sets of extremes, where distributions that use three parameters were required to express the upper tail data (J H Sung and Chung, 2014; Svensson et al., 2016; Todisco et al., 2013; Zaidman et al., 2003). On the other hand, it is suggested that for other durations of drought, other probability distribution functions can be explored (Dalezios et al., 2000; Razmkhah, 2016). However, in this study we took advantage of the versatility of the GEV distribution, considering its flexibility to fit a set of data through the expressions:

$$F(x) = exp\left[-\left\{1+\xi\left(\frac{x-\mu}{\sigma}\right)\right\}^{1/\xi}\right] \qquad \xi \neq 0 \qquad \text{Equation 2.}$$

$$F(x) = exp\left[-exp\left(-\frac{x-\mu}{\alpha}\right)\right] \qquad \xi = 0 \qquad \text{Equation 3.}$$

where the cumulative distribution function *F(x)* depends on μ as a location parameter, α as a scale parameter and ξ as a shape parameter. Therefore, if, $\mu+\alpha/\xi \leq x \leq \infty$ for $\xi < 0$ is a Type III (Weibull), $-\infty \leq x \leq \infty$ for $\xi = 0$ is a Type I (Gumbel), and $-\infty \leq x \leq \mu+\alpha/\xi$ for $\xi > 0$ is a Type II (Frechét) distribution (Stedinger et al., 1993).

In order to fill a considerable number of events per interval, droughts were classified into four time intervals 31, 90, 180 and up to 365 days. Thus, considering the adoption of the GEV distribution, the model parameters ξ, α and μ for cumulative durations defined and return periods of 2, 10 and 100 years were estimated using the Method of Maximum Likelihood Estimator (MLE).The SDF curves of the hydrological drought in the Cantareira System are shown in Figure 4. In addition, the adjusted parameters table and the diagnostic plots QQ-plot and Return Level vs. Return Period for the GEV distribution can be seen in the supplementary material as sections C and D.

3.3. Water price and Hydrological drought relationship

According to the flowchart of Figure 2, drought can be addressed as a somewhat unusual economic phenomenon in that it affects both supply (the source) and demand (users), especially in systems dependent on water from a single source (Moncur, 1987). As expected, episodes of water scarcity pose technical, legal, social and economic problems for managers of urban water systems. Traditionally to overcome these episodes, reservoirs play a key role in water supply and demand management, providing security against hydrological extremes (Mehran et al., 2015). However, when the water deficit intensifies, the structural measures are not enough and they must be accompanied by contingency measures.

In recent years, the Cantareira System played an important role to guarantee the water supply in the SPMR. Figure 5 shows the TLM analysis with a constant threshold under two discharge scenarios, a) monthly natural discharge and b) regulated discharge, where the regulated discharge is represented by the annual average aggregation of monthly natural discharges. Thus, without the reservoirs, i.e. withdrawals dependent on the instantaneous inflow, the average accumulated deficit over these 17 years would be 225% greater. Considering this assumption, the analysis showed two hydrological drought periods in 2000-2003 and 2010-2015 (Figure 5b); one with a lower and another with a higher deficit, respectively. While for the period from 2004 to 2009, a series of smaller droughts in both magnitude and frequency could be overcome by the reservoir system. On the other hand, in 2010-2015, the accumulated deficit, under the regulated scenario, would exceed the useful storage in 70%; while for the period 2000-2003, the accumulated deficit only reached 43% of the system's useful storage capacity. Therefore, it is clear that over a long period of deficit or strong multi-year droughts, the system of storage could be accompanied by contingency complementary measures.

Urban drought management programs incur costs that must be assumed to overcome the water crisis with equity (Molinos-Senante and Donoso, 2016). SABESP in the SPMR, for example, through price-based policies controlled the consumption rates of water users when the hydrological deficit scenarios were presented in the Cantareira System (Millerd, 1984, SABESP, 1996, Iglesias and Blanco, 2008), see Figure 6. Thus, during the 2014/2015 drought in SPRM, reactive economic contingencies were implemented, such as increased water tariff costs, extra fees and price incentives, which had a detrimental effect on the company's profit margin, which provides the water resource. (GESP, 2016). Although the relationship between the Water Deficit and the tariff Adjustment Rate show a relatively low Pearson correlation

coefficient "r_{xy}" of 0.398, this may be useful given the lack of information regarding drought and its economic impacts on the study area.
In Brazil, each state-owned sanitation company has its own water charging policy, where the vast majority use block tariffs as a pricing policy, including SABESP (De Andrade Filho et al., 2015; Mesquita and Ruiz, 2013; Ruijs et al., 2008). In Sao Paulo State, the tariff policy system is regulated by Decree 41.446/96, also for services provided by SABESP. For the water tariff setting, several factors are taken into account, such as service costs, debtors forecast, expenses amortization, environmental and climatic conditions, quantity consumed, sectors and economic condition of the user (SABESP, 1996). These sectors are divided into residential, industrial, commercial or public, and the value that is charged for the service is always progressive. In other words, there is a standard minimum consumption with a fixed value and, based on that, such factors vary the consumption ranges (SABESP, 2016b). From the total water withdrawn from the Cantareira System, urban use is predominant in SPRM, where approximately 49% of the total is for household needs, 31% for industrial needs and 20% for irrigation (Consórcio/PCJ, 2013). In this study, we consider the water-withdrawal for domestic and industrial use in the SPMR, because the direct dependence of these sectors on the SABESP water supply network, as well as the supply priority that these sectors have according to Brazilian law.

The water price formation study is not part of this work as it entails a complex microeconomic analysis, due to the diversity of variables in the process (Garrido, 2005). Additionally, the financial exposure does not always exhibit a strong correlation with weather indices (Zeff and Characklis, 2013). Therefore, in order to establish a water appraisal for the economic analysis, an empirical relationship between the water tariff and its availability according to the drought duration was developed. For this, the TLM analysis here presented was performed from the monthly discharge series during from 2000 to 2016 (Figure 6a), aiming to associate the resulting information with the previously obtained SDF curves. Thus, the top part of Figure 7 shows the drought duration and the annual tariff adjustment with a Pearson correlation coefficient "r_{xy}" of 0.402 between them, while the lower part represents the volume deficit for each drought duration. Based on Figure 7, it can be observed that from greater drought durations and deficits, there is expected an increase in the water tariff for the following period. On the contrary, the smaller deficits are overcome with the water stored in the system and the increase in tariffs is a consequence of the annual Consumer Price Index (CPI) and other tariff updates according to the law.

According to the relationship established between the drought duration and the tariff adjustments, assigning the average water price for this study requires some additional assumptions explained as follows: (i) based on the current average rates for the domestic and industrial sectors that range from US$ 2.27 to US$ 4.48 per m^3, respectively (SABESP, 2016c), an average price was established for the analysis of US$ 3.38 per m^3, assuming that this value is given considering normal supply conditions, (ii) from the four intervals of drought duration considered for the SDF curve construction and the water tariff adjustments of the analyzed period (min. 3.15% to max. 18.9%, see Figure E-1 in supplementary material - section E), the water prices were established as a function of the drought duration by the "supply warranty time percentage" as shown in Table 2.

Based on the assumptions shown in Table 2, the demand curve for the Cantareira System was constructed as a function of the supply warranty time percentage (Figure 8). In this demand curve, the reservoir network is considered to ensure water supply and provides resilience during droughts of smaller magnitudes and duration. Overall, the curve represents the inelastic behavior of the Price Elasticity of Demand (PED); showing closer intervals as water supplies are reduced due to drought and higher prices imposed to try to reduce demands. Hence a successful price-based rationing policy, requires a progressive increase if the demand becomes predominantly inelastic (Mays and Tung, 2002), as the proposed hypothesis establishes in this case. More studies of price elasticity and water scarcity can be found in (Freire-González et al., 2017; Mansur and Olmstead, 2012; Ruijs et al., 2008).

From the drought events studied, i.e in 2000/2001(Cavalcanti and Kousky, 2001), in 2014/2015 (Nobre et al., 2016), which significantly affected the water supply, the TLM analysis showed the interdependence between annual events (Figure 6b). Consequently, the main impacts derived from water supply problems in the SPRM appear to be related to multi-year drought events and medium to high severity such as the recent event. Therefore, based on the 2000/2016 drought severity-duration-rate adjustment scenarios, three water supply warranty scenarios were established (see Figure 8): 100% water availability, water availability with storage dependency and water deficit with extra fees and other savings measures as a good management practice to prevent strong impacts.

Thus, the baseline scenarios were configured to estimate the projections of the loss of economic profits in the water utility company, due to the financial cost of the drought periods. These scenarios are represented by the Severity-Duration-Impact curves, which are shown in

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-615
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 20 November 2017

Figure 9, under different recurrence events, climate projections and demand variability scenarios. Each pair of lines in Figures 9 a. b. (continuous and dashed) show the range of uncertainty associated with the considered change variables.

The final step of the methodology (see Figure 2) calculated the impacts in terms of the drought financial planning through the management horizons (2007-2040, 2041-2070 and 2071-2099). This calculation was carried out for the cumulative drought duration periods greater than 180 days, considering that from this duration, the supply begins to show important dependence of the Cantareira reservoir System.

4. Results and discussions

The results section will be divided into: (i) hydrological modeling, (ii) SDF curves and (iii) economic results under climate changes.

4.1. Hydrological modeling

The hydrological model structure performed in monthly time steps, calibrated and validated following a manually and automatic procedure. To improve the calibration procedure, multiple statistical evaluation criteria were used, aiming to reduce the specific bias of any of these, given the characteristics of the modeled series (Kumarasamy and Belmont, 2017). The performance criteria of calibration and validation periods are shown in Table 3. The colors in the Table 3 represent the classifications suggested by (Moriasi et al., 2007) and are as follows: green for "very good" (NSE > 0.75; PBIAS < ±10%; RSR < 0.50), yellow for "good or satisfactory" (0.75 > NSE > 0.5; ±10% < PBIAS < ±25%; 0.50 < RSR < 0.60), red for "unsatisfactory" (NSE < 0.5; PBIAS > ±25%; RSR > 0.70). Moreover, the correlation coefficient (R^2) and the VE criterion values close to 1.0 mean that the prediction dispersion is equal to that of the observation (Krause and Boyle, 2005; Muleta, 2012). Additionally, the hydrographs for calibration and validation periods are shown in Figure 10. It is important to note that in the validation period (2011-2015), part of the recent drought event was simulated.

Individual watershed hydrological modelling performance ratings are presented in supplementary material - section A, Table A-1; also several statistical criteria were considered to evaluate the calibration process, where each criterion covers a different aspect of the resulting hydrograph. This is important because analyzing multiple statistics can provide an overall view of the model based on a comprehensive set of indexes on the parameters representing the statistics of the mean and extreme values of the hydrograph (Moriasi et al., 2007). Five basins were modeled within the Jaguarí-Jacareí sub-system (Sub B-F28, B-F23, B-F25, Jaguarí and Jacareí). This sub-system represents approximately 46% of the total available water and showed the best modelling performance statistics, compared to the other subsystems.

4.2. SDF curves

Using the traditional frequency analysis, the severity-duration-frequency curves for two threshold levels and two RCMs discharge outputs were developed as shown in Fig. 4. For the SDF curves configuration, the Generalized Extreme Values (GEV) function was used. Thus, from the SDF results it can be observed that:

According to the fit data set (supplementary material - section C), the shape parameter (ξ) varies with the drought duration, therefore for a drought interval of more than 180 days, the Probability Distribution Function (PDF) Type I presents a better fit, even for the two proposed demand scenarios. On the other hand, droughts with duration intervals of less than 90 days, under stationary and non-stationary demand scenarios, had a better fit to FDP Type III (see Tables D-1 to D-4 in supplementary material - section D). Moreover, the fit diagnostic plots "Empirical quantile vs Model quantile” (QQ-plot) and "Return level vs Return period" (RR-plot) show the relationship between the model, the data fit and prediction capacity (supplementary material - section C). Thus, in terms of the quantiles, the QQ-plot shows the data trend to follow the model line in most cases. While the predictive capacity of the model, represented by the RR-plot, shows a decrease as the return period increases.

4.3. Economic impacts under climate change

Based on the methodological approach (see Figure 2), the potential economic impacts were calculated, produced by hydrological droughts greater than 180 days. These impacts are presented considering the climate, demand, time and recurrence scenarios. Thus, the net present value (NPV) of the economic detriment to the water utility company and the percentage difference (Dif. %) between the demand scenarios are shown in Tables 4, 5 and 6 for each period.

From the results in Tables 4, 5 and 6, it can be observed that the economic impact is higher for higher return periods as well as the step of stationary demand to non-stationary demand, as expected. In addition, it is not possible to observe a differentiated trend in the results, when they are forced by two different radiative scenarios over time. However, the scenarios nested within HadGEM-ES, on average, presented lower values or with less economic impact, when compared to the nested scenarios within MIROC5. Overall, the loss of economic profit from

2041 to 2070 showed lower values compared to the other two periods analyzed, probably due to a more optimistic climate scenario in terms of surface water availability.

In Figure 11a, the box plot shows the dispersion of the economic impacts grouped under each climate model by time periods. Results related to the MIROC5 model present a greater dispersion than those related to the HadGEM-ES model. In this case, the upper extreme values are related to the MIROC5 model, while the lower extreme values are similarly distributed between the models. On the other hand (Figure 11b), the difference, in percentage, related to the MIROC5 model show higher magnitudes and more stable differences over time than those related to the HadGEM-ES model, denoting an impact-driven differentiation between climatic models. Moreover, it can be observed in Figure 11 that, in response to the growing projected demand, it will be expected an increase, in terms of the average percentage of differences, for different time periods and for both climatic models.

In general, these results show the high complexity of the SPRM's drought risk and the fragility of local GDP heavily dependent on water for their development. In the specific impacts on the company's economy, the results showed losses per period between US$ 7929 and US$ 64582 million; these values, compared to the Gross Domestic Product (GPD), represent an amount of between 1.3% and 10.3% of the last GDP in the state of São Paulo in 2016. As a consequence, the direct economic impacts on the water utility company, added to other inherent problems to water shortage, can lead to a financial crisis with serious repercussions in local economies.

5. Conclusions and recommendations

This paper developed a methodology with application to assess economic impacts of drought risks for water utilities through a framework under climate change scenarios. The SDF framework has linked climate, hydrology and economy factors, using Sao Paulo Metropolitan Region dependence on the Cantareira Water Supply System, Brazil. In this paper, we consider these results preliminary, but with valuable information for a water utility interested in the drought risk losses. Thus, the expected profit loss over the long-term would serve as the initial estimate for financial contingency arrangements as insurance schemes, or community contingency funds. In general, the SDF framework here developed can be proposed as a planning tool to mitigating drought-related revenue losses as well as being useful for development of water resource securitization strategy in sectors that depend on water to sustain their economies.

Methodologically, first we characterized the hydrological droughts through the SDF curves, from the hydrological modeling by the baseline period of the RCM. Second, the SDF was coupled with a local water demand development based on the supply warranty time percentage during the drought events. Under these assumptions, an empirical drought economic impact curve was setup, representing the Water Utility Company profit losses due to the impossibility of supplying demand during hydrological drought periods. Additionally, our results could elicit further implications for drought risk reduction and management.

On the one hand, this SDF framework could help analyzing the impacts from key drivers, like climate, land use and water withdrawal rates in complex or recurrent drought patterns. Also, this SDF framework could couple interdisciplinary studies, with better relationships towards the nexus of water security, energy security and food security. Thus, we recommend future research of SDF framework linked to: Palmer's drought indices (Rossato et al., 2017), model-based framework to disaster management (Horita et al., 2017), ecosystem-based assessment for water security modeling (Taffarello et al., 2017), effectiveness of drought securitization under climate change scenarios (Mohor and Mendiondo, 2017). Moreover, SDF framework is capable of integrating actions towards: dynamic price incentive programs related to wise human-water co-evolution patterns, water-sensitive programs under deep cultural features, socio-hydrological observatories for water security, feasibility analysis of the economic impacts of implementing new technologies for water economy and flow measurement, leakage control, detecting and legalizing illegal connections and water reuse, among others. Furthermore, dissimilarities pointed from climate scenarios (see i.e. Figure 11) would suggest a set of possibilities to face the uncertainty. For instance, that SDF framework would guide the decision-making of water utility profits to cope with economic impacts of drought risks in long and medium term.

For further studies, it should be considered: that despite having achieved an acceptable performance, the inclusion of more gauge stations could not only improve calibration performance but also cover a larger sample space of events, increasing the confidence of projections. On the other hand, in order to have a methodological comparative standard, more regional studies of SDF curves need to be implemented, considering the spatialized analysis and broader statistics methods. Finally, it is a fact that the reliability of SDF curve estimates depends on the quality and extent of the records used, or in this case, the capacity of regional climate models to reproduce the observed distribution of extreme events.

Acknowledgments

The authors thank the support of several agencies of Brazil and Colombia: the Administrative Department of Science, Technology and Innovation (COLCIENCIAS) Doctoral Program Abroad, CAPES-PROEX-1650/2017/23038.013525/2017-30, CAPES Pró-Alertas #88887.091743/2014-01, CNPq #307637/2012-3, CNPq #312056/2016-8 PQ and CNPq #465501/2014-1 and FAPESP 2014/50848-9 Water Security of the INCT-Climate Change II. The Sao Paulo State Water Utility Company, SABESP, kindly provided relevant information for this study. All co-authors declare no conflict of interest.

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Tables.

Table 1. Description of variables

Scenarios' variables	*Description*
RCM Scenarios	Eta-Model nested in the GCMs: • MIROC5 • HADGEM2-ES
RCP Scenarios [W/m^2]	Forcing by two greenhouse gas concentration scenarios: • 4.5 as optimistic scenario • 8.5 as pessimistic scenario
RMSP Water Demand Scenarios [m^3/s]	• Stationary Demand (SD) 31 m^3/s • Non-Stationary Demand (NSD) 31 to 42 m^3/s
Return period analysis Scenarios [Rp]	Rp = {2, 10, 100} years; drought severity (deficit m^3) and duration (days) scenarios.

Table 2. Main assumptions for establishing the tariff water price according to the drought duration.

Drought Duration Interval (days)	Water Tariff Adjustment adopted (%)	Average price (US$/ m^3)	Scenario of Supply warranty for SPRM	Supply warranty time percentage (%)*
(0, 31)	0	3.38	100% water availability	1
(0, 90)	6	3.58	100% water availability	0.34
(0, 180)	10	3.71	Water availability with storage dependency	0.17
> 365	17	3.95	Water deficit (multi-year droughts)	0.084

*** As [100% Supply warranty time during 31 days / Analysis Scenario of Supply warranty time (days)]**

Table 3. The Cantareira Equivalent System (ES) performance criteria for Calibration-Validation periods. *Cal. =Calibration period and Val. =Validation period. The calibration and validation performance criteria for each basin in the system can be found in the "Complementary Material" - supplementary material - section A. – Table A-1.

Cantareira Equivalent System	*Area (km^2)*	*VE*		*NSE*		*NSE_{Log}*		*RSR*		*R^2*		*PBIAS (%)*	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
	2265.0	0.91	0.80	0.95	0.90	0.94	0.74	0.21	0.38	0.96	0.92	-3.40	-12.36

Table 4. Economic profit loss projection scenario for the period 2007-2040 (x10^6 US$)

RCM scenario	RCP scenario	Demand scenario	2007-2040					
			Rp_2	Dif.%	Rp_{10}	Dif.%	Rp_{100}	Dif.%
Eta-MIROC5	4.5	SD	13818	17.13	19696	27.18	22965	32.61
		NSD	16674		27049		34079	
	8.5	SD	19953	16.73	28443	26.82	33035	32.54
		NSD	23961		38865		48971	
Eta-HADGEM	4.5	SD	14713	8.80	25254	13.36	32242	14.61
		NSD	16132		29146		37758	
	8.5	SD	13667	8.62	23440	13.15	29761	14.54
		NSD	14956		26990		34825	

Note: SD: stationary and NSD: non-stationarity

Table 5. Economic profit loss projection scenario for the period 2041-2070 (x10^6 US$)

RCM scenario	*RCP scenario*	*Demand scenario*	*2041-2070*					
			Rp_2	*Dif.%*	*Rp_{10}*	*Dif.%*	*Rp_{100}*	*Dif.%*
Eta-MIROC5	4.5	SD	10168	50.28	14487	56.34	16788	59.84
		NSD	20453		33178		41799	
	8.5	SD	8733	61.61	12498	66.09	14378	69.06
		NSD	22747		36855		46476	
Eta-HADGEM	4.5	SD	10232	30.44	17550	33.91	22316	34.98
		NSD	14710		26555		34321	
	8.5	SD	8544	36.24	14645	39.41	18594	40.26
		NSD	13399		24170		31125	

Note: SD: stationary and NSD: non-stationarity

Table 6. Economic profit loss projection scenario for the period 2007-2040 (x10^6 US$)

RCM scenario	*RCP scenario*	*Demand scenario*	*2071-2099*					
			Rp_2	*Dif.%*	*Rp_{10}*	*Dif.%*	*Rp_{100}*	*Dif.%*
Eta-MIROC5	4.5	SD	14698	53.45	20956	59.20	24237	62.47
		NSD	31575		51367		64582	
	8.5	SD	7929	60.23	11338	64.93	13017	68.04
		NSD	19938		32332		40734	
Eta-HADGEM	4.5	SD	8508	49.19	14569	51.80	18459	52.81
		NSD	16743		30225		39116	
	8.5	SD	16553	22.40	28392	26.31	36213	27.39
		NSD	21329		38532		49873	

Note: SD: stationary and NSD: non-stationarity

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-615
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 20 November 2017

Figures.

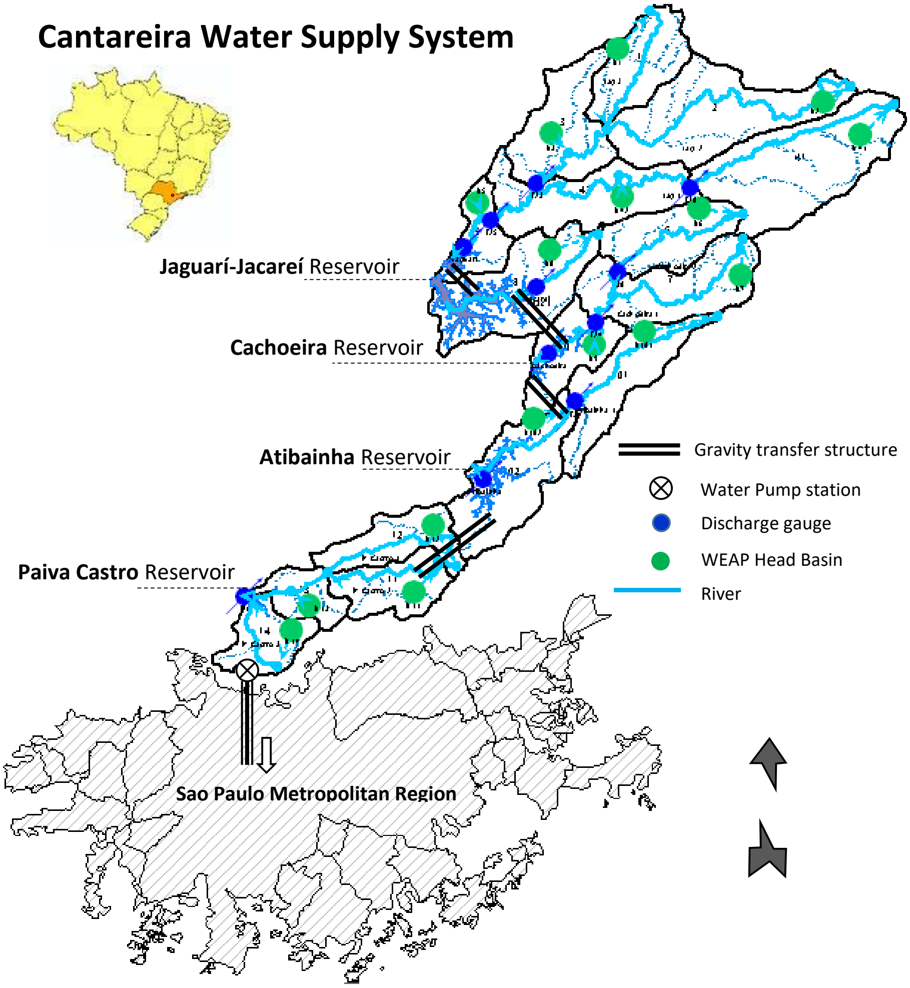

Figure 1. System structure composition and catchment areas: Jaguarí-Jacareí, Cachoeira, Atibainha and Paiva Castro watersheds.

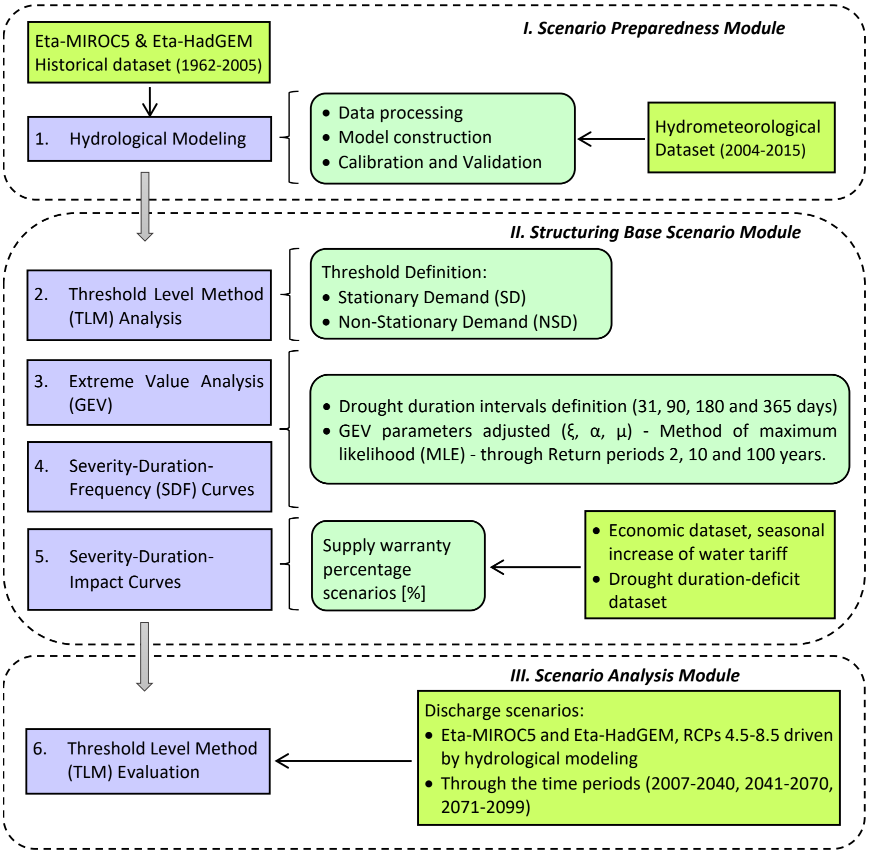

Figure 2. Methodology flowchart and main inputs.

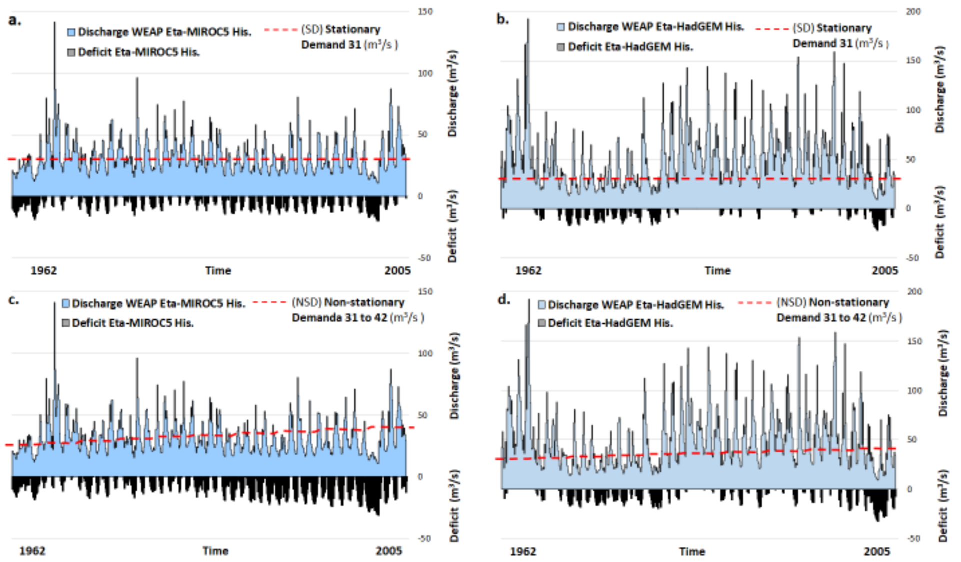

Figure 3. TLM Evaluation from historical discharge WEAP-Eta scenarios, under Stationary (SD) and Non-Stationary Demand (NSD) assumptions as the "threshold level": a. 31 m^3/s and Eta-MIROC5. b. 31 m^3/s and Eta-HadGEM. c. 31 to 42 m^3/s and Eta-MIROC5. d. 31 to 42 m^3/s and Eta-HadGEM.

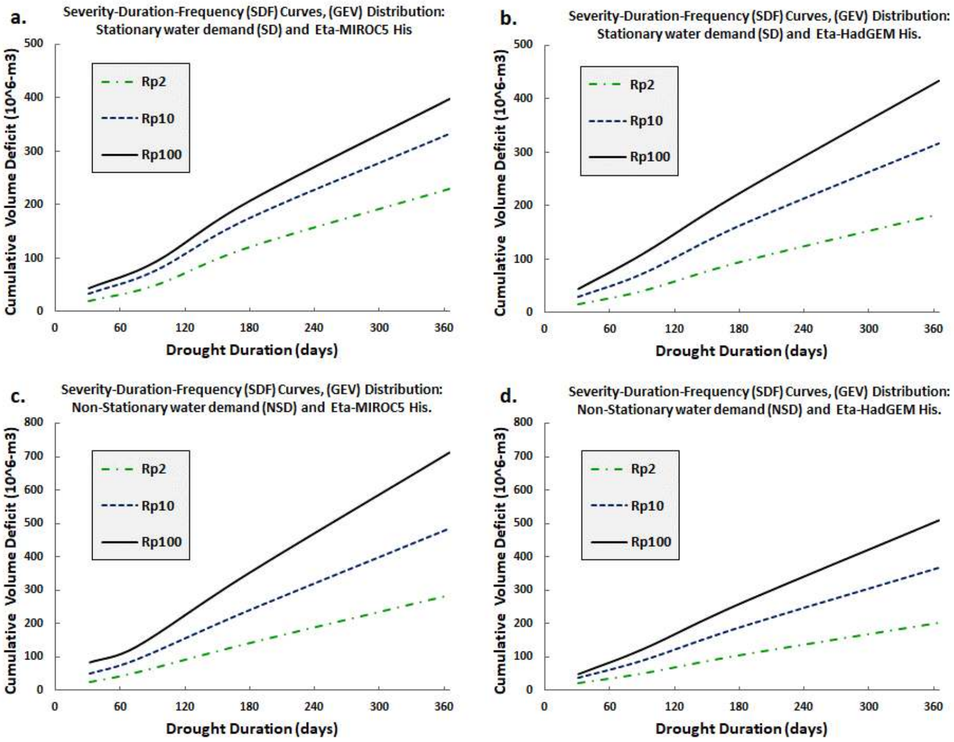

Figure 4. SDF curves under stationary and non-stationary demand assumptions and historical discharge WEAP-Eta scenarios: a. (SD) 31 m^3/s and Eta-MIROC5. b. (SD) 31 m^3/s and Eta-HadGEM. c. (NSD) 31 to 42 m^3/s and Eta-MIROC5. d. (NSD) 31 to 42 m^3/s and Eta-HadGEM.

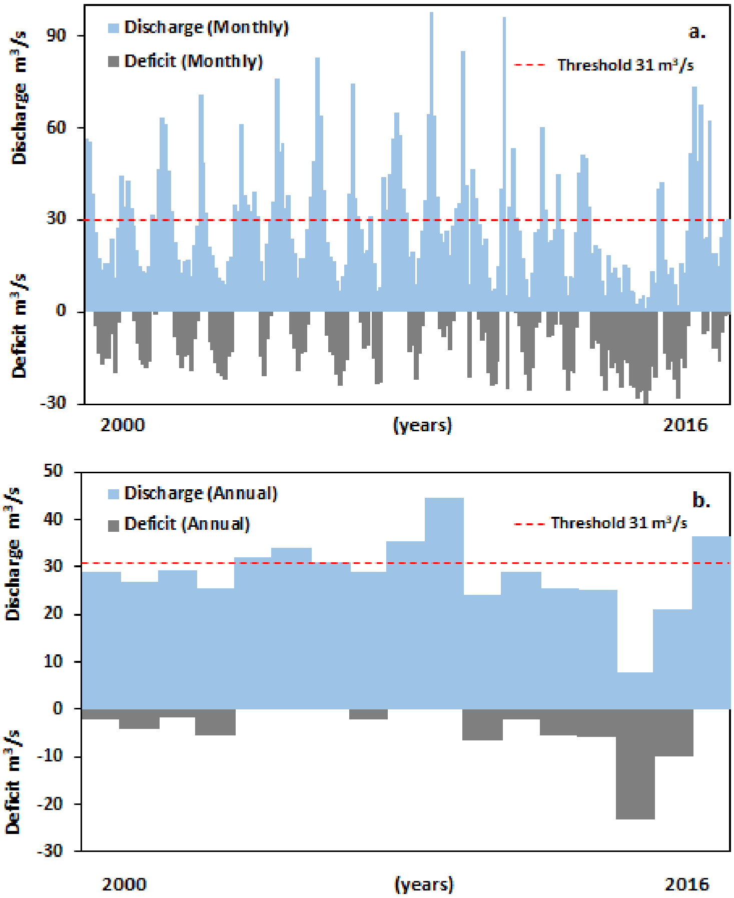

Figure 5. TLM analysis under two discharge scenarios, 2000-2016 period. a) Monthly average discharge and b) Annual average discharge.

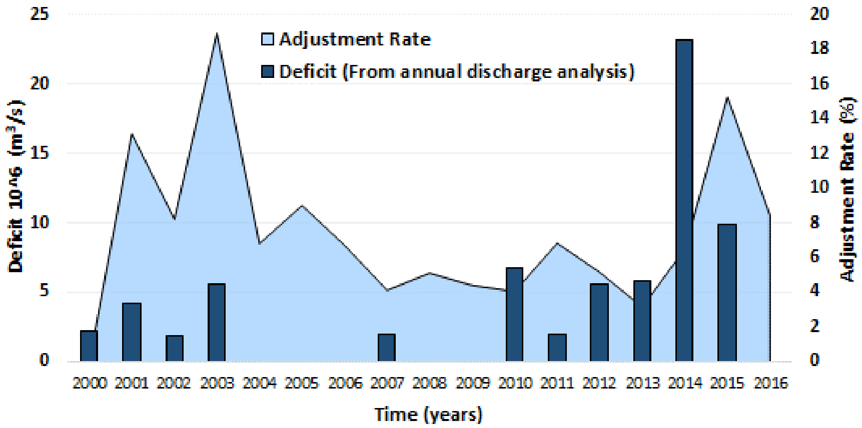

Figure 6. Co-evolution of the drought deficit and price adjustment rates (SABESP – Cantareira System) during 2000-2016 period. Note: deficits defined from TLM analysis under a demand threshold of 31 m3/s and annual average discharge

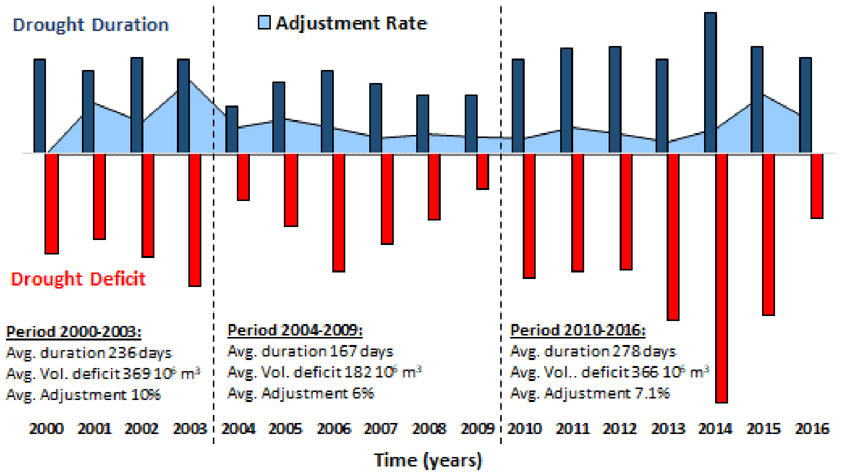

Figure 7. Empirical relationship between Cantareira System drought duration "blue-bar in days" [derived from monthly average discharge analysis], Cantareira System drought deficit "red-bar in 10^6-m^3" [assessed from monthly average discharge analysis] and annual price adjustment rates under variate hydrological conditions in percentage.

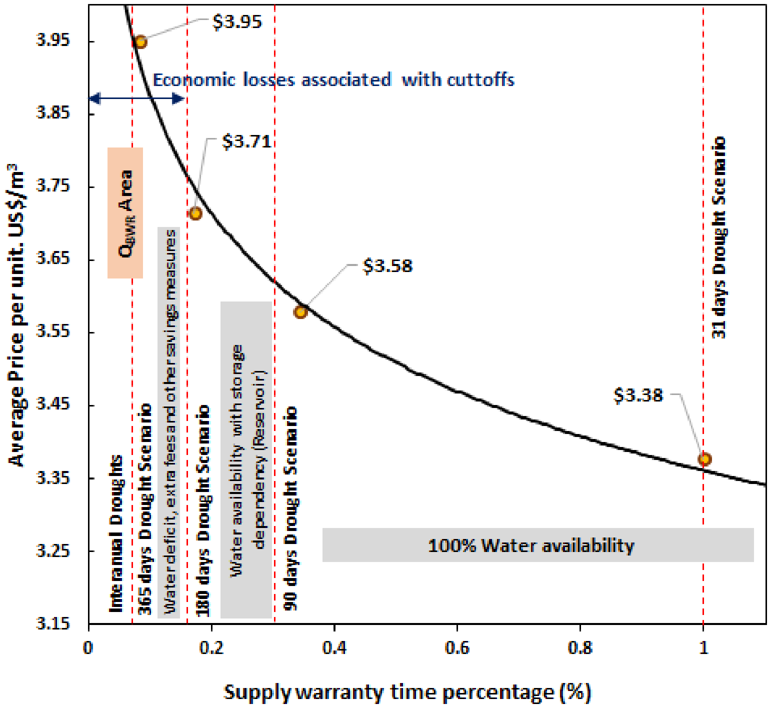

Figure 8. Cantareira System demand curve based on the supply warranty time percentage

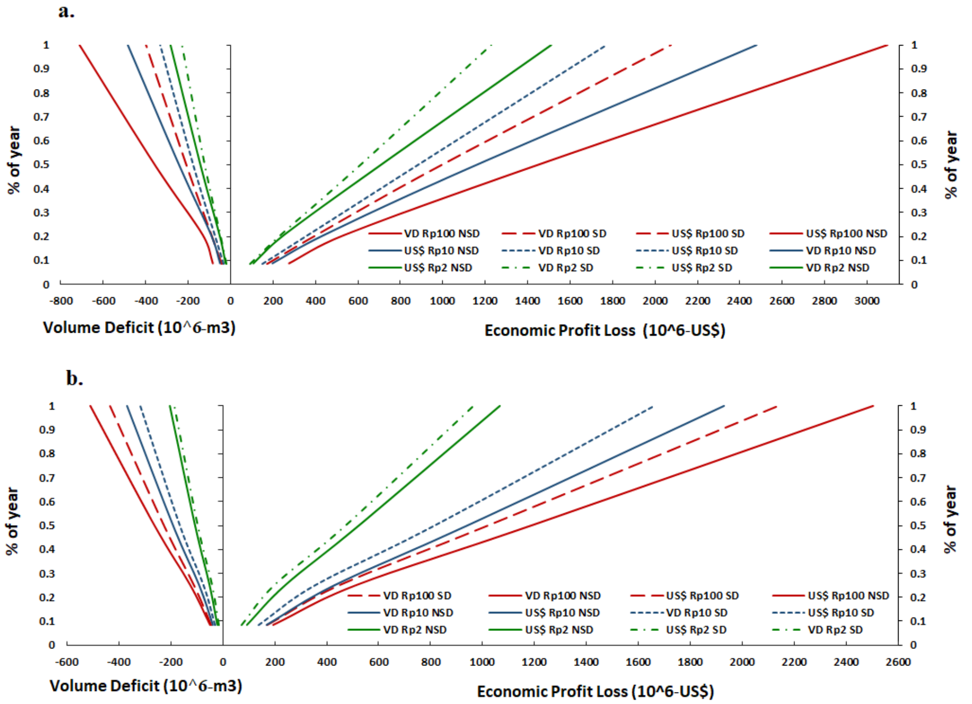

Figure 9. Severity-Duration-Impact curves. Sector **a.** Severity-Duration-Frequency-Profit Loss under the historical *Eta-MIROC5* scenario. Sector **b.** Severity-Duration-Frequency-Profit Loss under the historical *Eta-HadGEM* scenario. Note: *SD* and *NSD* are the stationary or non-stationary demands, respectively; "*VD*" is the volume deficit, under return period of 2, 10 and 100 years; *% of year* is the drought event duration in relation to one year.

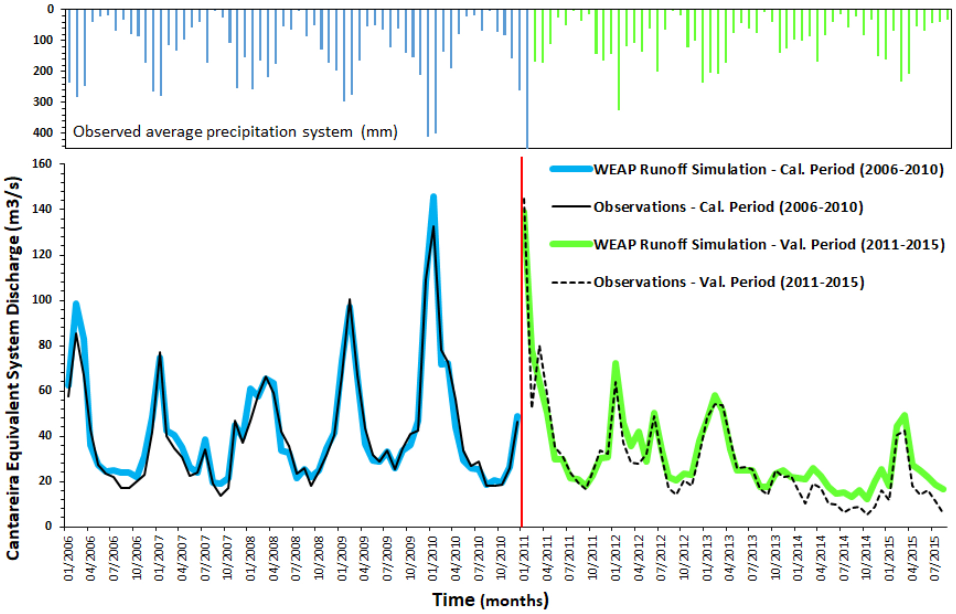

Figure 10. WEAP Hydrographs, Calibration period (2006-2010) and Validation period (2011-2015)

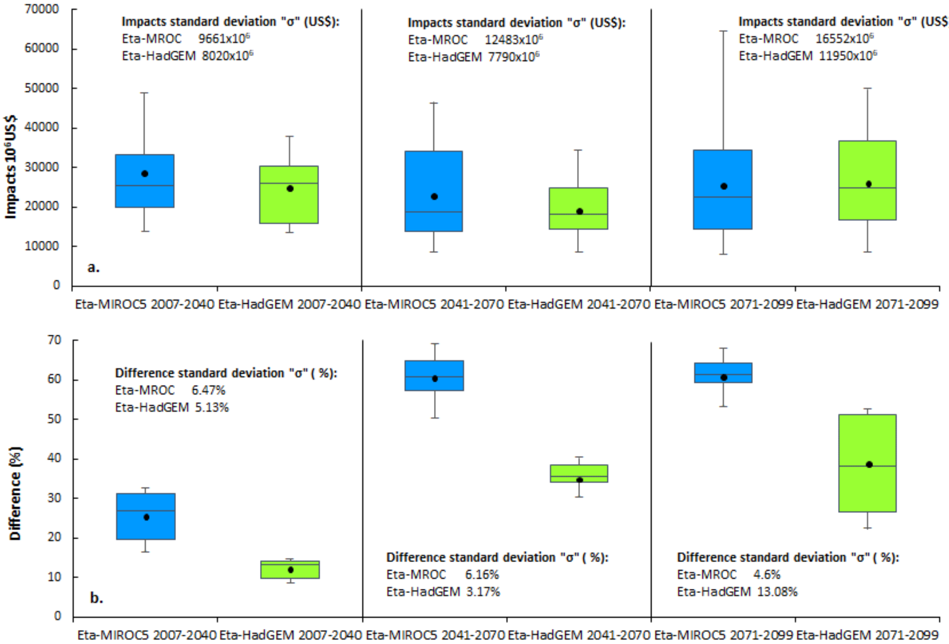

Figure 11. Box plots with impacts and relative differences between climate change scenarios. Sector a: Economic impacts under time periods of climate change scenarios. Sector b: Percentage difference between the demand scenarios under time periods of climate change scenarios.