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DIEGO ALEJANDRO GUZMAN ARIAS

Planejamento da transferência de riscos hidrológicos sob a abordagem "severidade-duração-frequência" da seca como uma estratégia de mitigação dos impactos das mudanças climáticas.

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Thesis presented at São Carlos School of Engineering, the University of São Paulo, as part of the requirements for obtaining the Degree of Doctor in Science: Hydraulics and Sanitary Engineering.

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“I hereby declare this written research is original, with no conflict of interest, and complies with the Codes of Ethics of the main research funding agencies and Higher Education boards, either Brazilian or International ones”.

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ABSTRACT

Guzman, D. (2018) **Hydrological risk transfer planning under the drought "severity-duration-frequency" approach as a climate change impact mitigation strategy.** Doctoral Thesis, Sao Carlos School of Engineering, University of Sao Paulo, Sao Carlos.

Climate change and increasing water demands prioritize the need to implement planning strategies for urban water security in the long and medium term. However, risk planning requires robust and timely financial support during and after the disaster. Therefore, risk transfer tools, such as insurance, have emerged as an effective strategy to ensure financial resilience and as an element that could encourage the implementation of hydrological risk reduction mechanisms. Among the main insurance design problems are the lack of information on the real drought impacts and climate uncertainty, which may incur adverse selection and/or moral hazards among the most common drawbacks in insurance practice. Currently, most of the income from water utility companies is based on water resources management, therefore during prolonged drought periods these economies can be strongly affected, despite having robust storage schemes as support. Thus, this thesis proposes an insurance plan for the water utility company of the State of Sao Paulo (SABESP) to deal with revenue reductions during long drought periods. The methodology is implemented on the MTRH-SHS model, developed under ex-ante damage cost calculation through the risk-based approach. The synthetic ('what-if') approach uses a "set of change drivers" to estimate the optimal premium through a multi-year insurance contract (MYI). The methodology integrates the hydrological simulation procedures under radiative climate forcing scenarios RCP 4.5 and 8.5, from the regional climate model outputs Eta-HadGEM and Eta-MIROC5, with time horizons of 2007-2040, 2041-2070, and 2071-2099, linked to the 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 the Sao Paulo Metropolitan Region, Brazil, with severe vulnerability to droughts. As a result, the evaluated indexes showed that multi-year contracts with drought coverage higher than 240 days offer better financial performance than contracts with wider coverages. Moreover, this MYI adopted in the installed storage residual risk generates both a higher level of solvency for the insurance fund in the long term and annual average premiums closer to the expected revenue reductions by scenario. Finally, the approach can help the systematic evaluation of moral hazards and adverse selection. In the first case, the progressive evaluation must generate useful information to change or maintain the behavior of both the insured and insurers considering future risks related to climate change. In the second case, the multi-scenario valuation can help the insurer to set price thresholds, offering risk differential cover options in the premium value.

Keywords: Risk transfer, Climate change, Water security, Hydrological drought

RESUMO

Guzman, D. (2018) **Planejamento da transferência de riscos hidrológicos sob o abordagem "severidade-duração-frequência" da seca como uma estratégia de mitigação dos impactos das mudanças climáticas.** Tese de Doutorado, Escola de Engenharia de São Carlos, Universidade de São Carlos.

As mudanças climáticas e o incremento na demanda de água priorizam a necessidade de implementar estratégias de planejamento para a segurança hídrica urbana no longo e mediano prazo. No entanto, o planejamento dos riscos exige um suporte financeiro robusto e oportuno durante e após do desastre. Portanto, as ferramentas de transferência de risco, como os seguros, emergem como uma estratégia efetiva para garantir a resiliência financeira e como um elemento que poderia incentivar a implementação de mecanismos de redução do risco hidrológico. Entre os principais problemas no planejamento de seguros, estão a falta de informações sobre os impactos reais das secas e a incerteza climática, que podem levar a seleção adversa e/ou perigo moral como as problemáticas mais comuns na prática dos seguros. Atualmente, a maior parte da renda das empresas de serviços de água é baseada na gestão do recurso hídrico; portanto, durante períodos prolongados de seca, essas economias podem ser fortemente afetadas, apesar de ter sistemas de armazenamento robustos como suporte. Assim, esta tese propõe um plano de seguro para a empresa de serviços de água do Estado de São Paulo (SABESP), para enfrentar as reduções de receita durante longos períodos de seca. A metodologia é implementada no modelo MTRH-SHS, desenvolvido no cálculo “ex-ante” de custos de dano, através da abordagem baseada em risco. A abordagem sintética ("what-if"), usa um "conjunto de drivers de mudança" para estimar o prémio óptimo através de um contrato de seguro plurianual (SPA). A metodologia integra os procedimentos de simulação hidrológica, sob cenários de forçamento climático radiativo RCP 4.5 e 8.5, do modelo de clima regional Eta-HadGEM e Eta-MIROC5, com horizontes temporais de 2007-2040, 2041-2070 e 2071-2099, vinculados ao modelo hidrológico do sistema de avaliação e planejamento da água (WEAP) e sob pressupostos de demanda como abastecimento de água estacionária e não estacionária. A estrutura do modelo é aplicada ao Sistema de Abastecimento de Água de Cantareira na Região Metropolitana de São Paulo, Brasil, região com alta vulnerabilidade às secas. Como resultado, os índices de rendimento do seguro avaliados mostraram que os contratos plurianuais com cobertura para secas superiores a 240 dias, oferecem melhor desempenho financeiro do que os contratos com coberturas mais amplas. Além, o SPA adotado para o risco residual do armazenamento instalado, gera um nível mais alto de solvência para o fundo de seguros no longo prazo com prêmios médios anuais mais próximos das reduções de receita esperadas por cenário. Finalmente, a abordagem pode ajudar na avaliação sistemática do risco moral e na seleção adversa. No primeiro caso, a avaliação progressiva deve gerar informações úteis para mudar ou manter o comportamento de segurados e seguradoras considerando riscos futuros relacionados à mudança climática. No segundo caso, a valoração de múltiplos cenários pode ajudar a estabelecer limiares de preços, oferecendo opções de cobertura diferencial de risco no valor prêmio de seguro.

Palavras-chave: Transferência de riscos, Mudanças climáticas, Segurança hídrica, Seca hidrológica.

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LIST OF ABBREVIATIONS

ANA	National Water Agency / Agência Nacional de Águas
APR	Annual Percentage Rate
BOD	Biological Oxygen Demand
BWR	Basic water requirements
CNSP	National Council of Private Insurance / Conselho Nacional de Seguros Privados
CPTEC	Center for Weather Forecasting and Climate Research / Centro de Previsão de Tempo e Estudos Climáticos
DAEE	São Paulo state Water and Electricity Department / Departamento de Águas e Energia Elétrica
D_d	Drought duration (coverage)
GCM	Global Climate Model
GDP	Gross Domestic Product
GEV	Generalized Extreme Value
HEC	Hydrologic Engineering Center
IBGE	Brazilian Institute of Geography and Statistics
INPE	National Institute for Space Research
IPCC	Intergovernmental Panel on Climate Change
MGB-IPH	Modelo Hidrológicos de Grandes Bacias - Institute of Hydraulic Research of UFRGS (Universidade Federal do Rio Grande do Sul)
MTRH	Water Risk Transfer Model / Modelo de Transferência de Riscos Hídricos in Portuguese
MYI	Multi-year insurance contract
Munich RE	Munich Re-insurance Company
NSE	Nash-Sutcliffe Efficiency index
NVP	Net present value
PADB	Potential Annual Discount Bonus
PBIAS	Percent bias
PDF	Probabilistic Distribution Functions
Rp	Return Period
RCP	Representative Concentration Pathway

RCM	Regional Climate Model
RSR	Ratio of Standard Deviation of Observations to RMS
SABESP	Brazilian water and waste management company owned by São Paulo state
SDF	Severity-duration-frequency curves
SD	Stationary Demand – Non Stationary Demand
SPMR	Sao Paulo Metropolitan Region
SUSEP	Superintendence of Private Insurance
SWAT	Soil & Water Assessment Tool
TLM	Threshold Level Method
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
VE	Volumetric Efficiency
WEAP	Water Evaluation and Planning System
WTP	Willingness to pay

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CHAPTER 1

GENERAL INTRODUCTION

1.1. RESEARCH CONTEXT

Since the recent water crisis (2013-2015) that affected the south east of Brazil (Marengo et al. 2015; Nobre et al. 2016; Taffarello et al. 2016), the Sao Paulo state water utility company has adopted contingency measures to face future impacts (WRG-2030 2014; SABESP 2016d). However, the water crisis showed the company's high financial dependence on the water supply business and that non-structural measures, such as consumption control based on pricing policies do not represent a sustainable economic guarantee during long drought events (GESP 2016). To deal with the economic impacts on the company's profits due to drought risk (Zeff & Characklis 2013), this thesis proposes an insurance scheme to transfer the residual risks from the prolonged droughts that exceed the Cantareira System´s installed storage capacity, the latter of which is the major water supplier for the Sao Paulo Metropolitan Region (SPMR).

The Hydrologic Risk Transfer Model, hereafter called MTRH-SHS (Portuguese: "Modelo de Transferência de Riscos Hidrológicos"; SHS stands for the Department of Hydraulics and Sanitation at the University of São Paulo) was configured under the "what if" approach through the systematic financial calculation of equiprobable driver scenarios of climate and water demand (see Figure 1.1-1) (Graciosa 2010; Laurentis 2012; Mohor & Mendiondo 2017; Righetto 2005; Pilar & Mendiondo 2001). In Figure 1, the approach proposes the offer (blue line) and water withdrawal or demand (red line) scenario evaluation, modeled under future climate projections from the outputs of the RCM Eta-INPE under RCP 8.5 - 4.5 (Chou et al. 2014a-b) and population growth[1] (ANA & DAEE 2004), as pessimistic and optimistic scenarios. Based on the hydrological projections, water deficit hypotheses can be defined from the characterization of drought events according to their duration "di", severity "volume deficit" "Vi" and frequency "Rp" (Hisdal, et al. 2004; Şen 2015; J H Sung & Chung 2014; Lee & Kim 2013; Razmkhah 2016).

[1] https://ww2.ibge.gov.br/home/mapa_site/mapa_site.php#populacao

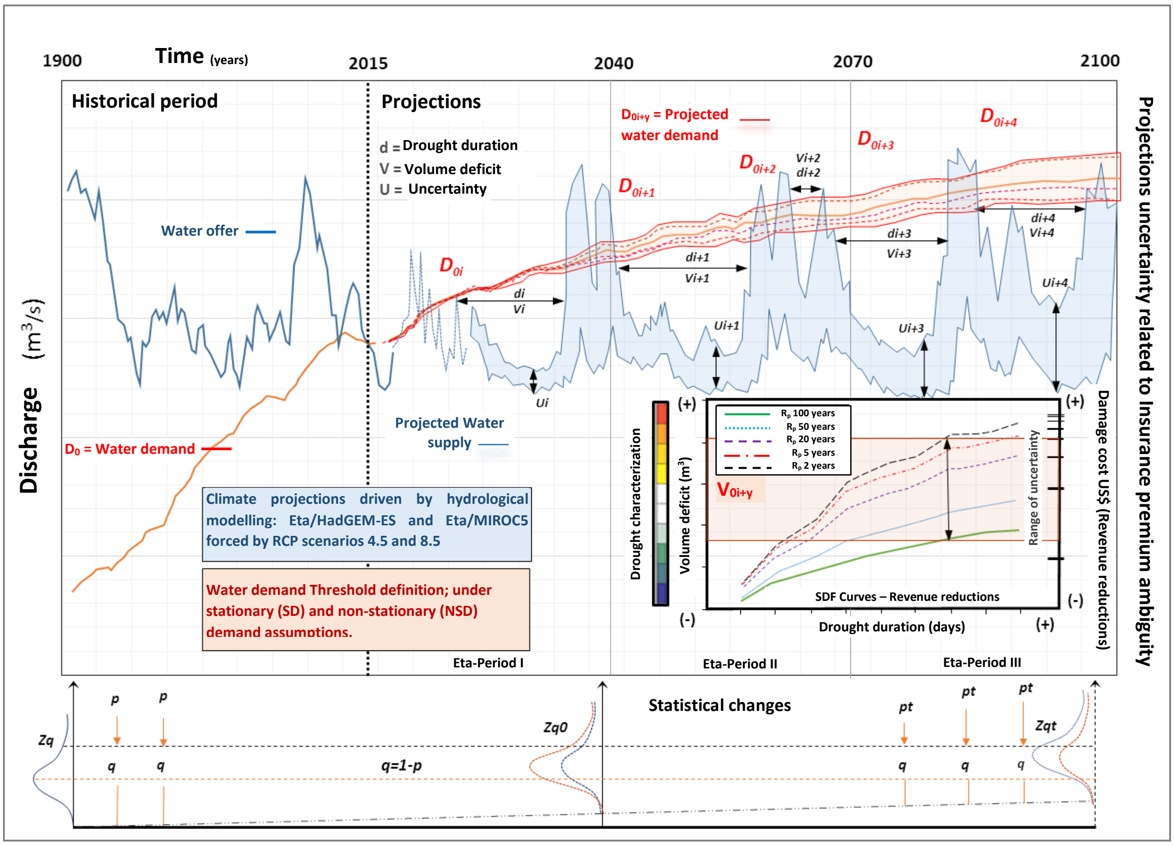

Figure 1.1-1 Description of drivers under MTRH-SHS approach

The insurance model (MTRH-SHS) is a risk-based model that uses hydrological (discharge[2]) projections to simulate the optimal premium, based on the systematic evaluation of a fixed premium under a contractual scheme of "N" consecutive years (Mohor 2016). Figure 1.1-2 shows the general model flowchart, consisting of three main modules. In the hazard module, the discharge series are processed to adopt a specific series or index. From the selected series in the hazard module, the cost damage analysis is defined in the vulnerability module and loaded by a function of damage in the financial module (Meyer et al. 2013). This vulnerability module works as a "plug-in" that can be modified according to the method and variables for the damage analysis. Finally, the financial module that systematically simulates an insurance fund, from "M" equiprobable series which are generated in the process, to deal with the insurance premium ambiguity “α” (Kunreuther & Michel-Kerjan 2014).

[2] Understand as "Discharge" the "Streamflow"

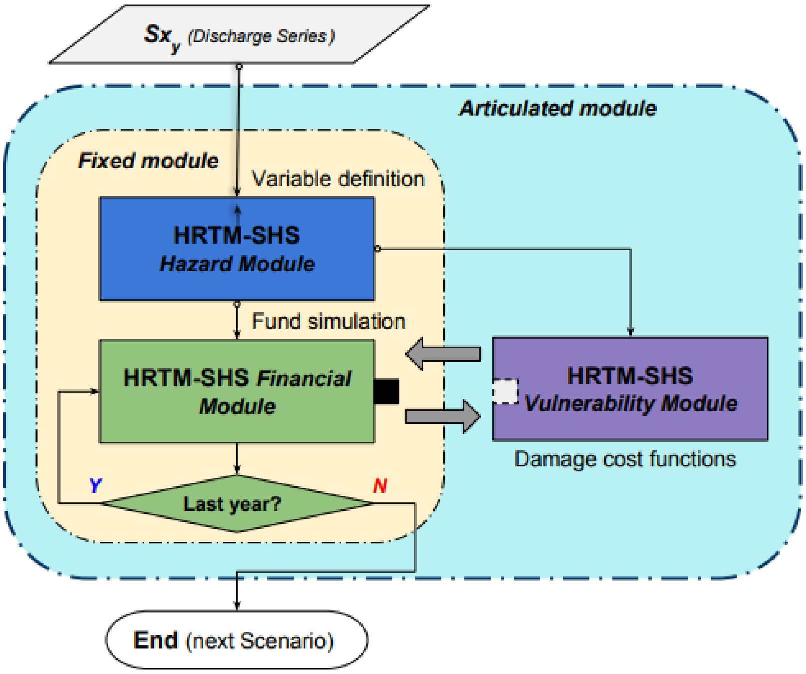

Figure 1.1-2 MTRH-SHS general flowchart (for a better description of the modules, see Appendix and Figure 2.2-3 for a description of the Financial module)

Due to the catastrophe vulnerability increase, caused by global climate change, non-life insurance strategies are being promoted and implemented (IPCC 2014a; Doncaster et al. 2017; Lee & Chiu 2016). However, the difficulty in understanding the growing risks, the lack of information on disasters and the low penetration of insurance in low-income countries increases the gap in regions where these problems converge (Zhu 2017; MCII 2016; Sampson et al. 2014; Kunreuther et al. 2013) .

1.2. HYPOTHESIS

The central hypothesis of the research assumes the influence of the climatic changes on planning and pricing procedures in the insurance contracts over the medium and long term. Considering this, the thesis seeks to answer two specific questions:

- How can the traditional hydrological drought risk analysis view be configured when new evidence of climate change and anthropocentric conditions is being incorporated?

- How can risk transfer models integrate recent evidence of non-stationarity and provide an ambiguity measure approach?

1.3. OBJECTIVES

The main objective of this thesis is to integrate the measurement uncertainty under non-stationary hydrological conditions into the hydrological risk transfer model planning, based on regional circulation model dataset projections; as a mitigation strategy to face the water scarcity economic impacts. To achieve this main objective, the thesis is divided into three specific objectives defined below:

(i) To characterize the hydric deficit in the Cantareira system, based on the water offer and demand scenarios, generated from the regional circulation model (Eta-INPE) projections and historical databases;

(ii) Incorporate non-stationarity conditions in risk transfer model planning, based on the hydric deficit characterization;

(iii) Propose and incorporate an insurance risk premium ambiguity measure under the MTRH-SHS approach.

Each of the specific objectives is addressed in the chapters of this thesis, following the proposed structure in Figure 1.4-1.

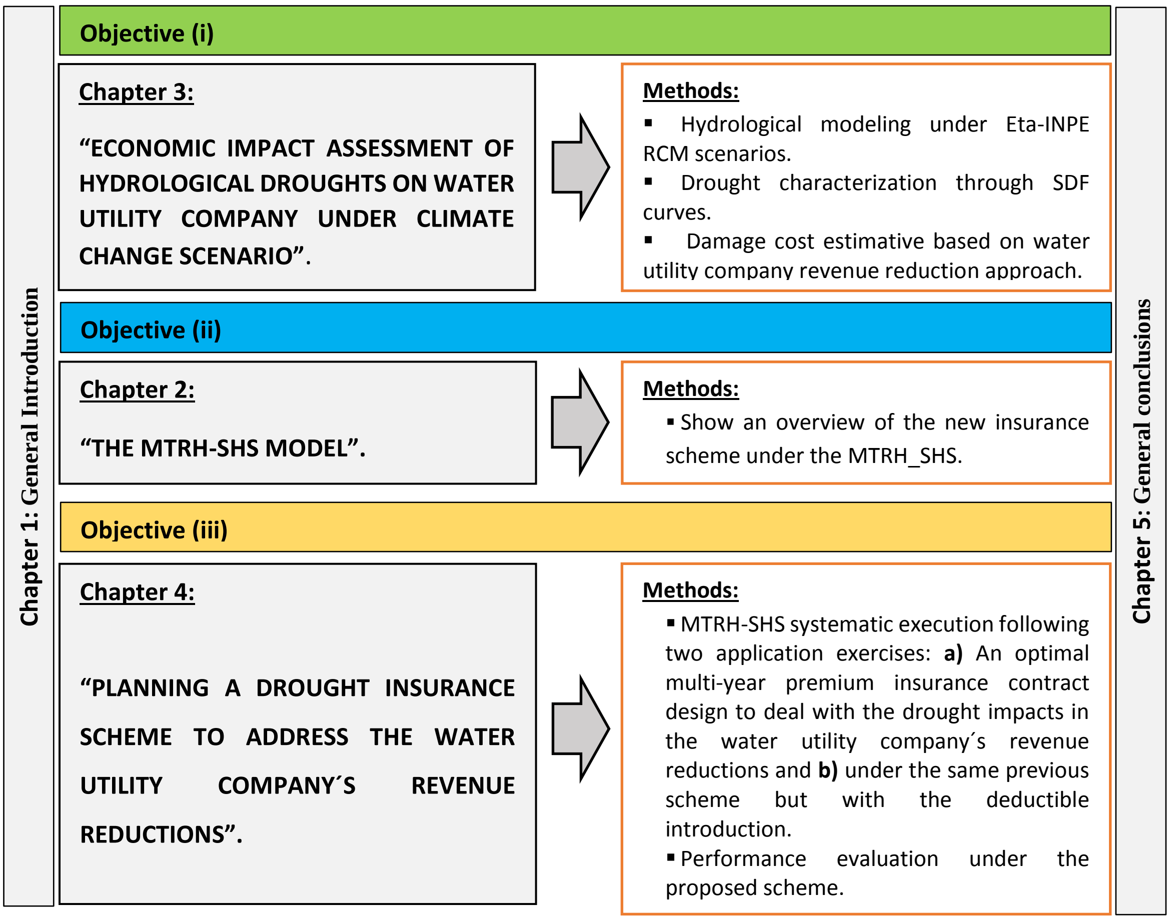

Figure 1.3-1 Methodological structure of thesis

1.4. STRUCTURE OF THESIS

This Doctoral Thesis is organized into three chapters, besides this introduction and a final section with the general conclusions (see Figure 1.4-1). The three main chapters (2, 3 and 4) are aimed at responding to each of the proposed specific objectives. **Chapter 2** shows the general structure of the hydrological risk transfer model (MTRH-SHS) through the description of each of its "hazard-vulnerability-financial analysis" modules. Afterwards, different hydrological insurance approaches to deal with the financial impacts of the risks of floods and droughts, which were developed under the MTRH-SHS scheme, are reviewed. In parallel with this review, a new approach is proposed for the mitigation of economic impacts in the water company during periods of water deficit, following the MTRH-SHS methodology, which will be described in the fourth chapter by two theoretical exercises.

The third chapter presents the severity-duration-frequency (SDF) curve construction to evaluate the potential water utility company damage cost represented by the revenue reductions, during hydrological drought periods. Considering this, on one hand, the WEAP model was implemented (Water Evaluation and Planning system) to generate the future water supply projections in the Cantareira System. Thus, from the climatological projections of the Eta-INPE regional model, nested within the MCGs MIROC5 and HADGEM2-ES, forced by two greenhouse gas concentration scenarios (RCPs) 8.5 and 4.5 used in AR5 (IPCC 5th Assessment Report) and under land use in current conditions, the hydrological model was executed. Moreover, the water demand projections were established based on two scenarios defined as the stationary and non-stationary water withdrawal for supplying the SPMR. Therefore, using the threshold level method (TLM), drought events were characterized in duration-severity-frequency and subsequently related to the cost of each cubic meter that was not invoiced by the company during the water deficit period.

In the **fourth chapter**, the proposed MTRH-SHS approach is implemented using two application exercises. In both cases, the insurance premium value is systematically evaluated under a multi-year contract scheme (MYI), configured through the ex-ante "cost of interrupting the business" analysis in the SPMR water service company. Finally, an average risk premium ambiguity measure is proposed, shown as a set of probable values derived from the drivers of change induced by the analysis.

Finally, a **general conclusion** summarizes the lessons learnt from all the stages of this research, as well as suggestions for future improvements in similar experiments. Although they are still only academic proposals, the outcomes of this thesis showed potential for some alternative paths. For example, multi-year insurance contracts under the ex-ante analysis of the cost of damages; review of preliminary approaches under the MTRH-SHS methodology and configuration of an overview to make improvements, considering the complexity of the drought phenomenon; and finally, the insurance premium ambiguity estimation, useful for a more accurate evaluation of insurance contracts in the long term.

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CHAPTER 2

THE MTRH-SHS MODEL*

* A modified version of this chapter has been submitted as Guzman, D. et al. (2017). Adaptation to Hydrological Extremes through Insurance Assessment Model under Changing Conditions in Brazilian Watersheds. ASCE Journal*: Journal of Water Resources Planning and Management.*

Abstract

Both global change and the political difficulties to deal with hydrological risks show the need for financial adaptation mechanisms. Risk transfer tools, such as insurance, have emerged as an effective strategy to ensure economic resilience and as an element that encourages the implementation of hydrological risk reduction mechanisms. However, changes in socio-natural drivers lead stakeholders to better assess insurance premiums for water security planning and management. In turn, coupling insurance through climatic, hydrological and economic mechanisms is a highly interconnected and complex procedure. This work describes a Multi-year insurance (MYI) scheme, with a funding assessment for watershed-based and multi-sector management in the long term. The risk-based insurance model uses a "what if" approach, to face the hydrological hazards under climatic change. The methodology involves a sequential drought and flood risks analysis for changing conditions; its characteristics and calculation modules are discussed throughout Chapter 2. Thus, the approach can be considered as a complementary tool for the systematic financial risk evaluation with feasible replication, especially for independent initiatives in water resources planning and management.

Keywords: Risk Transfer, Water Security, Financial resilience, Floods and Droughts Damage Mitigation.

2.1 Introduction

Hydrological records have shown that there has been a trend in recent years towards more severe droughts and catastrophic floods in many land areas (Prudhomme et al. 2014; IPCC 2014; Hirabayashi et al. 2013). Due to alterations in magnitude and frequency of natural events and people´s exposure to them (Güneralp et al. 2015; Aerts & Botzen 2011), there has been an increase in the loss of lives, goods, and services throughout the world

(UNISDR 2015), showing evidence of new scenarios of water insecurity. According to the World Meteorological Organization (2012), between 1970 and 2012, 55% of disasters in the world were attributed to hydrometeorological hazards such as floods, droughts, and extreme temperatures, incurring economic losses of approximately US$ 1.1 trillion and 1.13 million deaths.

Water security can be defined as a condition in which a community has access to adequate quantities of clean water to sustain its basic requirements and, at the same time, is protected against water related disasters produced by the extremes (UN-Water 2013). Therefore, when extreme events occur, an adequate quantification of the impacts on water security is essential for planning and evaluating effective mitigation strategies.

After a natural catastrophic event or any incident that causes serious damage, there is a recovery phase when people, governmental and non-governmental organizations attempt to restore services and provide the victims with essential supplies. The restoration process usually weakens the local economy, affects the inhabitants' livelihood and increases the vulnerability to the next loss event on the horizon (Schwank et al. 2010; Cummins & Mahul 2009). At this stage, risk transfer tools, such as insurance, play a decisive role in contributing to reconstructing and re-establishing the economy (Munich Re 2014; The Hyogo Framework for Action 2005-2015). For this reason, having insurance can provide effective economical protection while enabling policyholders and the government to (a) assume risks in investments towards increasing livelihoods, (b) provide the public with advice concerning risk reduction, and (c) change people`s perception of the hazards (UNEP FI 2007; Sanders et al. 2005).

In some developing countries, which tend to be the most affected by natural disasters in terms of their gross domestic product "GDP" (Munich Re 2014), insurance only covers a small part of society (Candel 2007; Gaschen et al. 1998; Mendiondo 2010), and usually not the most vulnerable or the poorest (Gupta 2015). Traditionally, low penetration of the insurance market in developing economies is due to inadequate risk perception, lax urban development regulations, and low purchasing capability, among others (Lamond & Penning-Rowsell 2014). Additionally, private companies own most of the risk or insurance models, so they are not available for studies and testing (Sampson et al. 2014; Zhu 2017; Dietz et al. 2016). In this scenario, risk transfer incurs higher costs, which results in adverse selection and/or maladaptation (Contador 2007; The World Bank 2014; Grey et al. 2013; Glade et al. 2001). Taking this into account, integrating economic and technical conditions would justify the efforts of analyzing and pricing the damage, raising the awareness of the population and fostering the coverage of the insurance market to a broader population.

Various institutional arrangements and insurance models can be found throughout the world, each suited to different situations (Lamond & Penning-Rowsell 2014; Hudson et al. 2016; Dixit & McGray 2009). The traditional approach to designing an insurance scheme adopts the calculation of the insurance premium based on the expected risk of the disaster. (Borch 1967; Kunreuther & Michel-Kerjan 2014). However, the expected uncertainty in risks, driven by global change, is an insurance design problem in the long-term (i.e. moral hazard), and likewise, conventional schemes of one-year contracts may lead to insurance fund insolvency in the face of increasing hydrological risks.

To face the resilience inability, this document describes a new methodology for planning a Multi-year insurance (MYI) contract associated to hydrological risks, considering the coupling of climate-hydrology-economic processes of iterative scenarios under the "what if" approach (Graciosa 2010; Laurentis 2012; Mohor & Mendiondo 2017; Righetto et al, 2007). In essence, the methodology was designed for financing initiatives of collective risk management in the Brazilian context (Mohor 2016; Guzman & Mendiondo. 2018), where the hydrological insurance market has low penetration (GFDRR 2014). The text continues with the insurance model description, which includes an analysis of its modules for bundled water risks, such as floods and droughts, in Section 2.2. Later in Section 2.3, the main MTRH-SHS developments and model features that have been implemented is shown. In Section 2.4, the advantages and disadvantages of the approach are discussed, followed by the conclusion and further observations in Section 2.5.

2.2 MTRH: An insurance fund simulator

The Hydrologic Risk Transfer Model, hereafter called MTRH-SHS (Portuguese: "Modelo de Transferência de Riscos Hidrológicos"; SHS stands for the Department of Hydraulics and Sanitation at Sao Paulo University) was configured under the "what if" approach through the intensive financial calculation of future equiprobable scenarios of climate, land use and water demand (to drought analyses). It is spatially lumped on a watershed scale as an administrative unit of water management, and run at the multi-annual basis, in medium or long-term scenarios (see Graciosa 2010; Laurentis 2012; Mohor & Mendiondo 2017; Righetto et al 2007; Guzman & Mendiondo 2018).

The MTRH-SHS incorporates a general risk-assessment process (Kunreuther & Useem 2010; Botzen 2013) including analytical elements of hydrological hazards, vulnerability, and economic loss, with local or sectorial damage impacts (see Laurentis 2012; Pilar et al. 2001). The approach focuses on the analysis of the damage risk expected from flash floods, droughts, or both, through a collective multi-sectoral insurance fund model. The approach does not include a reinsurance calculation for the most harmful events, i.e. losses above a maximum coverage are covered by a reinsurance policy without incurring any financial loss to the initial fund.

In Brazil, there is a lack of any official insurance methodology for hydrological hazards in both the public and private sectors due to their low coverage and penetration. (Lamond & Penning-Rowsell 2014; GFDRR 2014). However, the model complies with the current national rules of the "Brazilian Superintendence of Private Insurance" (SUSEP 2004; CNSP 2016) for different types of coverage. The main MTRH-SHS assumptions are shown as follows:

- The financial assets of the targeted population and production benefits of different sectors are initially regarded at equilibrium. Within the vulnerability module, however, the loss functions can be changed or updated over time, as changing or non-stationary conditions.

- Some local information is required to construct and analyze loss functions, which means that the model is not entirely transferrable (see Righetto et al. 2007).

- The fund's initial capital is derived from annual premium payments for the first period (first year) if there is no other capital specified previously (public or private).

- The initial premium or seed value to optimize the model can be the insurer´s willingness to pay (WTP). This value is highly recommended as it may offer an insight into the risk perception of the potential policyholder considering that the information is available (see Graciosa 2010; Righetto et al. 2007).

- The adopted damage cost functions are a simplified representation of the potential disaster economic impacts (Meyer et al. 2013).

- The maximum coverage limit guidelines are defined by return period. According to (Mechler et al. 2014; Surminski et al. 2016a), risk financing may be appropriate for maximum coverage up to 100 years; minor risks can be handled with insurance contract retentions or fully assumed by the collective.

- The results should be understood as an average trend, and not as a prediction for a given period (see discussions in Allen & Ingram 2002; Bravo et al. 2014; Demaria et al. 2013; Siqueira Júnior et al. 2015; Wood 2002).

2.2.1 Description of MTRH-SHS Modules

Following Sampson et al. (2014) and Charpentier (2008), the MTRH-SHS itself comprises three modules, the hazard module (i) that provides information to the other modules and the vulnerability (ii) module, which is inserted in the financial module (iii) (see Fig. 1). The model begins with the hazard module by analyzing the characteristics of a flow series previously provided as input information (see Fig. 2.2-1). These characteristics can spread from low-flow indices such as "$Q_{7,10}$" or "D_l" drought duration characteristics (Gottschalk 2004; J. H. Sung & Chung 2014; Modarres and Sarhadi 2010; Kreibich et al., 2010) to the maximum flood height "h_{Qmax}" (or corresponding Q_{max} flow). Later in the vulnerability module, the water deficit (for droughts) or the affected assets per water level (for floods) are estimated. Afterwards, the economic loss is quantified per sector independently as a function of the hazard level, from damage functions pre-established in each case (see Nascimento et al. 2007 and Machado et al. 2005 for Brazilian situations or Brozović et al. 2007; Aubuchon & Morley 2013). Thus, the losses are linked to the return period “R_p” and a loss function in monetary value "$ls" is obtained. Finally, the financial module is triggered by the synthetic generation of equiprobable flow series, based on the hazard module outputs that involves hydrological modeling under coupled climatic-hydrologic scenarios or streamflow time series data. The main purpose of generating “M” equiprobable series is to deal with the projection uncertainty when estimating the premium (Naghettini 2017). Each of these *M* series is evaluated by the adopted analysis scheme, resulting in an annual insurance premium optimized under a multi-year contract. After equiprobable series are calculated, the model adopts the average of the optimized premiums per scenario as a potential actuarially fair premium.

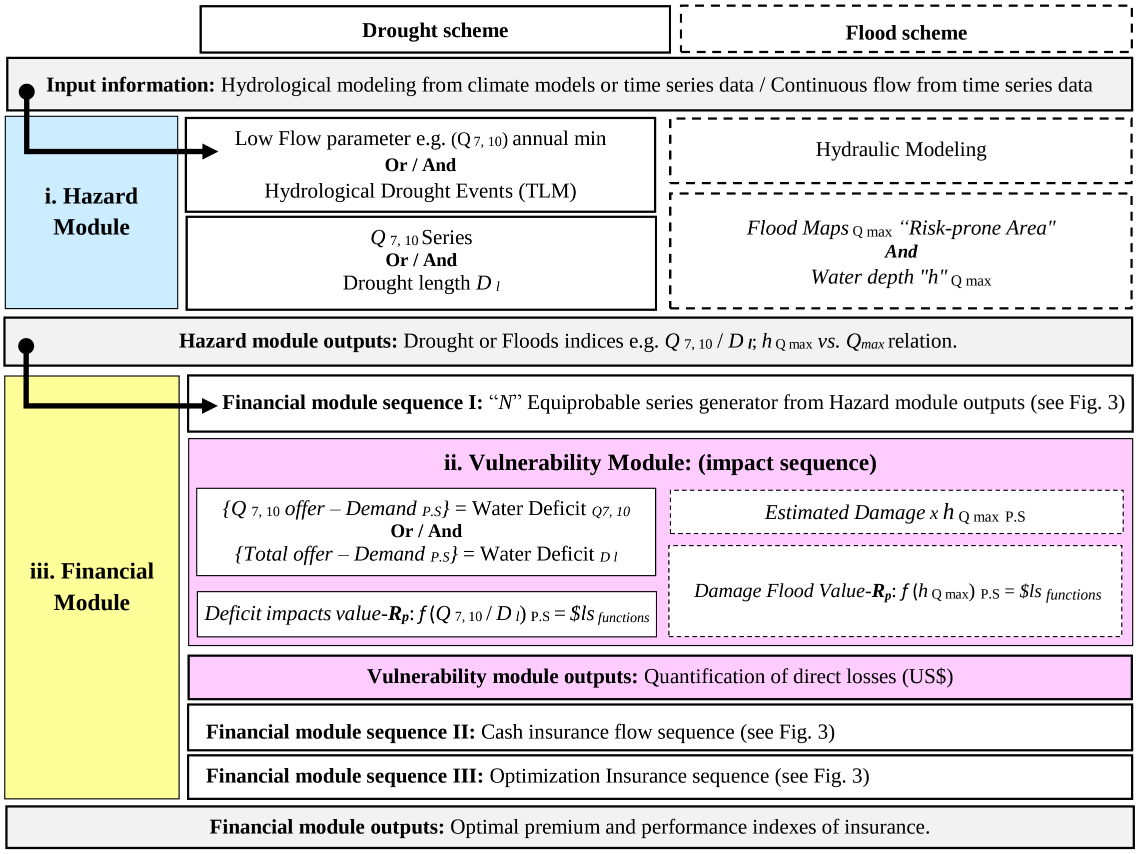

Figure 2.2-1 MTRH-SHS general structure for drought and flood applications. *TLM*= Threshold Level Method approach; *$ls* = economic losses; R_p = Return period; $Q_{7,10}$= 7-day, 10-year return period flow; D_l = Drought duration; h_{Qmax} = maximum water level; PS = per sector.

2.2.1.1 Hazard module

In Figure 2.2-1, the hydrologic hazards can be characterized from a time series of historical data or hydrologic modeling, coupled (or not) with a hydraulic model, i.e. driven by local impacts of the earth system model which makes projections of global changes to the water level calculation. One insurance approach in MTRH-SHS relies on the previous characterization of extreme hydrologic events, i.e., according to the magnitude degree, frequency, and severity (AECOM 2013). This classification makes a link between the extreme event and the level of impact on the insured object; thus, the occurrence of extreme phenomena is associated with Probabilistic Distribution Functions (PDF) (Chow et al. 1988; Naghettini 2017).

In MTRH-SHS (see Fig. 2.2-1), the observed data or modeled time series obtained by the simulation are later adjusted to the Generalized Extreme Value (GEV), i.e. annual maxima or annual minima indices. A range of possibilities based on the return period "R_p" can provide an extensive view of risk. On the one hand, for flood risk, the probabilities linked to different degrees of intensity and frequency for the phenomenon defines the degree of threat and, to some extent, its relation to damage. On the other hand, for drought risk, the current version of MTRH-SHS is based on the water deficit, taken as the gap between surface water available to multi-users and their actual or projected demand, characterizing a socio-economic drought hazard. Various demand scenarios can be tested using MTRH-SHS, divided into user sectors such as domestic, industrial, crop production, livestock and environmental, the latter only referring to the water volume needed to dilute organic loads in sewage dumping without treatment, i.e. biological oxygen demand (BOD) (see Mohor & Mendiondo 2017). Other environmental damage is not yet considered.

2.2.1.2 Vulnerability module

The vulnerability module in the MTRH-SHS is based on ex-ante damage cost assessment (Meyer et al. 2013), through the empirical loss functions under several risk scenarios (Brozović et al. 2007; Nascimento et al. 2007; Kreibich et al. 2010; Machado et al. 2005). However, the structure for evaluating the damage cost is flexible as it can adopt alternative methodologies such as (a) direct loss datasets for floods or assets economic values, (b) business interruption cost datasets, and (c) ante-approaches that assess the willingness-to-pay (WTP) against potential losses (Schröter et al. 2014; Notaro et al. 2014; Dutta et al. 2003). Due to the fact that the MTRH-SHS is a model designed for watershed analysis area, the scale of losses is a mesoscale approach, disaggregated on land-use or sector categories, which acknowledges both empirical data and conceptual models (Messner & Meyer 2005).

MTRH-SHS damage estimation consists of two separate pathways for floods and droughts (see Fig. 2.2-1). The vulnerability module calculates direct damage and economic loss of each equiprobable series within the financial module. Losses due to droughts are mapped out individually for each economic activity (or sector) considering the accumulation of wealth, productive value and dependence on water (Mohor 2016). In the case of flooding, sectors are defined as residential, commercial and services (Graciosa 2010).

2.2.1.2.1 Damage functions for floods

The flood damage direct loss curve estimation in MTRH-SHS consists of four steps (Meyer et al. 2013; USACE, 1975; 1986): (a) the relationship of the flow to return period estimated by statistical modeling; (b) the relationship of flow to over-floor water depth, estimated by hydraulic modeling; (c) the relationship of over-floor water depth to economic loss estimation by loss models; and (d) the relationship of economic losses to return period (see Fig. 2.2-2).

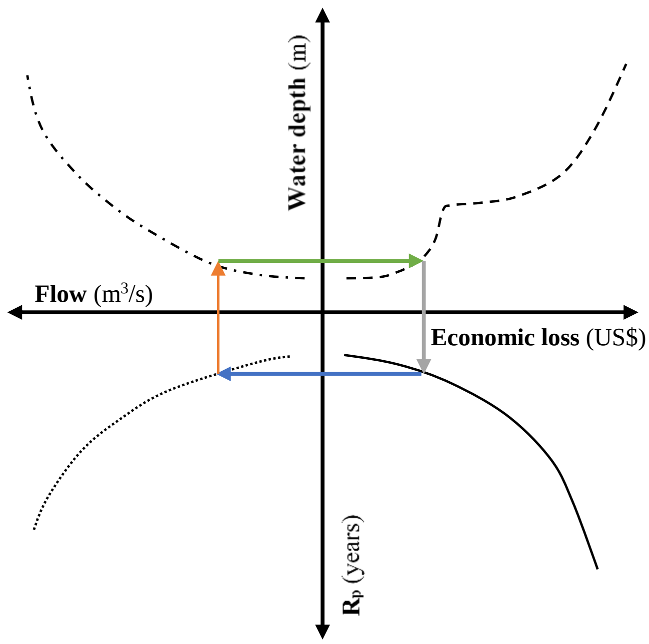

Figure 2.2-2 A conceptual scheme to flood loss function construction based on US Army Corp of Engineering ("Adapted from Graciosa 2010"). Relationship between: Water depth; Economic losses; Return period "R_p" and Flow.

Based on the results of hydraulic modeling, digital terrain models and a direct loss estimation methodology, the damage functions are developed for the flood-prone areas. Then, these flood-prone areas are superimposed on the land use, occupation maps and over-floor water depth for each time period analysis. Finally, the stage-damage curves were provided for each category of land use and occupation (Graciosa 2010; Righetto et al 2007; Abreu 2016). For this version of MTRH-SHS, two different types of stage-damage curves were adopted: actual and potential (Graciosa 2010; Abreu 2016). Actual curves use observed damage datasets, the logic being that past event losses are indicative of future flood losses. On the contrary, potential stage-damage curves involve hypothetical assessments of the vulnerability of assets at different over-floor heights for managing and planning future risks (Gissing & Blong 2004).

2.2.1.2.2 Damage functions for droughts

The damage costs[3] of each water use sector were estimated as the average relationship between the cost of 'execution', production or supply and the corresponding

[3] In chapters 3 and 4, the economic losses are addressed through the water company revenue reduction empirical curves.

water use, according to Meyer (2013) the "Business interruption costs". One equation is the annual value of production per volumetric demand, resulting in a fixed ratio in monetary value (dollars per unit volume), thus establishing a relationship between the deficit and economic losses. For example, for the domestic sector, we used the formulation from Aubuchon & Morley (2013), a modified method proposed by Brozović et al. (2007), (Eq. 2.1):

$$Domestic_{lossperday} = \frac{\eta}{1+\eta} * Price * Q_0 * \left[1 - \left(\frac{BWR}{Q_0}\right)^{(1+\eta)/\eta}\right] \tag{2.1}$$

Where η is price elasticity, *Price* is the average price of water supply charged by the water supply company, Q_0 is water demand and *BWR* is the basic water requirements. In MTRH-SHS, prices charged by the water supply and sewage treatment company, as well as the cost of production and the value added by the sector to the economy are needed. Furthermore, regarding the domestic sector, price elasticity and regular water supply prices are also required by MTRH-SHS.

Considering the environmental sector, BOD natural concentration is required by MTRH-SHS, as well as the permitted concentration in the released effluents, according to Brazilian freshwater quality norms. The natural concentration was derived from the water quality gauging stations. The dilution water demand (DWD) is addressed by MTRH-SHS as the grey water footprint, the amount of water required to dilute the load to the permitted value of dumping (Hoekstra et al. 2011) as:

$$Dilution\, Water\, Demand = Qefl * \frac{(Cefl - Cperm)}{(Cperm - Cnat)} \tag{2.2}$$

Where Q_{efl} is the discharge of the effluent, C_{efl} is the remaining concentration of BOD in the effluent, C_{perm} is the BOD permitted by Brazilian norm, and C_{nat} is the BOD natural concentration in the water body. The effluent discharge is derived from local and specific information. The value of the remaining BOD load was converted into a discharge equivalent of what is needed to dilute the load to make it comparable with the demand levels and losses from the other sectors.

Financial damage from the industrial sector was based on the value added by the local industrial sector, as proposed by Brozović et al. (2007):

$$Industrial = \frac{1 - r_s}{0.95} * [\alpha_s * (1 - z_s) - 0.05] * Production_{perday} \tag{2.3}$$

Where r_s is the resilience of sector s to the lack of water, α_s is the dependence of sector s to the water source (surface water in this case), and z_s is the percentage of water supply for the sector (0 for the complete outage, 1 for normal supply). The resilience varies from sector to sector of activity with an average value adopted from Aubuchon & Morley (2013). In this case, the economic losses per m^3 were calculated under a total outage in water supply, and the actual loss per event is a relation to the actual outage. Finally, in the crop production and livestock sectors, MTRH-SHS proposes a ratio of annual production per water demand. The figures for crop production were derived from the Agricultural Census (Brazilian Institute of Geography and Statistics (IBGE), 2006) and in the case of livestock, the cost of production was adopted. Furthermore, MTRH-SHS could be used, with proper adaptations and integration into other tools, to evaluate total losses in terms of spatial units, or directly for each sector concerned, potentially suitable for large-scale water management where economic activities and land use are generally quite homogeneous.

2.2.1.3 Financial module

The financial module MTRH-SHS (see Fig. 2.2-3) can generate random variables using the Gumbel distribution and Monte Carlo method of monthly equiprobable synthetic series generated by the Thomas and Fiering method (Vaghela & Vaghela 2014; Harms & Campbell 1967). These equiprobable series are used to assess the occurrence of estimating the damage occurrences, damage-related claims and corresponding optimized premiums to achieve fund solvency (Mohor & Mendiondo 2017).

The basic financial scheme adopted for the flow of insurance funds is formulated by assuming the existence of a market without competition, free of administrative costs (optional) and the incorporation of deductibles or retentions (optional). Under stable economic conditions over a period of time and with an initial storage "$S_{(t)}$", the result of total capital from the premiums in the first period follows a flow-storage money fund equation (Eq. 2.4) “insurance fund storage balance equation”, at the watershed scale:

$$S_{(t)} = S_{(t-1)}(1 + tx_2) + I_{(t-1)} - L_{(t-1)}(tx_1) + Pr_{(t-1)} \tag{2.4}$$

Where t is the year, S is the capital stored in monetary units, tx_2 is the interest rate on the stored capital or interest in loans, $I_{(t-1)}$ is the compensation above the deductible, $P_{(t-1)}$ is the premium paid by the insured and $L_{(t-1)}$ is the amount of the annual payable loan.

The financial sustainability of the insurance fund is evaluated by optimizing the objective function (Eq. 2.5) with key financial constraints: (a) the optimized premium must be equal or less than the maximum premium, $O_p \leq Pr_{max.}$, or $O_p \leq WTP$, and (b) the insurance fund storage is greater than or equal to zero $S_{(t)} \geq 0$. The premium optimization uses the nonlinear Generalized Reduced Gradient (Lasdon et al. 1974) to reduce the loans required for each of the M equiprobable series of N years. In a watershed system x, in the t_{th} step, there is the capital stored in monetary units S_t, and the total loss in the system $\$ls_{x,t}$, or indemnification, one scenario-based, watershed-scale, optimized premium is assessed as:

$$O_p = min \sum_{t=1}^{N} (\$ls_{x,t} - S_t) \tag{2.5}$$

Each scenario series has a fixed length of N years established. The insurance adopted by MTRH-SHS depends not only on the magnitude of events but also on their timing sequence. This situation can be compared to the threshold for an evolution framework outlined by Siebert 2016, in which the premium is kept constant for a given return period of an event, but the magnitude of the event changes. In the proposed MTRH-SHS scheme, a basin-scale aggregate premium is estimated as a function of the probability and the expected risk loss (Şen 2015; Kunreuther et al. 2013; Cummins & Mahul 2009).

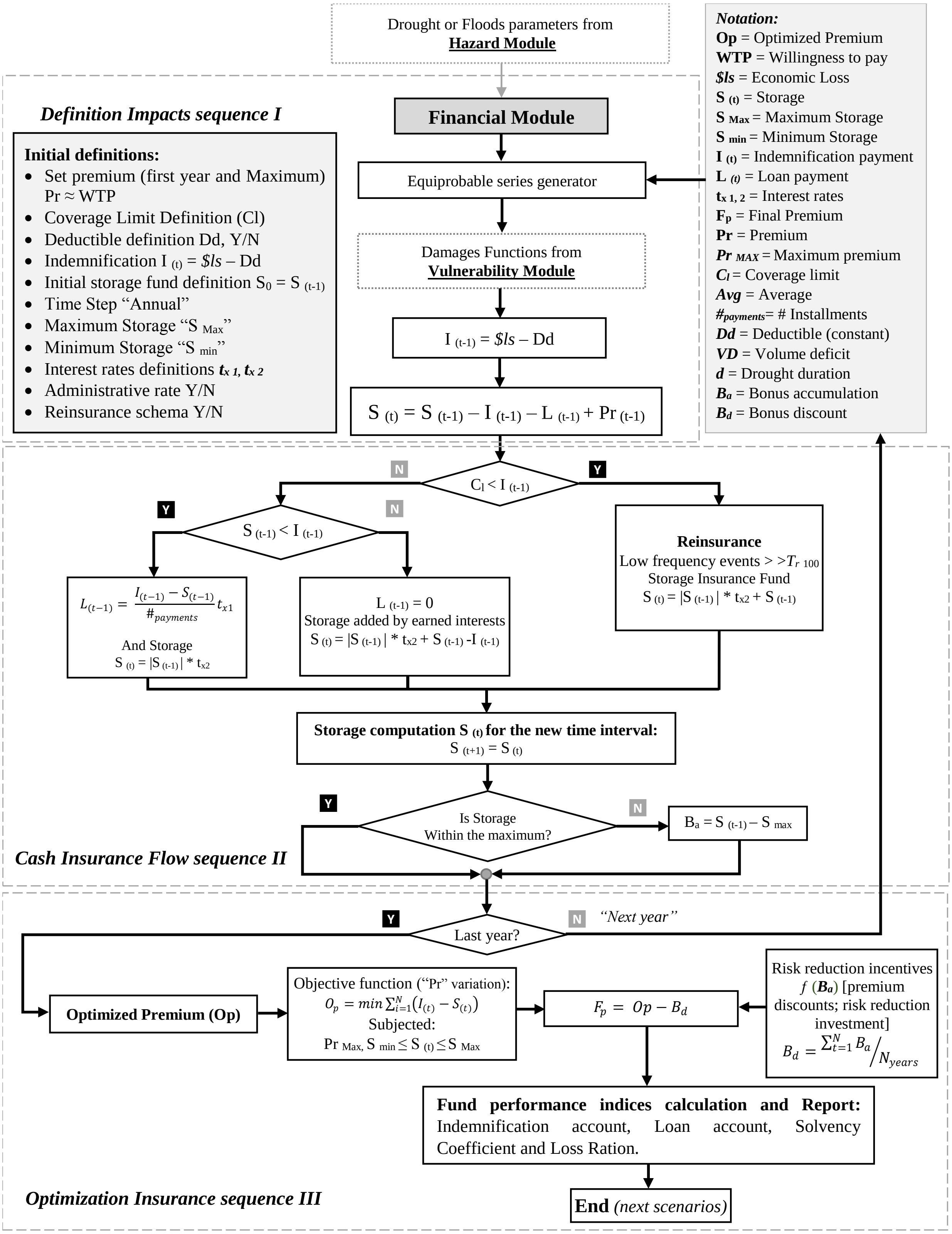

Figure 2.2-3 Flowchart of the financial module in the risk transfer model MTRH-SHS for the area at risk.

With MTRH-SHS, the final premium *Fp* is calculated by combining (i) the average of premiums *Avg* (*Op*) from equiprobable scenarios and (ii) the risk of occurrence of a disaster event (probability "p") during "n" successive years covered by the insurance policy as:

$$Fp = Avg\ (O_p) * (1 - (1 - p)^n) \tag{2.6}$$

Adopting risk transfer tools, as financial mitigation systems and promoters of a change in the risk-awareness of policyholders, strengthens strategies for risk reduction (Hudson et al. 2016; Hayes & Asce 2004), e.g. by offering economic incentives such as a reduction in the annual premium value (NFIP 2014). For this case, at the end of the MTRH-SHS financial module runs, a stored result of the successive accumulation of premiums might exceed the maximum limit of the fund balance. These accumulated profits are theoretically surplus amounts for the fund, and they can be returned to the insured in the form of a bonus or discount scheme on the average value of the planned insurance premium (Li & Xu 2017). On the other hand, insurance companies can encourage investment in risk reduction strategies, i.e. new infrastructure for larger future hazards, development of strong policies in post-disaster recovery, or anticipatory measures such as early warnings and drought monitoring systems (Horita et al. 2017; Mohor & Mendiondo 2017; Tsakiris 2017; Ran et al. 2017), thus the implementation of this type of strategies positively influences the insurance premium value.

MTRH-SHS performance measures (see Fig. 2.2-4) are: (a) accounting for requested loans and indemnities paid, (b) the efficiency coefficient, as the fraction of M runs of scenarios where $Fp \geq Op$ (M), as the number of favorable scenarios with lower optimized premiums, (c) the loss ratio as the ratio between the average losses and optimized premium at the watershed scale (Eq. 8), and (d) the solvency coefficient calculated as in Eq. 2.7 (Graciosa 2010; Laurentis 2012; Mohor 2016):

$$Solvency\ Coefficient = \frac{Optimized\ Premium - Average\ Losses}{Average\ Losses} \tag{2.7}$$

In Figure 2.2-4, each of the M equiprobable scenarios is adjusted to an optimal premium to tradeoff economic losses throughout the scenario period of N years; the continuous horizontal line describes Avg (Op), the discontinuous upper line represents initial non-optimized premium or WTP of potential policyholders at the watershed scale, and the thick discontinuous lower line represents the average losses of the scenarios. The difference (WTP – Avg (Op)) suggests a surrogate solvency margin, (see Laurentis 2012), where *WTP* is adopted here as initial risk aversion perception. Conversely, the lower *loss ratio*, the better the performance of the insurance fund, as in Equation 2.8:

$$Loss\ Ratio\ = \frac{Average\ Losses}{Optimized\ Premium} x\ 100 \tag{2.8}$$

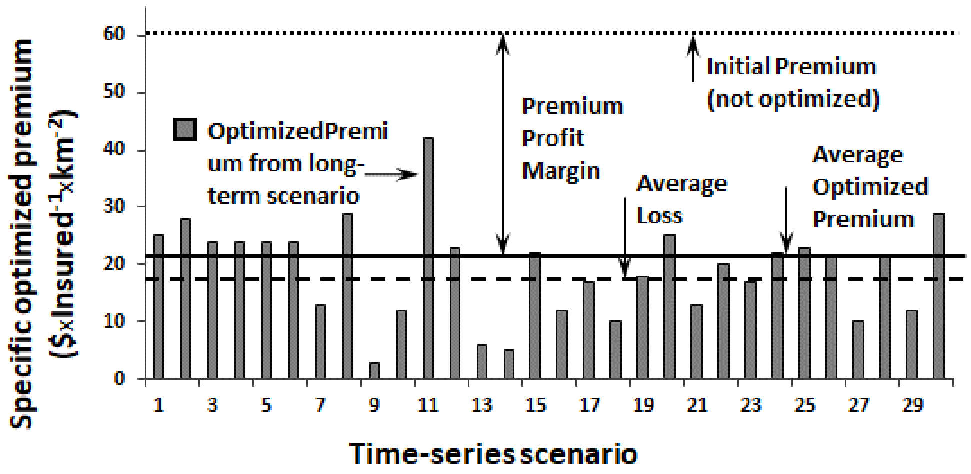

Figure 2.2-4 Variables and performance assessment of optimized insurance premium for different scenarios of extreme drought or floods.

2.3 MTRH-SHS: Comparative features

Based on the most recent applications of MTRH-SHS methodology (Graciosa 2010; Laurentis 2012; Mohor 2016), a comparison was made of the main model characteristics for flood and drought risks. Table 2.3-1 shows the evolution of the approaches under the same structure of the model, which have been adjusted to the need of each study. To sum up, in this work, some characteristics of the MTRH-SHS were modified and others were incorporated, among the most relevant are: new cost damage analysis functions which were proposed, given the insurance coverage designed for the water utility company. The drought analysis variable acquired temporal dimensionality in this work, which had not been taken into consideration in previous studies. The proposed optimization function considers, at the end of the contractual period, a debt-free fund and a final minimum storage to control excessive premiums. On the other hand, the adjustment model for extreme data (GEV) incorporates Gumbel, Frechét and Weibull PDFs, so that the data adjustment processes depend on the best value of the "ξ" (shape parameter) found. Features such as deductible (retentions) and administrative charges appear for first time in the financial balance equation. Finally, a bonus is proposed as an annual discount on insurance premium, based on the fund surpluses.

Table 2.3-1. MTRH-SHS comparative approaches

MTRH-SHS Features	Graciosa 2010.	Laurentis 2012.	Mohor 2016.	Guzman 2018.[4]
Hazard class	Urban Streamflow floods	Hydrological droughts		
Insurance regulations	SUSEP Law (resolution)			
Risk damage covered	Direct losses per sectors for events up to 100 years of return period.	Losses of farm production and costs for disruptions in water supply (Business interruption costs or indirect) for events up to 100 years of return period.		Revenue reductions in water utility company (business interruption costs or indirect cost), for drought duration scenarios between 100 and 2 years of return period.
Damage cost evaluation (Meyer et al. 2013)	Empirical regional functions adopted aggregated per sector (Susceptibility function Specific. Single-parameter models).	Empirical functions adopted (event analysis: comparison hazard and non-hazard time periods based on reported cost figure -aggregated per sector).		Empirical revenue reduction curves in water utility company (event analysis: Comparison hazard and non-hazard time periods based on reported cost figure -aggregated per sector).
Hydrological variable	Water depth related with Q_{max}	Annual Q_{7-10} (as the water offered)		Annual drought Maximum Duration, from the TLM analysis of monthly discharges.
Generated Synthetic Scenarios	Q_{max} annual generator series with Gumbel (PDF) by Monte Carlo.	Minimum Q_{7-10} annual generator series with Gumbel (PDF) by Monte Carlo.		Monthly flow series Generator by the Thomas-Fiering method.
Purchase requirement	Compulsory and collective scheme at the watershed scale			Compulsory to water utility company and consequently collective for the dependent sectors of network water distribution.
Extreme adjustment models	Gumbel (Max. flows)	Gumbel (low flows)		Generalized Extreme Values (GEV) under PDF approach (maximum deficits by drought duration intervals)
Premium setting	Aggregated (pool risk)	Aggregated (pool risk), according to priority order of demand and as actuarially fair premium.		Aggregated (pool risk), according to priority order of demand and as actuarially fair premium (optional).
Administrative taxes.	N/A			Defined by **[At_t]** in balance equation. [Optional]
Deductible	N/A			Deductible is implemented in case of compensation, defined by **[Dd_t]*** in balance equation. [Optional]
Resilience Assessment for Water Storage (Residual Risk Option)	N/A			Through the selective drought duration [days]
Risk reduction incentive	N/A			Annual profit bonus discount (optional): SS: Surplus Storage; N= Contractual period in years $Bonus = \sum_t^N SS_{t-1}(1+t_{x3}) + SS_t/_N$
Input data and analysis of time step	Annual extreme value series $Q_{max.}$	Annual extreme value series $Q_{7,min}$		Annual drought deficit events series by TLM approach.
Insurance fund storage balance $S_{(t)}$	$S_{(t)} = S_{(t-1)}(1+tx_2) + I_{(t-1)} - L_{(t-1)}(tx_1) + Pr_{(t-1)}$ $S_{(t)}$= Storage in period "i" t_{xa-x2}= Interest rates			$S_{(t)} = S_{(t-1)}(1+tx_2) + I_{(t-1)} - L_{(t-1)}(tx_1) + Pr_{(t-1)} - [At_t] + [Dd_t]^*$

[4] Detailed description in Chapter 4.

	$Pr_{(t)}$= Premium added $I_{(t)}$= Indemnification $L_{(t)}$= Loans			$[At_t]$ = Administrative taxes[5] $[Dd_t]$* = deductible
Optimization function (OF)	$$Op = min\sum_{i=1}^{N}(\$ls_{(x,t)} - S_{(t)})$$ Restricted to: $S_{(t)}min < S_{(t)} < S_{(t)}max.$; N= Contractual period in years			$$Op = min(S_{(nf)})$$ Restricted to: Ln_f = 0 (loans in the last period step "N") Sn_f = Final storage in period "N"
Hydrological/Hydraulic simulation	HEC-HMS hydrological model and HEC-RAS hydraulic model under land use scenarios as drivers.	MGB-IPH hydrological model and land use scenarios.	SWAT and MGB-IPH hydrological models.	WEAP hydrological model.
Future Climate scenarios (RCM driven hydrological models).	N/A	Eta-HadCM3	Eta-HadGEM	Eta-HadGEM and Eta-MIROC5
Radiative climate forcing scenarios	N/A	A1B	RCP 4.5.	RCPs 4.5 and 8.5.
Water withdrawal scenarios (Demand)	N/A	N/A	Stationary demand analyses with % increase and decrease scenarios	Stationary and non-stationary demand analysis under growth population scenarios projections

[5] See Chapter 4. Administrative taxes and Deductibles schemes were implemented under Brazilian regulations.

2.4 Discussion

Concerning the viability and solvency of an insurance fund, some issues should be addressed to improve the success of the MTRH-SHS mechanism if it is applied in the real world, or in changing conditions very different from Brazilian ones. The estimation of adequate insurance premium versus the potential damage of hydrological drivers can be useful in the exploration of other variables and/or financing schemes for adaptation. An example is examining the behavior, moral hazard and risk aversion of potential insurance consumers in test scenarios involving changes in hydrometeorological conditions and land use, which is particularly suitable for low-penetration markets. Indeed, asymmetric information in risk aversion and insurance incorporates external factors are highly relevant, but out of the scope of this research. Alternatively, the tool can help to properly choose the deductible value such as the maximum insurance coverage, among other aspects (Paudel et al. 2015). Thus, the scheme outlined in this document is recommended as a support tool to appropriately select an insurance premium that is financially viable for both the insurance company and the insured.

Based on the revision of MTRH-SHS applications, mainly derived from studies carried out by Graciosa 2010 and Laurentis 2012 (droughts and floods), it was found that the resulted premium amount was close to the claims values. This is because the optimally actuarially fair premium resulted from the expected losses frequency of proposed hydroclimatological scenarios, following the classical economic approach, (see i.e. Dionne 2013). In addition, the restrictions of loan and maximum coverage limit control the emergence of excessively high and inaccessible insurance premiums as a result of extreme events of greater magnitude, (see Mohor & Mendiondo 2017). The increase in average losses and final premiums (see Eq. 6) can also be observed as a result of change of risk or R_p, land use scenario or present or future conditions and water availability for the demand imposed. Thus, the currently applications are a mix of theoretical and empirical perspectives to explore water planning and management for community economic benefits, considering the difficulty of accessing information concerning damage and loss in the Brazilian context.

It is important to mention that this type of initiative requires actions such as educational programs and proper communication, risk forecasting and other risk-management strategies (Kunreuther & Useem 2010; Mendiondo et al. 2013; Moura 2011; Smith 1992). For example, due to the risk of drought, the Brazilian Water Authority

(ANA – Agência Nacional de Águas) can also discuss instruments of the Federal Law 9.433 considering the market and insurance under SUSEP restrictions. These actions range from raising community awareness of likely risks to demonstrating the advantages of long-term financial planning and water management to address risk aversion (see various authors for Brazilian conditions, some discussions are presented in de Araújo & Bronstert 2016; Araújo et al, 2004; ANA, 2004). Taking this into account, the implementation of the proposed model has implications for risk management decisions in terms of cost loss - WTP analysis. The importance of this is to reduce the ambiguity of the premium value to be paid, by determining a fair price for long-term coverage and promote the social diversification of insurance in the population.

There are other hydrology-economy bond markets, which can be addressed as ex-ante reserve fund planning for the following purposes: financing the payment for environmental services (Baumgärtner & Strunz 2014) by evaluating economic impacts due to environmental deterioration and the ecosystem services provided; calculating fixed charges as Reliability Charges for services dependent on surface water resources or watershed restoration financial schemes, among other areas. Regarding drought management, the local river basin agency (in this document, the Tietê-Jacaré River Agency for the flood example, and PCJ Agency for the drought example Tafarello 2017) could decide whether to permit the requested use of water depending on the ability of the region to cover the expected financial costs incurred by an increase in demand. Alternatively, it could add the cost as a condition for the permit authorization, and obtain extra revenue by introducing new measures for risk reduction (Mohor & Mendiondo 2017). Similarly, extra taxes could be imposed on buildings in flood-prone areas, as is already done in various places around the world.

Implementing hydrologic insurance entails more than restoring the economic conditions of those affected to ensure the protection of their economic sustainability or accelerating the recovery process (Hazell & Hess 2010; Kost et al. 2012). In some countries, insurance agencies even share the obligation to mitigate risks by giving advice about housing standards, encouraging land use planning or appropriate water management and providing investment lines for lower-risk crops (Clemo 2008; Crichton 2008; Ward et al. 2008; Botzen et al. 2009; Botzen 2013, Pérez-Blanco & Gomez 2014). Considering this, efforts have recently been focused on introducing insurance not only as a tool to promote financial resilience but also as an instrument that encourages risk reduction for adaptation considering global changes (Surminski et al. 2016b).

2.5 Conclusion and recommendations

In this document, we have put forward a risk based insurance fund simulator (MTRH-SHS) that shows the hypotheses and limitations of using an insurance premium-setting model to cope with economic impacts caused by hydrological extremes under changing conditions in Brazilian watersheds. On the one hand, the characteristics of this model developed here are: multi-year insurance analysis, multi-hazard setup and multi-sector, with flexible versatility of coupled modules of hazard, vulnerability and financial assessment (see Figure 2.2-1). On the other hand, the limitations of this premium-setting model are explained as follows. First, in spite of the simplicity of lumped hydrological modeling in regional units such as catchments, market negotiation of premiums might be not only complex but biased addressed inside these catchment regions. Second, although damage cost assessment has been refined over the last years, fair actuarial premium setting is still constrained with high uncertainty. For instance, the transferability and replication of valid damage curves used in multi-hazard models are still restrained by local factors, such as climate, lack of information, economy and social aspects.

Based on the presented methodology, future requirements and further development are proposed to strengthen this analysis and to promote the penetration and acquisition of insurance in the Brazilian context. Incorporating a series of tasks is highly recommended: ensuring easy transferability of the methodology; verification, disaggregation and calibration of damage cost assessment based on current and real information; the selection-analysis-fit of a wide range of probability distribution functions; integration of other hydrometeorological variables and water sources (e.g. rainfall, groundwater and temperature) and examination of financial prospects over extended analysis periods.

In conclusion, a multi-year insurance fund simulation for the future depends on the projected data, which is provided by the chosen scenario and the structure of the adopted hydrological model. The better the input data and the feasibility of the setting, the more realistic the outputs of the insurance model for decision-makers. Moreover, it is a fact that consolidating these strategies depends on integrating and delegating responsibilities for public-private partnerships, as well as introducing strict control procedures to create a suitable environment for their development.

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CHAPTER 3

ECONOMIC IMPACT ASSESSMENT OF HYDROLOGICAL DROUGHTS ON A WATER UTILITY COMPANY UNDER CLIMATE CHANGE SCENARIOS *

* A modified version of this chapter has been submitted as Guzman, D**.** et al. (2017). Economic Impacts of Drought risk for Water Utilities through Severity-Duration-Frequency Framework under Climate Change Scenarios. EGU Journal*: Hydrology and Earth System Science.*

Abstract

Climate change 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 calculating economic losses derived from combining 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 work 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 represents the preparedness for risk aversion to cope with potential future impacts of droughts, involving a set of options for planning water resources under different demands and climate projections. The methodology integrates through an “ex-ante” analysis, 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 the 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), the SDF curves were characterized. On the one hand, water tariff prices 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 the same order, non-stationary demand trends impose larger differences in the drought resilience gap, when the future securitization is linked to regional climate outputs.

Key Words: Climate change, Water Security, Severity-Duration-Frequency curves, Revenue reductions

3.1 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 (Van Loon, Stahl, et al. 2016; Wada et al. 2013; Van Loon, Gleeson, et al. 2016; Lloyd-hughes 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 & Lannerstad 2004; Kunreuther, Heal, et al. 2013; Wanders & 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 & Bressers 2016; Smakhtin & Schipper 2008; Van Lanen et al. 2013; Frick et al. 1990). 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 (Shi et al. 2015; Stahl et al. 2016; Freire-González et al. 2017; Balbus 2017; Asadieh & Krakauer 2017; Prudhomme et al. 2014; Berman et al. 2013; 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 (Mishra & Singh 2010; Nam et al. 2015; Bachmair et al. 2016).

The need for a broader perspective in terms of comprehending and managing the impacts of drought requires actions to integrate their states or categories (Van Loon 2015; Hao & Singh 2015). This implies in studying droughts, understanding their propagation from meteorological phenomena, underground-surface dynamics and alterations of anthropogenic origin such as storage (Van Loon, Stahl, et al. 2016; Huang et al. 2017; 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, in this work we address hydrological droughts as the main driver of direct economic impacts when water demand exceeds supply (Bressers & Bressers 2016).

The availability of new water supply sources are becoming more scarce every day, therefore demand regulation is a strategy that is being considered by the supply companies to guarantee reliability during droughts (Zeff & Characklis 2013). Among the demand control strategies are price-based policies ones, which attempt to change the user's consumption pattern based on economic penalties or incentives (Millerd 1984). However, implementing these strategies entails great complexity in terms of 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 & Teixeira 2015). During the (2013-2015) period, the population of the SPMR experienced a significant reduction in water resources availability and a decrease in the water supply (Nobre & Marengo 2016; Taffarello et al. 2016; Coutinho et al. 2015). 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, were 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 document aims to assess the economic impacts of drought risks for water utilities by integrating a severity-duration-frequency framework under climate change scenarios. Moreover, this document 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 document outline interconnected methods and criteria, explained as follows. In Section 3.2, the text describes the study area (see Figure 3.2-1) and water crisis contextualization. Section 3.3 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 between the climatic, hydrological and economic aspects of the methodology (Figure 3.3-1). In Section 3.4, the results are shown as financial drought planning scenarios. Finally, in Section 3.5, the discussion and conclusions are presented regarding the proposed approach.

3.2 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. 3.2-1). 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 (Nobre & Marengo 2016; De Andrade 2016; Marengo et al. 2015; Nobre et al. 2016; PCJ/Comitês 2006; PCJ/Comitês 2016).

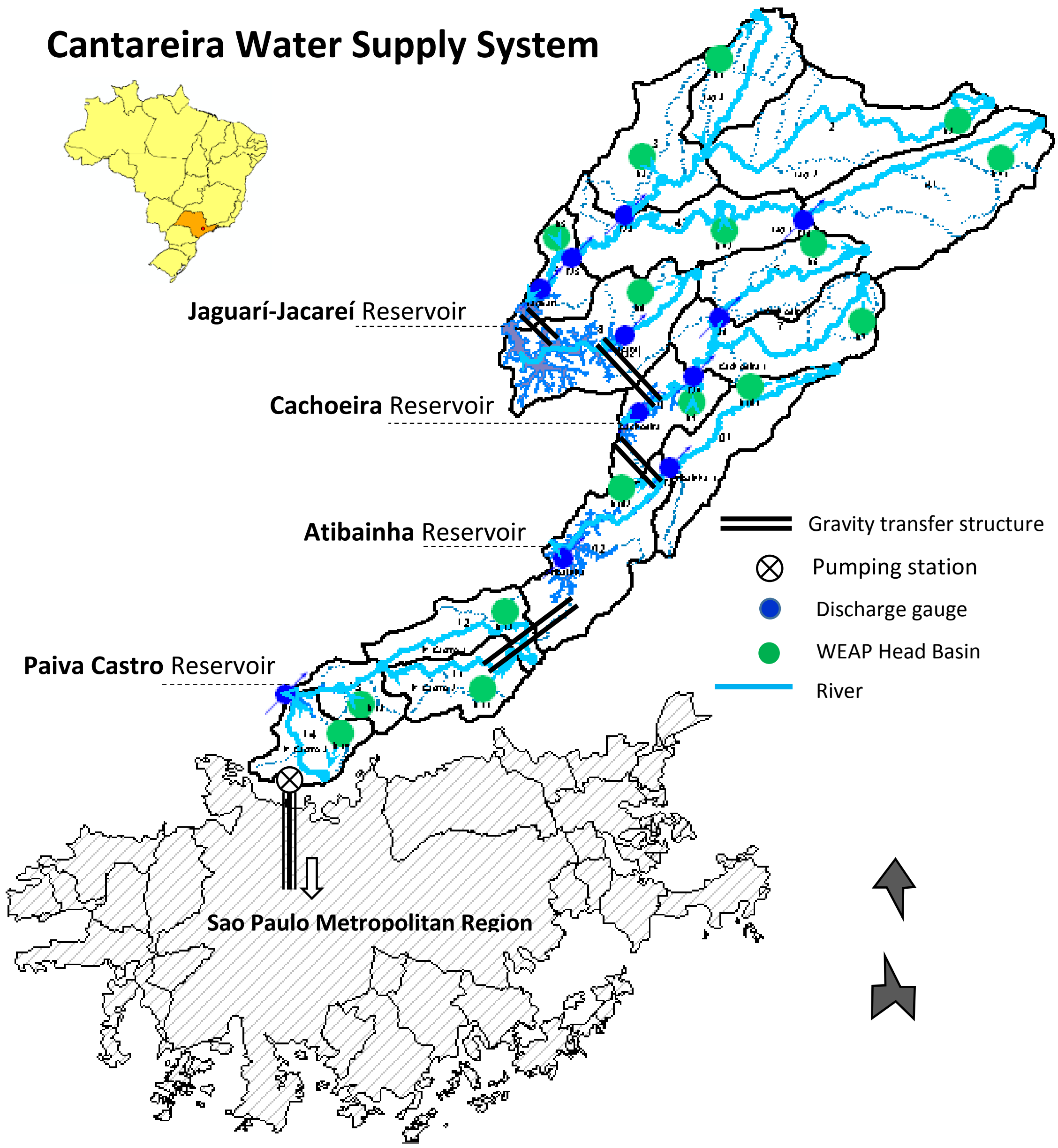

Figure 3.2-1 System structure composition and catchment areas: Jaguarí-Jacareí, Cachoeira, Atibainha and Paiva Castro watersheds.

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 & 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 & Mendiondo 2017; Taffarello et al. 2016). The

Cantareira System is currently administered by SABESP, which mainly operates the water network in the SPRM. The State of Sao Paulo Government is 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 (Haylock et al. 2006; Dufek & Ambrizzi 2008; Jose A. Marengo et al. 2009; Marengo et al. 2009; Marengo et al. 2009; Nobre et al. 2011; Chou et al. 2014; Zuffo 2015). Although historically, the SPRM study area is not affected by droughts of the same order as the Northeast of Brazil, the SPRM is progressively becoming vulnerable to water shortages. Therefore, during the recent period of the acute crisis 2013/2015, SABESP took 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 costs; 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 2016d).

3.3 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. 2005). 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 period 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 curves (SDF) were developed (J. H. Sung & 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 baseline 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, for 2005-2040 the consumption corresponds to 31 m^3/s, for 2041-2070 it corresponds to 38 m^3/s and for the period from 2071 to 2099 it corresponds to 43m^3/s.

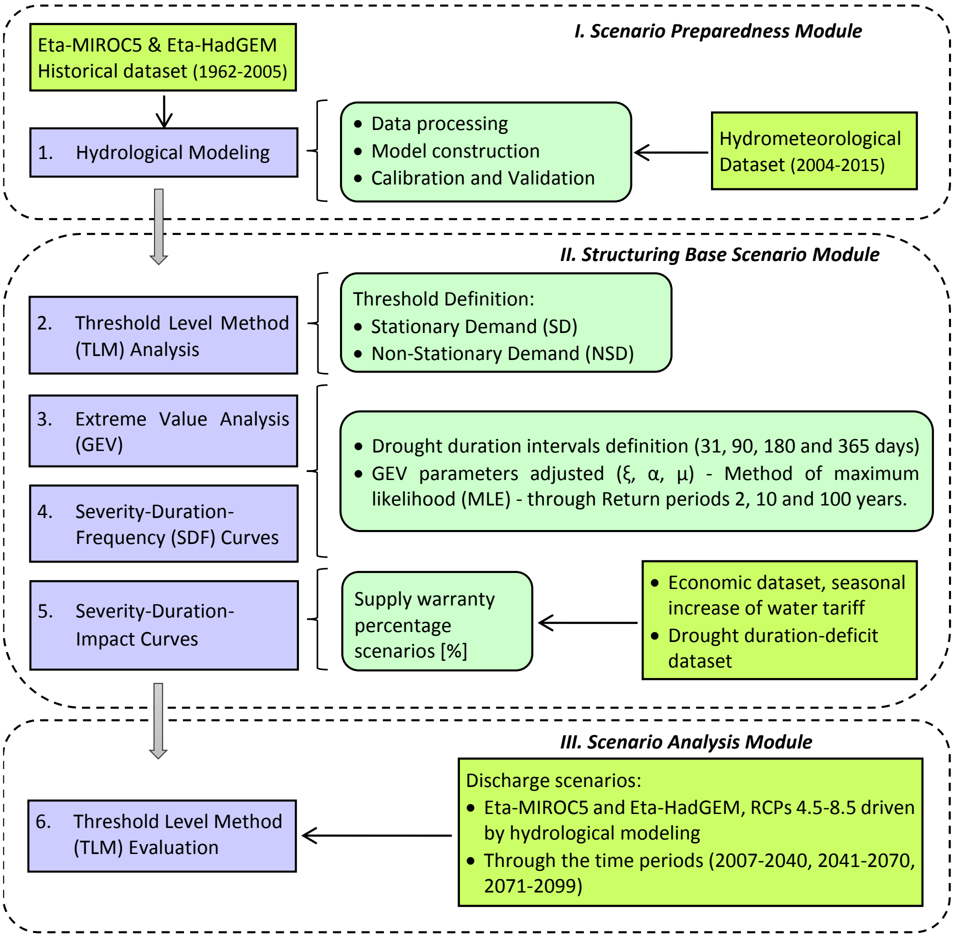

Figure 3.3-1 Methodology flowchart and main inputs.

The results of the methodology of Figure 3.3-1 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 & Strunz 2014; Wanders & 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 3.3-1, the main variables that induce the change scenarios for this study are shown in Table 3.3-1.

Table 3.3-1 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.

* Water demand was established based on the average daily discharge withdrawn from the entire Cantareira System, sent to the Santa Isabel pumping station.

3.3.1 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. 2014a-b). In order to assess the uncertainties of climate change impacts, the simulation results of the Eta-INPE model were used in this document. The model is nested within the GCMs MIROC5 and HADGEM2-ES, forced 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-b). 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. 2005). 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 (Mousavi & Anzab 2017; Psomas et al. 2016; Groves et al. 2008; Purkey et al. 2008; Yates et al. 2005; Vicuña et al. 2011; Vicuna & Dracup 2007; Howells et al. 2013; Bhave et al. 2014; Esteve et al. 2015). 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 3.5-1 in supplementary material - section 3A), 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 & Skahill 2006; Skahill et al. 2009; Seong et al. 2015; 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 (NSE_{Log}) 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) 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 & DAEE 2004; PCJ/Comitês 2006). This ES can be expressed as follows:

$$\boldsymbol{ES_{Cantareira}} = \sum_{i}^{n} \boldsymbol{QN_i} - \sum_{i}^{n} \boldsymbol{WD_i} \tag{3.1}$$

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-basin 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 the supplementary material – section 3B (Fig. 3.5-1) 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 2014b).

3.3.2 SDF curve development

Following the flowchart of Figure 3.3-2, 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; Şen 2015; Nordin & Rosbjerg 1970). Usually different values are used to define the threshold in hydrological drought analysis by the TLM approach (Tosunoglu & Kisi 2016). In this study, two demand scenarios, approached as "threshold levels", were used in the average daily 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 3.3-2). 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[6].

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

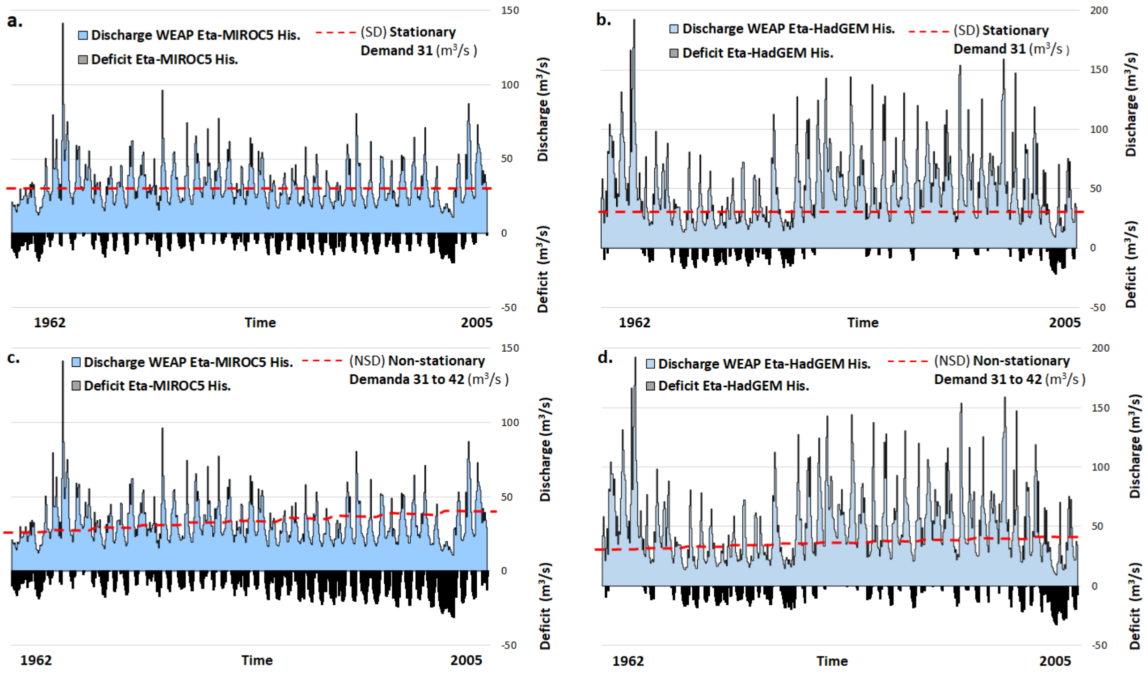

Figure 3.3-2 TLM Evaluation from historical discharge WEAP-Eta scenarios, under Stationary (SD) and Non-Stationary Demand (NSD) assumptions as the "threshold level": a. 31 m^3/s and Eta-MIROC5. b. 31 m^3/s and Eta-HadGEM. c. 31 to 42 m^3/s and Eta-MIROC5. d. 31 to 42 m^3/s and Eta-HadGEM.

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 (Sung & Chung 2014; Todisco et al. 2013; Zaidman et al. 2003; Svensson et al. 2016). On the other hand, it is suggested that for other durations of drought, other probability distribution functions can be explored (Razmkhah 2016; Dalezios et al. 2000). 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:

$$F(x) = exp\left[-\left\{1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right\}^{1/\xi}\right] \qquad \xi \neq 0 \tag{3.2}$$

$$F(x) = exp\left[-exp\left(-\frac{x-\mu}{\alpha}\right)\right] \qquad \xi = 0 \tag{3.3}$$

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).

The SDF curves of the hydrological drought characteristics in the Cantareira System are shown in Figure 3.3-3. 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 adjusted SDF parameter table, the diagnostic plots QQ-plot and Return Level vs. Return Period for the GEV distribution can be seen in the supplementary material as sections 3-C and 3-D. The SDF curves calculated showed a greater deficit for non-stationary demand conditions, as well as for the results based on the MIRCO5 climate model.

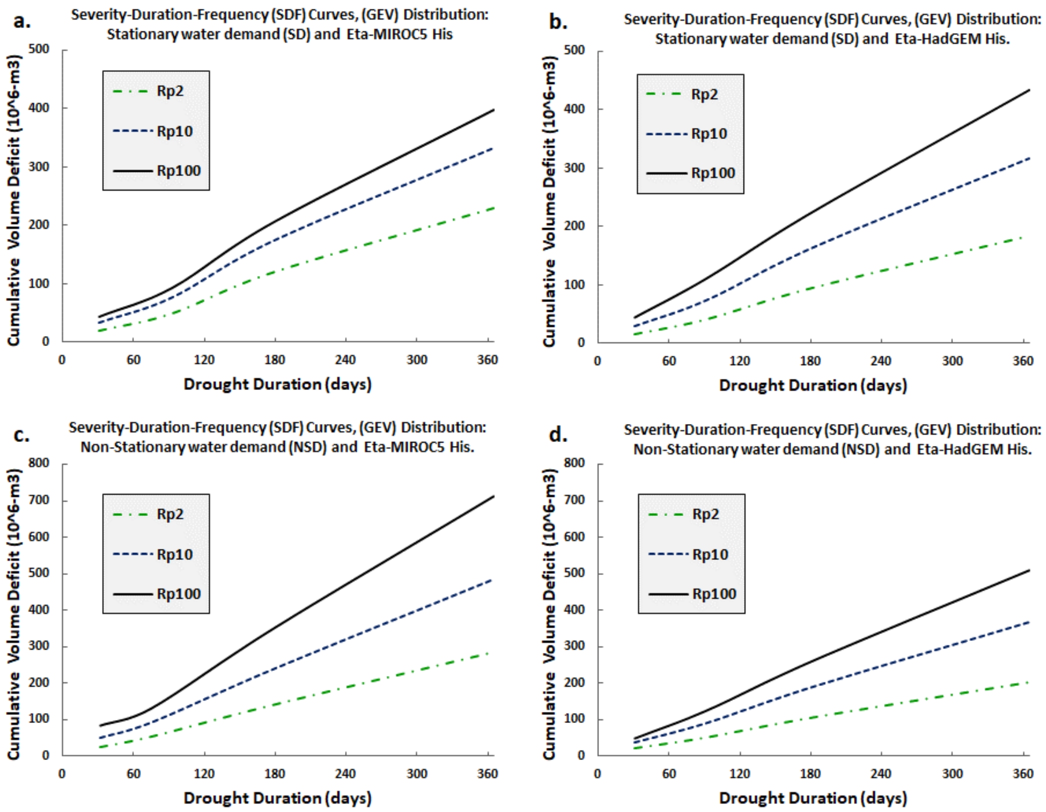

Figure 3.3-3 SDF curves under stationary and non-stationary demand assumptions and historical discharge WEAP-Eta scenarios: a. (SD) 31 m^3/s and Eta-MIROC5. b. (SD) 31 m^3/s and Eta-HadGEM. c. (NSD) 31 to 42 m^3/s and Eta-MIROC5. d. (NSD) 31 to 42 m^3/s and Eta-HadGEM.

3.3.3 Water price and Hydrological drought relationship

According to the flowchart of Figure 3.3-1, 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 3.3-4 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 3.3-4b); 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.

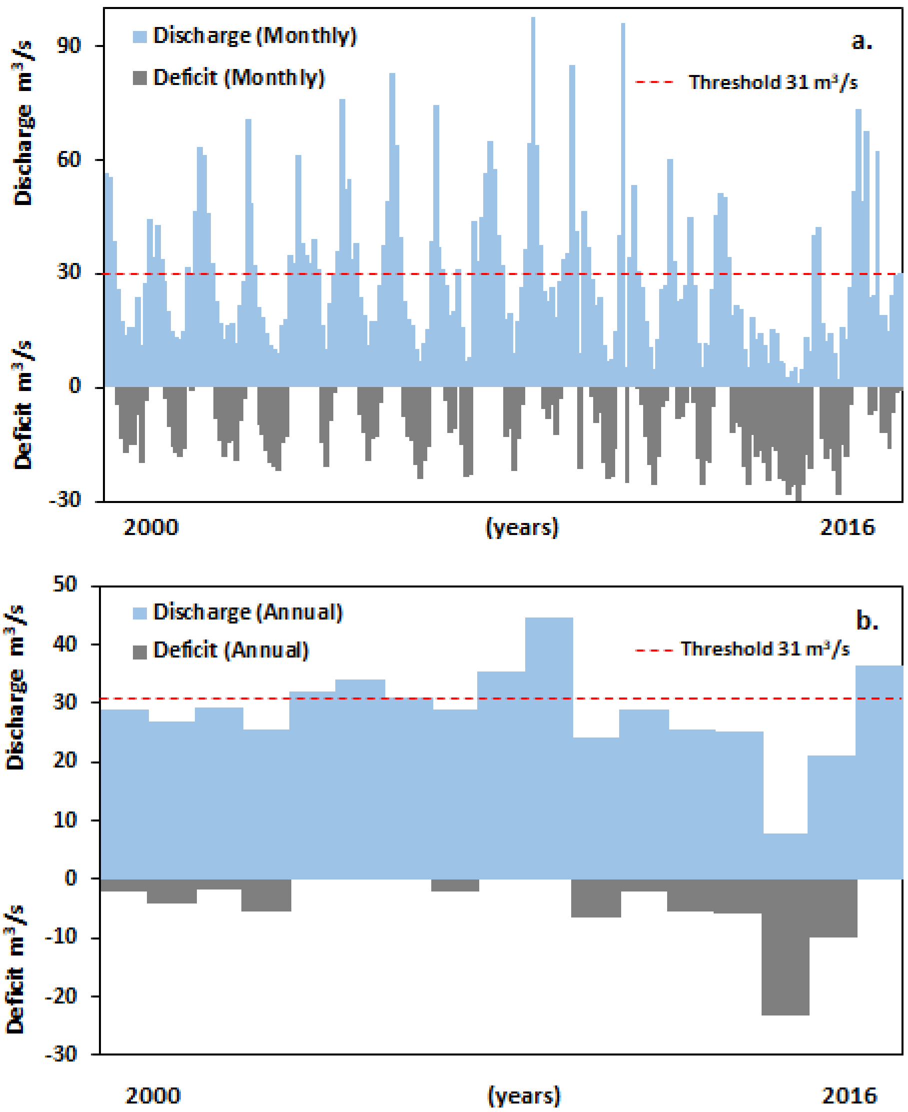

Figure 3.3-4 TLM analysis under two discharge scenarios, 2000-2016 period. a) Monthly average discharge and b) Annual average discharge.

Urban drought management programs incur costs that must be assumed to overcome the water crisis with equity (Molinos-Senante & 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 & Blanco 2008), (see Figure 3.3-5). 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.

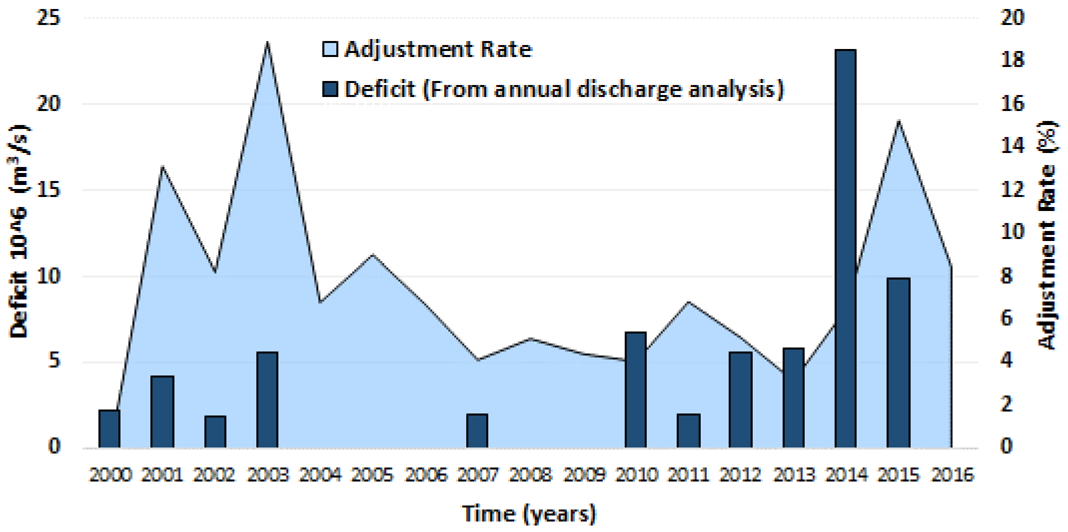

Figure 3.3-5 Co-evolution of the drought deficit and price adjustment rates (SABESP – Cantareira System) during 2000-2016 period. Note: deficits defined from TLM analysis under a demand threshold of 31 m3/s and annual average discharge.

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 & 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 2016c). 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 of 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 & 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 presented here was performed from the monthly discharge series from 2000 to 2016 (Figure 3.3-4a), aiming to associate the resulting information with the previously obtained SDF curves. Thus, the top part of Figure 3.3-6 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 3.3-6, it can be observed that from greater drought durations and deficits, an increase in the water tariff for the following period is expected. 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. From the calculated correlation coefficients r_{xy} (adjustment rate vs. drought duration - water deficit), a T-student´s significance test with an alpha of 5% was implemented. Based on the test, it was found that the adjustment rate and the water deficit present a high to medium significance, despite having a lower Pearson correlation coefficient.

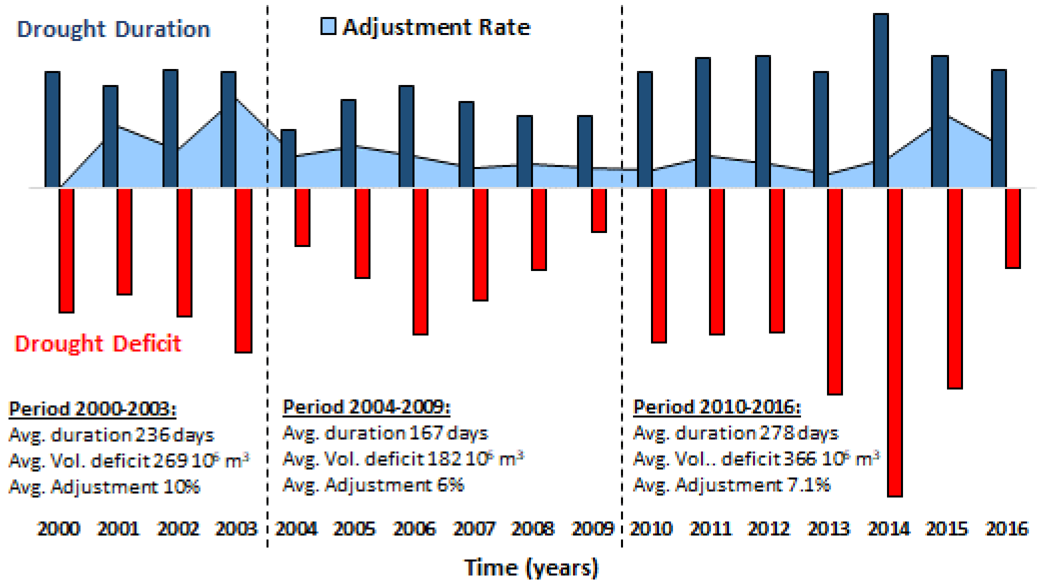

Figure 3.3-6 Empirical relationship between Cantareira System drought duration "blue-bar in days" [derived from monthly average discharge analysis], Cantareira System drought deficit "red-bar in 10^6-m^3" [assessed from monthly average discharge analysis] and annual price adjustment rates under variate hydrological conditions in percentage.

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 3.5-6 in supplementary material - section 3E), the water prices were established as a function of the drought duration by the "supply warranty time percentage" as shown in Table 3.3-2.

Table 3.3-2 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)]**

Based on the assumptions shown in Table 3.3-2, the demand curve for the Cantareira System was constructed as a function of the supply warranty time percentage (Figure 3.3-7). 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 & Tung 2002), as the proposed hypothesis establishes in this case. More studies of price elasticity and water scarcity can be found in (Ruijs et al. 2008; Freire-González et al. 2017; Mansur & Olmstead 2012).

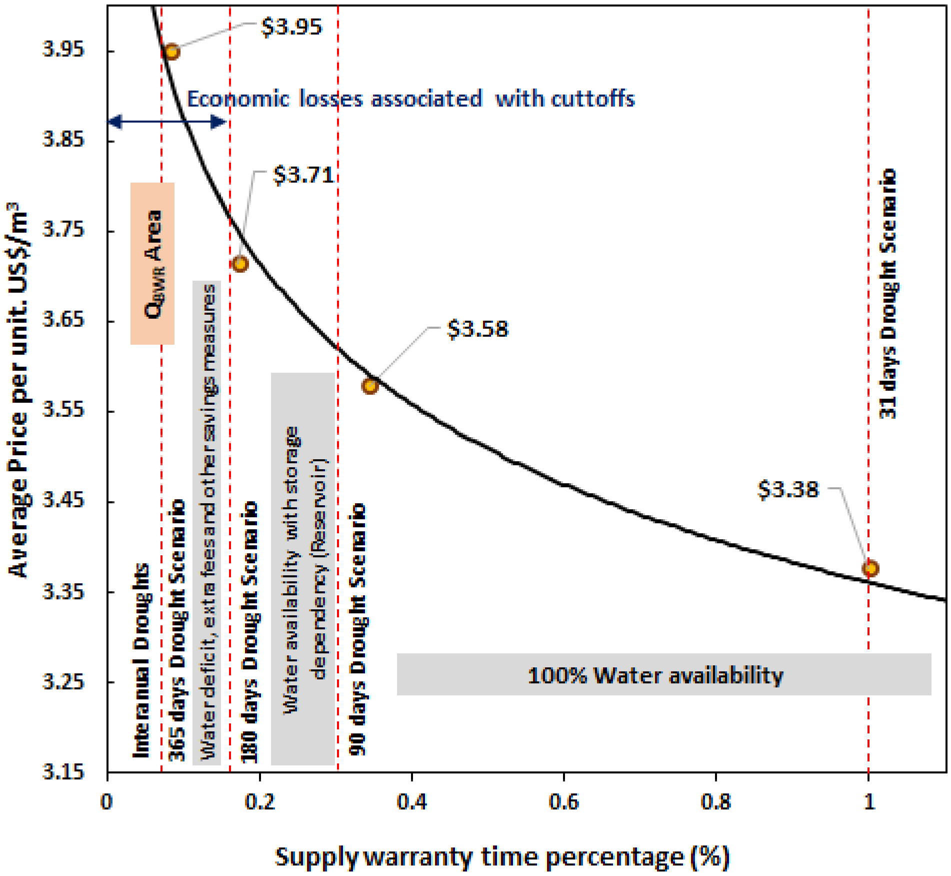

Figure 3.3-7 Cantareira System demand curve based on the supply warranty time percentage

From the drought events studied, i.e. in 2000/2001 (Cavalcanti & 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 3.3-4b). 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 3.3-7): 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 business interruption (Meyer et al. 2013). These scenarios are represented by the Severity-Duration-Impact curves, which are shown in Figure 3.3-8, under different recurrence events, climate projections and demand variability scenarios. Each pair of lines in Figures 3.3-8 a. b.

(continuous and dashed) show the range of uncertainty associated with the considered change variables.

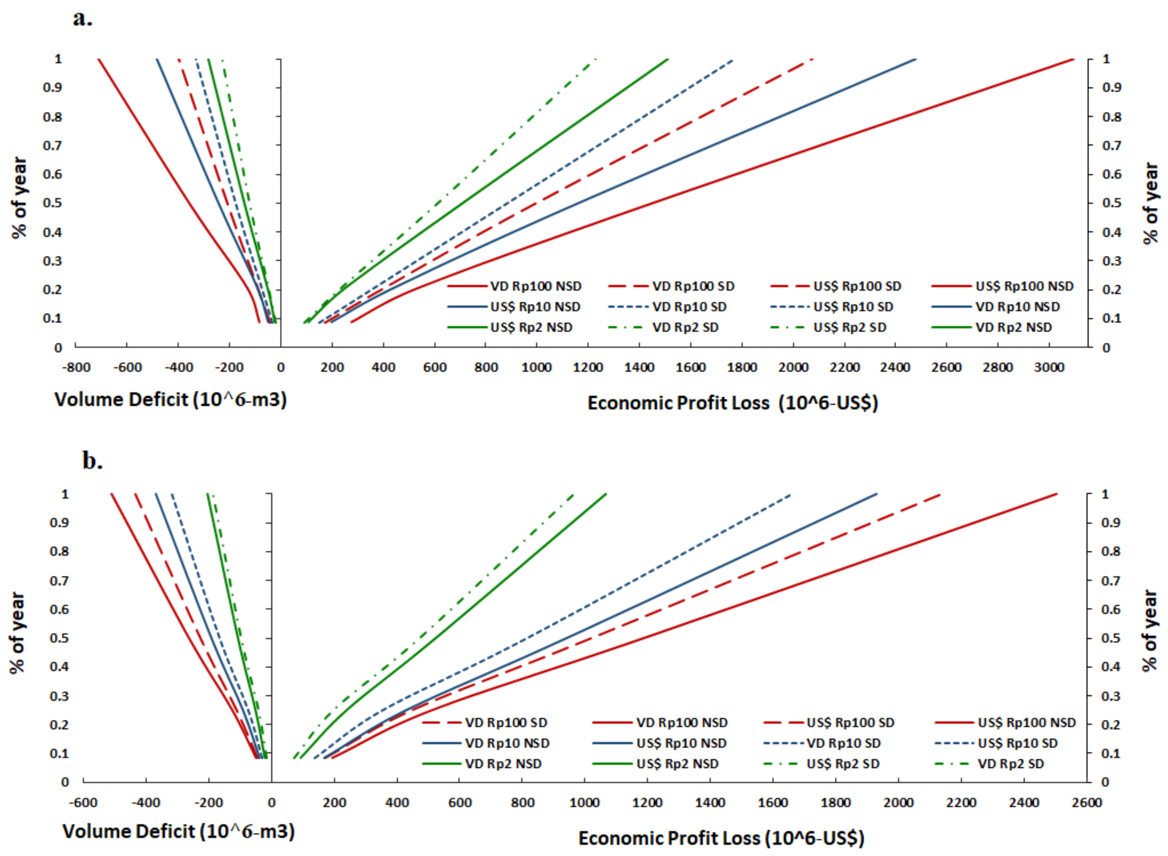

Figure 3.3-8 Severity-Duration-Impact curves. Sector a. Severity-Duration-Frequency-Profit Loss under the historical Eta-MIROC5 scenario. Sector b. Severity-Duration-Frequency-Profit Loss under the historical Eta-HadGEM scenario. Note: SD and NSD are the stationary or non-stationary demands, respectively; "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.

The final step of the methodology (see Figure 3.3-1) 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 an important dependence on the Cantareira reservoir System.

3.4 Results and discussions

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

3.4.1 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 & Belmont 2017). The performance criteria of calibration and validation periods are shown in Table 3.4-1. The colors in the Table 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 (Muleta 2012; Krause & Boyle 2005). Additionally, the hydrographs for calibration and validation periods are shown in Figure 3.4-1. It is important to note that in the validation period (2011-2015), part of the recent drought event was simulated.

Table 3.4-1 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 3A. – Table 3.5-1.

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

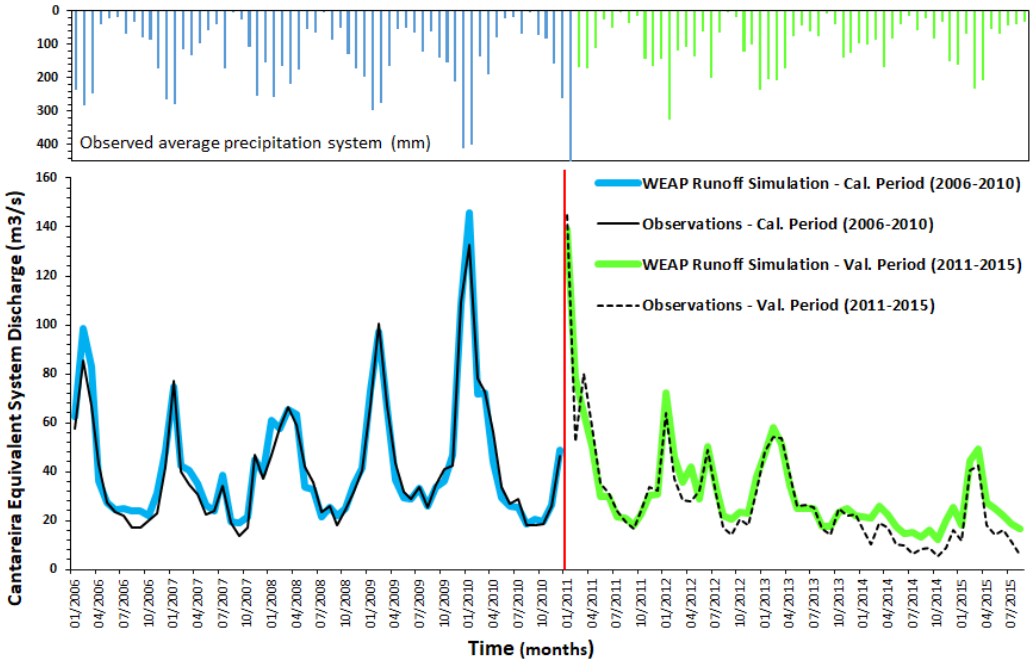

Figure 3.4-1 WEAP Hydrographs, Calibration period (2006-2010) and Validation period (2011-2015)

Individual watershed hydrological modelling performance ratings are presented in the supplementary material - Section 3A, Table 3.5-1; 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.

3.4.2 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. 3.3-3 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 3C), 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 the FDP Type III (see Tables 3D-1 to 3D-4 in the 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 3C); in general, the fit based on the MIROC5 and HadGEM-ES models datasets, did not show significant differences between them. In terms of the quantiles, the QQ-plot showed that non-stationary fit dataset presented a better alignment than the data sets under the stationary demand scenario. While the predictive capacity of the model, represented by the RR-plot, shows a decrease as the return period magnitude increases.

3.4.3 Economic impacts under climate change

Based on the methodological approach (see Figure 3.3-1), the potential water utility company´s economic impacts were calculated, from the 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 (in terms of revenue reductions) and the percentage difference (Dif. %) between the demand scenarios are shown in Tables 3.4-2, 3 and 4, for each period.

Table 3.4-2 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 3.4-3 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 3.4-4 Economic profit loss projection scenario for the period 2071-2099 (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

From the results in Tables 3.4-2, 3 and 4, 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, some Eta model outputs periods (specially 2041-2070) could show projections of future climate with local variability, that can directly affect the general results by period.

In Figure 3.4-2a, 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, in Figure 3.4-2b, 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 3.4-2 that, in response to the growing projected demand scenarios (NSD), it will be expected an increase, in terms of the average percentage of differences, for different time periods and for both climatic models.

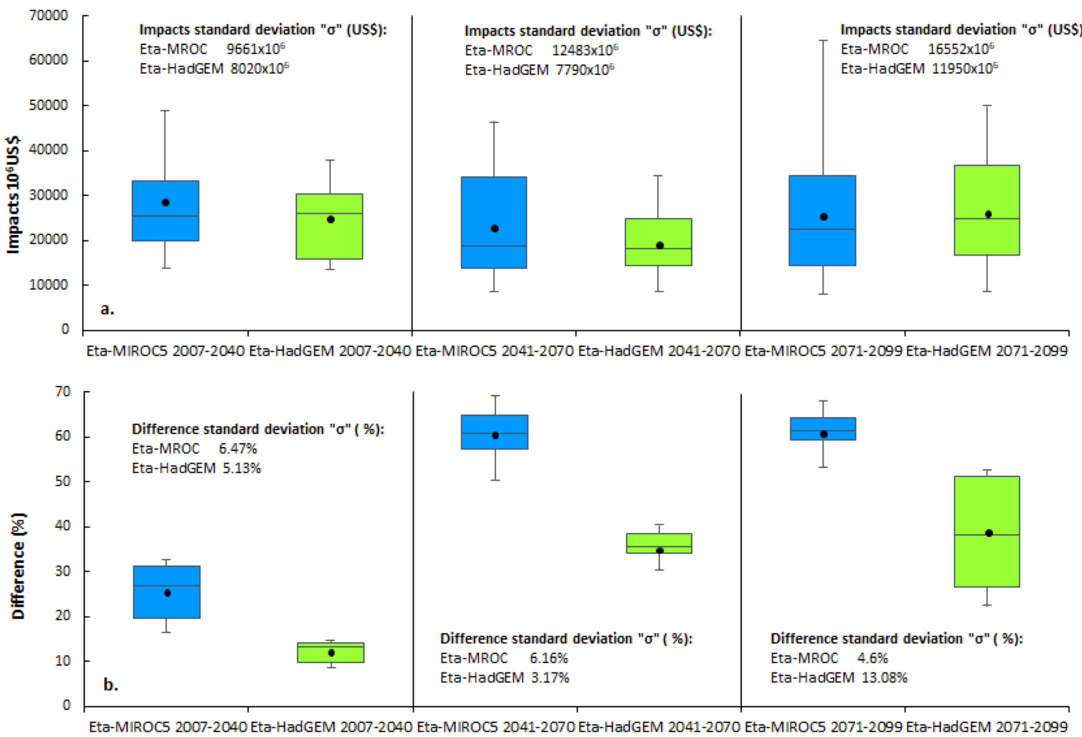

Figure 3.4-2 Box plots with impacts and relative differences between climate change scenarios. Sector a: Economic impacts under periods of climate change scenarios. Sector b: Percentage difference between the demand scenarios under periods of climate change scenarios.

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. Consequently, 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.

3.5 Conclusions and recommendations

This document developed a methodology with applications 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 the Sao Paulo Metropolitan Region dependence on the Cantareira Water Supply System, Brazil. In this document, 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 such as insurance schemes, or community contingency funds. In general, the SDF framework developed here can be proposed as a planning tool to mitigating drought-related revenue reductions as well as being useful for developing 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 analyze the impacts from key drivers, such as climate, land use and water withdrawal rates in complex or recurrent drought patterns. Moreover, 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 the SDF framework linked to: Palmer's drought indices (Rossato et al. 2017), a model-based framework for 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 & Mendiondo 2017). Moreover, the 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 from climate scenarios (see i.e. Figure 3.4-2) 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 the 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 a review of other statistical methods of adjustment. 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.

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Complementary Material: Section 3-A.

Statistics evaluation have been selected based on recommendations in the literature (Moriasi et al. 2007; Muleta 2012).

Nash-Sutcliffe Efficiency (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}(S_i - O_{mean})^2}$$

Where, "S_i" is the model simulated output and "O_i" observed hydrologic variable.

Volumetric Efficiency (VE)

$$VE = 1 - \frac{\sum_{i=1}^{N}|S_i - O_i|}{\sum_{i=1}^{N} O_i}$$

Ratio of Standard Deviation of Observations to RMS (RSR)

$$RSR = \frac{\sqrt{\sum_{i=1}^{N}(S_i - O_i)^2}}{\sqrt{\sum_{i=1}^{N}(S_i - O_{mean})^2}}.$$

Percent bias (PBIAS)

$$PBIAS = \frac{\sum_{i=1}^{N}(O_i - S_i)}{\sum_{i=1}^{N} O_i} \cdot 100$$

Coefficient of Determination (R^2)

$$R^2 = \left(\frac{\sum_{i=1}^{N}[O_i - O_{mean}]\cdot[S_i - S_{mean}]}{\left\{\sum_{i=1}^{N}[O_i - O_{mean}]^2\right\}^{0.5}\cdot\left\{\sum_{i=1}^{N}[S_i - S_{mean}]^2\right\}^{0.5}}\right)^2$$

Cantareira basins performance criteria for Calibration and Validation periods. *Cal. = Calibration period and Val. =Validation period, are shown in the Table 3.5-1. The classification of colors 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.

Table 3.5-1. Performance criteria results on the Cantareira modeled basins.

Watersheds	*Area* (km^2)	*VE*		*NSE*		*RSR*		*PBIAS* (%)		NSE_{Log}		R^2	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
Sub B-F28	269.0	0.79	0.72	0.74	0.52	0.49	0.57	1.64	4.89	0.69	0.69	0.74	0.53
Sub B-F23	508.4	0.83	0.8	0.87	0.86	0.38	0.38	9.52	5.58	0.78	0.85	0.9	0.88
Sub B-F25	179.5	0.87	0.77	0.93	0.84	0.27	0.42	5.45	-9.54	0.91	0.78	0.94	0.86
Jaguarí	67.8	0.88	0.72	0.93	0.84	0.27	0.48	-3.3	-21.1	0.89	0.61	0.93	0.9

Watersheds	*Area* (km^2)	*VE*		*NSE*		*RSR*		*PBIAS* (%)		NSE_{Log}		R^2	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
Jacareí	201.0	0.8	0.75	0.71	0.87	0.44	0.42	2.08	-1.54	0.49	0.75	0.79	0.87

Watersheds	*Area* (km^2)	*VE*		*NSE*		*RSR*		*PBIAS* (%)		NSE_{Log}		R^2	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
Sub B-F24	172.8	0.83	0.78	0.85	0.76	0.41	0.47	-9.91	10.5	0.83	0.79	0.89	0.82
Sub B-F30	119.7	0.92	0.85	0.85	0.73	0.36	0.5	1.54	2.56	0.84	0.79	0.86	0.73
Cachoeira	97.1	0.71	0.70	0.78	0.81	0.5	0.53	-20.3	-13.5	0.58	0.53	0.87	0.85

Watersheds	*Area* (km^2)	*VE*		*NSE*		*RSR*		*PBIAS* (%)		NSE_{Log}		R^2	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
Sub B-F34	135.5	0.85	0.84	0.53	0.35	0.7	0.68	14.6	2.59	0.42	0.38	0.84	0.69
Atibainha	176.2	0.80	0.72	0.75	0.74	0.44	0.53	9.41	-12.2	0.77	0.66	0.83	0.85

Watersheds	*Area* (km^2)	*VE*		*NSE*		*RSR*		*PBIAS* (%)		NSE_{Log}		R^2	
		Cal.	*Val.*	*Cal.*	*Val.*	*Cal.*	*Cal.*	*Val.*	*Val.*	*Cal.*	*Val.*	*Cal.*	*Val.*
P. Castro	333.7	0.81	0.78	0.73	0.72	0.58	0.53	-2.81	8.54	0.67	0.63	0.9	0.74

Complementary Material: Section 3-B

Fig. 3.5-1 shows that in the future there is no clear trend in the average discharge, since in some periods the curve exhibits an increase and in other periods a decrease. In addition, the average discharge per time period showed higher values during the 2041-2070 scenarios. On the other hand, the average discharge per model showed higher values in the Eta/HadGEM model results compared to the Eta/MIROC5 model.

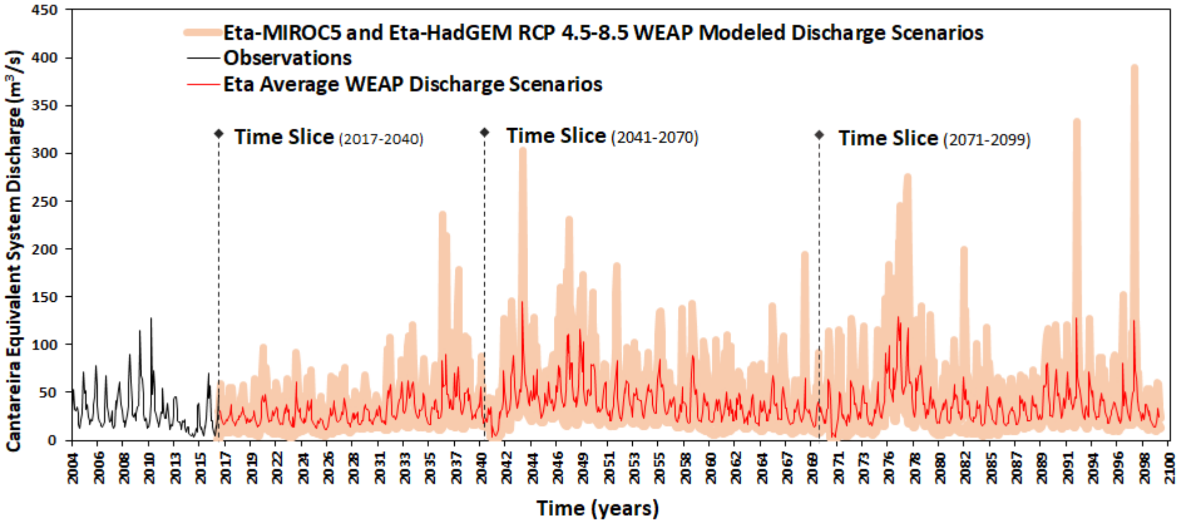

Figure 3.5-1. Discharge projection scenarios modeled in WEAP, driven by RCM Eta-MIROC5 and Eta-HadGEM under RCP 4.5 - 8.5 scenarios.

Complementary Material: Section 3-C

Fit diagnostic plot of Generalized Extreme Value (GEV) distribution.

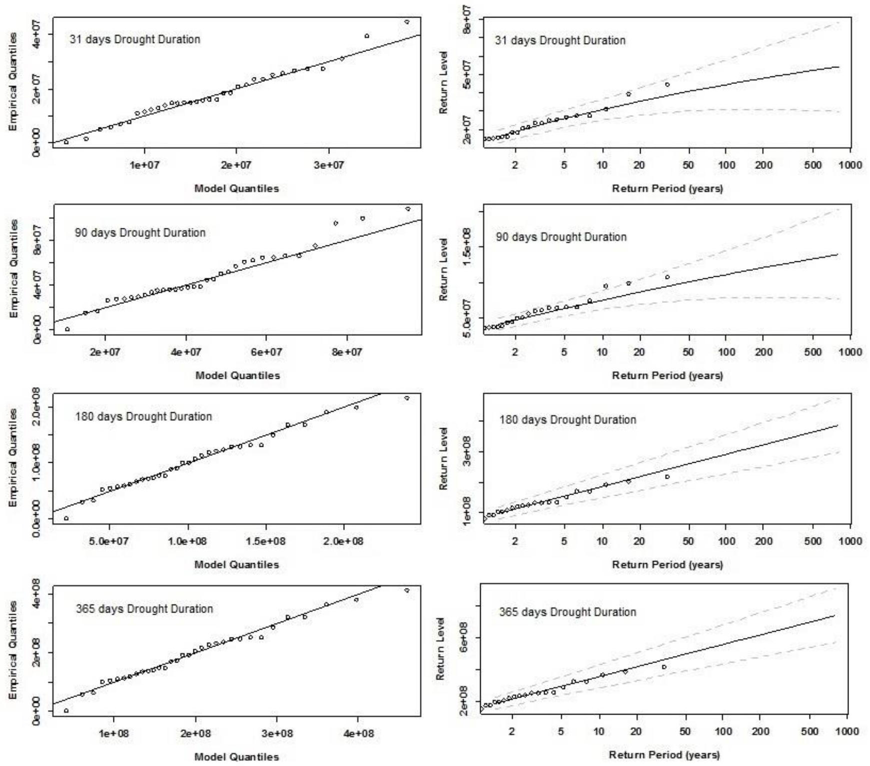

Figure 3.5-2. Diagnostic plots for stationary GEV model under historical Eta-HadGEM scenario and stationarity demand (monthly drought duration intervals): Left panel QQ-plot in [m^3]; Right panel, return level [m^3] vs return period plot.

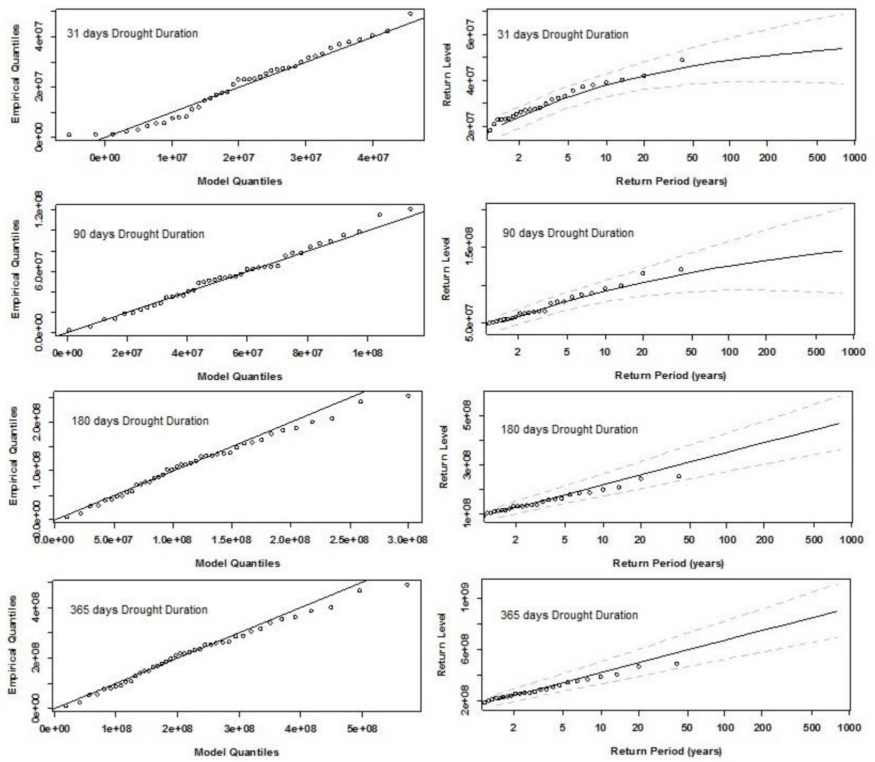

Figure 3.5-3. Diagnostic plots for stationary GEV model under historical Eta-HadGEM scenario and non-stationarity demand (monthly drought duration intervals): Left panel QQ-plot [m^3]; Right panel [m^3], return level vs return period plot.

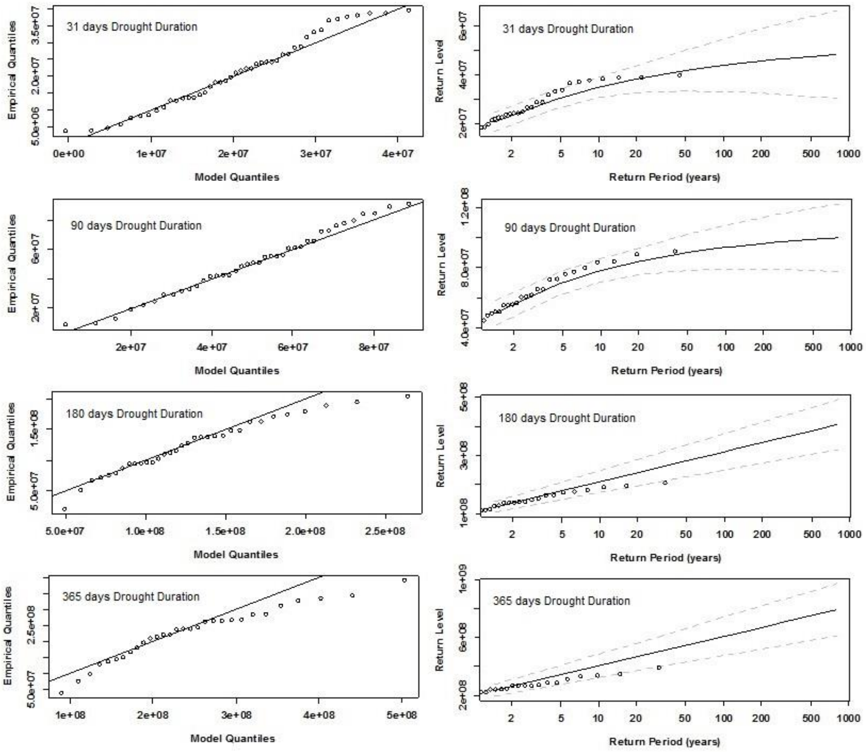

Figure 3.5-4. Diagnostic plots for stationary GEV model under historical Eta-MIROC5 scenario and stationarity demand (monthly drought duration intervals): Left panel QQ-plot [m^3]; Right panel, return level [m^3] vs return period plot.

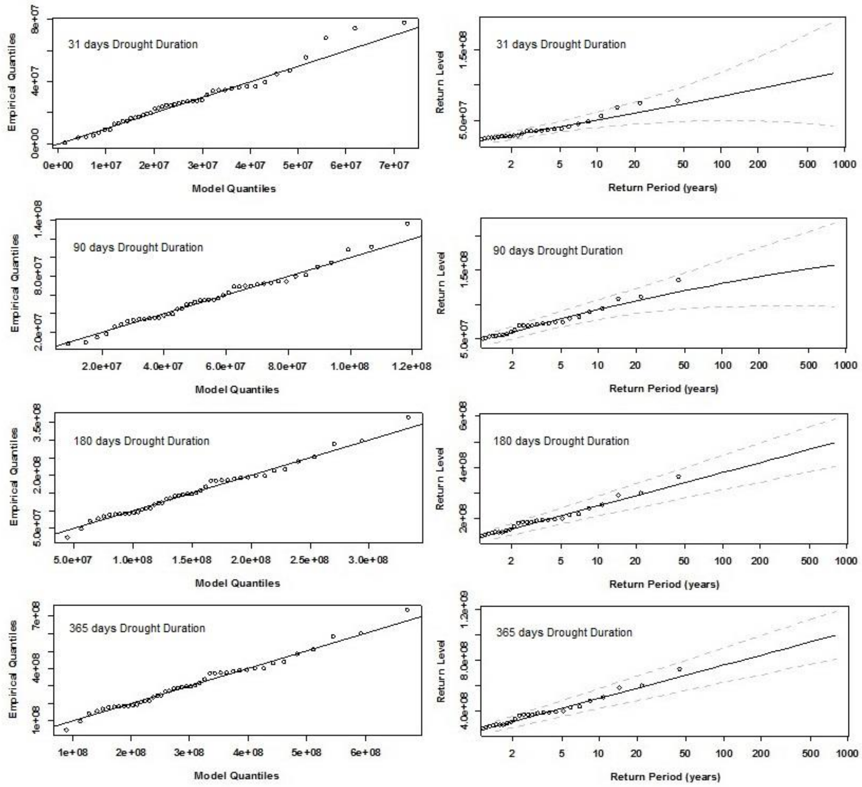

Figure 3.5-5. Diagnostic plots for stationary GEV model under historical Eta-MIROC5 scenario and non-stationarity demand (monthly drought duration intervals): Left panel QQ-plot [m^3]; Right panel, return level [m^3] vs return period plot.

Complementary Material: Section 3-D

Table 3.5-2. Adjusted parameters GEV distribution Adjusted for SDF curve under Eta-MIROC5. Hist.-Stationary Demand scenario.

Drought Duration	Eta-MIROC5 Hist. Stationary Demand			Negative Log-Likelihood
	Location (μ)	**Scale** (σ)	**Shape** (ξ)	
31 days	1.69E+07	1.06E+07	-2.88E-01	773.50
90 days	4.25E+07	2.29E+07	-3.67E-01	714.02
180 days	1.06E+08	4.48E+07	0.00E+00	629.90
365 days	2.00E+08	8.86E+07	0.00E+00	592.68

Table 3.5-3. Adjusted parameters GEV distribution Adjusted for SDF curve under Eta-MIROC5. Hist.-Non-Stationary Demand scenario.

Drought Duration	Eta-MIROC5 Hist. Non-Stationary Demand			Negative Log-Likelihood
	Location (μ)	**Scale** (σ)	**Shape** (ξ)	
31 days	1.90E+07	1.33E+07	2.74E-02	791.25
90 days	4.36E+07	2.40E+07	-1.07E-01	813.71
180 days	1.20E+08	5.62E+07	0.00E+00	853.50
365 days	2.42E+08	1.13E+08	0.00E+00	884.40

Table 3.5-4. Adjusted parameters GEV distribution Adjusted for SDF curve under Eta-HadGEM. Hist.-Stationary Demand scenario.

Drought Duration	Eta-HADGEM-ES Hist. Stationary Demand			Negative Log-Likelihood
	Location (μ)	**Scale** (σ)	**Shape** (ξ)	
31 days	1.33E+07	8.64E+06	-1.10E-01	576.79
90 days	3.53E+07	1.88E+07	-5.54E-02	605.61
180 days	8.00E+07	4.56E+07	0.00E+00	631.75
365 days	1.53E+08	8.73E+07	0.00E+00	653.16

Table 3.5-5. Adjusted parameters GEV distribution Adjusted for SDF curve under Eta-HadGEM. Hist.-Non-Stationary Demand scenario.

Drought Duration	Eta-HADGEM-ES Hist. Non-Stationary Demand			Negative Log-Likelihood
	Location (μ)	**Scale** (σ)	**Shape** (ξ)	
31 days	1.62E+07	1.32E+07	-3.04E-01	728.85
90 days	4.13E+07	2.71E+07	-1.84E-01	761.14
180 days	8.63E+07	5.73E+07	0.00E+00	792.70
365 days	1.65E+08	1.10E+08	0.00E+00	819.49

Complementary Material: Section 3-E

Histogram for the SABESP tariff adjustment data series during the period 2000-2016.

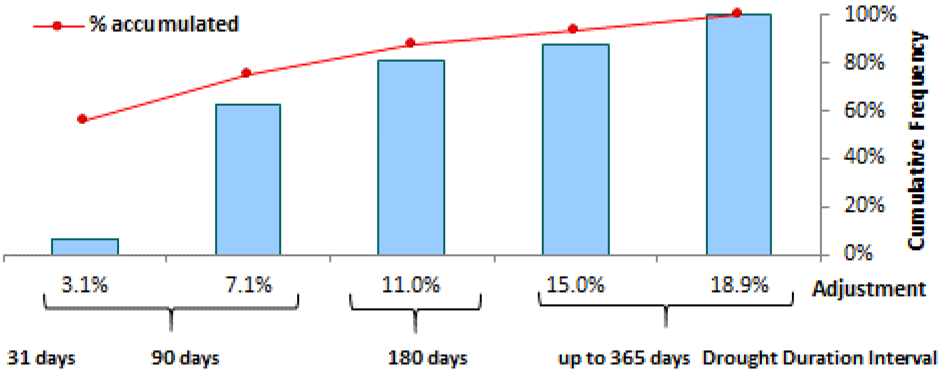

Figure 3.5-6. Relationship assumptions between Drought duration intervals and water tariff adjustments. Series structure: 16 pieces of data in total; first interval 1 frequency, second interval 9 frequencies, third interval 3 frequencies, fourth interval 1 frequency and fifth interval 2 frequencies; average 7.85%, minimum 3.14% and maximum 18.9%.

CHAPTER 4

PLANNING A DROUGHT INSURANCE SCHEME TO ADDRESS THE WATER UTILITY COMPANY´S REVENUE REDUCTIONS *

* A modified version of this chapter has been submitted as **Guzman, D.** Mohor, G. and Mendiondo, EM. (2018). Planning Water Utility Financial Protection through a Risk Transfer Approach in a Hydrological Drought Context. Elsevier Journal*: Journal of Ecological Economics.*

Abstract

Currently, most of the income from water utility companies is based on water management from surface and groundwater sources. However, non-stationary drivers, such as climate change, economic development and human interventions lead to substantial economic losses in water utility companies. To face these losses, financial instruments such as insurance can be useful tools for mitigating weather-based financial risks. Nevertheless, limitations on data and highly uncertain risks affect model estimates, leading to significant ambiguity in the final insurance premium appraisal and business sustainability. Therefore, this paper addresses the water deficit and its economic impacts on a water utility company using a hydrological insurance design as a complement of the structural resilience measures already implemented in the Sao Paulo Metropolitan Region, Brazil (SPMR). The methodology is based on an insurance model, developed under the synthetic ('what-if') approach, using a "set of change drivers" to calculate an optimal premium of a multi-year insurance (MYI) policy against intra-annual hydrologic droughts. The drivers are defined by three steps: "the climate driver" by the Eta-INPE regional climate model (RCM) outputs; "the Human interventions driver" through the variability in water demand projections; and "the economic driver" associated with the water price policies adopted by the water company under drought scenarios. The results are shown in three contractual planning horizons: 2007-2040, 2041-2070 and 2071-2099, using two simulation exercises to estimate a risk actuarially fair premium. On the one hand, “as a function of the residual drought risk to the installed storage capacity” and on the other hand, “implementing a retention scheme or deductible”. Adopting this insurance approach for the SPMR case, the evaluated indexes showed that multi-year contracts with drought coverage higher than 240 days offer better financial performance than contracts with wider coverages. Moreover, this MYI adopted in the installed storage residual risk

generates both a higher level of solvency for the insurance fund in the long term and annual average premiums closer to the expected revenue reductions by scenario.

Keywords: Multi-year insurance, Hydrological drought, Climate change, Residual risk, Premium ambiguity.

4.1 Introduction

In recent years, natural disasters have substantially increased, as have the economic losses associated with them. The link between climate change and natural disaster economic impacts are a fact that can hardly be contradicted (Müller-Fürstenberger & Schumacher 2015; IPCC 2014a; PBMC 2013). According to a report published by the World Meteorological Organization (2014), from 1970 to 2010 the number of reported disasters and economic losses by decade increased. Moreover, this trend continues despite policy and adaptation actions against climate change which have been adopted (Di Giulio et al. 2017). The report specifies that close to 11% of natural disasters reported from 1971 to 2012 corresponded to severe droughts and extreme temperatures. Moreover, these events account for 34 percent of all deaths and approximately US$286.88 billion in economic losses (WMO 2014).

On the one hand, the lack of rainfall and rising temperatures predict an increase in intensity and frequency of worldwide droughts (Wanders & Wada 2015; Trenberth et al. 2013; Williams et al. 2015; Shi et al. 2015; MCII 2016). On the other hand, population growth and water-based economic development increase demands considering the lack of new supply sources (Liu et al. 2017; Ceola et al. 2016; Veldkamp et al. 2017; Mekonnen & Hoekstra 2016; Güneralp et al. 2015; Sivapalan & Blöschl 2015). As a result, in recent years, many regions of the world have seen some of the worst drought conditions and few future expectations for a better scenario according to climate projections (Van Lanen et al. 2013; Touma et al. 2015). Their impacts cause serious consequences by limiting economic and social development, especially in low-income countries (MCII 2016; Felbermayr & Gröschl 2014; Freire-González et al. 2017; Distefano & Kelly 2017; Marin & Modica 2017; Caruso 2017). For example, the last drought experienced in the Sao Paulo Metropolitan Region (SPRM), Brazil from 2013 to 2015 triggered considerable economic impacts on the population and productive sectors who are highly dependent on water (Nobre et al. 2016; Marengo et al. 2015). Although the SPRM has a water storage system called "Cantareira” that was implemented in the mid-1970s to meet growing water demands, rationing and increases in water rates were introduced during the last drought for a large part of the population to control consumption (Soriano et al. 2016). As a result of the low supply of water and the price policies adopted, the Sao Paulo State Water Utility Company (SABESP) witnessed the worst water and financial crisis in its history (GESP 2016).

An important part of water utility companies' income generally comes from water capitation-distribution-commercialization processes. Therefore, the economy of these companies, including SABESP, has become more susceptible to increasingly frequent and severe drought events, even with large storage systems that provide extra water security levels (Zeff & Characklis 2013; Mehran et al. 2015; Foster et al. 2015). To deal with economic losses and accelerate post-disaster recovery triggered by increasing hazards, instruments such as insurance, catastrophe (CAT) bonds and contingency funds are being promoted and adopted in emerging - vulnerable countries (IPCC 2014a; UNISDR 2015; Ranger & Surminski 2013; Breckner et al. 2016; Doncaster et al. 2017; Lee & Chiu 2016; Borensztein et al. 2017; MCII 2016). However, insurance schemes must consider problems related with adverse selection, moral hazards and highly correlated losses from extreme events (Kunreuther & Michel-Kerjan 2014). This situation generally derives from a lack of information about the disasters' impacts, the uncertain nature of the hazards and the high capital costs that insurers incur to be able to cover exceptionally great indemnities. These factors can lead to a high degree of ambiguity when determining the premium. (Zhu 2017; Paudel et al. 2015; Meyer et al. 2013; MCII 2016; Daron & Stainforth 2014; Sampson et al. 2014).

Water storage systems are generally protection structures designed to deal with drought risk, among other natural hazards. However, when projected minimum storage limits are exceeded, the impacts are difficult to handle and recovery can be slow and costly (Coutinho et al. 2015; Cunningham et al. 2017). Therefore, the aim of this study is to have an overview of the allocation of the financial risk caused by hydrological drought in the water services company; (Lamond and Penning-Rowsell, 2014), considering the acquisition of an insurance contract in the medium and long term. To achieve this, we propose a risk based multi-year hydrological drought insurance scheme, based on the MTRH-SHS approach (Mohor & Mendiondo 2017; Guzman, Mohor, Freitas, et al. 2017) influenced by climatic, anthropogenic and economic drivers. The methodology was developed using an ex-ante simulation exercise that includes two parts: first, the insurance design scenarios under a set of drought duration (D_d) coverages; and second, the insurance design for longer drought events, conditioning the premium to a deductible scheme equal to the expected losses under a 2-year return period (R_p) scenario. The results are shown as a set of actuarially fair premiums of annual payment, contracted in periods of "n" years delimited by the Eta-INPE RCM output time-slices.

The sections of this article outline methods and general assumptions that explain the articulation between the processes as follows. In Section 2, the text describes the study area (see Fig. 1) and a brief discussion of the SABESP hydro economic crisis in the SPMR as a study case. Afterwards, the general methodological approach is shown (see Fig. 2), followed by the insurance design description. Section 3 outlines the results and discussion from the intensive financial simulations as a set of potential risk premium scenarios. Finally, in Section 4, the conclusions and recommendations are presented regarding the adopted methodological approach.

4.2 Methods and Materials

4.2.1 Study area and water utility financial crisis context

The SPMR, located in the State of Sao Paulo in southeast Brazil, lies approximately between latitudes 23°24’S and 23°48’ S and in the west between longitudes 46°18’W and 46°48’ W. According to the Brazilian Institute of Geography and Statistics (IBGE[7]) and the State System of Data Analysis Foundation (SEADE[8]), the SPMR has an area of 7946 km^2 with a population of over 21 million people and it is considered the fourth largest urban agglomeration in the world and the largest urban agglomeration in Brazil. Accounting for approximately 10% of the Brazilian population, its GPD represents approximately 19% of the national economy (Haddad & Teixeira 2015). Thus, to supply the growing demand for water in the urban center, the Cantareira System was gradually introduced in the mid-20th century. The system is currently withdrawing an average of 28.8 $m^3 \cdot s^{-1}$ to supply 9 million people in the SPMR (SABESP 2017).

The system consists of four interconnected major reservoirs installed in four sub watersheds of the Piracicaba River (Jaguarí-Jacarei, Cachoeira, Atibainha and Paiva Castro) and a pumping station (ANA & DAEE 2004), (see Fig. 4.2-1). The Jaguarí-Jacarei sub-basins account for approximately 58% of the total water produced in the Cantareira, a percentage close to the total water withdrawn for the SPRM (SABESP 2017). Thus, the water withdrawn by SABESP from the SPMR supply system is mainly distributed for human consumption (domestic use), industrial and agricultural production.

[7] https://ww2.ibge.gov.br/home/mapa_site/mapa_site.php#populacao
[8] http://www.imp.seade.gov.br/frontend/#/

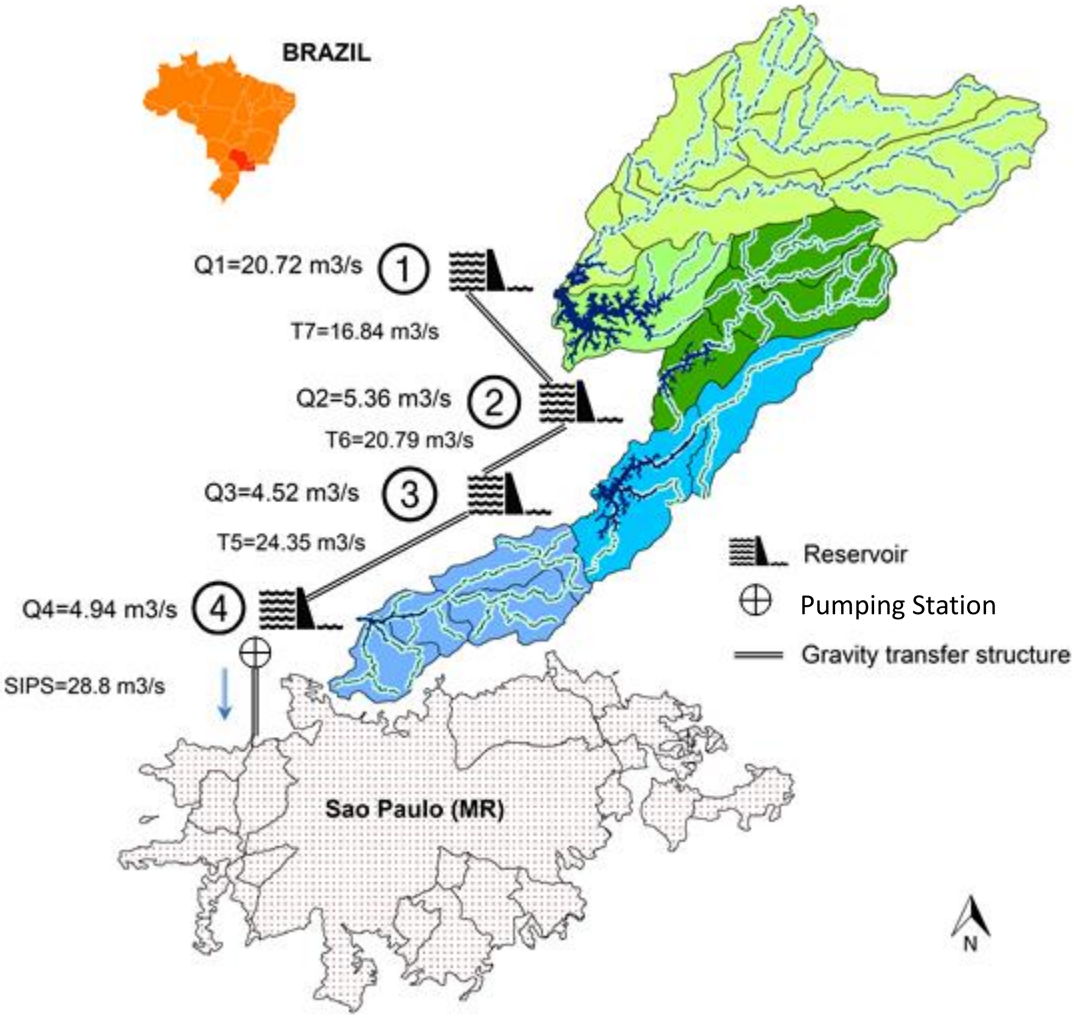

Figure 4.2-1 Cantareira water supply system description: 1. Jaguarí-Jacareí Subsystem, 2. Cachoeira Subsystem, 3. Atibainha Subsystem, and 4. Paiva Castro Subsystem. (Q_x = 2004-2016 daily average discharge, T_y = 2004-2016 Tunnel Water withdrawal daily average and SIPS = Santa Isabel Pump Station daily average).

In recent decades, some drought events have been recorded in the SPMR (Cavalcanti & Kousky 2001; Nobre et al. 2016), but none such as the 2013-2015 event that caused the major water crisis, causing severe socio-economic impacts on the region (Mello & Randhir 2017; Marengo et al. 2015; Taffarello, Samprogna Mohor, et al. 2016). Thus, despite having a robust water storage system, the water deficit worsened in the 2014-2015 period, a time in which it was necessary to implement contingency measures such as programmed rationing and water policy prices to control consumption among others (2030WRG 2016). However, the resulting revenue losses of these measures and the financial uncertainty are arguments that do not make these strategies attractive to be implemented in water utility companies. (Zeff & Characklis 2013). For example, the 2016

SABESP administrative report showed, among other financial indicators, the liquidity margin and liquid profits before-during-after the drought period of 2012-2016 (see Table 4.2-1); this table emphasizes the economic impact generated by the water deficit causing the business interruption in the water utility company during 2014 and 2015. For the final period 2016, the Table 4.2-1 shows a financial recovery generated especially by the major water availability and the price policies dismantling, which were established during the crisis. It is worth mentioning that this water deficit caused direct and indirect economic losses in other sectors such as households, industry and agriculture, highly dependent on the water supplied by the SABESP, that were not considered in this work.

Table 4.2-1 SABESP Liquidity margin and Liquid profits under the last drought condition scenario (GESP 2016).

Index	**2012** (Before)	**2013** (During)	**2014** (During)	**2015** (During)	**2016** (After)
Liquidity margin (%)	17.8	17.0	8.1	4.6	20.9
Liquid profits ($10^6 \cdot$ US$)*	597	601	282	168	921

*Present value (foreign exchange R$ to US$)

4.2.2 Methodology

The drought configuration is generally defined from a serious rainfall deficiency accompanied with an increased potential evapotranspiration (Huang et al. 2017). Thus, when a drought event extends over a long period of time, it can lead to the lower availability of surface and groundwater in the system to finally establish a hydrological drought (Van Loon 2015; Hisdal, Tallaksen, Clausen, Peters, et al. 2004; Wu et al. 2017). Thus, due to the significant dependence of the water supply network in urban areas, our insurance scheme was organized from the surface water deficit, induced by the hydrological drought.

The MTRH-SHS is a hydrological insurance fund simulation model, coupled in three analysis modules "Hazard-Vulnerability-Financial" (see Fig. 4.2-2). The model, based on the "what-if" approach, calculates the optimal insurance risk premium, conditioned to a multi-year contract scheme (Guzman, Mohor, Freitas, et al. 2017). The methodology follows the model structure, established by sequential modules to carry out multiple realizations, guided by different drivers of change such as climate, representative concentration pathways scenarios (RCP), water demand and economic policies adopted during water deficit periods.

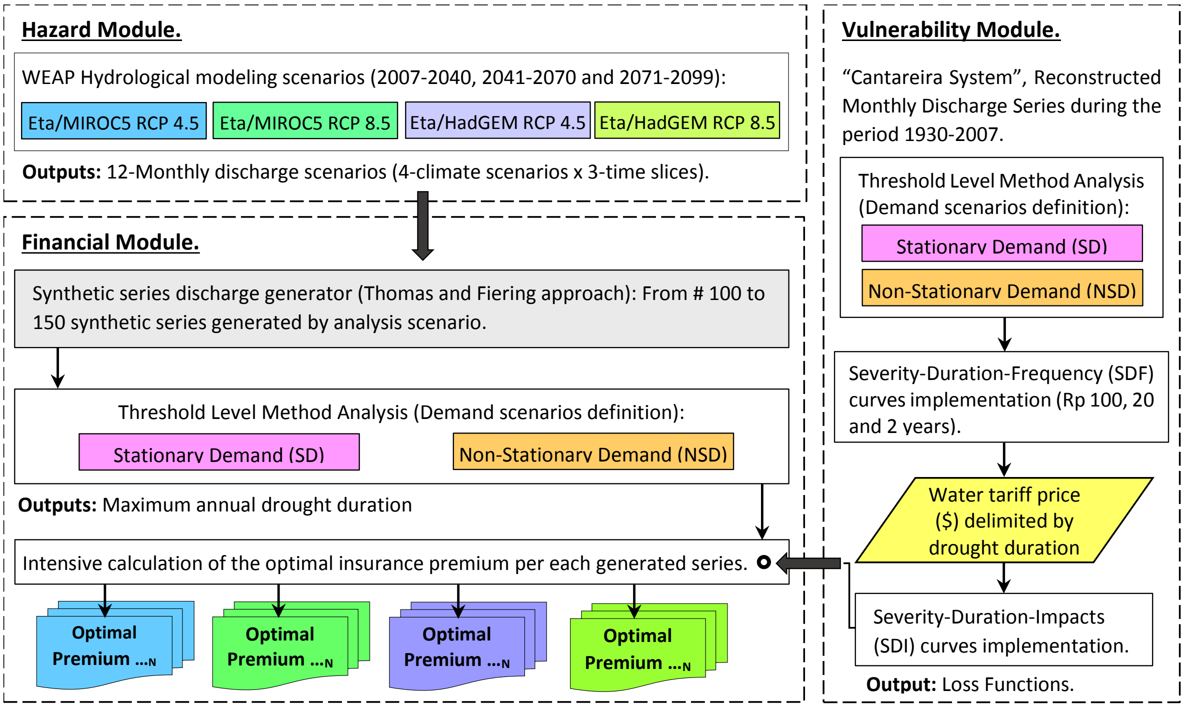

Figure 4.2-2 Methodology flowchart in MTRH-SHS approach.

In the methodological proposal, three main drivers of change are studied, as follows. First, "the climate driver", using an Eta-INPE RCM output dataset with grid sizes of 20x20 Km, is nested within two global climate models (GCM) HadGEM2 ES - MIROC5 IPCC AR5 and forced by two RCP 4.5 - 8.5 scenarios (Chou, Lyra, Mourão, Dereczynski, Pilotto, Gomes, Bustamante, Tavares, Silva, Rodrigues, Campos, Chagas, Sueiro, Siqueira, Nobre, et al. 2014; Chou, Lyra, Mourão, Dereczynski, Pilotto, Gomes, Bustamante, Tavares, Silva, Rodrigues, Campos, Chagas, Sueiro, Siqueira & Marengo 2014). Its outputs are shown in future time-slices of approximately 30 years: 2007-2040, 2041-2070 and 2071-2099; adopted as multi-year insurance scheme contractual periods. Second, "the Human interventions driver" through the variability in water demand projections. Based on the historical water withdrawal records in the Santa Isabel pumping station of the Cantareira system (see Fig. 2.1-1), two water demand scenarios were defined (SABESP 2017). The first, a "stationary demand" (SD), equal to 31 $m^3 \cdot s^{-1}$ calculated from the average daily historical discharge and a second "non-stationary" (NSD), estimated as the discharge projection and related to the IBGE and the maximum grantable limit (ANA & DAEE 2004), that goes from 24 $m^3 \cdot s^{-1}$ to 36 $m^3 \cdot s^{-1}$. Third, "the economic driver" associated with the water price policies adopted by the SABESP under the last drought scenario (SABESP 2016b; Guzman, Mohor, Taffarello, et al. 2017).

Having defined the drivers, two simulation exercises were established with the objective of finding the actuarially fair premium under a multi-annual contract scheme. For the first simulation exercise, scenarios were systematically performed under the influence of climate drivers, water demand and drought duration. Each simulation scenario was carried out from 100 equiprobable discharge series and was subsequently evaluated by three performance indicators namely Loss ratio, Efficiency and Solvency coefficients (Laurentis 2012; Mohor & Mendiondo 2017; Contador 2007; Mapfumo et al. 2017; Graciosa 2010). Following the same procedure as the systematic scenarios, the second simulation exercise was developed, however in this stage, scenarios of D_d < 240 days were selected and 100-year R_p under an evaluation set of 150 equiprobable series. Thus, for each of these scenarios, a deductible arrangement was implemented, equivalent to the average expected losses under 2-year R_p scenarios, assuming that the water utility company could financially cover this amount of losses.

4.2.2 Water utility insurance scheme features

The proposed scheme is a private agreement where the water services company and insurers have the possibility to evaluate the financial risk to be covered by an insurance contract. Insurance is mandatory for the water company, however, we are looking at how insurance costs can be shared across affected sectors. Although this implies that, despite the water deficit, the company must provide the vital minimum level of water in homes, and a basic volume for industries that rely on water for their production in all cases. Therefore, an additional rate for reliability in the water supply can be set, which could be invoiced monthly in the monthly water tariffs. Table 4.2-2 shows the description of the main features adopted under the MTRH-SHS approach and current Brazilian insurance regulations.

Table 4.2-2 Features: Adopted drought insurance design under the MTRH-SHS approach (Adapted from UNISDR-IDF, 2016).

Features	Description
Insurance regulations	Superintendence of private insurance SUSEP (Brazil): - National Private Insurance council (CNSP). Legal Resolution No. 343, from 26 December 2016. - SUSEP Circular No. 256, of June 16, 2004.
Hazard approach	Hydrological droughts
Insurance sector	Private insurance
Coverage (What & Who)	What: Disaster cover for businesses interruption cost in the domestic and industrial sectors during hydrological deficit Who: Public services (water utility company revenue losses)
Coverage scale	Meso-scale (SPMR)

Insurance planning scenarios	- Hydrological droughts severity between 2, 20 and 100-year R_p scenarios, under 2 water withdrawal scenarios (SD – NSD). - The Residual risk related to the storage deficit, under the drought severity of Rp 100 years and two water withdrawal scenarios.
Purchase requirement	Compulsory under a multi-year contract scheme
Premium setting	Risk actuarially fair premium
Hydrological variable	Inter annual Droughts - 0 days < D_d < 365 days, from the monthly TLM analysis
Damage cost evaluation	Empirically curves, as a function of the annual maximum drought duration (days) and the tariff policy price adopted during deficit periods (US$).
Insurance performance analysis indexes	Loss ratio, Efficiency and Solvency coefficients

On the other hand, the MTRH-SHS model simulation parameters were defined. First, the initial storage capital was established from the minimum solvency capital, in this case, without considering assets of the insurance company. Thus, the minimum solvency capital was defined as 0.33 the value of the average annual loss per coverage scenario and the premium amount collected in the first period (Laurentis 2012; Graciosa 2010). Graciosa, 2010; Laurentis, 2012). Next, the loans and savings interest rates were assumed according to the Central Bank of Brazil rates, 13% and 8.5% (APR) respectively. Later, so as to control the high premium values during the optimization process, Graciosa (2010) defined a maximum insurance fund storage limit. This value is limited to twice the loss value, corresponding to the maximum hydric deficit in each simulation. Thus, in this study, the surplus fund is stored at an intermediate interest rate equal to 9% (APR) and can be distributed as a discount bonus to the annual premium during the contracted period. Alternatively, the stored surplus fund could be used to invest in adopting risk reduction strategies (Hudson et al. 2016), however this alternative scenario should be studied more in future work. Finally, the maximum coverage was settled by a set of drought magnitude scenarios, delimited by the Return periods and the Drought duration.

4.2.3 A Multi-year water utility insurance design under the MTRH-SHS approach

Following the proposed methodological structure based on the hydrological risk transfer model MTRH-SHS (see Fig. 4.2-2), future water supply scenarios were developed from the RCM Eta-INPE outputs, which were conducted through hydrological modeling in the Water Evaluation and Planning System (WEAP) in the risk module. The modeling framework was used as an equivalent storage system, consisting of 16 sub basins distributed over 2265 km^2 (see Fig. 4.2-1), 52 rain gauge stations, 11 discharge gauge stations and meteorological data from 14 stations from 2004 to 2015. As a criterion of the model performance, several indexes, including NSE and PBIAS, were evaluated, which presented mean values between 0.9 to 0.95 and -12.36 to -3.4 (see Chapter 4 page 54 – calibration and validation modelling processes) , respectively (Guzman, et al. 2017).

Based on the monthly discharge reconstructed series (1930-2016), recent data observed in the Cantareira System (ANA and DAEE, 2004) for the study of availability and water withdrawal authorization, severity-duration-frequency (SDF) curves were constructed (J H Sung & Chung 2014; Tallaksen et al. 1997; Zaidman et al. 2003; Firoz et al. 2018). The SDF curves were developed from two water consumption assumptions (SD and NSD), three frequency scenarios 2, 20, 100-year R_p and the generalized extreme value distribution (GEV) was adopted as a probability function (FDP) (see Fig. 4.2-3 and Supplementary material: Section 4-A – SDF - Fit diagnostic plots).

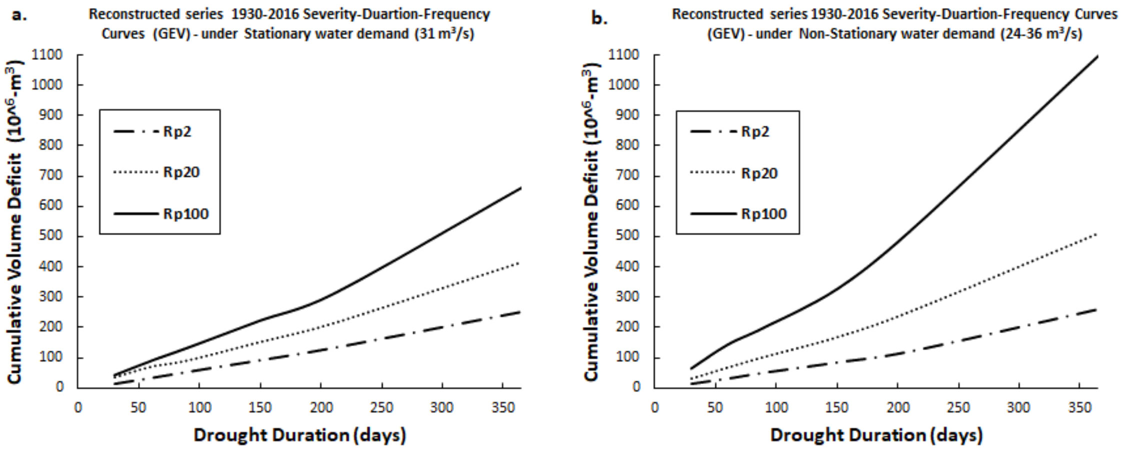

Figure 4.2-3 SDF curves through the stationary (SD) and non-stationary (NSD) demand assumptions under reconstructed discharge scenarios 1930-2016: a. SD=31 m^3/s. b. NSD=24 to 36 m^3/s.

Since the SDF curves do not include the economic impact variable, characteristics such as drought duration and intensity (volume deficit) were related to the water utility company revenue losses (Guzman, Mohor, Taffarello, et al. 2017), based on the average price policies adopted during the most recent drought event (SABESP 2016b; SABESP 1996; SABESP 2016a). Thus, the empirical water utility company profit loss curves were constructed (see Fig. 4.2-4 and Supplementary material: Section 4-B - Profit loss curves equations), establishing a difference from the tariff prices by consumption sector “Industrial or household”, as priority and highly dependent sectors of the urban water supply network. Figure 4.2-4 shows the profit losses of the water utility company vs. drought duration, under demand and return period frequency scenarios; the blue and red bars in the figure represent the average percentage of economic affectation of the water utility company, estimated from water not billed by the consumption sectors. Therefore, the predominance of the blue bars shows that the initial economic impacts on the company (in all the scenarios analyzed) are produced by the industrial sector, due to the priority that, by law, has the domestic sector in Brazil. On the other hand, the greater frequency scenario (Rp100) represents more severe events with greater hydric deficit, where both analyzed sectors show a simultaneous impact.

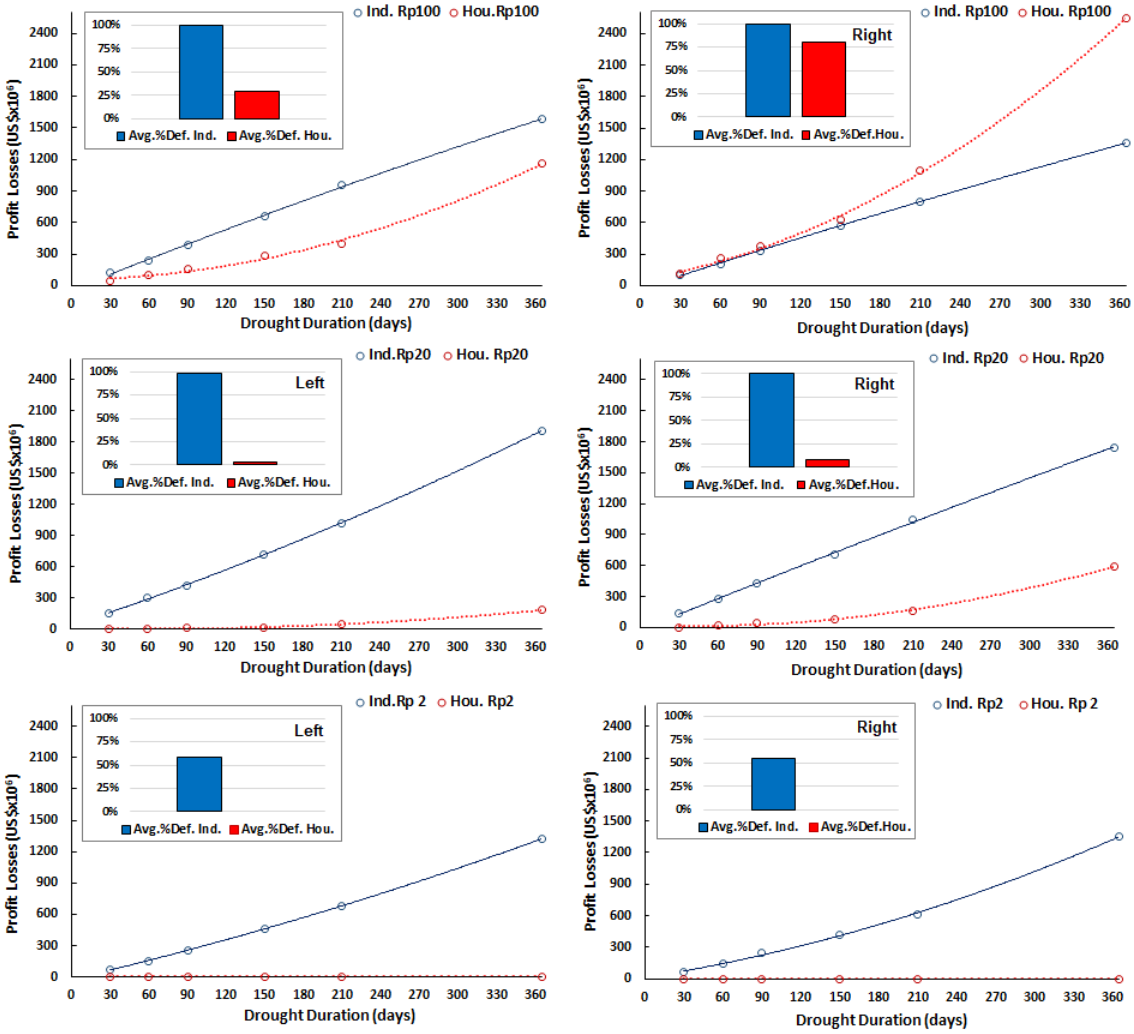

Figure 4.2-4 Drought profit loss curves per sector “Industrial (Ind. - in blue and continuous line) and household (Hou. - in red and dashed line)”. From top to bottom, return period (Rp) from 100, 20 and 2 years. Under water demand scenarios, left Stationary Demand SD= 31 m^3/s and right Non-Stationary Demand NSD= 24 - 36 m^3/s.

The insurance financial simulation continues with the equiprobable series generator (Harms & Campbell 1967; Vaghela & Vaghela 2014), which reproduces monthly discharges from the Climate and RCP baseline modeled scenarios. Next, the systematic analysis is carried out under the assumption of the stationary and non-stationary water demand assumption by the threshold level method (Hisdal, Tallaksen, Clausen & Peters 2004). Thus, the difference between water supply and demand could result in an accumulated water deficit during the analyzed period. Finally, the relationship between deficit, drought duration and profit losses is assessed by the drought profit loss curves (see Fig. 4.2-4). In this case, the actuarially fair premium $P_{x,N,y}$ is calculated in annual step simulations from the balance storage equation (Eq. (4.1)), the optimization function (Eq. (4.2)) and the restriction:

$$S_{(t)} = S_{(t-1)}(1 + tx_2) + I_{(t-1)} - L_{(t-1)}(tx_1) + Pr_{(t-1)} - [At_t] + [Dd_t]^* \qquad (4.1)$$

$$OF = min\big(S_{(nf)}\big) \qquad (4.2)$$

Restricted to,
Loans "L" in the last period "n_f", $L_{(nf)} = 0$.

Where $S_{(t\,)}$is the fund storage in the period i, tx1-x2 are the interest rates, $Pr_{(t)}$ the annual premium added, $I_{(t)}$ is the indemnification or paid claims per period, $L_{(t)}$ the loans, At_t[9] administrative taxes, Dd_t deductible[10] and n_f is the contractual period final step. Thus, we propose that the risk premium is calculated according to (Eq. (4.3)) (Kunreuther, Pauly, et al. 2013; Kunreuther & Useem 2010; Şen 2015; Mays & Tung 2002).

$$\mathrm{R}is\mathrm{k\ Premium}_{x,y} = \bar{P}_{x,N,y} \cdot \left(1 - \left(1 - \frac{\bar{C}_{x,N,y}}{\overline{TC}_{\ x,N}}\right)^n\right) \qquad (4.3)$$

Where "x" is the evaluation scenario under the set of drivers; "N" refers to the total equiprobable series evaluated; "y" as the drought duration scenario and "n" the number of years adopted in the contract. On the other hand, $\bar{P}_{x,N,y}$ is the average expected actuarially fair premium; $\bar{C}_{x,N,y}$ is the projected average number of paid claims per drought duration scenario "y" and $\overline{TC}_{x,N,y}$ is the total projected average claims per "x" scenario. The relation between $\bar{C}_{x,N,y}$ and $\overline{TC}_{x,N,y}$, can be defined as the claims probability "p" during the successive years covered by the contract.

In order to define the value of the actuarially fair premium with a certain level of confidence, our model includes the "α" ambiguity associated with the probability of an extreme event occurring (Kunreuther & Michel-Kerjan 2014; Zhu 2017; Kunreuther, Heal, et al. 2013) through the "what-if" analysis of the proposed drivers. In this case, alpha is related to the risk premium standard deviation, as follows, (Eq. (4.4)):

$$\mathrm{R}is\mathrm{k\ Premium}^*_{x,y} = \mathrm{R}is\mathrm{k\ Premium}_{x,y} \cdot (1 \pm \alpha_\delta) \qquad (4.4)$$

[9] Concerning the surtaxes imposed on the risk premium, SUSEP in Brazil, as a simplified case, suggests 10% as an administrative fee, 15% for brokerage commission and 5% for profit (SUSEP 2017; Silva 2010).
[10] $[At_i]^*$ and $[d_i]^*$: Optional

Where "*" denotes the risk premium related with the ambiguity and α_δ the ambiguity range associated with the drivers or premium uncertainty.

Three insurance performance indices are evaluated as the financial module outputs: Loss ratio, Solvency coefficient and Efficiency coefficient. The loss ratio "*LR"*, which is the ratio between the paid claim summations and the total earned premiums (Eq. (4.5)). This index evaluates the relationship between the average amounts of premiums collected ($\overline{TEP}_{x,N,y}$) which is used to cover the average claims ($\overline{PC}_{x,N,y}$) during the contractual coverage period. Therefore, LR values close to the unit represent low profit levels and unattractive schemes for insurers (Dionne 2013).

$$LR_{x,y} = \left(\frac{\sum_1^n \overline{PC}_{x,N,y}}{\sum_1^n \overline{TEP}_{x,N,y}}\right) \tag{4.5}$$

To complement the *LR* evaluation, the solvency coefficient "*SC*" (Eq. (4.6)) and the efficiency coefficient "*EC*" (Eq. (4.7)) previously defined by Guzman et al. (2017a) and Mohor & Mendiondo (2017) are proposed. The *SC* index assesses the insurance fund capacity to cover its financial commitments, in this case, through the initial capital defined and the annually collected premiums. The *EC* index appraises the probability of occurrence, or not, of an unfavorable scenario (Laurentis 2012).

$$SC_{x,y} = \frac{Risk\ Premium_{x,y} - \bar{C}_{x,N,y}}{\bar{C}_{x,N,y}} \tag{4.6}$$

$$EC_{x,y} = \frac{TES_{x,N,y}}{TS_{x,N,y}} \tag{4.7}$$

Where $TES_{x,N,y}$ is the total number of efficient series in each scenario "x, y", in the *N* equiprobable series generated. The *TES* calculation is defined by the account expression ($\bar{P}_{x,N,y} - P_{x,N,y}) > 0$, with $P_{x,N,y}$ as each expected actuarially fair premium. Likewise, $TS_{x,N,y}$ is the total of series evaluated "*N".* Thus, for higher EC values, the index results will be better, i.e. there is more likelihood of having a favorable scenario for the insurance implementation. Finally, this index is mostly influenced by the RCM projections and the covered risk magnitude.

4.3 Results and discussion

Given the proposed methodological framework, the results are shown based on the simulation exercises defined by: i) drought insurance coverage scenarios and ii) risk premium analysis under the deductible scheme implementation.

4.3.1 Drought insurance coverage scenario simulation

In this section, the results are shown as a set of potential average risk premiums under a multi-year contract scheme considering the RCM's output data periods and the drivers of change forced by the MTRH-SHS insurance fund simulation (see Fig. 4.3-1). Each drought insurance coverage set consists of a combination of 24 driver scenarios, each one of them resulting from the 100 equiprobable intensive simulation series. Figure 4.3-1 shows the average risk premium present value, based on a multi-year contract and different drought duration coverages. It was to be expected that a wide coverage level and increasing return periods would imply higher premiums, compared with the coverage restriction to events with a lower recurrence probability. In addition, a slight decrease in premium values can be identified during the 2041-2070 period compared to the other two periods; this is probably due to the one during the 2041-2070 period, in which hydrometeorological projections were presented that favored surface water availability (Guzman, Mohor, Taffarello, et al. 2017). Although in the Eta future projections there is no clear trend in average precipitation, the annual cycle of precipitation shows that the Eta simulations driven by MIROC5 produces more precipitation than the Eta driven by HadGEM2-ES during the rainy season, and generally less during the dry season (Chou et al., 2014a).

In general, the results based on the Eta-MIROC4.5 model outputs showed higher premium values than the other climate scenarios implemented, especially for the range of drought cover from 0 to 180 days (see Table 4.3-1). On the other hand, the Eta-HadGEM 8.5 model outputs showed to be the lowest for the coverage range mentioned above. Thus, drought duration coverages over 300 days between the different climate change scenarios analyzed did not show a difference that can be highlighted because the frequency of these greater magnitude events is similar under all climate scenarios (see Supplementary material: Section 4C– Average insurance risk premiums box plots).

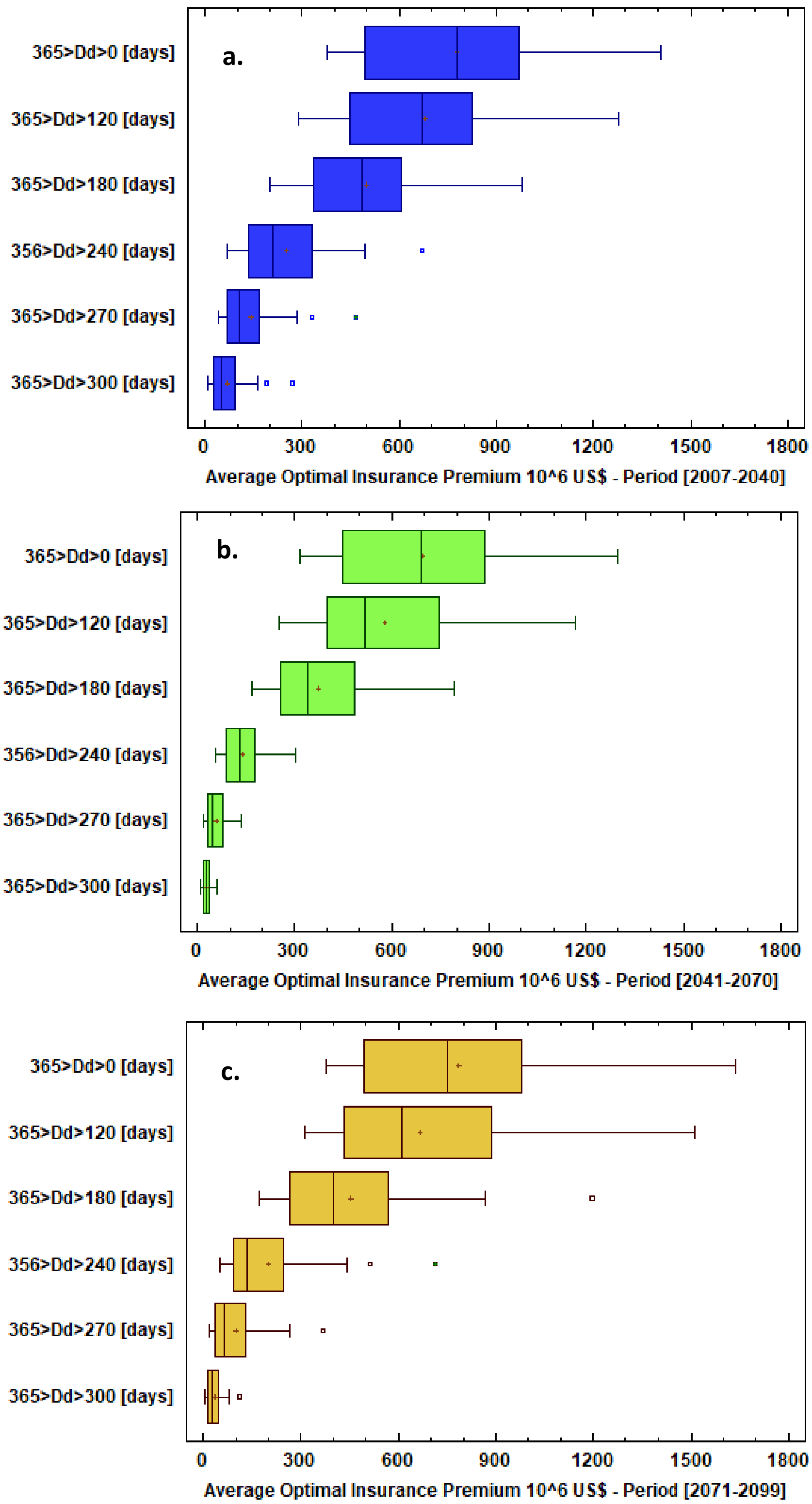

Figure 4.3-1 Average risk premium simulation per drought duration coverage considering the set of change drivers (climate, demand and frequency): RCM output data period a) 2007-2040, b) 2041-2070 and c) 2071-2099.

To estimate the uncertainty associated with the drought scenario occurrence probability and their potential losses, we proposed the insurance premium ambiguity representation through the set of drivers evaluated (Eq. (4.4)). Thus, if the risk premium is given by $ARP_{y,\ Rp}$, then we suggest observing the range of $\alpha_{y,}\ R_p$, where it reflects the ambiguity degree regarding the coverage risk assumed (Kunreuther 1989). The results in Table 4.3-1 show that an insurance coverage only for the most unlikely events has a higher ambiguity value. However, a broader insurance coverage to protect against an extended range of drought durations can be economically unfavorable despite the low ambiguity values, given the high costs of premiums (Zeff & Characklis 2013). On the other hand, having a similar behavior to premiums, during the projected period 2041-2070 from drought coverages higher than 180 days, the ambiguity values were relatively low and stable, if compared with the projected periods of 2007-2040 and 2071-2099.

Table 4.3-1 Insurance premium coverage against droughts with ambiguity interval per return period

Drought duration "D_d" Coverage (days)	Parameter*	Rp (years)	2007-2040	2041-2070	2071-2099
D_d coverage > 0	$ARP_{0,100}$	100	1109.51	993.61	1122.52
	$\alpha_{0,100}$		0.20	0.21	0.23
	$ARP_{0,20}$	20	774.60	697.84	785.13
	$\alpha_{0,20}$		0.12	0.15	0.17
	$ARP_{0,2}$	2	456.51	397.36	449.82
	$\alpha_{0,2}$		0.11	0.15	0.17
D_d coverage > 120	$ARP_{120,100}$	100	966.50	826.16	955.16
	$\alpha_{120,100}$		0.25	0.28	0.28
	$ARP_{120,20}$	20	670.04	576.16	664.83
	$\alpha_{120,20}$		0.19	0.23	0.23
	$ARP_{120,2}$	2	398.44	332.44	384.31
	$\alpha_{120,2}$		0.18	0.22	0.23
D_d coverage > 180	$ARP_{180,100}$	100	714.02	533.29	650.91
	$\alpha_{180,100}$		0.27	0.27	0.41
	$ARP_{180,20}$	20	491.34	368.17	448.90
	$\alpha_{180,20}$		0.22	0.22	0.38
	$ARP_{180,2}$	2	292.62	214.74	262.08
	$\alpha_{180,2}$		0.21	0.21	0.37
D_d coverage > 240	$ARP_{240,100}$	100	365.16	219.05	297.66
	$\alpha_{240,100}$		0.48	0.27	0.72
	$ARP_{240,20}$	20	248.42	149.35	202.71
	$\alpha_{240,20}$		0.45	0.21	0.69
	$ARP_{240,2}$	2	148.13	88.15	119.76
	$\alpha_{240,2}$		0.44	0.21	0.69
D_d coverage > 270	$ARP_{270,100}$	100	219.30	100.47	160.04
	$\alpha_{270,100}$		0.60	0.36	0.74
	$ARP_{270,20}$	20	148.20	67.96	108.23
	$\alpha_{270,20}$		0.57	0.32	0.72
	$ARP_{270,2}$	2	88.35	40.39	64.34
	$\alpha_{270,2}$		0.56	0.31	0.71

D_d coverage > 300	$ARP_{300,100}$	100	117.10	52.59	63.87
	$\alpha_{300,100}$		0.73	0.31	0.63
	$ARP_{300,20}$	20	78.46	34.66	42.92
	$\alpha_{300,20}$		0.70	0.26	0.60
	$ARP_{300,2}$	2	46.80	21.10	25.66
	$\alpha_{300,2}$		0.69	0.25	0.60

* *ARP*=Average Risk Premium in 10^6 US$ and α =Ambiguity [±].

Based on the administrative and financial report of SABESP (GESP 2016), on average, the liquid profit of the company before (2012) and after the drought (2016) was US$759 million dollars per year, however from 2013 to 2015 (during the drought period), this average liquid profit value lowered to US$350 million dollars per year (see Table 4.2-1). Therefore, if the difference is calculated between the average annual liquid profit under drought conditions and outside it, the result suggests a revenue reduction of approximately US$409 million dollars per year in the water utility company. Thus, it would be convenient for the water utility company to contract a multi-year insurance scheme with premiums close to the value of the average revenue reductions. Therefore, Table 4.3-2 shows the average annual risk premium and other important results of the proposed insurance scheme; where it is clear that extensive coverage against drought events is financially unsustainable. Thus, the results suggest insurance coverages only for the most unlikely events, which in this case, may be droughts lasting longer than 240 days. Among the other results shown in Table 4.3-2, we find the average difference between stationary and non-stationary water demand scenarios in column 3, which increases as insurance coverage decreases to less frequent events of a longer duration. Afterwards in column 4, the annual risk premium average value based on the SPMR gross product domestic 2016 is shown, clarifying that in this case, only the profit losses from the water utility company losses are considered and other SPMR economical representative sectors are not included. Finally, columns 5 and 6 show the potential discount on the annual risk premium value and the average loans to which the insurance fund would have to resort to in case of illiquidity respectively. These characteristics of the insurance fund show that the higher the insurance premium, the higher the discount and the lower the loans. However, the coverages only for greater drought magnitude events show a different loan behavior since in these cases the average loans are reduced, probably indicating a better convergence in the premium optimization process.

Table 4.3-2 Insurance scheme results under the main analysis drivers

[1]Hydroclimatological Scenario "X"	[2]Avg. annual Risk premium (10^6 US$)	[3]Dif. Demand Scenarios (%)*	[4]Avg. annual Risk premium (GPD %)**	[5]Potential annual bonus discount (10^6 US$)	[6]Avg. Loans (10^6 US$)
Tr100 - Dd > 0 – 2007-2099					
4.5 Eta/MIROC5	938-1636	42	0.27-0.47	268-1133	20-43
4.5 Eta/HadGEM	779-1362	43	0.22-0.40	161-1044	70-127
8.5 Eta/MIROC5	889-1408	37	0.25-0.42	405-1408	8-49
8.5 Eta/HadGEM	701-1128	38	0.20-0.33	141-479	26-149
Tr100 - Dd > 180 – 2007-2099					
4.5 Eta/MIROC5	578-1198	52	0.16-0.35	27-86	204-517
4.5 Eta/HadGEM	378-980	61	0.11-0.29	2-208	310-551
8.5 Eta/MIROC5	458-951	51	0.13-0.28	9-137	289-666
8.5 Eta/HadGEM	356-570	38	0.11-0.16	3-14	342-520
Tr100 - Dd > 300 – 2007-2099					
4.5 Eta/MIROC5	21-110	81	0.005-0.04	0-0	99-315
4.5 Eta/HadGEM	36-269	87	0.01-0.07	0-3.5	131-593
8.5 Eta/MIROC5	9-82	89	0.002-0.02	0-0.3	51-244
8.5 Eta/HadGEM	29-93	69	0.009-0.02	0-0	117-275
Tr2 - Dd > 0 – 2007-2099					
4.5 Eta/MIROC5	427-584	27	0.13-0.16	117-394	10-14
4.5 Eta/HadGEM	352-484	27	0.10-0.14	59-497	35-46
8.5 Eta/MIROC5	403-505	20	0.11-0.15	185-560	3-17
8.5 Eta/HadGEM	316-409	23	0.09-0.11	47-231	13-48
Tr2 - Dd > 180 – 2007-2099					
4.5 Eta/MIROC5	269-425	38	0.07-0.13	8-48	100-186
4.5 Eta/HadGEM	176-345	49	0.05-0.11	0.4-71	150-202
8.5 Eta/MIROC5	212-338	37	0.06-0.09	2-87	133-239
8.5 Eta/HadGEM	166-203	18	0.04-0.05	1.2-8	158-181
Tr2 - Dd > 300 – 2007-2099					
4.5 Eta/MIROC5	10-38	74	0.002-0.011	0-0	48-109
4.5 Eta/HadGEM	18-92	80	0.005-0.02	0-1.2	63-203
8.5 Eta/MIROC5	5-28	82	0.0015-0.009	0-0.1	25-83
8.5 Eta/HadGEM	14-32	56	0.004-0.010	0-0	56-94

* Premium difference between stationary and non-stationary interval demand scenarios in column 2.
** % Sao Paulo Metropolitan Region GPD – 2016

As a complement to column 2 in Table 4.3-2, Figure 4.3-2 shows the average risk premium dispersion for each water demand scenario and duration of drought. The analysis, made from the return periods 2, 20 and 100 years, showed that for drought scenarios with low magnitudes and frequencies, such as R_p2 years, the stationary and non-stationary water demand conditions do not affect the risk premium average values. On the other hand, a gradual reduction in the premium dispersion was observed as the insurance coverage was reduced. Thus, the current Cantareira System configuration is presented in theory as a potential scenario for the insurance scheme implementation, because with the installed storage, the low to medium drought risk is resisted and the residual risk (such as the 2013-2015 crisis) is transferred through an insurance instrument.

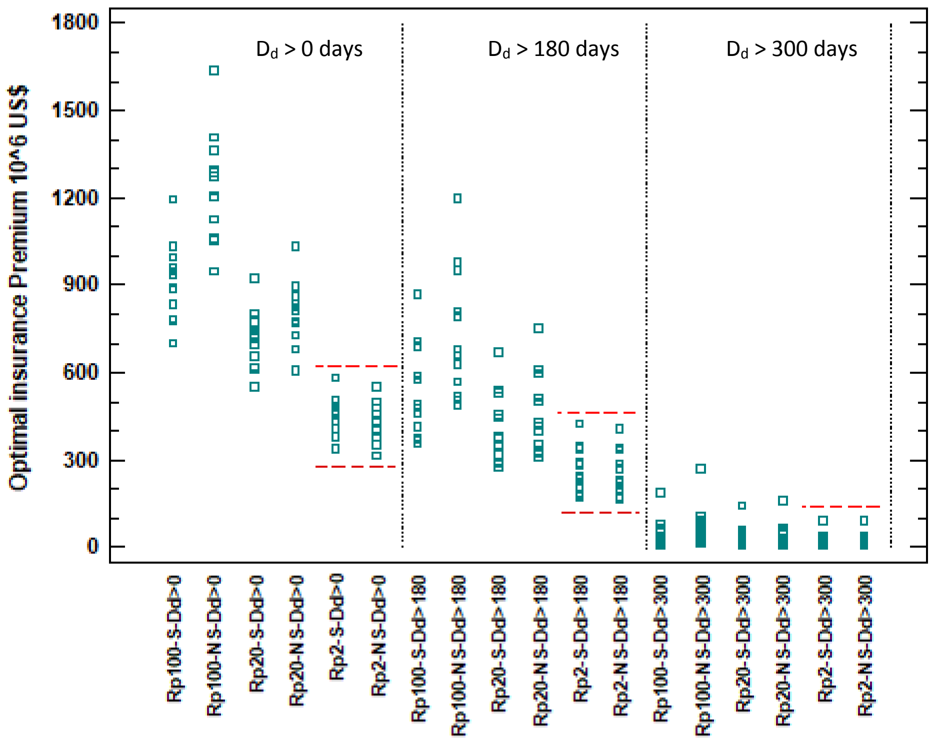

Figure 4.3-2 Dispersion plot between average insurance risk premium values, stationary or non-stationary water demand and drought coverage scenarios under return period analyses.

4.3.2 Insurance performance evaluation

In order to find an insurance fund performance comprehensive view during the projected periods, the efficiency, solvency, loss ratio and claim number indicators were evaluated (Laurentis 2012; Mohor & Mendiondo 2017; Graciosa 2010; Guzman, Mohor, Freitas, et al. 2017). Figure 4.3-3 shows the average value of each of these indices as a function of insurance coverage through the analyzed time scenarios. Based on the results of the loss ratio, perhaps one of the most used indicators to measure the economic sustainability of the insurance funds (Dionne 2013; Contador 2007), it was found that for the less probable event coverages, approximately those greater than <240 days, the index line shows an inflection point that suggests favorability against the collection of premiums and paid indemnities of contracts that include the most recurring events. In the same way as the loss ratio, the efficiency and solvency coefficients improve their performance under exclusive coverage conditions to greater magnitude events that consequently present fewer claims during the contractual period.

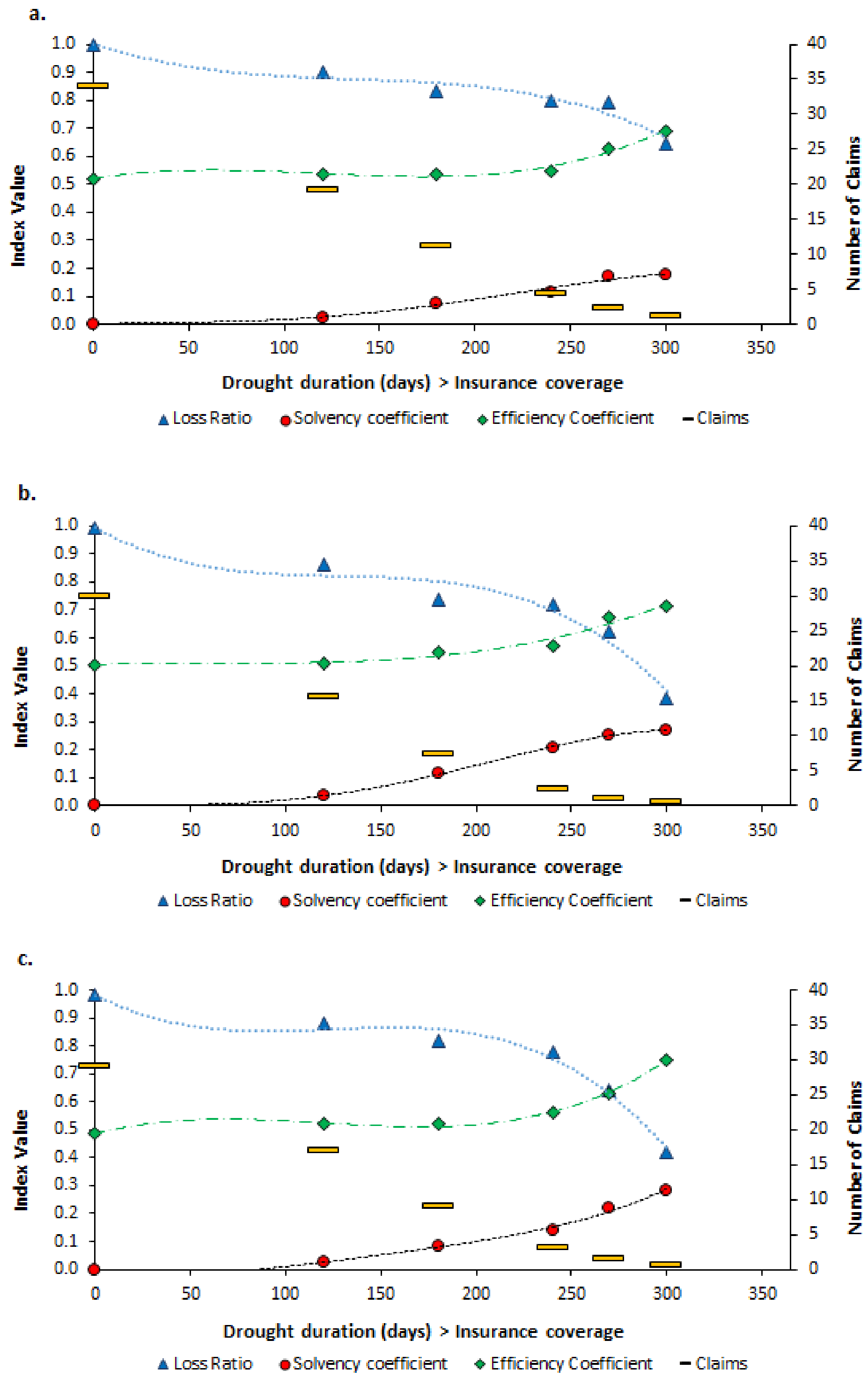

Figure 4.3-3 Performance indices of the insurance scheme against hydrological droughts (lost ratio-Solvency coefficient-Efficiency coefficient-Claims): a. period 2007-2040, b. 2041-2070 and c. 2071-2099.

Based on the insurance fund optimization function (FO), defined as the minimization of the final step stored balance "SA_{nf}" (see Section 4.2.3), a comparison was made between the SA_{nf} and the minimum solvency capital required (MSCR) for the fund's subsistence (see Figure 4.3-4). The difference between SA_{nf} and MSCR offers a measure of the premium optimization process, that is, on the one hand, higher differences (shown by the blue semi-bar as a percentage in Figure 4.3-4) denote an optimal premium capable of responding to the fund obligations, but from extremely high premiums due to the sequence of claims. On the other hand, smaller differences between parameters can be explained as a better convergence to the optimal premium, in response to scenarios with a better claims distribution over time facilitating the optimization process. Therefore, it is not an objective to ensure coverage close to the 100% of drought risk, such as coverage scenarios 0< D_d<365, 0< D_d<120 and 0< D_d<180 days, since this can lead to the insured's economic loss due to the high cost of coverage.

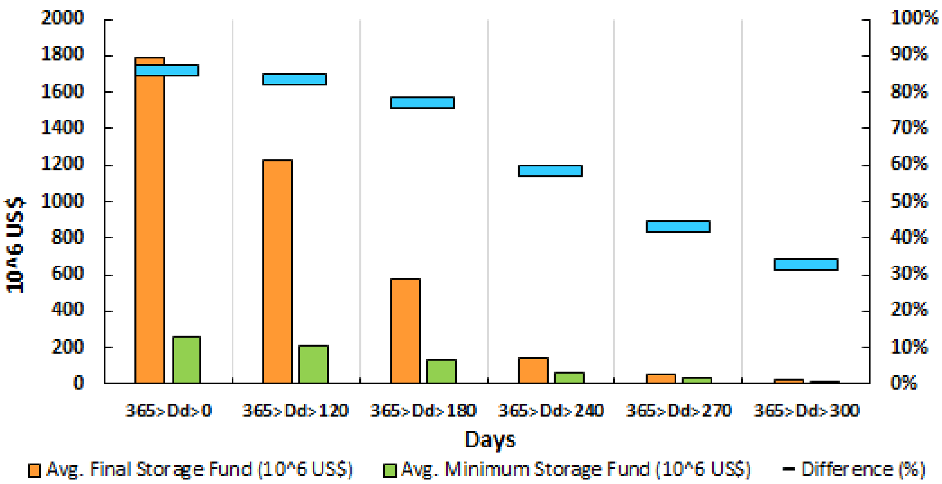

Figure 4.3-4 Comparison between the final balance stored SA_{nf} (orange bar) and the minimum storage, initially defined as "minimum solvency capital" (green bar).

4.3.3 Drought insurance scenario simulation under deductible implementation

Among the tools used to reduce moral hazards in insurance initiatives is the introduction of the deductible scheme in contracts; they induce the insured to adopt risk awareness considering an adverse event or constitute a strategy for negotiating the premium value with the insurer, according to the insured´s risk aversion (Kunreuther, Pauly, et al. 2013). In this case, we introduced a deductible scheme denoted by "R" in Figure 4.3-5, established from the expected value of the average losses of R_p 2 years, executed in the MTRH-SHS model under the systematic simulation of 150 equiprobable series per scenario, with drought coverages greater than 240 days, frequency of events equal to R_p 100 years, climate drivers from 2007 to 2099 and water demand scenarios SD and NSD. Figure 4.3-5 shows the performance indexes loss ratio (red bar), the solvency coefficient (orange bar), efficiency coefficient (yellow bar), the potential annual discount bonus (PADB) and the average risk premium (grey semi-bar), evaluated based on the implementation or not of the deductible scheme. Therefore, from the deductible implementation, a low proportion premium value reduction, a decrease fund financial performance and lower PADB values were observed, given that the amount premiums collection decreased. While the potential discount bonus also decreases due to the premium income reduction, considering a constant maximum storage and equal to that of the first exercise. Thus, the work to find the appropriate deductible scheme in an optimal insurance contract is still a challenge, both for traditional methodologies (Li & Xu 2017) and for new approaches such as this one.

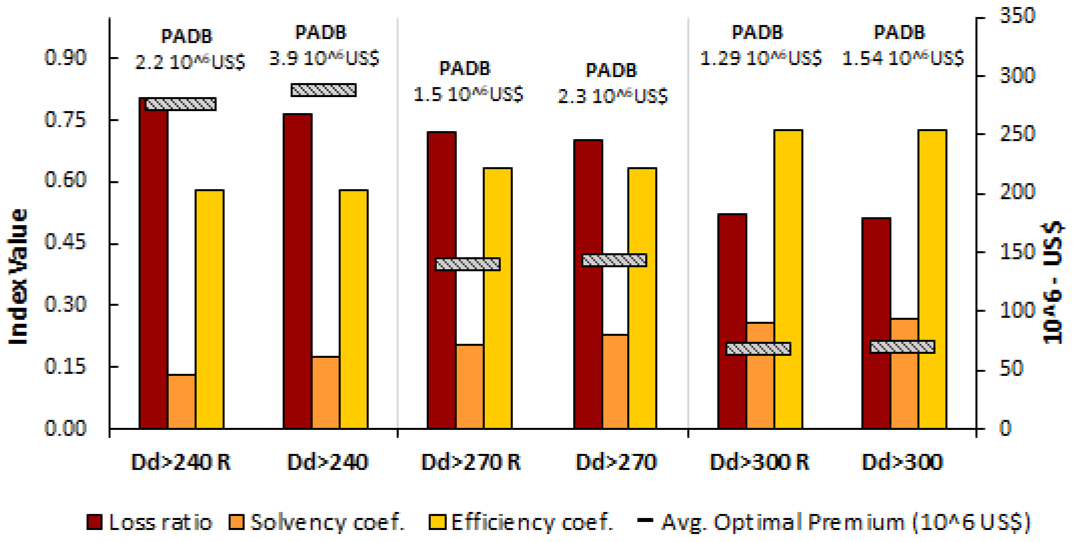

Figure 4.3-5 Insurance design evaluation under a deductible scheme introduction, where PADB is the Potential Annual Bonus Discount and R is the deductible scenario evaluation.

4.4 Conclusions

In this article, we proposed a multi-year insurance scheme to face the revenue losses in the water utility company during hydric deficit periods, which in recent years have intensified in the SPMR. The insurance scheme is based on the MTRH-SHS methodology, executed mainly under the influence of climate and water-demand drivers. The approach was presented through two academic application exercises; the first describes how the proposed drivers influence the annual risk premium value from the medium to the long term and the second evaluates the insurance fund performance by introducing a deductible scheme. Additionally, based on the obtained results, a premium ambiguity measure was estimated, useful for defining pricing policies in the insurance sector.

The methodology implemented can also help the systematic evaluation of moral hazard and the adverse selection in insurance contracts. In the first case, the probable scenarios´ intensive evaluation must generate useful information to change or maintain the behavior of both the insured and insurers considering future risks related to climate change. In the second case, the multi-scenario residual risk evaluation can help the insurer to set thresholds for prices set in insurance contracts, offering a differential portfolio in the premium amount.

Regarding the proposed insurance scheme results, it can be concluded that contracts for exclusive coverage of more unlikely events, that is, the more severe and prolonged, present more promising financial conditions than contracts for broader coverage, representing a more attractive alternative for water service companies. Thus, the complement between strategies to mitigate drought impacts, such as reservoirs for low to medium risk and insurance for higher residual risks, is a robust and efficient structure considering current dynamics of risk changes.

Finally, based on the recent SABESP annual revenue losses and the average risk premium calculated, it is convenient to acquire insurance to cover the economic impacts of the hydrological drought in the SPMR. Finally, evaluating the insurance scheme under the new driver configuration, such as longer-term multiannual insurance contracts and the introduction of variable deductible (franchise) schemes, is open for future analysis.

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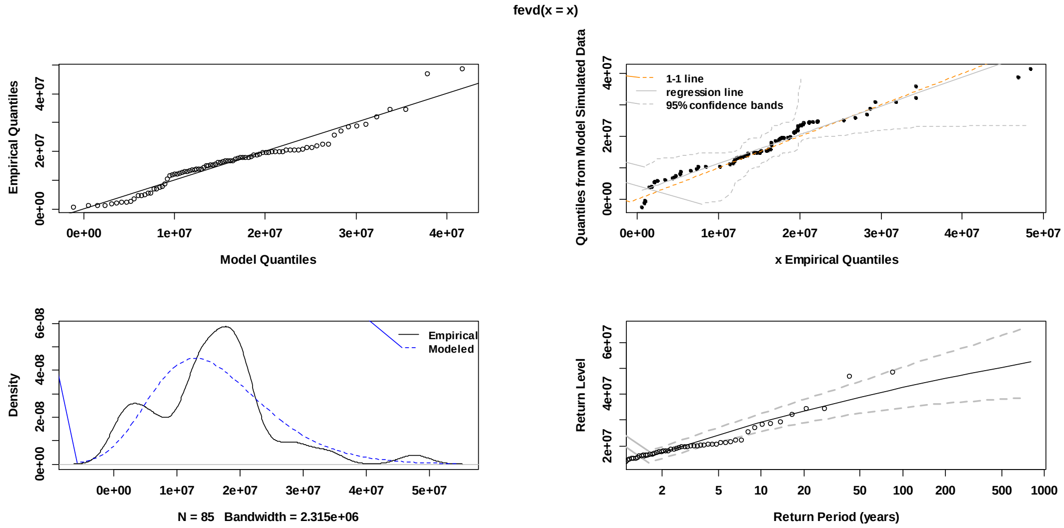
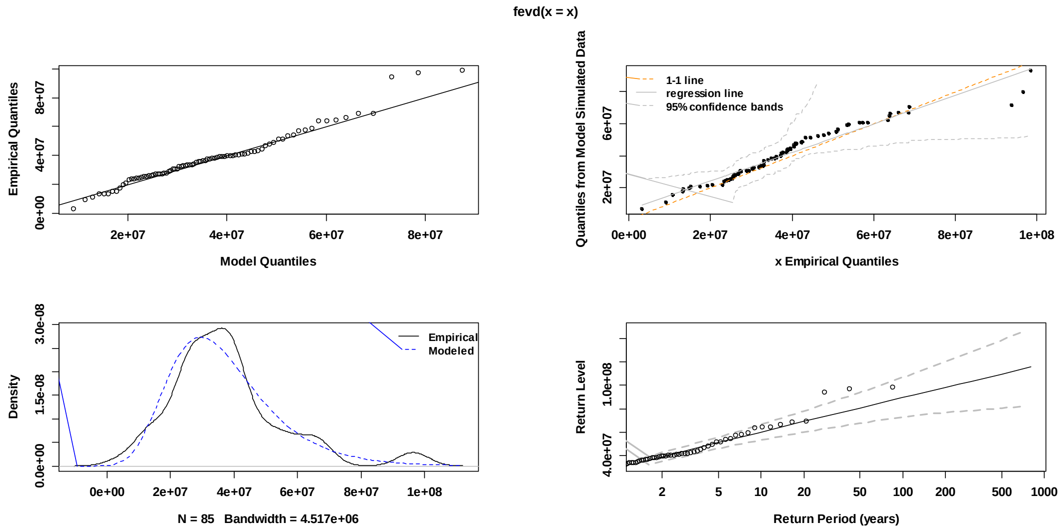
Complementary Material: Section 4-A

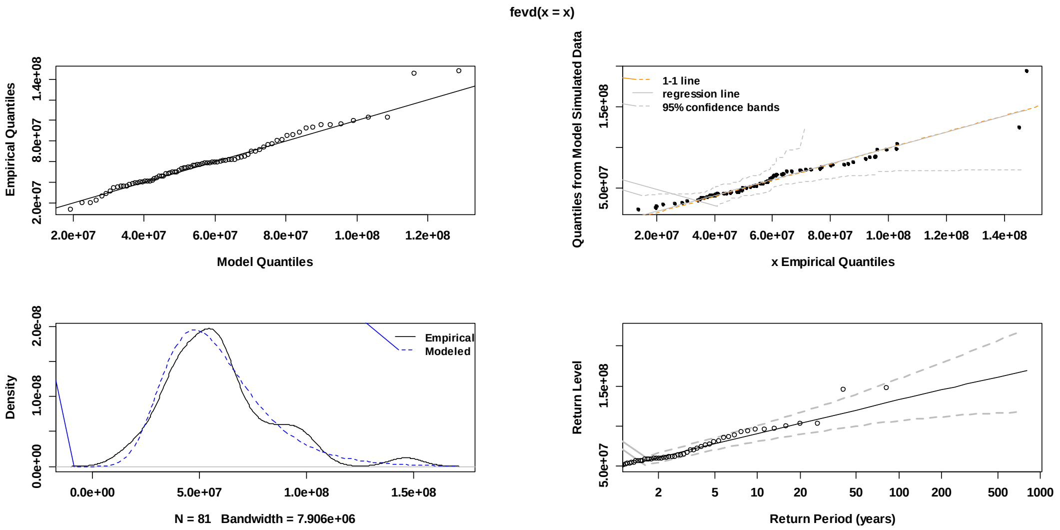
Fit diagnostic plot of Generalized Extreme Value (GEV) distribution under stationary demand (SD) assumption.



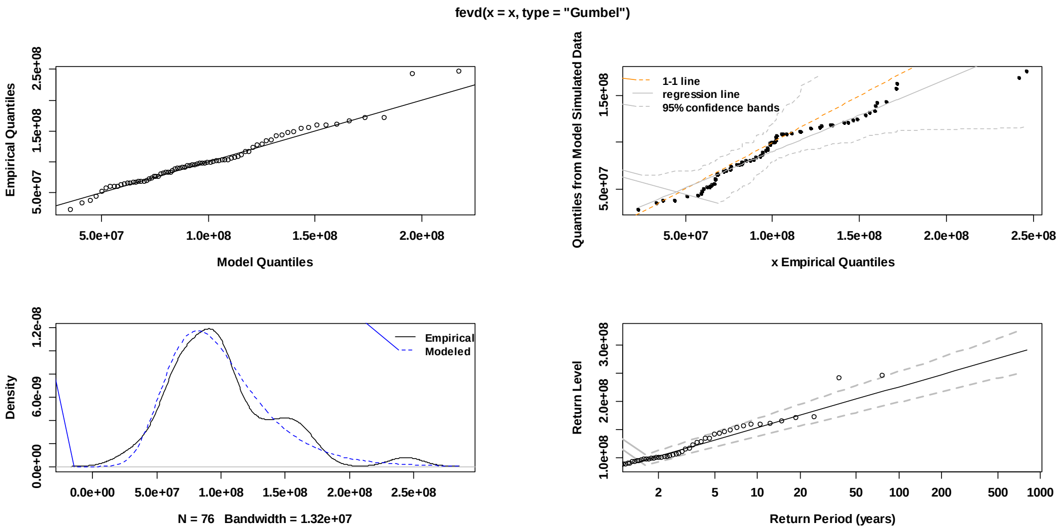
Diagnostic plots for stationary GEV model (Drought duration - 30 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1480.526; Location parameter (μ): 1.213687×10^7; Scale parameter (σ): 8.207381×10^6 and Shape parameter (ξ): -9.747522×10^{-2}.



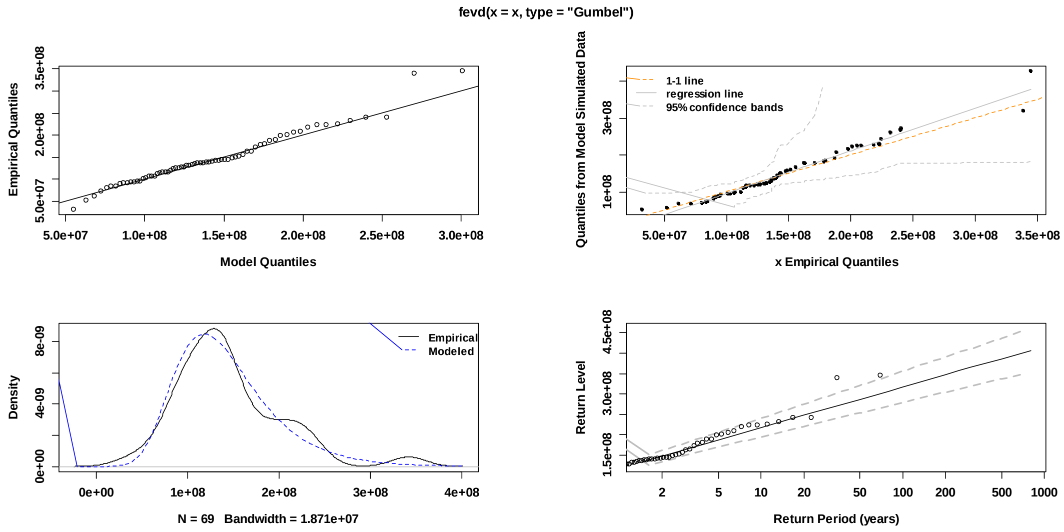
Diagnostic plots for stationary GEV model (Drought duration - 60 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1532.391; Location parameter (μ): 2.937720×10^7; Scale parameter (σ): 1.346090×10^7 and Shape parameter (ξ): -1.241951×10^{-2}.



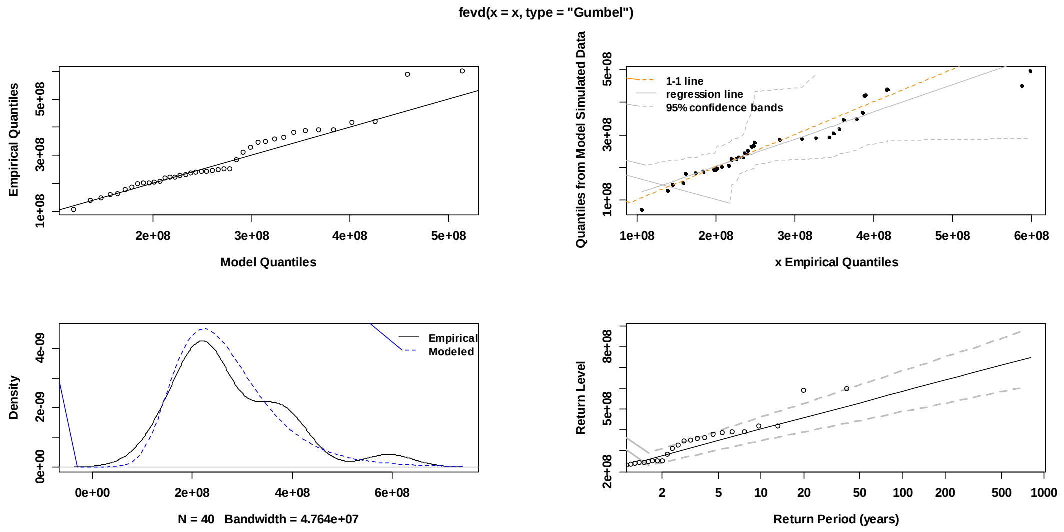
Diagnostic plots for stationary GEV model (Drought duration - 90 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1486.271; Location parameter (μ): 4.763000x10^7; Scale parameter (σ): 1.886958x10^7 and Shape parameter (ξ): -9.822971x10^{-3}.



Diagnostic plots for stationary GEV model (Drought duration - 150 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1433.856; Location parameter (μ): 8.1709645x10^7; Scale parameter (σ): 3.1328080x10^7 and Shape parameter (ξ): 0.

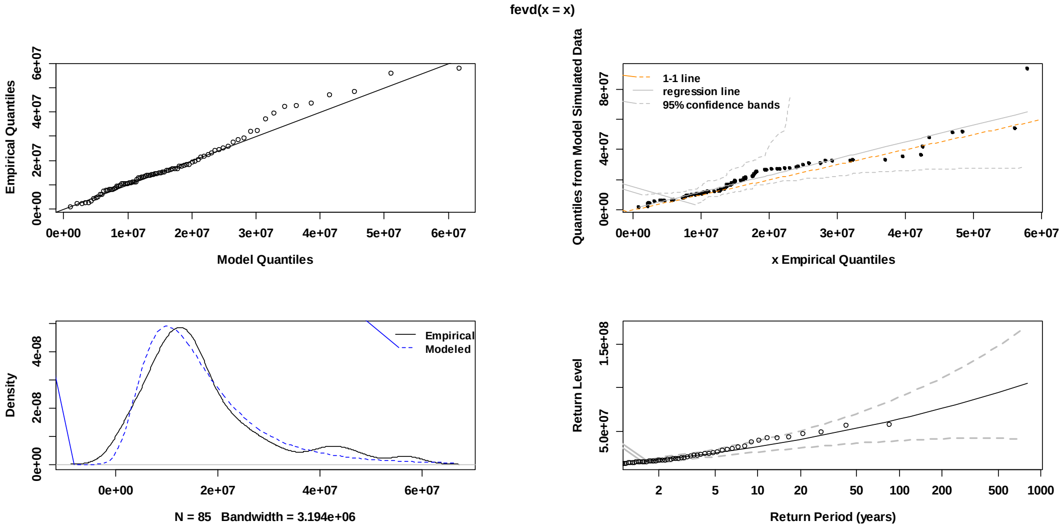


Diagnostic plots for stationary GEV model (Drought duration - 210 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1324.77; Location parameter (μ): 1.17815593×10^8; Scale parameter (σ): 4.3254889×10^6 and Shape parameter (ξ): 0.

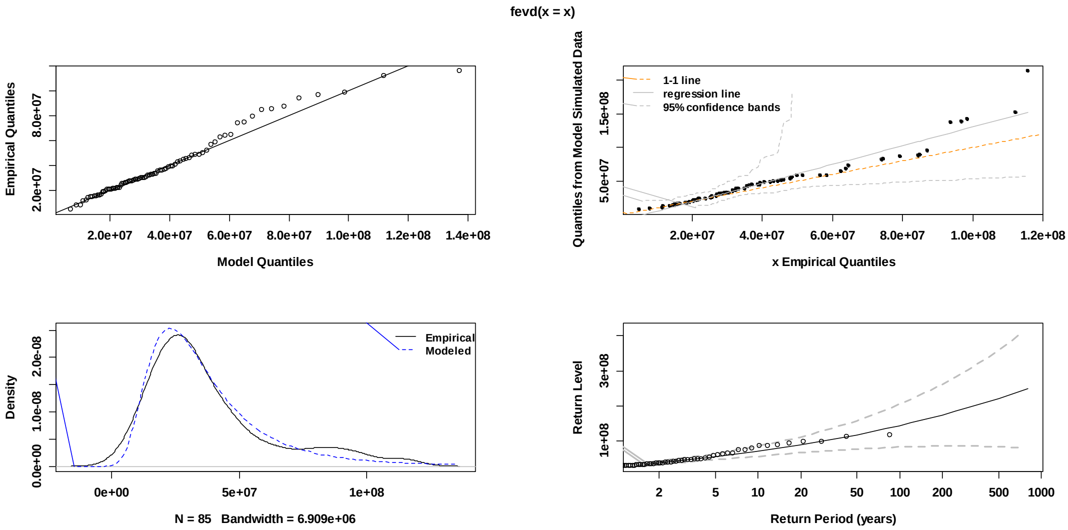


Diagnostic plots for stationary GEV model (Drought duration - 365 days - SD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 729.3155; Location parameter (μ): 2.23097007×10^8; Scale parameter (σ): 7.8784380×10^7 and Shape parameter (ξ): 0.

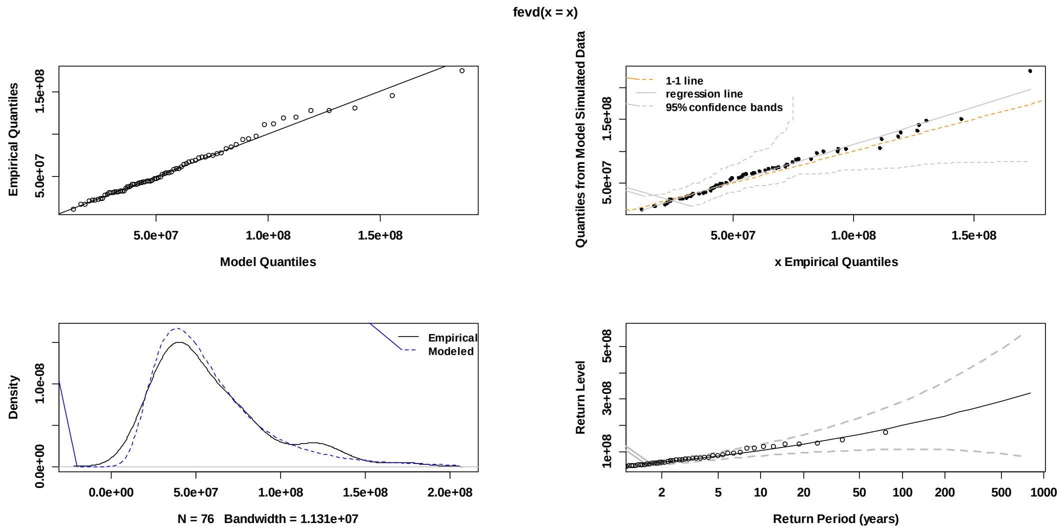
Fit diagnostic plot of Generalized Extreme Value (GEV) distribution under non-stationary demand (NSD) assumption.



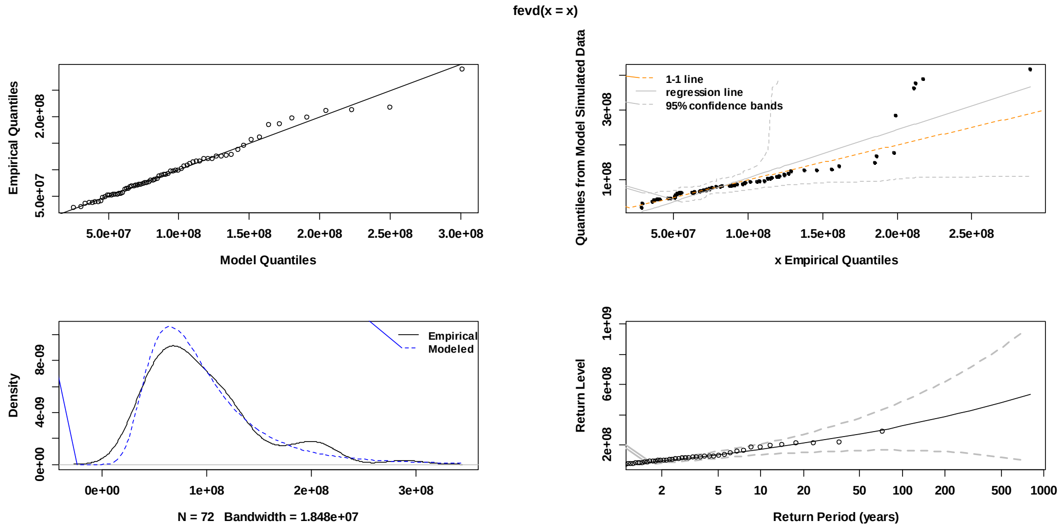
Diagnostic plots for stationary GEV model (Drought duration - 30 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1490.224; Location parameter (μ): 1.120252×10^7; Scale parameter (σ): 7.610827×10^6 and Shape parameter (ξ): 1.695044×10^{-1}.



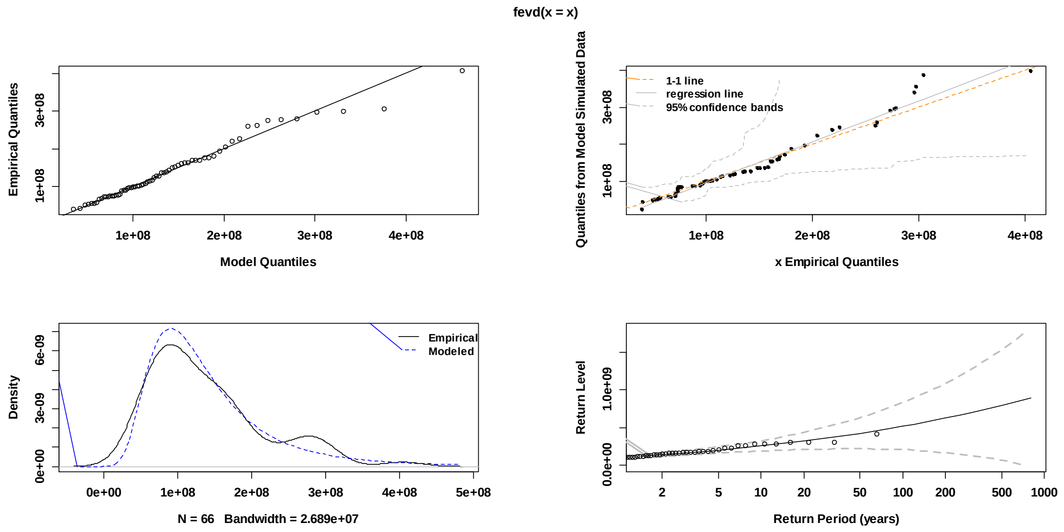
Diagnostic plots for stationary GEV model (Drought duration - 60 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1547.743; Location parameter (μ): 2.580426×10^7; Scale parameter (σ): 1.484396×10^7 and Shape parameter (ξ): 2.177838×10^{-1}.



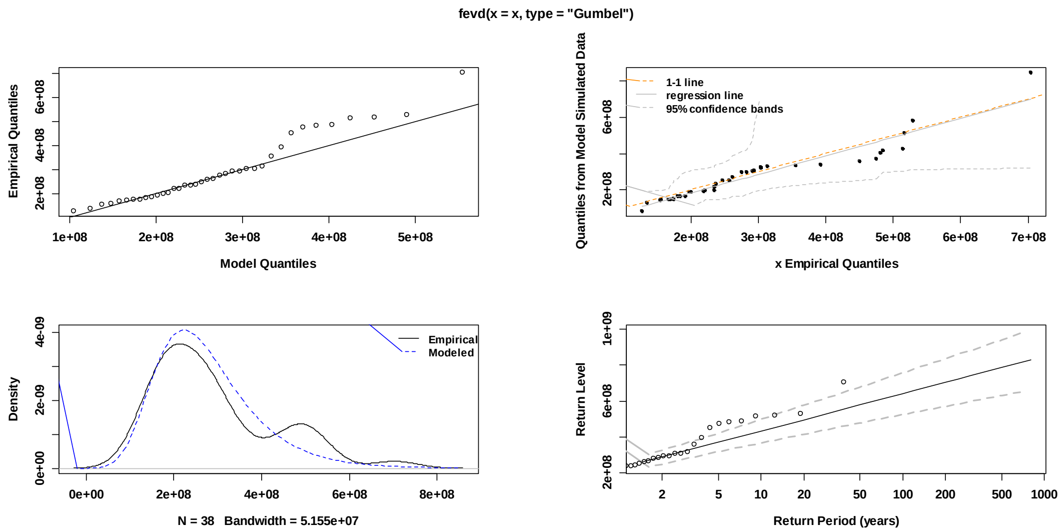
Diagnostic plots for stationary GEV model (Drought duration - 90 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1410.762; Location parameter (μ): 4.221907x10^7; Scale parameter (σ): 2.235388x10^7 and Shape parameter (ξ): 1.739300x10^{-1}.



Diagnostic plots for stationary GEV model (Drought duration - 150 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1368.805; Location parameter (μ): 7.070287x10^7; Scale parameter (σ): 3.519520x10^7 and Shape parameter (ξ): 1.858808x10^{-1}.



Diagnostic plots for stationary GEV model (Drought duration - 210 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 1280.815; Location parameter (μ): 1.002170x10^8; Scale parameter (σ): 5.247338x10^7 and Shape parameter (ξ): 2.201009x10^{-1}.



Diagnostic plots for stationary GEV model (Drought duration - 365 days - NSD): top left panel - top right panel: QQ-plots in [m^3]; bottom left panel: density plot in [m^3] and bottom right panel: return level plot in [m^3]. Negative Log-Likelihood Value: 759.825; Location parameter (μ): 2.23385171x10^8; Scale parameter (σ): 9.0668063x10^7 and Shape parameter (ξ): 0.

Complementary Material: Section 4-B

Empirical profit losses curves. Where “P_L” are the profit losses in 10^6xUS\$ and “D_d” the drought duration in days.

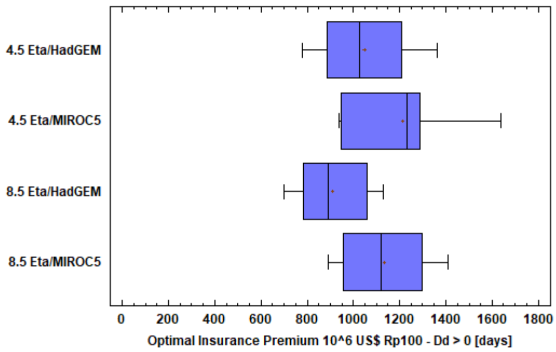
B1. Stationary Demand (31 m³/s)
R_p 100 - Industrial demand. $R^2 = 0.9993$
P_L (10^6xUS\$) = $-0.0013*D_d^2+4.9425*D_d-41.448$
R_p 100 - Household demand. $R^2 = 0.9965$
P_L (10^6xUS\$) = $0.0078*D_d^2+0.1739*D_d+55.283$
R_p 20 - Industrial demand. $R^2 = 0.9998$
P_L (10^6xUS\$) = $0.0027*D_d^2+4.1712*D_d+27.914$
R_p 20 - Household demand. $R^2 = 0.9990$
P_L (10^6xUS\$) = $0.0018*D_d^2-0.1885*D_d+6.312$
R_p 2 - Industrial demand. $R^2 = 1$
P_L (10^6xUS\$) = $0.0021*D_d^2+2.9049*D_d-23.631$
R_p 2 - Household demand.
P_L (10^6xUS\$) = 0

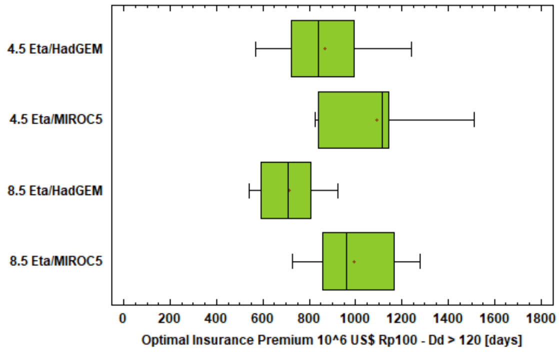
B2. Non-Stationary Demand (24 - 36 m³/s)
R_p 100 - Industrial demand. $R^2 = 0.9997$
P_L (10^6xUS\$) = $-0.001*D_d^2+4.147*D_d-29.852$
R_p 100 - Household demand. $R^2 = 0.9990$
P_L (10^6xUS\$) = $0.0129*D_d^2+2.1219*D_d+57.601$
R_p 20 - Industrial demand. $R^2 = 0.9992$
P_L (10^6xUS\$) = $-0.0009*D_d^2+5.2043*D_d-28.55$
R_p 20 - Household demand. $R^2 = 0.9977$
P_L (10^6xUS\$) = $0.0054*D_d^2-0.4064*D_d+22.025$
R_p 2 - Industrial demand. $R^2 = 0.9995$
P_L (10^6xUS\$) = $0.0047*D_d^2+1.9613*D_d+8.6416$
R_p 2 - Household demand.
P_L (10^6xUS\$) = 0

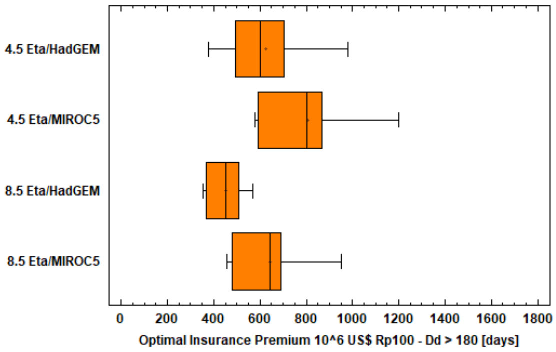
Complementary Material: Section 4-C

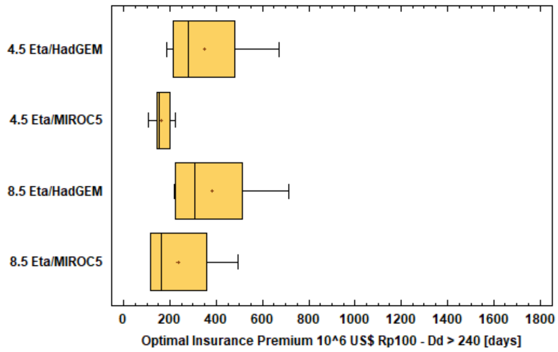
Average insurance risk premiums box plots per climate scenario under return period analysis.

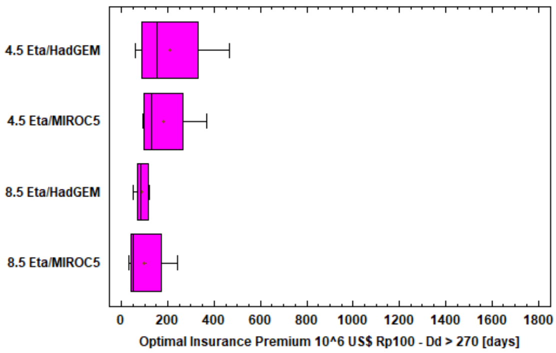
4-C.1 R_p 100 (years)

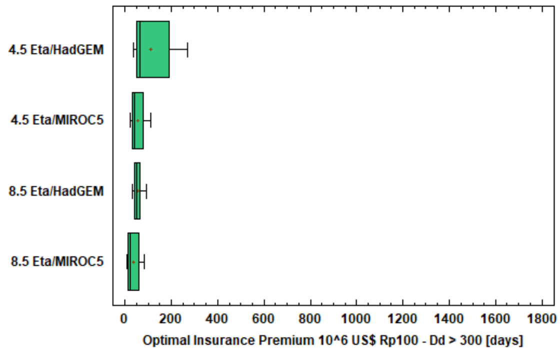




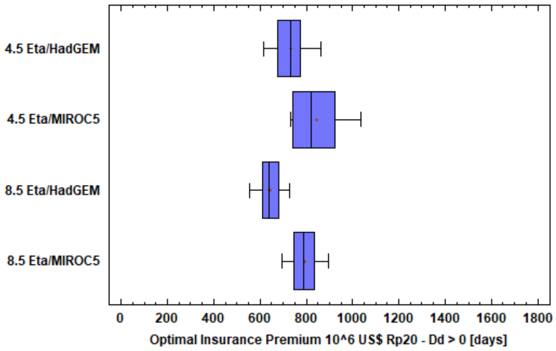


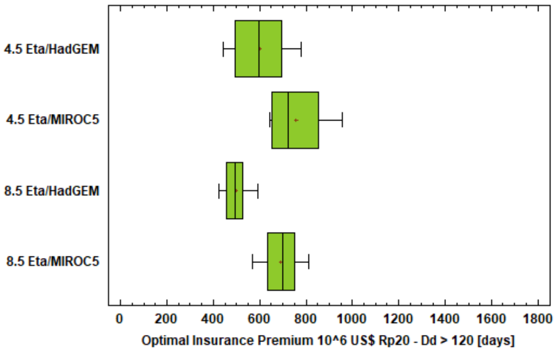


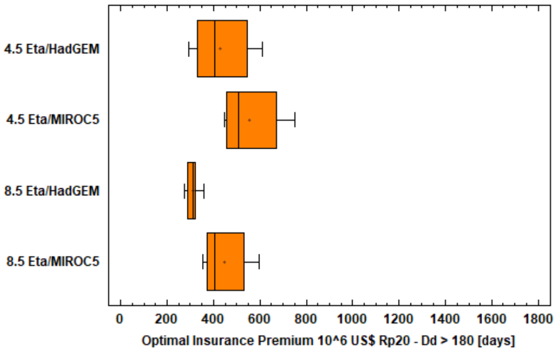


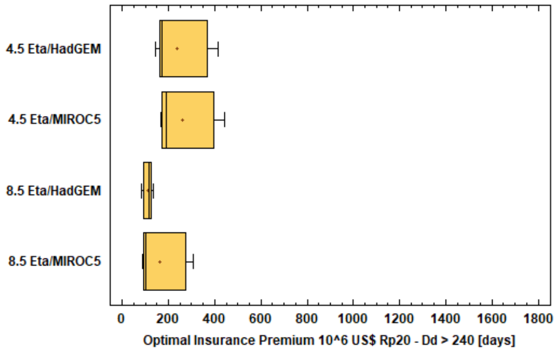


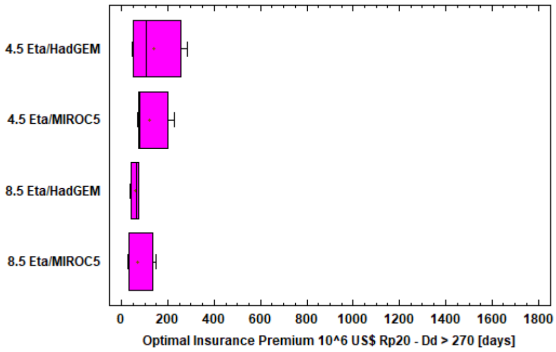
4-C.2 R_p 20 (years)

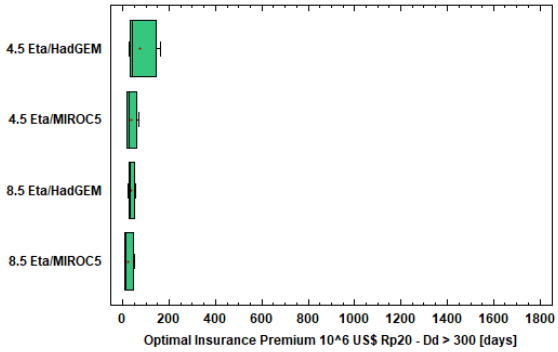




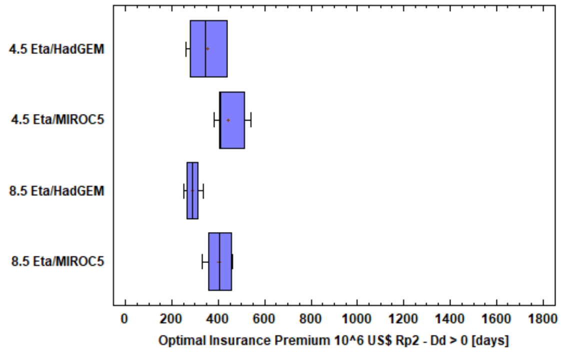


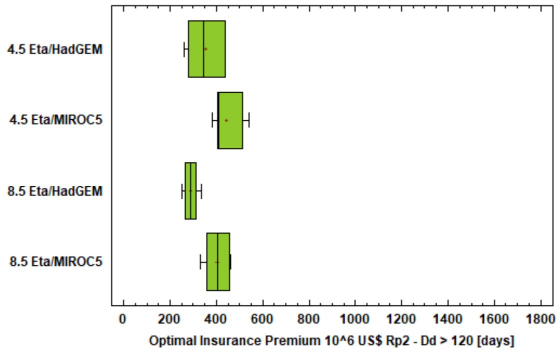


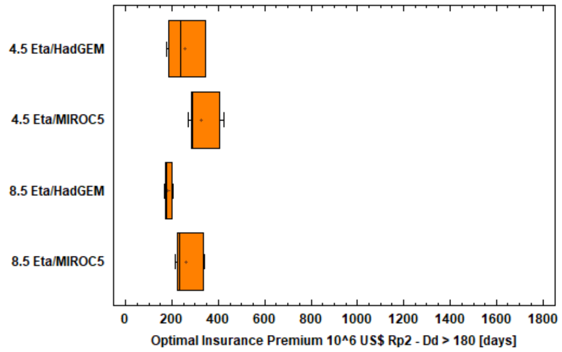


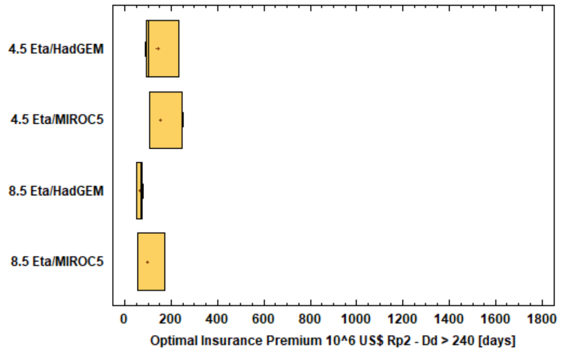


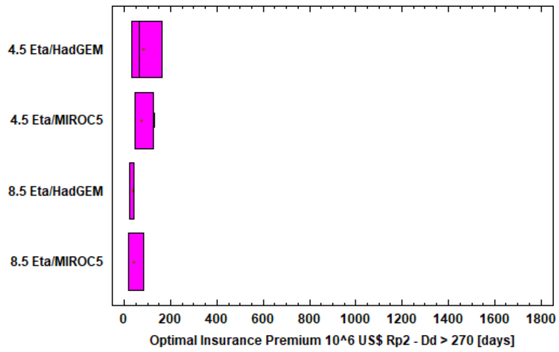
4-C.3 R_p 2 (years)

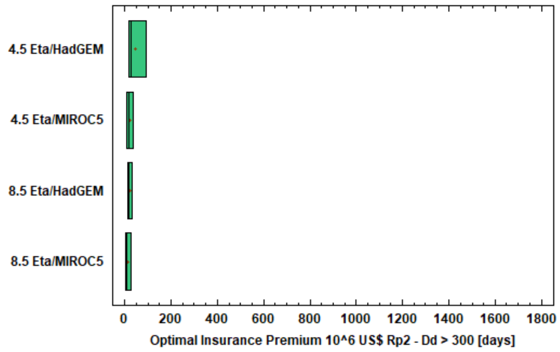












CHAPTER 5

GENERAL CONCLUSIONS

(i) To characterize the hydric deficit in the Cantareira system, based on the water offer and demand scenarios, generated from the regional circulation model (Eta-INPE) projections and historical databases;

This work comprised an application of an insurance fund model (MTRH-SHS) with synthetic discharge data series generated from the hydrologic model projections (WEAP) driven by the climate model projections Eta-HadGEM2-ES and Eta-MIROC5 under radiative forcing scenarios RCP 8.5 y 4.5, fitting series of water deficit for different drought durations by “GEV" extreme value distribution. The methodology was planned to reduce the drought economic impacts in the Sao Paulo water utility company. Hydrological modeling covered the Cantareira reservoir system, the main supplier to SPMR and significantly affected during the recent water crisis (2013-2015).

The SDF drought characterization framework in this thesis was compiled from two basic information sources. The first one (Chapter 3), based on the modeled discharge projections in WEAP, under the historical outputs period of Eta-HadGEM and Eta-MIROC5 model. The second one (Chapter 4), from the discharge data reconstruction for the water concession study ANA-DAEE 2004 (1930-2004) and complementary data (2005-2016). In both cases, water withdrawal scenarios were assumed, according to the SPRM historical withdrawal and the region population growth projections (IBEG).

(ii) Incorporate non-stationarity conditions in risk transfer model planning, based on the hydric deficit characterization;

First, in this thesis, a general review of the MTRH-SHS model and its most recent applications was made (Graciosa 2010, Laurentis 2012 and Mohor 2016). Regarding the review (Chapter 2), a MTRH-SHS overview was proposed (see appendix) and the scope of each application was established, configuring different versions of the model that have been progressively improved. On the one hand, with the joint work (Mohor & Mendiondo 2017; Guzman et al., 2017), the hydrological conception of the MTRH-SHS was gradually configured within the insurance sector scheme; e.g. terminology and concepts. On the other hand, in this version, which deals with hydrological drought, the financial balance equation was complemented with the deductible and the administrative fee insertion; a bonus discount option was included; the drought duration was considered and the optimization objective function was reconsidered.

Second, from the model general revision, the need to incorporate the temporal variable "duration" for droughts application was observed. Therefore, the SDF (severity-duration-frequency) analysis was implemented, under hypothesis of climate and demand drivers, to configure a non-stationary framework prior to the economic valuation of the damage.

Third, based on the stationary and non-stationary hypothesis of water supply and demand, on which the SDF framework was established, the deficit costs per m^3 were attributed from the duration of the drought and the consumption sector previously defined. Thus, under three drivers of change (climate-demand-economic) a non-stationary conditions analysis approach was introduced (see Chapters 3 and 4).

(iii) Propose and incorporate an insurance risk premium ambiguity measure under the MTRH-SHS approach.

The MTRH-SHS set of results should be understood as an average trend, and not as a prediction for a given period. Therefore, an insurance premium ambiguity measure was provided to help understand the model outputs (Chapter 4) through 43200 systematic modeling scenarios. Additionally, the provided ambiguity measure may be useful to help specify the pricing policies by insurers. Taking this into account, the model uncertainty reduction poses as a challenge for MTRH-SHS future approaches.

The methods for determining the cost of the damage must be improved and/or adapted, assuming that this process can add uncertainty to the insurance premium. Likewise, the disaggregation and distribution of risk within the calculation unit "the watershed", can be a strategy to reduce ambiguity and the premium adverse selection in the insurer´s case.

This PhD Thesis contributes with the specific objectives of INCT-MC-2’s Water Security Component (Marengo & Ambrizzi 2014): “10.2.4.4 Evaluation of adaptation strategies for water security of user sectors in non-stationary conditions.” and “10.2.5.3 Establishment of an adaptation strategy "climate-water-resilience" for sustainable development in Brazilian river basins.”

RECOMENDATIONS

To address the most frequent and major drought events that have been occurring in the SPRM, and to better manage the growing water demand that in recent years has highlighted the vulnerability of the supply sector, management measures will be needed, thinking about the near future. As part of the measures, the company needs to guarantee financial solvency during crisis periods, reaching goals of coverage and water security for the population. Therefore, risk transfer tools can be a key role in water management and financing of catastrophic risks considering future uncertainty.

The implementation of calculating the economic damage caused by drought under the ex-ante approach and the systematic analysis of probable climate scenarios make the MTRH-SHS a potential tool to help reduce moral hazards and adverse selection when designing insurance schemes. However, we are aware of the need to explore other model configurations (multi-hazard approaches, larger MYI contracts, and exercises with different deductible values), as well as more accurate damage cost estimates, among others.

Finally, the following items are considered for future developments under the MTRH-SHS scheme, especially to extend its reach to other watersheds:

- Despite the successful use of the generalized extreme values function (GEV) in similar applications (drought characterization), it may not be the best model for data fitting. Hence, future research should be encouraged to find the best probability function;
- Although it was not explored in this thesis, the frequency analysis of trends and shifts in input datasets should be considered; since the risk assessment may be sensitive to these factors (Salas & Obeysekera 2014);
- Other optimization techniques and objective functions could be tried, as well as the implementation of the model within other programming languages. This could provide more options for this topic;
- As mentioned in the document, it is essential to improve the estimate of damage costs; first to promote transferability and second to reduce uncertainty (Meyer 2013);

Literature cited

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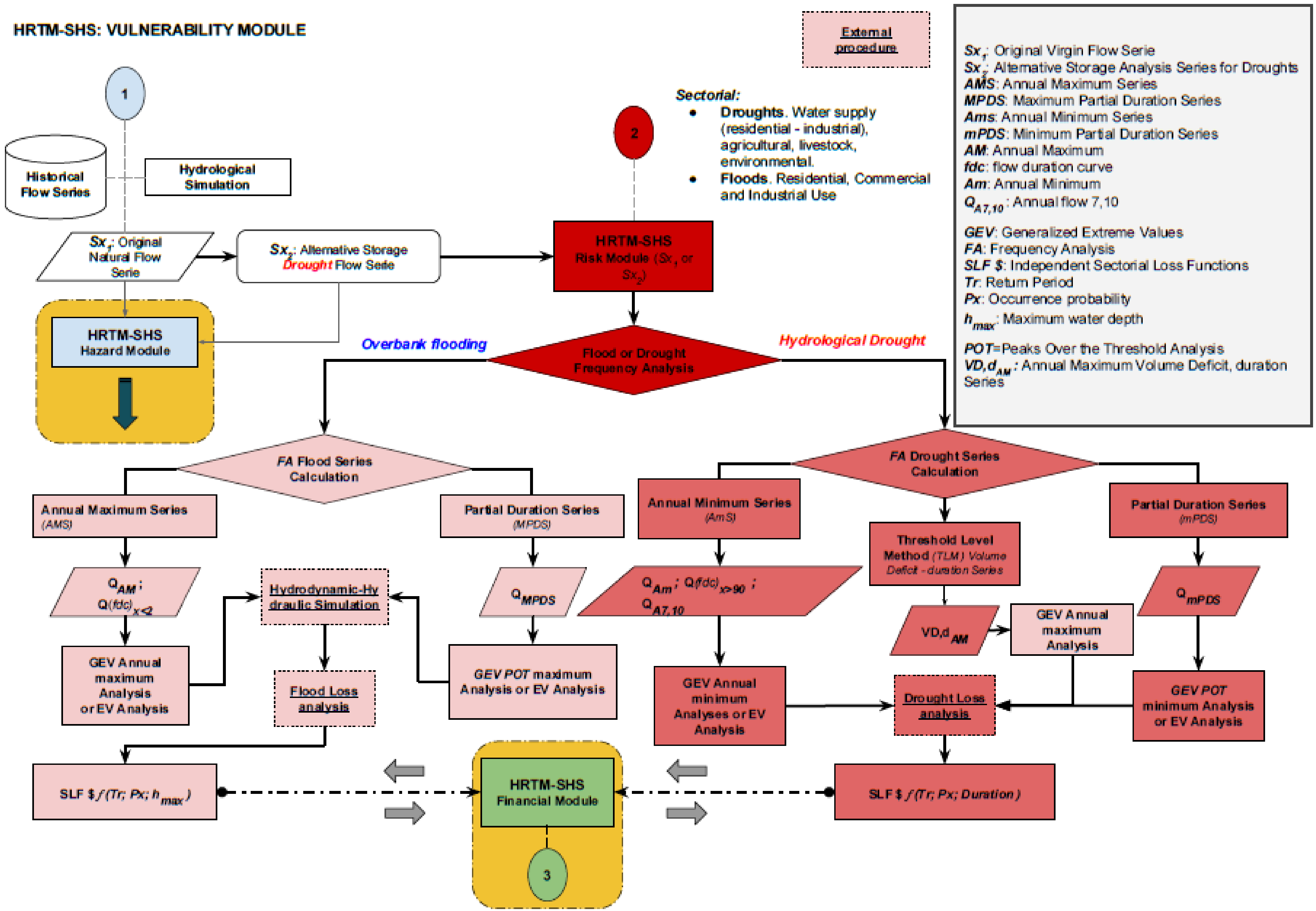
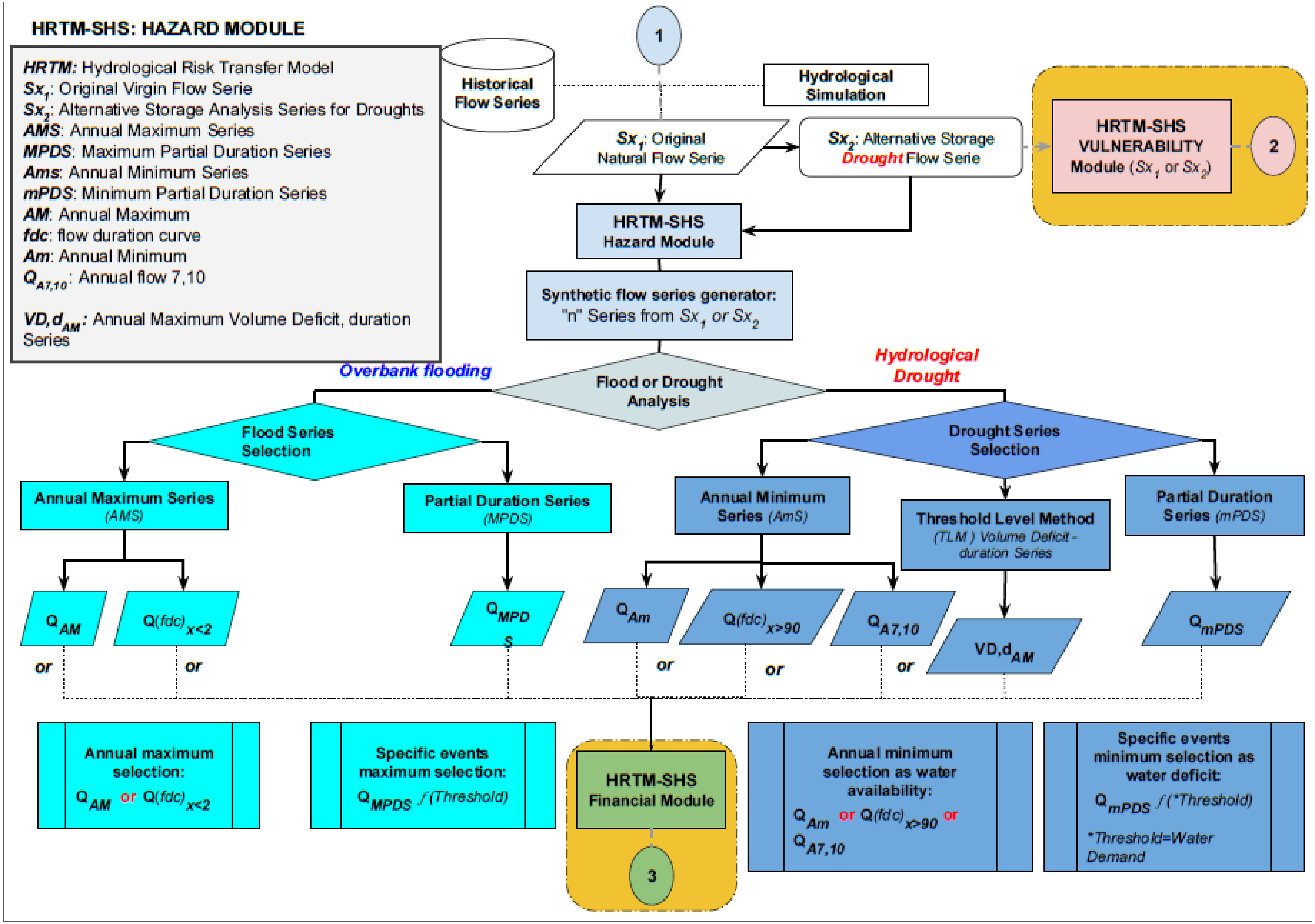
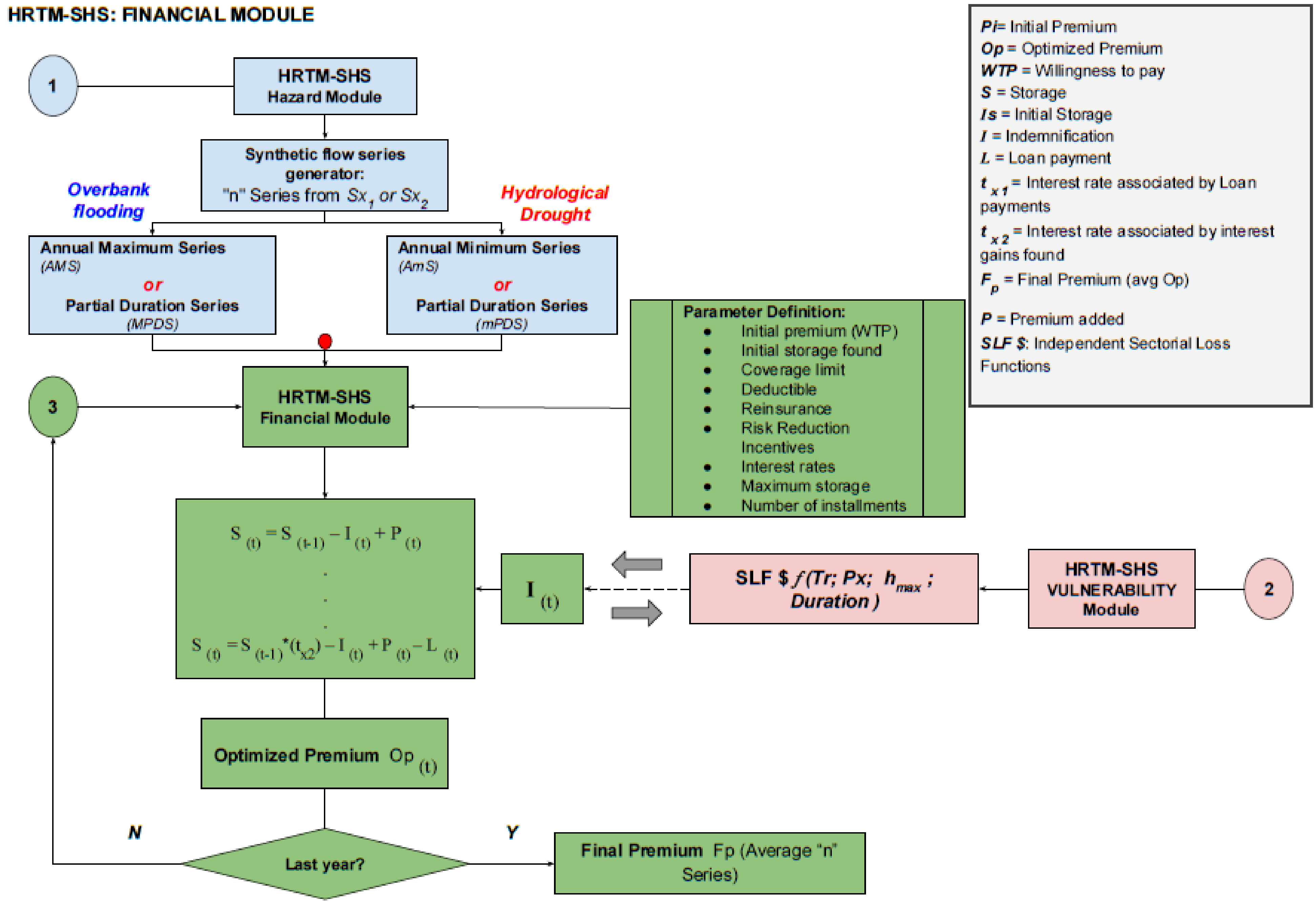
APPENDIX


HRTM-SHS: VULNERABILITY MODULE
External procedure
1
Historical Flow Series
Hydrological Simulation
Sx1: Original Natural Flow Serie
Sx2: Alternative Storage Drought Flow Serie
HRTM-SHS Hazard Module
2
HRTM-SHS Risk Module (Sx1 or Sx2)
Sectorial:
Droughts. Water supply (residential - industrial), agricultural, livestock, environmental.
Floods. Residential, Commercial and Industrial Use
Overbank flooding
Flood or Drought Frequency Analysis
Hydrological Drought
FA Flood Series Calculation
Annual Maximum Series (AMS)
Partial Duration Series (MPDS)
QAM; Q(fdc)x<2
Hydrodynamic-Hydraulic Simulation
QMPDS
GEV Annual maximum Analysis or EV Analysis
Flood Loss analysis
GEV POT maximum Analysis or EV Analysis
SLF $ f(Tr; Px; hmax)
HRTM-SHS Financial Module
3
FA Drought Series Calculation
Annual Minimum Series (AmS)
Threshold Level Method (TLM) Volume Deficit - duration Series
Partial Duration Series (mPDS)
QAm; Q(fdc)x>90; QA7,10
VD,dAM
GEV Annual maximum Analysis
QmPDS
GEV Annual minimum Analyses or EV Analysis
Drought Loss analysis
GEV POT minimum Analysis or EV Analysis
SLF $ f(Tr; Px; Duration)
Sx1: Original Virgin Flow Serie
Sx2: Alternative Storage Analysis Series for Droughts
AMS: Annual Maximum Series
MPDS: Maximum Partial Duration Series
Ams: Annual Minimum Series
mPDS: Minimum Partial Duration Series
AM: Annual Maximum
fdc: flow duration curve
Am: Annual Minimum
QA7,10: Annual flow 7,10
GEV: Generalized Extreme Values
FA: Frequency Analysis
SLF $: Independent Sectorial Loss Functions
Tr: Return Period
Px: Occurrence probability
hmax: Maximum water depth
POT=Peaks Over the Threshold Analysis
VD,dAM: Annual Maximum Volume Deficit, duration Series



HRTM-SHS: HAZARD MODULE
HRTM: Hydrological Risk Transfer Model
Sx1: Original Virgin Flow Serie
Sx2: Alternative Storage Analysis Series for Droughts
AMS: Annual Maximum Series
MPDS: Maximum Partial Duration Series
Ams: Annual Minimum Series
mPDS: Minimum Partial Duration Series
AM: Annual Maximum
fdc: flow duration curve
Am: Annual Minimum
QA7,10: Annual flow 7,10
VD,dAM: Annual Maximum Volume Deficit, duration Series
Historical Flow Series
1
Hydrological Simulation
Sx1: Original Natural Flow Serie
Sx2: Alternative Storage Drought Flow Serie
HRTM-SHS VULNERABILITY Module (Sx1 or Sx2)
2
HRTM-SHS Hazard Module
Synthetic flow series generator: "n" Series from Sx1 or Sx2
Overbank flooding
Flood or Drought Analysis
Hydrological Drought
Flood Series Selection
Drought Series Selection
Annual Maximum Series (AMS)
Partial Duration Series (MPDS)
Annual Minimum Series (AmS)
Threshold Level Method (TLM) Volume Deficit - duration Series
Partial Duration Series (mPDS)
QAM
Q(fdc)x<2
QMPDS
QAm
Q(fdc)x>90
QA7,10
VD,dAM
QmPDS
or
Annual maximum selection: QAM or Q(fdc)x<2
Specific events maximum selection: QMPDS ƒ(Threshold)
HRTM-SHS Financial Module
3
Annual minimum selection as water availability: QAm or Q(fdc)x>90 or QA7,10
Specific events minimum selection as water deficit: QmPDS ƒ(*Threshold)
*Threshold=Water Demand


HRTM-SHS: FINANCIAL MODULE
1
HRTM-SHS Hazard Module
Synthetic flow series generator: "n" Series from Sx_1 or Sx_2
Overbank flooding
Hydrological Drought
Annual Maximum Series (AMS) or Partial Duration Series (MPDS)
Annual Minimum Series (AmS) or Partial Duration Series (mPDS)
3
HRTM-SHS Financial Module
Parameter Definition:
Initial premium (WTP)
Initial storage found
Coverage limit
Deductible
Reinsurance
Risk Reduction Incentives
Interest rates
Maximum storage
Number of installments
$S_{(t)} = S_{(t-1)} - I_{(t)} + P_{(t)}$
$S_{(t)} = S_{(t-1)}{}^{*}(t_{x2}) - I_{(t)} + P_{(t)} - L_{(t)}$
$I_{(t)}$
SLF \$ ƒ(Tr; Px; h_{max}; Duration)
HRTM-SHS VULNERABILITY Module
2
Optimized Premium $Op_{(t)}$
N
Y
Last year?
Final Premium Fp (Average "n" Series)
Pi= Initial Premium
Op = Optimized Premium
WTP = Willingness to pay
S = Storage
Is = Initial Storage
I = Indemnification
L = Loan payment
t_{x1} = Interest rate associated by Loan payments
t_{x2} = Interest rate associated by interest gains found
F_p = Final Premium (avg Op)
P = Premium added
SLF \$: Independent Sectorial Loss Functions