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Seguros Hídricos como Mecanismos de Adaptação às Mudanças do Clima para Otimizar a Outorga de Uso da Água

VERSÃO CORRIGIDA

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Orientador: Prof. Dr. Eduardo Mario Mendiondo

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DEDICATION

To all the scientists that aim a better society. More sustainable and harmonious.

To all persons that aim a better world. Happier and healthier.

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I thank my family and “side-family”, for all care, inspiration, example, and supportiveness.
I am every day under your wings.

I thank all my old friends for understanding my absence, and hope for even more, but still for all the encouragement.
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What is good shall last.

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See my epigraph…

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“Standing on the shoulder of giants”

ABSTRACT

Mohor, G. S. (2016). **Water Insurance as Climate Change Adaptation Tool for Optimization of Water Permits.** Master Thesis, São Carlos School of Engineering, University of São Paulo, São Carlos.

Recent prolonged droughts make the urgent need to revise the criteria for water use permits in Brazil, especially in basins under conflicts for water use. Mechanisms for water risks transfer are an important adaptation tool. However, in Brazil, there is no established methodology that adapts this technique to assist the water use permit instrument. Moreover, there is no water risk insurance methodology with uncertainty analysis that complements its effectiveness in reducing losses from extreme events. Hydrologic modelling is the basis for development of these tools, which carries uncertainties that must be considered in decision-making. The objectives of this project were: i) coupling climatic, hydrologic and water insurance models to evaluate the use permit decision-making; ii) analyse sensitivity of performance indicators of a water risk insurance model through the application of different hydrologic models driven by climate change projections. The methodology was applied in donor basins of the Cantareira Water Supply System, which supplies water to an important metropolitan region that showed itself vulnerable to hydrologic extremes in the last years. The MHD-INPE and SWAT hydrologic models were applied, driven by the Eta-HadGEM2-ES climate model projections to characterize the future hydrologic regime in the region and also to compare the structure, performances and gaps of the models. Structural differences are most likely the greater responsible for the results differences, though no result could be identified as “more certain”. With the hydrologic models outputs fitted the the Gumbel extreme values distribution, a proposed insurance fund simulator, MTRH-SHS, was run with 100 equiprobable scenarios of 50-year annual low-flow events to calculated an optimized premium capable of paying all indeminities of hydrologic drought. Besides the future hydrologic regimes, water demand scenarios were also tested. The optimized premiums were compared to the local GDP to assess the apparent affordability of the insurance, with some premium representing up to 0.54% of local GDP, but in the water resources management framework, the decision should be made collectively by several actors within the basin’s committee.

Keywords: Water Resources Management, Water Security, Hydrologic Insurance, Water use permit, Climate Change Adaptation

RESUMO

Mohor, G. S. (2016). **Seguros Hídricos como Mecanismos de Adaptação às Mudanças do Clima para Otimizar a Outorga de Uso da Água.** Dissertação de Mestrado, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos.

Recentes estiagens fazem reconsiderar a necessidade de aperfeiçoar critérios de outorga de água no Brasil, especialmente em bacias com conflitos pelo uso da água. Seguros (transferência de risco) são importante ferramenta de adaptação. Contudo, no Brasil ainda não há metodologia consolidada que adapte esta técnica para auxiliar o instrumento de outorga de recursos hídricos. Ainda, não há metodologia de seguros hídricos com análise de incertezas, complementando sua efetividade ao reduzir os prejuízos advindos de eventos extremos. Modelos hidrológicos são a base de desenvolvimento destas ferramentas e carregam incertezas que devem ser integralizadas nos processos de decisão. Os objetivos deste projeto foram: i) acoplar modelos: climático, hidrológico e de seguros hídricos para a avaliação do processo de decisão de outorga; ii) realizar análise de sensibilidade dos indicadores de desempenho de modelo de seguros hídricos com diferentes modelos hidrológicos sob cenários de mudanças do clima. A metodologia foi aplicada nas bacias doadoras do Sistema Cantareira, que abastece importante região metropolitana e mostrou-se vulnerável a extremos hidrológicos nos últimos anos. Os modelos hidrológicos MHD-INPE e SWAT foram aplicados, forçados pelas projeções climáticas do modelo Eta-HadGEM2-ES a fim de caracterizar o regime hidrológico future na região, assim como comparar a estrutura, diferenças e performances dos modelos hidrológicos. As diferenças estruturais são provavelmente as maiores responsáveis pela diferença nos resultados, embora não seja possível apontar um modelo “melhor” que o outro. As saídas dos modelos foram ajustadas na distribuição de Gumbel e utilizada no modelo proposto de simulação de fundo de seguros, MTRH-SHS, rodado com 100 séries equiprováveis de 50 anos de eventos mínimos anuais. A cada série um prêmio otimizado é calculado para cobrir todas as indenizações de seca hidrológica. Além das projeções hidrológicas, cenários de demanda foram testados. Os prêmios otimizados foram comparados com o PIB local para demonstrar a viabilidade em implementar o seguro. Os valores representam até 0.54% do PIB local em um dos casos, mas na gestão de recursos hídricos, a decisão final pela implementação deve ser feita no âmbito do comitê de bacias por múltiplos atores.

Palavras-chave: Gerenciamento de recursos hídricos, Segurança hídrica, Seguros hídricos, Outorga de uso de água, Adaptação a mudanças climáticas.

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LIST OF ABBREVIATIONS

ANA	National Water Agency / Agência Nacional de Águas
BOD	Biological Oxygen Demand
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
CWSS	Cantareira Water Supply System
DAEE	São Paulo state Water and Electricity Department / Departamento de Águas e Energia Elétrica
DEM	Digital Elevation Model
FDC	Flow Duration Curve
GCM	Global Climate Model
GDP	Gross Domestic Product
HRU	Hydrologic Response Units
IAHS	International Association of Hydrologic Sciences
IGAM	Minas Gerais Water Management Institute / Instituto Mineiro de Águas
INMET	National Institute of Meteorology / Instituto Nacional de Meteorologia
INPE	National Institute for Space Research / Institute Nacional de Pesquisas Espaciais
LAI	Leaf Area Index
LULC	Land Use – Land Cover
MHD	Distributed Hydrologic Model / Modelo Hidrológico Distribuído
MTRH	Water Risk Transfer Model / Modelo de Transferência de Riscos Hídricos
NLCD	National Land Cover Database
NSE	Nash-Sutcliffe Efficiency index
PET	Potential Evapotranspiration
PNRH	National Water Resources Policy / Política Nacional de Recursos Hídricos
RCP	Representative Concentration Pathway
RCM	Regional Climate Model
SCE	Shuffled Complex Evolution
SPMR	Sao Paulo Metropolitan Region / Região Metropolitana de São Paulo
SSiB	Simplified Simple Biosphere model

SUFI-2	Sequential Uncertainty Fitting
SRI	Standardized Runoff Index
SWAT	Soil & Water Assessment Tool
SWAT-CUP	Calibration and Uncertainty Programs
UNEP FI	United Nations Environment Programme Finance Initiative
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
WHO	World Health Organization

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1 GENERAL INTRODUCTION

Recent prolonged droughts in Northeast Brazil since 2010 (Gutiérrez, Engle, De Nys, Molejón, & Martins, 2014; Santos, Matos, Alvarenga, & Sales, 2012) and Southeast Brazil since 2013 (Coutinho, Kraenkel, & Prado, 2015) made evident the need to improve water resources management mechanisms in Brazil, especially in basins with water transfer structures. The Brazilian National Water Agency (ANA), created in 2000, have indicated that the projected water offer/demand relationship in 55% of Brazilian cities would be in deficit in 2015 (National Water Agency, 2010), a situation confirmed in the Sao Paulo Metropolitan Region (SPMR) in a drought period (Escobar, 2015).

Water availability is affected by the climate variability (Marengo, 2008; Nóbrega, Collischonn, Tucci, & Paz, 2011), as well as water transfer operations, which, despite aiming water security, leads to impacts that might be intensified by land use changes (Bravo, Collischonn, da Paz, Allasia, & Domecq, 2013; Laurentis, 2012). Such alterations in the river regimes also affect the biota, the hydropower generation, and increases the risk of droughts or floods (Poff et al., 2010). In this work, we refer to drought generally as the diminution of water in terrestrial compartments as channels, the soil or reservoirs, i.e., hydrologic drought, and specifically to a period of low streamflow when water supply, for different user sectors, is affected, also configuring a socioeconomic drought (Mishra & Singh, 2011; Wilhite, 2000).

Several developments of climate change adaptation in the context of water resources are connected to hydrologic modelling, each one with its peculiarities. Nevertheless, the variability among models and how it affects adaptation strategies are not fully explored, but there are mainly individual experiments with different finalities and specific hydrologic model types (Vansteenkiste et al., 2013).

Wilhite et al. (2014) highlight the gap between the usual "crisis management" opposed to the "risk management", that is, mitigation actions, preparation and prediction, which consequently improve the post-event action. In Brazil, the "crisis management" still reigns (Gutiérrez et al., 2014), as well as an apparent preference for conventional engineering works (Tucci, 2008), whilst Wilhite et al. (2014) reinforces the importance of institutional frameworks for planning and fight against extreme events.

Water risks can be managed by introducing structural (e.g. the construction of dams) and non-structural measures (e.g. the installation of flood warning systems), including the transfer of third party risks through insurance (Dawson et al., 2011; Mendiondo, 2005, 2010). Insurance against water risks is ancillary to the development of a locality. Such insurance provides effective and useful studies of the threats, vulnerabilities, and risks of natural events while enabling policyholders and the government to take risks (Sanders, Shaw, MacKay, Galy, & Foote, 2005; UNEP FI, 2007). It also provides advice and, in the event of damage, can rehabilitate the insured individuals financially. The implementation of insurance against water scarcity offers more than recovering the economic condition of the affected in a watershed (e.g. home users, industries, agriculture, livestock) in order to ensure the economic sustainability of individuals (Hazell & Hess, 2010; Kost, Läderach, Fisher, Cook, & Gómez, 2012). Its implementation affects the sustainability of the water resource itself, as it promotes good water management (Pérez-Blanco & Gómez, 2014). In some countries, insurer agencies even share the obligation to reduce risk by adopting housing standards, encouraging land use planning, providing lines of investment for lower-risk cultures, and managing the post-event recovery (Clemo, 2008; Crichton, 2008; Ward, Herweijer, Patmore, & Muir-Wood, 2008).

The objective of this Master Thesis is to apply an insurance fund simulation model driven by streamflow data from two hydrologic models to show some of the gaps in such procedure and reinforce the products the insurance model generates and how they can help risk management, regarding droughts.

This Master Thesis is organized in three chapters besides this general introduction. The **second chapter** presents the application of two hydrologic models driven by climate projections and a comparison of their results along with the similarities and differences between the two models that can increase or reduce uncertainty in applied experiments. A distributed (MHD-INPE; Rodriguez & Tomasella, 2015) and a semi-distributed (SWAT; Arnold, Srinivasan, Muttiah, & Williams, 1998) hydrologic models were applied in the drainage areas of the donor reservoirs of the Cantareira Water Supply System (CWSS), driven by Eta-HadGEM2-ES (Chou et al., 2014b) climate projections from until the end of the century (2099). Focused on low-flow situations, several indices were calculated, including the low-flow segment volume of the flow duration curve (FDC), the slope of the FDC medium range, and seasonality proposed by Ley, Casper, Hellebrand, & Merz (2011), plus the Q90, Base Flow Index (Smakhtin, 2001) and the Standardized Runoff Index (Farahmand & AghaKouchak, 2015) of 6 months (SRI-6). The indices, calculated with each hydrologic model output, were compared, showing that MHD-INPE has more heterogeneity among sub-basins, whilst SWAT has simulated a more homogeneous basin. These differences are likely due to the structure of the models since SWAT delineates each sub-basin by its geographic contour as a single watershed and MHD-INPE divides the whole basin into regular cells, which were user-defined to be smaller than the SWAT subbasins. The scarcity of data within the studied area hinders such developments, increasing uncertainty for decision-making.

The **third chapter** presents an insurance fund simulator, MTRH-SHS, its implementation and results, driven by the hydrologic models' outputs and water demand scenarios as complementary criteria for water use permits. Because the Brazilian insurance market, as in other developing countries, has low penetration and diversified portfolio, there is also a lack of data and experience in insurance developments in the water science community. The MTRH-SHS simulates 'n' equiprobable scenarios of 50-year annual low-flow events based on the outputs of the hydrologic models (chapter two), and optimizes the premium to be paid by all the users to cover all damages up to a 100-year return period event. The exercise had some simplifications: in the varied demand scenarios, the ratio of water demand among sectors was kept constant; the currency value was not corrected in the future; and the added value of production was kept constant. The optimized premiums were compared to the local GDP of the subbasins, representing up to 0.54% of local GDP in one case. The absolute and relative results should be considered in decision-making and could be explored not only as a water resource management instrument complimentary to the existent water use permit and charge, but for educational purposes, raising awareness and fostering risk reduction.

Finally, a **general conclusion** summarizes the lessons from all stages of this research, along with suggestions for future improvements in similar experiments. Though not tested nor proved, the outcomes of this research showed light to some alternative paths for water resources management strategies, such as lowering the water use permit lifetime or bundling the proposed insurance premium into the water use charge.

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2 ASSESSMENT OF UNCERTAINTIES IN AN APPLICATION OF HYDROLOGIC MODELS FOR LOW-FLOW RISK MANAGEMENT UNDER CLIMATE CHANGE CONDITIONS *

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ABSTRACT

The application of hydrologic models driven by a number of climate projections is standard in many applications regarding water resources management as a way to explore the uncertainties involved. However, the uncertainties regarding the hydrologic models' structure deserve a similar approach, which is not usually followed. In this chapter, we present and compare the structure and application of two hydrologic models in the same watershed, and assess the gaps between the impacts they project in hydrologic regime, especially in the low-flow segment. SWAT-TAMU (semi-distributed) and MHD-INPE (distributed) hydrologic models were applied driven by the regional climate model (RCM) Eta-HadGEM2-ES outputs under the RCP4.5 scenario, in the drainage watersheds of the Cantareira Water Supply System. The impacts assessment was made through the comparison of the future periods to the historical run with the RCM data. Precipitation is considered the most important driver of streamflow in the basin, and the structure of the hydrologic models explain some difference in results. The impacts under climate projections differ between models in magnitude and even in signal of change in some cases, with MHD-INPE showing more negative changes in the indices explored. Precipitation is considered the most important driver of streamflow in the basin, and the structure of the hydrologic models explain some difference in results. The fully distributed nature of MHD-INPE resulted in a larger spread of results among sub-basins in comparison to SWAT. Before a large quantity of good data is available for improvements in the modelling, decision-makers are suggested to consider the application of different hydrologic models to incorporate the uncertainties implied, as this application has shown differences of much importance to management.

Keywords: Hydrologic modelling, SWAT, MHD-INPE, Brazil, Low flow, Climate change

2.1 INTRODUCTION

Societies are facing larger damages caused by climatic and hydrologic extreme events due to higher exposure or vulnerability of growing and denser settlements and wealth, besides the likely changes of magnitude and frequency of natural events. Developing countries, for lack of good data and preparedness, still face frequent and large damages.

The International Association of Hydrologic Sciences (IAHS) in the last decade (2003-2012) dedicated efforts to better understand and explain hydrologic systems, through theoretical and analytical approaches (Hrachowitz et al., 2013). Therefore, the aim was to carefully develop and apply numerical models as assistant tools, instead of using traditional empirical methods aiming to better understand isolated components. The current scientific decade proposed by IAHS focus on the science advance under the paradigm of hydrology-society interface (Montanari et al., 2013). Although current hydrologic models are not coupled with the social system in order to study the feedback between them, the offline introduction of scenarios and certain studies' finalities have the potential to foster such developments (Sivapalan, Savenije, & Blöschl, 2012).

Many hydrologic studies, such as those regarding the impacts of climate change are usually done through a chain of models, using climate projections as drivers for hydrologic models. Each step carries intrinsic constraints and uncertainties from parameterization and scale issues (Chen, Xu, & Guo, 2012; Cornelissen, Diekkrüger, & Giertz, 2013; Thompson, Green, Kingston, & Gosling, 2013; Vansteenkiste et al., 2013). The application of climate models outputs for hydrologic modelling studies, including droughts assessments, is highly suggested (Mishra & Singh, 2011), especially to provide a better understanding of decadal dynamics. The scientific findings of these coupled models can be greatly used for a diverse range of water management applications, as to advance the understanding of the water cycle, to design conservation plans, water use projects, and protection measures against extreme events (Singh & Woolhiser, 2002).

In hydro-climatic impact assessments, many studies indicate that the climate models are responsible for the largest uncertainty in the model chain (Bates, Kundzewicz, Wu, & Palutikof, 2008; Jones, 2000; Nóbrega et al., 2011; Vetter et al., 2015). Still, every component of the model chain should receive a thorough assessment in order to provide more reliable and robust results for its applications in water management. As Vetter et al. (2015) exemplified, evapotranspiration, for example, is one component calculated by the hydrologic model, so the more the basin is driven by this process, the more the hydrologic model contributes to the uncertainty. The same could be said for other processes as snowmelt, groundwater recharge, etc.

Comprehensive models usually require the performance of calibration and validation processes with a considerable number of parameters adjustment, which may even decrease the model's accurate representation of reality (Blöschl, Sivapalan, Wagener, Viglione, & Savenije, 2011; Christofoletti, 1999). Due to this trade-off, the choice of models to be applied is a singular task that must be accomplished by each user considering characteristics of the catchment, the objectives of the application, and the main drivers of streamflow (Kampf & Burges, 2007). Nonetheless, despite of the using of observed discharge series for calibration/validation, in many cases a transformation based on water level is used to estimate discharge, with a rating curve, therefore collecting field data to check these values in cases of interest is recommended (Blöschl, 2013; Taffarello et al., submitted). The spatiotemporal variability of hydrologic variables, such as precipitation, is very important in extreme events studies, either in low-flow or high-flow conditions (Mishra & Singh, 2011; Tomasella et al., 2011). Therefore the increased interest in applying distributed hydrologic models, or to evaluate how different spatial scales or structures may improve the watershed representation (Beven, 2006; Montanari et al., 2013).

Different from climate models, there are few studies comparing a number of hydrologic models outputs for the same region as a way of uncertainty (Cornelissen et al., 2013; Gosling, Taylor, Arnell, & Todd, 2011; Thompson et al., 2013; Vansteenkiste et al., 2013; Vetter et al., 2015). Vansteenkiste et al. (2013) have found similarities among the tested hydrologic models, however, mostly lumped and semi-distributed models were considered, while distributed models still deserve further comparison.

The objectives of this study are: (i) to compare the standard structure and configuration of two hydrologic models, a semi-distributed and a distributed one, applied in an important Brazilian river basin; (ii) to assess the models' performance in simulating a known period of observed data; and (iii) to evaluate the gap between the models' outputs when driven by climate projections, with focus on low flows indicators.

2.2 MATERIAL AND METHODS

2.2.1 Study case

The study area are the drainage watersheds of the Cantareira Water Supply System (CWSS), located within the Piracicaba River Basin, partially in Sao Paulo and Minas Gerais states, Southeast Brazil (Figure 2.1).

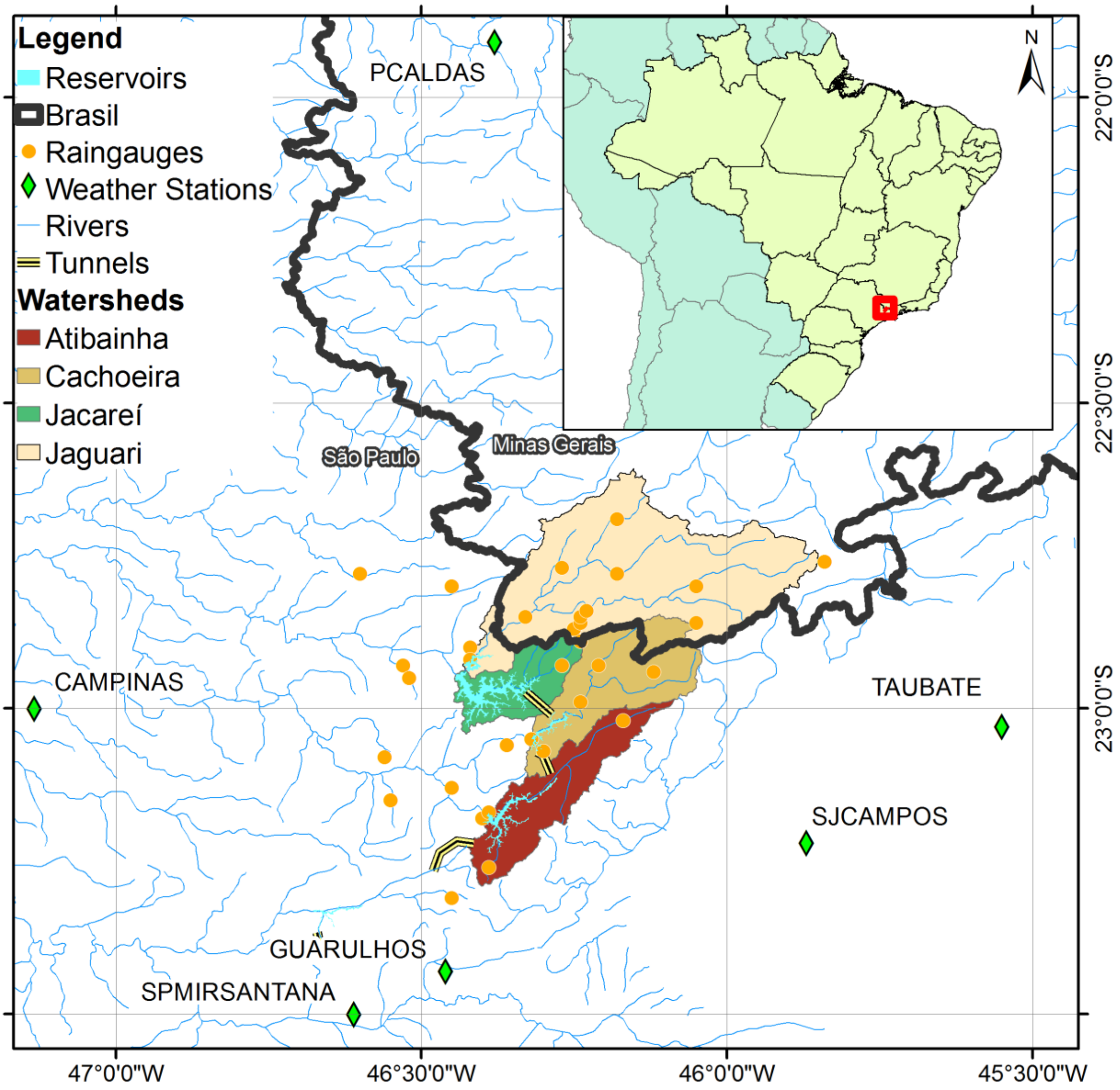

Figure 2.1. Location of study case – donor basins of Cantareira Water Supply System

The CWSS is composed by a set of reservoirs connected through channels and a tunnel to transfer water from the Piracicaba River Basin to the Upper Tietê River Basin. The CWSS supplies water to the Metropolitan Region of São Paulo, the biggest Brazilian metropolis, with around 20 million people (Escobar, 2015). Despite the existence of important reservoirs in the CWSS, this study focuses on the inflow of the reservoirs. The reservoirs were not themselves modelled because MHD-INPE, one of the models applied, doesn't have a numerical solution for reservoir operations, and our major interest lies in modelling the reservoirs' inflow.

The donor basins are in the Atlantic Forest Biome, one of the most biodiverse regions in the world, with mean annual rainfall of 1577 mm (1930 – 2004 precipitation data series). The perennial rivers have considerable seasonality, with wet summers (October - March) and dry winters (April - September).

The CWSS started its operation in 1974, with a first 30 years of use permit. Then it received extra 10 years of operation from 2004 to 2014 with a condition of conducting new hydrologic studies. In the last few years, the CWSS supplied water for about 8.8 million people in the SPMR, but a period of low precipitation started, observing 92% of long-term average precipitation (1577 mm) in 2012, 69% in 2013, 61% in 2014, and 105% in 2015 (SABESP, n.d.). In May 2014 it started the pumping of the "technical reserve", and now it supplies water for only 5.4 Million people (SABESP, 2015).

2.2.2 Hydrologic models structure comparison

The adopted hydrologic models have important differences, which may lead to substantial variations on the application and results. In this section, a structural comparison of the models' standard and optional configurations is made in the view of model users.

The Soil & Water Assessment Tool (SWAT) was developed by the US Agricultural Research Service and Texas A & M University. It is a semi-distributed conceptual model with more than 30 years of ongoing development. The model divides the watershed into subbasins, which are further divided into Hydrologic Response Units (HRUs) according to a combination of a soil type, land use type and slope class (Arnold, Srinivasan, Muttiah, & Williams, 1998; Gassman, Reyes, Green, & Arnold, 2007). Coded in FORTRAN, the model can also be run within an ArcGIS interface, named ArcSWAT, where its tools are used for basin delineation, HRU setting and database management (Krysanova & White, 2015; Winchell, Srinivasan, Di Luzio, & Arnold, 2013). The model has been applied worldwide and increasingly used in Brazil for several goals (Bressiani et al., 2015).

The Distributed Hydrologic Model (MHD-INPE) was developed at the Brazilian National Institute for Space Research (INPE). It is a semi-conceptual distributed model that represents the watershed in regular grid-cells. The model has been applied in several Brazilian large basins, such as Tapajós, Ji-Paraná, and Madeira, in the Amazon Basin (Mohor, Rodriguez, Tomasella, & Siqueira Júnior, 2015; Rodriguez & Tomasella, 2015; Siqueira Júnior, Tomasella, & Rodriguez, 2015). Each cell is comprised of a number of Hydrologic Response Units (HRUs) according to the combination of land use and soil type.

The models were chosen due to the basin’s physical characteristics. Both models integrate subsurface components and spatial distribution to account to some extent the differences in headwaters, the steeper hills, and the lower parts. The study case is a rainfall-driven basin with considerable vegetation and no presence of wide floodplains. Besides that, the access to auxiliary tools, help from experts, and the agreement between the required input data and available data led to the choice of these two models. The main attributes of each model are confronted in Table 2.1.

Table 2.1. Hydrologic Model's Characteristics and Standard Configuration

Feature	**SWAT**	**MHD-INPE**
Formulation (Kampf & Burges, 2007)	Parametric (physically based and empirical formulations)	Parametric (physically based and empirical formulations)
Spatial Discretization (Kampf & Burges, 2007)	Hillslope to catchment scale. Distributed integral (sub-basins)	Hillslope to catchment scale. Distributed differential (regular cells)
Default Soil Classification (Can Be Specified by The User)	Pedological classes, Default classes from US STATSGO Database (Winchell et al., 2013)	Textural classes, with hydrologic characteristics from pedotransfer functions (J Tomasella & Hodnett, 2004)
Default Land Cover / Vegetation Classes (Can Be Specified by The User)	Default classes from USGS LULC and NLCD (National Land Cover Database) (Winchell et al., 2013)	Default classes according to SSiB classification (Xue, Sellers, Kinter, & Shukla, 1991)
Meteorological Inputs	Air temperature; relative humidity; wind speed; and solar radiation for Priestley-Taylor or Penman-Monteith methods. Maximum and minimum air temperature for Hargreaves method.	Air temperature; dew point; wind speed; solar radiation; and atmospheric pressure
Time Step (Solution)	Daily* or sub-daily	Daily* or sub-daily
Rainfall Interception	Storage approach, function of LAI	Gash model (Gash et al., 1995)
Potential Evapotranspiration (PET)	Priestley-Taylor*; Penman-Monteith; Hargreaves; or user specified	Penman-Monteith
Actual Evapotranspiration	Calculated separately for evaporation and transpiration; reduction of PET by soil water content	Root water uptake based on Jarvis model (1989) + Calculated separately for evaporation and transpiration; reduction of PET by soil water content
Soil Module	Tipping bucket. Soil is divided into numerous layers	Soil is divided into 3 layers

* Adopted methodology, when more than one is possible. Source: (Arnold et al., 2012; Cornelissen et al., 2013; Rodriguez & Tomasella, 2015)

Table 2.1. (continued) Hydrologic Model's Characteristics and Standard Configuration

Feature	**SWAT**	**MHD-INPE**
Overland Flow	Modified SCS curve number* or Green & Ampt	Combination of the Xinanjiang model (Zhao 1992, Zhao & Liu 1995) and the Topmodel formulation (Beven & Kirkby 1979)
Infiltration	Modified SCS curve number* or Green & Ampt	Local topographic surface and a non-linear variation of transmissivity in depth (Beven & Kirkby 1979, Iorgulescu & Musy 1997)
Percolation	Storage routing; water content must be above field capacity	The same from above
Interflow (Lateral Flow)	Kinematic storage model	The same from above
Baseflow	Linear storage approach	The same from above
Routing	1-d flow. Variable Storage* or Muskingum-Cunge	1-d flow. Muskingum-Cunge (linear and non-linear)

* Adopted methodology, when more than one is possible. Source: (Arnold et al., 2012; Cornelissen et al., 2013; Rodriguez & Tomasella, 2015)

The application of SWAT in a watershed from the U.S.A. is much easier than in basins elsewhere when using ArcSWAT because it has a database within it for soil and land cover for that country. Brazilian soil and land cover maps are increasing in number, but there is still a difficulty in acquiring these data. Mainly global but not finer scale resolution sources of data are available for many watersheds.

SWAT has a number of formulation choices; thus, it should fit a range of hydrologic units, more than the single-formulated MHD-INPE. SWAT also has more components (e.g. plant growth, water quality), making it useful for a larger number of applications. On the other hand, MHD-INPE formulation is more modular, making it easier to apply and to modify, if desired.

2.2.3 Models set-up

In order to assess the uncertainties of climate change impacts associated with hydrologic modelling, we developed numerical experiments with both models, after calibration and validation procedures.

2.2.4 Data sets and processing

The observed meteorological data (temperature, relative humidity, wind speed, radiation, and pressure) were consulted from National Institute of Meteorology (National Institute of Meteorology, 2014) and Center for Weather Forecasting and Climate Research (CPTEC, personal communication, 2014) databases. The stations location is shown in Figure 2.1, and listed in Appendix A. The meteorological interpolation was accomplished using the "PCP_SWAT" extension for ArcGIS (Zhang & Srinivasan, 2009) and the SWAT-WGEN to fill gaps in the data series (Boisramé, 2011). It is worth noting that it is expected precipitation interpolation to have a lower influence on uncertainty than the quality of the precipitation data (Cornelissen et al., 2013).

The observed hydrologic data (discharge and precipitation) were consulted from Hidroweb (the National Water Agency database [ANA], 2015), SABESP (personal communication, 2014), and São Paulo state Water and Electricity Department [DAEE] (personal communication, 2014). Water withdrawals and effluent releases were consulted from the state environmental institutions from Sao Paulo (São Paulo state Water and Electricity Department, 2014) and Minas Gerais (Minas Gerais Water Management Institute, 2014) states. Solely the water use permits were considered, that is, minor diversions that do not require a permit were not taken into account.

For the basin characterization, we adopted the soil map from Oliveira (1999) (1:500,000); the land use map of 2010 from Molin et al. (2015) (1:60,000); and the ASTER v.2 Digital Elevation Model (DEM) (1:60,000) (Tachikawa, Hato, Kaku, & Iwasaki, 2011). Because the default classes in SWAT were developed for the USA context, the soil and land use characteristics for this model were developed by Bressiani et al. (in press), whilst for MHD-INPE the classes in the maps were fit to existent more general default classes.

In SWAT, the river network is only determined above a certain drainage area threshold defined by the user, defined in this case at 710 ha (7.1 km²), implying in the finer definition of stream networks and the sub-basins size. Outlets are automatically generated above the threshold, but can be changed by the user. Here, we chose only outlets of interest regarding existence of discharge data or expected installation of gauging stations (Taffarello et al., 2013).

For MHD-INPE, the basin delineation is made within TerraView/Hidro (Rosim et al., 2012). The cell-grid size is user determined. Here, we defined the cells at 1x1 km. Every cell has a virtual river network, though with variable extension.

Table 2.2 shown a summary of soil and land use classes and the number of sub-basins and HRUs in each model.

Table 2.2. Hydrologic models set up

Feature	SWAT	MHD-INPE
Sub-Basins Delineated	21	25
Adopted Soil Classes	Pedological classes from (Bressiani et al., in press): 3 (Red-Yellow Latosol (LVA); Dystrophic Haplic Cambisol (CX); and Dystrophic Red-Yellow Argisol (PVAd)	Default textural classes: 3 (clay; sandy clay loam; sandy loam)
Adopted Land Cover / Vegetation Classes	Default ArcSWAT classes: 7 (Sugar Cane – representing annual crops; Forest evergreen; Pine; Water; Pasture; Residential – representing Urban areas; Orange - representing perennial crops)	Default SSiB classes: 6 (Crop; Broadleaf evergreen trees; Broadleaf and needleaf trees; Water; Groundcover/grassland; Bare soil)
HRUs	49	20
Output Time Step	Monthly	Monthly
Spatial Resolution	Sub-basins above 7.1 km² (from 12 to 1037 km²)	1 km² regular-cell grid

2.2.5 Calibration and Validation

Both models were separately calibrated using automatic and manual techniques in a monthly step. The main differences rely on the techniques for automatic calibration and the set of parameters used for calibration.

In SWAT, practically all model parameters can be calibrated, although several papers (see Arnold et al., 2012; Bressiani et al., in press) indicate the most used and the most sensitive parameters, based on several different applications of the model. Although the parameters may be specific for each basin, the expertise from previous papers provided a list for a good start on our case-specific sensitivity analysis. Firstly, for the automatic stage of calibration, the SWAT-CUP (Calibration and Uncertainty Programs) software and SUFI-2 (Sequential Uncertainty Fitting) method were adopted. SUFI-2 is based on Latin Hypercube sampling (Abbaspour et al., 2015; Abbaspour, 2014). Then, a finer adjustment with manual calibration was accomplished.

In MHD-INPE, a previous sensitivity analysis was accomplished by Rodriguez & Tomasella (2015) to find the most indicated parameters for calibration, resulting in 9 parameters. The Shuffled Complex Evolution method (SCE-UA) (Duan, Gupta, & Sorooshian, 1993) was adopted for the automatic calibration step, firstly. Secondly, the manual calibration was accomplished for finer adjustments.

Both models were calibrated for the same period, between October 2007 and September 2009, when the region received an average precipitation of 1678 mm (varying from 1599 to 1756 mm). The validation period was divided in two periods: from January 2006 to September 2007 and from October 2009 to June 2014 (before and after the calibration period), with an average precipitation of 1463 mm (from 965 to 1764 mm). The chosen efficiency criteria, widely used indices in hydrologic applications, were volumetric error (PBias), Nash-Sutcliffe Efficiency (NSE), and NSE of the logarithmic of discharges (NSELog), which is more sensitive to low-flows (Krause & Boyle, 2005; Moriasi et al., 2007).

In general, for hydrologic regimes alterations (such as under climate change applications), soil / groundwater parameters are the most indicated in SWAT literature and are also the ones determined for MHD-INPE to be calibrated. The chosen parameters are shown in Table 2.3.

Due to hydrologic and meteorological data spatial distribution, the calibration and validation periods were set from 2004 onwards. Discounting a 2-year period for model warm-up, calibration period was set from October 2007 to September 2009 (2 years), period in which all chosen gauging stations have available discharge data series. Validation period was from January 2006 to September 2007 and from October 2009 to June 2014 (6.5 years), depending on the gauge station.

Moreover, non-calibrated subbasins upstream the calibrated ones were checked with punctual field measures (Taffarello et al., 2013) against strong incongruences, avoiding unwanted tendencies under climate projections, which were not noted.

2.2.6 Climate model historical and projected data

Climate projection were adopted from the Regional Climate Model (dynamical downscaling) Eta-INPE with boundaries from the HadGEM2 – Earth System Model (Eta-HadGEM2-ES) driven by the Representative Concentration Pathway (RCP) scenario 4.5 (Chou et al., 2014a; 2014b). A total of 12 cells (20x20km grid) of the climate model cover the studied area. This is one among the new runs of Eta-INPE with boundaries from GCMs used in AR5 (IPCC 5th Assessment Report) based on RCP4.5, which have a better resolution (20 km) than the previous Eta runs with GCMs used in AR4 (40 km). The run with boundaries from another climate models have underestimated temperature (Chou et al., 2014a).

The Eta-HadGEM2-ES historical run goes from 1960 to 2005, although we have only used data from 1976 onwards, summing up 30 years of data. Due to the disagreement of periods, the data used in calibration/validation are incomparable to meteorological data from Eta. Even though, a bias correction is suggested by several authors in applications of climate models to hydrologic models (Intergovernmental Panel on Climate Change [IPCC], 2012; Mishra & Singh, 2011; Teutschbein & Seibert, 2013). Therefore, we applied the linear scaling method (Teutschbein & Seibert, 2013) using observed data, if any, from the same meteorological stations adopted in the calibration/validation period, but only 9 stations were used.

Table 2.3. Calibrated parameters of each model

Process	**SWAT**		**MHD-INPE**	
	Parameter name	**Description**	**Parameter name**	**Description**
Soil physical parameters	SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)	D1	Thickness of upper soil layer (m)
	SOL_BD	Moist bulk density (g/cm^3)	D2	Thickness of intermediate soil layer (m)
			D3	Thickness of bottom soil layer (m)
Soil- and Groundwater	Alpha_BF	Baseflow alpha factor (1/days)	μ	A parameter that represents the decay of the transmissivity with the thickness of the saturated zone (-)
	SHALLST	Initial depth of water in the shallow aquifer (mm H_2O)	CSI	Minimum effective subterraneous storage that generates return flow (%)
	GW_DELAY	Groundwater delay time (days)	T_{sub}	Maximum transmissivity of the bottom layer (m/day)
	RCHRG_DP	Deep aquifer percolation fraction		
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)		
	REVAPMN	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm H2O)		
	GW_REVAP	Groundwater "revap" coefficient		

Source: (Arnold et al. 2012; Mohor et al. 2015, Suppl. Material)

Table 2.3. (continued) Calibrated parameters of each model

Process	SWAT		MHD-INPE	
	Parameter name	Description	Parameter name	Description
Vegetation Growth	CANMX	Maximum canopy storage (mm H_2O)		
	ESCO	Soil evaporation compensation factor		
Infiltration	SOL_K	Saturated hydraulic conductivity (mm/hr)	K_{ss}	Saturated hydraulic conductivity (mm/day)
	CN2	Initial SCS CN for moist condition 2		
Flow routing	GW_DELAY	Groundwater delay time (days)	C_b	Routing water storage parameter for base flows (seconds)
	Ch_N2	Manning's coefficient "n" value for the main channel	C_{sup}	In-cell routing parameter for surface and subsurface flows (seconds)
	Ch_K2	Effective hydraulic conductivity in main alluvium channel (mm/hr)		
	SURLAG	Surface runoff lag coefficient		

Source: (Arnold et al. 2012; Mohor et al. 2015, Suppl. Material)

The SWAT and MHD-INPE models' results were also compared through hydrologic indicators. The use of indices that characterize the hydrologic regime much eases the comparison between basins or periods (Yilmaz, Gupta, & Wagener, 2008). The compared indicators were low-flow segment volume of the flow duration curve (FDC) (named MWL, Eq. 2.1), slope of the FDC medium range (QSM, Eq. 2.2), and seasonality (Eq. 2.3) (Ley, Casper, Hellebrand, & Merz, 2011), Q90, Base Flow Index (Smakhtin, 2001) and the Standardized Runoff Index (Farahmand & AghaKouchak, 2015) of 6 months (SRI-6).

$$MWL = \frac{\sum_{l=1}^{L} Q_l}{L} \tag{2.1}$$

$$QSM = \frac{0.8\ quantile - 0.2\ quantile}{mean\ Overall} \tag{2.2}$$

$$SEASONALITY = \frac{mean\ Wet\ season + mean\ Dry\ season}{mean\ Overall} \qquad 2.3$$

where: L is the number of discharges with an exceedance probability between 70 and 90%.

The SRI-6 was calculated through the Standardized Drought Analysis Toolbox (SDAT) (Farahmand & AghaKouchak, 2015). The index is the standard normal distribution function based on the empirical Gringorten probability of a given data series (Eq. 2.4).

$$\text{Probability}\,(x) = (i - 0.44) / (n + 0.12) \qquad 2.4$$

where *n* is the data series length; *x* is the variable, discharge in this case; and *i* is the rank of the variable from the smallest.

2.3 RESULTS

2.3.1 Basin representation

Due to structural differences between the models, the basin is differently represented in each model applied. The differences were highlighted in Table 2.3. It is important to note that the number of subbasins delimited is higher than the subbasins calibrated and studied due to the existence of discharge series. Table 2.4 shows the percentage of land use classes within each basin and in each model, according to its defined HRUs. Figure 2.2 shows the final delineation on ArcGIS, for SWAT, and on TerraHidro, for MHD-INPE.

Table 2.4. Basins characteristics within the models

SUB-BASIN	**SWAT**							**MHD**						
		Percentage of Land use							Percentage of Land use					
	Area (km²)	Crop *	Forest	Pine	Pasture	Water	Urban	Area (km²)	Crop *	Forest	Pine	Pasture	Water	Urban
JAGUARI	1037	14.1	43.2	7.6	33.9	0.5	0.8	1047	16.6	36.3	8.3	37.3	0.3	1.1
F25B	972	14.0	43.6	7.9	33.6	0.0	0.8	981	16.5	37.0	8.2	37.3	0.0	1.0
F23	508	19.2	33.7	2.3	44.2	0.0	0.5	511	19.6	31.1	3.2	45.4	0.0	0.6
CACHOEIRA	392	8.7	48.0	18.3	23.1	2.0	0.0	397	12.1	33.9	9.8	38.0	4.2	2.0
ATIBAINHA	314	9.3	55.2	17.6	11.2	6.7	0.0	332	10.5	43.5	15.0	22.0	7.2	1.8
F24	294	8.4	51.2	18.0	22.4	0.1	0.0	295	12.1	36.7	11.2	37.9	1.1	1.0
F28	277	3.4	68.5	21.5	6.2	0.0	0.3	282	10.8	49.9	20.2	19.0	0.0	0.0
JACAREI	201	10.9	30.6	2.7	33.3	20.4	2.0	230	12.7	29.1	2.6	29.1	20.2	6.3
4600	12	13.6	13.9	0.7	71.8	0.0	0.0	13	9.9	45.2	0.0	36.3	0.0	8.6

* perennial and annual crops

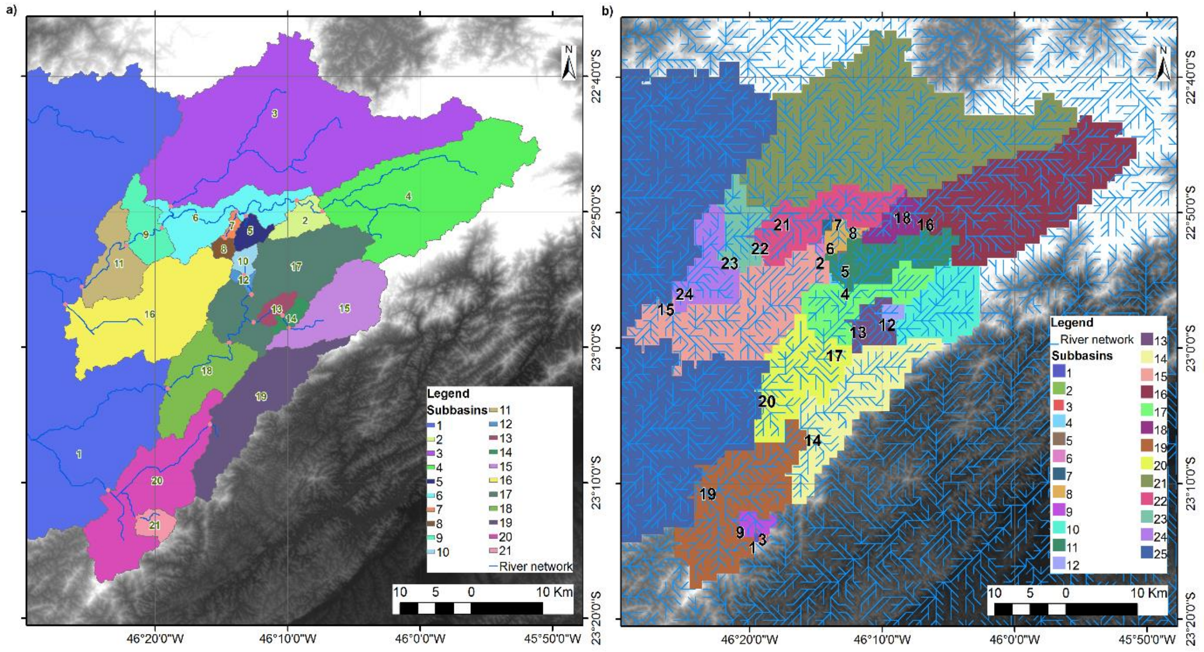

Figure 2.2. Basin delineation within a) ArcGIS and b) TerraHidro

2.3.2 Calibration and Validation

The efficiency criteria of calibration and validation periods are shown in Table 2.5. The colours in the table represent the ratings suggested by Moriasi et al. (2007).

Table 2.5. Efficiency criteria for Calibration and Validation periods

Station	Calibration (Oct/07-Sep/09)						Validation (Jan/06-Sep/07 + Oct/09-Jun/14)					
	Pbias (%)		NSE (-)		NSELog (-)		Pbias (%)		NSE (-)		NSELog (-)	
	MHD	SWAT	MHD	SWAT	MHD	SWAT	MHD	SWAT	MHD	SWAT	MHD	SWAT
Jag+Jac	-20.1	-12.0	0.65	0.83	0.80	0.87	-27.1	-8.4	0.63	0.82	0.57	0.73
F25B	-7.2	3.6	0.83	0.91	0.82	0.89	-7.7	11.4	0.75	0.77	0.76	0.72
F23	-7.9	-1.8	0.81	0.88	0.86	0.90	-12.6	12.0	0.82	0.84	0.74	0.77
Cachoeira	-28.7	-26.6	0.50	0.49	0.62	0.31	-41.6	-46.7	0.18	0.27	0.28	0.05
Atibainha	-16.3	-14.5	0.53	0.60	0.77	0.55	-8.1	1.7	0.67	0.71	0.50	0.54
F24	3.7	-13.3	0.92	0.69	0.90	0.71	5.5	-1.7	0.75	0.65	0.74	0.34
F28	-8.4	5.3	0.71	0.80	0.80	0.68	-6.3	14.2	0.87	0.72	0.83	0.31
4600	-18.7	-22.0	0.54	0.68	0.59	0.52	-6.7	15.4	0.71	0.78	0.62	0.38

Colours classification stand for: green for “very good” (NSE>0.75; Pbias<10%), yellow for “good or satisfactory” (0.75>NSE>0.5; 10%<Pbias<25%), red for “unsatisfactory” (NSE<0.5 ; Pbias>25%) (Moriasi et al., 2007)

Here we were interested in the performance rating as an indication of the models' ability in representing the river basin satisfactorily for the following applications. The thorough assessment of the models formulations, parameterizations and the consequent efficiency criteria are not in the scope of this work, though we reinforce the importance of such procedure in more specific works and in the development of the tools, the hydrologic models.

The hydrographs for calibration and validation periods are shown in Figure 2.3, with SWAT and MHD-INPE simulation. One can see the drought period (2013-2014) validation. The error bars in field campaigns represent discharge calculated with maximum and minimum measured celerity at the river sections. The error bars in the precipitation data show the variability of precipitation among the cells within the sub-basin, as integrated in MHD-INPE, only.

2.3.3 Scenarios comparison

Climate projections from Eta-HadGEM2-ES under RCP 4.5 scenario, were applied in the hydrologic models to evaluate the impacts on hydrologic regime and low flows. From Table 2.4, it is worth noting that the basins areas are in general smaller than each one of the adopted climate model cells (400 km²). Because the weather stations are all outside the basins boundaries, a data interpolation was necessary before applying the data. Therefore, with the bias correction procedure, we understand that the data does not lose much information. Although it is not in an ideal resolution, it is acceptable. The average shifts in the meteorological variables for each future period, in relation to the historical run of Eta-HadGEM2-ES are shown in Table 2.6.

Table 2.6. Changes of long-term average meteorological variables, in relation to the historical (1976-2005) run

Variable	**Period**			
	2007-2040	**2041-2070**	**2071-2099**	
Air temperature	0.9	1.5	1.9	° C
Radiation	-4.0	-0.2	0.7	%
Relative Umidity	1.1	2.5	4.1	%
Wind speed	-1.3	-1.0	-0.3	%
Atmospheric Pressure	-5.6	0.0	-2.1	%
Precipitation	0.3	-2.6	-9.5	%
Dry Spell (threshold 0.1 mm)	17	49	85	%

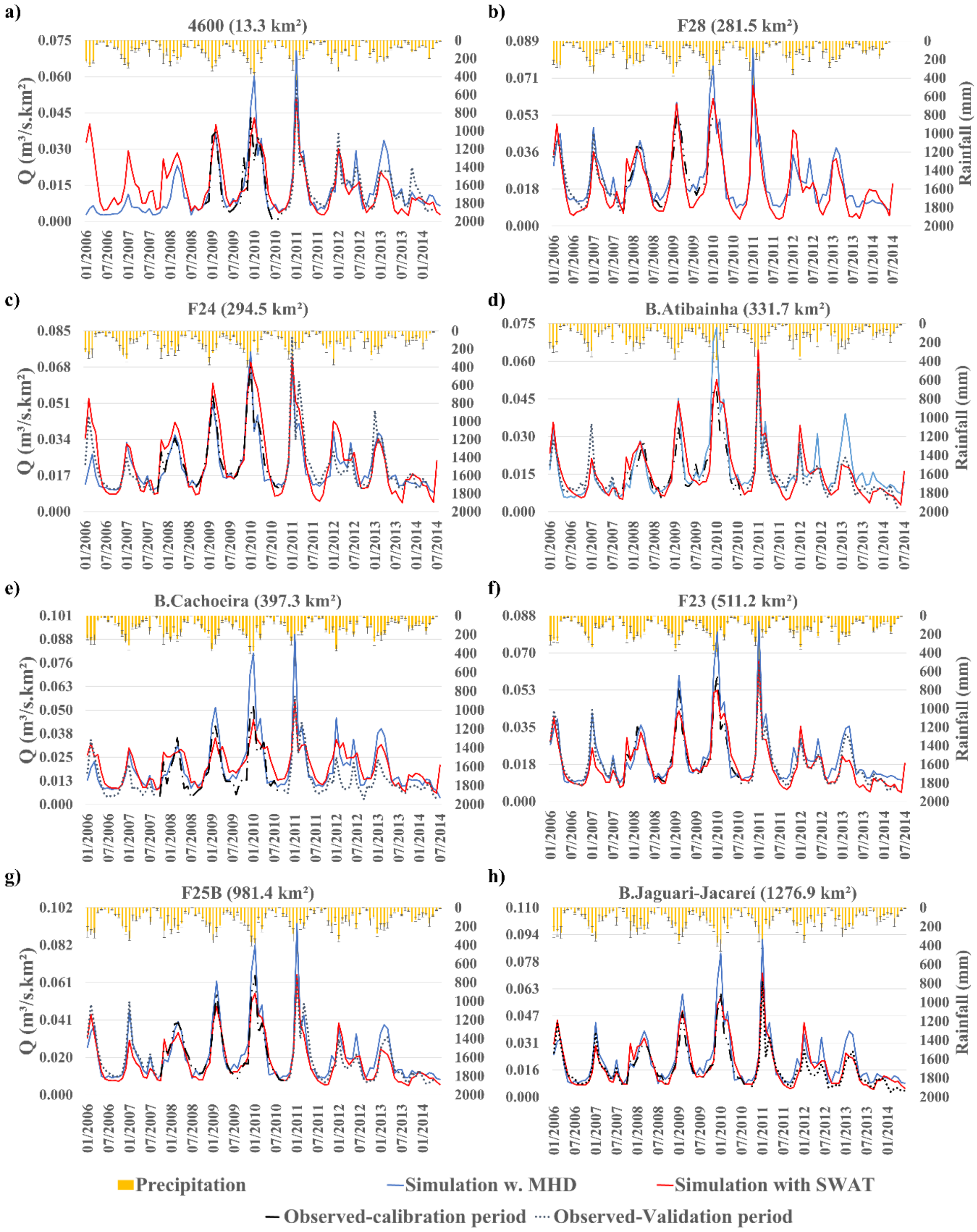

Figure 2.3. Calibration and Validation period hydrographs

The water balance components average shifts, in relation to 1976-2005 run, of each hydrologic model, are shown in Table 2.7. The difference of precipitation inputs of each model is due to the structure of the models. Since SWAT considers a single rain for the whole sub-basin, after the interpolation, while MHD-INPE reads single values for each cell.

Some patterns are identifiable. The potential evapotranspiration (PET) increases from the near future (2007-2040) to the distant future (2071-2099) in all cases, but the shifts in SWAT runs start with drop in the near future (of about -4%), then it goes back to the historical values (0% of change). Whilst in MHD-INPE runs, even the near future simulations present an increase between 1 to 2%, which keeps increasing in the following periods, reaching a positive 7% change, in relation to the historical period. Since PET is based directly on input data, the difference between models is likely due to the structure difference and the formulation options (see again Table 2.1). However, the real evapotranspiration (ET) decreases, in general, with the larger impacts felt in SWAT runs than MHD-INPE runs. There is a general change in soil water content, in opposite sign to PET. SWAT runs show an increase in the near future, followed by a decrease, whilst MHD-INPE runs are irregular, with a partial increase from the near future (2007-2040) period to the intermediate period (2041-2070), but followed by a decrease in the last period. Impacts in SWAT runs are overall less negative than MHD-INPE runs.

Table 2.8 shows the changes in hydrologic indices in projections driven by Eta-HadGEM2-ES. It is important to note, from Table 2.6, that precipitation projections are higher in the first period (2007 to 2040), followed by a decrease in the next periods (2041 to 2070 and 2071 to 2099). We see that rainfall seasonality increases in all three future periods, but low-flow indices (MWL, from (Ley et al., 2011), and Q90) follow the precipitation changes signal. The Q90 is a yearly minimum flow because the models were run with a monthly time step, which represents a 92% of permanence, in an empirical probability distribution.

Table 2.7. Percentage change of precipitation data input and hydrologic models' water balance components under climate change projections compared to historical period

	Precipitation			**Potential Evapo-transpiration**			**Evapo-transpiration**			**Soil water content**		
	2007-2040	**2041-2070**	**2071-2099**	**2007-2040**	**2041-2070**	**2071-2099**	**2007-2040**	**2041-2070**	**2071-2099**	**2007-2040**	**2041-2070**	**2071-2099**
B. Jaguari (1037 km²)												
SWAT	3	-1	-7	-4	-1	0	-4	-5	-8	2	-2	-7
MHD	1	-2	-9	2	5	7	0	-1	-6	-4	-5	-12
F25B (971.9 km²)												
SWAT	3	-1	-7	-4	-1	0	-4	-5	-9	2	-1	-7
MHD	1	-2	-9	2	5	7	0	-1	-6	-4	-3	-10
F23 (508.1 km²)												
SWAT	3	-1	-7	-4	-1	0	-5	-5	-8	0	-2	-7
MHD	1	-2	-9	1	5	7	-1	-1	-7	-2	-1	-9
B.Cachoeira (391.7 km²)												
SWAT	3	-1	-7	-4	-1	0	-4	-5	-8	6	-2	-8
MHD	0	-2	-9	2	5	7	0	0	-4	-6	-6	-16
B.Atibainha (313.8 km²)												
SWAT	3	-1	-7	-4	-1	0	-5	-4	-7	4	-3	-11
MHD	-1	-4	-10	2	6	7	1	0	-3	-9	-8	-16
F24 (293.5 km²)												
SWAT	3	-1	-7	-4	-1	0	-4	-5	-7	6	-1	-8
MHD	0	-2	-9	2	5	7	0	0	-5	-7	-7	-17
F28 (276.8 km²)												
SWAT	3	-1	-7	-4	-1	0	-2	-4	-9	21	6	-8
MHD	0	-2	-9	2	6	7	0	0	-6	-8	-7	-16
B.Jacarei (200.5 km²)												
SWAT	3	-1	-7	-4	-1	0	-5	-4	-5	0	-2	-5
MHD	1	-3	-10	2	5	7	-1	1	-2	-6	-5	-12
4600 (11.99 km²)												
SWAT	3	-1	-7	-4	-1	0	-5	-6	-10	1	-2	-5
MHD	1	-2	-9	2	5	7	0	1	-4	-5	-4	-11

Table 2.8. Impacts on hydrologic regime under climate change, by percent change to the historical period

	MeanQ			Seasonality			MWL			Q90		
	2007-2040	2041-2070	2071-2099	2007-2040	2041-2070	2071-2099	2007-2040	2041-2070	2071-2099	2007-2040	2041-2070	2071-2099
B.Jaguari (1037 km^2)												
SWAT	17	6	1	10	12	25	23	0	-2	31	-4	0
MHD	7	-2	-16	16	13	23	-3	-4	-15	-2	-4	-13
F25B (971.9 km^2)												
SWAT	17	6	1	11	12	25	23	0	-2	31	-3	0
MHD	7	-2	-15	16	13	23	-2	-3	-14	-1	-2	-11
F23 (508.1 km^2)												
SWAT	18	6	1	9	12	25	31	3	-1	46	1	4
MHD	9	0	-15	22	15	21	-1	0	-10	-2	1	-12
B.Cachoeira (391.7 km^2)												
SWAT	16	7	0	-9	4	28	36	11	0	40	6	-2
MHD	6	-6	-18	9	2	15	1	-4	-23	0	-5	-25
B.Atibainha (313.8 km^2)												
SWAT	23	7	0	14	16	30	41	6	4	61	5	7
MHD	3	-15	-30	3	-4	19	3	-20	-49	-9	-25	-54
F24 (293.5 km^2)												
SWAT	15	4	0	10	14	28	31	2	-4	42	-5	-5
MHD	6	-2	-14	11	6	19	3	0	-16	3	1	-18
F28 (276.8 km^2)												
SWAT	15	5	1	8	10	22	27	-1	-9	41	-5	-14
MHD	4	-2	-15	21	18	32	4	-4	-15	5	-3	-13
B.Jacarei (200.5 km^2)												
SWAT	22	7	-1	15	15	24	30	2	0	38	-1	4
MHD	7	-6	-17	6	7	21	-3	-9	-28	-2	-7	-29
4600 (11.99 km^2)												
SWAT	19	7	2	9	9	21	26	0	-6	29	-5	-7
MHD	6	-11	-26	3	20	44	-12	-26	-48	-33	-33	-51

There is a large increase in the near future MWL in SWAT runs. MHD-INPE runs, however, show both signals. Both models show a great decrease from the near future to the distant future.

We highlight some of the indices proposed by Ley et al. (2011): seasonality, the slope of the medium range of the FDC (QSM), and the low-flow segment volume of the FDC (MWL) in a graphic output. These three indices and the Base Flow index, described by Smakhtin (2001), are shown in Figure 2.4, including not only the calibrated subbasins.

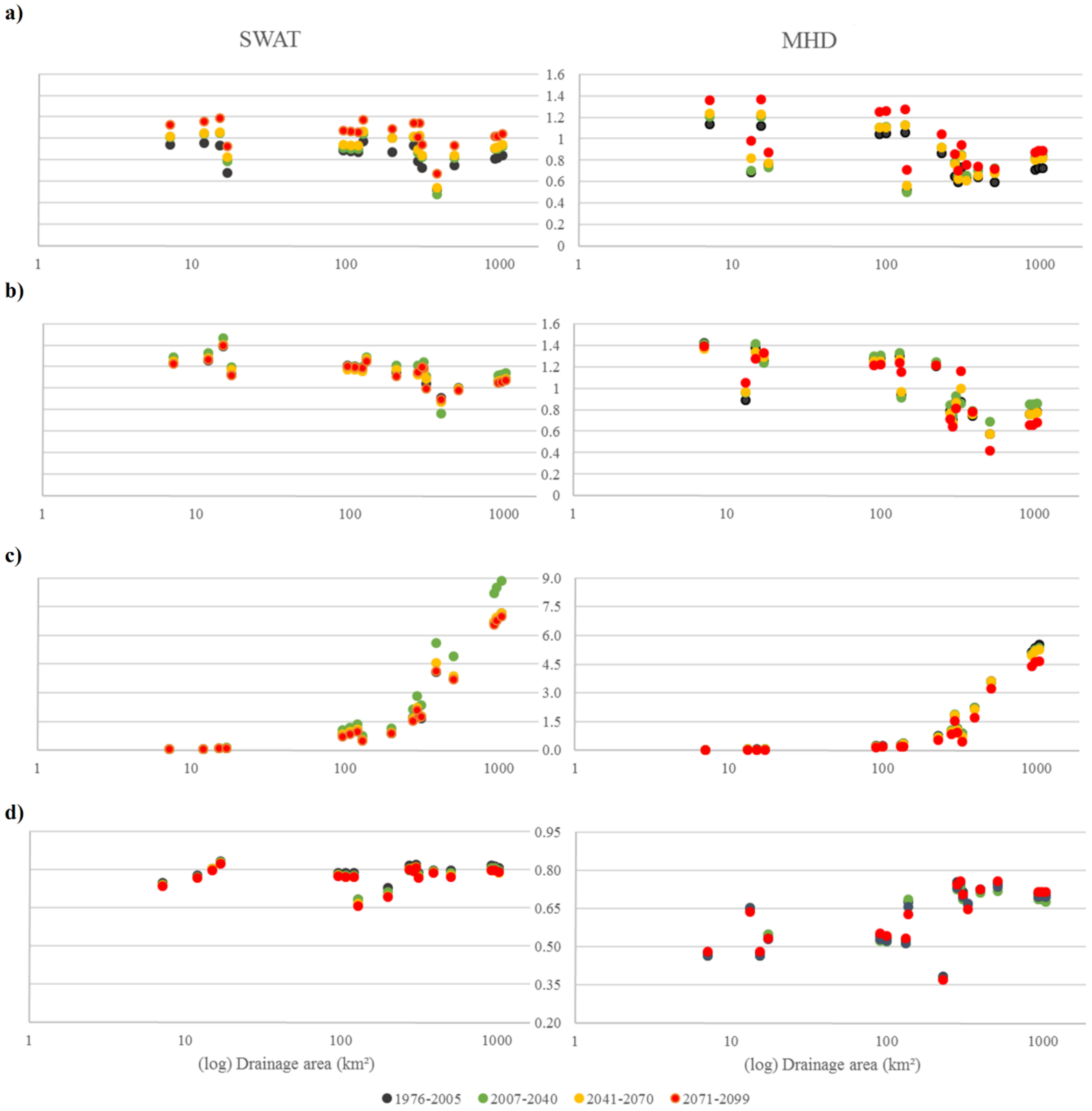

Figure 2.4. Hydrologic indices per subbasin and per period in each model: a) Seasonality, b) QSM (slope of the median segment of the FDC), c) MWL (volume of the low-flow segment of the FDC), and d) Base Flow Index

Regarding the Seasonality (Figure 2.4.a), there is no correlation between drainage area and seasonality, but the figure shows how climate projections indicate an increase in the pattern for all subbasins, as already shown in Table 2.8.

For the slope of the medium range of the FDC (QSM - Figure 2.4.b), there is also no correlation between the index and drainage area, which is lower for larger areas. On the other hand, impacts from climate change projections did not show the same signal for all subbasins.

The shifts of MWL (Figure 2.4.c) from historical period (1976-2005) to the last future period (2071-2099) are larger in MHD-INPE than SWAT runs, although in the near future period (2007-2040) SWAT showed a larger positive shift (Table 2.8). Clearly MWL is related to the drainage area, with similar water yield across the subbasins.

For the Base Flow Index (Figure 2.4.d), there are considerable differences between SWAT and MHD-INPE runs. With SWAT, there is a decrease in base flow from historical to future runs with Eta climatological data. This pattern is not strong in MHD-INPE runs, but only for some subbasins. As with other indices, MHD-INPE shows a larger spread among basins. The changes in SWAT are always negative (up to -5%), but in MHD-INPE, both signals of changed were present (from -7.4% to 4.3%).

A final indicator explored is the Standardized Runoff Index - 6 months (SRI-6) (Farahmand & AghaKouchak, 2015). The results are shown in Figure 2.5 with SWAT and with MHD-INPE outputs. Here we present the values as a tiles graph, instead of a line chart, so it is easier to compare the outputs from each basin, and each row are ordered by drainage area (descendent order), so it is immediate to check if there is some behaviour regarding drainage area. The line charts above the tiles show the histograms of SRI-6 for each period. Future periods show more frequently negative values than in historical and near future periods, in both models results.

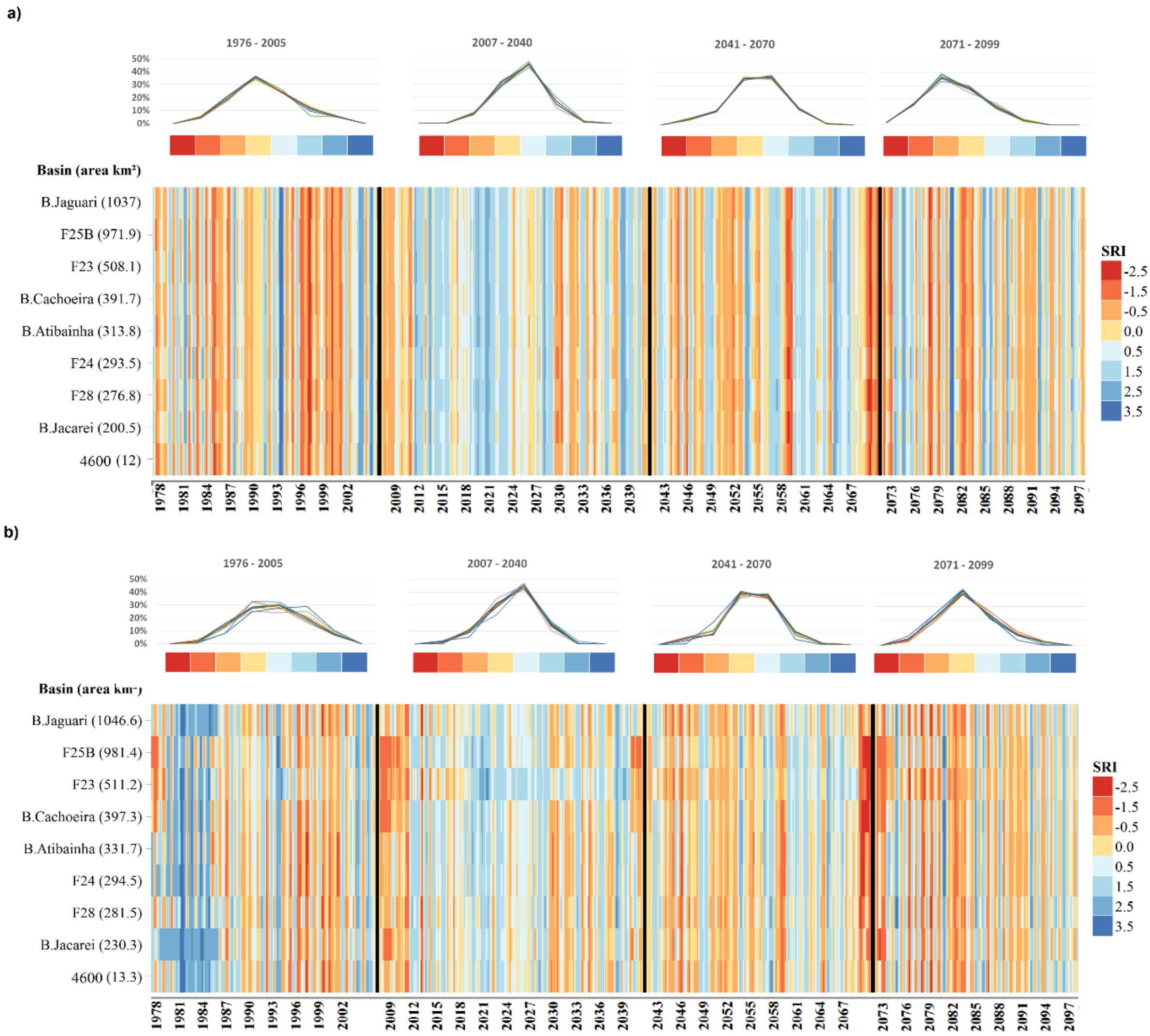

Figure 2.5. Tiles graph for SRI-6 months from a) SWAT and b) MHD-INPE data output

2.4 DISCUSSIONS

SWAT and MHD-INPE have differences in structure and formulation, but, where possible, input data were the same in both models. SWAT carries a much larger number of parameters (input and output data), which should make the model more complex and changeable, for the basin's characteristics and features may be more detailed, but it becomes much less user-friendly. MHD-INPE, on the other hand, has little pre-determined parameters for change, which makes it more user-friendly, though it could make it less changeable.

There was an increase in PET, which is an important observation, resulting from the increase in temperature, one of the most important component in the adopted methods for calculating PET. The decrease in evapotranspiration, however, may be explained by the decrease in precipitation, which is taken as the main driver of hydrologic components.

The impacts in Q90 projected by the models are the most irregular among the indicators compared in this chapter. It is important to remember that due to the input data available, the calibration was made in the monthly step, thus, the Q90 is actually the minimum monthly flow. This indicator is the one adopted by some states in Brazil as the reference discharge for water use permits, which makes it a very important indicator, although developed with daily discharge data series. Due to the limitations of data and other issues addressed here, we left the advance of this study to future works.

The impacts (changes) in an outlet between the runs driven by the climate model data are also significantly different. In the larger sub-basin, the changes in mean discharge may vary +1% (SWAT) or -16% (MHD-INPE) in the last period in relation to the historical period; the volume of low-flows (MWL) may be 2% (SWAT) or 15% (MHD-INPE) lower; but seasonality is most certain to be between 25% (SWAT) or 23% (MHD-INPE) higher.

From our results, MHD-INPE has more spread results among basins than SWAT in some indices (e.g. seasonality, medium segment slope (WSM), and base flow index), and opposite change signals in relation to the volume of water (MWL and Q90, Table 2.8).

Vansteenkiste et al. (2013) found large differences (though with the same signal) in low flows projections between the two distributed models applied (MIKE-SHE and WetSpa), which were larger than the uncertainties from the climate models, as stated by the authors. Gosling et al. (2011) however, have found opposite signals in some of the several comparisons of runoff change with a Global Hydrologic Model and a Catchment Hydrologic Model, different for each basin (from lumped to distributed ones).

From Figure 2.5, on average, in the smaller basins among the assessed ones (‘4600’, ‘F28’, ‘F24’, and ‘B.Atibainha’) MHD-INPE shows longer periods of consecutive positive or consecutive negative values, i.e., a less frequent shift from negative to positive values of SRI. In the larger basins among the assessed ones (‘B. Jaguari’, ‘F25B’, ‘F23’, and ‘B.Cachoeira’) and “B.Jacarei”, MHD-INPE shows a more frequent shift from positive to negative values then SWAT.

The homogeneity among sub-basins is visual in SWAT results, in contrast to MHD-INPE, where some basins behave differently from the others, firstly F23, and secondly F25B, which is downstream F23, and there are smaller shifts among the other basins. This is likely due to the distributed nature of MHD-INPE, which may respond faster or slower to rainfall upstream or downstream while SWAT reads solely a single value for each sub-basin.

2.5 CONCLUSIONS

Regarding streamflow generation, both models showed to be capable of representing acceptably the study case area, which are the headwaters of a precipitation-driven basin in a sub-tropical climate. The performance of both models in calibration/validation was similar. In general, both models showed a “good” performance in representing the basin’s response to the inputs. Still, with a longer data series covering different climatic conditions, a better calibration would be possible, which would increase confidence in the results with climate projections as well.

In general, the dispersion of the results with the distributed model (MHD-INPE), contrasted to the semi-distributed one (SWAT) among basins. This dispersion is expected as MHD-INPE incorporates precipitation for each cell while SWAT reads a single value for each sub-basin (default delineation procedure in each model). The evaluation of SRI-6, as presented in Figure 2.5, reinforces this difference between models and readily shows differences between periods of runs, and calls attention to some basins singular behaviour, as F23 in MHD-INPE runs.

The impacts of all indices presented related to or influenced by low-flows (MWL, Q90, Base Flow Index) are highly different between SWAT and MHD-INPE, not only the absolute values, but also the signal of change. Once both models are considered able to represent the basin, and the climate model is considered able to represent the local climate, both runs are virtually equiprobable, bringing a great uncertainty for decision-makers. The uncertainty should diminish with a more dense and reliable monitoring network providing data for a better calibration with a longer data series comprised of different climatic situations.

On the one hand, SWAT has a larger number of parameters, which could improve the representation of basin’s features while MHD-INPE was implemented with a finer input of meteorological data, including precipitation. It is not possible to prove a better representation of one model in relation to the other on the calibration and validation results. Therefore, runs driven by climate projections by one hydrologic model cannot be taken as better than the runs with the other model. These gaps between models show a range of uncertainty which a decision-maker must rely on. When the gap between the results are too large for a good decision, a shorter-term decision could be implemented, with lower uncertainty, while strategic long-term decision could be made under the more restrictive case until better data is available for an upgrade of the modelling.

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3 INDICATORS OF INSURANCE AGAINST HYDROLOGIC DROUGHT UNDER WATER DEMAND AND CLIMATE CHANGE SCENARIOS *

*A modified version of this chapter has been submitted as: **Mohor, G. S**.; Mendiondo, E. M. **Economic Indicators of Hydrologic Drought Insurance Under Water Demand and Climate Change Scenarios** to *Ecological Economics*

ABSTRACT

In Brazil and other countries, a water use permit, an important tool for managing water resources, relies solely on the remaining discharge regime. As demand increases, however, another criterion could be incorporated that indicates society's capacity to bear the consequences. In this study, we present an insurance model and suggest its outputs as complementary criteria or conditional features for water resources management. From the discharges developed by using the SWAT-TAMU and MHD-INPE hydrologic models driven by the RCP4.5 scenario, we apply the Hydrologic Risk Transfer Model (MTRH-SHS), an insurance fund simulator, to assess sustainability indicators and the premiums that the population would need to pay to cover the expenses of water deficits. A 20% increase in demand may elevate the premium to the equivalent of 0.1% of local GDP. Indeed, even under current demand, premiums may surpass 0.5% of GDP because of changes in the hydrologic regime. The information generated with MTRH-SHS might thus raise awareness and help decision-makers in the water management, for example adding a premium payment as a condition for demand increase.

Keywords: Brazil, Risk transfer, Water security, Drought Risk

3.1 INTRODUCTION

The loss of lives and goods due to natural events is rising worldwide (UNISDR, 2011) because of an increase in both the magnitude of such events and the wealth of the affected parties. Hydrologic events are, specifically, the most frequent natural catastrophes around the world with yearly losses exceeding 1% of national GDPs (The World Bank, 2014). About 6% of worldwide weather-related events were held in South America from 1980 to 2013. The losses accounted 2%

of the amount (about US$64bn), but the insured losses represented less than 1% of the world total (less than US$9bn) (Munich Re, 2014a).

The 2011 Global Assessment Report on Disaster Risk Reduction (UNISDR, 2011) reinforces that droughts are related to social and economic choices. On this basis, it is a good strategy to seek action and awareness by the population in order to improve decision-making and build resilience. Droughts are also a 'silent' risk that develops slowly, as climate change. Moreover, many people, especially those in urban areas, rarely pay attention to droughts and do not feel at risk of extreme events, meaning that they do not act to reduce their vulnerability (Oliveira & Nunes, 2007).

The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015) states four main priority areas for action: (1) Understanding disaster risk; (2): Strengthening disaster risk governance to manage disaster risk; (3) Investing in disaster risk reduction for resilience; and (4) Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction. Non-structural measures for resilience, as insurance schemes, points out as one of the third priority area actions. However, Mills & Warner (2003) point that the climate science is not yet aligned to the needs of insurance agencies.

The four priority areas are depicted in Figure 3.1 along with the main action points from the Third UN World Conference in Sendai report (UNISDR, 2015), plus the Hazards, as dismantling forces, and the components explored in this study as products (output arrows) and contributors (input arrows). The assessment of the hazards, drought in this case, is part of the Priority 1, while Insurance Mechanism is one of the main actions under the Priority 3, which contributes to the development of Priority areas 2 and 4 as a consequence of its successful implementation.

Indeed, climate change may affect insurance on many fronts. In particular, given that the frequency and magnitude of extreme events are likely to increase, current premiums, funds, and risk valuations may begin not to suit these changing conditions (Dlugolecki, 2008).

In developing countries, which tend to be the most affected by natural disasters in terms of GDP (Munich Re, 2014a), the low perception of risk by society and instability of the economy undermine the growth of the insurance market (Lamond & Penning-rowsell, 2014). This trend is perpetuating the dearth of data for insurer agencies to work with (Bank, 2014; Grey et al., 2013), leading in the low penetration of insurance and high losses. In 2013, non-life insurance penetration in Brazil was just 1.2% compared with 6.1% in the United States and 3.7% in Germany (OECD, 2016).

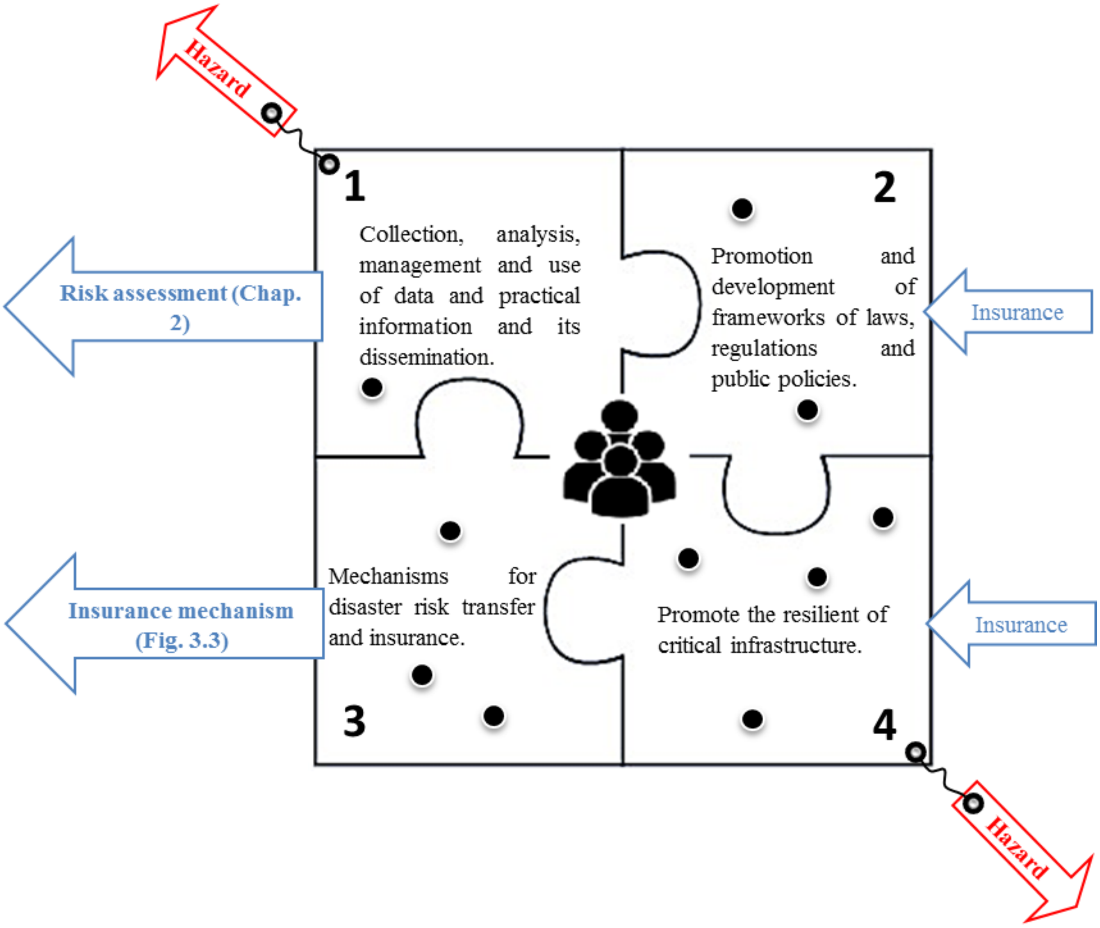

Figure 3.1. Sendai Framework four DRR Priority Areas (black), products and contributors explored in this study (output and input blue arrows), and dismantling forces (red). Adapted from Guzmán et al. (2015)

In this chapter, we propose the use of economic indicators from an insurance model to complement water resources management, specifically the demand management. The adoption of such insurance-based indicators should improve risk perception, reduce risk, and translate the potential water deficit into a more tangible value for managers and policymakers. Understanding expected losses (or equivalent premiums for the functioning of an insurance scheme) would allow the government or river basin committees to explore different mechanisms for compensating for such losses, such as charging for water use or paying for environmental services.

3.2 THEORETICAL BACKGROUND

3.2.1 Water use permits

As determined by Brazil’s National Water Resource Policy (*Política Nacional de Recursos Hídricos* – PNRH) (BRASIL, 1997), water is a limited natural resource and a public property that must be available in suitable quantity and quality; moreover, its multiple uses must be assured. The PNRH guides the quality and quantity of water supply as well as the prevention of and defence against extreme hydrologic events. Northeast Brazil has a long history of droughts, But the last National Water Resources Plan (2012–2015) has also indicated the need to create contingency plans for droughts for the southeast region.

One of the most important instruments of the PNRH is the water use permit, which aims to ensure the sustainable use of water resources based on the assessment of water availability and widespread use of the water body (National Water Agency [ANA], 2014). The other instruments of the PNRH are the i) Water Resources Plan; ii) classification of water bodies according to prevailing uses; iii) charge for water use; and iv) Water Resources Information System. The deferment of a use permit is discussed among diverse actors (users, water resource management agencies, civil society representatives, etc.).

In Brazil, the water resources management under the PNRH faces yet another challenge. There is a disagreement between watershed and administrative limits and management. Some of the water resources solutions are municipal and some are a state responsibility while the water resource plans should be decided collectively inside the basin committees and coupled with land use planning (Tucci, 2008). This gap affects data availability, which is in many cases developed for administrative limits, which not always represent the watershed situation, and challenges the implementation of the instruments regarding their acceptability and success (Philippi Jr. et al., 2009).

The water use permit aims to control the rational use of water (National Water Agency, 2014). In Brazil, any water use of significant quantity above a certain threshold depends on a permit being granted by the public sector, with criteria related to the locality, water body allocation, and multiple uses (National Water Agency, 2014). In each new request, the basic procedure is the assessment of water availability based on a reference discharge to be determined. In Brazil, the reference discharge is considered to be a remaining discharge (National Water Agency, 2014), although it is different in each federal state (Table 3.1). These discharges, however, are actually developed from historical series of naturalized discharges and do not consider changes in the hydrologic regime (Silveira, Robaina, Giotto, & Dewes, 1998).

Table 3.1. Decision criteria for granting water use permits from each management agency

MANAGEMENT AGENCY	MAXIMUM GRANTABLE DISCHARGE	REFERRING LEGISLATION	INSIGNIFICANT DISCHARGE
NATIONAL WATER AGENCY (ANA)	70% of Q95 (the discharge exceeded 95% of the time), but this may vary among regions according to peculiarities. Up to 20% for each user.	Inexistent due to the country's peculiarities, which change the criteria	1.0 L/s (Resolution ANA 542/2004)
MINAS GERAIS WATER MANAGEMENT INSTITUTE (IGAM)	30% of Q7,10 (7-day average 10-year minimum discharge) for surface withdrawals or reservoirs; higher discharge may be released, maintaining a minimum of 70% of Q7,10 all the time	IGAM Ordinances ('Portarias') nº 010/1998 and 007/1999	1.0 L/s for most of the State; 0.5 L/s for regions facing water scarcity (surficial waters); 10.0 m³/day for groundwater (Deliberation CERH-MG nº 09/2004)
SÃO PAULO STATE WATER AND ELECTRICITY DEPARTMENT (DAEE)	50% of Q7,10 by basin. Up to 20% of Q7,10 for each user	Inexistent	5.0 m³/dia for groundwater (State Decree 32.955/91)

Source: National Water Agency (2014)

3.2.2 Risk aversion and risk transfer

The utility function is a subjective representation of one's satisfaction or welfare, which can be a function of money, goods, or services. Its numerical definition, however, is difficult. Risk aversion is the behaviour of people regarding risks and/or conservative attitudes (Cárdenas & Carpenter, 2008), numerically developed by Pratt (1964) and empirically observed by Szpiro (1986). The concept of risk aversion, or the statement of one person being more risk averse than another, is that, in the face of a risk, one is willing to pay insurance to diminish the risk, but would rather pay less for the risk transfer (Pratt, 1964). It is reasonable that a person with more assets is willing to pay more for their protection; however, the same person may seek to pay less for that protection. Indeed, Pratt (1964), Friend and Blume (1975), and Szpiro (1986) found, from different approaches, that people tend to be risk averse, i.e. positive coefficients of risk aversion. Risk-averse individuals, which are known in the market to comprise the majority, only accept larger risks if there are larger returns, or they prefer lower risks for the same return (Contador, 2007; Machina, 2013).

As a first strategy, individuals and society seek for structural measures to avoid or lessen the impacts from extreme events. After a natural catastrophic event or any substantially damaging event, there is a restoration phase, when individuals, non-governmental or governmental organizations work to restore corrupted essential services and provide supplies, and subsequently recover damaged assets from different groups as agricultural, business and housing sectors. In bigger events, a more intensive help comes from international organizations, which might take months to succeed (UNEP FI, 2007). A long-term cycle of losses and restoration weakens the local economy, reduces the livelihood of inhabitants, and increases their vulnerability to the next catastrophic event (Cummins & Mahul, 2008; Schwank et al., 2010).

This vulnerability "trap" leads people to risk (or invest) even less and undermines the attempts of growth while risks are too high, or while people's perception of risk is too high. Specially in developing countries whose GDP is highly affected by catastrophic events, there is a clear need for economic or financial mechanisms to support them and bear them to a more stable situation (Dixit & Mcgray, 2009), out of the "Catastrophe-Poverty" cycle.

If a number of individuals (natural persons or legal persons) are exposed to similar risks (similar source and magnitude) that result in economic losses that can be estimated and have heterogeneous nature, as is the case of natural hazards, it is possible and convenient to "pool the risk" and transfer it. One type of risk transfer is an insurance contract, where the affected persons pay premiums to a third party to manage the fund and indemnify them in case of losses, constrained by limits and other configurations set in a contract, such as which natural hazards are included (The Geneva Association, 2009; Vaughan & Vaughan, 2013).

Risk transfer mechanisms, such as an insurance, are seen as a resilience building mechanism (The Hyogo Framework for Action 2005-2015), an adaptation to climate change (Schwank et al., 2010), and as a regulatory mechanism (Ford, 2011). Insurance is one of the adaptation instruments listed in the UNFCCC decisions (Dixit & Mcgray, 2009).

The insurance market in several developing countries, including Latin America (Candel, 2007; Gaschen, Hausmann, Menzinger, & Schaad, 1998), covers only a small part of the population, usually not the most vulnerable nor the poorest. In developing countries, the insurance coverage and the hydrologic infrastructure and monitoring are too small for statistics and proper studies (Grey et al., 2013). These emerging economies are usually the most affected by natural hazards, in terms of affected GDP (Munich Re, 2014b), which does not encourage the expansion of insurer agencies and maintain the small coverage (Lamond & Penning-rowsell, 2014). It is stated that more mature insurance markets, as well as international reinsurers, are able to share their experience and cope with emerging economies as the market in the latter countries grow (Candel, 2007; Re, 2014).

Premiums, which are a common indicator of a nation's insurance market, are considered to be a consequence of two main country-specific features: market penetration, which is influenced by the population's culture and regulations, and macroeconomy in terms of real income, inflation (negative elasticity), currency, and population (Eq. 3.2; Contador, 2007). These two features act in different ways. In the short-term, the increase in population and wealth increases demand for insurance, whereas in the long-term, the consolidation of the insurance might provide a basis for economic growth (Contador, 2007). As a consequence, uncertainty in one nation's economy leads to uncertainty in the insurance market. Indeed, Brazil has shown little recent growth in penetration despite its economic situation, mainly led by the growth in life insurance.

$$vp \approx \rho + yp + \delta + e^{-1} + pop \qquad 3.2$$

where vp is the premium growth, which is close to the sum of ρ, penetration growth; yp, per capta income growth; δ, inflation growth; e^{-1}, national currency appreciation; and pop, population (Contador, 2007).

3.2.3 Water risks insurance design

In the practical context of insurance against water risks, the return variable could be understood as the individual's wealth, which will decrease in the case of extreme events and/or the premium payment (Gollier, 2013). Catastrophes can be projected by numerical models that generate a range of possible outcomes, to each of which is assigned a risk. In the context of water risks, given that the hydrologic regime itself is a changing system, its characterization should not rely on stationary conditions (Ehret et al., 2014), leading to the adoption of probabilities or the risk concept (Sampson et al., 2014).

Hydrologic risk models, as flood or drought risk models, usually have two main uncertainty sources (as in Sampson et al. 2014): the hazard component, responsible for events generation; and the vulnerability model, responsible for damage curves development, due to the number of factors that compose these curves and the lack of empirical data. New gauge stations and appropriate choice of the models for each component, given the unity of each basin, are highly suggested to diminish these uncertainties.

The ‘wealth’, within the insurance scheme, could be interpreted by the insurer agency (or the insured person) as the insurance fund (the personal wealth), which increases (decreases) with premium received (paid) and decreases (increases) with indemnities paid (received). From the insurer’s point of view, this balance may be written as Eq. 3.1 (Gollier, 2013), where P stands for the premium, $I(\emptyset)$ for the indemnity to be paid if event $\emptyset$ occurs, w_0 for the initial ‘wealth’, and e for the extra expenses such as administrative costs. Depending on the fund’s operation, this can be invested to receive interest payments.

$$w(\emptyset) = w_0 + P - I(\emptyset) - e \tag{3.1}$$

Any robust analysis should consider other influencing factors, and is conditioned on the time horizon, which may improve the projections of some variables, but may also increase the uncertainty of others related to the economy. These issues should then be developed for each contract in the insurer’s portfolio (Contador, 2007).

Several institutional arrangements and insurance models are found worldwide, each one fitting different situations (Dixit & Mcgray, 2009; Lamond & Penning-rowsell, 2014). The insurance configuration may foster risk reduction and prevention, whilst in other cases it leads people to maladaptation (Dixit & Mcgray, 2009; UNEP FI, 2007). The main issues to be observed by insurance design are adverse selection, affordability, maladaptation, solvency/sustainability, and uncertainty, as well as the perception of the risk by the exposed population, all of which affect insurance demand (Aliagha, Mar Iman, Ali, Kamaruddin, & Ali, 2013; Dixit & Mcgray, 2009; Lamond & Penning-rowsell, 2014; Tariq, Hoes, & Van de Giesen, 2013).

The aforementioned lack of data in emerging economies allows the risk transfer only at a higher price, which results in adverse selection and/or maladaptation (Contador, 2007).

People’s perception are related to their own past experiences and values, including social, cultural and economic aspects (Moura, 2011; L. Oliveira & Machado, 2004). The latter involves a trade-off, when there is some gain in livelihood by living in dangerous areas. Alternatively, people living in risky areas because “they want to” is an idea that cannot be disregarded, as there is a choice involved (Cannon, 2008; Contador, 2007), which adds another degree of uncertainty in the insurance market. As societies are more urban, the direct contact with nature decreases and several structures and technologies increase the welfare, reducing population awareness to the environment and long-term changes, such as climate change (Oliveira & Nunes, 2007). Low frequency or low damaging events are usually little recalled by population, but the former are usually the most damaging, and the latter, the most frequent one. This apparent gap in perception might be reduced by education and proper informative campaigns, where technicians and population exchange interpretations and some psychological approach hold place (Moura, 2011; Smith, 1992), where insurance availability and data may help (Sayers, Hall, & Meadowcroft, 2002).

Comprehensive studies and modelling about risk, exposure and affordability of local population to the hazard would foster the insurance market. Data from insurance companies is generally important for disaster planning. However, private companies own the majority of risk or insurance models, so they are not open for study and experimentation; and specially in the hydrologic context, academic research with insurance models is still scarce (Sampson et al., 2014).

There are several institutional design options for insurance (Graciosa, 2010). These include: mandatory or optional; index-based (Hazell & Hess, 2010) or observed damage; for individuals or the state; fully public or with private support; with the possibility of profit or with bonus discounts; and isolated (only one type of risk) or bundled (various disasters) (Dixit & Mcgray, 2009; Lamond & Penning-rowsell, 2014).

One must take into account some of the likely difficulties and obstacles to the development of the insurance market. In an index-based insurance scheme, indemnification is activated by the magnitude of a characteristic variable such as precipitation, discharge, or reservoir levels. Such an approach overlooks a punctual local evaluation of losses, which while easing the insurance operation and diminishing administrative costs, requires a more accurate risk calculation because of spatial variability as well as a way of monitoring the index (Dixit & Mcgray, 2009; Hazell & Hess, 2010). As the insured individuals are subjected to the index, it is in their own interest to reduce their risk and thus their losses. For the drought case, the existence of insurance also discourages illegal water withdrawals, for example. Moreover, for low-income households, the index-based insurance scheme should be implemented as a way of supporting more productive actions than being solely a risk protection measure (Osgood & Shirley, 2010). Not only would insurance reduce the insured person’s income variability, but also other actions must be sought to elevate his or her average income and lead him or her out of the ‘poverty trap’.

Reducing risk is in the insurer agencies’ interest, leading them to interact with the different sectors of society and encourage innovation to meet these goals (de Moel, van Alphen, & Aerts, 2009; Dixit & Mcgray, 2009; UNEP FI, 2007). Indeed, insurance models allow researchers to assess risk exposure (Winsemius, Van Beek, Jongman, Ward, & Bouwman, 2013), estimate the economic loss (Merz, Kreibich, Schwarze, & Thieken, 2010), and optimize the premium to be paid, enabling the transfer of risk to the third party, namely the insurer (Sanders et al., 2005).

However, the problem of adverse selection exists (Lamond & Penning-rowsell, 2014), where only the most vulnerable seek out insurance. Moreover, the sense of security/support can lead to maladaptation, making the population reckless, which may intensify the risk, as found by Lamond and Penning-Rowsell (2014) and by Dixit and McGray (2009). Therefore, one should always pay attention to the solvency of the insurance fund to ensure that it is sustainable. Because operations are inherently uncertain, they requiring the constant updating of information to reduce such uncertainties. It is also important to employ a direct mechanism to increase the perception of risk so that people themselves acting to reduce the risk (Pérez-Blanco & Gómez, 2013), as it becomes more favourable to employment insurance.

3.3 MATERIAL AND METHODS

3.3.1 Study case

The Cantareira Water Supply System (CWSS) is a set of reservoirs in the Piracicaba Basin connected through tunnels and channels that transfer water to the Tietê Basin to supply part of the Sao Paulo metropolitan region (National Water Agency/São Paulo state Water and Electricity Department, 2015). The 2013–2015 drought in southeast Brazil revealed the extent to which the region is vulnerable to a water shortage (SABESP, 2015). In 2012, precipitation was only 92% of the average; this dropped to 69% in 2013 and 61% in 2014, before rising to 104% in 2015 (SABESP, n.d.), leading the System that once supplied water to 8.8 million people reducing its coverage to less than 6 million people (Costas, 2015). One study using 2015 data suggested that the drainage area of Cantareira approximates a regime shift, with a lower ratio between rainfall and the flow into the reservoirs (Coutinho et al., 2015), which might be a result of the decrease in soil water levels.

The methodology that follows was applied to the drainage area of the System's reservoirs (Figure 3.2). The region is under the Atlantic Forest Biome, with an average annual rainfall of 1577 mm and an average discharge of 39 m^3/s (National Water Agency/São Paulo state Water and Electricity Department, 2015). The System started operation in 1974 with a 30-year permit, which was renewed for 10 years, and is currently under new studies for a new permit.

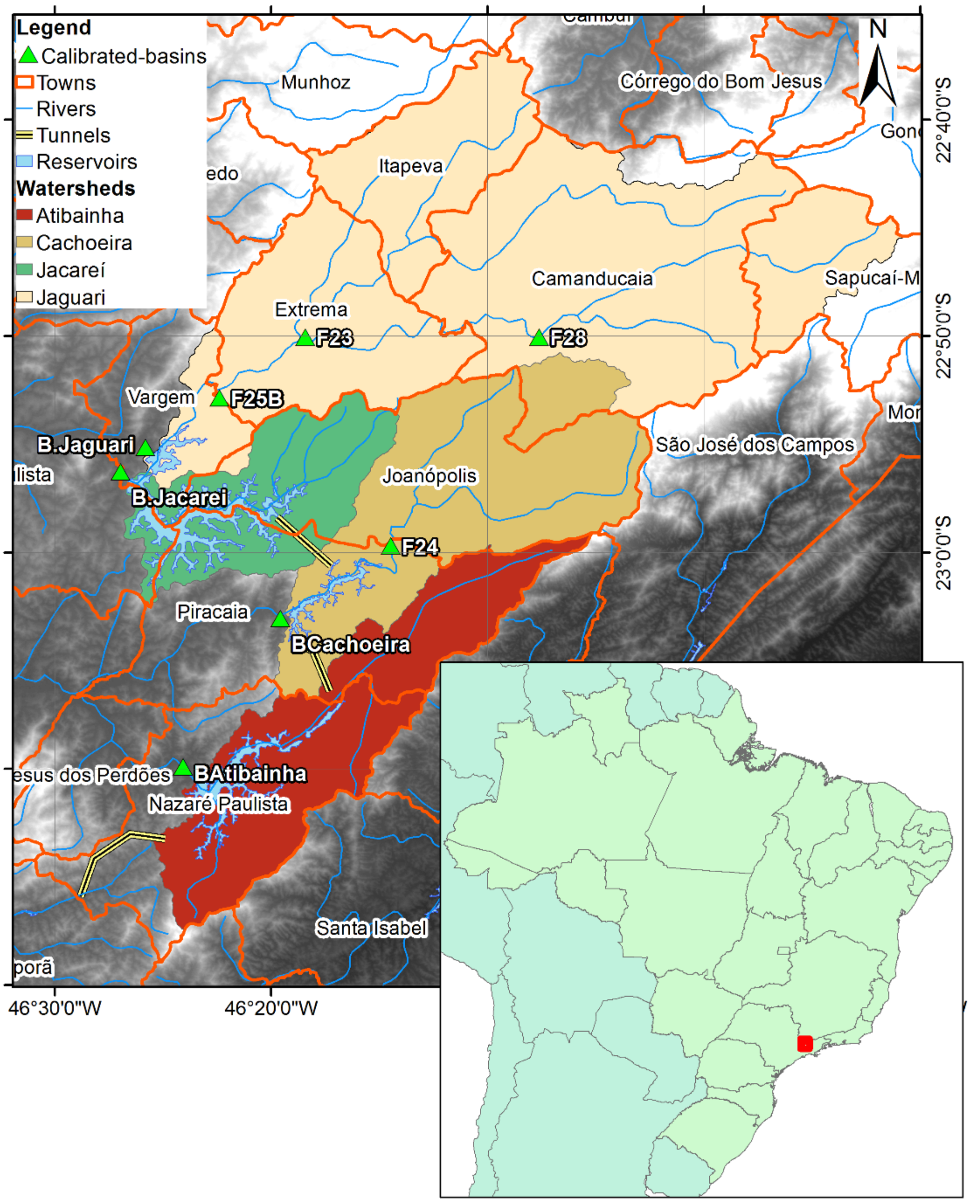

Figure 3.2. Location of the gauging stations – donor basins of Cantareira Water Supply System

Because the socioeconomic data are related to municipalities rather than watersheds, the outlets that delineate the drainage areas of the reservoirs (see ‘B’ for barrage in Figure 3.2) are more difficult to simulate the water withdrawal and the final use within a municipality may be in different watersheds. Therefore, only the watersheds upstream the reservoirs were considered. Their land uses and drainage areas, as integrated in each hydrologic model, are shown in Table 3.2. The differences in the table are a consequence of models’ structure and details in their basin delineation procedure.

Table 3.2. Land use and area of the watersheds

	SWAT				MHD			
SUB-BASIN	Area (km²)	Agriculture or Pasture	Forest (native or planted)	Urban	Area (km²)	Agriculture or Pasture	Forest (native or planted)	Urban
F25B	972	47.6%	51.5%	0.8%	981	53.8%	45.2%	1.0%
F23	508	63.4%	36.0%	0.5%	511	65.0%	34.3%	0.6%
F24	294	30.8%	69.2%	0.0%	295	50.0%	47.9%	1.0%
F28	277	9.6%	90.0%	0.3%	282	29.8%	70.1%	0.0%

3.3.2 MTRH-SHS structure

The Hydrologic Risk Transfer Model (MTRH) from the Hydraulic and Sanitary Engineering Department of the University of Sao Paulo (SHS), hereafter termed MTRH-SHS, is an insurance fund simulator developed to explore and study flood and drought risks from an economic perspective. It was first developed by Righetto and Mendiondo (2007) for floods, then extended by Graciosa and Mendiondo (2011) to include geographic information systems as auxiliary tools to develop flood risk maps and improve the representation of losses. Subsequently, Laurentis (2012) adapted the model to drought situations, constructing an off-line coupled sectoral damage-curve component that related the annual minimum distribution curve (from the Gumbel distribution) to economic losses.

Following Charpentier (2008) and Sampson et al. (2014), MTRH-SHS depends on an external module and comprises two more modules. The input data come from (i) the ‘hazard’ module (i.e. in this case, a hydrologic model developed for water yield scenarios); (ii) the ‘vulnerability’ module, which calculates economic losses per event; and (iii) the ‘financial’ module, which estimates the premium in light of the insurance configurations and simulations. The input data, which are specific for the study area, are as follows:

- Surficial flow (water yield, from module i): scale and location parameters of the Gumbel distribution for minimum flows.
- Water demand: usual demand in domestic, industrial, and agricultural sectors (annual volume); discharge of dumping and correspondent remaining organic load;
- Value of ‘execution’: price of m^3 of water for public supply; price elasticity; annual added value of industrial production; annual value of agricultural production; cost

of livestock raises per animal head (by size: large, medium, small); cost of sewage treatment.

Figure 3.3 shows the main components of the application of MTRH-SHS, specifying the models adopted in this case. It is worth noting that any given discharge series could be used as input data for the insurance fund simulation.

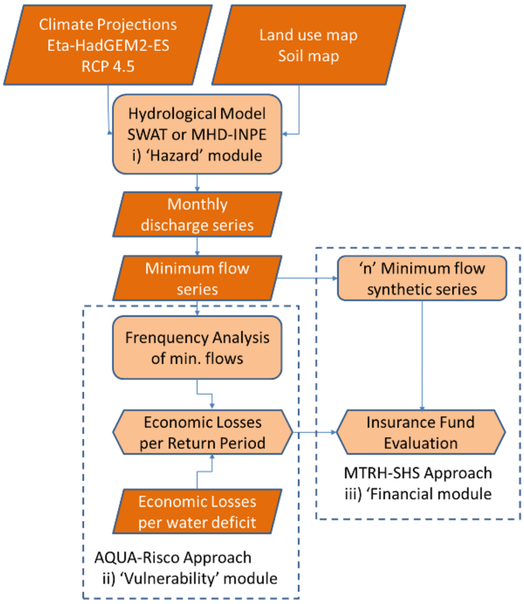

Figure 3.3. Flow chart of the MTRH-SHS application. Adapted from (Guzmán et al., 2015)

In light of global changes, projections are usually based on statistical information. Hence, the results should be understood as an average behaviour, and not as a prediction for a given moment. This implies that one should rely on the shifts/gaps in statistics from one characterized period to another instead of a data series (Allen & Ingram, 2002; Bravo et al., 2013; Demaria, Maurer, Thrasher, Vicuña, & Meza, 2013; Siqueira Júnior et al., 2015; Wood, 2002). Given the projection uncertainty, a way in which to internalize them is through the generation of equiprobable series by using the Monte Carlo method (Graciosa, 2010; Laurentis, 2012; Pinto & Naghettini, 2007).

The model is based on some premises and settings: (i) the construction of 'n' equiprobable discharge series to account for the uncertainty of the hydrologic regime (reconstructed or projected regime); (ii) index-based insurance, related to the period of return of the event (drought or flood); (iii) respect of maximum and minimum fund according to national rules; (iv) bundled, that is, all premiums and indemnities are one for the whole drainage area; and (v) the wealth of the target population and added value of the production of different sectors are considered to be constant (owing to the difficulty in making economic projections). Here, we adopted the generation of 100 series of low-flows, with 50 years each (probabilities had a range corresponding to 1 and 100 years of the return period). Each event has a fixed length and only its magnitude in terms of discharge changes. This is necessary because the insurance fund depends not only on the magnitude of events but also on their sequence. This behaviour may be compared to the threshold evolution framework presented by Siebert (2016), in which the premium is kept constant for a given return period event, but the magnitude of the event changes.

The MTRH-SHS proposed scheme is somewhat similar to a commercial "Business Interruption Insurance", which is a product against one type of loss possibly caused by a range of hazards (Association of British Insurers, 2014; Porto Seguro Seguros, personal communication, April 12, 2016), whilst we propose an insurance against one hazard that causes a range of loss types.

In an insurance mechanism the premiums are calculated by means of the expected risk of an event (Cummins & Mahul, 2008; Vaughan & Vaughan, 2013), i.e. the probability (Şen, 2015) multiplied by the averaged losses. In the drought (minimum extreme event) risk context, the premium takes the form of Eq. 3.3.

$$Insurance\ premium = \ Averaged\ Losses * \left(1 - \left(1 - \frac{1}{Return\ Period}\right)^{n}\right) \qquad 3.3$$

where n is the number of successive years, considered to be the insurance policy length of 50 years.

There are some more premises and configurations regarding the local regulation adopted in this version of MTRH-SHS. Resolution n.231, from the National Council of Private Insurance (CNSP, 2015), determines a minimum net worth to be assured, comprising the sum of the minimum required capital and risk capital. According to the resolution, the insurer has a period within which to solve an eventual low net worth (18 and 6 months for the minimum required capital and risk capital parcels, respectively). Because the values are in months and MTRH-SHS runs in an annual step, we consider that the fund may be in deficit in one year (SA < SA min) (one time step), requiring its solvency for the next year. When necessary, a loan is taken to address the balance, taking into account the following year's incoming premium. The number of parcels for the loan's payment, interest rate, and rate of return are open to change by the user. When observing the annual balance, the results may look negative in consecutive years; however, the balance is solved in an intermediate step and becomes negative again.

The premium optimization uses the nonlinear Generalized Reduced Gradient option of the Solver tool to minimize the loans required in each of the ‘n’ (100) series, according to the above-mentioned configuration. Then, the final optimized premium is the average of the ‘n’ premiums. Figure 3.4 summarizes the steps within the MTRH-SHS run.

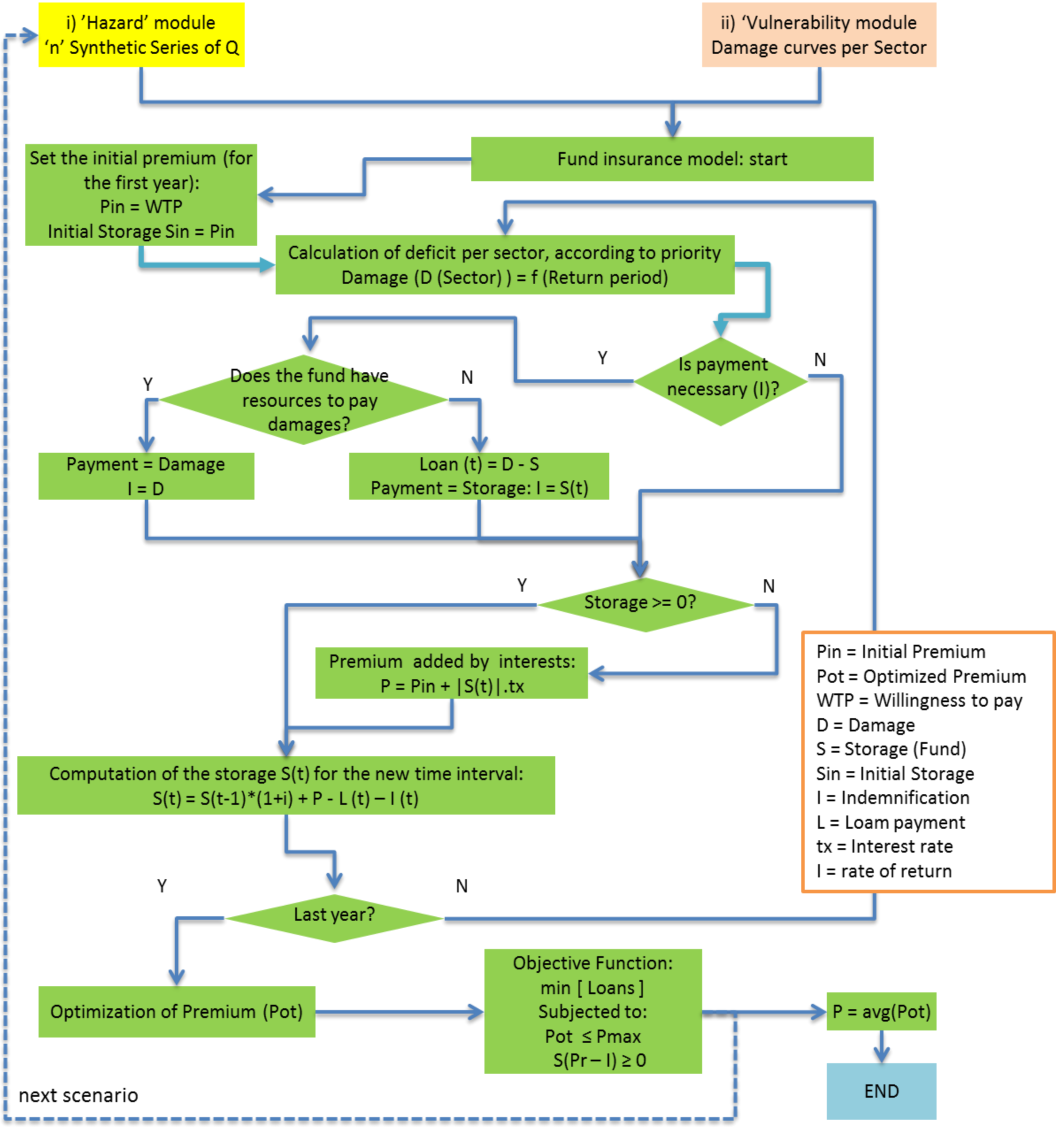

Figure 3.4. Calculations within MTRH-SHS

The sustainability indicators that MTRH-SHS calculates are the efficiency coefficient, which is the percentage of runs among the ‘n’ runs in each scenario, where the final optimized premium was larger than that calculated in that run; the Loss Ratio, which is the ratio between the average losses and optimized premium; and the solvency coefficient, calculated as in Eq. 3.4:

$$Solvency\ Coefficient = \frac{Optimized\ Premium - Average\ Losses}{Average\ Losses} \quad 3.4$$

To assess the water deficit, two pieces of information are needed: the water yield (i.e. the superficial discharge in this case); and water demand in the drainage area.

3.3.3 Water yield and demand

The water yield was developed from two hydrologic models, namely SWAT (Arnold, Moriasi, et al., 2012; Rodrigues, Gupta, & Mendiondo, 2014) and MHD-INPE (Mohor et al., 2015; Siqueira Júnior et al., 2015), driven by the Regional Climate Model Eta-INPE (Chou et al., 2012; Pilotto, Chou, & Nobre, 2012), with 20 km of horizontal resolution through dynamic downscaling. The model was run under the climate projections with the RCP 4.5 scenario (Thomson et al., 2011), with the boundary layer from HadGEM2-ES (Chou, Lyra, Mourão, Dereczynski, Pilotto, Gomes, Bustamante, Tavares, Silva, Rodrigues, Campos, Chagas, Sueiro, Siqueira, & Marengo, 2014; Chou, Lyra, Mourão, Dereczynski, Pilotto, Gomes, Bustamante, Tavares, Silva, Rodrigues, Campos, Chagas, Sueiro, Siqueira, Nobre, et al., 2014).

SWAT is a widely used semi-distributed model that divides the river basin into sub-basins and hydrologic response units determined by soil type, land use class, and slope. The model has been adopted in several applications of water resources impact assessment, including quality evaluation. This conceptual model comprises the following components: climate, hydrologic, soil properties, vegetation growth, nutrients, pesticides, bacteria and pathogens, and land use management (Gassman et al., 2007). Developed in the United States, it has increasingly been applied in Brazilian basins for many purposes (Bressiani et al., 2015).

MHD-INPE is a semi-conceptual distributed model developed in Brazil that has been applied in a number of Brazilian basins (Rodriguez, 2011; Mohor et al., 2015; Siqueira Júnior et al., 2015; *personal communication*). The model divides the river basin into regular cells and hydrologic response units for each soil type and land use class. It thus represents the soil in three layers and solves hydrologic sub-processes: soil water balance, evapotranspiration, superficial and sub-superficial runoff, and network water routing.

The calibration and validation of the hydrologic models have been presented in Chapter Two. Here, we choose to work only with basins that have information about current active water use permits and demand in the basin's committee plan (COBRAPE, 2008) and the state environmental management agencies.

For the calibration, the input data to the hydrologic models were:

- Soil map from Oliveira (1999) (1:500,000);
- Land cover map of 2010 from Molin (2014) (1:60,000);
- Digital Elevation Model Aster v.2 (Tachikawa et al., 2011) (1:60,000);
- Meteorological data from National Institute of Meteorology, (2014) and Center for Weather Forecasting and Climate Research (CPTEC, personal communication, 2014) databases;
- Discharge and precipitation data series from the National Water Agency database (http://hidroweb.ana.gov.br), SABESP (personal communication, 2014), and DAEE (personal communication, 2014);
- Water use (withdrawals or dumping) from DAEE and IGAM, the environmental management agencies of the states of Sao Paulo and Minas Gerais, and information from the basin's committee plan (COBRAPE, 2008).

The insurance model divides demand into five user sectors: domestic, industrial, livestock, agriculture, and environmental (meaning the water volume needed to dilute organic loads in sewage dumping without treatment). The data available from the basin's plan include domestic, industrial, and irrigation demand (m^3/s) and the remaining organic loads without treatment (the biological oxygen demand (BOD), in kg/day, is the variable adopted due to data availability and popularity among related studies, although it is not the most limiting factor). For the livestock sector, however, there is no indication of water use. The approach was to consult the animal herd in the region and consider the average amount of water needed per head of livestock per day.

Seven demand scenarios were tested, by varying the percentage of total demand from -20% to +20% and maintaining the ratio among sectors. Although we develop the water yield values for future periods through a climate projection, the comprehensive nature of economic development made us adopt a fixed demand rate and respective loss per water deficit for all periods and scenarios, except for a change in total demand, still keeping fixed the ratio among the sectors' demand levels.

3.3.4 Economic losses per water deficit

The economic losses of each sector were calculated as the average relationship between the cost of 'execution' (i.e. production or supply) and corresponding water use. The simpler equation is the annual value of production by volumetric demand, resulting in a fixed ratio in \$ per m³, thereby setting a linear relationship between deficit and economic losses.

For the domestic sector, we used the development from Aubuchon and Morley (2013), which is a modification of the method presented by Brozović et al. (2007):

$$Domestic_{loss\ per\ day} = \frac{\eta}{1+\eta} * Price * Q_0 * \left[1 - \left(\frac{BWR}{Q_0}\right)^{(1+\eta)/\eta}\right] \tag{3.5}$$

where η is the price elasticity; Price is the average price of water supply charged by the water supply company; Q_0 is the usual demand; and BWR is the basic water requirements.

The prices charged by the water supply and sewage treatment company (or companies) are needed as well as the cost of production or the value added by the sector to the economy. For the domestic sector, the price elasticity is required (Econômicas, 2009). The regular water supply price is also needed. In Sao Paulo State, the majority of the study case area, SABESP supplies water and collects and treats sewage dumping in most cities; this company also operates the System. Thus, for the domestic and environmental (dilution) sectors, we adopted the price charged by this company for their services.

For the environmental sector, the natural concentration of BOD is required as well as the permitted concentration in the sewage, according to national/local laws. The natural concentration was derived from the water quality stations from CETESB and IGAM, the environmental management agencies of Sao Paulo and Minas Gerais States, respectively.

The water demand for dilution is understood as the same as the grey water footprint, which represents the amount of water required to dilute the load to the permitted value of dumping (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011). The calculation is shown in Eq. 3.6:

$$Water\ demand\ for\ dilution \;\; = \; Qefl * \frac{(Cefl - Cperm)}{(Cperm - Cnat)} \tag{3.6}$$

where $Qefl$ is the discharge of the effluent; $Cefl$ is the remaining concentration of BOD in the effluent; $Cperm$ is the concentration of BOD permitted by law; and $Cnat$ is the natural concentration in the water body of BOD.

The effluent discharge was derived from the basin's plan (COBRAPE, 2008). The value of the remaining BOD load was converted into a discharge equivalent needed to dilute the load to make it comparable with the demand levels and losses from the other sectors.

The industrial sector's economic losses were based on the value added by the industry sector, derived from the Brazilian Institute of Geography and Statistics' SIDRA Database[1]. For the industrial sector, the work of Brozović et al. (2007) was adopted (Eq. 3.7):

$$Industrial_{loss\ per\ day} = \frac{1 - r_x}{0.95} * [\alpha_x * (1 - z_x) - 0.05] * Production_{per\ day} \quad 3.7$$

where r_x is the resilience of sector x to the lack of water; α_x is the dependence of sector x to the water source (surficial water in this case); and z_x is the percentage of water shortage for the sector (0 for complete outage, 1 for normal supply).

The resilience, in Eq. 3.7, varies from sector to sector of activity, meaning that an average value was adopted from Aubuchon and Morley (2013). The percentage of the shortage was considered to be the total outage for the calculation of economic losses per m³. Then, if there was not a complete outage, a linear relation is adopted. The dependence of the industrial sector to surficial water was derived from the basin's plan (COBRAPE, 2008).

For the agriculture and livestock sectors, a simple ratio of annual production per water demand was adopted. Agricultural production was derived from the Agricultural Census produced by the Brazilian Institute of Geography and Statistics[2]. For livestock, the cost of production was adopted, with values taken from the Brazilian Agricultural Research Corporation[3].

3.4 RESULTS AND DISCUSSION

The four stations presented allow a comparison between upstream (F28 and F23) and downstream (F25B) stations of the same basin as well as with a station from another basin (F24), presented in this order.

Table 3.3 shows the current demand per sector for each station and the cost per volume of the water deficit. Notably, the environmental sector (dilution of organic loads) has the most water demand (more than 75%). All values were calculated in Brazilian Reais and converted into US Dollars at the ratio of 2.85, the average of the past two years (2014–2015)[4].

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[1] http://www.sidra.ibge.gov.br/

[2] http://www.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/

[3] https://www.embrapa.br/

[4] http://economia.uol.com.br/cotacoes/cambio/dolar-comercial-estados-unidos/?historico.

Table 3.3. Summary of demands and cost per water deficit in the studied outlets

'COST' OF WATER	**F28**	**F23**	**F25B**	**F24**	
Environmental	0.84	0.27	0.84	0.84	USD/m³
Industrial	4.49	43.32	12.36	101.54	USD/m³
Agriculture	9.35	17.80	0.94	0.89	USD/m³
Livestock	68.51	2.88	55.20	49.90	USD/m³
Domestic	18.07	0.84	17.91	17.99	USD/m³
WATER DEMAND					
Environmental	42816	44314	354292	36620	m³/day
Industrial	5116	9682	15897	66	m³/day
Agriculture	1650	16897	22463	3972	m³/day
Livestock	598	480	1557	492	m³/day
Domestic	5446	2761	16587	3244	m³/day
Water Demand Without Environmental Sector	0.148	0.345	0.654	0.090	m³/s

We used five periods, or five hydrologic regimes, namely the simulation period with observed data (2004–2014, used for calibration and validation), the historical period using Eta-HadGEM2-ES data (1976–2005), and the three future periods with projected data from Eta-HadGEM2-ES (2007–2040, 2041–2070, 2071–2099). In each period, the annual minimum discharge in each outlet was fit to the Gumbel distribution by using a MatLab function. The Gumbel distribution, which has also been chosen in previous applications of the model (Graciosa, 2010; Laurentis, 2012), relies on two parameters: the location parameter, which gives a notion of magnitude, and the scale parameter, which gives a notion of variability. Figure 3.5 shows the curves created from the distribution, based on a 1- to 100-year return period. This figure shows that in some cases, the discharge never reaches zero, while in other cases, it declines rapidly as a result of the scale parameter fitted to the minimum values generated by the hydrologic models.

It is noticeable that the Gumbel distribution tends, in some cases, to very homogeneous values or extreme values reaching the global minimum. This behaviour is to some extent due to the input data, which is constrained by the time step used (monthly). However, in other cases the curve is similar to the expected behaviour.

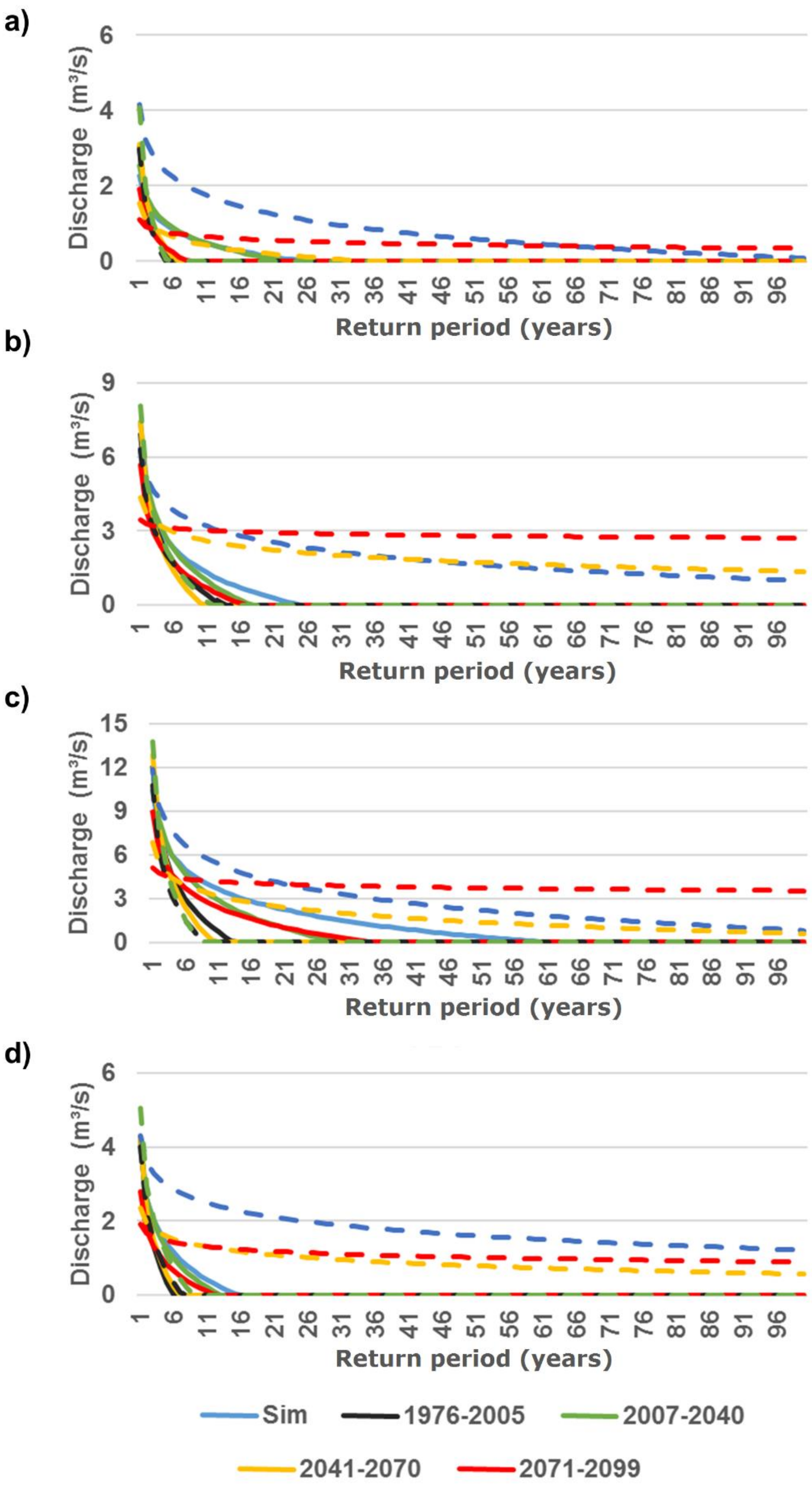

Figure 3.5. Minimum flows fitted to the Gumbel distribution for the a) F28, c) F23, c) F25B, and d) F24 outlets from SWAT (solid lines) and MHD (dashed lines) outputs

3.4.1 Economic losses per return period event

In this section, only the curves for the simulation period are presented for illustration purposes. These results relate the low-flow event magnitude (for a given return period) to the economic losses corresponding to deficit of water in each sector according to the priority of demand. This exercise considers that all water demand inside the drainage area of a watershed is met by the discharge in its rivers, regardless of the challenges of water transfer or other strategies that might be required (Zeff, Kasprzyk, Herman, Reed, & Characklis, 2014). Only the current (100%) and extreme demand scenarios are shown in Figure 3.6. In every case, the losses reach a maximum then remain constant even in more extreme events because a complete shortage was already reached. It is worth noting that other socioeconomic impacts could take place, but are out of the scope of this exercise. In the F24 station, for the simulation period, the MHD runs showed no deficit because of the minimum discharge generated by using the Gumbel distribution (see again Figure 3.5), even for the higher demand scenario.

A sensitivity analyses was accomplished varying the heterogeneity of the events during in a single run, with the average loss fixed. It was observed that more heterogeneous events (gradually varying from no loss to any given loss) results in a higher optimized premium than a run with more homogeneous events, i.e. a constant loss, or few levels of losses, for example, only two possible outcomes: no loss or a maximum loss.

3.4.2 MTRH-SHS runs

From Table 3.4 to Table 3.7 show, for each outlet, the maximum grantable water according to the State regulation and main results from the runs with MTRH-SHS for the current (100%) demand scenario. Despite the values shown in Table 3.3, the environmental sector represents virtual demand that should be summed up; however, these volumes do not count towards an actual use permit. We see that while the sum of the permitted uses (or actual demand, Table 3.3, last line) does not surpass the maximum amounts allowed in each State (from Table 3.4 to Table 3.7, column 2; according to the rules in Table 3.1), in the current hydrologic regime or near future periods, they are violated in the following periods.

We confirm that the hydrologic model runs were made in a monthly step, although the calculation of Q7,10 uses daily data. Moreover, the MTRH-SHS runs consider demand in all five sectors and the Gumbel distribution of minimum flows, with monthly data.

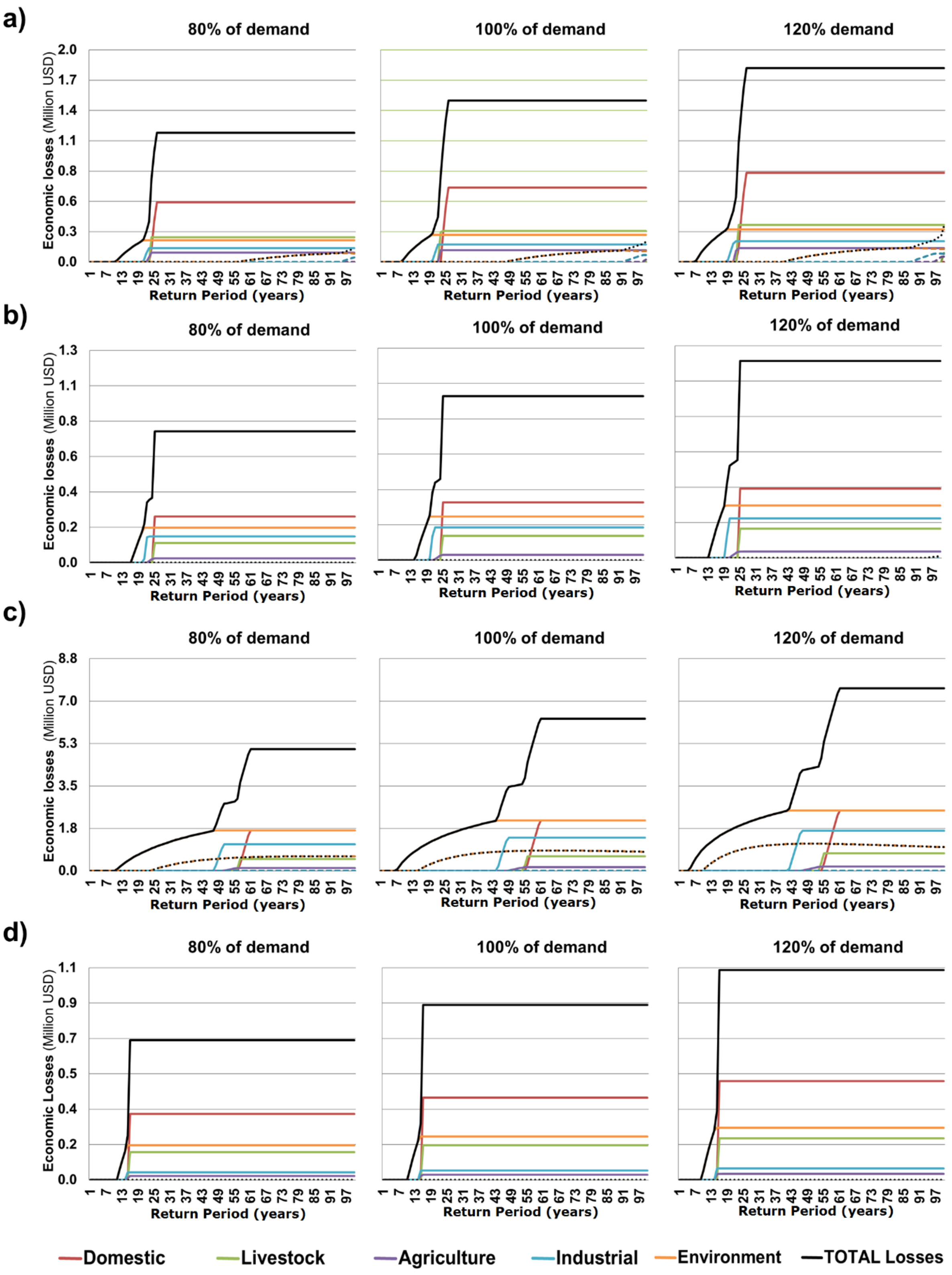

Figure 3.6. Economic losses due to water deficit in each sector per event in watersheds a) F28, b) F23, c) F25B, d) F24. Solid lines for SWAT runs, dashed lines for MHD runs

Table 3.4. Summary of the MTRH runs for the F28 outlet (inside Minas Gerais State)

F28 (MG)	**Max. grantable [m³/s]**	**Optimized Premium [USD] (% of GDP)**		**Losses (ann. avg) [USD]**	**Efficiency Coeff.**	**Solvency Coeff.**	**Loss Ratio**
SWAT							
Sim	0.201	128,744	(0.14%)	62,237	0.58	1.07	0.48
1976–2005	0.169	346,046	(0.38%)	275,652	0.52	0.26	0.80
2007–2040	0.222	137,614	(0.15%)	69,839	0.62	0.97	0.51
2041–2070	0.099	328,440	(0.36%)	258,009	0.52	0.27	0.79
2071–2099	0.071	296,906	(0.33%)	226,003	0.53	0.31	0.76
MHD							
Sim	0.639	6,882	(0.01%)	1,691	0.52	3.07	0.25
1976–2005	0.218	422,241	(0.46%)	357,383	0.58	0.18	0.85
2007–2040	0.229	397,232	(0.44%)	329,930	0.56	0.20	0.83
2041–2070	0.223	109,836	(0.12%)	50,813	0.52	1.16	0.46
2071–2099	0.197	8,798	(0.01%)	4,395	0.52	1.00	0.50

Table 3.5. Summary of the MTRH runs for the F23 outlet (inside Minas Gerais State)

F23 (MG)	**Max. grantable [m³/s]**	**Premium Optm. [USD] (% of GDP)**		**Losses (ann. avg) [USD]**	**Efficiency Coeff.**	**Solvency Coeff.**	**Loss Ratio**
SWAT							
Sim	0.672	81,491	(0.06%)	38,512	0.57	1.12	0.47
1976–2005	0.565	127,344	(0.10%)	79,028	0.54	0.61	0.62
2007–2040	0.700	57,269	(0.05%)	57,269	0.58	0.82	0.55
2041–2070	0.553	153,497	(0.12%)	103,814	0.56	0.48	0.68
2071–2099	0.418	111,316	(0.09%)	64,081	0.57	0.74	0.58
MHD							
Sim	1.056	0	(0%)	0	0.00	0.00	0.00
1976–2005	0.950	125,917	(0.10%)	77,630	0.53	0.62	0.62
2007–2040	0.928	92,093	(0.07%)	92,093	0.56	0.54	0.65
2041–2070	1.026	0	(0%)	0	0.00	0.00	0.00
2071–2099	0.856	0	(0%)	0	0.00	0.00	0.00

Table 3.6. Summary of the MTRH runs for the F25B outlet (inside Minas Gerais State)

F25B (MG)	**Max. grantable [m³/s]**	**Premium Optm. [USD] (% of GDP)**		**Losses (ann. avg) [USD]**	**Efficiency Coeff.**	**Solvency Coeff.**	**Loss Ratio**
SWAT							
Sim	1.349	350,600	(0.03%)	169,903	0.47	1.06	0.48
1976–2005	1.179	980,475	(0.10%)	678,576	0.58	0.44	0.69
2007–2040	1.504	574,738	(0.06%)	307,644	0.56	0.87	0.54
2041–2070	1.063	1,145,290	(0.11%)	838,261	0.60	0.37	0.73
2071–2099	0.919	602,121	(0.06%)	349,053	0.54	0.73	0.58
MHD							
Sim	1.999	94,707	(0.01%)	42,494	0.49	1.23	0.45
1976–2005	1.343	1,332,970	(0.13%)	1,040,801	0.54	0.28	0.78
2007–2040	1.359	1,316,457	(0.13%)	1,021,625	0.56	0.29	0.78
2041–2070	1.373	257,025	(0.03%)	188,840	0.56	0.36	0.73
2071–2099	1.234	109,058	(0.01%)	89,434	0.52	0.22	0.82

Table 3.7. Summary of the MTRH runs for the F24 outlet (inside São Paulo State)

F24 (SP)	**Max. grantable [m³/s]**	**Premium Optm. [USD] (% of GDP)**		**Losses (ann. avg) [USD]**	**Efficiency Coeff.**	**Solvency Coeff.**	**Loss Ratio**
SWAT							
Sim	0.493	97,146	(0.25%)	55,174	0.58	0.76	0.57
1976–2005	0.452	210,864	(0.54%)	169,850	0.52	0.24	0.81
2007–2040	0.542	115,855	(0.30%)	72,147	0.56	0.61	0.62
2041–2070	0.355	186,248	(0.48%)	144,712	0.54	0.29	0.78
2071–2099	0.327	122,171	(0.31%)	79,276	0.56	0.54	0.65
MHD							
Sim	1.318	0	(0%)	0	0.00	0.00	0.00
1976–2005	0.655	171,071	(0.44%)	129,522	0.53	0.32	0.76
2007–2040	0.698	150,326	(0.38%)	108,000	0.54	0.39	0.72
2041–2070	0.716	0	(0%)	0	0.00	0.00	0.00
2071–2099	0.528	0	(0%)	0	0.00	0.00	0.00

In F28, F23, and F25B, the sub-basins of the same watershed, the MHD projections resulted in sufficient water for the currently granted sum. However, when environmental demand is counted, the demand is not met, and the optimized premium may vary from 0.01% to 0.46% of local GDP in F28, from 0.05% to 0.12% in F23, and from 0.01% to 0.13% in F25B. It is noteworthy that these values are more extreme than the SWAT values in both cases. In the F28 outlet, the last periods of the SWAT runs resulted in a grantable water use, under the Q7,10 current rule, that was lower than actual demand (demand without the environmental sector).

In F24, all the scenarios indicate that actual demand has been met, while the MHD projections for some periods, fitted to the Gumbel distribution are not sufficiently low to provoke losses, as in F23; therefore, no premium was calculated in these cases. In relative terms, the optimized premiums for F24 reach the larger parcel of local GDP, up to 0.54% from the SWAT results, or 0.44% from the MHD results.

3.4.3 Optimized premium

Figure 3.7 shows the optimized premiums for the selected stations and scenarios per station. The behaviour is the same in all cases: an increase in demand, which varies linearly and which results in a linear increase in the premium. There is unexpected behaviour in the F23 simulation of the calibration period because only the highest demand scenario (120%) results in a water deficit, while in the lower demand scenarios, there is none. This behaviour seems different when the minimum flows in a scenario only partially meet a given demand level, but not a higher demand, as in the case of the F25B station MHD run driven by Eta-HadGEM2 from 2071 to 2099. In this hydrologic scenario, demand is partially met (up to 105%), above which there is an economic loss every year, changing the behaviour of the fund simulations.

In the F24 outlet, for the MHD runs in the 2071–2099 period and in the simulation period, the premium is zero because the discharge calculated from the Gumbel distribution is always sufficient for the demand levels. In the 2041–2070 period, only higher demand leads to a water deficit (as in the F23 simulation period), but only partially, resulting in the values being too low to be noted in Figure 3.7.d.

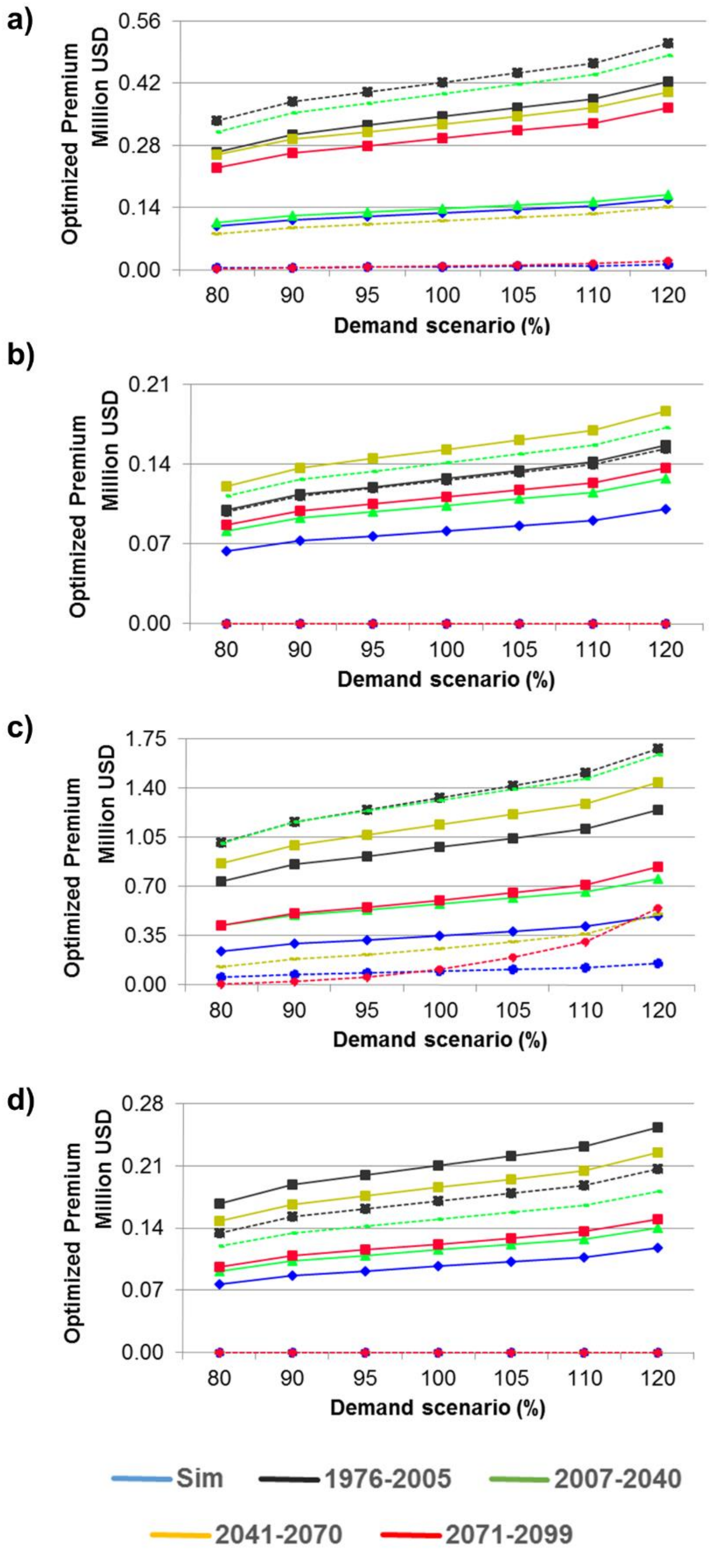

Figure 3.7. Optimized premiums for a) F28, b) F23, c) F25B, and d) F24

Table 3.8 shows the percentage change in each run between the lower demand (80%) and higher demand (120%) scenarios. A reduction or increase of 20% of demand from the current values may alter the premiums largely. The MTRH-SHS runs using SWAT data, as observed in hydrologic terms, are much steadier than those with MHD data. The premiums calculated with MHD for the 120% of demand scenario are at least 52% higher than those for the 80% of demand scenario.

Table 3.8. Percentage difference between premiums optimized for 120% of demand and 80% of demand

	SWAT					**MHD**				
Outlet	**Sim.**	**1976–2005**	**2007–2040**	**2041–2070**	**2071–2099**	**Sim.**	**1976–2005**	**2007–2040**	**2041–2070**	**2071–2099**
F28	62	59	60	55	59	198	52	56	74	625
F23	57	57	56	55	58	---	56	54	---	---
F25B	104	69	78	66	99	188	67	63	302	16507
F24	53	52	53	52	56	---	53	52	---	---

3.4.4 Insurance sustainability indices

The solvency coefficient, which indicates the capacity of the fund to honour its debts and/or make a profit, is based on the relationship between the optimized premium and average losses. Increasing demand tends to result in a decrease in the solvency coefficient, as shown in Figure 3.8, with the exception of the F28 station MHD run in the calibration and the validation periods. As noted in other indices, behaviour changes when low-flow events still meet most of demand, resulting in a biased premium, which is optimized to cover the minimum fund balance.

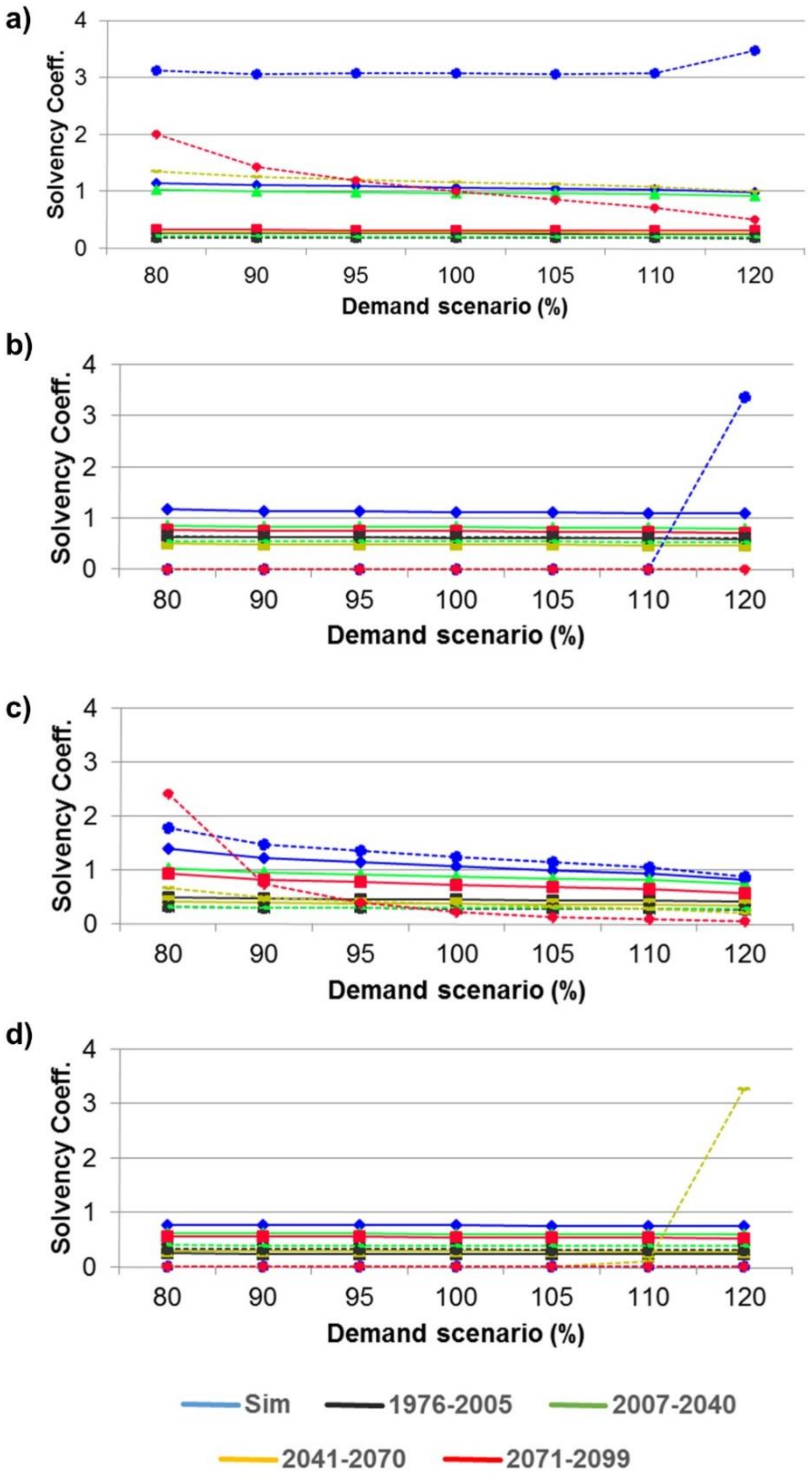

Figure 3.8. Solvency coefficients for the a) F28, b) F23, c) F25B, and d) F24 outlets

The loss ratio indicates how much of the premium is promised to the indemnities in the long-term (Figure 3.9). In F28, the loss ratio from the MHD runs with the Eta-HadGEM2-ES projections decreases from the historical period to the future periods, which means that the optimized premium becomes relatively large in order to assure that all losses are indemnified.

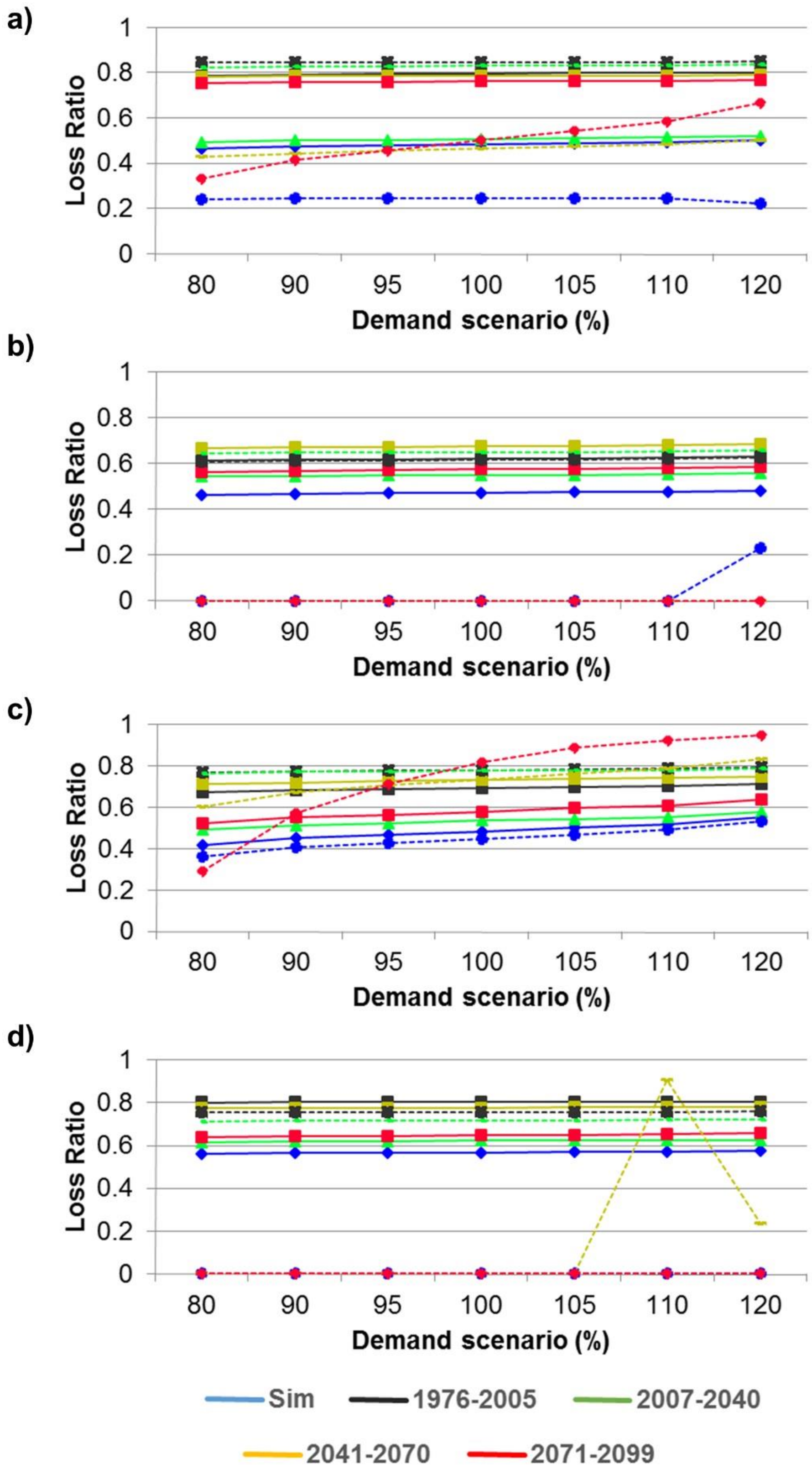

Figure 3.9. Loss ratios for the a) F28, b) F23, c) F25B, and d) F24 outlets

Different behaviour is found in the MHD run for the 2071–2099 in the F28 and F25B watersheds, upstream and downstream of the main river, as observed in previous features. This round behaves unexpectedly because of the Gumbel adjustment. In this run, although the annual minimum flows are on average lower, they are more homogeneous, meaning that a complete outage is not reached by using the Gumbel distribution.

In the F24 case (Figure 3.9.d), the strange behaviour of the MHD run in 2041–2070 is caused by the Gumbel-generated series. As seen before, the discharges generated with the Gumbel distribution are so close to demand that the Solver solutions shift from the usual behaviour, ending with an optimized premium just above the expected losses. According to de Souza (2007), the average loss ratio in Brazil is 0.67 (or 67%), which is considered to be very high. Our results confirm this standard, although with some exceptions because the Gumbel distribution fitted curves that do not reach zero streamflow.

3.4.5 Decisions on granting water use permits

The practical approach suggested here aims to verify whether the population affected by the studied drainage area is capable of contracting insurance to mitigate possible economic damage due to the water deficit foresaw in the case of higher demand (i.e. the deferment of a new water use permit). Because such a permit is valid for up to 35 years in Brazil, only the near and intermediate future periods are considered in this section. Figure 3.10 to Figure 3.13 show the optimized premiums for each demand scenario and period in each watershed, along with percentages of local GDP. We note a spread among the models and runs, showing that the hydrologic regime projected may change largely and that the premiums may also be different. The different percentages of GDP marked in the figures help observe how much of the region's wealth would be compromised by the water deficits, according to the methodology here applied.

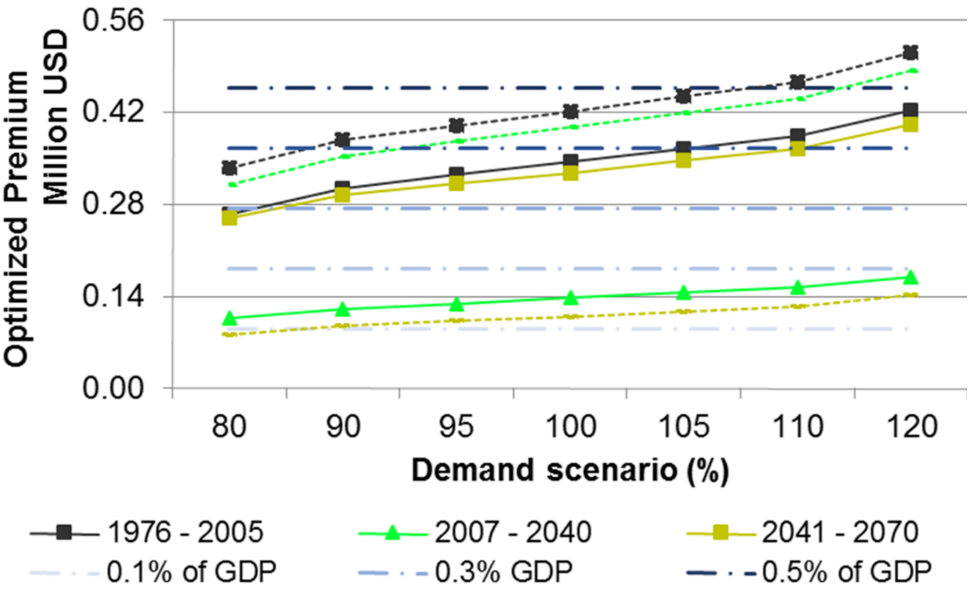

Figure 3.10. Optimized premiums and percentage of GDP in the F28 watershed

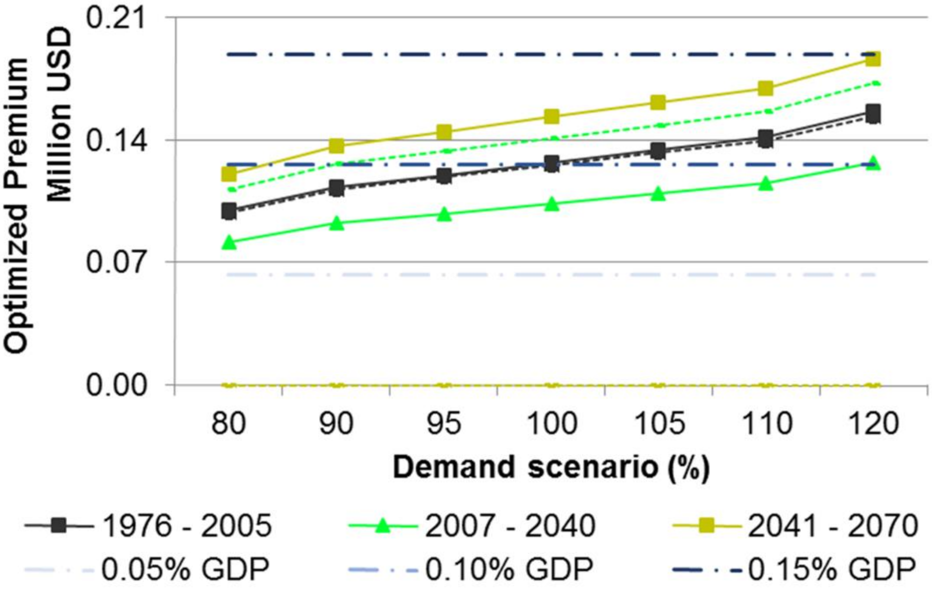

Figure 3.11. Optimized premiums and percentage of GDP in the F23 watershed

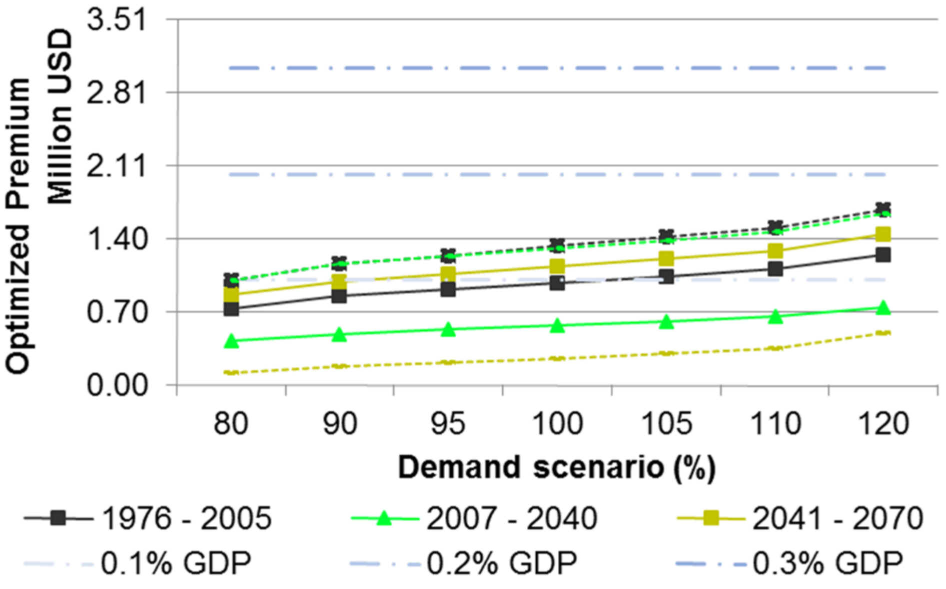

Figure 3.12. Optimized premiums and percentage of GDP in the F25B watershed

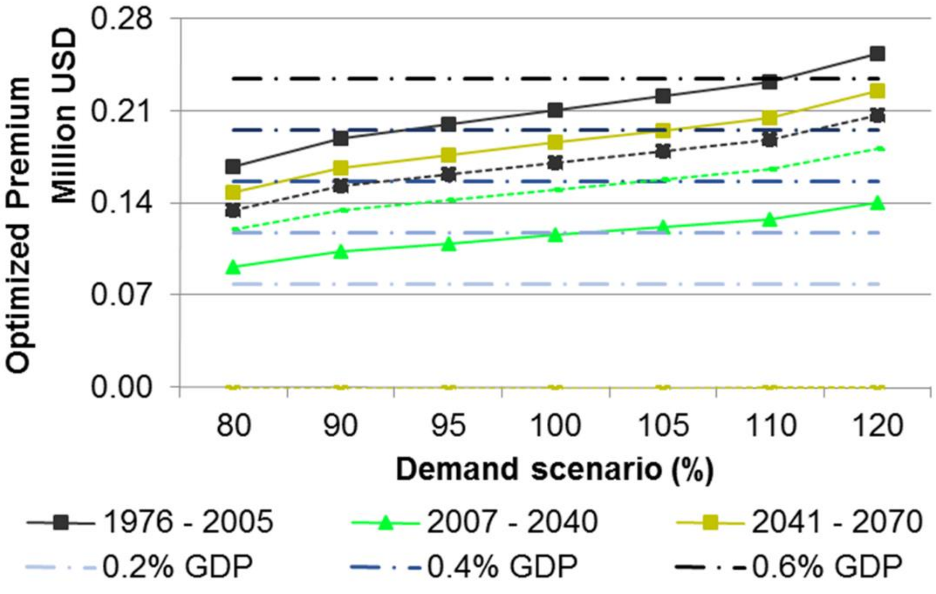

Figure 3.13. Optimized premiums and percentage of GDP in the F24 watershed

In F28 (Figure 3.10), for example, for an increase in demand of 20%, according to the MHD runs in the near future (2007–2040) hydrologic regime, the premium for this drainage area would become more than 0.5% of its GDP. However, with SWAT, for the same period, the premium is much lower, between 0.1% and 0.2% of GDP, leading to uncertain results. In F23 (Figure 3.11), the optimized premiums represent a smaller percentage of local GDP, reaching 0.15% in the worst scenario. The F25B results (Figure 3.12) are under 0.2% of GDP, while the variation in the premiums for the 80% to 120% demand scenarios in this watershed is the largest among all the basins (Table 3.8). For the F24 outlet (Figure 3.13), on the contrary, all scenarios result in premiums above 0.2% of GDP, with the exception of the MHD run (no deficit, already pointed out as an abnormality). Under the hydrologic regime characterized by the SWAT run for the historical period, an increase in demand would make the premium 0.6% of local GDP. In addition, Table 3.9 presents the differences between the premium for current demand (100%) and the case of a 20% increase in demand (120% of demand) in terms of the local GDP percentage. This demand increase may be as high as 0.10% of local GDP, as in the F28 MHD run.

Table 3.9. Increase in the optimized premium in the case of a 20% increase in demand, in terms of percentage of GDP

Hydrologic model	**SWAT**					**MHD**				
Period	**Sim.**	**1976–2005**	**2007–2040**	**2041–2070**	**2071–2099**	**Sim.**	**1976–2005**	**2007–2040**	**2041–2070**	**2071–2099**
F28	0.03	0.09	0.04	0.08	0.07	0.01	0.10	0.09	0.04	0.01
F23	0.02	0.02	0.02	0.03	0.02	0.00	0.02	0.02	0.00	0.00
F25B	0.01	0.03	0.02	0.03	0.02	0.01	0.03	0.03	0.02	0.04
F24	0.01	0.02	0.01	0.02	0.01	0.00	0.02	0.01	0.00	0.00

The methodology proposed here is carried out backwards. First, the parcel of GDP that could be reserved for the insurance is determined by the cities or population. Second, this value is confronted in the figures to find the percentage of demand that fits that value, according to the variation in hydrologic regimes. Finally, the environmental agency would decide if the water use permits may be deferred, according to the capacity of covering the foreseen economic costs. Alternatively, it would add the cost as a condition to the permit deferment, as an extra to tax revenues for further risk reduction measures.

3.5 CONCLUSION

In this chapter, we presented an application of the insurance fund simulator MTRH-SHS with hydrologic projections under climate change to show the products derived from the insurance model and to compare the optimized premiums with the local economic wealth, as represented by GDP. Regarding the feasibility and solvency of an insurance fund, some issues must be taken into account to enhance the mechanism’s success if it were to be applied in the real world. The chosen design may result in adverse selection or maladaptation, which would affect the fund’s affordability and sustainability. On the contrary, the scheme is influenced by the target population’s risk perception as well as the uncertainties of the risk itself. This assessment, however, is beyond the scope of our application.

Although the sustainability indices showed low sensitivity to the variation in demand, they were found to be sensitive to the hydrologic regime because of the model configuration. Indeed, the current configuration resulted in an optimized premium that was much larger than the expected losses, which is likely to have been caused by the random series and the chosen optimization procedure. To maintain the fund at its minimum, the optimization showed a preference to accumulate a large fund, even though a maximum amount had been set. We also discovered that a change in the hydrologic regime, as projected, might elevate the respective premium (after the optimization procedure) to more than 0.4% of local GDP. On the contrary, an increase in demand may elevate the premium to more than 0.5% of local GDP, an increase of more than 0.1% of GDP from the 100% to 120% of water demand scenarios.

As observed, even if there is no change in water demand, the current maximum grantable water discharge would not be sufficient for consumption demand in the later periods of the projections. If a reduction of demand is unfeasible – the inelastic zone where a change of price has little effect on demand (Hoffman & du Plessis, 2013), a conditional payment could be required to gather a fund to cover alternative water sources expenses.

According to the selected runs, the premiums are expected to decrease from the historical run onwards in general; however, this alleviation does not make the assessment useless for planning purposes. Indeed, the suggested methodology could be applied even if no insurance scheme existed in order to inform and lead people and decision-makers into action. The comparison of the premiums with local GDP values is informative and it could be used as a basis to reduce risk after raising awareness. Risk perception and society’s engagement are crucial in risk reduction programmes, as stated in the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015).

These results were limited to a constraint in economic information and projections. Since these projections would be much uncertain, as explained in the methods section, there is no correction in the currency value and no adjustment in future industrial or agribusiness products added value. Another simplification was the proportion of water demand among sectors, which was held constant. If any one sector proportionally changes its production value and/or demands more water in the future, the runs would give different outcomes. From the charge for water use, it is expected that water demand would change, but differently among sectors (Féres, Thomas, Reynaud, & da Motta, 2005). Future work should consider these data to greatly improve the reality of the results.

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4 GENERAL CONCLUSIONS

This work comprised an application of an insurance fund model (MTRH-SHS) with synthetic annual minimum streamflow data series generated from the projections of two hydrologic models (SWAT and MHD-INPE) driven by a climate model projection (Eta-HadGEM2-ES, radiative forcing scenario RCP4.5), fitted to Gumbel extremes distribution. The methodology was applied in the drainage area of the Cantareira Water Supply System's donor reservoirs, an area that is receiving much attention after its vulnerability, in terms of water supply, became evident.

In the spite of the study area importance, the existent hydrologic, meteorological, and economic data is less than desired, and not always easy to access. For that, the calibration and validation procedures were considered satisfactory, as well as the components included in the hydrologic models were considered suitable for application in a basin with such characteristics. The results under climate change showed that the two hydrologic models differ even when supplied with the same input data, due to structural and formulation differences.

The application of MTRH-SHS depends on even more local and reliable data regarding hydrologic regime, water demands, and respective economic values. As a vanguard development in Brazil, the exploration of the model's configurations and outputs is an ongoing process with many challenges, but much room for improvements.

The research showed that the decision-makers face a hard task in choosing which data rely on and, despite the efforts to make both hydrologic models the most similar to each other in terms of input data and performance, their results differ in substantial amount in some cases.

4.1 RECOMMENDATIONS FOR FUTURE WORK

This work was one attempt of reinforcing the water resources management, based on the current Brazilian legal framework. During the M.Sc. Thesis, technical development and discussions, other solutions were gathered, though not tested.

The water permit lifetime (up to 35 years) seems more and more disconnected to the knowledge that the climate and the hydrologic regime are likely to change. A reduction in the permit lifetime, which would require an update of the studies in each renewal, should align the exploration of the resource with its actual availability.

The insurance, here proposed, could be bundled with the already functioning charge for water use (and water pollution), with current values lower than the optimized premiums. The charge for water use has different purposes, but this bundled configuration might cost less than two different "charges" separately managed, and follow the charge calculation method weighed by the quality of the source river (Sao Paulo State, 2005), among other factors.

An insurance fund simulation for future periods depends on the projected streamflow data, which depends on the scenario, hydrologic model structure, and input data. The better the input data and scenario's feasibility, the more realistic prospect the insurance simulation will present to decision-makers. In this work, only climate change projections were explored; however, land use change also affects the water yield (D'Almeida et al., 2007; Laurentis, 2012; Siqueira Júnior et al., 2015). Thus, before setting an insurance scheme, land use change projections must also be developed and considered, both in the hydrologic modelling and into the insurance model.

The MTRH-SHS set-up should be tested with other formulas and suited to other objectives. For example:

i) Another minimum flow distribution model, besides Gumbel, should be tested for the case using streamflow. Despite the successful use of the Gumbel in similar applications, it may not be the best model for monthly data. Hence, future research should be encouraged to explore other probability functions, as well as testing daily data;

ii) Novel, alternative variables, such as reservoir volume, might be explored as the insurance trigger, though only after a good "calibration" procedure;

iii) Other optimization solving techniques could be tried. An implementation of the model within other languages or frameworks could provide more options in this subject;

iv) A deeper study on each user sector's demands and economical values.

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APPENDIX A

Table A1 – Gauging stations with observed data from 2004 to 2014

Controller	*Type*	*Code*	*Name*	*City*	*Latitude*	*Longitude*
SABESP	Rainfall	BRA	Barragem Atibainha	Nazaré Paulista	-23.174	-46.393
SABESP	Rainfall	BRC	Barragem Cachoeira	Piracaia	-23.050	-46.319
SABESP	Rainfall	P-10	Barragem Jaguari	Bragança Paulista	-22.923	-46.421
SABESP	Rainfall	P-11	Sertao Grande	Camanducaia	-22.685	-46.183
SABESP	Rainfall	P-12	Monte Verde	Camanducaia	-22.864	-46.049
SABESP	Rainfall	P-13	Ponte Nova	Camanducaia	-22.795	-46.053
SABESP	Rainfall	P-14A	Faz. Boa Vista	Sapucaí-Mirim	-22.755	-45.837
SABESP	Rainfall	P-3	Tapera Grande	Mairiporã	-23.310	-46.447
SABESP	Rainfall	P-4	Faz. Retiro	Joanópolis	-22.941	-46.121
SABESP	Rainfall	P-5	Agua Do Poco	Nazaré Paulista	-23.021	-46.170
SABESP	Rainfall	P-6	Bairro Cuiaba	Nazaré Paulista	-23.261	-46.394
SABESP	Rainfall	P-7	B. Cunhas (Mato Mole)	Joanópolis	-22.994	-46.242
SABESP	Rainfall	P-8	B. Pericos (Faz.Rabelo)	Camanducaia	-22.779	-46.180
SABESP	Rainfall	P-9	Extrema (MG)	Extrema (MG)	-22.775	-46.275
SABESP	Rainfall	F-23	Bairro Tenente	Extrema	-22.827	-46.314
SABESP	Rainfall	F-24	Conrado	Joanópolis	-22.996	-46.241
SABESP	Rainfall	F-25B	Extrema	Extrema	-22.875	-46.369
SABESP	Rainfall	F-28	Fazenda Jaguari	Camanducaia	-22.832	-46.123
SABESP	Rainfall	F-30	Cancan	Joanópolis	-22.935	-46.211

Controller	*Type*	*Code*	*Name*	*City*	*Latitude*	*Longitude*
SABESP	Rainfall	F-34	Atibainha Abaixo	Piracaia	-23.095	-46.264
INMET	Weather	83075	Guarulhos	Guarulhos	-23.430	-46.460
CPTEC	Weather	83721	Aeroporto VCP	Campinas	-23.000	-47.140
CPTEC	Weather	83829	Aeroporto SJK	São José Dos Campos	-23.220	-45.870
CIIAGRO	Rain and Temperature	at	Atibaia	Atibaia	-23.083	-46.560
CIIAGRO	Rain and Temperature	bj	Bom Jesus Dos Perdões	Bom Jesus Dos Perdões	-23.131	-46.450
CIIAGRO	Rain and Temperature	br	Bragança Paulista	Bragança Paulista	-22.949	-46.525
CIIAGRO	Rain and Temperature	ex	Extrema	Extrema	-22.852	-46.326
CIIAGRO	Rain and Temperature	nz	Nazaré Paulista	Nazaré Paulista	-23.177	-46.397
CIIAGRO	Rain and Temperature	pc	Piracaia	Piracaia	-23.060	-46.357
CIIAGRO	Rain and Temperature	va	Vargem	Vargem	-22.923	-46.421
DAEE	Rainfall	E3-099	Nazaré Paulista	Nazaré Paulista	-23.183	-46.400
DAEE	Rainfall	E3-074	Atibaia	Atibaia	-23.150	-46.550
DAEE	Rainfall	E3-229	Crioulos	Crioulos	-23.067	-46.300
DAEE	Rainfall	D3-054	Joanópolis	Joanópolis	-22.933	-46.267
DAEE	Rainfall	D3-063	Braganca Paulista	Braganca Paulista	-22.933	-46.533

Controller	*Type*	*Code*	*Name*	*City*	*Latitude*	*Longitude*
DAEE	Rainfall	D3-018	Vargem	Vargem	-22.900	-46.417
DAEE	Rainfall	D3-035	Pedra Bela	Pedra Bela	-22.800	-46.450
DAEE	Rainfall	D3-036	Pinhalzinho	Pinhalzinho	-22.783	-46.600
EESC/ USP e Convênio	Field campaigns		Montante Ribeirão Das Posses	Extrema	-22.879	-46.247
EESC/ USP e Convênio	Field campaigns		Foz Do Salto	Extrema	-22.838	-46.218
EESC/ USP e Convênio	Field campaigns		Alto Jaguari	Extrema	-22.820	-46.154
EESC/ USP e Convênio	Field campaigns		Pq. de Eventos – Jaguari	Extrema	-22.853	-46.325
EESC/ USP e Convênio	Field campaigns		Cachoeira Dos Pretos	Joanópolis	-22.968	-46.171
EESC/ USP e Convênio	Field campaigns		Chalé Pto Verde – Cachoeira	Joanópolis	-22.967	-46.176
EESC/ USP e Convênio	Field campaigns		Ponte Sobre Rio Cachoeira	Joanópolis	-22.968	-46.209
EESC/ USP e Convênio	Water level sensor		Jesuíno – Cancan	Joanópolis	-22.912	-46.225

Controller	*Type*	*Code*	*Name*	*City*	*Latitude*	*Longitude*
EESC/ USP e Convênio	Water level sensor		Domithildes – Cancan	Joanópolis	-22.886	-46.222
EESC/ USP e Convênio	Water level sensor		Ronaldo / Santa Lucia – Moinho	Nazaré Paulista	-23.232	-46.323
EESC/ USP e Convênio	Water level sensor		Bertolino – Moinho	Nazaré Paulista	-23.222	-46.325
ANA/ CPRM	Discharge	62584500	Portal Das Estrelas	Extrema	-22.867	-46.244
ANA/ CPRM	Discharge	62584600	Foz Ribeirão Das Posses (PCD)	Extrema	-22.833	-46.231
ANA/ CPRM	Discharge	62663800	Joanópolis (PCD)	Joanópolis	-22.935	-46.212
ANA/ CPRM	Discharge	62655800	Nazaré Paulista (PCD)	Nazaré Paulista	-23.209	-46.357
ANA/ CPRM	Rainfall	2246167	Nascente Principal	Extrema	-22.8878	-46.2408
ANA/ CPRM	Rainfall	2246168	Sítio São José	Extrema	-22.8694	-46.2472
ANA/ CPRM	Rainfall	2246169	Sítio Canto Da Siriema	Extrema	-22.86	-46.2411
ANA/ CPRM	Rainfall	2246170	Sítio Bela Vista	Extrema	-22.8497	-46.2417
ANA/ CPRM	Rainfall	2246171	Recanto Do Ratinho	Extrema	-22.8369	-46.2297
ANA/ CPRM	Rainfall	2246174	Joanópolis	Joanópolis	-22.9347	-46.2117

APPENDIX B

This appendix complements the information on Section 3.4.1, with the economic losses per water deficit in each one of the outlets under each hydrologic regime scenario defined by its period, namely: simulation period (calibration and validation); Eta-HadGEM2-ES historical period (1976-2005) and future periods (2007-2040, 2041-2070, and 2071-2099). Depending on the similarities between MHD and SWAT results, the curves are shown in the same figure or in two figures for the same period.

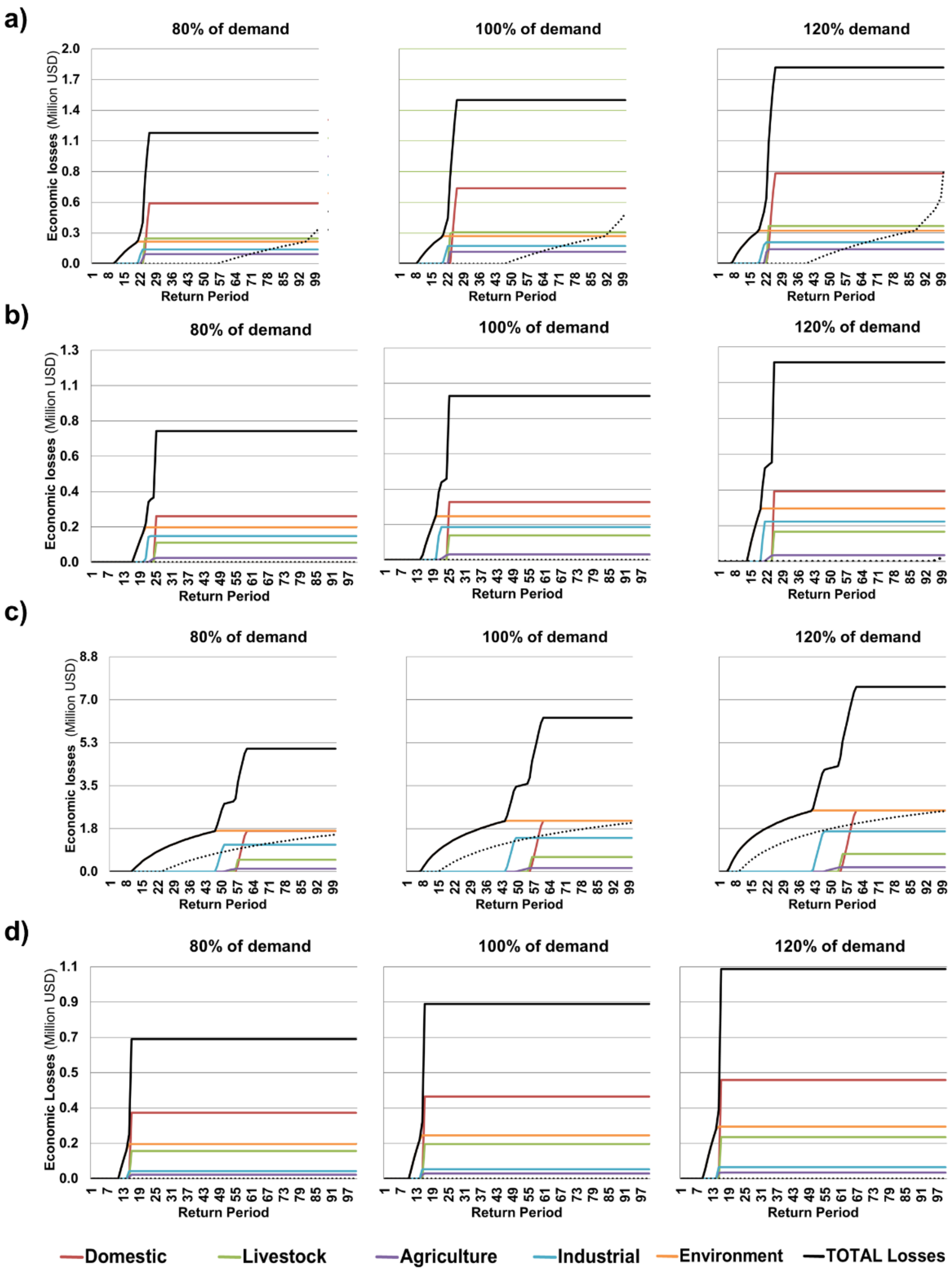

Figure B1. Economic losses due to water deficit in the SWAT run of the simulation period in watersheds a) F28, b) F23, c) F25B, and d) F24

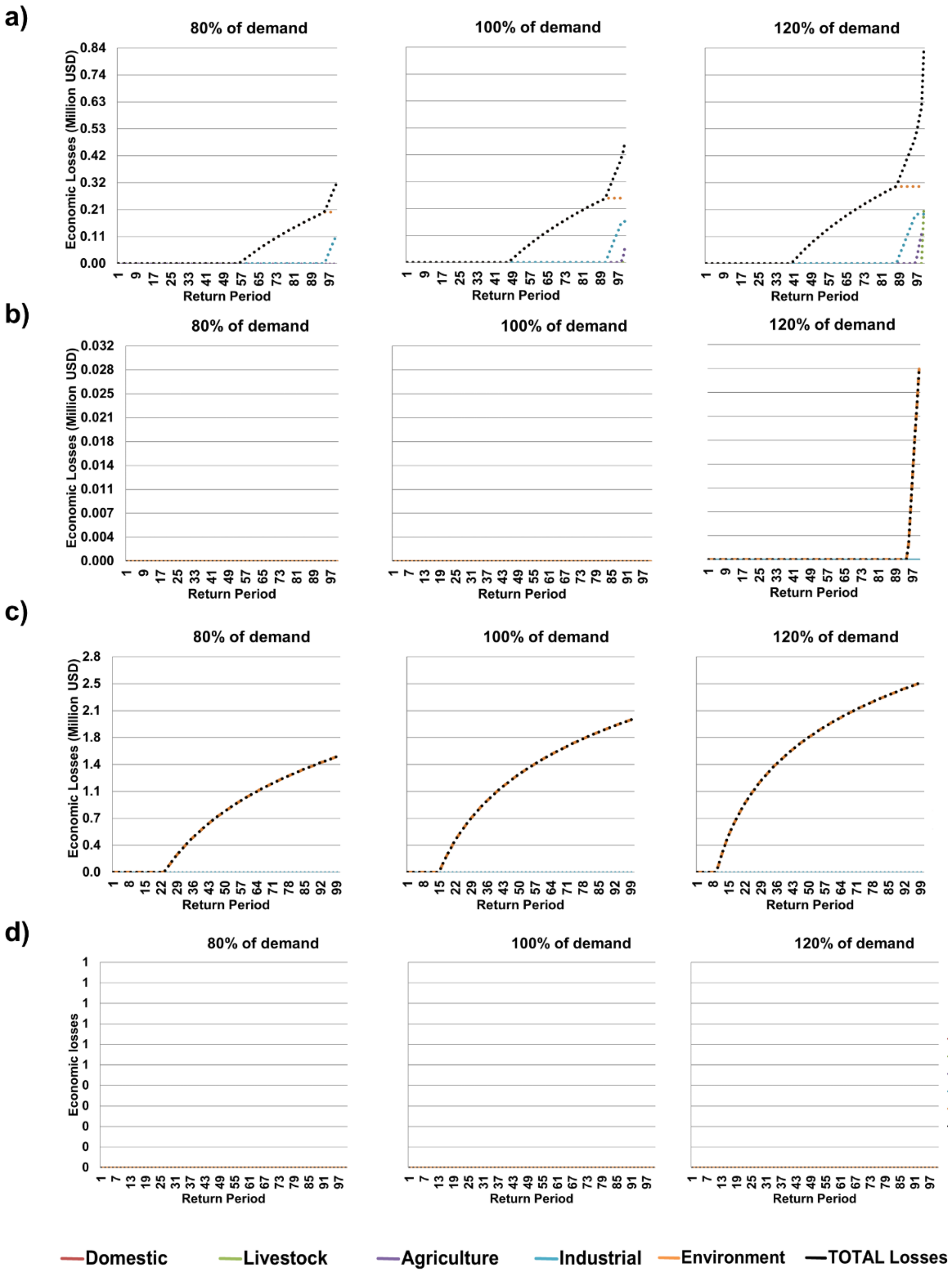

Figure B2. Economic losses due to water deficit in the MHD run of the simulation period in watersheds a) F28, b) F23, c) F25B, and d) F24

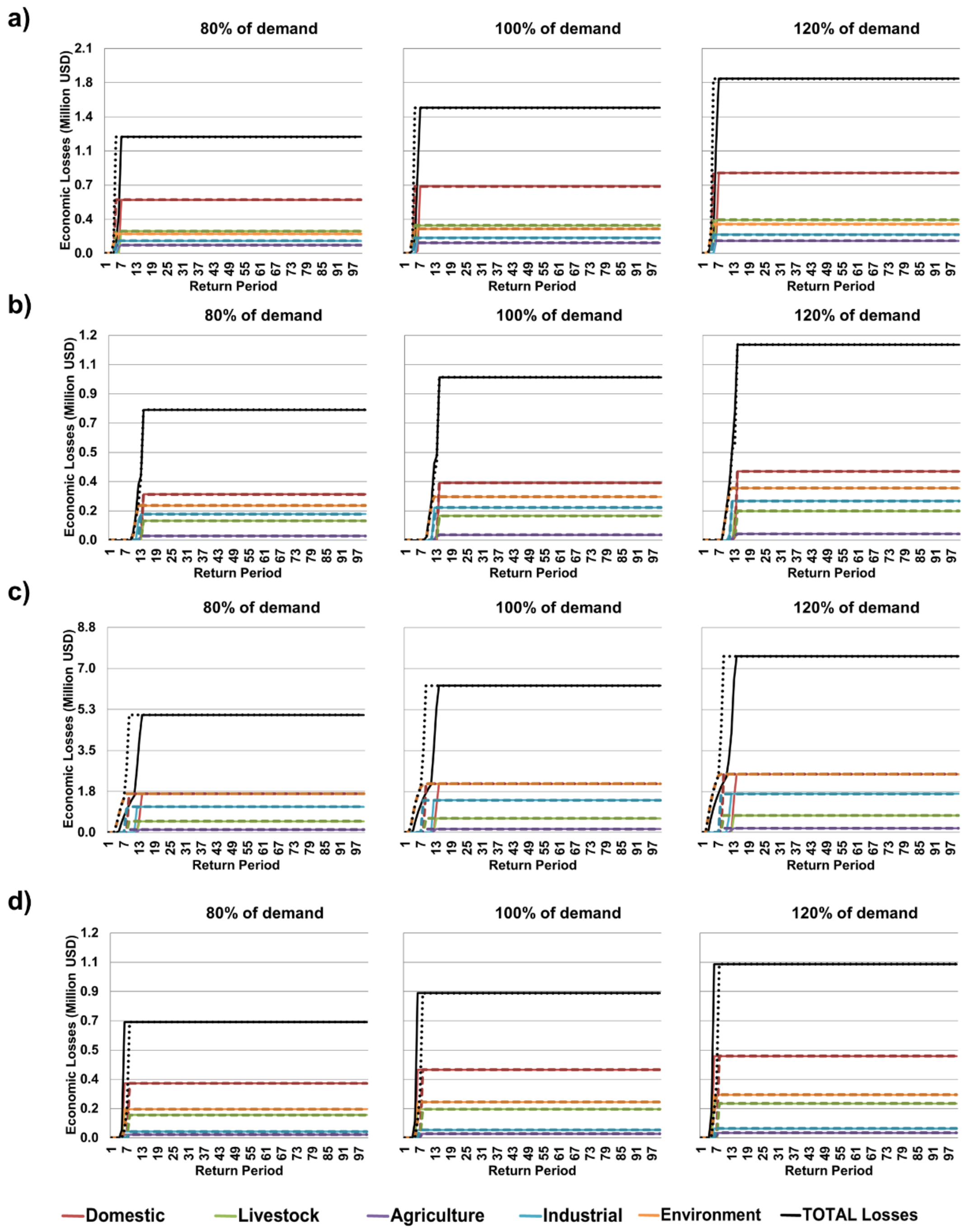

Figure B3. Economic losses due to water deficit in the SWAT (solid lines) and MHD (dashed lines) runs of the Eta-HadGEM2-ES historical period in watersheds a) F28, b) F23, c) F25B, and d) F24

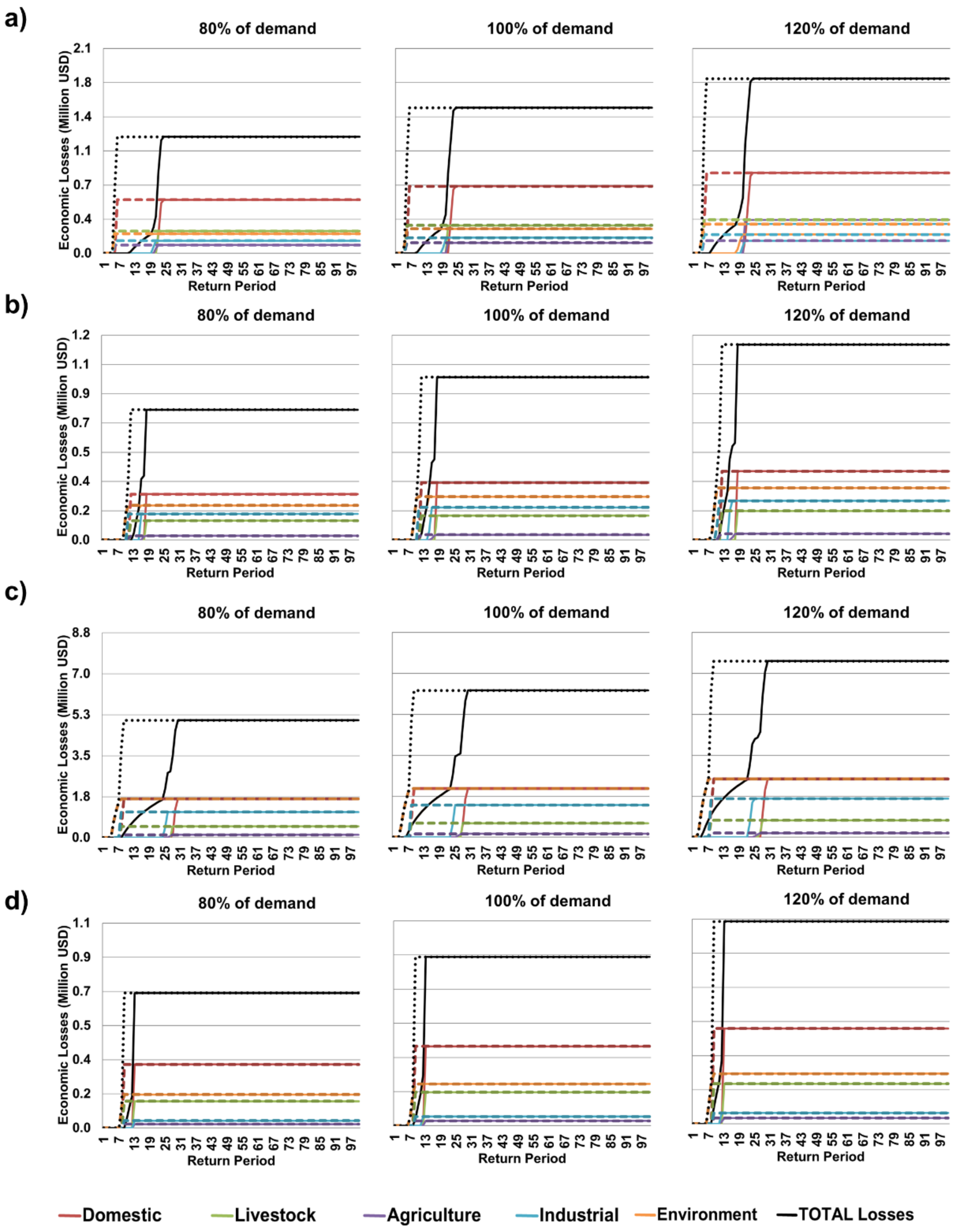

Figure B4. Economic losses due to water deficit in the SWAT (solid lines) and MHD (dashed lines) runs of the Eta-HadGEM2-ES 2007-2040 period in watersheds a) F28, b) F23, c) F25B, and d) F24

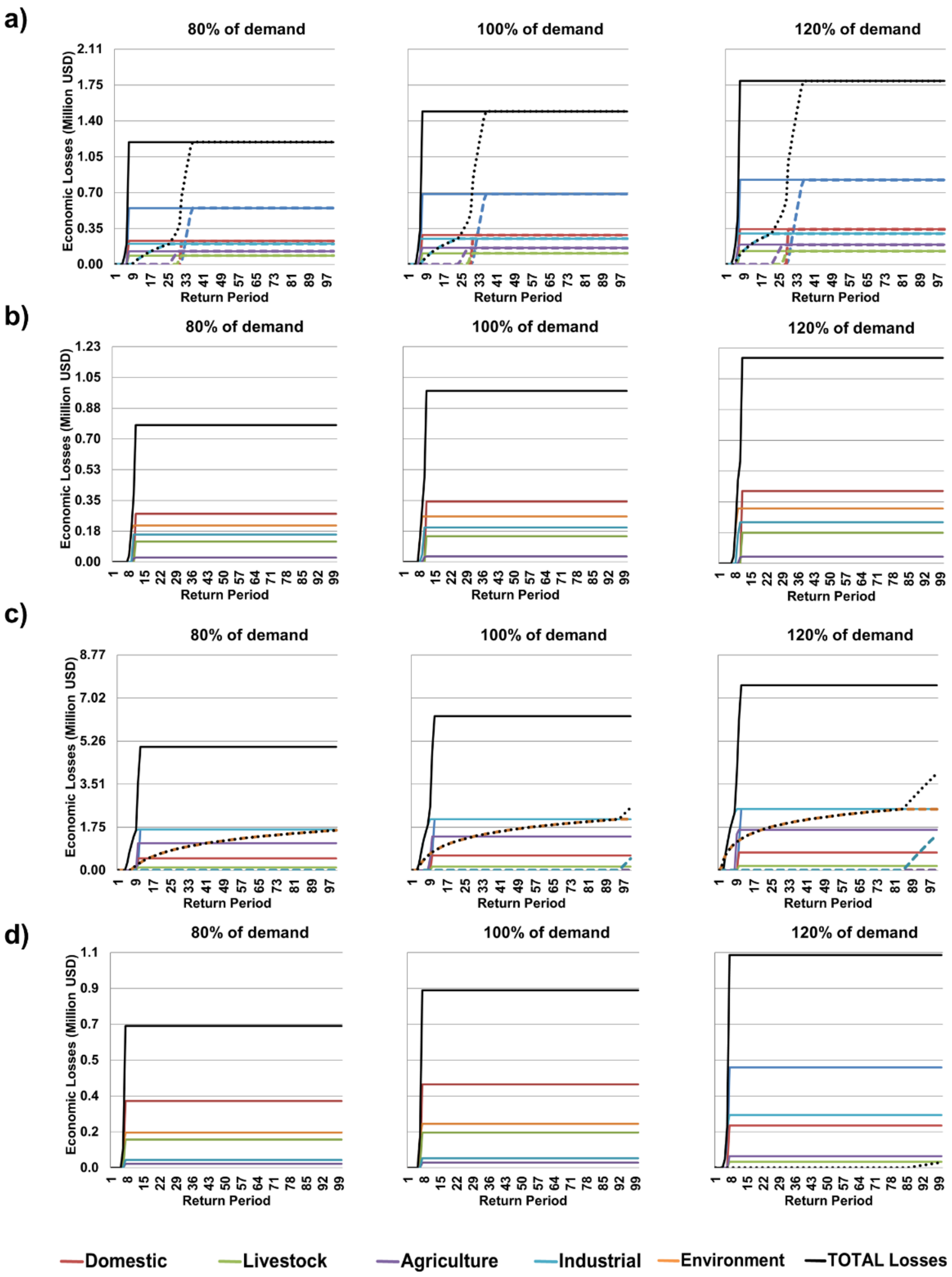

Figure B5. Economic losses due to water deficit in the SWAT (solid lines) and MHD (dashed lines) runs of the Eta-HadGEM2-ES 2041-2070 period in watersheds a) F28, b) F23, c) F25B, and d) F24

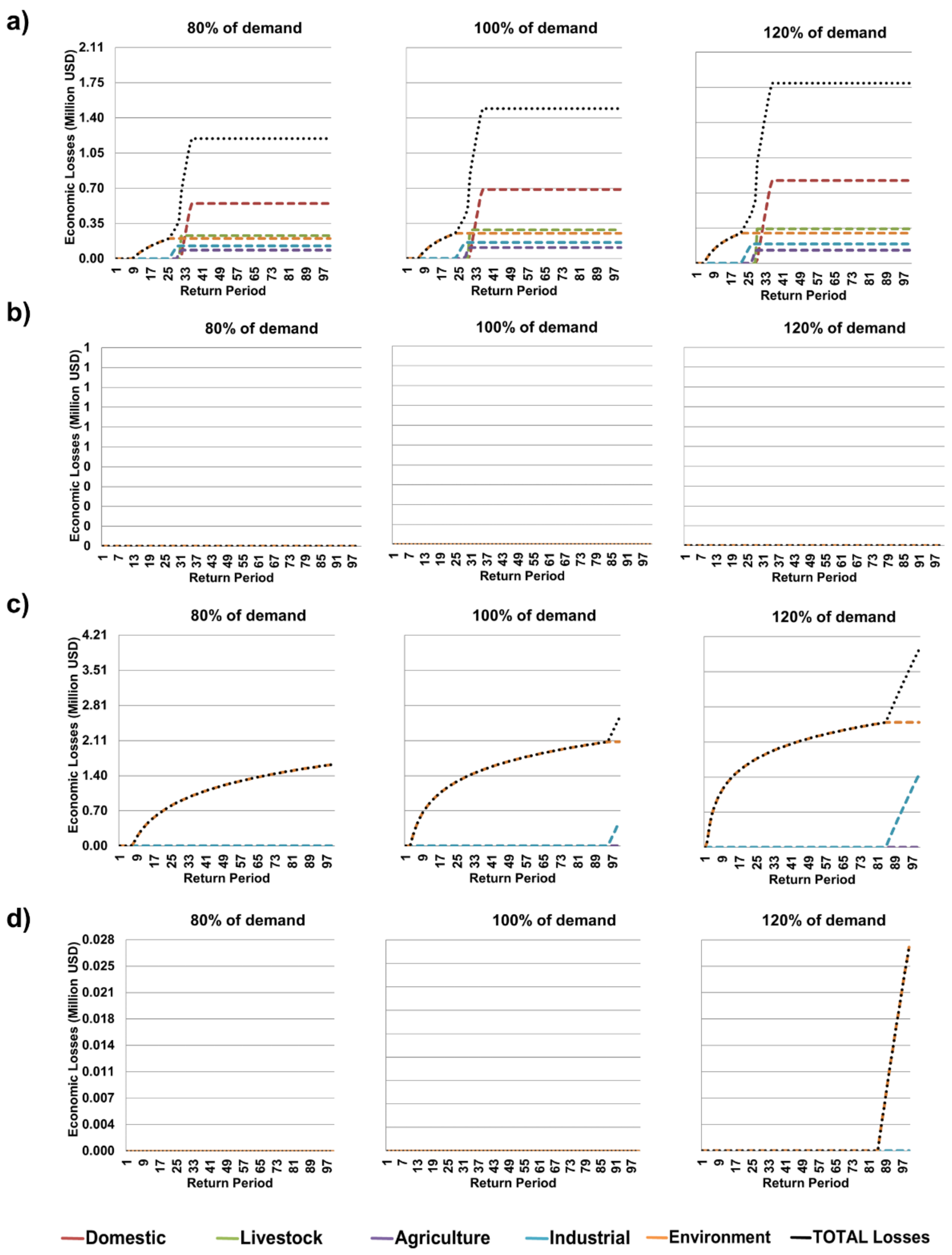

Figure B6. Economic losses due to water deficit in the MHD runs of the Eta-HadGEM2-ES 2041-2070 period in watersheds a) F28, b) F23, c) F25B, and d) F24

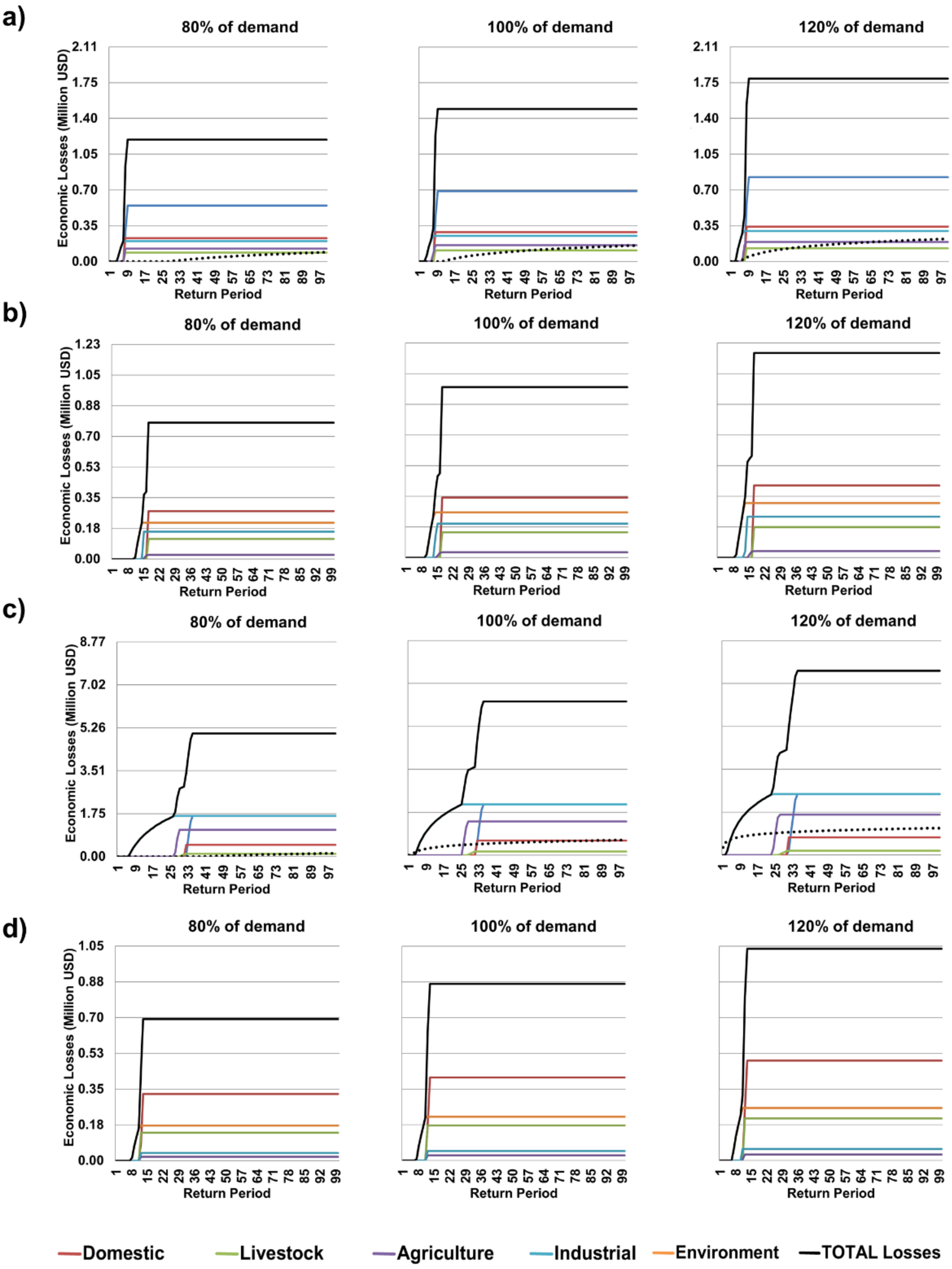

Figure B7. Economic losses due to water deficit in the SWAT (solid lines) and MHD (dashed lines) runs of the Eta-HadGEM2-ES 2071-2099 period in watersheds a) F28, b) F23, c) F25B, and d) F24

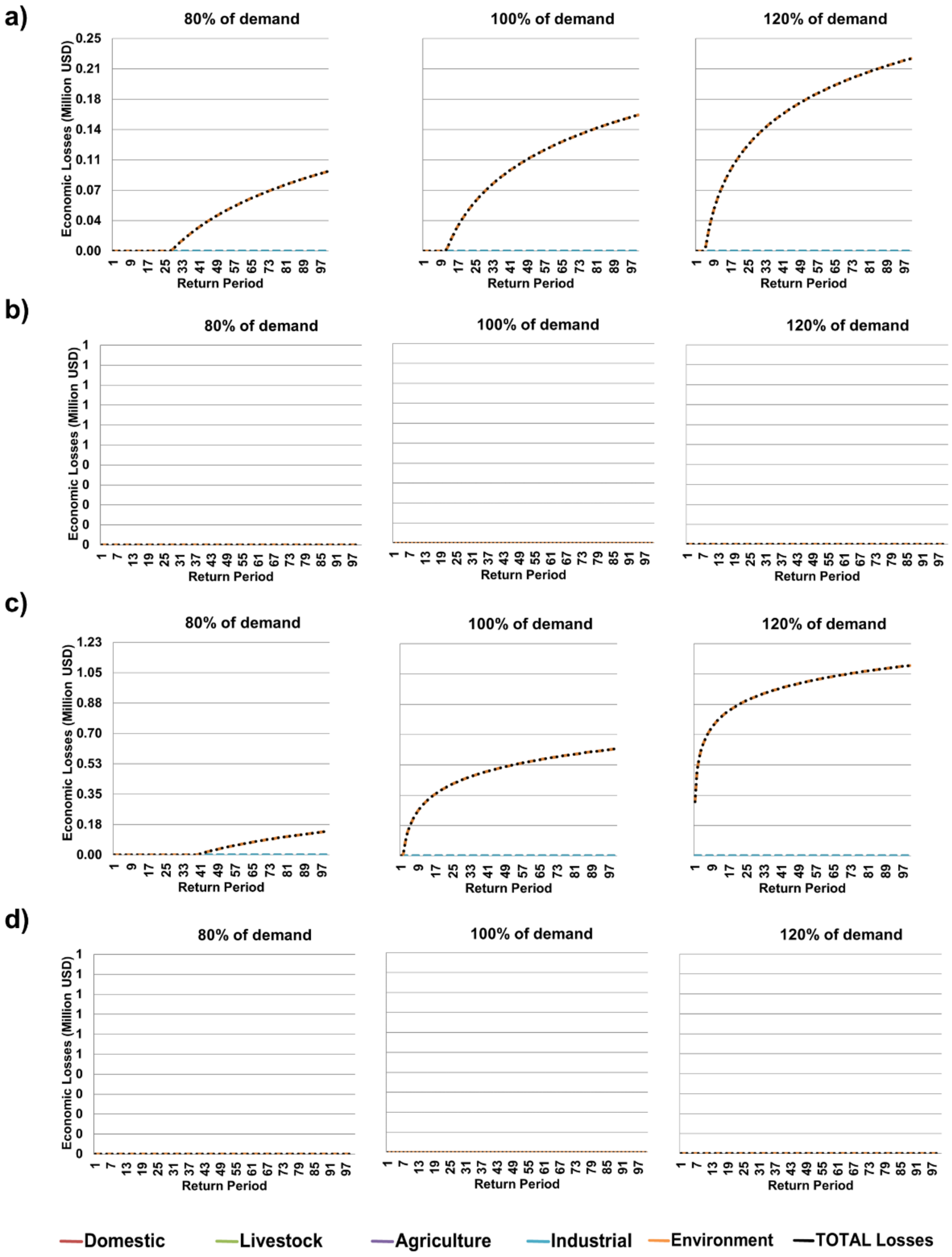

Figure B8. Economic losses due to water deficit in the MHD runs of the Eta-HadGEM2-ES 2071-2099 period in watersheds a) F28, b) F23, c) F25B, and d) F24