UNIVERSIDADE DE SÃO PAULO

FACULDADE DE ECONOMIA, ADMINISTRAÇÃO E CONTABILIDADE

DEPARTAMENTO DE ECONOMIA

PROGRAMA DE PÓS-GRADUAÇÃO EM ECONOMIA

Climate Change, Water Resources and Economic Impacts:
An Analysis of Brazilian Hydrographic Regions

Mudanças Climáticas, Recursos Hídricos e Impactos Econômicos:
Uma Análise das Regiões Hidrográficas Brasileiras

Aluno: Ademir Antônio Moreira Rocha

Orientador: Prof. Dr. Eduardo Amaral Haddad

São Paulo

2021

ADEMIR ANTÔNIO MOREIRA ROCHA

Climate Change, Water Resources and Economic Impacts: An Analysis of Brazilian Hydrographic Regions

Mudanças Climáticas, Recursos Hídricos e Impactos Econômicos: Uma Análise das Regiões Hidrográficas Brasileiras

Tese apresentada ao Programa de Pós-Graduação do Departamento de Economia da Faculdade de Economia, Administração e Contabilidade da Universidade de São Paulo, como requisito parcial para obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Eduardo Amaral Haddad

Versão Corrigida

São Paulo

2021

Catalogação na Publicação (CIP)
Ficha Catalográfica com dados inseridos pelo autor

Rocha, Ademir Antônio Moreira .
Climate Change, Water Resources and Economic Impacts: An Analysis of Brazilian Hydrographic Regions / Ademir Antônio Moreira Rocha. - São Paulo, 2021.

134 p.

Tese (Doutorado) - Universidade de São Paulo, 2022.
Orientador: Eduardo Amaral Haddad.

1. Brazilian hydrographic regions. 2. Climate change. 3. Water. 4. Economic impacts. 5. ICGE model. I. Universidade de São Paulo. Faculdade de Economia, Administração e Contabilidade. II. Título.

ACKNOWLEDGEMENTS

This thesis had the support of many people and institutions, without which it would have been impossible to develop a good job. Firstly, I would like to express my sincere gratitude to my advisor Prof. Eduardo Haddad for the continuous support of my Ph.D. study and related research. Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Carlos Azzoni, Prof. Fernando Perobelli, and Prof. Guilherme Marques, for their insightful comments and encouragement. I thank my colleagues at The University of São Paulo Regional and Urban Economics Lab (NEREUS) for the excellent academic environment. Last but not least, I would like to thank my family, especially my mother Ana and my sister Andréa.

FUNDING

This thesis was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [Grant No. 380931/2018-4, 380680/2021-1] and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) [Grant No. 88887.493251/2020-0], which the author acknowledge.

ABSTRACT

In the context of global climate change, one of the biggest challenges is water security. In Brazil, the prospect of water scarcity due to long-run climatic anomalies and the regional disparity between supply and demand for water resources point to limitations and risks to various economic and social activities. Given this scenario, an analysis integrating climate change, water availability, and economic vulnerabilities is necessary to find and apply adequate adaptation and mitigation instruments. Considering the complexity of the issue, we built an Interregional Computable General Equilibrium (ICGE) model named Brazilian Multisectoral and Regional/Interregional Analysis Model with Water Module (BMARIA-H_2O) composed of 67 economic sectors and 12 Brazilian hydrographic regions, all this integrated with hydroclimatic modelling. We evaluated two main channels of shock transmission, namely, Channel 1 linked to a change in the price of treated water and Channel 2 related to the capital demand to replace or save raw water. In our modelling, these two channels perform as endogenous ways of adaptation to climate change. We conclude that the economic losses resulting from the effect of climate change on water availability are considerable and are equivalent to a reduction in GDP of BRL 12.3 billion (or US$ 5.2 billion) in the realistic scenario and BRL 29.7 billion (or US$ 12.5 billion) in the pessimistic scenario (year reference 2015). The low substitutability of water (small price elasticity of the water demand) in most user sectors turns price increases into direct shocks to the Brazilian economy. The simulations show that water-intensive sectors, such as “water and sewage”, “forestry production”, “agriculture”, and “livestock” are the main ones impacted by climate change.

Keywords: Brazilian hydrographic regions, climate change, water, economic impacts, ICGE model

RESUMO

No contexto das mudanças climáticas globais, um dos maiores desafios é a segurança hídrica. No Brasil, a perspectiva de escassez de água devido a anomalias climáticas de longo prazo e a disparidade regional entre oferta e demanda por recursos hídricos apontam para limitações e riscos para diversas atividades econômicas e sociais. Diante desse cenário, é necessária uma análise integrando mudanças climáticas, disponibilidade de água e vulnerabilidades econômicas para encontrar e aplicar instrumentos adequados de adaptação e mitigação. Considerando a complexidade da questão, construímos um modelo de Equilíbrio Geral Computável Inter-regional (EGCI) denominado Brazilian Multisectoral and Regional/ Interregional Analysis Model with Water Module (BMARIA-H_2O) composto por 67 setores econômicos e 12 regiões hidrográficas brasileiras, integrado com modelagem hidro climática. Avaliamos dois canais principais de transmissão de choque, a saber, Canal 1 vinculado à variação do preço da água tratada e Canal 2 relacionado à demanda de capital para reposição ou economia de água bruta. Em nossa modelagem, esses dois canais funcionam como formas endógenas de adaptação às mudanças climáticas. Concluímos que as perdas econômicas decorrentes do efeito das mudanças climáticas sobre a disponibilidade de água são consideráveis e equivalem a uma redução do PIB de R$ 12,3 bilhões (ou US$ 5,2 bilhões) no cenário realista e R$ 29,7 bilhões (ou US$ 12,5 bilhões) no cenário pessimista (ano de referência 2015). A baixa substitutibilidade da água (pequena elasticidade-preço da demanda de água) na maioria dos setores usuários transforma os aumentos de preços em choques diretos para a economia brasileira. As simulações mostram que os setores intensivos em água, como “água e esgoto”, “produção florestal”, “agricultura” e “pecuária” são os principais impactados pelas mudanças climáticas.

Palavras-Chave: Regiões hidrográficas brasileiras, mudanças climáticas, recursos hídricos, impactos econômicos, modelo ICGE

CONTENTS

1. Introduction 13
   References 15

2. Availability and consumption of water resources 17
   References 25

3. Climate change, water availability and water cost 29
   3.1. Motivation 29
   3.2. Climate change and water availability 35
      3.2.1. Hydroclimatic modeling 35
      3.2.2. Hydroclimatic results 36
   3.3. Water cost change 45
   References 48

4. Price elasticity of the demand for water 55
   4.1. Motivation 55
   4.2. Price elasticity of the demand for water 56
      4.2.1. Theoretical aspects 56
      4.2.2. Database 60
      4.2.3. Empirical strategy 62
      4.2.4. Econometric results 63
   References 65

5. Climate change, water resources and economic impacts 69
   5.1. Motivation 69
   5.2. Model description 73
      5.2.1. Model dimensions 73
      5.2.2. Production 75
      5.2.3. Investment demand 77

5.2.4. Household demand 77

5.2.5. Government demand 79

5.2.6. External demand 79

5.2.7. Labor market 79

5.2.8. Capital accumulation and investment 79

5.2.9. Closure 80

5.2.10. Homogeneity test 81

5.2.11. Shock description 81

5.2.12. Model mechanisms (causal relation) 82

5.2.13. Formal mathematical description 84

5.2.14. Model database 91

5.3. Long-run results 98

5.4. Uncertainty 109

5.4.1. Approach 1 109

5.4.2. Approach 2 118

References 124

Appendix - Usage guide for the BMARIA-H_2O model 129

6. Conclusion 133

LIST OF TABLES

Table 2.1. Water resources per capita in selected regions 17

Table 2.2. Information about the Brazilian hydrographic regions 21

Table 2.3. Brazilian Environmental-Economic Accounting for Water 24

Table 3.1. Climate change and water availability in Brazil 31

Table 3.2. Hydroclimatic model results 44

Table 3.3. Average annual outflows of reservoirs in the Cantareira System 46

Table 3.4. Costs list of the Sabesp 46

Table 3.5. Water cost changes in the Brazilian hydrographic regions 47

Table 4.1. Main estimates of agricultural, industrial, and commercial water demand 58

Table 4.2. Sectoral compatibility 61

Table 4.3. GMM regression: price elasticities of the water demand 64

Table 5.1. CGE models with a focus on water resources 70

Table 5.2. BMARIA-H_2O sectors 74

Table 5.3. Water consumption by sector 94

Table 5.4. Key parameters 96

Table 5.5. Impacts on selected macroeconomic variables, long run 99

Table 5.6. Impacts on GDP, by hydrographic region 100

Table 5.7. Impacts on activity level, by sector group 101

Table 5.8. Impacts on activity level, by sector group and hydrographic region 104

Table 5.9. Impacts on water demand, by hydrographic region 105

Table 5.10. Impacts on raw water demand, by hydrographic region 106

Table 5.11. Capital used for saving water, by hydrographic region 108

Table 5.12. Robustness analysis for model parameters 112

Table 5.13. Robustness analysis for model shocks 115

LIST OF FIGURES

Figure 2.1. Brazilian hydrographic regions 19

Figure 2.2. Lorenz curve for water availability and consumption 22

Figure 3.1. Mean precipitation 40

Figure 3.2. Mean potential evapotranspiration 41

Figure 3.3. Mean water availability 42

Figure 3.4. Mean water availability – discrete data 43

Figure 5.1. Production structure 76

Figure 5.2. Investment demand 78

Figure 5.3. Household demand 78

Figure 5.4. Causal relations underlying the simulation results 83

Figure 5.5. BMARIA- H_2O database 93

Figure 5.6. Impacts on water demand, intra and inter-hydrographic regions water flow 107

Figure 5.7. Distribution of simulated shocks in hydrographic regions 120

Figure 5.8. Distribution of simulated impacts (real GDP) in hydrographic regions 122

Figure 5.1A. BMARIA-H_2O initial page 130

Figure 5.2A. BMARIA-H_2O model/data page 130

Figure 5.3A. BMARIA-H_2O closure page 131

Figure 5.4A. BMARIA-H_2O shocks page 131

Figure 5.5A. BMARIA-H_2O solve page 132

1. INTRODUCTION

Global climate warming (from both anthropogenic and natural sources) is associated with changes in a series of components in the hydrological cycle. It is very likely that throughout the 21st century, we will see a greater frequency of extreme water events characterized by intense and episodic rains with large amounts of runoff interspersed with long periods of drought and evaporation (IPCC, 2021; Bates et al., 2008; Fischer & Knutti, 2015 Willner, et al., 2018).

Irregular water supply resulting from climate change brings limitations and risks to several economic and social activities (Hirabayashi et al., 2013; IPCC, 2021). The cultivation of irrigated crops, forest production, fishing, hydroelectric power generation, industrial production, transport, tourism, water distribution, and sewage treatment are examples of affected sectors (Gleick et al., 2009; Rosegrant, 2014; Damania et al., 2017; Ritchie & Roser, 2017). This reality becomes even more severe when considering the increase in global demand for water-intensive goods and services. (UN, 2019).

Given this scenario, studies capable of integrating the topics of climate change, water availability, and economic impacts become necessary. They may unveil the vulnerabilities and help suggest possible mitigation and adaptation measures, thus seeking ways to guarantee the sustainable maintenance of the water supply and the social and environmental well-being (IPCC, 2021).

When we argue about the regional management of water resources the concept of virtual water is central (Allan, 1998; Hoekstra & Hung, 2002, 2005; Chapagain & Hoekstra, 2003; Zimmer & Renault, 2003; Hoekstra et al., 2011; Hoekstra & Mekonnen, 2012). The total volume of water required to produce a good or service includes its direct consumption used in the production process and its indirect consumption (embedded in the production of the inputs). This implies that it is not enough to consider only the demand for water captured in the region. It is also necessary to consider the flow of water resources embedded in interregional trade (i.e., water transfer by economic transactions). Thus, water use in a region can influence its use and availability in another location by trading goods and services. This complete analysis of regional and sectoral interdependence around water is relevant in a climate change scenario.

It is in this context that we find the motivation to develop this work. Our objective is to examine the economic impacts of the change in water availability caused by climate change, focusing on the Brazilian reality. Considering the complexity of the problem, we built an Interregional Computable General Equilibrium (ICGE) model named Brazilian Multisectoral and Regional/Interregional Analysis Model with Water Module (BMARIA-H_2O), composed of 67 economic sectors and 12 Brazilian hydrographic regions, all this integrated with hydroclimatic modelling.

Based on identifying sectoral and regional vulnerabilities, adaptation and mitigation actions can be taken to meet some of the Sustainable Development Goals (SDGs)[1] in Brazil. Our work is directly related to SDG 6, “Ensure availability and sustainable management of water and sanitation for all” and SDG 13, “Take urgent action to combat climate change and its impacts”, and indirectly to SDG 2, “End hunger, achieve food security and improved nutrition and promote sustainable agriculture ”, ODS 3, “Ensure healthy lives and promote well-being for all at all ages”, SDG 7, “Ensure access to affordable, reliable, sustainable and modern energy for all ”, SDG 8, “Promote sustained, including and sustainable economic growth, full and productive employment and decent work for all”, and SDG 14, “Conserve and sustainably use the oceans, seas and marine resources for sustainable development”.

To develop the discussion presented in this introduction, this work is organized as follows. The second chapter presents an overview of the availability and consumption of water resources in the Brazilian hydrographic regions. The third chapter assesses the potential effects of climate change on water availability in Brazilian hydrographic regions and measures possible variations in the cost of access to water. In the fourth chapter, we estimate

---

[1] The Sustainable Development Goals (SDGs) were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030 (UNDP, 2020).

the price elasticity of water demand in agriculture, industry, commerce, and government located in the Brazilian hydrographic regions, which will give us an idea of the essentiality of the water factor for the economic sectors. The fifth chapter presents the details of the ICGE BMARIA-H_2O model, including its database, equations, mechanisms, and the results of economic impacts from climate change scenarios and water availability in the Brazilian hydrographic regions. The sixth chapter concludes.

References

Allan, J. A. (1998). Virtual water: a strategic resource. *Ground water*, 36(4), 545-547. https://doi.org/10.1111/j.1745-6584.1998.tb02825.x

Bates, B., Kundzewicz, Z., Wu, S., & Palutikof, J. (2008). *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. Geneva: IPCC, 210 pp.

Chapagain, A. K., & Hoekstra, A. Y. (2003). Virtual water flows between nations in relation to trade in livestock and livestock products. In Hoekstra, A. Y. (Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series*, 13, Delft: UNESCO-IHE.

Damania, R., Desbureaux, S., Hyland, M., Islam, A., Rodella, A. S., Russ, J., & Zaveri, E. (2017). *Uncharted waters: The new economics of water scarcity and variability*. Washington, DC: World Bank Publications.

Fischer, E. M., & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, 5(6), 560-564. https://doi.org/10.1038/nclimate2617

Gleick, P. H., Cooley, H., Morikawa, M., Morrison, J., & Cohen, M. J. (2009). *The world's water 2008-2009: The biennial report on freshwater resources.* Washington, DC: Island Press.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., ... & Kanae, S. (2013). Global flood risk under climate change. *Nature climate change*, 3(9), 816-821. https://doi.org/10.1038/nclimate1911

Hoekstra, A. Y., & Hung, P. Q. (2002). Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. In Hoekstra, A. Y.

(Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series*, 11, Delft: UNESCO-IHE.

Hoekstra, A. Y., & Hung, P. Q. (2005). Globalisation of water resources: international virtual water flows in relation to crop trade. *Global environmental change*, 15(1), 45-56. https://doi.org/10.1016/j.gloenvcha.2004.06.004

Hoekstra, A. Y., Chapagain, A. K., Mekonnen, M. M. & Aldaya, M. M. (2011). *The water footprint assessment manual: Setting the global standard.* New York: Routledge.

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the national academy of sciences*, 109(9), 3232-3237. https://doi.org/10.1073/pnas.1109936109

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva: IPCC, 150 pp.

Ritchie, H. & Roser, M. (2017). *Water use and stress. Our World in Data*. Retrieved from https://ourworldindata.org/water-use-stress

Rosegrant, M. W. (2014). Global outlook for water scarcity, food security, and hydropower. In Burnett, K. et al. (Eds.) *Routledge Handbook of water economics and institutions*, 19-45. New York: Routledge.

UN (2019). *Climate Change and Water: UN-Water Policy Brief.* Geneva: UN-Water.

UNDP (2021). *Sustainable Development Goals description*. Retrieved from https://www.br.undp.org/content/brazil/pt/home/sustainable-development-goals.html

Willner, S. N., Otto, C., & Levermann, A. (2018). Global economic response to river floods. *Nature Climate Change*, 8(7), 594-598. https://doi.org/10.1038/s41558-018-0173-2

Zimmer, D., & Renault, D. (2003). Virtual Water in Food Production and Global Trade: Review of Methodological Issues and Preliminary Results. In Hoekstra, A. Y. (Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series*, 12, Delft: UNESCO-IHE.

2. AVAILABILITY AND CONSUMPTION OF WATER RESOURCES

Water covers approximately 75% of the Earth's surface. Current estimates are that the Earth's hydrosphere contains approximately 1.4 billion km^3 of water. Of this, about 97% of the water is saline and is in the oceans. The rest, about 3%, is freshwater, and its physical state varies between solid, liquid, and gas. Approximately 69% of the Earth's freshwater is present in glaciers, polar caps, and permanent snow cover in the polar regions. Groundwater represents 30% of the Earth's freshwater, while only 0.3% of all freshwater is contained in lakes, rivers, and reservoirs. Thus, 99% of the water is unfit or unavailable for human consumption. The remaining 1% consists mainly of groundwater the extraction of which incurs high economic costs. Thus, only 0.0067% of the total water on Earth is superficial, representing about 2,000 km^3 of fresh water available and economically viable for human use (Kibona et al., 2009; Cassardo & Jones, 2011; Lui et al., 2011; Du Plessis, 2017).

Brazil is privileged regarding water resource availability in this global scenario, concentrating about 12% of all freshwater available on Earth (SNRH, 2006a-l; ANA, 2015)[2]. Table 2.1 presents water availability values per capita in different regions of the world for 2015. It is possible to observe that water availability per capita in Brazil is around 41,000 m^3. This amount is above the average of most continents and is more than double the water availability of the world.

Table 2.1. Water resources per capita in selected regions, 2015

Regions	*Value (m^3/people/year)*
Brazil	41,316
Africa	10,326
Americas (with Brazil)	34,732
Americas (without Brazil)	34,544
Asia	9,563
Europe	22,270
Oceania	46,093
World	18,560

Source: FAO (2020).

---

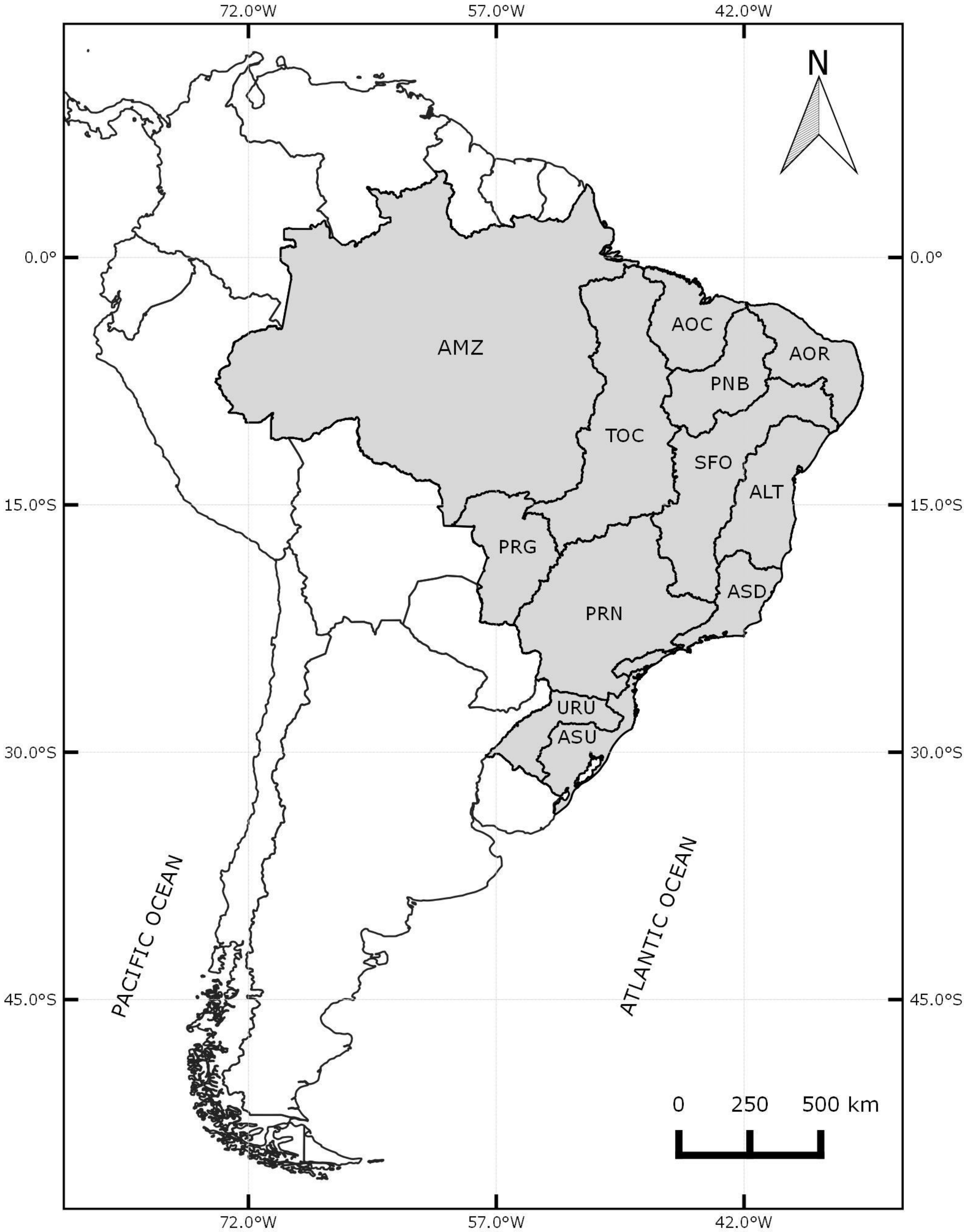
[2] The perception that water is abundant in Brazil is already being questioned and the current context points to another reality. The poor geographical distribution of water and its quality are worrisome aspects (ANA, 2021).

Amid the uneven distribution of water around the world, water-poor regions can compensate for their scarcity through the virtual water trade, that is, water contained in the manufacture of goods and services transacted with water-rich regions (Allan, 1998; Hoekstra & Hung, 2002; Chapagain & Hoekstra, 2003; FAO, 2003; Aldaya et al., 2010; Hoekstra et al., 2011; Liu et al., 2011; Zhang et al., 2011; Hoekstra & Mekonnen, 2012; Duarte et al., 2014; Fracasso, 2014; Zhang & Anadon, 2014; Zhang et al., 2016; Zhang et al. 2017; Han et al., 2018; Cai et al., 2019; Duarte et al., 2019; Visentin & Guilhoto, 2019; Wang et al., 2019; Haddad et al., 2020). Thus, the rich and poor in water can mutually benefit from exchanging water-intensive goods, whether profiting from the comparative advantage or easing the pressure on their water resources (Gil & Kamanda, 2015). According to the Water Footprint Network, the global volume of international virtual water flows concerning trade in agricultural and industrial products averaged 2,320 billion m^3 per year from 1996–2005 (Mekonnen & Hoekstra, 2011). In turn, Brazil is among the largest virtual water exporters globally, with an average of 112 Gm^3 per year during the period 1996-2005. The water contained in cereals and animal protein production for Asia, Europe, and North America represents the highest recorded values (Mekonnen & Hoekstra, 2011).

The Brazilian Water Resources Council (CNRH), through Resolution No. 32/2003, divide the country into 12 hydrographic regions. They are shown in Figure 2.1. They are named as Amazon hydrographic region (AMZ), East Atlantic (ALT), West Northeast Atlantic (AOC), East Northeast Atlantic (AOR), Southeast Atlantic (ASD), South Atlantic (ASU), Paraguay (PRG), Paraná (PRN), Parnaíba (PNB), São Francisco (SFO), Tocantins/Araguaia (TOC), and Uruguay (URU). Contiguous water basins make up these regions with similar natural, social, and economic characteristics and guide the planning and management of water resources (SNRH, 2006a-l).

Despite the apparent water comfort, there is an uneven spatial distribution of water supply and demand between the Brazilian hydrographic regions. Table 2.2 provides some data to support this. In 2015, about 83.5% of the national water availability was concentrated in the AMZ hydrographic region. However, this is a region of low water consumption, population, and gross production value. Therefore, the region is currently in a comfortable situation in terms of water availability.

Figure 2.1. Brazilian hydrographic regions



Hydrographic regions list - AMZ - Amazon, ALT - East Atlantic, AOC - West Northeast Atlantic, AOR - East Northeast Atlantic, ASD - Southeast Atlantic, ASU - South Atlantic, PRG - Paraguay, PRN - Paraná, PNB - Parnaíba, SFO - São Francisco, TOC - Tocantins/Araguaia and URU – Uruguay

Source: Authors’ own.

On the other hand, PRN and ASD regions, with respectively 5.5% and 1.6% of the Brazilian water availability, have rural areas with significant agricultural production and urban-industrial areas with high population density, such as the metropolitan areas of São Paulo and Rio de Janeiro. Water consumption in these regions accounts for almost half of the national total, which puts these areas in water stress conditions. Other examples of dissonance between water supply and demand occur in the AOR, ALT, and SFO regions. These regions are in a semi-arid area whose climate of prolonged droughts generates intense water scarcity. Water availability in these regions represents 0.2%, 0.3%, and 1.1% of the national total, respectively. Despite this, the consumption of water in these regions is high in order to produce irrigated agricultural goods, hydroelectric power, and manufacturing.

Using the information on water availability and consumption (see Table 2.2), we calculated the Gini coefficient to verify regional water inequality in Brazil. For the water availability variable, the calculated Gini coefficient was 0.90, while for the water consumption variable it was 0.52. Figure 2.2 shows the respective Lorenz curves. Thus, we can see that the regional water supply distribution is more unequal (concentrated) than its demand. This imbalance implies limitations (higher costs) of water-intensive economic activities in water-poor regions. Consequently, the trade of water-intensive goods from water-rich to water-poor regions is necessary.

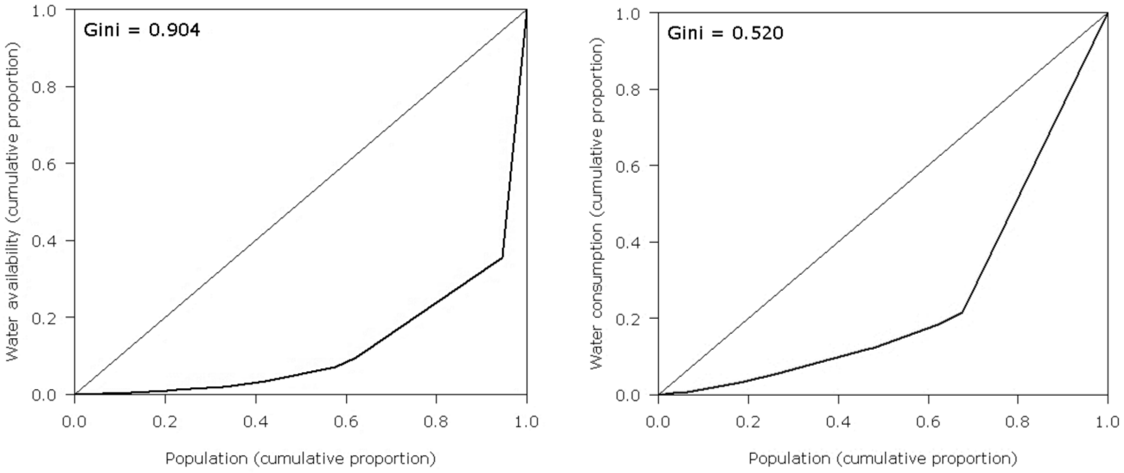
Still using Table 2.2, it is possible to see the water availability per capita and gross product per capita values for each Brazilian hydrographic region. From these data, it can be see that the hydrographic regions of the Brazilian Northeast (ALT, AOC, AOR, PNB, and SFO) have low values of water availability per capita while also having small production per capita rates. In other words, regions which are historically economically poor also suffer from severe water supply limitations. In turn, climate change and its impacts on water availability can increase barriers to economic development and possible economic convergence between rich and poor regions.

Table 2.2. Information about the Brazilian hydrographic regions, 2015

Regions	*Water availability*		*Water consumption*		*Population*		*Gross value product*		*Water availability per capita*	*Gross value product per capita*
	Value (m^3/s)	*% (sum = 100)*	*Value (hm^3)*	*% (sum = 100)*	*Value (people)*	*% (sum = 100)*	*Value (BRL million)*	*% (sum = 100)*	*Value (m^3/s/people × 1000)*	*Value (BRL million/people × 1000)*
AMZ	65,617	83.48	35,871	10.53	10,981,794	5.38	414,585	4.05	5.98	37.75
ALT	271	0.35	16,809	4.94	16,132,845	7.90	475,671	4.65	0.02	29.48
AOC	397	0.51	5,003	1.47	6,687,472	3.27	104,477	1.02	0.06	15.62
AOR	218	0.28	12,738	3.74	25,530,369	12.50	633,486	6.19	0.01	24.81
ASD	1,325	1.69	19,034	5.59	29,673,749	14.52	1,785,909	17.46	0.04	60.18
ASU	513	0.65	25,914	7.61	14,240,421	6.97	910,177	8.90	0.04	63.92
PRG	1,023	1.30	14,169	4.16	2,149,838	1.05	121,799	1.19	0.48	56.65
PRN	4,390	5.59	143,568	42.15	66,293,628	32.44	4,639,948	45.37	0.07	69.99
PNB	325	0.41	5,595	1.64	4,190,785	2.05	72,198	0.71	0.08	17.23
SFO	875	1.11	23,524	6.91	15,298,586	7.49	558,522	5.46	0.06	36.51
TOC	3,098	3.94	17,246	5.06	9,237,714	4.52	286,570	2.80	0.34	31.02
URU	550	0.70	21,117	6.20	3,913,806	1.92	223,527	2.19	0.14	57.11

Source: ANA (2015); NEREUS (2020).

Figure 2.2. Lorenz curve for water availability and consumption, 2015



Source: Authors' own.

Knowledge about the availability, extraction, and water consumption is fundamental for directing the planning, regulation, and management actions in hydrographic regions. This information can be obtained through Environmental-Economic Accounting for Water (IBGE, 2020).

In 1992, the United Nations Conference on Environment and Economic Development (Rio 92) presented an agenda to encourage the monitoring and accounting of natural resources in member countries. Using the stock and flows idea present in the System of National Accounts (SNA)[3], the international statistical community developed the methodological set of the Environmental-Economic Accounts System (SEEA). In 2012, during the Rio+20 Conference, the United Nations Statistics Division (UNSD) recommended that Brazil build its SEEAs. Since then, the country has instituted the Committee for Environmental-Economic Water Accounts (CEEWA) through Interministerial Ordinance No. 236/2012 to elaborate on them, observing the recommendations and international practices. Following the methodology recommended by UNSD (UN 2020), the Brazilian Institute of Geography and Statistics (IBGE) provides the System of Environmental-Economic Water Accounts (SEEWA). It is composed of tables with information on the stock and the flows of water resources extraction,

---

[3] The SNA is a standardized and organized set of data on a country's economic activity. The accounts provide a detailed record of flow and stock of the different economic activities. They generally represent a country's production, income, spending, and wealth, including transactions with the rest of the world.

return, and consumption by economic activities. This system sheds light on interaction between the environment and the economy regarding water.

Table 2.3 summarizes the Brazilian SEEWA made available by IBGE for the year 2015 (IBGE, 2020). The accounts “a” to “j” represents water inputs in the system. The primary water input occurs naturally and is represented by total precipitation (account “a”). Its value reaches 13.5 million hm^3/year. Economic activities return part of the water collected (for productive use) to the environment. The account “h” (sum of “b” to “g”) shows the return value of 3.3 million hm^3/year. In addition, there is the possibility of water resources entering Brazilian territory through the importation of goods and services. This is described in the Other water inputs (account “i”). Its value reaches 11.3 million hm^3/year. The “h” and “i” accounts represent water inputs of the economic source. Thus, the total added to the water stock (account “j”) is 28 million hm^3/year. In turn, the “k” to “t” accounts represent water extraction (or withdrawals) from the system. Most precipitation returns to the atmosphere through evaporation and evapotranspiration (account “k”), representing 9.1 million hm^3/year. This is the leading natural cause of water loss. Economic activities collect water to use as an input in their production. This is described in account “r” (sum of “l” to “q”). Its value reaches 3.6 million hm^3/year. A share of the water can leave Brazilian territory through exports of goods and services. This is described in the account “s” named other water outputs, the value of which reaches 21.9 million hm^3/year. The “r” and “s” accounts represent the economy’s extraction of water resources. In the end, the reduction in the water stock (account “t”) reaches 34.6 million hm^3/year. The water consumption of economic activities (account “u”) is the difference between the volume collected and the return. This value is 0.3 million hm^3/year. The main water user sectors are agriculture, livestock and forestry production, fisheries, and aquaculture. Together these sectors (considered very water-intensive) represent more than 95% of the total consumed by economic activities, totaling a volume of 334 hm^3/year. Almost all of this is raw water from the environment (account “w”), most likely not paid for. The rest is water consumed from the water and sewage sector (i.e., treated water) (account “v”).

Table 2.3. Brazilian Environmental-Economic Accounting for Water, 2015

Description	*Unit*	*Account*	*Value*
Precipitation	Million hm^3	a	13.498
Agriculture, livestock, forestry production, fisheries, and aquaculture	Million hm^3	b	0.255
Extractive industry	Million hm^3	c	0.001
Manufacturing industry and construction	Million hm^3	d	0.003
Electricity and gas	Million hm^3	e	2.978
Water and sewage treatment	Million hm^3	f	0.033
Other economic activities	Million hm^3	g	0.000
Water returns from economic activities	Million hm^3	h=b+c+d+e+f+g	3.269
Other water inputs †	Million hm^3	i	11.272
Addition to water stock	Million hm^3	j=a+h+i	28.039
Evaporation and evapotranspiration	Million hm^3	k	9.090
Agriculture, livestock, forestry production, fisheries, and aquaculture	Million hm^3	l	0.586
Extractive industry	Million hm^3	m	0.001
Manufacturing industry and construction	Million hm^3	n	0.006
Electricity and gas	Million hm^3	o	2.978
Water and sewage treatment	Million hm^3	p	0.019
Other economic activities	Million hm^3	q	0.000
Water abstraction from economic activities	Million hm^3	r=l+m+n+o+p+q	3.590
Other water outputs ‡	Million hm^3	s	21.940
Reduction to water stock	Million hm^3	t=k+r+s	34.620
Total consumption of water resources	Million hm^3	u=approx. r-h	0.341
Non-raw water	Million hm^3	v (share of u)	0.003
Raw water	Million hm^3	w (share of u)	0.337

† Water resources input in the Brazilian territory (e.g., water contained in the import of goods).

‡ Water resources output in the Brazilian territory (e.g., water contained in the export of goods).

Source: IBGE (2020).

References

ANA (2015). *Conjuntura dos Recursos Hídricos no Brasil - Informe 201*. Brasília: Agência Nacional de Águas.

ANA (2021). *Conjuntura dos Recursos Hídricos no Brasil*. Brasília: Agência Nacional de Águas.

Aldaya, M. M., Allan, J. A., & Hoekstra, A. Y. (2010). Strategic importance of green water in international crop trade. *Ecological Economics,* 69(4), 887-894. https://doi.org/10.1016/j.ecolecon.2009.11.001

Allan, J. A. (1998). Virtual water: a strategic resource. *Ground water*, 36(4), 545-547. https://doi.org/10.1111/j.1745-6584.1998.tb02825.x

Cai, B., Zhang, W., Hubacek, K., Feng, K., Li, Z., Liu, Y., & Liu, Y. (2019). Drivers of virtual water flows on regional water scarcity in China. *Journal of Cleaner Production*, 207, 1112-1122. https://doi.org/10.1016/j.jclepro.2018.10.077

Cassardo, C., & Jones, J. A. A. (2011). Managing water in a changing world. *Water*, 3(2), 618–628. https://doi.org/10.3390/w3020618

Chapagain, A. K., & Hoekstra, A. Y. (2003). Virtual water flows between nations in relation to trade in livestock and livestock products. In Hoekstra, A. Y. (Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series,* 13, Delft: UNESCO-IHE.

Du Plessis, A. (2017). Global water availability, distribution, and use. In Du Plessis, A. (Ed.) *Freshwater Challenges of South Africa and its Upper Vaal River*. Berlin: Springer, pp. 3-11.

Duarte, R., Pinilla, V., & Serrano, A. (2014). The effect of globalisation on water consumption: A case study of the Spanish virtual water trade, 1849–1935. *Ecological Economics*, 100, 96-105. https://doi.org/10.1016/j.ecolecon.2014.01.020

Duarte, R., Pinilla, V., & Serrano, A. (2019). Long term drivers of global virtual water trade: a trade gravity approach for 1965–2010. *Ecological Economics*, 156, 318-326. https://doi.org/10.1016/j.ecolecon.2018.10.012

FAO (2003). *Review of world water resources by country. Water Reports*, 23. Rome: FAO. Retrieved from http://www.fao.org/docrep/005/Y4473E/y4473e00.htm#Contents

FAO (2020). *AQUASTAT database*. Retrieved from http://www.fao.org/aquastat/statistics/query/index.html;jsessionid=F7ACA930D39D57D848C967648C3031EB

Fracasso, A. (2014). A gravity model of virtual water trade. *Ecological economics*, 108, 215-228. https://doi.org/10.1016/j.ecolecon.2014.10.010

Gil, J., & Kamanda, J. (2015). Policies and initiatives related to water and climate change in agriculture. Zolin, C. A., Rodrigues, R. (Eds.) *Impact of Climate Change on Water Resources in Agriculture*. Florida: CRC Press.

Haddad, E. A., Mengoub, F. E., & Vale, V. A. (2020). Water content in trade: a regional analysis for Morocco. *Economic Systems Research*, 32(4), 565-584. https://doi.org/10.1080/09535314.2020.1756228

Han, M. Y., Chen, G. Q., & Li, Y. L. (2018). Global water transfers embodied in international trade: Tracking imbalanced and inefficient flows. *Journal of Cleaner Production,* 184, 50-64. https://doi.org/10.1016/j.jclepro.2018.02.195

Hoekstra, A. Y., & Hung, P. Q. (2002). Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. In Hoekstra, A. Y. (Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series*, 11, Delft: UNESCO-IHE.

Hoekstra, A. Y., Chapagain, A. K., Mekonnen, M. M., & Aldaya, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. London: Routledge.

Hoekstra, A. Y., & Mekonnen, M. M. (2012). The water footprint of humanity. *Proceedings of the national academy of sciences*, 109(9), 3232-3237. https://doi.org/10.1073/pnas.1109936109

IBGE (2020). *Contas Econômicas Ambientais de Água para o Brasil.* Retrieved from https://www.ibge.gov.br/estatisticas/economicas/contasnacionais/20207-contas-economicas-ambientais-da-agua-brasil.html?=t=o-que-e

Kibona, D., Kidulile, G., & Rwabukambara, F. (2009). Environment, climate warming and water management. *Transition Studies Review*, 16(2), 484-500. http://dx.doi.org/10.1007/s11300-009-0084-z

Liu, X., Du, H., Zhang, Z., Crittenden, J. C., Lahr, M. L., Moreno-Cruz, J., ... & Zuo, J. (2019). Can virtual water trade save water resources?. *Water research*, 163, 114848. https://doi.org/10.1016/j.watres.2019.07.015

Lui, J., Dorjderem, A., Fu J, Lei, X., ..., & Zheng, Y. (2011). *Water ethics and water resource management. Ethics and Climate Change in Asia and the Pacific (ECCAP) Project, Working Group 14 Report*. Bangkok: UNESCO.

Mekonnen, M.M., & Hoekstra, A.Y. (2011). National water footprint accounts: the green, blue and grey water footprint of production and consumption. In Hoekstra, A. Y. (Ed.) *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series,* 50, Delft: UNESCO-IHE.

NEREUS (2020). *Matrizes Insumo-Produto para o Brasil*. Retrieved from http://www.usp.br /nereus/?fontes=dadosmatrizes

SNRH (2006a). *Caderno da Região Hidrográfica Amazônica*. Brasília: Ministério do Meio Ambiente.

SNRH (2006b). *Caderno da Região Hidrográfica Atlântico Leste*. Brasília: Ministério do Meio Ambiente.

SNRH (2006c). *Caderno da Região Hidrográfica Atlântico Nordeste Ocidental*. Brasília: Ministério do Meio Ambiente.

SNRH (2006d). *Caderno da Região Hidrográfica Atlântico Nordeste Oriental*. Brasília: Ministério do Meio Ambiente.

SNRH (2006e). *Caderno da Região Hidrográfica Atlântico Sudeste*. Brasília: Ministério do Meio Ambiente.

SNRH (2006f). *Caderno da Região Hidrográfica Atlântico Sul*. Brasília: Ministério do Meio Ambiente.

SNRH (2006g). *Caderno da Região Hidrográfica Paraguai*. Brasília: Ministério do Meio Ambiente.

SNRH (2006h). *Caderno da Região Hidrográfica Paraná*. Brasília: Ministério do Meio Ambiente.

SNRH (2006i). *Caderno da Região Hidrográfica Parnaíba*. Brasília: Ministério do Meio Ambiente.

SNRH (2006j). *Caderno da Região Hidrográfica São Francisco*. Brasília: Ministério do Meio Ambiente.

SNRH (2006k). *Caderno da Região Hidrográfica Tocantins-Araguaia*. Brasília: Ministério do Meio Ambiente.

SNRH (2006l). *Caderno da Região Hidrográfica Uruguai*. Brasília: Ministério do Meio Ambiente.

UN (2020). *System of Environmental-Economic Accounting*. Retrieved from https://seea.un.org/content/seea-water

Visentin, J. C., & Guilhoto, J. J. M. (2019). The role of interregional trade in virtual water on the blue water footprint and the water exploitation index in Brazil. *Review of Regional Studies*, 49(2), 299-322. https://doi.org/10.52324/001c.10168

Wang, Z., Zhang, L., Zhang, Q., Wei, Y. M., Wang, J. W., Ding, X., & Mi, Z. (2019). Optimization of virtual water flow via grain trade within China. *Ecological Indicators*, 97, 25-34. http://dx.doi.org/10.1016/j.ecolind.2018.09.053

Zhang, C., & Anadon, L. D. (2014). A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. *Ecological Economics*, 100, 159-172. https://doi.org/10.1016/j.ecolecon.2014.02.006

Zhang, Y., Zhang, J., Wang, C., Cao, J., Liu, Z., & Wang, L. (2017). China and Trans-Pacific Partnership Agreement countries: Estimation of the virtual water trade of agricultural products. *Journal of Cleaner Production*, 140, 1493-1503. https://doi.org/10.1016/j.jclepro.2016.10.001

Zhang, Z., Shi, M., Yang, H., & Chapagain, A. (2011). An input–output analysis of trends in virtual water trade and the impact on water resources and uses in China. *Economic Systems Research*, 23(4), 431-446. http://dx.doi.org/10.1080/09535314.2011.636733

Zhang, Z., Yang, H., & Shi, M. (2016). Spatial and sectoral characteristics of China's international and interregional virtual water flows–based on multi-regional input–output model. *Economic Systems Research*, 28(3), 362-382. https://doi.org/10.1080/09535314.2016.1165651

3. CLIMATE CHANGE, WATER AVAILABILITY AND WATER COST

3.1. Motivation

A hydrological model is a mathematical representation of the hydrological cycle on a surface. The hydrographic region is the object of study for most hydrological models, bringing together the surfaces that capture and pour water into one or more drainage channels that flow into a single outlet (Bonan, 2015).

From a hydrological point of view, the soil can be understood as a reservoir where a particular volume of water is stored. Thus, computing all inputs and outputs in the system can calculate the water balance in the soil. The primary water input into the system is precipitation. Considering a cover of vegetation, the rainwater is first intercepted by the forest canopy (or otherwise, it will directly reach the soil or water bodies). This intercepted water can then be evaporated. The water reaches the soil's surface, infiltrates, and the rest can runoff superficially. The infiltrated water will be redistributed in the soil profile. Simultaneously with water entry into the soil, it can evaporated from the surface or be removed by the roots and transpired by the leaves. The water can also descend the soil profile and reach the water table. In summary, the water availability (i.e., the water present in a region's soil or underground) can be computed as precipitation minus evapotranspiration (Oki & Kanae, 2006; Trenberth et al., 2007; Bonan, 2015).

In the long run, climate change can alter the regional water availability[4]. There are several studies in the literature that assess the impacts of climate change on water availability in Brazilian hydrographic regions through hydrological models (or hydroclimatic models). This includes the work of Medeiros (2003); de Araújo et al. (2004); Rosenzweig et al. (2004); Krol & Bronstert (2007); Mello et al. (2008); Montenegro & Ragab (2010); Nóbrega et al. (2011); Rivarola Sosa et al. (2011); Marengo et al. (2012); Montenegro & Ragab (2012); Adam & Collischonn (2013); Fill et al. (2013); Perazzoli et al. (2013); Pinheiro et al. (2013); Bravo et al. (2014); Ribeiro Neto et al. (2014); Silveira et al. (2014); Adam et al. (2015); Junior & Mauad (2015); Iensen et al. (2015); Mohor et al. (2015); Oliveira et al. (2015); Júnior et al.

---

[4] Changes in land use (e.g., deforestation) can also alter the water availability of a given region. This component will not be addressed in this study.

(2015); Valério et al. (2015); Viola et al. (2015); Alvarenga et al. (2016); Ho et al. (2016); Lamparter et al. (2016); de Queiroz et al. (2016); Ribeiro Junior et al. (2016); Neto et al. (2016); Silveira et al. (2016); Sorribas et al. (2016); Tejadas et al. (2016); Fernandes et al. (2017); Guimberteau et al. (2017); Melo & Wendland (2017); Mendes et al. (2017); Mohor & Mendiondo (2017); de Oliveira et al. (2017); Gondim et al. (2018) and Zaninelli et al. (2018)[5]. Table 3.1 summarizes some of these articles.

Changes in water availability, mainly in its surface form (i.e., in rivers, lakes, reservoirs), have implications for the cost of accessing it. Economic activities that require water collection, treatment or distribution will have to adopt more or less technology, human, and financial resources depending on the water supply. For example, in a case of scarcity, firms in the water and sewage treatment sector will have to invest in the construction of new water abstraction channels (probably more geographically distant from current sources), in the construction of new reservoirs, and in the modernization of distribution networks to reduce water loss. In the agricultural sector, especially those farms that use irrigated agriculture, they will have to look for new sources of extraction (new rivers, lakes, or drilling to collect groundwater) or invest in more efficient technological capital such as automated pivots or pumping systems. In water-intensive industries, firms will invest in capital capable of maintaining/increasing the output-water ratio and think of ways to reuse water resources. Climate change will put pressure on the various economic sectors that use water as an input to address this issue.

This chapter has two objectives. First, we look at changes in water availability (changes in precipitation and evapotranspiration values) in Brazilian hydrographic regions due to climate change. At this point, we use climatic data processed by the Eta-MIROC5 model for the period 2070-2099, considering the scenarios RCP 4.5 and RCP 8.5 and compare them with historic data from 1960-2005. Second, based on these changes in water availability, we calculate possible variations in the cost of access to water in Brazilian hydrographic regions.

---

[5] The YARA tool synthesizes studies related to the impacts of climate change on Brazil's water resources. For more details, see Amorim & Chaffe (2019) and Amorim et al. (2020).

Table 3.1. Climate change and water availability in Brazil, some references in the literature

Authors	*Regions*	*Main conclusion*
Medeiros (2003)	ALT	Reductions in precipitation and increases in potential evapotranspiration can significantly impact the region's water balance.
de Araújo et al. (2004)	AOR	Several municipalities analyzed may suffer from long-run water deficits.
Rosenzweig et al. (2004)	URU	In the tested climate change scenarios, there seems to be enough water for agriculture.
Krol & Bronstert (2007)	AOR	River flow, water storage, and irrigated production are specifically affected, assuming continuous regional development and unfavorable climate changes.
Mello et al. (2008)	SFO	There is a tendency towards an increase in water availability in fluvial stations.
Montenegro & Ragab (2010)	SFO	The model projects a reduction in groundwater recharge and streamflow.
Nóbrega et al. (2011)	PRN	An increase in the mean annual discharge is expected in relation to historical values. A substantial uncertainty was noted in the projected values, which is linked to the choice of the global circulation model.
Rivarola Sosa et al. (2011)	PRN	The results show the possibility of unchanging or reducing average annual runoff. Possible impacts on hydroelectric energy production are discussed.
Marengo et al. (2012)	AMZ, PRN, SFO	Significant rainfall reductions are simulated in Amazonia and Northeast Brazil, and rainfall increases in Southeastern South America. The precipitation minus evaporation suggests water deficits and river runoff reductions in the eastern Amazon and São Francisco Basin.

continued

Authors	*Regions*	*Main conclusion*
Montenegro & Ragab (2012)	AOR	The simulated impacts of climate change indicate the possibility of reducing the availability of surface water, groundwater recharge, and surface flows.
Adam & Collischonn (2013)	URU	Medium and high flow rates are more sensitive to changes in precipitation. The uncertainties related to the projections of precipitation and temperature anomalies were amplified when assessing the impact of climate changes on the flow regime.
Fill et al. (2013)	PRN, URU	Reduction in the dependable energy output of the hydropower plants could be expected during the 21st century.
Perazzoli et al. (2013)	PRN	Analysis of daily values and extreme events suggested that flood peaks could reach more extreme values in the future.
Pinheiro et al. (2013)	PRN	Future runoff depths are more significant than baseline values.
Bravo et al. (2014)	PRG	Patterns of temperature increase persist over the entire year for almost all models, increasing the hydrological model's evapotranspiration rate. The coupled hydrologic-hydraulic model shows nearly one-half of projections as increasing river discharge and the other half as decreasing river discharge.
Ribeiro Neto et al. (2014)	AOR	Industry and irrigation will be impacted by climate change unless other measures are implemented to control demand.
Silveira et al. (2014)	PRN, SFO, TOC	It makes projections of flows for Brazilian basins that have hydroelectricity-producing plants. Most models show reduced reservoir levels.
Adam et al. (2015)	PRN	The impacts on the flows are highly dependent on the model used to obtain the climate projections.
Arroio Júnior & Mauad (2015)	PRN	The flow level is quite vulnerable to potential climate change and subject to possible water availability problems in the future.
Iensen et al. (2015)	PRN	Changes were observed in hydro-sedimentological dynamics in the watershed analyzed, mainly in terms of decreased average sediment yield due to the reduction in precipitation and increase in evapotranspiration.

continued

Authors	*Regions*	*Main conclusion*
Mohor et al. (2015)	AMZ	The variability in the climate projections drives a high variability in the projected hydrological impacts. Results indicate an increase in the basin’s sensitivity to climate change and vulnerability to water exploitation.
Oliveira et al. (2015)	URU	Increased hydrological variability during the period analyzed, which indicates the possibility of occurrence of time series with more marked periods of droughts and floods.
Júnior et al. (2015)	AMZ	The scenarios indicated a decrease in the low-flow regime. Some simulations included forest conversion to pasture, climate change impacts on low flows.
Valério et al. (2015)	ALT	Lower rainfall and flow rates in the short and long-run scales for all the scenarios evaluated.
Viola et al. (2015)	PRN	In most of the analyzed periods, an increase in surface runoff levels is projected.
Alvarenga et al. (2016)	PRN	Runoff is very sensitive to rising temperatures and reduced precipitation. The hydrological simulation projected a drastic reduction in the runoff behavior and consequently in the water production capacity of the region.
Ho et al. (2016)	TOC	Climate models suggest declines in mean annual discharge.
Lamparter et al. (2016)	AMZ, TOC	Scenario simulation results show effects on the water balance proportional to land-use change. The conversion of native vegetation to pasture has the highest impact on the water balance.
de Queiroz et al. (2016)	AMZ, ALT, ASD, ASU, PRN, PNB, SFO, TOC, URU	Climate change can drastically impact the supply of hydroelectric energy.
Ribeiro Junior et al. (2016)	PRN	If the climate change scenarios occur, water reservoirs can be drastically emptied, compromising hydroelectric energy production. These losses can still be minimized.
Neto et al. (2016)	AMZ, ALT, AOC, AOR, ASD, ASU, PRG, PRN, PNB, SFO, TOC, URU	Water availability decreases in almost the entire study area, and the significant basins for hydroelectric power generation are affected.

continued

Authors	*Regions*	*Main conclusion*
Silveira et al. (2016)	PRN, SFO, TOC	Most models show that the reduced streamflow impacts the electricity sector in the Southeast, Midwest, and North regions.
Sorribas et al. (2016)	AMZ	Climate change and its effects on the hydrologic regime of the Amazon basin can impact bio-geochemical processes, transportation, flood vulnerability, fisheries, and hydropower generation.
Tejadas et al. (2016)	ASU	Climate change may increase flows in the region.
Fernandes et al. (2017)	AOR	Most reservoir yield projections indicated a reduction caused by climate change.
Guimberteau et al. (2017)	AMZ	Deforestation in the Amazon region is expected to decrease evapotranspiration and increase soil moisture and river discharge. The uncertainty in both evapotranspiration and runoff changes attributable to uncertain future deforestation is low.
Melo & Wendland (2017)	PRN	Mean recharge change depends on the land use type. The response given by the groundwater model indicates a lowering of the water table under most scenarios.
Mendes et al. (2017)	AMZ, TOC	The variations imposed by climate changes on some climatological variables create significant uncertainties about the power generation forecasts of the hydroelectric power plants to be installed in the Amazon region.
Mohor & Mendiondo (2017)	PRN	In a drought scenario, economic instruments can help manage water resources.
de Oliveira et al. (2017)	PRN	The results indicated a significant streamflow reduction and, therefore, reductions in runoff during all the simulated periods.
Gondim et al. (2018)	AOR	Projections indicate an increased need for irrigation water. Improved irrigation efficiency is crucial for adapting to higher future water demand levels, as gains in irrigation efficiency could compensate for climate change impacts.
Zaninelli et al. (2018)	AMZ, ALT, AOC, AOR, ASD, ASU, PRG, PRN, PNB, SFO, TOC, URU	This article shows changes in hydroclimate conditions for South America.

Source: Authors’ own.

3.2. Climate change and water availability

3.2.1. Hydroclimatic modelling

Changes in water availability in Brazilian hydrographic regions are evaluated by comparing historical and future information (precipitation minus potential evapotranspiration).

In our hydroclimatic modelling, the potential evapotranspiration is calculated using the Thornthwaite approach (Thornthwaite, 1948), which is calculated as follows (3.1),

$$E_i = \begin{cases} 0, & T_i < 26.5°C \\ 16\,(10\frac{T_i}{I})^a, & 0 \leq T_i < 26.5°C \\ -415.85 + 32.24T_i - 0.43T_i^2, & T_i \geq 26.5°C \end{cases}$$

$$a = 6.75\ 10^{-7}I^3 - 7.71\ 10^{-5}I^2 + 1.7912\ 10^{-2}I + 0.49239 \tag{3.1}$$

$$I = \sum_{i=1}^{12}(\frac{1}{5}T_i)^{1.514}$$

$$E_i' = E_i[(m/30)(h/12)] \quad \text{(month and daylight lengths adjust)}$$

where E_i is the average monthly evapotranspiration, T_i is the average monthly temperature and I is the region's heat index. The monthly potential evapotranspiration values are adjusted by the number of days in the month (m) and daylight duration (h).

Historical monthly precipitation data (mm), maximum and minimum temperature (°C) for the period 1960-2005 were provided by the National Institute for Space Research (INPE, 2020) in a spatial resolution of 2.5 minutes of a longitude/latitude degree (this is about 20 km^2).

The projected future data came from a regional climate model for Brazil (and South America) forced by global climate model MIROC5[6] (Eta-MIROC5) (Watanabe et al., 2010; Chou et al., 2014). The regional climate models (RCMs) play the vital role of downscaling the global

---

[6] Model for Interdisciplinary Research on Climate (MIROC) is a Japanese climate model and has been cooperatively developed at the Center for Climate System Research (CCSR; the precursor of a part of the Atmosphere and Ocean Research Institute), the University of Tokyo, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and the National Institute for Environmental Studies (NIES) (Watanabe et al., 2010).

climate simulations to smaller grid sizes in the area of interest where impact studies can be carried out (Chou et al., 2014). We selected monthly precipitation (mm), maximum and minimum temperature (°C) information from the Eta-MIROC5 in Representative Concentration Pathway scenarios, RCP 4.5 and 8.5 Wm^{-2} radiative forcing scenarios, using as reference the period between the years 2070 and 2099 (average of the period), with a spatial resolution of 2.5 minutes (this is about 20 km^2). The RCPs are Greenhouse Gases (GHG) concentration trajectories adopted by the Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC, 2014). RCP 2.6 assumes an optimistic scenario in which global GHG emissions peak between 2010 and 2020, with emissions decreasing substantially after that. Emissions in RCP 4.5 peak in around 2040, while in RCP 6.0, this will happen in 2080 and fall after that. In turn, the pessimistic scenario is outlined by RCP 8.5, in which emissions increase throughout the 21st century. It is worth noting that the projection of climatic impacts in hydrological processes is usually susceptible to uncertainties in the GHG emission scenarios. For more details on this topic, see Hawkins & Sutton (2009).

3.2.2. Hydroclimatic results

Figure 3.1a shows Brazil’s historical average annual precipitation (average of the months of the year). It can be seen that the highest values occurred in the North region (between 200 mm and 250 mm), more specifically over the humid Amazon region. In contrast, the Brazilian Northeastern semi-arid region has the lowest historical precipitation values (around 50 mm to 100 mm). The other regions have intermediate values (100 mm to 150 mm).

In Figure 3.1b, we observe the difference in the average annual precipitation between 2070-2099, considering the scenario RCP 4.5 and the historical values 1960-2005. We noticed a reduction in precipitation in the North, especially at the edge of the AMZ hydrographic region. This difference is around -35 mm to -70 mm. In the Brazilian Northeast, represented by the hydrographic regions ALT, AOC, AOR, PNB, and SFO, stability or reduction in average annual precipitation levels is expected (around 0 mm to -35 mm). Brazil’s South and Southeast regions, where the hydrographic regions of ASU, PRN, and URU are located, present stability or increased average annual precipitation levels (difference between 0 mm and 35 mm).

Figure 3.1c shows the difference in average annual precipitation between 2070-2099 and 1960-2005, considering the RCP 8.5 scenario. In this pessimistic scenario, extreme precipitation events are expected. In other words, the trends of reduction, stability or increase seen in the RCP 4.5 scenario (Figure 3.1b) are enhanced. Thus, more pronounced reductions are projected and spread at the edges of the AMZ region, in the AOC region, and part of the TOC region. In the interior of the AMZ region, there is an increase in the area where the difference between future and historical precipitation reaches 50 mm. The Northeastern region reinforces a situation of stability or reduction in precipitation levels. Finally, in this scenario, most South regions present a positive difference in the average annual precipitation levels, around 35 mm.

Figure 3.2a shows the calculated values of historical average annual potential evapotranspiration (average of the months of the year). These are the water outlets in the region and are related to the observed mean temperature. It is possible to note that the most prominent water outlets into the atmosphere were in the AMZ, AOC, PNB, PRG and TOC hydrographic regions, whose values are between 95 mm and 110 mm. The ASU, PRN, and URU regions have moderate values of evapotranspiration, around 65 mm.

Figure 3.2b shows the difference in average annual potential evapotranspiration between 2070-2099 and 1960-2005, considering the RCP 4.5 scenario. In this case, the increase in evaporation has values between 0 mm and 25 mm. The ASD, ASU, PRN, and URU regions have moderate increases in evapotranspiration (between 0 mm and 15 mm). The North region registers the most significant differences, with values from 25 mm to 50 mm.

Figure 3.2c shows the difference in evapotranspiration between 2070-2099 and 1960-2005, considering the RCP 8.5 scenario. In this case, the most significant differences are observed in parts of the AMZ, AOC, PNB, PRG, and TOC regions. The calculated values reach 75 mm. The other regions, highlighting the ASD, ASU, PRN, and URU, expect a lower change from the historical average, somewhere between 0 mm and 25 mm.

Figure 3.3a shows the historical average annual water availability values 1970-2000 (average of the months of the year). We define water availability as precipitation minus potential evapotranspiration. It can be seen that the areas with negative availability are in the Northeast region, such as ALT, AOC, AOR, PNB, and SFO (values are between -50 mm and 0 mm). These regions have a greater chance of water stress in this configuration. In turn, the areas with favorable water availability are the AMZ region (reaching 100 mm), PRN region (values between 50 mm and 100 mm), and the ASU and URU regions (with values reaching 50 mm).

Figure 3.3b shows the difference in water availability between 2070-2099 and 1960-2005, using the RPC 4.5 scenario. In this scenario, there is a trend towards declining water availability in most regions. The AMZ, AOC, and TOC hydrographic regions have the most extensive changes (between -50 mm and -100 mm). The ASU and URU hydrographic regions are exceptions. It is possible to see an increase in water availability (between 0 mm and 50 mm) in them.

Figure 3.3c shows the difference in water availability between 2070-2099 and 1960-2005, using the RCP 8.5 scenario. In this context, part of the North and Northeast regions will be severely affected, including the AMZ, AOC, AOR, PNB, and TOC regions. In some areas, a difference of around -150 mm is projected. A moderate reduction or slight increase in water availability in other regions of the country is projected, somewhere between -50 mm and 50 mm.

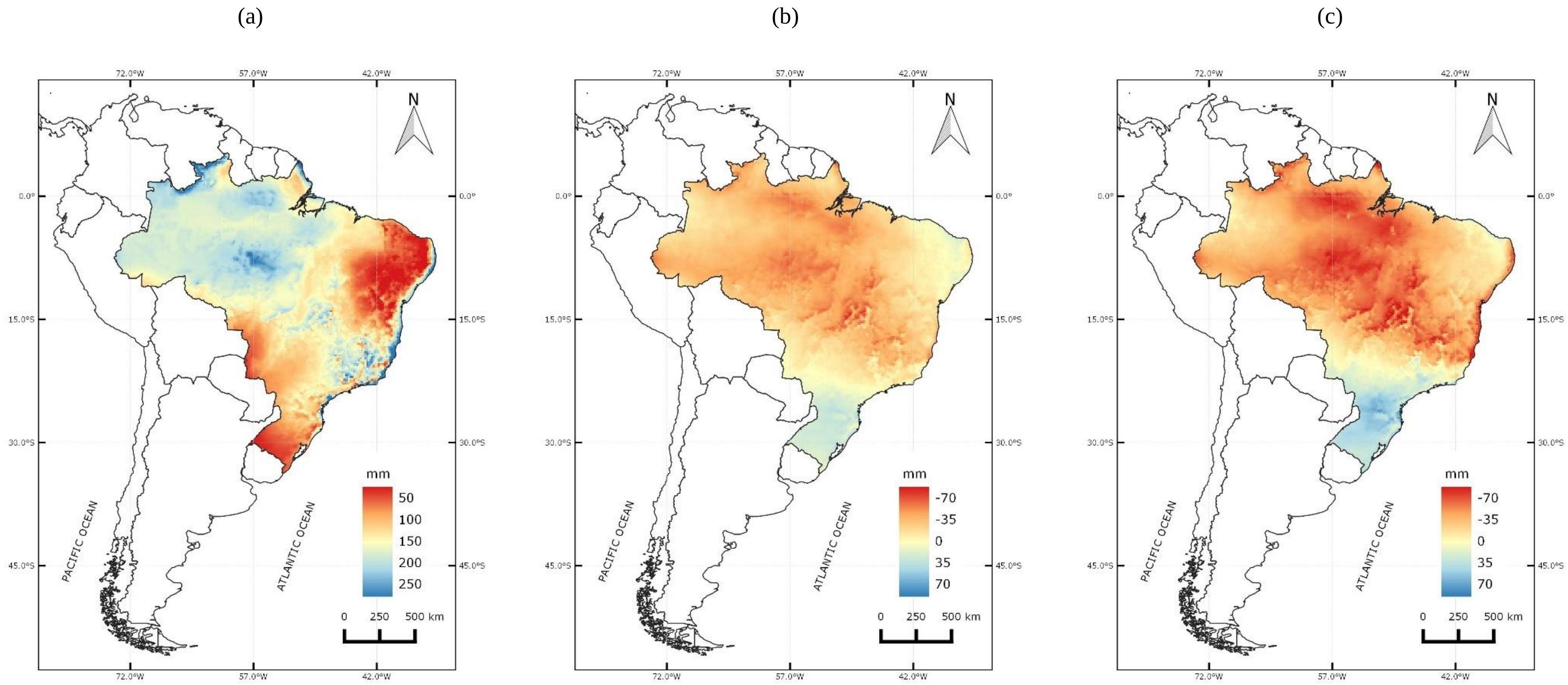
Figure 3.4 shows discretized information on average water availability in the Brazilian hydrographic regions. Figure 3.4a shows the average historical water availability for the years 1960-2005. Water criticality can be observed in the semi-arid region of the Northeast. In the AOR, the deficit is between 0 mm and 55 mm. The other regions of the semi-arid region (ALT, AOC, PNB, and SFO) have small surpluses between 0 mm and 55 mm. In turn, the AMZ, ASD, ASU, PRG, PRN, TOC, and URU have a moderate-good history of water availability but at levels that require attention. Surpluses are between 0 mm and 110 mm. The AMZ region has a good history of water availability, reaching 110.

Figure 3.4b shows the average water availability for the period 2070-2099 in an RCP 4.5 scenario. It can be seen that some regions fall into a deficit water condition; this is the case of the AOR, PNB, PRG, SFO, and TOC regions. Deficits are between 0 mm and 55 mm. The ALT, AMZ, AOC, ASU, PRN, and URU regions comprise an intermediate situation group with surpluses between 0 mm and 55 mm. In this scenario, only the ASD region has a positive value with an average surplus between 55 mm and 110 mm.

Figure 3.4c presents average water availability for the period 2070-2099 in the scenario RCP 8.5. In this case, there is a severe condition in the PRG and PNB regions. Potential deficits are between 55 mm and 110 mm. The ALT, AMZ, AOC, AOR, SFO, and TOC regions have intermediate water deficits. These deficits are between 0 mm and 55 mm. The PRN and URU regions have a moderate surplus condition, with values between 0 mm and 55 mm. Finally, the ASD and ASU regions maintain their surplus status. The average water availability values projected for the period are between 55 mm and 110 mm. In general, two movements are expected in terms of water availability in Brazil: (i) the maintenance or worsening of the deficit condition in the North, Northeast, and Midwest regions of Brazil; and (ii) the maintenance or improvement of the surplus condition in the South and Southeast regions.

Table 3.2 summarizes the average values of precipitation, temperature, potential evapotranspiration, and water availability in historical terms (1960-2005) and projected scenarios RCP 4.5 and RCP 8.5 (2070-2099) discretized by hydrographic regions. In addition, the percentage changes between the values of the projected scenarios and their respective historical values were calculated.

Figure 3.1. Mean precipitation



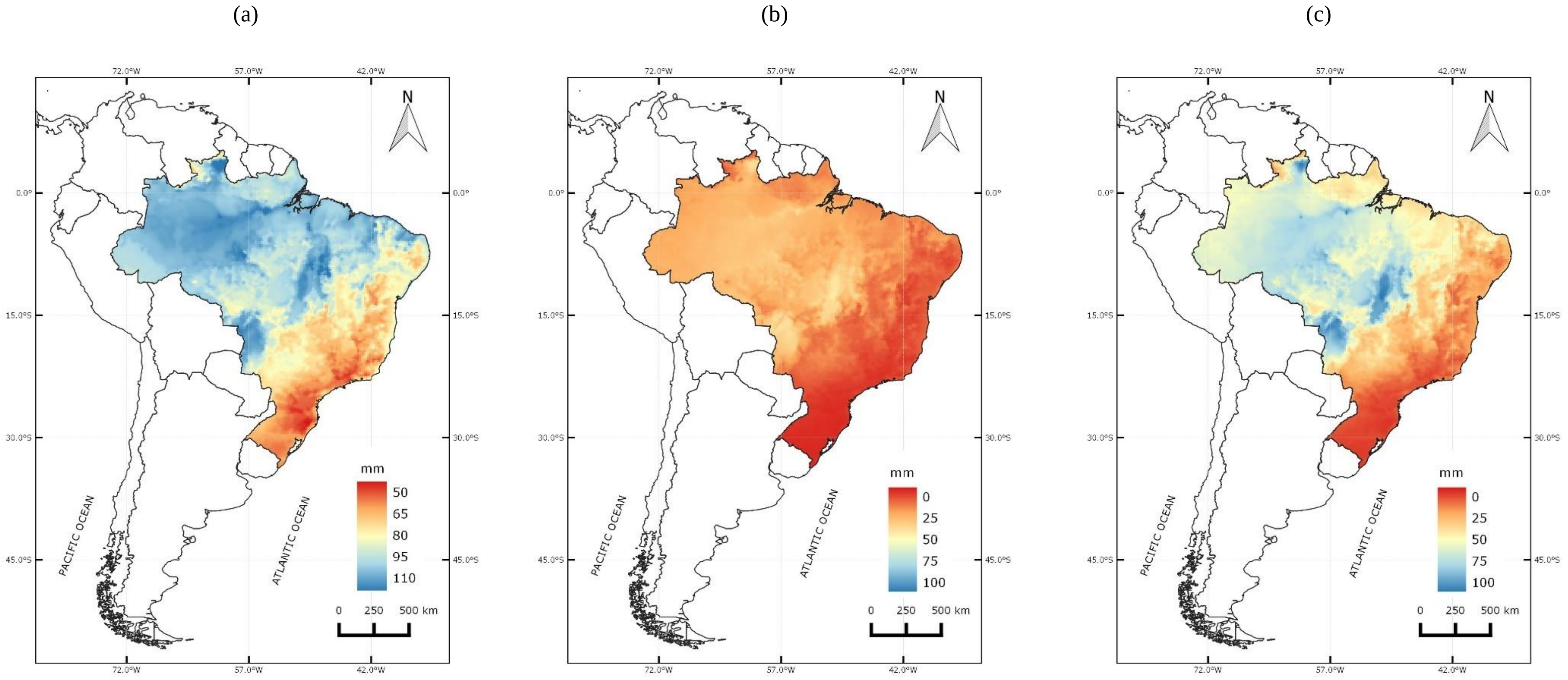
(a) Mean precipitation (1960-2005).

(b) Mean precipitation difference (2070-2099 minus 1960-2005) using RCP 4.5 scenario.

(c) Mean precipitation difference (2070-2099 minus 1960-2005) using RCP 8.5 scenario.

Source: Authors’ own.

Figure 3.2. Mean potential evapotranspiration



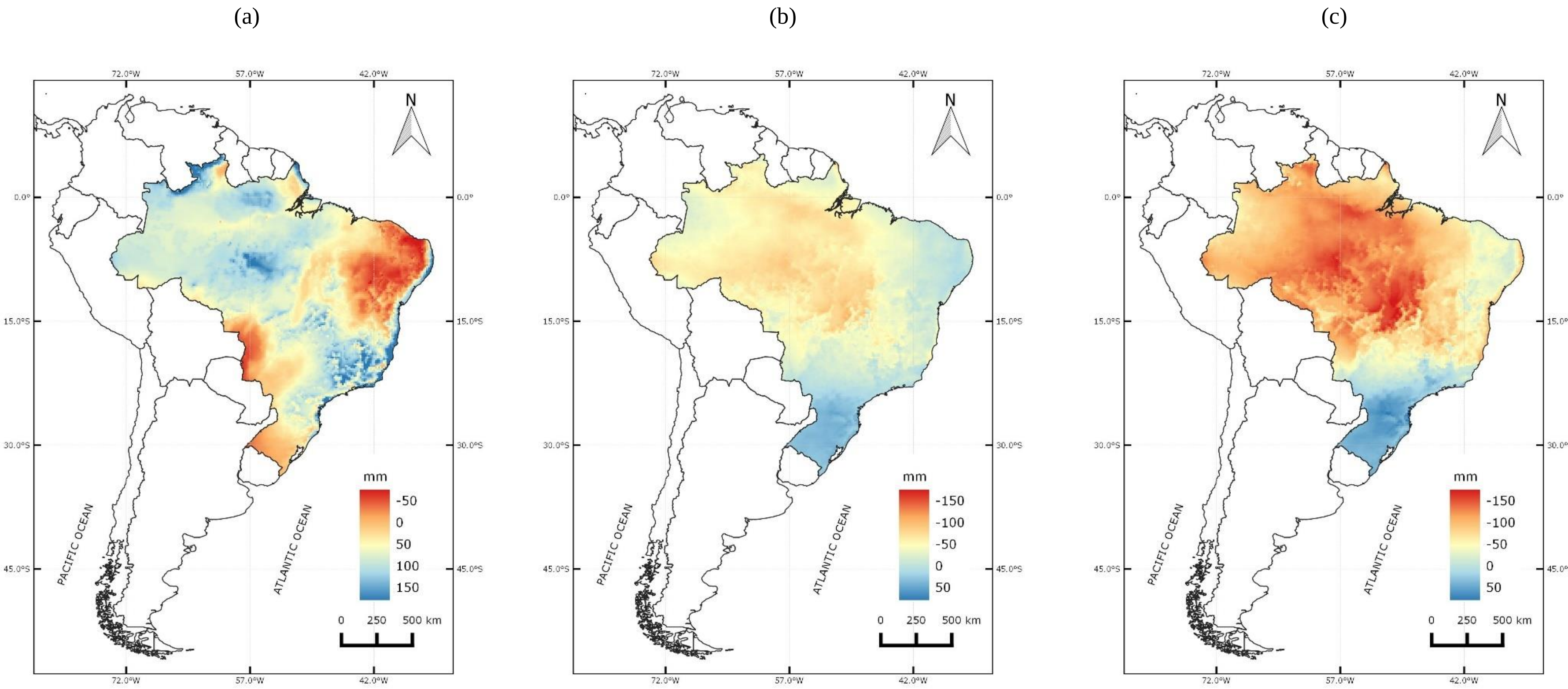
(a) Mean evapotranspiration (1960-2005).

(b) Mean evapotranspiration difference (2070-2099 minus 1960-2005) using RCP 4.5 scenario.

(c) Mean evapotranspiration difference (2070-2099 minus 1960-2005) using RCP 8.5 scenario.

Source: Authors’ own.

Figure 3.3. Mean water availability (precipitation minus evapotranspiration)



(a) Mean water availability (1960-2005).

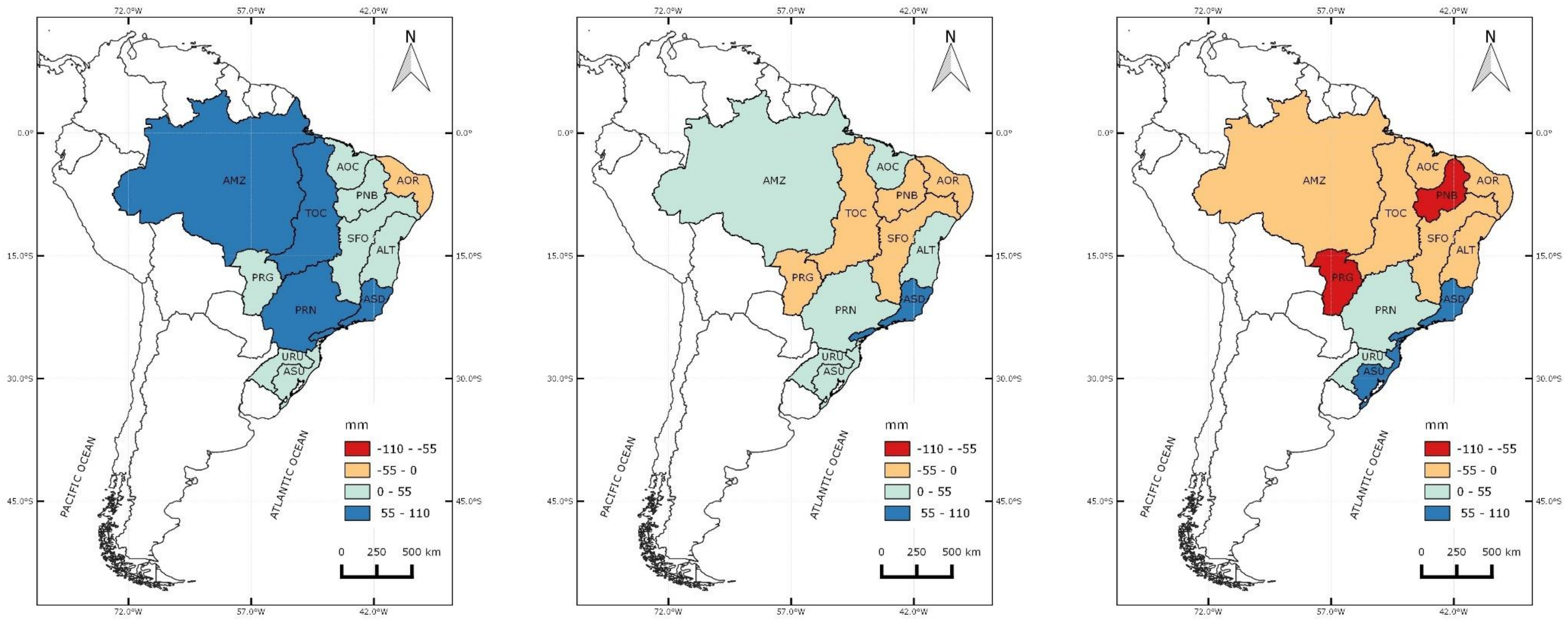
(b) Mean water availability difference (2070-2099 minus 1960-2005) using RCP 4.5 scenario.

(c) Mean water availability difference (2070-2099 minus 1960-2005) using RCP 8.5 scenario.

Source: Authors’ own.

Figure 3.4. Mean water availability (precipitation minus evapotranspiration) – discrete data

(a) (b) (c)



(a) Mean water availability (1960-2005).

(b) Mean water availability (2070-2099) using RCP 4.5 scenario.

(c) Mean water availability (2070-2099) using RCP 8.5 scenario.

Source: Authors’ own.

Table 3.2. Hydroclimatic model results

		Regions												
		AMZ	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*	*Brazil*
Historical	Prec. (mm)	176.12	113.56	142.60	83.39	175.95	97.98	104.56	133.78	95.53	103.27	154.51	84.50	147.11
	Temp. (°C)	23.50	19.78	23.50	22.26	17.88	16.37	23.24	18.79	23.02	20.46	23.11	16.49	22.06
	Evap. (mm)	96.93	73.61	96.57	88.18	66.51	61.45	95.17	70.06	92.91	77.09	94.35	62.13	88.53
	P-E (mm)	79.19	39.96	46.02	-4.79	109.44	36.53	9.39	63.72	2.61	26.18	60.16	22.36	58.58
RCP 4.5	Prec. (mm)	146.59	99.60	122.82	85.04	163.41	116.51	92.77	128.29	81.76	83.55	119.62	103.38	126.13
	Temp. (°C)	25.91	21.68	25.46	24.10	19.73	17.55	25.84	20.99	25.06	22.64	25.63	17.72	24.32
	Evap. (mm)	124.66	83.92	117.81	104.29	73.96	64.94	124.87	81.36	113.42	91.02	122.10	65.83	110.40
	P-E (mm)	21.93	15.68	5.02	-19.25	89.46	51.58	-32.10	46.93	-31.65	-7.46	-2.48	37.56	15.73
RCP 8.5	Prec. (mm)	137.71	81.24	113.09	73.47	164.49	128.04	93.12	138.51	71.07	73.49	106.82	117.23	119.66
	Temp. (°C)	27.76	23.23	27.02	25.53	21.15	18.67	27.78	22.63	26.73	24.46	27.55	18.92	26.07
	Evap. (mm)	158.61	95.40	142.52	121.57	81.55	68.87	161.66	93.58	138.21	108.38	156.15	70.23	136.83
	P-E (mm)	-20.90	-14.16	-29.43	-48.09	82.94	59.16	-68.54	44.92	-67.14	-34.89	-49.33	47.00	-17.18
RCP 4.5 - Historical	Prec. (Δ%)	-16.76	-12.30	-13.87	1.98	-7.12	18.92	-11.27	-4.10	-14.41	-19.09	-22.58	22.35	-13.18
	Temp. (Δ%)	10.23	9.61	8.32	8.26	10.33	7.21	11.14	11.70	8.87	10.65	10.89	7.45	10.19
	Evap. (Δ%)	28.61	14.01	21.99	18.27	11.19	5.68	31.21	16.14	22.07	18.06	29.41	5.95	23.84
	P-E (Δ%)	-72.30	-60.75	-89.09	-302.27	-18.26	41.19	-441.93	-26.35	-1,311.78	-128.51	-104.12	67.93	-140.47
RCP 8.5 - Historical	Prec. (Δ%)	-21.81	-28.46	-20.69	-11.89	-6.51	30.68	-10.94	3.53	-25.60	-28.83	-30.86	38.74	-17.53
	Temp. (Δ%)	18.12	17.48	14.99	14.68	18.28	14.09	19.50	20.44	16.14	19.58	19.19	14.71	18.17
	Evap. (Δ%)	63.64	29.60	47.57	37.87	22.62	12.08	69.86	33.58	48.75	40.59	65.49	13.04	52.56
	P-E (Δ%)	-126.39	-135.43	-163.94	-904.92	-24.21	61.95	-830.06	-29.50	-2,670.22	-233.27	-182.00	110.15	-276.15

Source: Authors’ own.

3.3. Water cost change

Water availability should have some influence on the cost of access to water. This information is more easily obtained in the water and sanitation sector (collecting, distributing, and treating water and sewage) than in farms or industrial firms.

Thus, we continue our analysis, assessing information from the São Paulo State Sanitation Company (Sabesp). Sabesp is a mixed capital company, and its majority shareholder is the Government of the State of São Paulo, Brazil. Sabesp is the largest sanitation company in the Americas and serves more than 25 million inhabitants inside and outside the metropolitan region of São Paulo (MRSP), with a production of 2.1 billion m^3/year (Sabesp, 2020). Given these attributes, we consider that Sabesp to be a good benchmark in analyzing the relationship between water availability (i.e., the quantity of water in a reservoir, etc.) and the cost of water extraction. We collected company cost information for 2010 to 2015 from its financial reports (Sabesp, 2020). In addition, in the same period, we used the levels of the reservoirs most used by the company to collect water. The list includes the Jaguari-Jacareí, Cachoeira River, Atibainha River, and Paiva Castro reservoirs (Cantareira System). These data were collected from the National Water Agency (ANA, 2020). A summary of these values can be found in Tables 3.3 and 3.4.

The 2014-2015 biennium was marked by the most significant drought in the history of the MRSP. The reservoirs of the Cantareira System, the primary source of water, reached critical outflow levels (see Table 3.3), requiring the emergency use of the dead storage. This extreme drought event brought to light water production cost changes (i.e., water extraction and treatment). Table 3.4 shows the significant increase in the cost per unit of water produced. In 2015 this was BRL 2.6/m^3, up from BRL 1.5/m^3 in 2010. Doing a simple regression analysis, we relate the cost data per unit of water and outflow (a measure of water availability). We obtain an estimated coefficient of -0.327 (std. error = 0.133; p-value = 0.069). In other words, -1% changes in the outflow level lead to a 0.327% increase in the water cost extraction.

Table 3.3. Average annual outflows of reservoirs in the Cantareira System, period 2010-2015 (m^3/s)

Reservoir	*2015*	*2014*	*2013*	*2012*	*2011*	*2010*
Jaguari-Jacareí	13.6	5.3	17.1	16.3	26.0	25.0
Cachoeira River	3.4	2.0	4.7	4.6	8.1	7.5
Atibainha River	2.7	1.4	3.9	4.6	6.3	6.3
Paiva Castro	3.0	2.6	5.4	5.3	5.5	7.6
Total	22.7	11.3	31.1	30.8	45.9	46.4

Source: ANA (2020).

Table 3.4. Costs list of the Sabesp, period 2010-2015 (BRL thousand, deflated values using IPCA)

Description	*2015*	*2014*	*2013*	*2012*	*2011*	*2010*
Wages	1,342,972	1,398,372	1,269,211	1,152,834	1,058,209	935,753
Construction costs	2,915,560	2,672,477	2,252,973	2,273,408	2,035,537	1,958,080
General materials	154,149	179,434	169,147	159,221	137,696	127,076
Treatment materials	240,560	244,462	226,503	167,090	144,689	128,464
Third-party services	706,740	802,029	740,032	682,168	624,709	568,162
Electricity	728,186	559,157	51,903	553,833	54,455	498,067
General costs	329,818	378,447	418,383	377,060	344,951	190,657
Total costs	6,417,984	6,234,378	5,128,152	5,365,614	4,400,247	4,406,259
Water production (million m^3)	2,466	2,840	3,053	3,059	2,992	2,952
Total costs/ Water production (BRL/m^3)	2.6	2.2	1.7	1.7	1.5	1.5

The Extended National Consumer Price Index (IPCA) is the reference for the Brazilian inflation-targeting system.

Source: Sabesp (2020).

Using the estimated coefficient and standard error as a benchmark and the percentual changes in water availability in the Brazilian hydrographic regions (see the bottom part of Table 3.2), we project possible values of water cost change (and lower and upper values in the confidence interval). These results are in Table 3.5. In the RCP 4.5 scenario, the PNB, PRG, and AOR regions have the most significant cost shocks, with 428.95%, 144.51%, and 98.84%, respectively. On the other hand, the cost of water abstraction in the regions ASU and URU is expected to fall, with -13.47% and -22.21%, respectively. The AMZ, AOC, ASD, PRN, PRG, and TOC regions have intermediate cost impacts, values around 5% to 45%. On average, an increase in the cost of access to water of around 45.93% is expected in Brazil. In the RCP 8.5 scenario, the interpretations are similar; in this case, they will affect only the magnitudes of the shocks that tend to increase. For the PNB, PRG, and AOR regions an increase in the cost of access to water of 873.16%, 295.91%, and 271.43%, respectively is expected. For the ASU and URU regions, changes of -20.26% and -36.02% are expected. In the other hydrographic regions, the calculated values are between 7% and 80%. The average increase in the cost of access to water in Brazil in this scenario is 90.30%.

Table 3.5. Water cost changes in the Brazilian hydrographic regions

Region		*RCP 4.5 (2070-2099)*			*RCP 8.5 (2070-2099)*	
	Baseline (%)	*Lower (%)*	*Upper (%)*	*Baseline (%)*	*Lower (%)*	*Upper (%)*
AMZ	23.64	14.03	33.26	41.33	24.52	58.14
ALT	19.87	11.79	27.95	44.29	26.27	62.30
AOC	29.13	17.28	40.98	53.61	31.80	75.41
AOR	98.84	58.64	139.04	295.91	175.55	416.26
ASD	5.97	3.54	8.40	7.92	4.70	11.14
ASU	-13.47	-18.95	-7.99	-20.26	-28.50	-12.02
PRG	144.51	85.73	203.29	271.43	161.03	381.83
PRN	8.62	5.11	12.12	9.65	5.72	13.57
PNB	428.95	254.49	603.42	873.16	518.02	1,228.30
SFO	42.02	24.93	59.11	76.28	45.25	107.30
TOC	34.05	20.20	47.90	59.51	35.31	83.72
URU	-22.21	-31.25	-13.18	-36.02	-50.67	-21.37
Brazil	45.93	27.25	64.62	90.30	53.57	127.03

Source: Authors' own.

Overall, assuming a unit water cost of BRL 1.5/m^3 in the current period (realistic value), the climate scenarios indicate that future water access cost will be in the range between BRL 0.75/m^3 in the best case - region URU hydrographic region in RCP 8.5-Lower and BRL 20/m^3 in the worst case - PNB hydrographic region with RCP 8.5-Upper.

The economic impacts of climate change are quite heterogeneous in regional terms. The most vulnerable situation is in the hydrographic regions located in the semi-arid region of Northeastern Brazil, which is currently economically poor. Meanwhile, the hydrographic regions located in the South-Southeast of Brazil are less impacted. This presents a further difficulty for regional income convergence.

References

Adam, K. N., & Collischonn, W. (2013). Análise dos impactos de mudanças climáticas nos regimes de precipitação e vazão na bacia hidrográfica do rio Ibicuí. *Revista Brasileira de Recursos Hídricos*, 18(3), 69-79. http://dx.doi.org/10.21168/rbrh.v18n3.p69-79

Adam, K. N., Fan, F. M., Pontes, P. R., Bravo, J. M., & Collischonn, W. (2015). Mudanças climáticas e vazões extremas na Bacia do Rio Paraná. *Revista Brasileira de Recursos Hídricos*, 20(4), 999-1007. http://dx.doi.org/10.21168/rbrh.v20n4.p999-1007

Alvarenga, L. A., Mello, C. R. D., Colombo, A., Cuartas, L. A., & Chou, S. C. (2016). Hydrological responses to climate changes in a headwater watershed. *Ciência e Agrotecnologia*, 40(6), 647-657. https://doi.org/10.1590/1413-70542016406027716

ANA (2020). *Portal HIDROWEB v3.1.1*. Retrieved from http://www.snirh.gov.br/hidroweb/apresentacao

Bonan, G. (2015*). Ecological climatology: concepts and applications*. New York: Cambridge University Press.

Bravo, J. M., Collischonn, W., Da Paz, A. R., Allasia, D., & Domecq, F. (2014). Impact of projected climate change on hydrologic regime of the Upper Paraguay River basin. *Climatic Change*, 127(1), 27-41. https://doi.org/10.1007/s10584-013-0816-2

Chou, S. C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., ... & Marengo, J.

(2014). Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios. *American Journal of Climate Change*, 3(05), 512. http://dx.doi.org/10.4236/ajcc.2014.35043

de Araújo, J. C., Döll, P., Güntner, A., Krol, M., Abreu, C. B. R., Hauschild, M., & Mendiondo, E. M. (2004). Water scarcity under scenarios for global climate change and regional development in semiarid Northeastern Brazil. *Water International*, 29(2), 209-220. https://doi.org/10.1080/02508060408691770

de Amorim, P. B., & Chaffe, P. B. (2019). Towards a comprehensive characterization of evidence in synthesis assessments: the climate change impacts on the Brazilian water resources. *Climatic Change*, 155(1), 37-57. https://doi.org/10.1007/s10584-019-02430-9

de Amorim, P. B., de Souza, K. I. S., & Chaffe, P. L. B. (2020). A web-based tool for synthesis assessments of the impacts of climate change on water resources. *Environmental Modelling & Software*, 133, 104848. https://doi.org/10.1016/j.envsoft.2020.104848

de Oliveira, V. A., de Mello, C. R., Viola, M. R., & Srinivasan, R. (2017). Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. *International Journal of Climatology*, 37(15), 5005-5023. https://doi.org/10.1002/joc.5138

de Queiroz, A. R., Lima, L. M. M., Lima, J. W. M., da Silva, B. C., & Scianni, L. A. (2016). Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. *Renewable Energy*, 99, 379-389. http://dx.doi.org/10.1016/j.renene.2016.07.022

Fernandes, R. D. O., Silveira, C. D. S., Studart, T. M. D. C., & Souza Filho, F. D. A. D. (2017). Reservoir yield intercomparison of large dams in Jaguaribe Basin-CE in climate change scenarios. *Revista Brasileira de Recursos Hídricos*, 22. https://doi.org/10.1590/2318-0331.011716033

Fill, H. D., Mine, M. R. M., Fernandes, C. V. S., & Bessa, M. R. (2013). Impact of climate change on hydropower production within the La Plata Basin. *International journal of river basin management*, 11(4), 449-462. https://doi.org/10.1080/15715124.2013.865638

Gondim, R., Silveira, C., de Souza Filho, F., Vasconcelos, F., & Cid, D. (2018). Climate change impacts on water demand and availability using CMIP5 models in the Jaguaribe basin, semi-arid Brazil. *Environmental Earth Sciences*, 77(15), 550. https://doi.org/10.1007/s12665-018-7723-9

Guimberteau, M., Ciais, P., Ducharne, A., Boisier, J. P., Aguiar, A. P. D., Biemans, H., ... & Poveda, G. (2017). Impacts of future deforestation and climate change on the hydrology of the Amazon Basin: a multi-model analysis with a new set of land-cover change scenarios. *Hydrology and Earth System Sciences*, 21, 1455–1475. https://doi.org/10.5194/hess-21-1455-2017

Hawkins, E., & Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, 90, 8, 1095-1108. https://doi.org/10.1175/2009BAMS2607.1

Ho, J. T., Thompson, J. R., & Brierley, C. (2016). Projections of hydrology in the Tocantins-Araguaia Basin, Brazil: uncertainty assessment using the CMIP5 ensemble. *Hydrological Sciences Journal*, 61(3), 551-567. https://doi.org/10.1080/02626667.2015.1057513

Iensen, I. R., Schultz, G. B., & Dos Santos, I. (2015). Simulation of hydrosedimentological impacts caused by climate change in the Apucaraninha River watershed, southern Brazil. *Proceedings of the International Association of Hydrological Sciences*, 367, 366. https://doi.org/10.5194/piahs-367-366-2015

INPE (2020). *Brazilian climatic data*. Retrieved from http://dadosclima.ccst.inpe.br/

IPCC (2014). *Intergovernmental Panel for Climate Change Assessment Report 5*. Retrieved from https://www.ipcc.ch/assessment-report/ar5/

Júnior, J. S., Tomasella, J., & Rodriguez, D. A. (2015). Impacts of future climatic and land cover changes on the hydrological regime of the Madeira River basin. *Climatic Change*, 129(1-2), 117-129. http://dx.doi.org/10.1007/s10584-015-1338-x

Junior, P. P. A., & Mauad, F. F. (2015). Simulação dos impactos das mudanças climáticas na vazão da Bacia do Ribeirão do Feijão–SP. *Revista Brasileira de Recursos Hídricos*, 20, 741-751. http://dx.doi.org/10.21168/rbrh.v20n3.p741-751

Krol, M. S., & Bronstert, A. (2007). Regional integrated modelling of climate change impacts on natural resources and resource usage in semi-arid Northeast Brazil. *Environmental Modelling & Software*, 22(2), 259-268. http://dx.doi.org/10.1016/j.envsoft.2005.07.022

Lamparter, G., Nobrega, R. L. B., Kovacs, K., Amorim, R. S., & Gerold, G. (2018). Modelling hydrological impacts of agricultural expansion in two macro-catchments in Southern Amazonia, Brazil. *Regional environmental change*, 18(1), 91-103.

https://doi.org/10.1007/s10113-016-1015-2

Lofgren et al. (1998). Tiger or turtle?: exploring alternative futures for Egypt to 2020. In Safadi, R. (Ed.), *Opening doors to the world: a new trade agenda for the Middle East*. Ottawa: IDRC.

Marengo, J. A., Chou, S. C., Kay, G., Alves, L. M., Pesquero, J. F., Soares, W. R., ... & Chagas, D. J. (2012). Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. *Climate dynamics*, 38(9-10), 1829-1848. https://doi.org/10.1007/s00382-011-1155-5

Medeiros, Y. D. P. (2003). Análise dos impactos das mudanças climáticas em região semi-árida. *Revista Brasileira de Recursos Hídricos*, 8(2), 127-136. http://dx.doi.org/10.21168/rbrh.v8n2.p127-136

Mello, E. L. D., Oliveira, F. A., Pruski, F. F., & Figueiredo, J. C. (2008). Effect of the climate change on the water availability in the Paracatu river basin. *Engenharia Agrícola*, 28(4), 635-644. https://doi.org/10.1590/S0100-69162008000400003

Melo, D. C., & Wendland, E. (2017). Shallow aquifer response to climate change scenarios in a small catchment in the Guarani Aquifer outcrop zone. *Anais da Academia Brasileira de Ciências*, 89(1), 391-406. https://doi.org/10.1590/0001-3765201720160264

Mendes, C. A. B., Beluco, A., & Canales, F. A. (2017). Some important uncertainties related to climate change in projections for the Brazilian hydropower expansion in the Amazon. *Energy*, 141, 123-138. https://doi.org/10.1016/j.energy.2017.09.071

Mohor, G. S., Rodriguez, D. A., Tomasella, J., & Júnior, J. L. S. (2015). Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant. *Journal of Hydrology: Regional Studies*, 4, 41-59. http://dx.doi.org/10.1016/j.ejrh.2015.04.003

Mohor, G. S., & Mendiondo, E. M. (2017). Economic indicators of hydrologic drought insurance under water demand and climate change scenarios in a Brazilian context. *Ecological Economics*, 140, 66-78. https://doi.org/10.1016/j.ecolecon.2017.04.014

Montenegro, A., & Ragab, R. (2010). Hydrological response of a Brazilian semi-arid catchment to different land use and climate change scenarios: a modelling study.

Hydrological Processes, 24(19), 2705-2723. https://doi.org/10.1002/hyp.7825

Montenegro, S., & Ragab, R. (2012). Impact of possible climate and land use changes in the semi-arid regions: A case study from Northeastern Brazil. *Journal of Hydrology*, 434, 55-68. https://doi.org/10.1016/j.jhydrol.2012.02.036

Neto, A. R., da Paz, A. R., Marengo, J. A., & Chou, S. C. (2016). Hydrological processes and climate change in hydrographic regions of Brazil. *Journal of Water Resource and Protection*, 8(12), 1103-1127. http://dx.doi.org/10.4236/jwarp.2016.812087

Nóbrega, M. T., Collischonn, W., Tucci, C. E. M., & Paz, A. R. (2011). Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrology and Earth System Sciences*, 15(2), 585-595. https://doi.org/10.5194/hess-15-585-2011

Oki, T., & Kanae, S. (2006). Global hydrologic cycles and world water resources. *Science*, 313, 1068–1072. https://doi.org/10.1126/science.1128845

Oliveira, G. G., Pedrollo, O. C., & Castro, N. M. R. (2015). Stochastic approach to analyzing the uncertainties and possible changes in the availability of water in the future based on scenarios of climate change. *Hydrology & Earth System Sciences*, 19(8). https://doi.org/10.5194/hess-19-3585-2015

Perazzoli, M., Pinheiro, A., & Kaufmann, V. (2013). Assessing the impact of climate change scenarios on water resources in southern Brazil. *Hydrological Sciences Journal*, 58(1), 77-87. https://doi.org/10.1080/02626667.2012.742195

Pinheiro, A., Graciano, R. L., & Kaufmann, V. (2013). Simulating effects of climate scenarios on hydrological processes in southern Brazil using a lysimeter. *International journal of climatology*, 33(9), 2206-2214. https://doi.org/10.1002/joc.3591

Ribeiro Junior, L. U., Zuffo, A. C., & Silva, B. C. D. (2016). Development of a tool for hydroeletric reservoir operation with multiple uses considering effects of climate changes. Case study of Furnas HPP. *Revista Brasileira de Recursos Hídricos*, 21(2), 300-313. https://doi.org/10.21168/rbrh.v21n2.p300-313

Ribeiro Neto, A., Scott, C. A., Lima, E. A., Montenegro, S. M. G. L., & Cirilo, J. A. (2014). Infrastructure sufficiency in meeting water demand under climate-induced socio-hydrological transition in the urbanizing Capibaribe River basin–Brazil. *Hydrology and Earth System Sciences*, 18(9), 3449-3459. https://doi.org/10.5194/hess-18-3449-2014

Rivarola Sosa, J. M., Brandani, G., Dibari, C., Moriondo, M., Ferrise, R., Trombi, G., & Bindi, M. (2011). Climate change impact on the hydrological balance of the Itaipu Basin. *Meteorological Applications*, 18(2), 163-170. https://doi.org/10.1002/met.213

Rosenzweig, C., Strzepek, K. M., Major, D. C., Iglesias, A., Yates, D. N., McCluskey, A., & Hillel, D. (2004). Water resources for agriculture in a changing climate: international case studies. *Global Environmental Change*, 14(4), 345-360. https://doi.org/10.1016/j.gloenvcha.2004.09.003

Sabesp (2020). *Demonstrações financeiras 2015*. Retrieved from http://www.sabesp.com.br/Calandraweb/CalandraRedirect/?temp=4&proj=investidoresnovo&pub=T&docid=BD73C2C77F33B20283257E4300729028&docidPai=AB82F8DBCD12AE488325768C0052105E&pai=filho0

Silveira, C. S., Souza Filho, F. A., Lopes, J. E. G., Barbosa, P. S. F., & Tiezzi, R. O. (2014). Análise das projeções de vazões nas bacias do setor elétrico brasileiro usando dados do IPCC-AR4 para o século XXI. *Revista Brasileira de Recursos Hídricos*, 19(4), 59-71. http://dx.doi.org/10.21168/rbrh.v19n4.p59-71

Silveira, C. D. S., Souza Filho, F. D. A. D., & Vasconcelos Junior, F. D. C. (2017). Streamflow projections for the Brazilian hydropower sector from RCP scenarios. *Journal of Water and Climate Change*, 8(1), 114-126. https://doi.org/10.2166/wcc.2016.052

Sorribas, M. V., Paiva, R. C., Melack, J. M., Bravo, J. M., Jones, C., Carvalho, L., ... & Costa, M. H. (2016). Projections of climate change effects on discharge and inundation in the Amazon basin. *Climatic Change*, 136(3-4), 555-570. https://doi.org/10.1007/s10584-016-1640-2

Tejadas, B. E., Bravo, J. M., Sanagiotto, D. G., Tassi, R., & Marques, D. M. L. D. M. (2016). Projeções de vazão afluente à lagoa mangueira com base em cenários de mudanças climáticas. *Revista Brasileira de Meteorologia*, 31(3), 262-272. https://doi.org/10.1590/0102-778631320150139

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 38, 55–94. https://doi.org/10.2307/210739

Trenberth, K. E., Smith, L., Qian, T., Dai, A., & Fasullo, J. (2007). Estimates of the global water budget and its annual cycling using observational and model data. *Journal of Hydrometeorology*, 8, 758–769. https://doi.org/10.1175/JHM600.1

Viola, M. R., De Mello, C. R., Chou, S. C., Yanagi, S. N., & Gomes, J. L. (2015). Assessing climate change impacts on Upper Grande River basin hydrology, southeast Brazil. *International Journal of Climatology*, 35(6), 1054-1068. https://doi.org/10.1002/joc.4038

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., ... & Kimoto, M. (2010). Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *Journal of Climate*, 23(23), 6312-6335. https://doi.org/10.1175/2010JCLI3679.1

Zaninelli, P. G., Menéndez, C. G., Falco, M., López-Franca, N., & Carril, A. F. (2019). Future hydroclimatological changes in South America based on an ensemble of regional climate models. *Climate Dynamics*, 52(1-2), 819-830. https://doi.org/10.1007/s00382-018-4225-0

4. PRICE ELASTICITY OF THE DEMAND FOR WATER

4.1. Motivation

Water is used as an input by several economic sectors. In agriculture and forestry production, it is used to irrigate fields; in livestock, it is used for animal consumption and irrigation of pastures; in industrial sectors, it can be incorporated directly into products, such as in the food, beverage, and chemical products sectors or indirectly as an essential part of the production process such as in the textile and paper and cellulose sectors; in the service and government sectors, it is used for hygiene and human consumption. Each of these activities has different levels of dependence on the water factor. Therefore, changes in the price of water (e.g., tariff changes or costs imposed by climate change) will affect its demand in different economic sectors differently.

In the literature, there is a diversity of economic analyzes about demand in water sector[7]. We highlight the works of Turnovsky (1969), Oh (1973), De Rooy (1974), Grebenstein & Field (1979), Babin et al. (1982), Ziegler & Bell (1984), Williams & Suh (1986), Renzetti (1988, 1990, 1992), Schneider & Whitlatch (1991), Rogers et al. (1998), Malla & Gopalakrishnan (1999), Dupont & Renzetti (2001), Hussain et al. (2002), Reynaud (2003), Féres & Reynaud (2005), Kumar (2006), Féres et al. (2008) and Féres et al. (2012). In general, it is possible to see that the water demand is mostly inelastic and quite heterogeneous; that is, it depends on the sector and region studied. Table 4.1 summarizes this information. For the Brazilian case, Féres & Reynaud (2005) characterize the demand for water in industries in São Paulo state (Southeastern Brazil) and assess the potential impact of the application of environmental policy instruments on the industrial use of water. They find an average elasticity of -1, high enough that charging for water resources is an effective mechanism to encourage reducing water demand for industrial use. Féres et al. (2008) estimated the demand for water from industrial users in the Paraíba do Sul River basin (basin located in the ASD hydrographic region) and evaluate the pricing power. Overall, they found a price elasticity of -0.58. This indicates the low effectiveness of pricing (charging) as a mechanism to inhibit water consumption. They also found elasticity values for some industrial activities, such as food and

---

[7] It should be noted that we do not address demand for residential water. For this purpose, see Agthe & Billings (1980), Carver & Boland (1980), Terza & Welsh (1982), Polzin (1984), Schfter & David (1985), Nauges & Thomas (2000), Ipe & Bhagwat (2002), Hussain et al. (2002), Arbues et al. (2003), Musolesi & Nosvelli (2007) and Worthington & Hoffmann (2008).

beverages (-0.82), cellulose and paper (-0.76), chemistry (-0.71), clothing (-0.31), and textile (-0.04).

This chapter aims to understand the factors influencing water demand and estimate the price elasticity of demand in agriculture, industry, commerce, and government in Brazilian hydrographic regions.

4.2. Price elasticity of the demand for water

4.2.1. Theoretical aspects

Suppose the production technology of a competitive firm is characterized by the production function given by (4.1):

$$y = f(q_1, q_2, \dots, q_N, w) \tag{4.1}$$

where y is the output of the firm, q_i are the quantities of inputs (e.g., labor, capital), and w is the quantity of water required.

A water demand model assumes that the firm chooses its input levels (among them water) to minimize its production costs. This behavioral assumption implies that the firm's productive technology can be represented by the cost function (4.2):

$$C(p_1, p_2, p_N, p_w, y) = \min_{q_i, w} \sum_{i=1}^{N} p_i q_i + p_w w$$

$$\text{s.a.} \tag{4.2}$$

$$f(q_1, q_2, \dots, q_N, w) \leq y$$

where w and p_w are respectively the quantity and price of the water consumed, q_i and p_i are the quantities and prices of the other inputs, y is the output level, and $f\,(.)$ is the production function.

Applying a partial difference to the cost function $C(p, y)$ to the price of inputs, we find the quantity of input required in equilibrium as a function of the vector of input prices and output level. This occurs for the demand for inputs (q_i^*) described by (4.3) and for the demand for water (w^*) described by (4.4):

$$q_i^* = \frac{\partial C(p_1, p_2, \dots, p_N, p_w, y)}{\partial p_i} \tag{4.3}$$

$$w^* = \frac{\partial C(p_1, p_2, \dots, p_N, p_w, y)}{\partial p_w} \tag{4.4}$$

Often only a subset of inputs from firms is observed. For example, we have detailed information on the use of water, but not on other inputs. In this case, it is necessary to assume that the production technology is separable (Jehle & Reny, 2001; Mas-Colell et al., 1995). A firm's technology is weakly separable if the cost function can be rewritten as follows (4.5):

$$C(p_1, p_2, \dots, p_N, y) = C(C_1(p_1, y), C_2(p_2, y), \dots, C_N(p_N, y), C_w(p_w, y), y) \tag{4.5}$$

Thus, the cost function is composed of cost sub-functions, each depending only on its price and the output level (4.6):

$$q_1^* = g_1(p_1, y);\ q_2^* = g_2(p_2, y); \dots; q_N^* = g_N(p_N, y) \tag{4.6}$$

This idea is also applicable to water demand (4.7):

$$w^* = g_w(p_w, y) \tag{4.7}$$

where w^* is the quantity of water required in equilibrium as a function of its price (p_w) and the firm's output level (y).

The price elasticity of demand for water is denoted as ε_w (4.8):

$$\varepsilon_w = \frac{\partial w}{\partial p_w}\frac{p_w}{w} \tag{4.8}$$

Theoretically, the value of ε_w, in absolute terms, can vary between 0 (perfectly inelastic demand) and infinite (perfectly elastic demand). Linear demand functions for water are often used because they are easily estimated. The linear function also implies that firms are less-sensitive to prices when $\varepsilon_w < 1$, and are highly-sensitive to price when $\varepsilon_w > 1$.

Table 4.1. Main estimates of agricultural, industrial, and commercial water demand, some referential

Authors	*Regions*	*Sectors*	*Price elasticity*
Turnovsky (1969)	Massachusetts, USA	Industrial	-0.84/-0.52
De Rooy (1974)	New Jersey, USA	Chemical	-0.89/-0.35
Grebenstein & Field (1979)	USA	Manufacturing	-0.80/-0.33
Babin et al. (1982)	USA	Manufacturing	-0.56
		Paper and Allied	-0.66
		Stone, Clay, Glass	-0.38
		Fabricated Metal	-0.41
Ziegler & Bell (1984)	Arkansas, USA	Industrial	-0.08
Williams & Suh (1986)	USA	Industrial	-0.74
		Commercial	-0.36
Nieswiadomy (1988)	Texas, USA	Agriculture (by crops)	Inelastic
Renzetti (1988)	British Columbia, CAN	Forest Industry	-0.51
		Petrochemical Industry	-0.12
		Light Industry	-0.54
		Heavy Industry	-0.25
Chambers & Just (1989)	USA	Agriculture (by crops)	Inelastic
Just et al. (1990)	USA	Agriculture (by crops)	Inelastic
Renzetti (1990)	Canada	Industrial	-0.60
Moore & Negri (1992)	USA	Agriculture (by crops)	Inelastic
Renzetti (1992)	Canada	Manufacturing	-0.38
		Beverage	-0.39
		Rubber	-0.15
		Textile	-0.33
		Paper	-0.59
		Metal	-0.27
		Mineral	-0.32
		Petroleum	-0.48
Schneider & Whitlatch (1991)	Ohio, USA	Industrial	-1.16/-0.42
		Commercial	-0.35/-0.24
		Governmental	-1.68/-0.43

continued

Authors	*Regions*	*Sectors*	*Price elasticity*
Renzetti (1992)	Canada	Industry	-0.59/-0.15
Hassine & Thomas (1997)	Tunisia	Agriculture (by crops)	Inelastic
Malla & Gopalakrishnan (1999)	Hawaii, USA	Food processing industry	-0.39
		Non-Food processing industry and Commercial	-0.11
Dupont & Renzetti (2001)	Canada	Manufacturing	-0.81
Hussain et al. (2002)	Sri Lanka	Industrial	-1.34
		Commercial	-0.17
Reynaud (2003)	France	Extractive Industry	-0.73
		Metal Fabrication	-0.24
		Chemicals	-0.38
		Alcohol	-0.10
		Food and Beverages	-0.30
		Paper and Wood	-0.22
		Commercial and Services	-0.27
		Other Industries	-0.79
Féres & Reynaud (2005)	Brazil	Industrial	-1.00
Kumar (2006)	India	Industrial	-0.90
Dongki (2007)	Korea	Industrial	-0.84
Féres et al. (2008)	Brazil	Food and Beverages	-0.82
		Textiles	-0.04
		Clothing	-0.31
		Wood, Rubber and Plastics	-0.40
		Pulp and Paper	-0.76
		Chemicals	-0.71
		Non-Metal Minerals	-0.22
		Iron and Steel	-0.48
		Mechanical Industry	-0.31
		Transport Equipment	-0.51
		Other Industries	-0.33
Féres et al. (2012)	Brazil	Manufacturing	-0.18
Guerreiro García Rojas et al. (2018)	Mexico	Industrial	-0.74
Ghinis et al. (2020)	Brazil	Industrial (general)	-0.28

Source: Authors' own.

4.2.2. Database

We create a panel composed of economic sectors, municipalities classified by hydrographic regions and years. Our analysis selected ten economic sectors: agriculture, food and beverages, textiles, clothing, cellulose and paper products, manufactured products, hotels and restaurants, education services, health services, and public administration. These activities operate in municipalities belonging to one of the 12 Brazilian hydrographic regions. Thus, we have the following aggregations: AMZ hydrographic region (composed of 101 municipalities), ALT (136), AOC (126), AOR (521), ASD (265), ASU (195), PRG (17), PRN (850), PNB (169), SFO (242), TOC (229), and URU (248). All the information used covers the years 2010 to 2015. Below we describe the variables used in the econometric exercises.

Dependent variable

Water demand by sector (W_{smt}): The water demand values by sector and municipality were obtained indirectly through the following procedure. First, we calculate the ratio between the amount of water used by sector ($WATER_{sct}$) and its wage bill ($wage_{sct}$). This coefficient will give us an idea of the amount of water consumed by a unit of wage paid in each of the s sectors, from a national perspective c and in a year t. We used data from the EORA input-output matrices (Lenzen et al., 2013). Then, we collected wage bill information for each s sector, in each of the m municipalities analyzed during a year t ($wage_{smt}$). In this case, the National Classification of Economic Activities 2.0 (CNAE) was used. These data were obtained with the Annual List of Social Information (RAIS, 2020). It should be noted that the sectorial classification of the EORA matrices and RAIS data are different making a compatibility process necessary. For more details, see Table 4.2. The multiplication of this information, described by (4.9), results in a proxy for water used by sector s (W_{smt}), in municipality m during year t.

$$W_{smt} = \frac{WATER_{sct}}{wage_{sct}} wage_{smt} \tag{4.9}$$

Table 4.2. Sectoral compatibility

Sector	*EORA*	*CNAE 2.0 (in portuguese)*
Agriculture, forestry production, fisheries, and mineral extraction	Agriculture and forestry	Agricultura, pecuária e serviços relacionados
	Grazing and fishing	Produção florestal
		Pesca e aquicultura
		Extração de carvão mineral
Food and beverages	Food and beverages	Fabricação de produtos alimentícios
		Fabricação de bebidas
Textiles	Textiles	Fabricação de produtos têxteis
Clothing	Clothing	Confecção de artigos do vestuário e acessórios
Cellulose and paper products	Cellulose and paper products	Fabricação de celulose, papel e produtos de papel
Manufactured products	Household appliances	Fabricação de móveis
	Office equipment	Fabricação de produtos diversos
	Furniture and other manufacturing	
Hotels and restaurants	Hotels and restaurants	Alojamento
		Alimentação
Private education	Private education	Educação
Private health	Private health services	Atividades de atenção à saúde humana
		Atividades de saúde integradas com assistência social
		Serviços de assistência social sem alojamento
Public services and administration	Public education	Administração pública, defesa e seguridade social
	Public health services	
	Public administration and social security	

Source: Authors' own.

Independent variables

Water price (P_{mt}): To calculate the price elasticity of water demand, we included the average water price in the municipalities. Data were obtained from the National Sanitation Information System (SNIS, 2020).

Added value by sector ($X1_{mt}$): It is expected that the demand for water increases with the level of economic activity in a region. Thus, we consider the added values of agriculture, industry and services sectors present in the municipalities. This information was collected from IBGE (IBGE, 2020).

Population ($X2_{mt}$): The size of the population living in the municipality may also explain the sector's demand for water, mainly in non-tradable sectors such as services. In this case, we use data from IBGE (IBGE, 2020).

Water connections ($X3_{mt}$): The number of water connections (water meters) is indicative of the demand for tariffed water. This information was collected from the SNIS (SNIS, 2020).

Temperature and precipitation ($X4_{mt}$): Climatic conditions are also an essential part of water consumption. We represent temperature and precipitation information. Temperature data come from the NCEP-DOE Reanalysis II project (Kanamitsu et al., 2002), while precipitation information was collected from the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) (Funk et al., 2015). We use average annual and seasonal (summer) values of temperature and precipitation.

4.2.3. Empirical strategy

We use a dynamic econometric specification described by (4.10) to estimate the price elasticities of the water demand:

$$\begin{gathered} \ln(W_{smt}) = \alpha + \beta \ln\left(W_{sm(t-1)}\right) + \varepsilon \ln(P_{mt}) + X'_{mt}\psi + \phi_{sm} + \eta_{smt} \\ \text{with } m = 1, \dots, M; t = 2, \dots, T \end{gathered} \tag{4.10}$$

where W_{smt} represents water demand by economic sector s, municipality m and year t. Its time-lag in $t-1$ period was also considered ($W_{sm(t-1)}$). P_{mt} is the average water price in the municipality m and year t. In a model log-log, the price elasticities of the water demand are represented by ε. X_{mt} indicates the vector of independent variables, and ψ is its estimated parameter set. $u_{smt} \equiv \phi_{sm} + \eta_{smt}$ is the fixed effect decomposition of the error term where

$\phi_{sm} \sim i.i.d.(0, \sigma_{\phi}^2)$ and $\eta_{sm} \sim i.i.d.(0, \sigma_{\eta}^2)$ are assumed to be independent of each other and among themselves.

The estimation bias arises due to the presence of unobserved fixed effects and endogeneity resulting from the serial correlation between the time-lagged dependent variable and the error term $E(W_{t-1}, \eta_t) \neq 0$ (Baltagi, 2001). The Generalized Method of Moments (GMM) proposed by Arellano & Bond (1991) solves these problems with a model difference process (that eliminates the fixed effect) and uses as instruments for $\Delta W_{(t-1)}$ the variable dependent in time-lag form (i.e., W_{t-3}, W_{t-4}, W_{t-5}, etc.). Blundell & Bond (1998) suggest the GMM-system estimator that corrects the unit root problem (when the estimated coefficient of ΔW_{t-1} tends to 1) seen in Arellano & Bond (1991). The statistical implementation of the models occurred in the R environment using the plm package (Croissant et al., 2020).

4.2.4. Econometric results

Table 4.3 shows that most of the estimated price elasticities of the water demand are inelastic, that is $|\,\varepsilon\,| < 1$. This is related to the essentiality of water as a factor of production. That is, water demand is little influenced by changes in price. Furthermore, the values show the sectorial and regional heterogeneity of the estimated elasticities.

In the agriculture and forestry sectors, the price elasticity of water demand is -0.165. This value is considered low and demonstrates each sector’s productive dependence on water input. This value is interpreted as follows: for each percentage-point increase in the price of water, approximately 0.165% of water required declines. The estimated regional coefficients are between -0.079 (PRN hydrographic region) and -0.272 (SFO hydrographic region).

Table 4.3. GMM regression: price elasticities of the water demand by sector in Brazilian hydrographic regions

Sectors\Regions	*Elasticities*												
	Brazil	*AMZ*	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*
Agriculture and forestry	-0.165^{a†}	NA§	-0.212^{a}	-0.249	-0.019	-0.220^{a}	-0.304	NA	-0.079^{c}	-0.284	-0.272^{a}	-0.190^{a}	-0.024
	(0.032) ‡		(0.093)	(0.201)	(0.090)	(0.092)	(0.257)		(0.057)	(0.354)	(0.128)	(0.087)	(0.134)
Food and beverages	-0.730^{a}	NA	-0.577^{a}	NA	-0.787^{a}	-0.606^{a}	-0.229	NA	-0.917^{a}	-0.512^{c}	-0.917^{a}	-0.792^{a}	-0.243
	(0.049)		(0.158)		(0.114)	(0.152)	(0.207)		(0.105)	(0.364)	(0.203)	(0.190)	(0.022)
Textiles	-0.441^{a}	NA	NA	NA	-0.730^{a}	-0.258	NA	NA	-0.432^{a}	NA	-0.597^{c}	NA	NA
	(0.049)				(0.174)	(0.282)			(0.193)		(0.430)		
Clothing	-0.294^{a}	NA	-0.354^{a}	NA	-0.278^{b}	-0.269^{c}	-0.175	NA	-0.160^{c}	NA	-0.264	NA	-0.248^{c}
	(0.058)		(0.118)		(0.150)	(0.208)	(0.201)		(0.118)		(0.211)		(0.154)
Cellulose and paper products	-0.512^{a}	NA	NA	NA	-0.317	-0.415	0.794	NA	-0.548^{a}	NA	NA	NA	NA
	(0.152)				(0.293)	(0.624)	(0.694)		(0.256)				
Manufacturing	-0.334^{a}	NA	NA	NA	-0.258^{c}	-0.106	-0.546^{a}	NA	-0.566^{a}	NA	-0.271	NA	-0.075
	(0.068)				(0.196)	(0.226)	(0.237)		(0.131)		(0.249)		(0.291)
Hotels and restaurants	-0.040	NA	-0.174^{c}	NA	-0.120	-0.103	-0.245	NA	-0.041	-0.432	-0.181	-0.283^{c}	-0.182
	(0.044)		(0.127)		(0.106)	(0.121)	(0.215)		(0.095)	(0.406)	(0.186)	(0.211)	(0.168)
Education	-0.532^{a}	NA	-0.193^{b}	NA	-0.332^{a}	-0.325^{a}	-0.060	NA	-0.765^{a}	-0.434^{c}	-0.750^{a}	-0.887^{a}	-0.818^{a}
	(0.041)		(0.101)		(0.093)	(0.105)	(0.237)		(0.089)	(0.325)	(0.217)	(0.217)	(0.311)
Health	-0.524^{a}	NA	-0.128	NA	-0.516^{a}	-0.367^{a}	-0.083	NA	-0.721^{a}	-0.726^{c}	-0.719^{a}	-1.264^{a}	-0.162
	(0.054)		(0.134)		(0.152)	(0.144)	(0.314)		(0.110)	(0.500)	(0.209)	(0.407)	(0.149)
Public administration	-0.201^{a}	NA	-0.150^{a}	0.062	-0.167^{a}	-0.256^{a}	-0.063	NA	-0.233^{a}	-0.068	-0.234^{a}	-0.146^{c}	-0.394^{a}
	(0.027)		(0.054)	(0.256)	(0.058)	(0.062)	(0.063)		(0.042)	(0.238)	(0.078)	(0.096)	(0.114)

† ^{a} p-value < 0.05; ^{b} p-value < 0.10; ^{c} p-value < 0.15.

‡ Std. errors in parentheses.

§ NAs represent coefficients not estimated due to insufficient sample size (N<30).

Source: Authors' own.

In industrial activities, we find price elasticity values of -0.730 for the food and beverage sector, -0.441 in the textile sector, -0.294 in the clothing sector, -0.512 in the cellulose and paper production and -0.334 in manufacturing. The estimated values for the hydrographic regions are close to the national average. In general, the price elasticities of demand for water in industrial sectors are inelastic.

In service activities, the average elasticities for Brazil are -0.174 or -0.283 in hotels and restaurants, -0.532 in private education services, and -0.524 in private health services. Most price elasticities of demand for water here are inelastic.

Finally, in the government sector that includes public education and health activities and government activities, the price elasticity of water demand is inelastic (-0.201).

References

Agthe, D. E., & Billings, R. B. (1980). Dynamic models of residential water demand. *Water Resources Research*, 16(3), 476-480. https://doi.org/10.1029/WR016i003p00476

Arbués, F., García-Valiñas, M. Á., & Martínez-Espiñeira, R. (2003). Estimation of residential water demand: a state-of-the-art review. *The Journal of Socio-Economics*, 32(1), 81-102. https://doi.org/10.1016/S1053-5357(03)00005-2

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The review of economic studies*, 58(2), 277-297. https://doi.org/10.2307/2297968

Babin, F. G., Willis, C. E., & Allen, P. G. (1982). Estimation of substitution possibilities between water and other production inputs. *American journal of agricultural economics*, 64(1), 148-151. https://doi.org/10.2307/1241187

Baltagi, B. H., & Kao, C. (2001). Nonstationary panels, cointegration in panels and dynamic panels: A survey. In Baltagi, B. H., & Kao, C. *Nonstationary panels, panel cointegration, and dynamic panels.* UK: Emerald Group Publishing Limited.

Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of econometrics*, 87(1), 115-143. https://doi.org/10.1016/S0304-4076(98)00009-8

Carver, P. H., & Boland, J. J. (1980). Short-and long-run effects of price on municipal water use. *Water Resources Research*, 16(4), 609-616. https://doi.org/10.1029/WR016i004p00609

Croissant, Y., Millo, G., Tappe, K., Toomet, O., Kleiber, C., Zeileis, A., ... & Croissant, M. Y. (2020). Package ‘plm’. *Choice*, 139(1), 227-240.

De Rooy, J. (1974). Price responsiveness of the industrial demand for water. *Water Resources Research*, 10(3), 403-406. https://doi.org/10.1029/WR010i003p00403

Dupont, D. P., & Renzetti, S. (2001). The role of water in manufacturing. *Environmental and resource economics*, 18(4), 411-432. https://doi.org/10.1023/A:1011117319932

Féres, J., & Reynaud, A. (2005). Assessing the impact of environmental regulation on industrial water use: Evidence from Brazil. *Land Economics*, 81(3), 396-411. https://doi.org/10.3368/le.81.3.396

Féres, J., Reynaud, A., Thomas, A., & Seroa da Motta, R. (2008). Competitiveness and effectiveness concerns in water charge implementation: a case study of the Paraíba do Sul River Basin, Brazil. *Water Policy*, 10(6), 595-612. https://doi.org/10.2166/wp.2008.103

Féres, J., Reynaud, A., & Thomas, A. (2012). Water reuse in Brazilian manufacturing firms. *Applied Economics*, 44(11), 1417-1427. https://doi.org/10.1080/00036846.2010.543070

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., ... & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. *Scientific data*, 2(1), 1-21. https://doi.org/10.1038/sdata.2015.66

Ghinis, C.P., Fochezatto, A., & Kuhn, C.V. (2020). Price elasticity of the demand for water in the Brazilian states: a panel data analysis, 2011–2017. *Sustainable Water Resources Management*, 6, 72. https://doi.org/10.1007/s40899-020-00429-0

Grebenstein, C. R., & Field, B. C. (1979). Substituting for water inputs in US manufacturing. *Water Resources Research*, 15(2), 228-232. https://doi.org/10.1029/WR015i002p00228

Hussain, I., Thrikawala, S., & Barker, R. (2002). Economic analysis of residential, commercial, and industrial uses of water in Sri Lanka. *Water international*, 27(2), 183-193. https://doi.org/10.1080/02508060208686991

Ipe, V. C., & Bhagwat, S. B. (2002). Chicago’s water market: dynamics of demand, prices and scarcity rents. *Applied Economics*, 34(17), 2157-2163. https://doi.org/10.1080/00036840210138383

Jehle, G. A., & Reny, P. J. (2001). *Advanced Microeconomic Theory*. New York: Pearson Education.

Kumar, S. (2006). Analysing industrial water demand in India: An input distance function approach. *Water Policy*, 8(1), 15-29. https://doi.org/10.2166/wp.2006.0002

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: a global multi-region input-output database at high country and sector resolution. *Economic Systems Research*, 25(1), 20-49. https://doi.org/10.1080/09535314.2013.769938

Malla, P. B., & Gopalakrishnan, C. (1999). The economics of urban water demand: The case of industrial and commercial water use in Hawaii. *International Journal of Water Resources Development*, 15(3), 367-374. https://doi.org/10.1080/07900629948871

Mas-Colell, A., Whinston, M. D., & Green, J. R. (1995). *Microeconomic theory*. New York: Oxford University Press.

Musolesi, A., & Nosvelli, M. (2007). Dynamics of residential water consumption in a panel of Italian municipalities. *Applied Economics Letters*, 14(6), 441-444. https://doi.org/10.1080/13504850500425642

Nauges, C., & Thomas, A. (2000). Privately operated water utilities, municipal price negotiation, and estimation of residential water demand: The case of France. *Land Economics*, 68-85. https://doi.org/10.2307/3147258

Oh, H. S. (1973). *Economics of urban water demand: a case study of the Honolulu Board of Water Supply*. Thesis, University of Hawaii.

Polzin, P. E. (1984). The specification of price in studies of consumer demand under block price scheduling: Additional empirical evidence. *Land Economics*, 60(3), 306-309. https://doi.org/10.2307/3146192

Renzetti, S. (1988). An econometric study of industrial water demands in British Columbia, Canada. *Water Resources Research*, 24(10), 1569-1573. https://doi.org/10.1029/WR024i010p01569

Renzetti, S. (1990). *The economics of seemingly abundant resource: efficient water pricing in Vancouver, Canada.* Thesis, University of British Columbia.

Renzetti, S. (1992). Estimating the structure of industrial water demands: the case of Canadian manufacturing. *Land Economics*, 396-404. https://doi.org/10.2307/3146696

Reynaud, A. (2003). An econometric estimation of industrial water demand in France. *Environmental and Resource Economics*, 25(2), 213-232. https://doi.org/10.1023/A:1023992322236

Rogers, P., Bhatia, R., & Huber, A. (1998). *Water as a social and economic good: How to put the principle into practice*. Stockholm: Global Water Partnership.

Schefter, J. E., & David, E. L. (1985). Estimating residential water demand under multi-part tariffs using aggregate data. *Land Economics*, 61(3), 272-280. https://doi.org/10.2307/3145842

Schneider, M. L., & Whitlatch, E. E. (1991). User-specific water demand elasticities. *Journal of Water Resources Planning and Management*, 117(1), 52-73. https://doi.org/10.1061/(ASCE)0733-9496(1991)117:1(52)

Terza, J. V., & Welch, W. P. (1982). Estimating demand under block rates: Electricity and water. *Land Economics*, 58(2), 181-188. https://doi.org/10.2307/3145892

Turnovsky, S. J. (1969). The demand for water: Some empirical evidence on consumers' response to a commodity uncertain in supply. *Water Resources Research*, 5(2), 350-361. https://doi.org/10.1029/WR005i002p00350

Williams, M., & Suh, B. (1986). The demand for urban water by customer class. *Applied Economics*, 18(12), 1275-1289. https://doi.org/10.1080/00036848600000003

Worthington, A. C., & Hoffman, M. (2008). An empirical survey of residential water demand modelling. *Journal of Economic Surveys*, 22(5), 842-871. https://doi.org/10.1111/j.1467-6419.2008.00551.x

Ziegler, J. A., & Bell, S. E. (1984). Estimating demand for intake water by self-supplied firms. *Water Resources Research*, 20(1), 4-8. https://doi.org/10.1029/WR020i001p00004

5. CLIMATE CHANGE, WATER RESOURCES AND ECONOMIC IMPACTS

5.1. Motivation

Climate change has a direct influence on water events. Most economies, including Brazil, are conditioned by the hydrological regimes of their hydrographic regions. The activities of agriculture, livestock, forestry and mineral extraction, aquaculture, water-intensive industries, and hydro-energy are potentially vulnerable (IPCC, 2021).

Interactions between sectors and hydrographic regions through trade relations, can systematize these vulnerabilities, i.e., as an indirect effect. The concept of virtual water epitomizes this (Allan, 1998; Hoekstra & Mekonnen, 2012; Haddad et al., 2020). The volume of water required to produce a good or service is defined as the amount of water contained in it and includes all the water contained in inputs and factors of production (Chapagain & Hoekstra, 2003).

Interregional computable general equilibrium (ICGE) models are particularly suitable for assessing the systemic effects of climate change and water availability on economic variables. ICGE models consider the economy as a system of interdependent markets, in which the numerical values of equilibrium of all variables must be determined simultaneously. Any exogenous disturbance (e.g., climate change) can be measured through the set of endogenous variables in the economy (Haddad, 1999). We can find different CGE models in the literature with a focus on water resources. They include the work of Lofgren et al. (1996), Seung et al. (1998, 2000), Goodman (2000), Gomez et al. (2004), Barrittella et al. (2005), Diao et al. (2005), Horridge et al. (2005), Peterson et al. (2005), Brouwer et al. (2008), Diao et al. (2008), Van Heerden et al. (2008), Jun et al. (2010), Calzadilla et al. (2011), Dixon et al. (2011), Hassan & Thurlow (2011), Wittwer (2011), Wittwer & Griffith (2011), Zhong et al. (2015) and Fang et al. (2016) - see summary in Table 5.1. They generally involve the themes of (i) economic restriction due to water scarcity; (ii) economic gains from better allocation of water resources, using instruments such as water tax, water rights, and the water market; and (iii) impacts from extreme hydrological events in the short and long run (climate change).

Table 5.1. CGE models with a focus on water resources

Authors	*Regions*	*Purpose*	*Main conclusion*
Lofgren et al. (1996)	Egypt	A dynamic CGE model is used to explore alternative scenarios for 1990-2020 in areas critical for Egypt's economy-productivity growth, investment, foreign trade, and water.	Increasing water scarcity hurts agriculture and labor absorption but has little effect on overall growth.
Seung et al. (1998)	USA	A CGE model is used to examine the impacts of reallocating water from agriculture to recreational use having compensation for water rights.	The combined effect of water rights compensation and the increase in recreation expenditures does not offset the reduction in agricultural production, resulting in a net decrease in the total regional output.
Seung et al. (2000)	USA	A dynamic CGE model is used to analyze the temporal effects of reallocating water from agriculture to recreational use.	Model results show that the increase in non-agricultural output does not offset the reduction in agricultural output due to water withdrawal.
Goodman (2000)	USA	A CGE model is used to compare the economic impacts between the construction of reservoir storage or the temporary transfer of water.	The economic benefits from increased water transfers are generally as high or higher than those from increased storage.
Gomez et al. (2004)	Balearic Islands, Spain	A CGE model is used to analyze the welfare gains associated with improving the allocation of water rights through voluntary water exchanges (mainly between the agriculture and urban sectors).	The increased efficiency provided by water markets makes this option more advantageous than building new desalinization plants. A water market can also have positive and significant impacts on agricultural income.
Barrittella et al. (2005)	World	A global CGE model is used to assess a series of water tax policies.	Water taxes reduce water use and lead to shifts in production, consumption, and international trade patterns.
Diao et al. (2005)	Morocco	A CGE model is used to analyze the potential economic gains obtainable from allocating surface irrigation water to its most productive use.	The results suggest that a water relocation mechanism can increase agricultural production and affect the entire economy.
Horridge et al. (2005)	Australia	An ICGE model is used to analyze the economic impacts of drought.	The effect of the drought was to reduce agricultural output severely. Consequently, a reduction in GDP is projected.

continued

Authors	*Regions*	*Purpose*	*Main conclusion*
Peterson et al. (2005)	Australia	An ICGE model is used to examine the regional effects of expanding trade of irrigation water.	Water trading dampens the impact of water allocation cuts on regional GDP. Permitting trade of seasonal allocations allows irrigators to reallocate water in reaction to climatic conditions and water availability; this flexibility minimizes economic losses.
Brouwer et al. (2008)	Netherlands	A CGE model is used to estimate the economic impacts of water quality policy.	Reducing pollution levels incurs economic costs. Most costs are borne by important sources of pollution like commercial shipping, the chemical and metal industry. Adaptations in the tertiary service sector must be made.
Diao et al. (2008)	Marocco	A CGE model is used to assess the economic importance of groundwater resources.	Groundwater has a crucial role in mitigating various economic and physical shocks (droughts and water cost access).
Van Heerden et al. (2008)	South Africa	A CGE model is used to compare new taxes on water demand by forestry and irrigated field crops sectors.	A tax on irrigated field crops saves more water than a tax on forestry. However, in economic terms, a tax on irrigated crops will further damage GDP and consumption by poor households.
Jun et al. (2010)	China	A CGE model is used to assess the economic impacts of a water demand reduction policy using water charges.	A water tax should be levied on water-intensive industries, saving more water than other industries. The increase in the price of water reduces the GDP and consumption levels of poor households. A water policy should not be short run.
Calzadilla et al. (2011)	World	A global CGE model is used to analyze potential water savings and the welfare implications of improvements in irrigation efficiency worldwide.	The results show that a water policy to improve irrigation efficiency led to global and regional water savings, but it is not beneficial for all regions. The final effect on regional well-being is mixed. For water-stressed regions, the effects on welfare are primarily positive. For non-water scarce regions, the results are more mixed and mostly negative.

continued

Authors	*Regions*	*Purpose*	*Main conclusion*
Dixon et al. (2011)	Australia	A dynamic ICGE model is used to analyze the effects of government buyback water from irrigators.	A buyback policy would increase economic activity in the region and have little effect on agricultural production. Given that farmers are owners of water rights, they would benefit from the price increase induced by the buyback.
Hassan & Thurlow (2011)	South Africa	A CGE model is used to assess policy reforms on water use and allocation.	The liberalization of regional irrigation water markets would improve the efficiency of water allocation between the regions analyzed, leading to expansions in agricultural production and exports and create additional jobs for agricultural workers.
Wittwer (2011)	Australia	A dynamic CGE is used to compare the impacts of buyback and drought.	The number of jobs lost due to drought is greater than the loss resulting from the buyback policy (in the short and long run).
Wittwer & Griffith (2011)	Australia	A dynamic ICGE is used to estimate the economic impacts of drought.	Drought drastically reduces real GDP and the number of jobs, especially in smaller regions. Depressed farm investment during drought results in farm capital not returning to baseline levels after drought.
Zhong et al. (2015)	China	A CGE model is used to assess the impacts of drought.	The effects on the macro-economy were insignificant. There are losses in agricultural production. Most farming production sectors employed more capital and labor to prevent losses in output from drought. Households suffered severe losses in welfare and food consumption
Fang et al. (2016)	China	A CGE model is used to quantify the economic impacts of discharge fees.	An increased fee will have a negative impact on GDP. With the economic costs, the increase in the discharge fee will lead to upgrading industrial structures from heavy pollution to one of light pollution.

Source: Authors' own.

This chapter describes the ICGE model named Brazilian Multisectoral and Regional/Interregional Analysis Model with Water Module (BMARIA-H_2O). It is capable of assessing the impacts of climate change and water availability on the Brazilian economy. The chapter includes the presentation of the database, set of equations, the shock mechanisms, and the results of the computer simulations.

5.2. Model description

5.2.1. Model dimensions

The BMARIA- H_2O model is an ICGE model with a water module capable of assessing the economic impacts of changes in water availability caused by climate change. The model files are available at https://github.com/aderocha-github/CGE-BMARIAH2O and implemented in the GEMPACK software (Harrison & Pearson, 1996; Harrison et al., 1996). The Appendix presents a guide to using the model. The structure of our model represents a variant of the ORANI-G model (Dixon et al., 1982; Dixon & Parmenter, 1996; Dixon & Rimmer, 2002; Horridge, 2003) and BMARIA model (Haddad, 1999, 2004), both well documented and widely used (Haddad & Domingues, 2000; Domingues, 2002; Domingues & Haddad, 2003; Perobelli, 2004; Santos, 2012 and Faria, 2015). Furthermore, it takes advantage of insights from the UPGEM model (Van Heerden et al., 2008). With a bottom-up structure (where national results are obtained from regional aggregations), the model recognizes the economies of the 12 Brazilian hydrographic regions. The model version identifies 67 economic sectors and goods/services located in these hydrographic regions - this implies that each sector produces only one good (see Table 5.2). Economic sectors can interact with domestic or foreign economic agents through the purchase of input and the sale of final goods. The sectors can use two types of water in production: water from the “water and sewage sector” and raw water extracted from the environment. The sectors are divided into four categories of water use: “A” are large users of water and with low charges, where: “A1” agriculture sector, “A2” livestock sector and “A3” the forestry, fisheries and aquaculture sector; “B” indicates users of non-potable water with a relative volumetric charge; “C” are users of treated water with good volumetric change; and “D” represents the public utility sectors that use water as an input, where: “D1” electricity, gas and other utilities and “D2” water, sewerage and drainage services. Labor and capital are also used as primary factors of production (one type). In demand, five groups of users are considered - producers, investors, households, foreign demand, and government. Furthermore, in this analysis, we consider the payment of taxes.

Table 5.2. BMARIA-H_2O sectors

Code	*Type*[†]	*Industry*
I01	A1	Agriculture, including support
I02	A2	Livestock, including support
I03	A3	Forestry, fisheries and aquaculture
I04	B	Coal and non-metallic minerals
I05	B	Crude oil and natural gas, including support
I06	B	Iron ore, including processing
I07	B	Non-ferrous metals, including processing
I08	C	Meat, milk products and processed fish
I09	C	Refined sugar
I10	C	Other food products
I11	C	Beverage
I12	C	Tobacco products
I13	C	Textiles
I14	C	Clothing
I15	C	Leather and footwear
I16	C	Wood products
I17	C	Cellulose and paper products
I18	C	Newspapers, magazines, and electronic publishing
I19	B	Petroleum refining and coke products
I20	B	Biofuels
I21	B	Chemical products, resins, and elastomers
I22	B	Pesticides, inks, varnishes, and other chemical products
I23	C	Soaps and detergents
I24	C	Pharmaceutical products
I25	B	Rubber and plastic products
I26	B	Non-metallic mineral products
I27	B	Manufacturing of steel and steel alloys
I28	B	Non-ferrous metals
I29	B	Fabricated metal products (except machines and equipment)
I30	C	Electronic, communication, medical and optical equipment
I31	C	Electric machines and materials
I32	C	Machines and equipment
I33	C	Passenger and light utility vehicles, trucks, and busses
I34	C	Vehicle parts
I35	C	Other transport equipment
I36	C	Furniture and other manufacturing
I37	C	Machinery and equipment maintenance
I38	D1	Electricity, gas, and other utilities
I39	D2	Water, sewerage, and drainage services
I40	C	Construction
I41	C	Wholesale and retail trade
I42	C	Land transport

continued

Code	*Type*[†]	*Industry*
I43	C	Water transport
I44	C	Air transport
I45	C	Storage and postal services
I46	C	Hotels
I47	C	Restaurants
I48	C	Editing and printing activities
I49	C	TV, radio, cinema, and sound/image activities
I50	C	Telecommunications
I51	C	Other information services
I52	C	Finance and insurance
I53	C	Property services and hiring
I54	C	Legal, accounting and consulting activities
I55	C	Engineering, technical analysis and R&D services
I56	C	Other scientific and technical activities
I57	C	Intellectual asset management
I58	C	Other administrative activities
I59	C	Security and investigation activities
I60	C	Public administration and social security
I61	C	Public education
I62	C	Private education
I63	C	Public health
I64	C	Private health
I65	C	Creative and entertainment activities
I66	C	Other personal services
I67	C	Domestic services

[†] “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

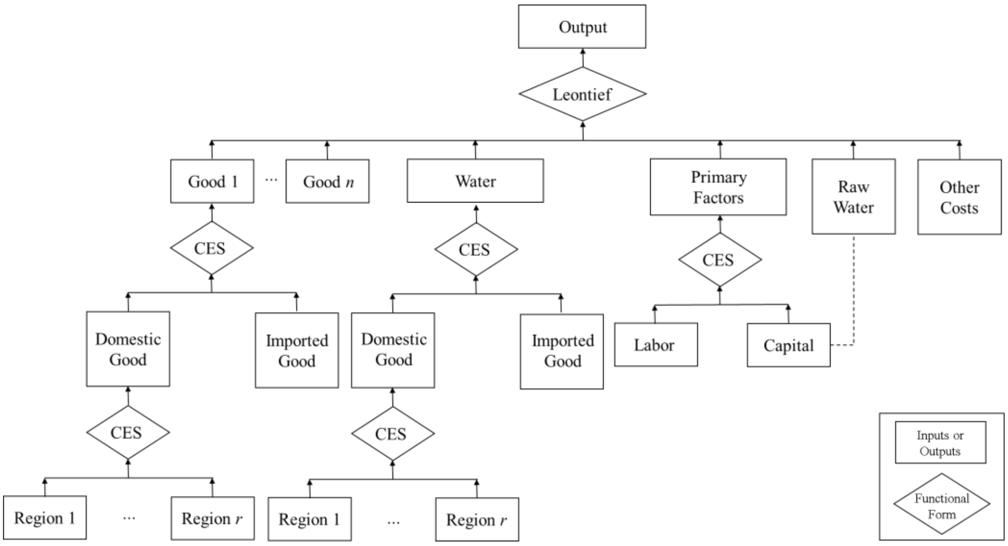
Source: Authors’ own.

5.2.2. Production

Figure 5.1 shows the nested production structure (= index of industry activity) of the BMARIA-H_2O model. To produce a final good (top-level), it is necessary to combine intermediate inputs, primary factors, and “other costs” using a Leontief type function (equivalent to a constant elasticity of substitution (CES) production function with the substitution elasticity set to zero).

The intermediate input nest (goods 1 to $n + 1$) is a CES-type combination of domestic (hydrographic regions) and imported goods. Here, we adopt the Armington hypothesis (Armington, 1969; 1970), in which there is an imperfect substitution between domestic and imported goods. Industries (= set of firms) minimize the total cost of purchasing domestic and imported goods subject to a production function. The substitution between goods will depend on their price relative to the average and the value of the Armington elasticity. This reasoning is repeated in the choice of purchase of domestic goods; in this case, the purchase substitution occurs between the hydrographic regions. The demand for water produced by the "water and sewage" sector follows this logic. Thus (i) water consumption will depend on its price - hence climate change comes as an exogenous cost shock and (ii) as essential water input is for a given industry in a region - this will depend on the elasticity of substitution.

Figure 5.1. Production structure



Source: Authors' own.

Each industry's demand for labor, capital, and raw water is determined in the nest of primary factors. Labor and capital are chosen through a problem of cost minimization subject to the production function. The model structure allows the substitution between these factors depending on their relative price and the elasticity present in the CES function. In addition, technical changes that alter the productivity of factors can affect their demand. Raw water is also used as a primary factor by industries. Some modelling mechanisms should be highlighted: (i) raw water has no price defined by the market, so its use does not follow an optimization problem; (ii) we assume that the activity level in the industry positively determines the demand for raw water; (iii) we consider that the cost of access to water resources is affected by climate change. Thus, an economical cost related to this type of natural resource is inserted in the modelling framework. The demand for raw water will depend on its elasticity (a parameter of resistance to changing demand and indicates how essential the factor is) and of the cost shock related to the change in water availability (scarcity or not) caused by climate change; and (iv) the substitution between raw water and capital is possible, i.e., with the shock of climatic cost, industries can adopt a greater or lesser amount of capital in the production process. For example, this is particularly relevant in the agriculture sector, where a possible increase in the cost of access to water can lead the user to adopt more efficient irrigation pivots, invest in new forms of storage or water reuse tools. The same can occur in industrial or service sectors where water-saving or reuse technologies can be purchased.

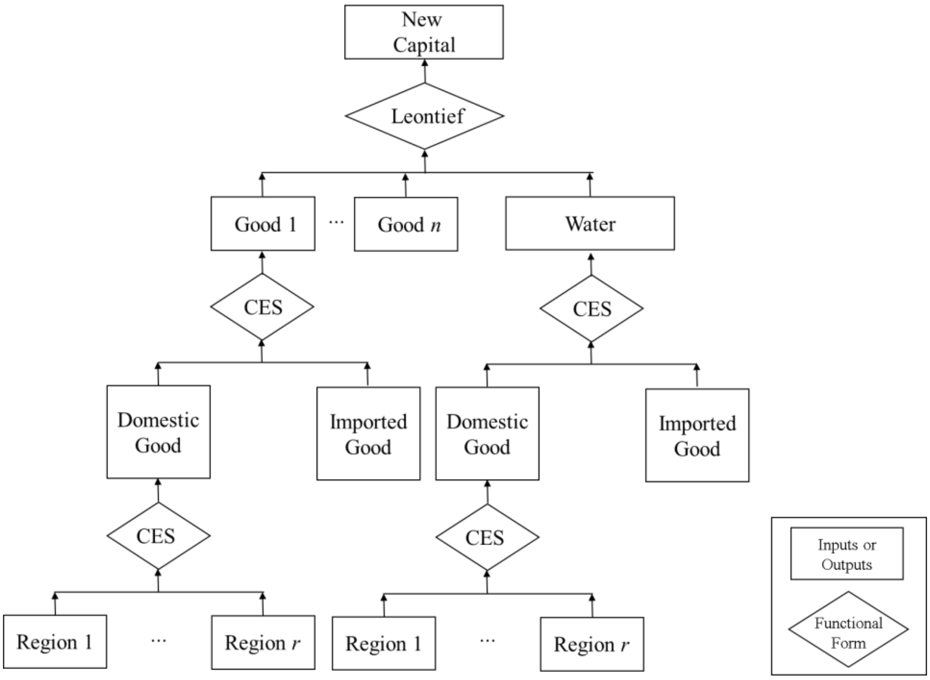
5.2.3. Investment demand

Figure 5.2 shows the nested structure to produce new units of fixed capital. The demand for investment goods is obtained through the solution of cost minimization problems. At the top, the total cost of commodities is minimized subject to Leontief's production function. At the base (bottom level), investors minimize the cost of domestic and imported goods subject to the CES production function. Primary factors are not used directly in capital formation.

5.2.4. Household demand

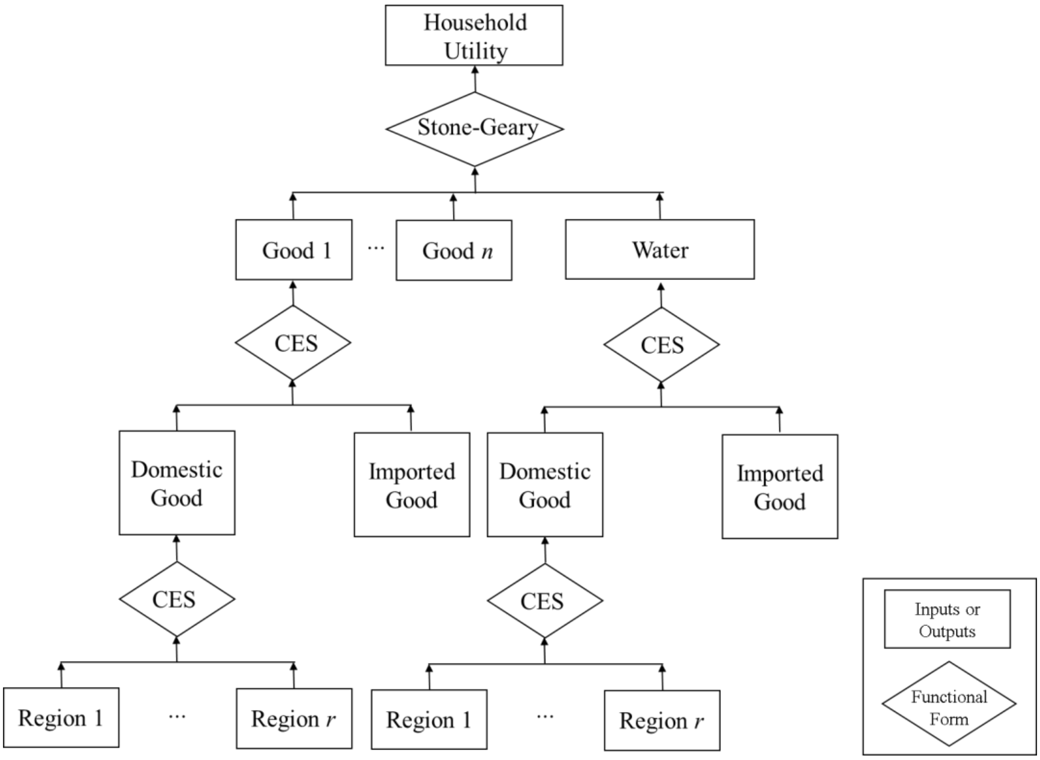
In the nested structure of household demand, the commodity composites are aggregated by a Stone-Geary utility function, leading to the linear expenditure system (LES) - see Figure 5.3. Families determine the composition of consumption by choosing allocations that maximize the utility function subject to disposable income. The Stone-Geary utility function considers that the budget is spent on subsistence and luxury goods, which allows variations in household income to cause various changes in the consumption of goods. Purchased goods can come from domestic sources or be imported, modelled by a CES function.

Figure 5.2. Investment demand



Source: Authors' own.

Figure 5.3. Household demand



Source: Authors' own.

5.2.5. Government demand

In each hydrographic region analyzed, there are expenditures from regional and federal governments. In our modelling framework, these expenses are endogenized and move according to domestic absorption.

5.2.6. External demand

In the specification of external demand for national products, the demand curve of each sector negatively slope in the international market prices. If a shock improves the price competitiveness of an export sector, the result will be an increase in the volume of exports at a lower international relative price. A vector of elasticities defines the response of external demand to changes in the FOB price of regional exports, and hypothetically, these elasticities are identical by region and differentiated by good.

5.2.7 Labor market

In modelling the labor market, the region’s total population and working-age population are observed and related to the labor supply. Furthermore, the demand for labor is related to the level of economic activity in the region. From the interaction between labor supply and demand (in an environment where labor mobility is possible through migration), it is possible to determine the level of wages and the rate of unemployment (or employment) in the region. Hypotheses of exogeneity/endogeneity about labor supply, wage differentials, and unemployment rates are defined.

5.2.8. Capital accumulation and investment

Capital accumulation considers that the level of future capital in an industry is determined by current capital minus depreciation and increased by the investment value. In turn, the investment trajectory is a function of its expected rate of return. With static expectations, it is assumed that investors only consider current income and asset prices when forming expectations about rates of return.

5.2.9. Closure

The BMARIA- H_2O model contains 6,199,865 equations and 6,236,065 variables, which implies determining 36,200 exogenous variables since the number of endogenous variables must equal the number of equations. However, implementing the model using the GEMPACK software allows it to be condensed, reducing computational requirements. This can be done by substituting endogenous variables in order to eliminate some equations from the model. This procedure provided a reduced version of the model containing 52,990 equations and 77,950 variables, making it necessary to determine 24,960 exogenous variables.

The choice of exogenous variables depends on the closure hypothesis. Short-run closure is characterized by the inter-sector and inter-regional immobility of capital. Furthermore, it is not possible to substitute raw water and capital to save water. Therefore, there is no possibility of technological adaptation to save water. The other technological shocks are exogenous. The population and the labor supply are fixed, and the regional real wage differential and the national real wage level are constant. Thus, regional employment derives from the assumptions made about regional unemployment rates. In this case, changes in the unemployment rate (and not in real wages) generate changes in labor absorption. In this situation, there is interregional labor immobility, i.e., migratory movements do not occur. In final demand, investment is exogenous, so firms do not reevaluate investment decisions in the short run.

Long-run closure represents a situation in which capital and labor are flexible; that is, they can move between sectors and regions. Capital grows at the rate of investment and tends to move to more attractive sectors and regions. There is a possibility of a partial substitution between raw water and capital to save water. In the labor market, aggregate employment is determined by population growth, labor force participation rates and the natural rate of unemployment. The real wage is not fixed as labor distribution can vary between sectors and regions.

Considering the impacts of climate change, all our analyzes will be related to long-run closure.

5.2.10. Homogeneity test

A homogeneity test was performed to check possible computational errors and the balancing of the database. The model must be homogeneous of degree zero, so if we shock the numeraire by 1%, we expect to see that all nominal variables will increase by 1%, and all real variables remain unchanged. Thus, a shock of 1% was applied to the exchange rate. The expected result was achieved so that the BMARIA- H_2O model proved to be homogeneous.

5.2.11. Shock description

Our model classifies water in two ways: treated water from the "water, sewerage and drainage services" sector and raw water extracted directly from the environment. Given this, water cost shocks resulting from the greater/lesser difficulty in capturing water will be imputed in the model differently.

The first shock, related to the effects of climate change on the availability of treated water, will be introduced into basic water prices, described in equation (5.1):

$$p_j^r = \lambda_j^r + \varepsilon_j^r \tag{5.1}$$

where the basic prices (p_j^r) of the good j of the hydrographic region r are formed from a unit cost index (λ_j^r). The exogenous shock ε_j^r represents the change in the cost of water due to climate change. The shock was attributed to the "water, sewerage and drainage services" ($j = 39$) located in the hydrographic regions ($r = 1, \dots, 12$). The shock values used in the simulations are described in Chapter 3 - see Table 3.5. The economic effects resulting from this disturbance are referred to as "Channel 1".

The second shock, related to climate change on the availability of raw water, will be introduced indirectly through capital expenditures to substitute or save water. This modelling "trick" was used because most of the raw water used in Brazil is not linked to any economic mechanism (e.g., collection, taxation, etc.). Following Van Heerden et al. (2008), we used (5.2):

$$x(k)_j^r = \frac{1}{V(k)_j^r} \psi_j^r \varepsilon_j^r \tag{5.2}$$

where $x(k)_j^r$ indicates the amount of capital to substitute or save water adopted by sector j in the hydrographic region r, $V(k)_j^r$ is the current level of capital used, ψ_j^r is a price semi-elasticity of demand for water and ε_j^r represents the shock of water cost access from climate change. In this case, shocks were imputed to “agriculture, including support” ($j = 1$), “livestock, including support” ($j = 2$), “forestry, fisheries and aquaculture” ($j = 3$), and “beverage” ($j = 11$) present in the hydrographic regions ($r = 1, \dots, 12$). The shock values used in the simulations are described in Chapter 3 - see Table 3.5. These goods/sectors correspond to more than 95% of the raw water consumed in the Brazilian economy. The economic effects of this disorder are named “Channel 2”.

These two channels represent endogenous forms of economic adaptation to climate change. Channel 1 represents an adaptation by increasing the water price. In other words, with the changes in water availability, it will be necessary to adjust the price of water in order to adapt demand to the new reality. Channel 2 represents a productive adaptation in which the primary factors raw water and capital can be replaced (this is limited by the dependence of the economic sector on the water factor).

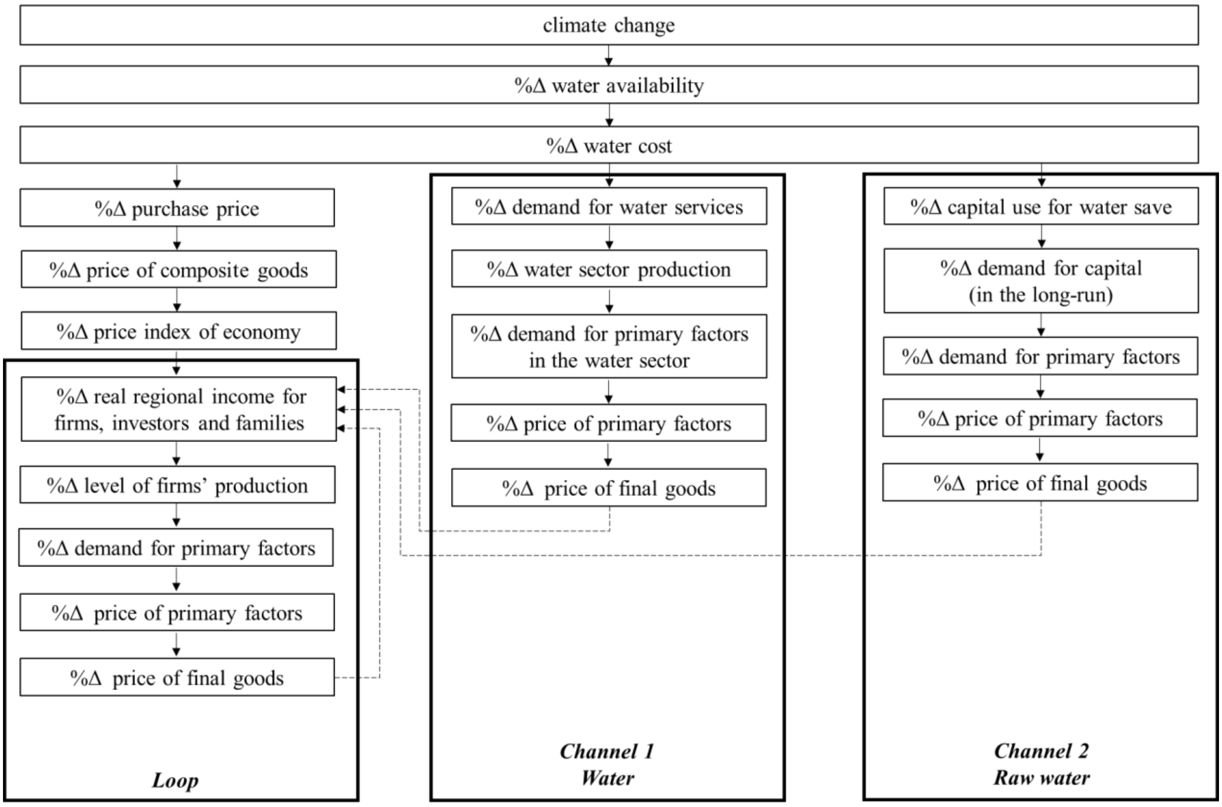
5.2.12. Model mechanisms (causal relation)

The water cost shocks from climate change will be transmitted to the economy through both channels. Figure 5.4 is a schematic representation of the causal relationships present in the modelling underlying these channels. Channel 1 describes the shock path in the basic price of water produced by the “water, sewerage, and drainage services” sector. The initial shock will promote a shift in demand for water and sewage services. This change will depend on the climate shock value and how important the water factor is for each economic sector in each hydrographic region, which will be quantified by the Armington substitution elasticity and the price elasticity for water demand parameters. In response to changes in demand, water-producing sectors will alter their production, which will have consequences on the quantity of primary factors (labor and capital) required by the industry and their respective market prices.

Consequently, all prices of final goods in the economy change. This enters a loop in which the real income of economic agents is altered, which changes the firms’ production plans, including their demand for factors of production, leading to another round of price adjustment. These dynamics are repeated until the economy reaches a new equilibrium.

Channel 2 describes the causal path of the cost shock related to raw water access. The change in water availability can lead the sectors to use capital to substitute or save water (i.e., capital that can lead to greater efficiency, less waste, or water resource storage). This could lead to changes in the quantity required by primary factors (labor and capital) and their respective prices in the long run. All of these disturbances have an impact on the final price of goods. This channel is also taken into a loop where the agents’ income is altered; the firms reevaluate their production plans, including the amount of factors to be used. In the end, there are changes in the prices of final goods. This mechanism is repeated until it reaches a new equilibrium.

Figure 5.4. Causal relations underlying the simulation results



Source: Authors’ own.

5.2.13. Formal mathematical description

In our model, uppercase letters represent the levels of variables, while lowercase letters represent their percentage changes. The superscript u, $u = 0, 1j, 2j, 3, 4, 5, 6$ refer, respectively, to production (0) and the six different users identified in the model as producers in the sector j ($1j$), investors in sector j ($2j$) with $j = 1, \dots, h$, families (3), external sector (4), regional governments (5) and federal government (6); the second superscript r identifies the domestic region where the user is located ($r = 1, \dots, q$). Two subscripts identify the i input subscripts: the first assumes the values $1, \dots, g$ for goods, $g + 1$ for primary factors and $g + 2$ for "other costs" (taxes and subsidies on production); the second subscript identifies the source of the input, which may be from a domestic region b ($1b$, where $b = 1, \dots, q$), imported (2), or from labor or capital (3). In this case {(1), (2), (3)} $\in s$. There are two types of water: $w(1)$ identifies treated water, and $w(2)$ indicates raw water. Taxes and trade margins are represented by t and m, respectively. The (•) is used to indicate the sum in relation to an index. The main equations, variables and parameters of the model are presented below.

Substitution between goods of different domestic sources

$$x_{(i(1b))}^{(u)r} = x_{(i(1\bullet))}^{(u)r} - \sigma_{(i)}^{(u)r}(p_{(i(1b))}^{(u)r} - \sum_{l \in b}(V(i, 1l, (u), r)/V(i, 1\bullet, (u), r)(p_{(i(1l))}^{(u)r})) \quad (5.3)$$

$\forall\, u = (kj, 3$ with $k = 1{,}2$ and $j = 1, \dots, h)$; $i = 1, \dots, g$; $r = 1, \dots, q$; $b = 1, \dots, q$

where x and p are respectively the quantity and price of goods demanded by users, σ is the elasticity of Armington and V is a constant of input-output flow related to the total production value (purchase prices).

Substitution between domestic and imported goods

$$x_{(is)}^{(u)r} = x_{(i\bullet)}^{(u)r} - \sigma_{(i)}^{(u)r}(p_{(is)}^{(u)r} - \sum_{l=1\bullet,2}(V(i, l, (u), r)/V(i,\bullet, (u), r)(p_{(il)}^{(u)r})) \quad (5.4)$$

$\forall\, u = (kj, 3$ with $k = 1{,}2$ and $j = 1, \dots, h)$; $i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1\bullet,2$ $(b \subset s)$

where x and p are respectively the quantity and price of goods demanded by users, σ is the elasticity of Armington and V is a constant of input-output flow related to the total production value (purchase prices).

Substitution between labour and capital

$$\begin{aligned} x_{(g+1,s)}^{(1j)r} - a_{(g+1,s)}^{(1j)r} & \\ &= \alpha_{(g+1,s)}^{(1j)r} x_{(g+1\bullet)}^{(1j)r} - \sigma_{(g+1)}^{(1j)r}\{p_{(g+1,s)}^{(1j)r} + a_{(g+1,s)}^{(1j)r} \\ &- \sum_{l=1,2,3} (V(g+1,l,(1j),r)/V(g+1,\bullet,(1j),r))(p_{(g+1,l)}^{(1j)r} \\ &+ a_{(g+1,l)}^{(1j)r})\} \end{aligned} \tag{5.5}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q;\ s = 1,2,3$

where x and p are respectively the quantity and price of primary factors demanded by users, a is a variable of technical change for the primary factors, σ is the elasticity of substitution of primary factors, α is a parameter of returns to scale, and V is an input-output flow constant related to the total factor value (purchase prices).

Demand for composite goods and primary factors

$$x_{(i\bullet)}^{(u)r} = \mu_{(i\bullet)}^{(u)r} z^{(u)r} + a_{(i)}^{(u)r} \tag{5.6}$$

$\forall\, u = (kj, 3$ with $k = 1,2$ and $j = 1, \dots, h),$ if $u = (1j)\ \therefore\ i = 1, \dots, g+2$ and if $u = (2j) \therefore i = 1, \dots, g; r = 1, \dots, q$

where x is the quantity of goods and primary factors used by users, z is the level of activity (production and investment), a is a variable of technical change for goods and primary factors, and μ is a parameter of returns to scale of primary factors.

Household demand

$$\begin{aligned} V(i,\bullet,(3),r)\left(p^{(3)r}_{(i\bullet)} + x^{(3)r}_{(i\bullet)}\right) \\ = \gamma^{r}_{(i)} P^{(3)r}_{(i\bullet)} Q^{r}\left(p^{(3)r}_{(i\bullet)} + x^{(3)r}_{(i\bullet)}\right) + \beta^{r}_{(i)}(C^{r} \\ - \sum_{j} \gamma^{r}_{(i)} P^{(3)r}_{(i\bullet)} Q^{r}(p^{(3)r}_{(i\bullet)} + x^{(3)r}_{(i\bullet)})) \end{aligned} \tag{5.7}$$

$\forall\, i = 1, \dots, g;\ r = 1, \dots, q$

where x and p are respectively the quantity and price of goods demanded, Q is the number of households, C is the total household expenditure, γ is a subsistence parameter in the linear expenditure system, β is a parameter of marginal budgetary participation in the linear expenditure linear and V is an input-output flow constant related to the total production value (purchase prices).

Commodity outputs

$$x^{(0j)r}_{(i1)} = z^{(1j)r} + \sigma^{(0j)r}(p^{(0)r}_{(i1)} - \sum_{t\epsilon\tau}(Y(t,j,r)/Y(\bullet,j,r))\, p^{(0)r}_{(t1)}) \tag{5.8}$$

$\forall\, j = 1, \dots, h;\ i = 1, \dots, g;\ r = 1, \dots, q, \tau = 1, \dots, t$

where x and p are respectively the quantity and price of goods demanded by users, z is the activity level (production and investment), σ is the elasticity of transformation in the production of different goods, and Y is an input-product flow constant related to the total production value (basic prices).

Indirect taxes

$$t(\tau, i, s, (u)r) = f_{(\tau)} + f_{(\tau i)} + f^{(u)}_{(\tau i)} + f^{(u)r}_{(\tau i)} \tag{5.9}$$

$\forall\, u = (kj, 3, 4, 5, 6$ with $k = 1{,}2$ and $j = 1, \dots, h)$; $i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1b, 2$;

$b = 1, \dots, q$; $\tau = 1, \dots, t$

where t is the tax power τ on sales and f are shift terms in the indirect tax τ.

Consumer prices

$$\begin{aligned} V(i,s,(u),r)p_{(is)}^{(u)r} \\ &= \left(B(i,s,(u),r) + \sum_{\tau \epsilon T} T(\tau,i,s,(u),r)\right)\left(p_{(is)}^{(0)} + t(\tau,i,s,u,r)\right) \\ &+ \sum_{m \epsilon i} M(m,i,s,(u),r)\, p_{(m1)}^{(0)r} \end{aligned} \tag{5.10}$$

$\forall\, u = (kj, 3, 4, 5, 6$ with $k = 1{,}2$ and $j = 1, \dots, h)$; $i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1b, 2$;

$b = 1, \dots, q$; $\tau = 1, \dots, t$

where p is the price of goods demanded by users, t is the tax power τ, and V, B, T, M are constant input-output related to the total production value in the purchase and basic prices, taxes, and margins values, respectively.

Export demand

$$x_{(is)}^{(4)r} - fq_{(is)}^{(4)r} = \eta_{(is)}^{r}(p_{(is)}^{(4)r} - e - fp_{(is)}^{(4)r}) \tag{5.11}$$

$\forall\, i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1b, 2$; $b = 1, \dots, q$

where x and p are the quantity and price of goods demanded, fq is a shift term in quantity demanded, fp is a shift term in the price of goods, e represents the exchange rate and η is the elasticity of demand for exports.

Regional governments demand

$$x_{(is)}^{(5)r} = x_{(\bullet\bullet)}^{(3)r} + f_{(is)}^{(5)r} + f^{(5)r} + f^{(5)} \tag{5.12}$$

$\forall\, i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1b, 2$; $b = 1, \dots, q$

where x is the quantity of goods demanded, and f are shift terms in demand.

Federal government

$$x^{(6)r}_{(is)} = x^{(3)\bullet}_{(\bullet\bullet)} + f^{(6)r}_{(is)} + f^{(6)r} + f^{(6)} \tag{5.13}$$

$\forall\, i = 1, \dots, g; r = 1, \dots, q; s = 1b, 2; b = 1, \dots, q$

where x is the quantity of goods demanded, and f are shift terms in demand.

Demand for margins

$$x^{(is)(u)r}_{(m1)} = \theta^{(u)r}_{(is)} x^{(u)r}_{(is)} + a^{(is)(u)r}_{(m1)} \tag{5.14}$$

$\forall\, u = (kj, 3, 4b, 5$ with $k = 1,2$; $j = 1, \dots, h$ and $b = 1, \dots, q)$; $m, i = 1, \dots, g$; $r = 1, \dots, q$; $s = 1b, 2$

where x is the quantity of goods demanded, a is a variable of technical change, and θ is a parameter of transport economies of scale.

Market-clearing

$$\sum_j Y(l, j, r)\, x^{(0j)r}_{(l1)} = \sum_u B(l, 1, (u), r) x^{(u)r}_{(l1)} + \sum_i \sum_s \sum_u M(l, i, s, (u), r) x^{(is)(u)r}_{(l1)} \tag{5.15}$$

$\forall\, j = 1, \dots, h; l = i = 1, \dots, g;\ r = 1, \dots, q;\ s = 1b, 2; b = 1, \dots, q$

where x is the demand for goods and Y, B, M are respectively input-output flow constants related to values at basic prices and margins.

Zero-profit condition

$$\sum_i Y(l, j, r)(p^{(0)r}_{(l1)} + a^{(0)r}_{(l1)}) = \sum_{i,g+1} \sum_s V(l, s, (1j), r)(p^{(1j)r}_{(is)}) \tag{5.16}$$

$\forall\, j = 1, \dots, h; l = i = 1, \dots, g;\ r = 1, \dots, q;\ s = 1b, 2; b = 1, \dots, q$

where p represents the prices of goods, a is a variable of technological change, Y represent input-product constants of production value (basic prices), and V represent a total purchase value of goods or factors.

Basic price of imported goods

$$p_{(i(2))}^{(0)} = p_{(i(2))}^{(v)} - e + t_{(i(2))}^{(0)} \tag{5.17}$$

$\forall\ i = 1, \dots, g$

where p and p^{v} represent the prices of goods in domestic currency and dollars, respectively, e represent the exchange rate, and t is the power of taxation.

Cost of capital

$$V(\bullet,\bullet,(2j),r)\left(p_{(k)}^{(1j)r} - a_{(k)}^{(1j)r}\right) = \sum_{i}\sum_{s} V(i,s,(2j),r)(p_{(is)}^{(2j)r} + a_{(is)}^{(2j)r}) \tag{5.18}$$

$\forall\ j = 1, \dots, h;\ r = 1, \dots, q$

where p is the price of goods and primary factors, a is a variable of technical change, and V is an input-output flow constant related to the total production value (purchase prices).

Investment

$$z^{(2j)r} = x_{(g+1,2)}^{(1j)r} + 100 f_{(k)}^{(2j)r} \tag{5.19}$$

$\forall\ j = 1, \dots, h;\ r = 1, \dots, q$

where z is an activity level variable (production or investment), x is the demand for goods or factors and f is a shift term.

Capital stock - comparative statics

$$x_{(g+1,2)}^{(1j)r}(1) = x_{(g+1,2)}^{(1j)r} \tag{5.20}$$

$\forall\ j = 1, \dots, h;\ r = 1, \dots, q$

where x is the demand for goods or factors.

Rates of return

$$\pi_{(j)}^{r} = \Pi_{(j)}^{r}(p_{(g+1,2)}^{(1j)r} - p_{(k)}^{(1j)r}) \tag{5.21}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q$

where π is the rate of return on capital, p represents the price of goods and factors, and Π is a ratio between gross return and net return on capital (constant).

Capital stock and rates of return

$$\pi_{(j)}^{r} - \omega = \xi_{(j)}^{r}\left(x_{(g+1,2)}^{(1j)r} - x_{(g+1,2)}^{(\bullet)r}\right) + f_{(k)}^{r} \tag{5.22}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q$

where π is the rate of return on capital, ω is the rate of return on capital in the short run, x is the quantity of goods or factors demanded, f is a shift term, and ξ is a sensitivity parameter of stock growth capital at rates of return.

Climate change and water price

$$p_{j}^{r} = \lambda_{j}^{r} + \varepsilon_{j}^{r} \tag{5.23}$$

$j = 39\ ;\ r = 1, \dots, q$

where p is the basic price of water, λ is a unit cost index, and ε represents the shock of the water cost access from climate change.

Climate change and capital to substitute or save raw water

$$x(k)_{j}^{r} = \frac{1}{V(k)_{j}^{r}}\psi_{j}^{r}\varepsilon_{j}^{r} \tag{5.24}$$

$j = 1, 2, 3, 11;\ r = 1, \dots, q$

where $x\ (k)$ indicates the amount of capital to substitute or save water, $V(k)$ is the current level of capital used, ψ is a price semi-elasticity of demand for water and ε represents the shock of water cost access from climate change.

Water and raw water demand change

$$w(1)_j^r = w(2)_j^r = z_j^r - \Psi_j^r \varepsilon_j^r \tag{5.25}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q$

where w indicates the water demand (treated or raw), z represents the activity level (production), Ψ is the price elasticity of the water demand, and ε represents the shock of the water cost access from climate change.

Water level change

$$\widehat{W}(1)_j^r = w(1)_j^r W(1)_j^r \tag{5.26}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q$

where W represents the change in the water level demanded and w is the percentage change in the water demand.

Raw water level change

$$\widehat{W}(2)_j^r = w(2)_j^r W(2)_j^r \tag{5.27}$$

$\forall\, j = 1, \dots, h;\ r = 1, \dots, q$

where W represents the change in the raw water level demanded and w is the percentage change in the raw water demand.

5.2.14. Model database

The BMARIA- H_2O model uses a hybrid Interregional Input-Output matrix (hybrid IIOA) for 2015. Figure 5.5 is a representation of the database structure. The hybrid IIOA is composed of the dimensions: number of commodities (C = 67), number of industries (I = 67), regions of origin, and destination of goods and services (S = 13 and R = 12, respectively), and trade margin (M=1).

The absorption matrix makes it possible to identify domestic producers, investors, households, foreign demand (exports), government demand, and changes in stocks. In basic flows, BAS1 represents the demand for goods/services by producers, its total value was BRL 4,269,315 million, BAS2 = BRL 955,815 million is demand for investments, BAS3 = BRL 2,821,517 million is household demand, BAS4 = BRL 744,066 million is export, BAS5+BAS6 = BRL 1,179,808 million is demand from governments (municipalities, states and federal) and BAS7 = BRL -19,926 million is the value of the inventory change.

Margins represent payments to the sector “wholesale and retail trade”. In this structure, we consider as margins values: MAR1 = BRL 437,690 million (paid by producers), MAR2 = BRL 61,803 million (paid by investors), MAR3 = BRL 591,514 million (paid by households), MAR4 = BRL 22,966 million (paid in export process) and MAR5+MAR6 = BRL 4,086 million (paid by the municipal, state, and federal governments). In implementing the model, the margins were added to the BAS values.

The tax values are TAX1 = BRL 364,263 million (paid by producers), TAX = BRL 51,781 million (paid by investors), TAX3 = BRL 422,161 million (paid by households), TAX4 = BRL 99 million (paid in the export process) and TAX5+TAX6 = BRL 1,883 million (paid by the municipal, state, and federal governments).

Producers consume water from the water/sewage distribution and treatment sector W = 3,287 hm^3 and raw water from environment RAWW = 337,301 hm^3. In Table 5.3, we present the water and raw water consumption by sector. Agriculture, livestock, forestry and aquaculture, beverages, water and sewage are the main consumers (99% of all water consumed). In addition, labor (one type of occupation) LABR = BRL 2,672,020 million and capital (one type of capital) CPTL = BRL 2,424,832 million, are also used as inputs. Other costs are also considered in OCTS = BRL 58,749 million.

The MAKE matrix presents the values produced for commodities (goods and services) by each industry in the regions analyzed. In our model, each industry produces only one good. The MAKE matrix has a total value equal to BRL 10,226,869 million. Finally, the TRDE matrix shows the values traded for goods and services between the origin and destination regions. The total value of this matrix is BRL 10,302,451 million.

Figure 5.5. BMARIA- H_2O database (BRL million)

Absorption Matrix

Account\Users	Producers	Investors	Household	Export	Regional government	Federal government	Change in stocks
Basic Flows	BAS1 (C, S, I, R) 4,269,315	BAS2 (C, S, I, R) 955,815	BAS3 (C,S,R) 2,821,517	BAS4 (C,R) 744,066	BAS5 (C,S,R) 0	BAS6 (C,S,R) 1,179,808	BAS7 (C,R) -19,926
Margins	MAR1 (C, S, I, R, M) 437,690	MAR2 (C, S, I, R, M) 61,803	MAR3 (C, S, R, M) 591,514	MAR4 (C, R, M) 22,966	MAR5 (C, S, R, M) 0	MAR6 (C, S, R, M) 4.086	NA
Taxes	TAX1 (C, S, I, R) 364,263	TAX2 (C, S, I, R) 51,781	TAX3 (C,S,R) 422,161	TAX4 (C,R) 99	TAX5 (C,S,R) 0	TAX6 (C,S,R) 1,884	NA
Water†	W (I,R) 3,287						
Raw water†	RAWW (I,R) 337,301						
Labor	LABR (I,R) 2,672,020						
Capital	CPTL (I,R) 2,424,832						
Other Costs	OCTS (I,R) 58,749						

Joint Production Matrix

MAKE (C,I,R) 10,226,869

Trade Matrix

TRDE (C,S,R) 10,302,451

C = Number of commodities (67)
I = Number of industries (67)
S = Regions source (13)
R = Regions destination (12)
M = Margin goods/services (1)

† Hydric resources measured in hm^3.

Source: Authors' own.

Table 5.3. Water consumption by sector (hm^3)

Code	*Type*[†]	*Industry*	*Water*	*Raw water*	*Total*
I01	A1	Agriculture, including support	1,968	254,756	256,724
I02	A2	Livestock, including support	60	7,764	7,824
I03	A3	Forestry, fisheries and aquaculture	532	68,865	69,397
I04	B	Coal and non-metallic minerals	1	22	23
I05	B	Crude oil and natural gas, including support	4	149	152
I06	B	Iron ore, including processing	2	76	78
I07	B	Non-ferrous metals, including processing	1	22	23
I08	C	Meat, milk products and processed fish	31	374	405
I09	C	Refined sugar	31	374	405
I10	C	Other food products	41	498	539
I11	C	Beverage	102	1,246	1,349
I12	C	Tobacco products	0	5	6
I13	C	Textiles	2	21	23
I14	C	Clothing	1	8	9
I15	C	Leather and footwear	1	7	7
I16	C	Wood products	0	4	5
I17	C	Cellulose and paper products	1	10	10
I18	C	Newspapers, magazines, and electronic publishing	1	8	9
I19	B	Petroleum refining and coke products	4	54	58
I20	B	Biofuels	1	8	9
I21	B	Chemical products, resins, and elastomers	3	36	39
I22	B	Pesticides, inks, varnishes, and other chemical products	2	23	25
I23	C	Soaps and detergents	1	10	10
I24	C	Pharmaceutical products	1	10	11
I25	B	Rubber and plastic products	1	16	17
I26	B	Non-metallic mineral products	1	15	16
I27	B	Manufacturing of steel and steel alloys	2	19	21
I28	B	Non-ferrous metals	1	10	11
I29	B	Fabricated metal products (except machines and equipment)	1	12	13
I30	C	Electronic, communication, medical and optical equipment	2	21	23
I31	C	Electric machines and materials	1	11	12
I32	C	Machines and equipment	1	15	16
I33	C	Passenger and light utility vehicles, trucks, and busses	2	28	30
I34	C	Vehicle parts	1	13	15
I35	C	Other transport equipment	1	14	15
I36	C	Furniture and other manufacturing	20	247	267
I37	C	Machinery and equipment maintenance	0	4	4
I38	D1	Electricity, gas, and other utilities	5	97	102
I39	D2	Water, sewerage, and drainage services	0	2,426	2,426
I40	C	Construction	0	3	3
I41	C	Wholesale and retail trade	0	0	0
I42	C	Land transport	17	0	17
I43	C	Water transport	17	0	17

continued

Code	*Type*[†]	*Industry*	*Water*	*Raw water*	*Total*
I44	C	Air transport	17	0	17
I45	C	Storage and postal services	17	0	17
I46	C	Hotels	33	0	33
I47	C	Restaurants	33	0	33
I48	C	Editing and printing activities	0	0	0
I49	C	TV, radio, cinema, and sound/image activities	0	0	0
I50	C	Telecommunications	0	0	0
I51	C	Other information services	0	0	0
I52	C	Finance and insurance	0	0	0
I53	C	Property services and hiring	0	0	0
I54	C	Legal, accounting and consulting activities	0	0	0
I55	C	Engineering, technical analysis and R&D services	0	0	0
I56	C	Other scientific and technical activities	0	0	0
I57	C	Intellectual asset management	0	0	0
I58	C	Other administrative activities	0	0	0
I59	C	Security and investigation activities	0	0	0
I60	C	Public administration and social security	0	0	0
I61	C	Public education	95	0	95
I62	C	Private education	61	0	61
I63	C	Public health	101	0	101
I64	C	Private health	67	0	67
I65	C	Creative and entertainment activities	0	0	0
I66	C	Other personal services	0	0	0
I67	C	Domestic services	0	0	0
		Total	3,287	337,301	340,588

[†] "A" are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); "B" are users of raw water with a relative volumetric charge; "C" are users of treated water with high volumetric charge; "D" represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

Source: Authors' own.

We used a wide range of parameters estimated or taken from the literature. Table 5.4 summarizes the key parameters. Armington elasticity refers to the substitution between inputs from different regions (including domestic and imported goods) and the price elasticities and semi-elasticities of demand for water that represent the sensitivity of the demand for water by different users/regions given changes in its price. We perform sensitivity tests involving these parameters.

Table 5.4. Key parameters

Code	*Type*[‡]	*Industry*	*Armington*[†§]	*Water elasticity*[†¶]	*Water Semi-elasticity*[†¶]
I01	A1	Agriculture, including support	2.40	-0.18	-100.00
I02	A2	Livestock, including support	2.40	-0.18	-100.00
I03	A3	Forestry, fisheries and aquaculture	2.40	-0.18	-100.00
I04	B	Coal and non-metallic minerals	0.90	-0.32	-15.27
I05	B	Crude oil and natural gas, including support	0.80	-0.48	-22.65
I06	B	Iron ore, including processing	0.90	-0.32	-15.27
I07	B	Non-ferrous metals, including processing	0.90	-0.32	-15.27
I08	C	Meat, milk products and processed fish	2.46	-0.73	-9.81
I09	C	Refined sugar	2.46	-0.73	-9.81
I10	C	Other food products	2.46	-0.73	-9.81
I11	C	Beverage	2.46	-0.73	-9.81
I12	C	Tobacco products	2.46	-0.73	-9.81
I13	C	Textiles	3.56	-0.48	-8.27
I14	C	Clothing	3.56	-0.28	-8.27
I15	C	Leather and footwear	3.56	-0.28	-8.27
I16	C	Wood products	2.05	-0.51	-8.27
I17	C	Cellulose and paper products	2.05	-0.51	-27.76
I18	C	Newspapers, magazines and electronic publishing	2.05	-0.51	-9.54
I19	B	Petroleum refining and coke products	1.16	-0.37	-22.65
I20	B	Biofuels	3.53	-0.37	-22.65
I21	B	Chemical products, resins and elastomers	2.80	-0.37	-7.24
I22	B	Pesticides, inks, varnishes and other chemical products	2.80	-0.37	-7.24
I23	C	Soaps and detergents	2.80	-0.37	-7.24
I24	C	Pharmaceutical products	2.80	-0.37	-7.24
I25	B	Rubber and plastic products	2.80	-0.37	-7.24
I26	B	Non-metallic mineral products	3.13	-0.37	-11.61
I27	B	Manufacturing of steel and steel alloys	2.40	-0.37	-9.77
I28	B	Non-ferrous metals	2.43	-0.37	-9.77
I29	B	Fabricated metal products (except machines and equipment)	2.18	-0.37	-9.77
I30	C	Electronic, communication, medical and optical equipment	2.18	-0.37	-9.50
I31	C	Electric machines and materials	2.18	-0.37	-9.50
I32	C	Machines and equipment	2.18	-0.37	-9.50
I33	C	Passenger and light utility vehicles, trucks and busses	2.18	-0.37	-9.50
I34	C	Vehicle parts	2.18	-0.37	-9.50
I35	C	Other transport equipment	2.18	-0.37	-9.50
I36	C	Furniture and other manufacturing	2.32	-0.37	-9.54
I37	C	Machinery and equipment maintenance	2.32	-0.37	-9.54
I38	D1	Electricity, gas and other utilities	0.00	-0.05	-37.74
I39	D2	Water, sewerage and drainage services	0.00	-0.05	-28.30

continued

Code	*Type*[‡]	*Industry*	*Armington*[†§]	*Water elasticity*[†¶]	*Water Semi-elasticity*[†¶]
I40	C	Construction	0.00	-0.37	-9.54
I41	C	Wholesale and retail trade	0.69	-0.18	-4.75
I42	C	Land transport	1.40	-0.18	-3.11
I43	C	Water transport	1.40	-0.18	-3.11
I44	C	Air transport	1.40	-0.18	-3.11
I45	C	Storage and postal services	1.40	-0.18	-3.11
I46	C	Hotels	0.15	-0.18	-3.11
I47	C	Restaurants	0.15	-0.18	-3.11
I48	C	Editing and printing activities	0.15	-0.18	-3.11
I49	C	TV, radio, cinema, and sound/image activities	0.15	-0.18	-3.11
I50	C	Telecommunications	0.15	-0.18	-3.11
I51	C	Other information services	0.15	-0.18	-3.11
I52	C	Finance and insurance	0.15	-0.18	-3.11
I53	C	Property services and hiring	0.15	-0.18	-3.11
I54	C	Legal, accounting and consulting activities	0.15	-0.18	-3.11
I55	C	Engineering, technical analysis and R&D services	0.15	-0.18	-3.11
I56	C	Other scientific and technical activities	0.15	-0.18	-3.11
I57	C	Intellectual asset management	0.15	-0.18	-3.11
I58	C	Other administrative activities	0.15	-0.18	-3.11
I59	C	Security and investigation activities	0.15	-0.18	-3.11
I60	C	Public administration and social security	0.07	-0.22	-3.11
I61	C	Public education	0.15	-0.58	-3.11
I62	C	Private education	0.15	-0.58	-3.11
I63	C	Public health	0.15	-0.62	-3.11
I64	C	Private health	0.15	-0.62	-3.11
I65	C	Creative and entertainment activities	0.15	-0.18	-3.11
I66	C	Other personal services	0.15	-0.18	-3.11
I67	C	Domestic services	0.15	-0.18	-3.11

[†] Mean values considering the hydrographic regions.

[‡] “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

[§] See Haddad et al. (2009) and Santos (2012).

[¶] See Chapter 4 and Van Heerden et al. (2008).

Source: Authors’ own.

5.3. Long-run results

Table 5.5 presents the results of the simulations for the macroeconomic aggregates[8]. The total effects are decomposed into Channel 1 (climate change shock on water prices in the “water and sewerage services” sector) and Channel 2 (climate change shock on access to raw water that leads to capital demand to substitute or save water). Part “a” of the table shows the drop in the real GDP-expenditure side and its components. In the RCP 4.5 (realistic) scenario, the negative impact was -0.233%, while in the RCP 8.5 (pessimistic) scenario, an impact of -0.564% is projected. In both cases, Channel 1 has a more significant contribution to these results. The low substitutability of water in most user sectors turns price increases into direct shocks to the economy. Among the GDP components, there is a reduction in demand from government (-1.230 and -1.970), export volume (-0.411% and -1.344%), and household consumption (-0.312% and -0.621%). With the increase in water price, there is an increase in the import volume (0.07% and 0.340%). It is possible to note that the shock related to Channel 2 enabled a positive change in real investment (0.052% and 0.072%). In other words, the greater the difficulty in accessing raw water in most regions can lead to investments by firms. Part “b” presents results related to the economy’s price indices. Overall, climate change and its effect on the price and availability of water leads to a decrease in the GDP price index (-0.086% and -0.050%). In the decomposed results, it is possible to see that Channel 1 (price effect on water) increases the GDP price while Channel 2 (capital effect) has an opposite result reducing the price of the economy. As shocks increase (more pessimistic scenarios), Channel 1 increases more than Channel 2. Thus, the GDP price index result may change sign depending on the size of the shock. Part “c” presents results related to the use of primary factors. In both climatic scenarios, there is a reduction in demand for labor (-0.382% and -0.967%) and a maintenance/increase in the capital stock (0.016% and 0.022%). In this case, it is interesting to note the effect of each channel. In Channel 1, firms receive the shock of water prices and change their level of production. Consequently, they will make less (more) use of labor (capital). In Channel 2, firms will be able to buy capital to substitute or save water. Indirectly, labor will also be required. Part “d” presents information on the amount of water and raw water that will no longer be required. In the RCP 4.5 scenario, there is a reduction in the demand for water and raw water by 16.1 hm^3 and 18,046 hm^3, respectively. In the RCP 8.5 scenario, these values reach 37.9 hm^3 and 37,385 hm^3. In the case of treated water, it represents around 0.004% to 0.011% of the total treated water currently required. For raw

---

[8] The results presented refer to the long-run closure. Other results can be made available upon request.

water, this represents somewhere between 5.298% to 10.976% of the total raw water currently demanded. These results show that Channel 2 has a greater potential to reduce water demand than Channel 1. Finally, part "e" presents information related to social welfare. The level of national utility is reduced in both scenarios (-12.3% and -29.7%). This negative value comes from the increase in the water cost (Channel 1). The acquisition of raw water-saving capital (Channel 2) generated an increase in welfare, but this could not offset the Channel 1 effects. We conclude that the economic losses resulting from the effect of climate change on water availability are considerable and are equivalent to a reduction in GDP of BRL 12.3 billion (or US$ 5.2 billion) in the realistic scenario and BRL 29.7 billion (or US$ 12.5 billion) in the pessimistic scenario (reference year 2015).

Table 5.5. Impacts on selected macroeconomic variables, long run (% change)

	Variable	*RCP 4.5 (2070-2099)*			*RCP 8.5 (2070-2099)*		
		Channel 1 (Water)	*Channel 2 (Raw water)*	*Total*	*Channel 1 (Water)*	*Channel 2 (Raw water)*	*Total*
a	Real GDP from expenditure side	-0.205	-0.028	-0.233	-0.505	-0.059	-0.564
	Aggregate real investment expenditure	0.034	0.018	0.052	0.034	0.038	0.072
	Real household consumption	-0.244	-0.068	-0.312	-0.480	-0.142	-0.621
	Export volume index	-0.310	-0.101	-0.411	-1.137	-0.207	-1.344
	Real government demands (regional)	-1.035	-0.195	-1.230	-1.572	-0.398	-1.970
	Real government demands (federal)	0.086	0.010	0.096	0.180	0.023	0.203
	Import volume index, CIF weights	0.233	-0.163	0.070	0.672	-0.333	0.340
b	GDP price index. expenditure side	0.019	-0.105	-0.086	0.166	-0.216	-0.050
	Consumer price index	0.019	-0.084	-0.064	0.132	-0.171	-0.039
	Investment price index	-0.014	-0.090	-0.105	0.074	-0.186	-0.111
	Exports price index, local currency	0.218	-0.051	0.167	0.635	-0.103	0.532
	Government price index (regional)	-0.784	-0.212	-0.996	-1.760	-0.424	-2.184
	Government price index (federal)	-0.096	-0.149	-0.245	-0.071	-0.309	-0.379
c	Aggregate capital stock, rental weights	0.010	0.005	0.016	0.010	0.012	0.022
	Aggregate employment, wage bill weights	-0.426	0.043	-0.382	-1.057	0.090	-0.967
d	Water demand (hm^3)	6.6	-22.8	-16.1	8.1	-45.9	-37.9
	Raw water demand (hm^3)	174.9	-18,221.6	-18,046.8	-579.6	-36,805.4	-37,385.0
e	National average utility	-1.363	0.378	-0.986	-3.563	0.766	-2.797
	Real GDP (BRL billion)	-10.8	-1.5	-12.3	-26.6	-3.1	-29.7
	Real GDP (US$ billion)	-4.6	-0.6	-5.2	-11.2	-1.3	-12.5

Source: Authors' own.

Table 5.6 shows the drop in GDP in each Brazilian hydrographic region. Computer simulations indicate values between -0.006% and -4.292% in the RCP 4.5 scenario and between -0,021% and -8.667% in the RCP 8.5 scenario. These results depend on the projected climate shock for each region, but it is not the only requirement taken into consideration. The region's productive structure (i.e., the representative economic sectors and how they use water) and regional trade are also important in the analysis.

This result shows us that the impacts of climate change are not restricted directly to affected regions alone. It is possible to see that the hydrographic regions located in the semi-arid Northeast and their neighbors, PNB, AOR, ALT, and AOC, are mainly affected. In this case, the impact of the unavailability of water from climate change is even more serious, as the region is currently more economically vulnerable. This potential future limitation may further delay their development process. However, hydrographic regions that are little or not affected by water availability/climate change are also significantly affected. This is the case for ASU, PRN and ASD. In other words, economic interdependence spreads damage to all regions of the system.

Table 5.6. Impacts on GDP, by hydrographic region (% change)

	RCP 4.5 (2070-2099)			*RCP 8.5 (2070-2099)*		
Region	*Channel 1 (Water)*	*Channel 2 (Raw water)*	*Total*	*Channel 1 (Water)*	*Channel 2 (Raw water)*	*Total*
AMZ	-0.118	-0.016	-0.134	-0.352	-0.022	-0.374
ALT	-0.224	-0.024	-0.248	-0.530	-0.053	-0.583
AOC	-0.059	-0.133	-0.193	-0.021	-0.251	-0.272
AOR	-0.451	-0.077	-0.527	-1.182	-0.226	-1.408
ASD	-0.182	0.017	-0.164	-0.429	0.037	-0.392
ASU	-0.338	0.026	-0.312	-0.678	0.049	-0.628
PRG	0.641	-0.646	-0.006	1.190	-1.211	-0.021
PRN	-0.145	0.016	-0.129	-0.379	0.035	-0.344
PNB	-1.703	-2.589	-4.292	-3.398	-5.269	-8.667
SFO	-0.089	-0.026	-0.115	-0.271	-0.043	-0.314
TOC	-0.167	-0.047	-0.215	-0.467	-0.077	-0.544
URU	-0.147	0.069	-0.079	-0.278	0.119	-0.159

Source: Authors' own.

Table 5.7 shows the impacts of climate change on the level of sectoral activity. We categorize the sectors into water use classes. It is possible to note that type "A" sectors saw a drop in sectoral activity in both scenarios. This group is composed of large water users, especially raw water with low charges. In this case, the most significant impacts will be perceived in the forestry sector (-2.591% and -5.350%), followed by livestock (-0.462% and -1.146%) and agriculture (-0.154% and -0.566%). These sectors use more raw water in their productive structure than treated water from the water and sewage sector, which explains why Channel 2 predominates over Channel 1. Sectoral group “B” is composed of raw water users with relative charging. The mineral and crude oil extraction sectors and some industrial activities are present in this group. The simulations indicate a moderate negative impact on the level of sectoral activity (-0.113% and -0.428%). Group “C” contains sectors that consume treated water with a high volumetric charge. The service sectors are present in this group. The reduction in the level of activity is -0.114% and -0.258%. In this case, given the greater relevance of treated water, the effects of Channel 1 predominates over Channel 2. Group “D” is composed of public utility sectors that use water as a critical input. It contains the energy sector (mainly hydroelectric energy) and water and sewage sector. The energy sector has a projected impact of -0.240% and -0.593%, respectively, for the realistic and pessimistic scenario. In turn, the water and sewage sector have the most significant drop in activity level among all sectors (-18.233% and -40.713%).

Table 5.7. Impacts on activity level, by sector group (% change)

	RCP 4.5 (2070-2099)			*RCP 8.5 (2070-2099)*		
Sector group†	*Channel 1 (Water)*	*Channel 2 (Raw water)*	*Total*	*Channel 1 (Water)*	*Channel 2 (Raw water)*	*Total*
A1	0.233	-0.387	-0.154	0.240	-0.806	-0.566
A2	0.315	-0.777	-0.462	0.486	-1.632	-1.146
A3	0.554	-3.145	-2.591	1.244	-6.594	-5.350
B	-0.114	0.001	-0.113	-0.430	0.002	-0.428
C	-0.130	0.016	-0.114	-0.289	0.031	-0.258
D1	-0.220	-0.021	-0.240	-0.552	-0.041	-0.593
D2	-18.241	0.007	-18.233	-40.729	0.016	-40.713

† “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

Source: Authors’ own.

Table 5.8 complements the analysis made above by providing information by sector and hydrographic region. In both scenarios and for all regions, the water and sewage sector “D2” is highly affected by climate change and the unavailability of water resources. The sectors of forest production “A3” and agriculture “A1” saw a drop in activity level in almost all regions. The sectors included in groups “B” and “C” had less significant economic losses.

The changes observed in the economy directly impact the amount of water (treated and raw) used/required by economic activities. Some sectors will require more water while others will substitute or save the resource. Changes in the water price, the use of capital that saves water, the level of sectoral activity, and water’s essentiality as an input (= price elasticity of demand) determine these results. Table 5.9 shows how much water is saved (-) or spent (+) by sector groups. In general, considering a long-run scenario, sectors tend to substitute or save water. In the realistic scenario RCP 4.5, the forestry and aquaculture sector “A3” saves 12.2 hm^3, followed by the agriculture sector “A1”, which reduces use by 4.4 hm^3. In the pessimistic scenario RCP 8.5, these values are even higher. The reduction values reach 23.9 hm^3 and 15.2 hm^3 for forestry and agriculture production, respectively.

Table 5.10 provides similar information, considering the change in the demand for raw water. In this case, in an RCP 4.5 scenario, agriculture “A1” reduces demand by 11,945 hm^3, forestry production and aquaculture “A3” will save 4,842 hm^3, and livestock “A2” reduces its use by 396 hm^3. In the RCP 8.5 scenario, these values reach 24,690 hm^3, 9,847 hm^3, and 823 hm^3, respectively. The water and sewage sector will also reduce the amount of water collected (= demand). The value is close to 579 hm^3 in the RCP 4.5 scenario and 1,375 hm^3 in the RCP 8.5 scenario.

Based on the idea of virtual water, or water transport through trade, we look at the flow information of an increase or decrease in water demand within and between regions. This analysis is relevant because we will know the origin-destination of the water saved or spent due to climate change. Figure 5.6a shows the origin-destination of water saved (-) or spent (+) resulting from changes in water availability resulting from climate change, considering scenario RCP 4.5. The mapped information refers to total water demand (treated water + raw water). Bubbles indicate the amount of water saved/spent intra regionally. When the economic sectors of the destination region are impacted by climate change, they decide to save/spend water from the hydrographic region itself. In this case, significant water demand reductions (water saved) are noted in PNB, PRG, AOR, SFO, and PRN. This may be a result of the magnitude of the shock (change in the cost of access to water) and/or due to the region’s internal production structure, which may be more likely to save water in a shock scenario. In our case, water savings can occur in response to a price increase or through capital acquisition. Arrows indicate the amount of water saved/spent in the source region due to changes in the destination region. This shows the strength of the interregional water trade. It is possible to note that PRN is the region of origin that saves the most water due to the “virtual water effect”. In other words, the other hydrographic regions are impacted by climate change, have regional GDP drops, and reduce the amount of goods purchased from PRN. Therefore, in this process, water is saved. This happens in most cases. This is relevant in the relationship between PRG, SFO, and PNB (destination) and PRN (origin). PRG, SFO, PNB, and AOR hydrographic regions are the regions that most lead to water savings in the origin regions. The impacts of climate change on these regions and the regional production structure (dependence on water by sectors located in these regions) explain these flows. Figure 5.6b shows the flows between origin-destination of water saved/spent due to climate change, considering the RCP 8.5 scenario. In this case, the analyses made for the RCP 4.5 scenario are maintained. The difference between scenarios is in the amounts of water saved/spent. In RCP 8.5, the water flows are more significant. Virtual water analyses broaden the notion of economic interdependence, water consumption, and non-geographic frontier in issues related to climate change.

To close the discussion about the possibility of saving water through economic adaptation reactions, Table 5.11 provides information related to the use of capital for this purpose. In general, it is possible to note that climate change and its effects on water availability can lead to capital demand to compensate for possible water scarcity. In practice, this demand for capital may involve the purchase of more efficient irrigation pivots, in the construction of water extraction/storage places, and others. The sectors of forest production “A3”, livestock “A2”, and agriculture “A1” are the sectors that will tend to make higher capital investments.

Table 5.8. Impacts on activity level, by sector group and hydrographic region (% change)

						RCP 4.5 (2070-2099)						
Sector group[†]\Region	*AMZ*	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*
A1	-0.401	-0.724	-2.672	2.242	-0.666	-0.643	-1.256	-0.441	8.215	0.641	-0.034	-1.108
A2	-0.201	-0.665	-3.469	0.269	-0.206	-0.172	0.751	-0.031	-27.748	0.415	0.203	-0.727
A3	-0.303	-0.762	-3.346	-3.015	-0.015	0.746	-17.927	0.202	-114.557	-1.285	-2.145	1.955
B	-0.348	-1.024	-2.822	-2.114	-0.096	-0.207	1.797	0.120	-0.382	0.604	-0.096	-0.145
C	-0.132	-0.332	-0.746	0.706	-0.232	-0.508	1.320	-0.158	-0.820	0.489	0.030	0.075
D1	-0.407	-0.229	-0.276	-0.015	-0.273	-0.301	-0.203	-0.261	-2.519	-0.042	-0.132	-0.226
D2	-23.530	-22.471	-34.035	-79.599	-8.816	1.135	-59.557	-8.902	-198.907	-29.283	-24.597	5.520
						RCP 8.5 (2070-2099)						
A1	-1.317	-1.973	-6.427	7.650	-1.768	-1.376	-2.618	-1.272	15.641	0.376	-0.904	-2.224
A2	-0.776	-1.759	-7.909	1.183	-0.457	-0.313	1.382	-0.215	-57.629	0.299	-0.393	-1.216
A3	-0.535	-1.701	-7.003	-8.764	0.336	1.476	-33.516	0.676	-233.824	-2.369	-4.028	3.479
B	-1.010	-2.751	-6.714	-5.889	-0.271	-0.322	3.412	0.229	-1.595	0.652	-0.870	-0.166
C	-0.462	-0.932	-1.747	2.539	-0.659	-0.980	2.457	-0.498	-1.702	0.645	-0.202	0.178
D1	-0.993	-0.598	-0.699	0.228	-0.734	-0.667	-0.543	-0.656	-5.160	-0.193	-0.448	-0.546
D2	-46.018	-51.495	-72.309	-230.063	-16.103	-0.516	-113.387	-13.880	-414.888	-57.188	-46.582	5.472

[†] “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

Source: Authors’ own.

Table 5.9. Impacts on water demand, by hydrographic region (hm^3)

						RCP 4.5 (2070-2099)						
Sector group[†]\Region	*AMZ*	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*
A1	-0.93	-0.53	-0.64	1.38	-0.55	-0.84	-0.85	-3.90	3.13	0.82	-0.04	-1.46
A2	-0.01	-0.02	-0.03	0.01	-0.01	-0.01	0.03	-0.01	-0.13	0.02	0.01	-0.04
A3	-0.11	-0.37	-0.42	-0.80	-0.01	0.46	-6.48	0.36	-4.48	-0.58	-0.23	0.47
B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.02	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
D1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
						RCP 8.5 (2070-2099)						
A1	-3.06	-1.46	-1.54	4.70	-1.46	-1.79	-1.78	-11.24	5.95	0.48	-1.04	-2.93
A2	-0.03	-0.05	-0.07	0.04	-0.02	-0.01	0.05	-0.05	-0.27	0.01	-0.02	-0.06
A3	-0.19	-0.82	-0.89	-2.33	0.17	0.91	-12.12	1.19	-9.14	-1.06	-0.43	0.84
B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	-0.01	0.00	0.07	-0.01	-0.01	0.01	-0.02	0.01	0.00	0.00	0.00
D1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
D2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[†] “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

Source: Authors’ own.

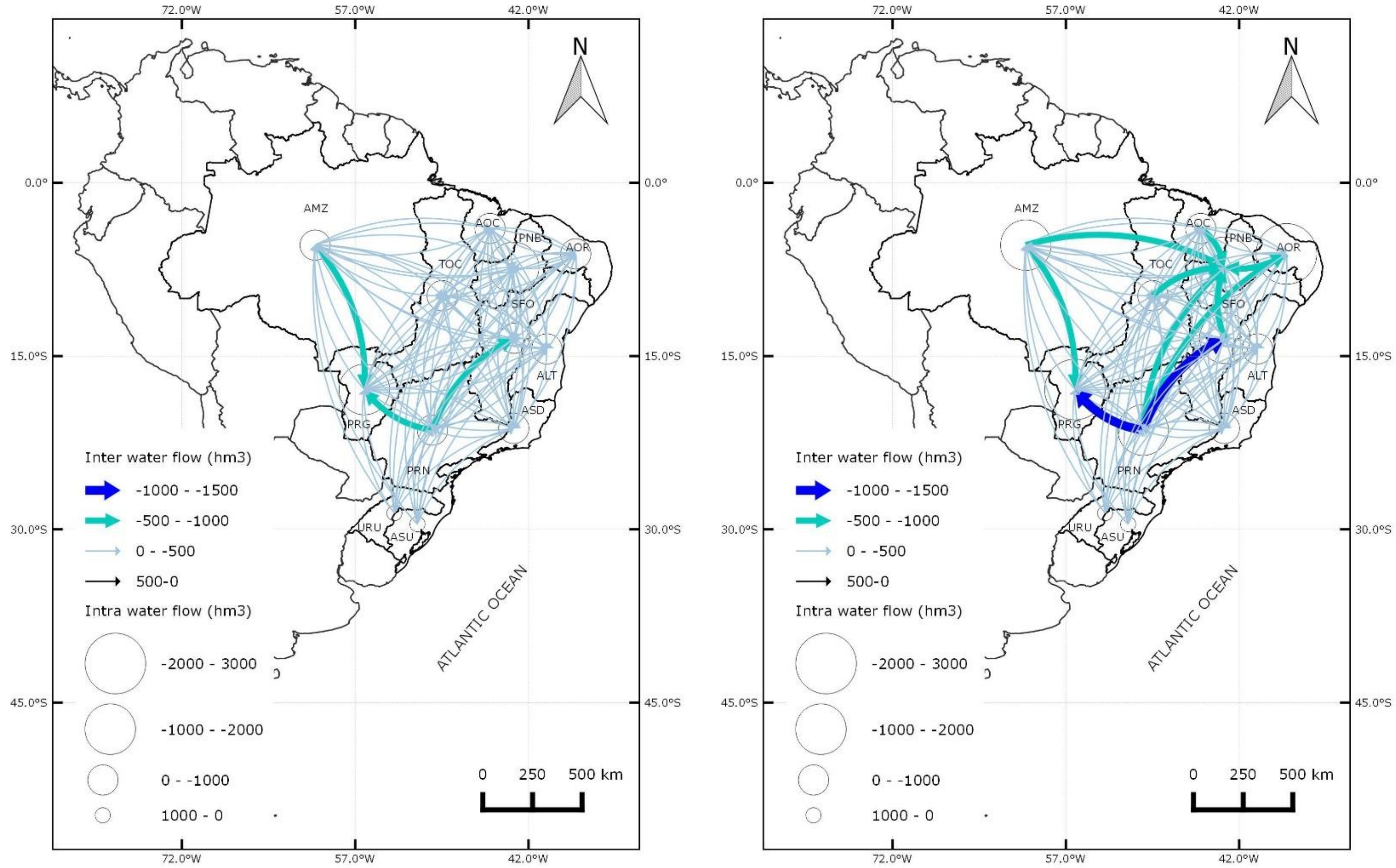
Table 5.10. Raw water demand change by hydrographic region (hm^3)

						RCP 4.5 (2070-2099)						
Sector group[†]\Region	*AMZ*	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*
A1	-1293.37	-471.61	-231.99	-1118.99	-211.44	265.85	-2205.74	-1284.07	-3082.55	-1781.18	-966.91	436.31
A2	-21.91	-18.13	-9.62	-61.69	-8.65	10.03	-113.92	-19.64	-60.73	-71.16	-40.81	20.12
A3	-197.77	-310.43	-133.68	-665.34	-87.74	237.21	-1955.76	-108.87	-938.02	-738.44	-118.93	175.28
B	-0.01	-0.02	-0.01	0.00	-0.02	-0.01	0.01	-0.01	0.01	0.02	0.00	0.00
C	-0.06	-0.29	-0.16	-2.56	-0.13	0.15	-0.97	-0.94	-0.43	-0.36	-0.06	0.04
D1	-0.02	-0.01	-0.01	0.00	-0.03	-0.02	0.00	-0.07	-0.04	0.00	-0.01	-0.01
D2	-30.33	-43.62	-16.21	-263.20	-45.17	1.89	-4.81	-65.52	-45.02	-45.72	-23.51	1.52
						RCP 8.5 (2070-2099)						
A1	-2446.49	-1085.44	-473.76	-3275.45	-374.88	330.97	-4165.81	-2327.36	-6328.06	-3363.41	-1815.59	634.75
A2	-40.57	-41.44	-19.48	-183.25	-12.52	14.83	-214.12	-26.99	-124.33	-132.12	-76.20	32.38
A3	-345.99	-692.06	-259.86	-1982.89	-92.96	385.11	-3666.18	-19.73	-1912.61	-1342.60	-211.71	293.87
B	-0.02	-0.06	-0.02	0.00	-0.05	-0.01	0.03	-0.02	0.02	0.04	-0.01	0.00
C	-0.11	-0.66	-0.31	-7.54	-0.20	0.22	-1.82	-1.16	-0.88	-0.67	-0.12	0.07
D1	-0.06	-0.03	-0.02	0.04	-0.08	-0.05	0.00	-0.19	-0.07	-0.02	-0.02	-0.02
D2	-59.32	-99.96	-34.44	-760.72	-82.50	-0.86	-9.16	-102.16	-93.90	-89.29	-44.51	1.50

[†] “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

Source: Authors’ own.

Figure 5.6. Impacts on water demand, intra and inter-hydrographic regions water flow



(a)

(b)

Source: Authors' own.

Table 5.11. Capital used for saving water, by hydrographic region (% change)

						RCP 4.5 (2070-2099)						
Sector group†*\Region*	*AMZ*	*ALT*	*AOC*	*AOR*	*ASD*	*ASU*	*PRG*	*PRN*	*PNB*	*SFO*	*TOC*	*URU*
A1	0.152	0.311	1.029	1.433	0.108	-0.107	3.921	0.015	12.398	0.463	0.400	-0.178
A2	0.467	0.728	2.201	2.492	0.236	-0.375	7.587	0.063	85.706	1.383	0.665	-0.436
A3	0.583	1.104	2.575	5.185	0.434	-0.590	22.847	0.187	157.119	2.494	3.194	-2.371
B	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
C	0.005	0.004	0.013	0.011	0.001	-0.002	0.079	0.000	0.783	0.017	0.016	-0.017
D1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
						RCP 8.5 (2070-2099)						
A1	0.267	0.694	1.894	4.290	0.144	-0.162	7.364	0.017	25.238	0.840	0.700	-0.289
A2	0.817	1.623	4.051	7.460	0.313	-0.564	14.251	0.070	174.462	2.511	1.162	-0.707
A3	1.018	2.462	4.739	15.523	0.575	-0.888	42.913	0.209	319.827	4.527	5.581	-3.845
B	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
C	0.010	0.009	0.024	0.033	0.001	-0.003	0.148	0.000	1.595	0.031	0.028	-0.028
D1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

† “A” are large raw water users with low charges ((1) agriculture, (2) livestock, (3) forestry and other); “B” are users of raw water with a relative volumetric charge; “C” are users of treated water with high volumetric charge; “D” represents the public utility sectors ((1) energy, (2) water and sewage) that use water as an input.

NAs represents sectors with a low level of capital use and that in the marginal analysis have huge percentage variations (explosive results).

Source: Authors’ own.

5.4. Uncertainty

In studies on the economics of climate change, impact assessments are shrouded in uncertainty (Stern, 2006). In the modelling process, especially in integrated valuation models, there are several sources of possible inconsistencies (long-run events, insufficient or inaccurate databases, and mathematical modelling structure).

The possibility of uncertainties justifies the need to evaluate the robustness of the results from the simulations. We proceed with two approaches to this assessment. In the first, we perform a systematic sensitivity analysis based on changes in the numerical structure of the model. In this case, intervals with lower and upper limits are constructed for a set of key parameters and exogenous shocks, and their relevance in determining endogenous results is observed. In the second, using an approach proposed in Garber & Haddad (2012) and Souza & Haddad (2021), normalized distributions of exogenous shocks (change in the cost of access to water) were constructed, and robustness (ability to reach the target) and the variability (dispersion) of the results of endogenous variables are observed.

5.4.1. Approach 1

In the first approach, we assume that the uncertainties come from the values of the key parameters (Armington elasticity and price elasticity/semi-elasticity of the water demand) and water access cost shocks due to climate change. Our sensitivity analysis tests the numerical structure of the model but does not consider possible modelling errors (mathematical structure).

For the sensitivity test of the results from changes in Armington elasticities and price semi-elasticity of the water demand, an interval of ±20% was established for parameter values with a triangular and symmetric distribution. From this definition, the mean and standard deviation results used to elaborate the confidence intervals (lower and upper values) were obtained. The calculation of the intervals considered a value of 3.16 standard deviations from the mean (90% confidence interval using Chebyshev’s inequality).

In testing the sensitivity of the results to changes in price elasticity of the water demand parameters, we calculated confidence intervals (lower and upper bounds) from the standard error information estimated in Chapter 4.

Finally, in the sensitivity analysis related to climate change shocks (cost of access to water), we calculated confidence intervals (lower and upper bounds) from the standard error of the estimated coefficient relating to water cost access and outflow presented in Chapter 3.

In general, it can be concluded that a given result is more sensitive (less robust) to a set of parameters or shocks if its result is further away from its baseline result. The Mean Square Error (MSE) statistic shows the sensitivity of the results to changing parameters and shock values. A higher MSE indicates that the result is more sensitive (less robust) to parameter/shock variations. The baseline result is used as a target. We analyzed the robustness of endogenous variables regional real GDP, treated water demand and raw water demand.

Tables 5.12ab show the regional real GDP results from the baseline simulation (main results) and from the sensitivity analysis simulations in which the values of key parameters for climate scenarios RCP 4.5 and RCP 8.5 are changed. Comparing with the baseline simulation, it is possible to see that the results are robust to changes in the set of key parameters. The MSE statistic indicates that the lower and upper changes in the Armington elasticity bring more significant change to the regional real GDP results. In regional terms, the PNB and AOR hydrographic regions have more sensitive results than the other regions. The down (up) shift in Armington elasticities generates smaller (larger) percentage changes in regional real GDP.

Tables 5.12cd show information from robustness tests for percentage change in treated water demand. Observing the MSE statistics, it can be seen that Armington’s elasticities are more relevant when compared to the other sets of parameters evaluated. Again, the PNB, AOC, and AOR regions show a more significant difference from the target (baseline simulation). In these regions, the down (up) shift in the Armington parameter leads to positive (negative) shifts in water demand.

Tables 5.12ef show the sensitivity results for the percentage change in raw water demand. According to the MSE statistic, the price elasticity of water demand plays a vital role in the variability of raw water demand. The PNB, AOR, AOC, and PRG hydrographic regions have more sensitive results than the other regions. In this case, down (up) shifts in price elasticity of the water demand leads to positive (negative) changes in raw water demand. The results are also sensitive to Armington parameters. In this case, the down (up) shift in the Armington parameter leads to positive (negative) shifts in raw water demand.

The MSE statistics for parameter tests in the RCP 8.5 climate scenario are higher than in the 4.5 scenario. This indicates that the results related to the RCP 8.5 climate scenario are more uncertain (less robust) than for the RCP 4.5 scenario.

Table 5.13 shows the robustness assessment of the results from changes in shock values. We observe the regional real GDP, treated water and raw water sensitivity in the RCP 4.5 and 8.5 scenarios.

Tables 5.13ab show the regional real GDP results from the baseline simulation and alternative simulations shifting the shock values. According to the MSE statistic, reductions in shocks bring more sensitivity to the results. In this case, down (up) shocks shift lead to positive (negative) changes in the real GDP of the hydrographic regions. Regionally, PNB and AOR have less robust results than the other regions.

Tables 5.13cd show the robustness test information for the treated water demand variable. Considering the MSE statistic, lower limit shocks have a more significant impact (generate greater sensitivity) on the results. In this case, down (up) shifts in shock positively (negatively) affect the demand for treated water. In the PNB, AOR, and AOC regions, the results are less robust.

Tables 5.13ef show the robustness test of raw water demand results to changes in shocks. When shocks are pushed to their lower limit, the results are less robust. Down (up) changes in shocks positively (negatively) affect raw water demand. In the PNB, AOR, and AOC regions, the results are less robust.

In the analysis of the robustness of the results from changes in exogenous shocks, it can be seen from the MSE statistic that the simulation results in the RCP 8.5 scenario are more uncertain than in the RCP 4.5 scenario.

Table 5.12. Robustness analysis for model parameters

(a) Regional GDP, RCP 4.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-0.153	-0.150	-0.157	-0.150	-0.156	-0.153	-0.153
ALT	-0.219	-0.331	-0.107	-0.198	-0.239	-0.219	-0.219
AOC	-0.214	-0.179	-0.249	-0.188	-0.240	-0.214	-0.214
AOR	-0.481	-0.562	-0.399	-0.465	-0.496	-0.481	-0.481
ASD	-0.199	-0.193	-0.205	-0.202	-0.197	-0.199	-0.199
ASU	-0.331	-0.277	-0.385	-0.335	-0.328	-0.331	-0.331
PRG	-0.072	-0.108	-0.038	-0.040	-0.105	-0.072	-0.072
PRN	-0.158	-0.151	-0.165	-0.160	-0.156	-0.158	-0.158
PNB	-1.055	-1.135	-0.972	-0.908	-1.202	-1.055	-1.055
SFO	-0.125	-0.187	-0.064	-0.116	-0.134	-0.125	-0.125
TOC	-0.253	-0.248	-0.260	-0.246	-0.261	-0.253	-0.253
URU	-0.073	-0.033	-0.114	-0.078	-0.068	-0.073	-0.073
Brazil	-0.223	-0.228	-0.217	-0.220	-0.226	-0.223	-0.223
MSE		0.00281	0.00285	0.00186	0.00186	0.00000	0.00000

(b) Regional GDP, RCP 8.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-0.374	-0.365	-0.384	-0.370	-0.378	-0.374	-0.374
ALT	-0.583	-0.509	-0.658	-0.573	-0.594	-0.583	-0.583
AOC	-0.272	-0.044	-0.503	-0.222	-0.322	-0.272	-0.272
AOR	-1.408	-1.695	-1.122	-1.363	-1.453	-1.408	-1.408
ASD	-0.392	-0.368	-0.415	-0.399	-0.384	-0.392	-0.392
ASU	-0.628	-0.525	-0.729	-0.638	-0.618	-0.628	-0.628
PRG	-0.021	-0.485	0.444	0.221	-0.264	-0.021	-0.021
PRN	-0.344	-0.315	-0.372	-0.351	-0.337	-0.344	-0.344
PNB	-8.667	-9.411	-7.882	-7.613	-9.721	-8.667	-8.667
SFO	-0.314	-0.363	-0.267	-0.306	-0.323	-0.314	-0.314
TOC	-0.544	-0.534	-0.557	-0.529	-0.560	-0.544	-0.544
URU	-0.159	-0.037	-0.280	-0.183	-0.135	-0.159	-0.159
Brazil	-0.564	-0.565	-0.562	-0.552	-0.576	-0.564	-0.564
MSE		0.07209	0.07714	0.09041	0.09039	0.00000	0.00000

continued

(c) Water demand, RCP 4.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-0.556	-0.488	-0.619	-0.553	-0.559	-0.553	-0.559
ALT	0.167	-0.102	0.407	0.194	0.140	0.181	0.153
AOC	-0.824	-0.710	-0.913	-0.801	-0.847	-0.819	-0.829
AOR	-0.974	-1.289	-0.669	-0.950	-0.997	-0.959	-0.989
ASD	-0.354	-0.331	-0.370	-0.355	-0.352	-0.352	-0.356
ASU	-0.421	-0.354	-0.481	-0.426	-0.416	-0.422	-0.420
PRG	-0.266	-0.278	-0.255	-0.225	-0.307	-0.260	-0.272
PRN	-0.288	-0.255	-0.319	-0.291	-0.286	-0.287	-0.290
PNB	-2.071	-2.465	-1.696	-1.871	-2.271	-2.052	-2.089
SFO	0.119	-0.002	0.226	0.136	0.102	0.128	0.110
TOC	-0.470	-0.425	-0.506	-0.460	-0.479	-0.466	-0.474
URU	0.014	0.141	-0.104	0.011	0.016	0.013	0.015
Brazil	-0.494	-0.546	-0.442	-0.466	-0.521	-0.487	-0.500
MSE		0.02971	0.02596	0.00344	0.00343	0.00008	0.00007

(d) Water demand, RCP 8.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-1.306	-1.189	-1.418	-1.301	-1.310	-1.299	-1.299
ALT	-2.107	-1.959	-2.228	-2.107	-2.107	-2.100	-2.100
AOC	-4.029	-3.291	-4.651	-4.016	-4.041	-4.021	-4.021
AOR	-2.936	-4.058	-1.874	-2.870	-3.002	-2.892	-2.892
ASD	-0.820	-0.721	-0.908	-0.830	-0.810	-0.819	-0.819
ASU	-0.785	-0.650	-0.909	-0.800	-0.771	-0.788	-0.788
PRG	0.037	-0.566	0.582	0.327	-0.253	0.077	0.077
PRN	-0.556	-0.473	-0.635	-0.566	-0.546	-0.555	-0.555
PNB	-12.592	-17.164	-8.322	-11.153	-14.032	-12.462	-12.462
SFO	-0.340	-0.413	-0.282	-0.320	-0.361	-0.329	-0.329
TOC	-1.142	-1.090	-1.193	-1.123	-1.162	-1.133	-1.133
URU	0.199	0.516	-0.092	0.185	0.213	0.194	0.194
Brazil	-2.198	-2.588	-1.827	-2.048	-2.348	-2.177	-2.177
MSE		1.79963	1.56412	0.16807	0.16807	0.00165	0.00165

continued

(e) Raw water demand, RCP 4.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-0.874	-0.806	-0.936	-0.871	-0.877	-0.834	-0.913
ALT	-1.429	-1.698	-1.189	-1.402	-1.456	-0.829	-2.029
AOC	-1.418	-1.304	-1.508	-1.395	-1.442	-1.345	-1.492
AOR	-2.830	-3.146	-2.526	-2.807	-2.854	-2.469	-3.192
ASD	-0.585	-0.563	-0.601	-0.587	-0.584	-0.504	-0.667
ASU	-0.280	-0.213	-0.341	-0.285	-0.275	-0.298	-0.263
PRG	-0.926	-0.938	-0.915	-0.886	-0.967	-0.845	-1.008
PRN	-0.480	-0.446	-0.510	-0.482	-0.477	-0.432	-0.528
PNB	-3.809	-4.204	-3.435	-3.609	-4.009	-2.974	-4.645
SFO	-1.363	-1.483	-1.256	-1.345	-1.380	-0.846	-1.880
TOC	-0.998	-0.954	-1.035	-0.988	-1.007	-0.816	-1.179
URU	0.135	0.263	0.018	0.133	0.138	0.120	0.151
Brazil	-1.238	-1.291	-1.186	-1.210	-1.266	-1.006	-1.470
MSE		0.02982	0.02585	0.00343	0.00344	0.12036	0.12055

(f) Raw water demand, RCP 8.5 scenario (% change)

		Armington		*Water semi-elasticity*		*Water elasticity*	
Region	*Baseline*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
AMZ	-2.030	-1.914	-2.143	-2.026	-2.035	-1.941	-2.120
ALT	-2.876	-2.728	-2.997	-2.876	-2.876	-2.587	-3.165
AOC	-4.969	-4.231	-5.591	-4.956	-4.982	-4.853	-5.085
AOR	-8.377	-9.499	-7.316	-8.311	-8.444	-7.317	-9.437
ASD	-0.964	-0.865	-1.052	-0.974	-0.953	-0.913	-1.014
ASU	-0.430	-0.294	-0.554	-0.444	-0.415	-0.474	-0.386
PRG	-4.723	-5.326	-4.178	-4.433	-5.013	-4.136	-5.311
PRN	-0.715	-0.632	-0.794	-0.725	-0.705	-0.676	-0.755
PNB	-25.064	-29.635	-20.793	-23.624	-26.503	-19.069	-31.059
SFO	-2.257	-2.329	-2.198	-2.236	-2.277	-1.588	-2.925
TOC	-2.308	-2.255	-2.358	-2.288	-2.327	-1.907	-2.708
URU	0.831	1.148	0.540	0.817	0.845	0.753	0.909
Brazil	-4.490	-4.880	-4.119	-4.340	-4.641	-3.726	-5.255
MSE		1.79963	1.56412	0.16807	0.16807	2.97809	2.97809

Source: Authors' own.

Table 5.13. Robustness analysis for model shocks

(a) Regional GDP, RCP 4.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-0.134	-0.070	-0.198
ALT	-0.248	-0.140	-0.355
AOC	-0.193	-0.112	-0.274
AOR	-0.527	-0.305	-0.749
ASD	-0.164	-0.089	-0.239
ASU	-0.312	-0.253	-0.371
PRG	-0.006	0.007	-0.018
PRN	-0.129	-0.068	-0.189
PNB	-4.292	-2.550	-6.034
SFO	-0.115	-0.063	-0.167
TOC	-0.215	-0.117	-0.312
URU	-0.079	-0.061	-0.096
Brazil	-0.233	-0.138	-0.329
MSE		0.24157	0.24157

(b) Regional GDP, RCP 8.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-0.374	-0.207	-0.541
ALT	-0.583	-0.335	-0.832
AOC	-0.272	-0.156	-0.388
AOR	-1.408	-0.823	-1.993
ASD	-0.392	-0.220	-0.563
ASU	-0.628	-0.471	-0.785
PRG	-0.021	0.004	-0.047
PRN	-0.344	-0.191	-0.496
PNB	-8.667	-5.147	-12.187
SFO	-0.314	-0.178	-0.451
TOC	-0.544	-0.307	-0.782
URU	-0.159	-0.120	-0.198
Brazil	-0.564	-0.333	-0.796
MSE		1.00334	1.00332

continued

(c) Water demand, RCP 4.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-0.552	-0.297	-0.807
ALT	-0.827	-0.477	-1.177
AOC	-1.769	-1.032	-2.505
AOR	-1.163	-0.682	-1.644
ASD	-0.341	-0.184	-0.498
ASU	-0.391	-0.287	-0.494
PRG	0.039	0.061	0.017
PRN	-0.240	-0.119	-0.360
PNB	-6.002	-3.551	-8.453
SFO	0.002	0.020	-0.016
TOC	-0.421	-0.223	-0.618
URU	0.124	0.231	0.017
Brazil	-0.962	-0.545	-1.378
MSE		0.55719	0.55724

(d) Water demand, RCP 8.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-1.306	-0.727	-1.884
ALT	-2.107	-1.229	-2.985
AOC	-4.029	-2.362	-5.695
AOR	-2.936	-1.728	-4.144
ASD	-0.820	-0.457	-1.182
ASU	-0.785	-0.542	-1.028
PRG	0.037	0.083	-0.009
PRN	-0.556	-0.294	-0.819
PNB	-12.592	-7.453	-17.731
SFO	-0.340	-0.173	-0.508
TOC	-1.142	-0.636	-1.648
URU	0.199	0.370	0.028
Brazil	-2.198	-1.262	-3.134
MSE		2.55365	2.55356

continued

(e) Raw water demand, RCP 4.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-0.967	-0.543	-1.390
ALT	-1.172	-0.682	-1.662
AOC	-2.279	-1.335	-3.224
AOR	-2.981	-1.760	-4.201
ASD	-0.450	-0.248	-0.651
ASU	-0.154	0.045	-0.354
PRG	-2.495	-1.442	-3.548
PRN	-0.382	-0.203	-0.560
PNB	-12.128	-7.186	-17.072
SFO	-1.054	-0.606	-1.501
TOC	-1.088	-0.619	-1.556
URU	0.513	0.779	0.248
Brazil	-2.053	-1.150	-2.956
MSE		2.28917	2.28937

(f) Raw water demand, RCP 8.5 scenario (% change)

		Shock	
Region	*Baseline*	*Lower*	*Upper*
AMZ	-2.030	-1.157	-2.904
ALT	-2.876	-1.685	-4.066
AOC	-4.969	-2.920	-7.018
AOR	-8.377	-4.956	-11.798
ASD	-0.964	-0.543	-1.385
ASU	-0.430	-0.042	-0.817
PRG	-4.723	-2.741	-6.705
PRN	-0.715	-0.388	-1.043
PNB	-25.064	-14.853	-35.275
SFO	-2.257	-1.309	-3.204
TOC	-2.308	-1.327	-3.288
URU	0.831	1.259	0.403
Brazil	-4.490	-2.555	-6.425
MSE		10.19244	10.19200

Source: Authors’ own.

5.4.2. Approach 2

We use a robustness test proposed in Garber & Haddad (2012) and Souza & Haddad (2021) in the second approach.

Consider the basic mathematical structure of the ICGE model given by (5.28)

$$F(V) = 0 \tag{5.28}$$

where V is an equilibrium vector of size n (number of variables) and F is a vector of differentiable functions of size m (number of equations). To obtain a solution, it is necessary that $n > m$, where $n - m$ variables are exogenous. The model solution is given by V^* such that $F(V^*) = 0$.

Following Johansen's approach, equation (5.29) is a linearized version of (5.28)

$$A(V)v = 0 \tag{5.29}$$

where $A(V)$ is a matrix of size $m \times n$ that contains partial derivatives of $F(V)$, and v represents percentage changes in vector V.

Consider V_I as an initial equilibrium vector of the linearized system of equations. To solve (5.29), we separate it into an endogenous and an exogenous part. In this case, α indicates endogenous variables, and β indicates exogenous variables. This procedure is described in (5.30)

$$\begin{gathered} A(V^I)v = A_\alpha(V^I)v_\alpha + A_\beta(V^I)v_\beta = 0 \\ v_\alpha = -A_\alpha(V^I)^{-1}A_\beta(V^I)v_\beta \qquad (5.30) \\ v_\alpha = Bv_\beta \end{gathered}$$

where v_α is a $m \times 1$ vector that contains the percentage changes of the endogenous variables, $B(V_I)$ is $-A_\alpha(V^I)^{-1}A_\beta(V^I)$ and v_β is a $(nm) \times 1$ vector of percentage variations of exogenous variables. For more details on Johansen's approach, see Dixon et al. (1992).

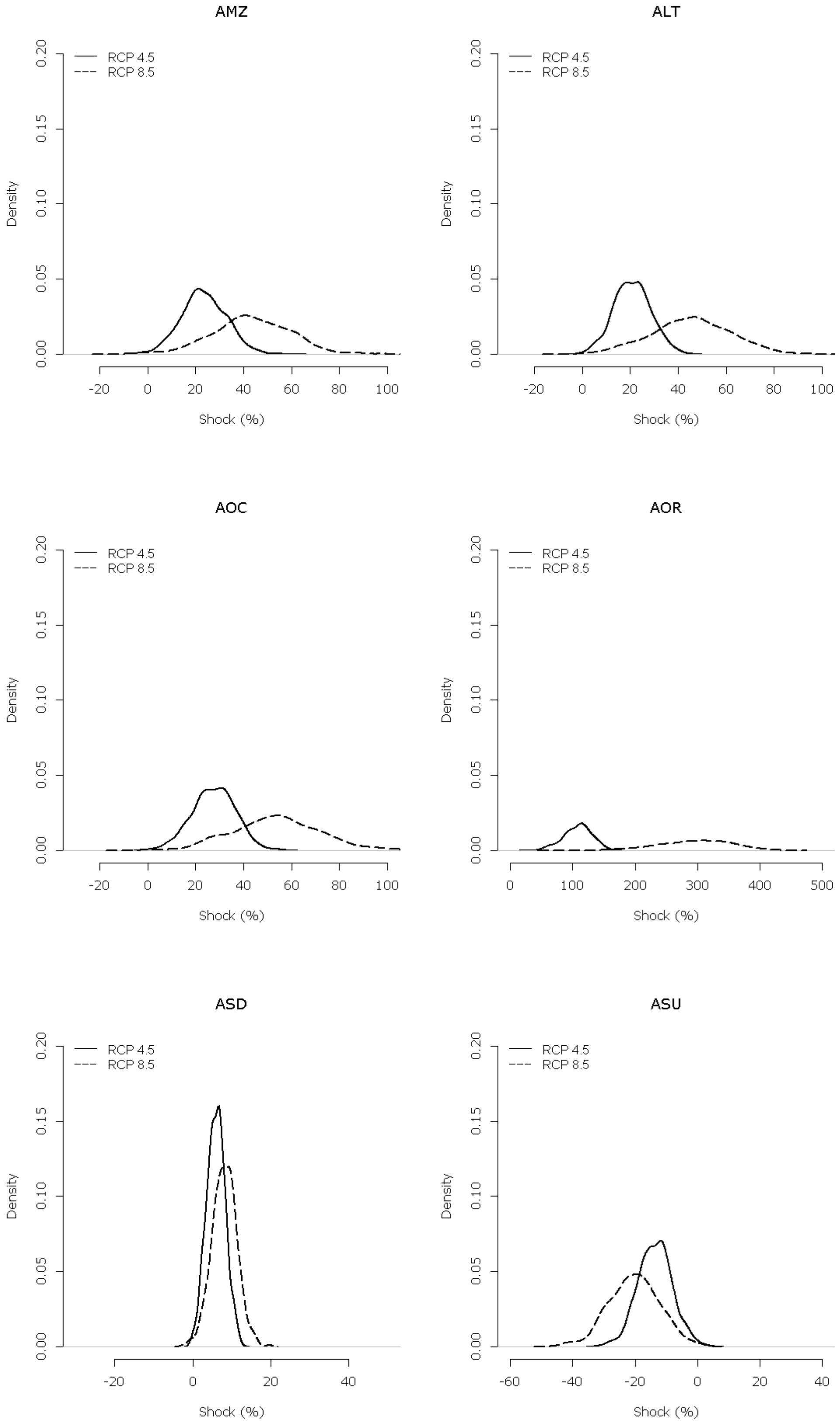
Take a subset of v_α as targets. Denote this subset as $\hat{v}_\alpha$. The vector t contains all these targets. Furthermore, we select a subset of v_β that contains relevant exogenous variables to influence t. Denote this subset as $\hat{v}_\beta$.

$\hat{v}_\alpha$ depends on $\hat{v}_\beta$. Thus, given the values of target t, the best choice of $\hat{v}_\beta$ will be the one that minimizes a squared percentage distance $(\hat{v}_\alpha - t)^2/t^2$. Thus, we obtain an optimal vector of exogenous variables $\hat{v}_\beta^*$ and consequently an optimal vector of endogenous variables $\hat{v}_\alpha^*$.

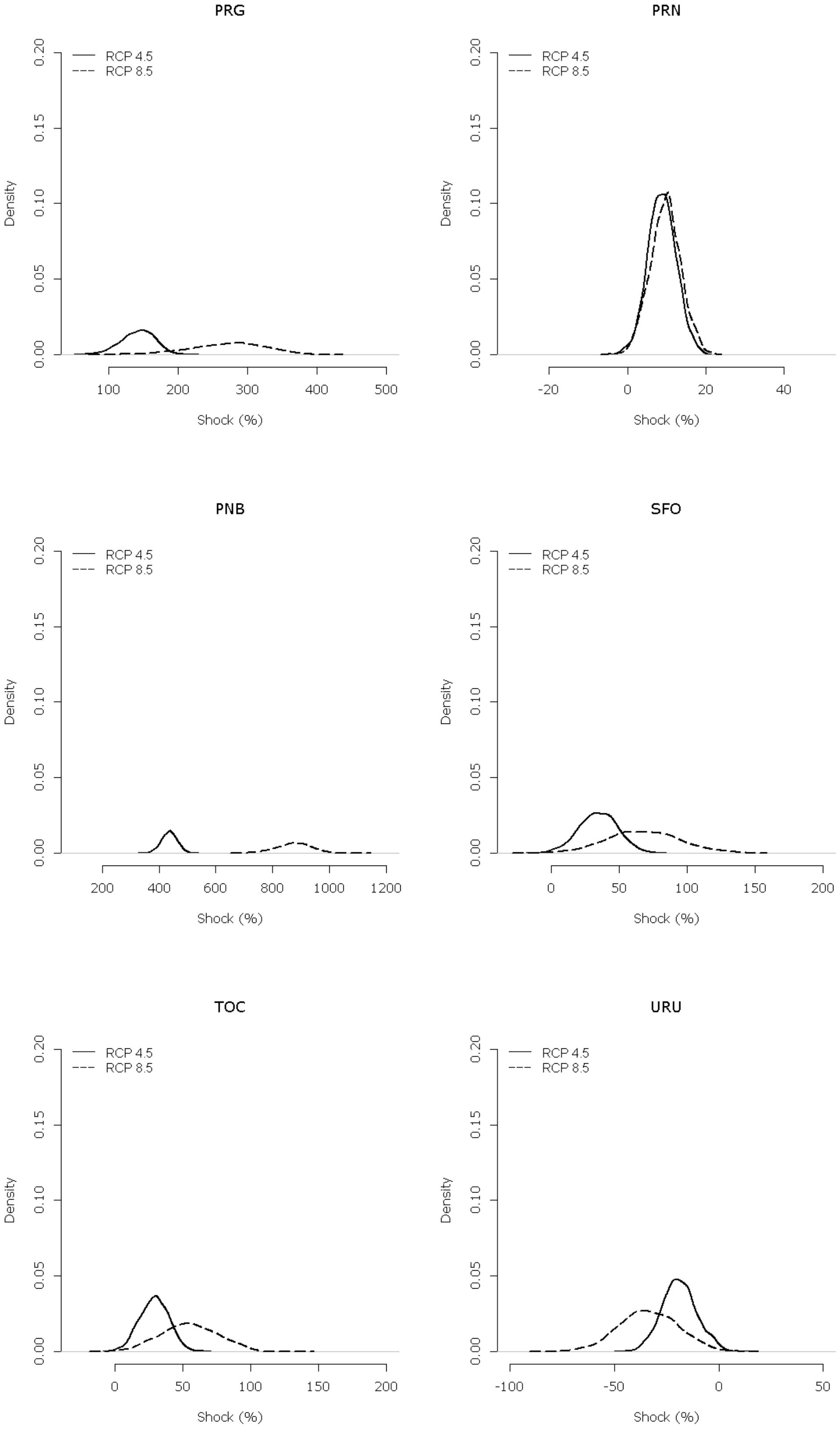
In practice, we use as target t the real GDP of the hydrographic regions from the baseline simulations and the vector of exogenous variables ($\hat{v}_\beta$) is represented by the shocks of change in the cost of access to water due to climate change. Square matrix B contains information on regional real GDP simulated from exogenous unitary water cost access shocks. All this information comes from the BMARIA-H_2O model. We performed 10,000 exogenous shock simulations to evaluate the one that minimizes the distance function. Each simulation was built from a random draw for the shock from a normal distribution with a mean equal to the shock and variance calculated from the standard error statistic of the coefficient that relates to the cost of access to water and outflow. After this process, the results for the endogenous variable (real regional GDP) are observed.

Figure 5.7 shows the exogenous shock distributions (change in the cost of access to water) for the Brazilian hydrographic regions in the RCP 4.5 and RCP 8.5 climate scenarios. The ALT, AOC, AOR, PRG, PNB, SFO, and TOC regions have greater dispersion of shock distributions. In our case, this is because the magnitude of the shocks and consequently their deviations are more significant in these regions. The other regions have distributions more concentrated around the average of the shock. Furthermore, it is possible to note that the density curves in the RCP 8.5 scenario in most cases shifted to the right, indicating a distribution of larger shocks in a pessimistic climate scenario. In ASU and URU, where there may be an increase in water availability, this shift is the opposite.

Figure 5.7. Distribution of simulated shocks in hydrographic regions



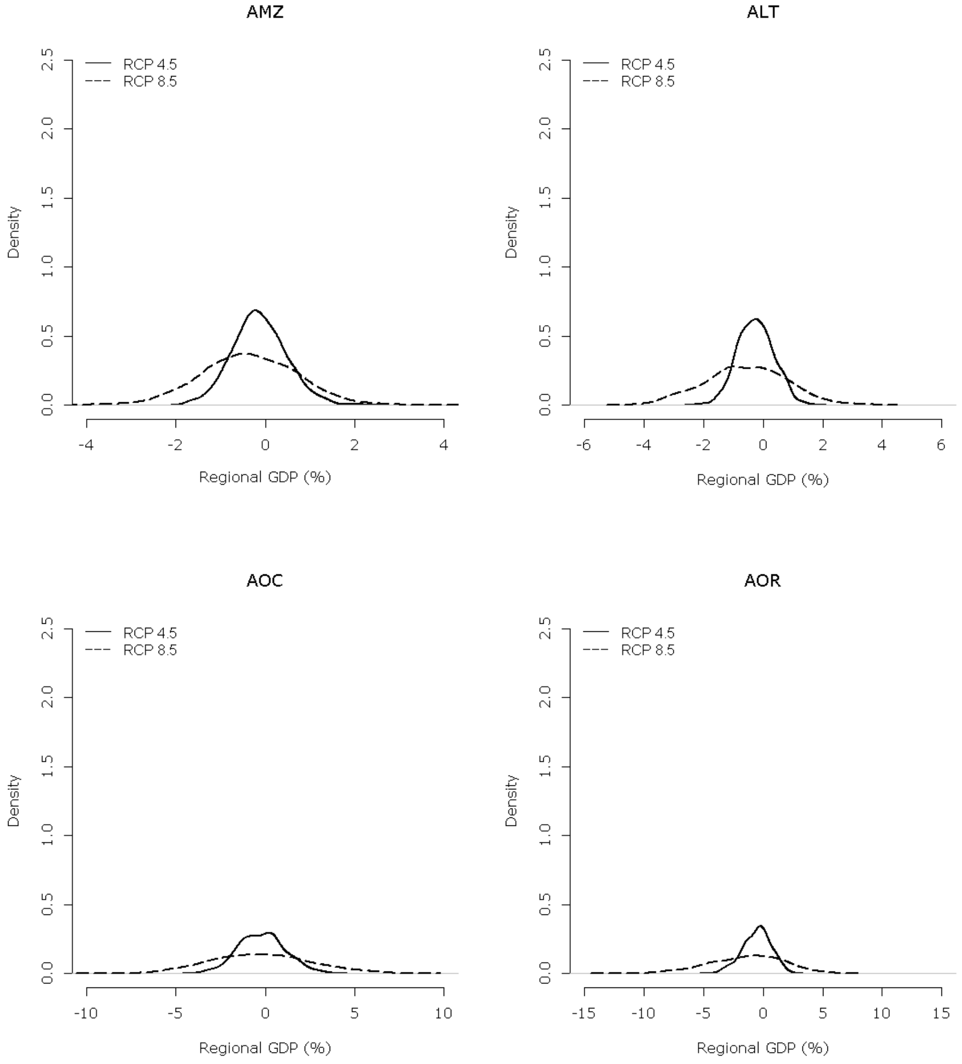
continued



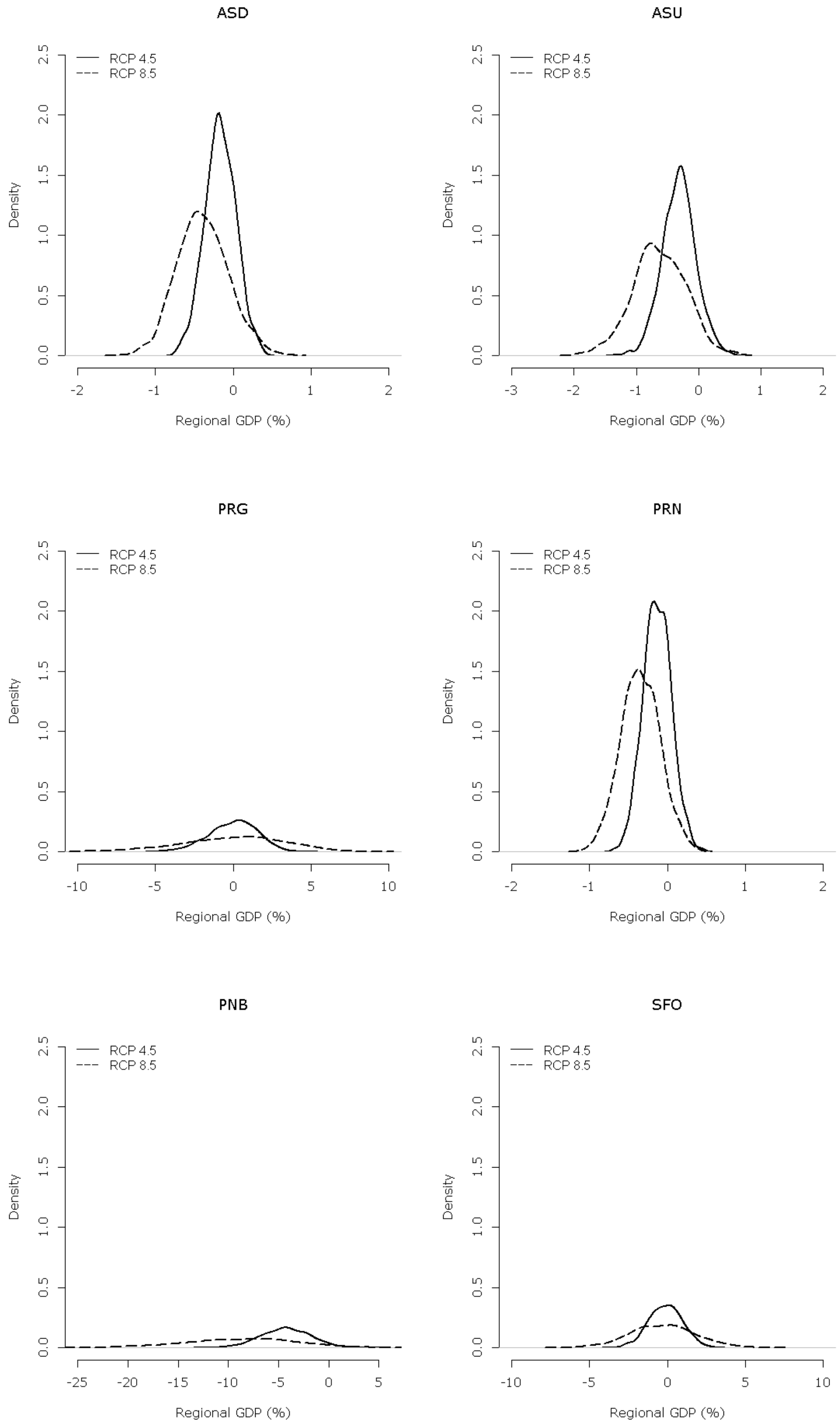
Source: Authors’ own.

Figure 5.8 shows the simulated real GDP result distributions for the Brazilian hydrographic regions considering scenarios RCP 4.5 and RCP 8.5. In general, simulated values hit their respective targets (baseline simulation results). In other words, there is a large area of distribution that is located around the target. This indicates that the results generated by BMARIA-H_2O, especially for the real GDP variable, are robust.

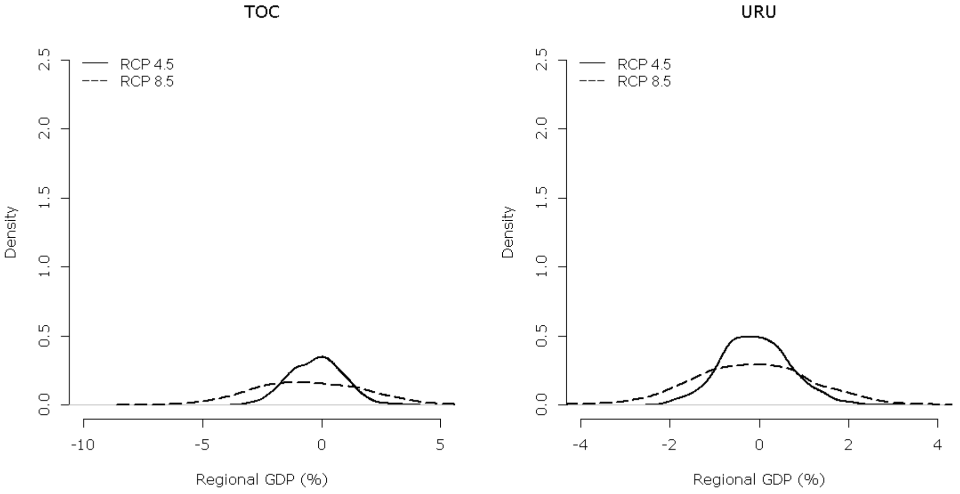
Figure 5.8. Distribution of simulated impacts (real GDP) in hydrographic regions



continued


ASD
ASU
PRG
PRN
PNB
SFO
RCP 4.5
RCP 8.5
Density
0.0
0.5
1.0
1.5
2.0
2.5
-3
-2
-1
0
1
2
-10
-5
5
10
-25
-20
-15
Regional GDP (%)

continued



Source: Authors' own.

Despite hitting the target, the dispersion (variability) of the results differs between regions and, in some cases, presents uncertainties. As it is a result of shock structures, the distribution of real regional GDP follows a similar line. Most regions present a relevant dispersion of the endogenous results. This seems most relevant for ALT, AOC, AOR, PRG, PNB, SFO, and TOC. In these cases, there is the possibility of a change in the impact sign. In other regions, it is also present; however, it seems less worrying.

References

Berrittella, M., Rehdanz, K., Roson, R., & Tol, R. S. (2005). The economic impact of water pricing: A computable general equilibrium analysis. *FNU-96, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg*.

Brouwer, R., Hofkes, M., & Linderhof, V. (2008). General equilibrium modelling of the direct and indirect economic impacts of water quality improvements in the Netherlands at national and river basin scale. *Ecological Economics*, 66(1), 127-140. https://doi.org/10.1016/j.ecolecon.2007.11.015

Calzadilla, A., Rehdanz, K., & Tol, R. S. (2011). Water scarcity and the impact of improved irrigation management: a computable general equilibrium analysis. *Agricultural Economics*, 42(3), 305-323. https://doi.org/10.1111/j.1574-0862.2010.00516.x

Diao, X., Roe, T., & Doukkali, R. (2005). Economy-wide gains from decentralized water allocation in a spatially heterogenous agricultural economy. *Environment and Development Economics*, 249-269. http://dx.doi.org/10.1017/S1355770X05002068

Diao, X., Dinar, A., Roe, T., & Tsur, Y. (2008). A general equilibrium analysis of conjunctive ground and surface water use with an application to Morocco. *Agricultural Economics*, 38(2), 117-135. http://dx.doi.org/10.1111/j.1574-0862.2008.00287.x

Dixon, P. B., Parmenter, B. R., Sutton, J., & Vincent, D. P. (1982). *Orani: a multisectoral model of the Australian economy* (Vol. 142). Amsterdam: North-Holland.

Dixon, P. B., & Parmenter, B. R. (1996). Computable general equilibrium modelling for policy analysis and forecasting. *Handbook of computational economics*, 1, 3-85.

Dixon, P., & Rimmer, M. T. (2002). *Dynamic general and equilibrium modelling for forecasting and policy: A practical guide and documentation of MONASH* (Vol. 256). Amsterdam: Elsevier.

Dixon, P. B., Rimmer, M. T., & Wittwer, G. (2011). Saving the Southern Murray-Darling Basin: the economic effects of a buyback of irrigation water. *Economic Record*, 87(276), 153-168. https://doi.org/10.1111/j.1475-4932.2010.00691.x

Domingues, E. P. (2002). *Dimensão regional e setorial da integração brasileira na Área de Livre Comércio das Américas.* Doctoral dissertation. Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo, São Paulo.

Domingues, E. P., & Haddad, E. A. (2003). Política tributária e re-localização. *Revista Brasileira de Economia*, 57(4), 849-871. https://doi.org/10.1590/S0034-71402003000400009

Fang, G., Wang, T., Si, X., Wen, X., & Liu, Y. (2016). Discharge fee policy analysis: A computable general equilibrium (CGE) model of water resources and water environments. *Water*, 8(9), 413. https://doi.org/10.3390/w8090413

Faria, W. R. (2015). *Modelagem e avaliação de fenômenos relacionados ao uso da terra no Brasil*. Doctoral dissertation. Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo, São Paulo.

Garber, G., & Haddad, E. (2012). *Target fitting and robustness analysis in CGE models* (No. 2012_14). Universidade de São Paulo, São Paulo.

Gomez, C. M., Tirado, D., & Rey-Maquieira, J. (2004). Water exchanges versus water works: Insights from a computable general equilibrium model for the Balearic Islands. *Water Resources Research*, 40(10). https://doi.org/10.1029/2004WR003235

Goodman, D. J. (2000). More reservoirs or transfers? A computable general equilibrium analysis of projected water shortages in the Arkansas River Basin. *Journal of Agricultural and Resource Economics*, 698-713. http://www.jstor.org/stable/40987085

Haddad, E. A. (1999). *Regional inequality and structural changes: lessons from the Brazilian experience*. Ashgate: Aldershot.

Haddad, E. A., & Domingues, E. P. (2001). EFES-Um modelo aplicado de equilíbrio geral para a economia brasileira: projeções setoriais para 1999-2004. *Estudos Econômicos*, 31(1), 89-125.

Haddad, E. A. (2004). *Retornos crescentes, custo de transporte e crescimento regional*. São Paulo: Universidade de São Paulo.

Haddad, E. A., Domingues, E. P., & Perobelli, F. S. (2009). *Avaliação de impactos de mudanças climáticas sobre a economia brasileira*. São Paulo: Universidade de São Paulo, Instituto de Pesquisas Econômicas (IPE).

Haddad, E. A., Mengoub, F. E., & Vale, V. A. (2020). Water content in trade: a regional analysis for Morocco. *Economic Systems Research*, 32(4), 565-584. https://doi.org/10.1080/09535314.2020.1756228

Harrison, W. J., & Pearson, K. R. (1996). Computing solutions for large general equilibrium models using GEMPACK. *Computational Economics,* 9(2), 83-127. https://doi.org/10.1007/BF00123638

Harrison, W. J., Pearson, K. R., & Powell, A. A. (1996). Features of multiregional and intertemporal AGE modelling with GEMPACK. *Computational Economics*, 9(4), 331-353. https://doi.org/10.1007/BF00119479

Hassan, R., & Thurlow, J. (2011). Macro–micro feedback links of water management in South Africa: CGE analyses of selected policy regimes. *Agricultural Economics*, 42(2), 235-247. https://doi.org/10.1111/j.1574-0862.2010.00511.x

Horridge, M. (2003). *ORANI-G: A generic single-country computable general equilibrium model.* Clayton: Centre of Policy Studies and Impact Project, Monash University, Australia.

Horridge, M., Madden, J., & Wittwer, G. (2005). The impact of the 2002–2003 drought on Australia. *Journal of Policy Modeling*, 27(3), 285-308. http://dx.doi.org/10.1016/j.jpolmod.2005.01.008

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Geneva: IPCC, 150 pp.

Jun, X., Qun, D., & Yangbo, S. (2010). Integrated water and CGE model of the impacts of water policy on the Beijing's economy and output. *Chinese Journal of Population Resources and Environment*, 8(2), 61-67. https://doi.org/10.1080/10042857.2010.10684978

Lofgren, H., Robinson, S., & Nygaard, D. F. (1996). *Tiger or turtle?: exploring alternative futures for Egypt to 2020* (No. 607-2016-40367).

Perobelli, F. S. (2004). *Análise das interações econômicas entre os estados brasileiros.* Doctoral dissertation. Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo, São Paulo.

Peterson, D., Dwyer, G., Appels, D., & Fry, J. (2005). Water trade in the southern Murray–Darling Basin. *Economic Record*, 81, S115-S127. http://dx.doi.org/10.1111/j.1475-4932.2005.00248.x

Santos, G. F. D. (2012). *Política energética e desigualdades regionais na economia brasileira*. Brasília: Banco Nacional de Desenvolvimento Econômico e Social.

Seung, C. K., Harris, T. R., MacDiarmid, T. R., & Shaw, W. D. (1998). Economic impacts of water reallocation: A CGE analysis for walker river basin of Nevada and California. *Journal of Regional Analysis and Policy*, 28(1100-2016-89752), 13-34. http://dx.doi.org/10.22004/ag.econ.130523

Seung, C. K., Harris, T. R., Englin, J. E., & Netusil, N. R. (2000). Impacts of water reallocation: A combined computable general equilibrium and recreation demand model approach. *The Annals of Regional Science*, 34(4), 473-487. https://doi.org/10.1007/s001689900011

Souza, B., & Haddad, E. (2021). Climate change in Brazil: dealing with uncertainty in agricultural productivity models and the implications for economy-wide impacts. *Spatial Economic Analysis*, 1-18. https://doi.org/10.1080/17421772.2021.1934524

Stern, N. (2006). *The Stern review: the economics of climate change*. London: HM Treasury.

Van Heerden, J. H., Blignaut, J., & Horridge, M. (2008). Integrated water and economic modelling of the impacts of water market instruments on the South African economy. *Ecological economics,* 66(1), 105-116. http://dx.doi.org/10.1016/j.ecolecon.2007.11.011

Wittwer, G. (2011). Confusing policy and catastrophe: buybacks and drought in the Murray–Darling Basin. *Economic Papers: A journal of applied economics and policy*, 30(3), 289-295. https://doi.org/10.1111/j.1759-3441.2011.00122.x

Wittwer, G., & Griffith, M. (2011). Modelling drought and recovery in the southern Murray-Darling basin. *Australian Journal of Agricultural and Resource Economics*, 55(3), 342-359. https://doi.org/10.1111/j.1467-8489.2011.00541.x

Zhong, S., Shen, L., Sha, J., Okiyama, M., Tokunaga, S., Liu, L., & Yan, J. (2015). Assessing the water parallel pricing system against drought in China: A study based on a CGE model with multi-provincial irrigation water. *Water,* 7(7), 3431-3465. https://doi.org/10.3390/w7073431

Appendix – Usage guide for the BMARIA-H_2O model

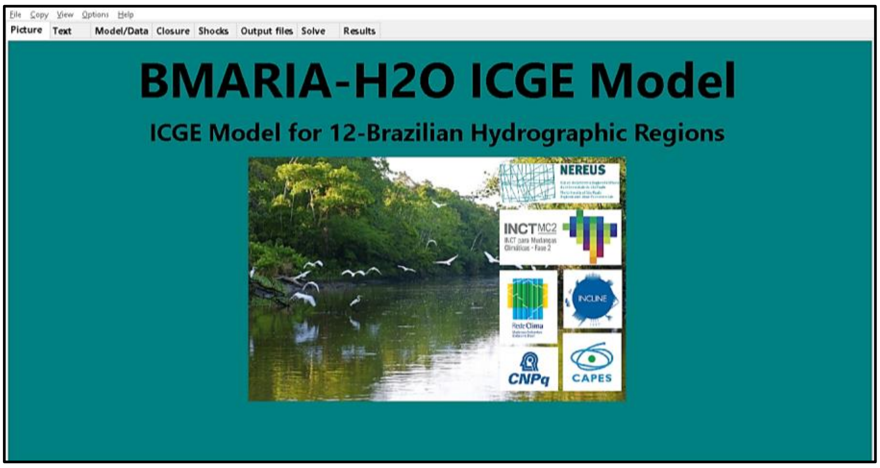
The BMARIA-H_2O is an interregional computable general equilibrium (ICGE) model, implemented using GEMPACK and designed for policy analysis in Brazilian hydrographic regions. RunGEM is a windows program that makes it easy to run any CGE model created with GEMPACK. Customized RunGEM is a particular version of RunGEM that has been hard-wired to work only with one or a few particular models (such as BMARIA-H_2O ICGE). This document assumes that a recent version of Customized RunGEM (dated March 2001 or later) that contains the BMARIA-H_2O ICGE model is installed.

To see RunGEM in action, double-click on the Customized RunGEM (BMARIA-H_2O ICGE model) icon on your desktop (see Figure 5.1A).

RunGEM uses a tabbed notebook or card index interface. The pages, Picture and Text, contain general information about the model. Model/Data page contains information about files used by the BMARIA-H_2O ICGE model. For simulations, the last pages Closure - Shocks - Output files - Solve - Results are usually accessed in that order (from left to right).
Take a look at RunGEM's Model/Data page (Figure 5.2A). It gives two pieces of information:

- The model is BMH2O.EXE, an executable program. This has been produced by the GEMPACK program TABLO using, as input, the text file BMH2O.TAB. To change the model specifications, you need to (a) edit BMH2O.TAB, and (b) run TABLO to make BMH2O.EXE. That procedure is not covered in this introductory document, and TABLO is not supplied with the Customized RunGEM package.
- There are five input data files. MDATA1.HAR contains the database with interregional input-output and parameters information. PDATA1.HAR contains data about population and labour force. WDATA.HAR contains data about water and raw water demand by sector and hydrographic region and parameters related to water demand (elasticities). Terminal_LR.HAR is a database used in closure. BMH2O.TAB is the code file of the BMARIA-H_2O model.

Figure 5.1A - BMARIA-H_2O initial page



In the Closure page (Figure 5.3A), there is a list of the exogenous variables in the currently selected closure. You can choose between several different closures when running a simulation. The panel below shows which variables are exogenous in the selected closure. RunGEM allows you to load different closures already prepared. To see this, use the Load Closure button to load the long-run closure file (BMH2O.CLS).

Figure 5.2A - BMARIA-H_2O model/data page

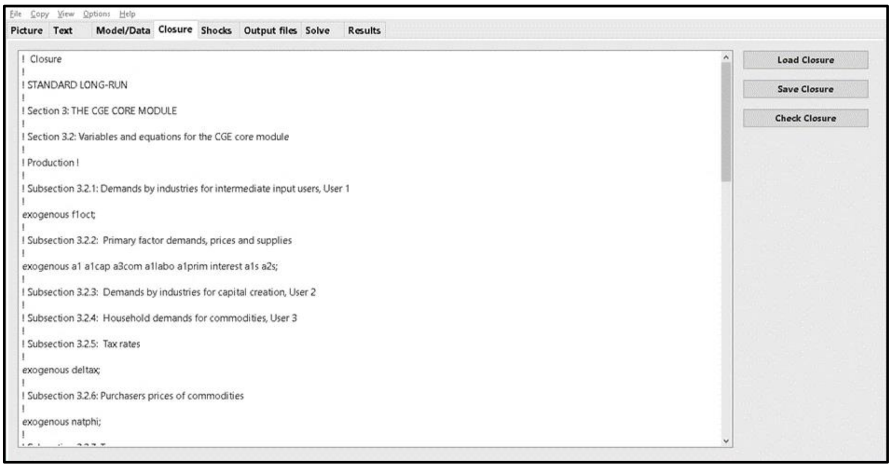
Model: C:\CRunGem\BMH2O\BMH2O.exe

Input Data Files:

Right click on any line below to see details of these files

```
File MDATA = C:\CRunGem\BMH2O\MDATA1.HAR ; !  File containing input-output tables and other data for the CGE core module
File PDATA = C:\CRunGem\BMH2O\PDATA1.har ; ! File Containing population data
File WDATA = C:\CRunGem\BMH2O\WDATA.har ; ! File containing water data
File Terminal = C:\CRunGem\BMH2O\Terminal_LR.HAR ; !  Terminal file for FRED and PRIOD
```

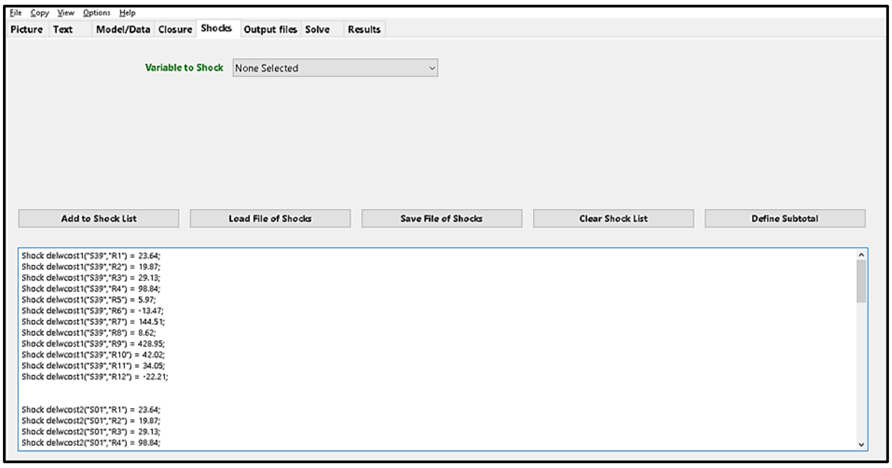
Figure 5.3A - BMARIA-H_2O closure page



```
! Closure
!
! STANDARD LONG-RUN
!
! Section 3: THE CGE CORE MODULE
!
! Section 3.2: Variables and equations for the CGE core module
!
! Production !
!
! Subsection 3.2.1: Demands by industries for intermediate input users, User 1
!
exogenous f1oct;
!
! Subsection 3.2.2:  Primary factor demands, prices and supplies
!
exogenous a1 a1cap a3com a1labo a1prim interest a1s a2s;
!
! Subsection 3.2.3:  Demands by industries for capital creation, User 2
!
! Subsection 3.2.4:  Household demands for commodities, User 3
!
! Subsection 3.2.5:  Tax rates
!
exogenous deltax;
!
! Subsection 3.2.6: Purchasers prices of commodities
!
exogenous natphi;
!
```

Now go to the Shocks page (see Figure 5.4A). Click on the Clear Shocks List button to remove whatever shocks are shown. Now you will specify a shock list. Copy the information present in SHOCK_LIST45.txt (RCP 4.5) or SHOCK_LIST85.txt (RCP 8.5) and paste it into the edit box.

Figure 5.4A - BMARIA-H_2O shocks page



Variable to Shock: None Selected

```
Shock delwcost1("S39","R1") = 23.64;
Shock delwcost1("S39","R2") = 19.87;
Shock delwcost1("S39","R3") = 29.13;
Shock delwcost1("S39","R4") = 98.84;
Shock delwcost1("S39","R5") = 5.97;
Shock delwcost1("S39","R6") = -13.47;
Shock delwcost1("S39","R7") = 144.51;
Shock delwcost1("S39","R8") = 8.62;
Shock delwcost1("S39","R9") = 428.95;
Shock delwcost1("S39","R10") = 42.02;
Shock delwcost1("S39","R11") = 34.05;
Shock delwcost1("S39","R12") = -22.21;


Shock delwcost2("S01","R1") = 23.64;
Shock delwcost2("S01","R2") = 19.87;
Shock delwcost2("S01","R3") = 29.13;
Shock delwcost2("S01","R4") = 98.84;
```

Output controls the names of output files produced by the simulation. Don’t change anything now. Go to the Solve page of RunGEM (see Figure 5.5A). First, click on the Change button (the one with the Solution method before it). Click on Johansen to select Johansen’s method (or Euler/Gragg method). You will learn more about the different solution methods available later in this document. Now click on the Solve button. A “Please Wait” window will appear while the model is solved. Then RunGEM will show you a box telling you how long the solution took. Just press OK. The next natural step is to look at the results.

Figure 5.5A - BMARIA-H_2O solve page

Solution method :

Johansen: 1 step

Verbal Description: BMH2O simulations

The Help menu item gives access to extensive online help about RunGEM. Customized RunGEM is a slightly simplified version of RunGEM, so some of the options described there may not apply. There is a Help menu item, “Customized RunGEM Help”, dealing with these differences.

6. CONCLUSION

This work has computed the economic impacts from climate change and water availability in the Brazilian hydrographic regions using an ICGE model with a water module calibrated for the Brazilian economy. We evaluated two main channels of shock transmission, namely, Channel 1 linked to a change in the price of treated water and Channel 2 related to the capital demand to replace or save raw water. In our modelling, these two channels perform as endogenous ways of adaptation to climate change. The general equilibrium approach allows us to make systematic analyses about climate change impacts on the economy.

The results show a drop in real GDP driven by reducing household consumption and exports and increased imports. We conclude that the economic losses resulting from the effect of climate change on water availability are considerable and are equivalent to a reduction in GDP of BRL 12.3 billion (or US$ 5.2 billion) in the realistic scenario and BRL 29.7 billion (or US$ 12.5 billion) in the pessimistic scenario (year reference 2015). The low substitutability of water (low price elasticity of the water demand) in most user sectors turns price increases into direct shocks to the Brazilian economy. The simulations show that water-intensive sectors, such as “water and sewage”, “forestry production”, “agriculture”, and “livestock” are the main sectors impacted by climate change.

The drop in GDP in the hydrographic regions depends on the climatic shock, the region’s productive structure, and interregional trade relations. The hydrographic regions in the semi-arid Northeast of Brazil, where historically economic restrictions of a climatic nature have been observed (low precipitation), are potentially more vulnerable to water unavailability resulting from climate change. However, hydrographic regions more fortunate in climate projections, located in the South-Southeast of Brazil, can also be significantly affected. The economic interdependence between regions alerts us to the fact that the effects of climate change go beyond geographic borders.

Some lessons can be learned from our analyses. First, integrated models are robust tools capable of evaluating the economic impacts of changes in water availability resulting from climate change. Second, economic sectors and regions respond differently to water availability shocks. Their individual productive structures and economic interactions can determine the economic effects. This interdependence also determines virtual water flows. Third, the water and sewage sector can be highly affected by climate change. Given this, it is necessary to reduce water losses. In the long run, this implies (i) improvements in water distribution infrastructure, sewage collection and treatment (avoiding water leaks); (ii) implementation of reuse water systems; (iii) changes in production processes seeking greater efficiency in water use; and (iv) increased awareness aimed at a voluntary water saving. Fourth, it is necessary to reduce administrative conflicts around water management. In this case, political and social agents must seek agreements on their responsibilities in shared territories. Finally, it is necessary to create economic instruments aimed at paying for water resources. In other words, it is necessary to charge economic agents/sectors that use large amounts of water in their production process and later use the amounts collected in infrastructure actions and water bodies preservation.

Economic losses highlight the need for more effective management of water supply and demand. Some points can be mentioned. First, action is needed to protect areas around water springs and river courses. This involves (i) identifying degraded areas; (ii) protection of areas through fencing; (iii) recovery and preservation of the area with native plant species; (iv) monitoring; and (v) remuneration of agents who help with preservation actions (landowners and social organizations). Second, natural area conservation policies are needed. Increased soil cover contributes to regulate river flows as well. Third, it is necessary to reduce water losses. In the long term, this implies (i) improvements in water distribution infrastructure, sewage collection and treatment (avoiding water leaks); (ii) implementation of reuse water systems; (iii) changes in production processes seeking greater efficiency in water use; and (iv) increased awareness aimed at a voluntary water saving. Fourth, it is necessary to create economic instruments aimed at paying for water resources. In other words, it is necessary to charge agents/economic sectors that use large amounts of water in their production process and subsequently use the amounts collected in actions for preservation of the environment and water bodies.