Hydropower in Brazil through the lens of the water-energy nexus

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Thesis abstract

Brazil's high historical dependency on hydroelectricity, coupled with recent severe droughts in the Southeast and the Northeast, has unveiled water availability issues that affect the electricity sector. The relationship of water and energy and its importance is recognised in literature, but there is still scope for advancements regarding methods for the link between resources. By using the Water-Energy Nexus concept, this study suggests a model calculating evaporation and water consumption of hydropower, as well as performing a water budget analysis for individual reservoirs, states, and regions for the Brazil case study. The analysis is performed for 163 reservoirs for the time periods 2010-2016 and 2015-2049. The model was designed to overcome spatial and temporal issues that inhibit water models to be meaningfully linked to energy models. The time step for evaporation and water consumption is hourly, and daily for the water budget analysis, while political spatial boundaries are used, along with hydrological boundaries for estimating future projections of river flows. Detailed future climatic scenarios for the reservoirs were created to perform a future scenario analysis of the main hydropower system of Brazil. For every 1°C future increase in temperature, the average annual evaporation increase will be around 90mm. Seasonality is important since evaporation varies (69-151mm per month). Water footprint values increase in the future, reaching a high of 147-201 m3/MWh in the North. While, reservoir levels can periodically drop enough in the 2015-2049 timeframe, that electricity production will be impossible to even 30% of particular months in the Southeast and 35% in the Northeast. Furthermore, water availability through the use of capacity factors is proposed as a link with energy models, and an example is presented. Finally, results are discussed in order to offer insight regarding policy implications for the future of hydropower in Brazil and elsewhere.

Impact statement

This thesis tries to pinpoint and measure the criticality of the links between water and electricity in the case of hydropower in order to allow for better present and future planning and more efficient use of both these resources.

The main benefits inside academia are advancements in terms of novel methodological contributions, since a water model estimating evaporation, water footprint, and performing a water budget analysis of hydroelectric reservoirs for Brazil was constructed, with energy modelling needs in mind. The modelling and analysis are performed for 163 large reservoirs (218 in total were considered) in the country, overcoming fundamental conceptual differences between water and energy models by aligning models in spatial and temporal terms.

Perhaps the single most important aspect when it comes to knowledge is its dissemination. Parts of the work done in this thesis have been presented in conferences in Brazil, the USA, Portugal, Croatia, and Slovenia, as well as in MSc classes at UCL's Institute for Sustainable Resources. Additionally, most of the work has already been published in journals, with the remaining parts of the work to be included in future journals as well. It is my conviction to pursue producing and disseminating my findings for years to come for the benefit of society, and for this reason I would like to apply this methodology to other case studies, especially in countries in the Global South, and include other resources (like food) that could be important depending on the particular case study in question.

The benefits outside academia include lessons learned about Brazil's electricity future in terms of water availability and specific recommendations that have practical value since they can be used for policy making, which in turn would benefit the public since it would lead towards improved water and energy security in Brazil. This can have impacts on improvements of surrounding ecosystems and societies, therefore improving quality of life to a

certain extent. More specifically, the metrics chosen (evaporation, water footprint, water budget) are simple to comprehend by non-experts, and the water model code is available upon request. In terms of policymaking, the relatively simple metrics used, can create an understanding of what is "normal" and "acceptable" in terms of water and electricity links in hydropower.

The results and the analysis performed in this thesis could help in terms of current assessment of hydroelectric reservoirs, evaluating their effectiveness under different water availability scenarios. Research organisations would particularly benefit, while the analysis could provide a different angle for industry that could improve planning of future hydropower plants. Also, the analysis could be used to address regulatory policies in Brazil. Furthermore, the methods employed in the thesis are replicable, and they would particularly benefit South American and African countries that either depend on hydropower or are planning on such investments. The benefits of the work could be local, since the analysis was performed for individual reservoirs, but also on a regional or national scale. The work has in part already been shared with the university of Rio de Janeiro and it is hoped that following future publications in esteemed journals, in collaboration with experts in different disciplines, the results and conclusions of this work will reach further into Brazilian politics and potentially assisting in public policy design regarding hydropower.

Modelling of interactions between resources can be fairly complicated, and this thesis attempted to provide a better understanding of water and electricity connections, which could to a certain extent change perceptions regarding the value of water in hydropower, and hopefully embed the value of water and other resources into culture.

Publications

Semertzidis T., Bleischwitz R., Spataru C. (2019) The water-energy nexus of Brazil's hydropower, Factor X chapter *(in process of publication)*

Semertzidis T., Spataru C., Bleischwitz R. (2019) Water budget analysis of hydroelectricity in Brazil, *Proceedings of the 1st SDEWES Latin American Conference (currently under review by the Journal of Cleaner Production)*

Semertzidis T., Spataru C., Bleischwitz R. (2019) The nexus: Estimation of water consumption for hydropower in Brazil, *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 7, issue 1, pp. 122-138.

Semertzidis T., Bleischwitz R., Spataru C. (2018) Cross-sectoral integration of the Water-Energy Nexus in Brazil, *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 6, issue 1, pp. 114-128.

Semertzidis T. (2015) Can energy systems models address the resource nexus? *Energy Procedia*, 83, 279-288.

Acknowledgments

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AEZ	Agro-Ecological Zones land production planning model
ANA	Agência Nacional de Águas (Brazilian National Water Agency)
ANEEL	Agência Nacional de Energia Elétrica (The Brazilian Electricity Regulatory Agency)
AQUASTAT	FAO's information system on water and agriculture
BRIICS	Brazil-Russia-India-Indonesia-China-South Africa
CGE	Computable General Equilibrium
CLEW	Climate Land Energy and Water
EIA	Energy Information Administration
ENSO	El Niño Southern Oscillation
EPE	Empresa de Pesquisa Energética (Brazilian Energy Research Company)
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Models
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IBGE	Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics)
IEA	International Energy Agency
INMET	Instituto Nacional de Meteorologia (Brazilian National Institute of Meteorology)
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
IWRM	Integrated Water Resources Management
LEAP	Long-range Energy Alternatives Planning system
MARKAL	Market Allocation
MDG	Millennium Development Goals
MME	Ministério de Minas e Energia (Ministry of Mines and Energy)
NAO	North Atlantic Oscillations

OECD	Organisation for Economic Cooperation and Development
ONS	Operador Nacional do Sistema Elétrico (Brazilian Electric System National Operator)
OSeMOSYS	Open Source Energy System Model
PDE	Plano Decenal de Expansão de Energia (Brazilian National Ten Year Plan for Energy)
PDO	Pacific Decadal Oscillation
PNE	Plano Nacional de Energia (Brazilian National Energy Plan)
PNRH	Plano Nacional de Recursos Hídricos (Brazilian National Policy of Water Resources)
RCM	Regional Climate Models
SDG	Sustainable Development Goals
SINGREH	Sistema Nacional de Gerenciamento de Recursos Hídricos (Brazilian National Water Resources Management System)
SST	Sea Surface Temperature
TIMES	The Integrated MARKAL EFOM System
UN	United Nations
USGS	United States Geological Survey
WASA	Model of Water Availability in Semi-Arid Environments
WEAP	Water Evaluation and Planning system
WEN	Water-Energy Nexus
WEO	World Energy Outlook

Chapter 1. Introduction

"For only what is rare is valuable; and water, which, as Pindar says, is the 'best of all things', is also the cheapest." – Plato, Euthydemus (384 BC)

Even 2,400 years ago people contemplated the paradox of water being very valuable to life, but being treated like it is infinite. Since those times, several people have dwelled about the paradox of value, using water as the prime example. One of the most famous ones was the economist Adam Smith in his classic work *"Of the Origin and Use of Money - An Inquiry into the Nature and Causes of the Wealth of Nations"* in 1776. In his diamond-water paradox, he observed that although water is significantly more useful than diamonds in terms of surviving, diamonds have a much higher exchange value. The word value can be deceiving, and so Smith differentiates its two meanings into "value in use" and "value in exchange", and argued that things that have the greatest value in use, usually have very little value in exchange, and vice versa. With this example Smith gave an explanation about the market dynamic of supply and demand at the time, which resonates to a certain extent up until our days.

Water is considered a common pool resource (Ostrom, 1998) and water resources are considered a public health and welfare issue. Due to climate change, population rise and human activities, water stress has increasingly become an important political issue, but even so, water management and data could be improved. Data on water availability, be that surface water or groundwater, evaporation estimates, etc. are sometimes not available in a lot of countries, or their periodical estimation creates problems in terms of modelling and in consequence puts water at a political disadvantage in terms of priority decision-making. This does not apply to energy for example, which is reflected in economic, social and political aspects. A parallel can be drawn to Plato's "*Euthydemus*" again, since in the book,

Plato describes through the words of Socrates the logical fallacies of the Sophists. Two brothers, Euthydemus and Dionysodorus attempt to entangle Socrates in his arguments and demonstrate their philosophical superiority, while Socrates argues that wisdom is good for man, and ignorance is the only evil. If the lack of data on water, which hinders the ability to adequately understand its processes and what they mean, were a form of ignorance, then perhaps wisdom would be a sufficiency of data coupled with the understanding of what this data might mean for the value of water? Moreover, what happens when water is not assessed alone, but along with other resources?

1.1. Context

Water issues are numerous and it would be difficult to address the subject of the value of water in a single thesis, nevertheless, it is possible to address certain aspects of it and therefore it is important to generate the context within which certain water issues will be examined.

The population of Earth is rising, while at the same time billions of people are improving their lifestyle through increased consumption rates. The rate of consumption of resources could, and in all probability will, create resource competitions in the coming decades. Some of the key resources include water, energy, food, land, and minerals, and it is important to manage potential dangers concerning them (Andrews-Speed et al., 2012). Water in particular has been in the discussion since it is directly affected by climate change, which in turn is one of the greatest problems of our times. By 2011, 89% of the world population had 'improved drinking water' (for which the definition is: "…*includes sources that, by nature of their construction or through active intervention, are protected from outside contamination, particularly faecal matter*" (WHO, 2013)), while 55% also had piped supply. At the same time, 768 million people did not use an improved source of drinking water, while 185 million relied on surface water to meet their daily drinking water needs (WHO and UNICEF, 2013). However, water

availability does not only affect humans directly, but also indirectly by affecting availability of other resources. The energy sector in particular is highly dependent upon the availability of water, since the energy industry along with mining account for 19% of the world's water withdrawal (Frenken & Gillet, 2012). Nearly all aspects of energy supply are impacted by water availability, including electricity production, future capacity siting, costs, technologies, etc. (U.S. DOE, 2013). The International Energy Agency (IEA) had forecasted in 2008 that the world will demand 40% more energy in 2030 than in 2007, which has not changed since and has been a continuing trend even in subsequent publications (IEA, 2013), when electricity demand in particular was projected to grow by 70% from 2010 to 2030 (Granit, 2010; IEA, 2013). Concurrently, global water demand will likely rise by between 35% and 60% between 2010 and 2025, and could double by 2050 (Foresight, 2011). Electricity in particular will likely consume three times more water in 2095 as compared to 2005 (Davies et al., 2013).

The above-mentioned forecasts seem dim for the global future, but these effects are not uniformly spread. All regions and countries have their own issues to deal with. As seen in figure 1.1, North African, Asian and South European countries, along with Australia, the USA and Mexico are projected to have high to extremely high water stress (which is defined as: "*the water available to agriculture, domestic, and industrial users that is withdrawn annually*" (World Resources Institute, 2015)) issues by 2040. At the same time, some South American countries like Chile and Peru are also projected to have high to extremely high water stress, while countries like Brazil and Paraguay have a very low probability (<10%) for water stress by 2040 (World Resources Institute, 2015).
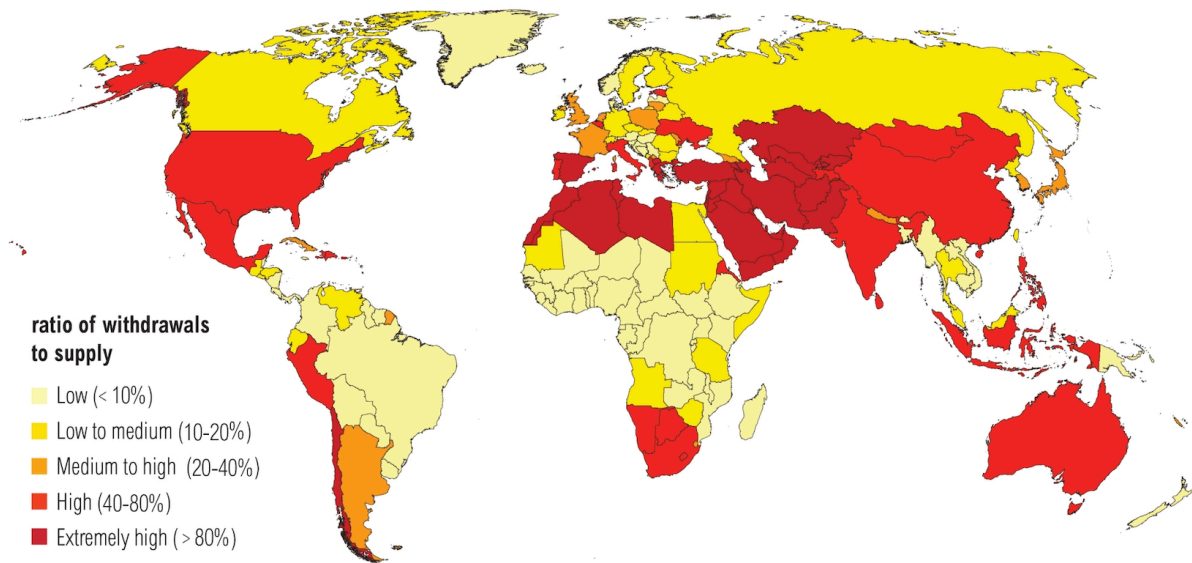
Figure 1.1 – Water stress by country in 2040 (Source: World Resources Institute, 2015)

Nevertheless, in 2014-2015 Brazil faced its worst drought in 40 years. As a consequence, inhabitants in the large southeastern cities like Rio de Janeiro and São Paulo, the agriculture sector, but also hydroelectricity production, suffered due to the lack of water, and blackouts were a common phenomenon for months. Consequently, and to alleviate the lack of electricity, the country burned more fossil fuels. This was not the first time Brazil faced a drought, nor is it going to be the last, since their frequency and intensity are projected to increase in the future (World Bank, 2013). Water availability has been an issue for the northeastern region of the country for decades, but it seems that it might become an issue for most of the country. These issues will be further discussed in the introduction of Brazil as a case study. Hydroelectricity in Brazil has historically provided around 70% of the country's needs, which coupled with the possible drop of water availability raises questions about the viability of the electricity sector. Despite the risks, Brazil is expected to invest further into hydropower, especially in the North (Westin et al., 2014). Recent additions to the hydropower sector include the construction of the large-scale hydropower plants in Santo Antonio (3,150MW) and Jirau (3,300MW) on Madeira River, and Belo Monte (11,233MW) on Xingu River, all three being in the Amazon Basin (Andrade Guerra et al., 2015).

The fact that climate change will inevitably affect water availability all over the planet one way or another, with the recent drought in Brazil being an example, coupled with the country's plan for further investment in hydropower, but also their backup plan that is thermoelectric power, seem contradicting. Decreasing water availability directly impacts all aspects of electricity supply. Hydropower and thermal plants with once-through cooling are technologies particularly exposed to water availability (IEA, 2012a). In a future of reduced water availability, but also increased demand for both water and electricity, competition for water can rise significantly and cause a variety of problems in the country. Is Brazil's hydropower resilient under extreme weather conditions? Are all regions in the country affected the same way? If not, what does the future hold for Brazil? These are questions that need to be investigated.

1.2. Possible way forward and hypothesis

There are, and have been through the years, frameworks trying to address multiple issues of resources. Recently, the 17 Sustainable Development Goals (SDGs) (Sustainable Development Solutions Network, 2015) and their 169 targets are trying to raise awareness and provide a useful framework within which governments can work towards improvements of various aspects of life. SDGs have water and energy as separate goals, but there are links between them. Although, there are certain omissions concerning such links, and one important one is that water consumption of energy is not mentioned in the original document. Subsequent work by Nerini et al. (2018) and McCollum et al. (2018) has been aimed at linking various SDGs, which needs to be incorporated into the original work. Also, the point of focus is national, whereas water availability is a highly local issue. Nevertheless, it is important to operate within a framework, a concept that allows taking into account important aspects of resources, allowing for synergies and helping to avoid competition.

An approach taking more than one resource into account at any one time and investigating multiple levels of connectivity could in theory lead to more optimal allocation of resources, decreased susceptibility of the electricity sector to water availability, and better social and economic development conditions. The resource nexus, which will be properly discussed later on, could in theory fit the role of such a concept/approach, since it attempts to integrate important aspects of sustainable development. Water and energy interconnections, or the Water-Energy Nexus (WEN), are part of the overall resource nexus thinking, and it is time that they are treated together rather than separately and as distinct resources with their ensuing issues. This way of thinking could help into identifying critical tensions between the two resources, highlighting possible synergies, and in turn providing solutions to pressing problems.

Brazil's future in terms of hydropower is a subject that deserves to be analysed in detail, since supply of electricity and appropriate water management are at stake, both at present and in the future. Although Brazil is not projected to have serious water stress issues, unlike other parts of the world, nevertheless droughts like the one in 2014-2015 can have serious effects not only in terms of water availability itself but also in terms of electricity supply. This becomes even more of an issue in the Southeast of the country, due to its large population, and the Northeast, due to an extended droughts precedent. Taking into account that the energy plans of the country include new hydropower to be installed, especially in the North of the country where the Amazon rainforest is, a number of questions regarding sustainability arise.

Trying to tackle such large and difficult concepts needs to be based upon empirical evidence, and this evidence could in theory be provided by results from the detailed analysis of certain situations, in this case upon water and energy analysis of hydropower plants. Such analyses are usually achieved through indicators and modelling. Modelling of water with electricity in

mind and vice versa is challenging, and traditional models do not perform, nor are they designed to take some important matters into consideration.

More specifically, there are knowledge gaps in terms of evaporation estimates, and therefore detailed water availability analysis. This gap further translates into gaps in terms of water consumption of hydropower, which is a highly local issue, and generic values that are being used extensively in literature can lead to false results in terms of water availability and the performance of hydropower plants. It is important to be precise as to which regions, states, and individual reservoirs are efficient in terms of water use and electricity production, and which are not, both at present and in the future. There have been modelling exercises attempting to perform such analyses, but none for the whole large hydropower system of Brazil and at fine spatial and temporal detail, which is an important knowledge gap. Indeed, spatiotemporal scales of water and energy models are a prohibiting factor when trying to investigate water and energy in conjunction, which will be further discussed in chapter 3.

Another important question is if it makes sense to model the country as a whole or in separate regions, states of even individual reservoirs/power plants. Finally, metrics such as evaporation and water consumption of hydropower are simple to understand, no matter the audience, but at the same time they are important and could form the basis for better public understanding and decision-making processes, and deserve further analysis, which is at present missing for the whole Brazilian large hydropower system.

Hence, the hypothesis of this thesis is that a spatiotemporal analysis of water availability and water consumption of hydropower could pinpoint the criticality of the links between water and electricity, which would firstly improve the understanding of the problems at hand, and pave the path for better management of water, improved efficiency of both water and electricity, and improved decision-making in terms of hydropower in Brazil.

The analysis of the WEN has an overall goal of advising towards securing supply for both water and electricity, and to inform policy towards a more sustainable future for both resources in relation to hydropower.

The main novel contributions of this thesis are investigating hydropower in Brazil under the prism of the WEN, estimating evaporation, water consumption, and water availability for hydropower, improving on existing methodologies, and finally analysing what the results mean in terms of Brazil's electricity future.

1.3. Aims and objectives

Based on the literature review of water and energy (chapter 2), as well as the gaps identified in methods and approaches to address the WEN for hydropower (chapter 3), the following aims and objectives were devised and are presented here in order to have a better grasp of what is to be accomplished in this thesis:

Aims:
- Build a water model that is able to investigate water consumption of hydropower plants in Brazil, and assess water availability for electricity production for the period 2010-2016
- Design an appropriate link between the built water model and a suitable energy model, create future climatic scenarios, and perform a combined analysis providing projections of water consumption, water availability and generation capacity of the country for the period 2015-2049
- Propose improvements of methods, and make recommendations about Brazil's future energy plans, also offering a more general context

Objectives:

- Perform granular spatiotemporal modelling of evaporation, water consumption (water footprint) and water budget analysis of hydropower for each reservoir/power plant, state and region in Brazil, on an hourly basis for the first two variables and daily for the third for the period 2010-2016

- Overcome spatiotemporal water-energy linking issues in a simple and replicable manner, devise climatic scenarios taking locality and actual past climatic conditions of individual reservoirs into account by improving data downscaling techniques, and perform granular spatiotemporal modelling of evaporation, water consumption (water footprint) and water budget analysis of hydropower on a regional level, on an hourly basis for the first two variables and daily for the third for the period 2015-2049. Also, perform an annual analysis of generation capacity on a regional level by soft-linking the water model to a suitable energy model

- Discuss the results of the historical and future analysis, pinpoint shortcomings of methods and propose improvements, and provide policy recommendations for the future of the electricity sector in Brazil, finally discussing the value of the work done in a non country-exclusive context

1.4. Structure of thesis

Chapter **2** contains the introductory literature review about water and energy matters. It describes how water and energy are intrinsically linked and how water availability impacts energy production. The SDGs and other frameworks are discussed concerning their relation to water and energy, and the factors making up useful indicators for water and energy are examined. The concept of the Water-Energy Nexus is introduced, firstly by presenting the resource nexus concept, and also what exactly the WEN entails is explained. Specific interlinkages, metrics, and important

definitions are presented, and the importance of water consumption of electricity generation technologies in particular is introduced.

Chapter **3** reviews existing methods and approaches for water and energy. The gaps of existing methods and approaches are presented, and the three possible approaches to address the WEN in a modelling framework are introduced. Following this, the review concentrates on specific issues that have already been recognised, firstly by investigating evaporation, its issues, and methods for its estimation. Next, the water footprint indicator is discussed along with methods for estimating it. Continuing with water related matters; the water budget analysis is introduced, explaining the importance of assessing the operation of hydroelectric plants through such an analysis, specifically defining it and how it works. Finally, the ability of energy models to address the WEN is investigated, different tools are categorised, their limitations are discussed, and specific tools that have been used to address the WEN are presented.

Chapter **4** describes the methodology that will be used to do the analysis of the WEN for hydropower in Brazil. Firstly, the framework followed is presented, along with a diagram showing the different inputs, outputs, and processes involved. What follows is the equation used (spherical law of cosines) to determine the nearest meteorological stations to reservoirs. Then, the main equation for evaporation estimation (Penman-Monteith) adjusted for deep lakes is presented, along with its accompanying 26 equations, which make up the first part of the water model. The 8 different kinds of inputs are also presented, along with their sources. The equation for estimating water footprint is then presented. Subsequently, the equation for the water budget analysis is presented, coupled with the algorithms used setting the operation rules of the reservoirs, along with the outputs of the second part of the water model. Lastly, the equations of the energy-water-land IDA3 model (the chosen model to link with the water model) are presented, which will provide future generation capacity and power supply of the Brazilian electricity system.

***Chapter* 5** exhibits the case study of the thesis, and namely Brazil. Firstly, some general information about Brazil is presented; along with the main issues the country is facing regarding water and electricity. The 2014-2015 drought, existing regulations, and future plans are discussed. Subsequently, the water and energy sectors of Brazil are analysed with appropriate graphs and tables to have a picture of the situation in the country. Following, there is a hydroelectric analysis in terms of capacity and reservoir area, setting the scene for the hydropower analysis in the following two chapters. Methods and models used in literature to address the WEN in Brazil are then presented. After the case study analysis, the input data and assumptions made specifically for Brazil for the evaporation and water budget analysis calculations are presented in detail.

***Chapter* 6** presents the historical results and analysis for Brazil, performed for the periods 2010-2016 for evaporation and water footprint, and 2010-2015 for the water budget analysis. The analysis for evaporation was done per region, state, and individual reservoirs, presenting annual and monthly results of evaporation (mm) and volume of water evaporated (km³). A comparison between results for specific reservoirs of this analysis and the only other existing one performed for all hydropower reservoirs in Brazil done by the Brazilian Electric System National Operator (ONS) is then presented, followed by a sensitivity analysis of evaporation. The water footprint analysis was done per region, state and individual reservoirs, presenting annual and monthly results of water footprint (m³/MWh). Subsequently, water budget analysis results are presented, which were done per region, state, and individual reservoirs. The results include: aggregated volume level of reservoirs, aggregated percentage of days when the reservoir level was lower than the minimum useful capacity, aggregated difference of actual outflow and minimum safe outflow, and aggregated difference between precipitation and evaporation. Finally, the method and sequence followed to prepare a link between this water model and energy models is presented, which is based on the correlation of outflow and capacity factors.

Chapter **7** presents the future scenarios results and analysis, performed in this thesis for the period 2015-2049. At first, the way the climate scenarios were developed is presented, discussing meteorological phenomena in Brazil and future projections for the country. The role of General Circulation Models (GCMs) and the need for downscaling their projections in order for them to be used in the water model (on a specific power plant/reservoir level) is discussed. Consequently, eight devised climate scenarios are presented, four of which are used for the analysis. Then, energy scenario work done for Brazil in literature is discussed, along with the scenarios (stemming from past IDA3 work) to be used in the thesis. Furthermore, the regional capacity factors for hydropower estimated by the water model are presented, which act as the link between the water model and the energy-water-land IDA3 model. Subsequently, regional evaporation, water footprint, and water budget (annual and monthly results) for the period 2015-2049 are presented for four of the climatic scenarios that have been devised. Finally, the detailed future capacity factors, based on the water availability analysis of the water model, are used as input for the IDA3 model and the results for water and energy are presented.

Chapter **8** discusses findings from the previous two chapters. What the results from the historical analysis, and also the future projections, of evaporation, water footprint, and water budget actually mean by themselves for individual reservoirs, for states and regions, but also for Brazil as a whole. The importance of analysis done in at least a regional basis is discussed, along with the significance of seasonality. The value of water availability for electricity in the country is highlighted along with the need for better management, since climate change is not the only source of future problems for both water and electricity security. Furthermore, the implications of these findings in a more general sense is discussed, along with the lessons learned that could prove to be of value for other countries. Finally, the correlation of the WEN with other frameworks and their contribution to policy is discussed, providing more specific policy recommendations.

***Chapter* 9** concludes the thesis, by detailing how it has addressed the research aims and objectives. The specific contributions to knowledge are presented in summary, along with the strengths and limitations of the work done. What follows the brief summary of important findings is the identification of particular pathways that could be followed in future work.

Chapter 2. Water and energy review

Chapter 1 set the scene of the thesis and presented the aims and objectives. In this chapter the link between water and energy will be further explored, frameworks that have been and are being used, will be investigated, and what makes a useful indicator for water and energy will be discussed. Furthermore, the concept of the Water-Energy Nexus (WEN) will be analysed in detail, starting with the concept of the resource nexus, and discussing interlinkages, metrics and definitions. Lastly, the importance of water consumption of electricity generation technologies will be analysed, which will allow for further investigation of methods and approaches for the WEN in chapter 3.

2.1. The link between water and energy

The growing demand for natural resources and global warming has raised discussions and disputes in politics over the years, however there are some undeniable realities that need to be acknowledged. Billions of people are moving out of poverty (UNDP, 2018) and toward a better lifestyle, which translates into higher consumption rates, leading to substantial growth of global resource consumption in the coming decades. At the same time, climate change impacts depend on the amount of climate change that occurs, but also the effectiveness of development in reducing exposure and vulnerability. Timely decisions in a setting of incomplete knowledge are a challenge in effectively dealing with climate change, which may cause degradation of ecological processes, leading to losses in human well-being, and threatening human security. Additionally, climate change is projected to affect various resources (water, energy, food, etc.), while for example energy sources and technologies could be affected by water flows (IPCC, 2014).

Water has been the subject of much discussion, since it is directly affected by climate change and in turn it directly affects humanity. Thus, it is worth

having an idea of how much water actually exists on Earth. The hydrosphere (all water on Earth) is stored in different reservoirs in the geosphere and namely in the atmosphere, in water bodies primarily consisting of liquid and solid water (oceans, lakes, rivers, snow and ice), and also in wetlands, soils and groundwater bodies.
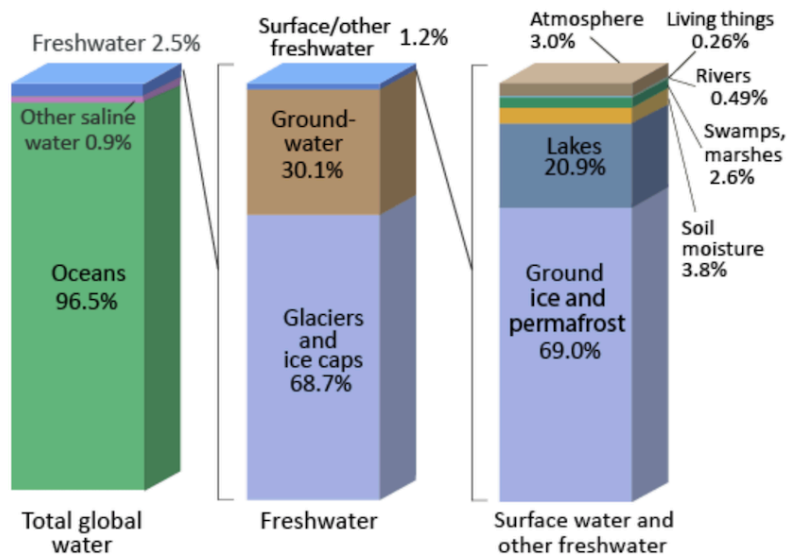
Figure 2.1 – World fresh water resources (Source: Shiklomanov, 1993)

As seen in figure 2.1 from the total global water, 96.5% is in the oceans, and freshwater accounts for 2.5%. From this, 68.7% is stored in glaciers and ice caps, 30.1% in groundwater, and surface freshwater accounts for 1.2%. Furthermore, lakes possess only 20.9% of this water, and rivers 0.49%. However it needs to be noted that there is great uncertainty about some of these values, like for example the volume of fresh groundwater, which ranges from 7 to 23 million km^3 (UN WWAP, 2003; Vörösmarty et al., 2005). In terms of sustainable use of a resource, what is important is not the storage however, rather the fluxes that are relevant. Nevertheless, in general surface water resources (river flows and lake levels) are not adequately monitored and hydrographic networks are shrinking worldwide. Knowledge about the historical development and current state of groundwater resources worldwide is even scarcer than surface water resources (Kundzewicz & Döll, 2009).

Climate cycles and water are inextricably linked. Rising temperatures will accelerate the movement of water, increasing both evaporation and precipitation. The expected impacts will include, among others, falling average surface water flows, higher surface water temperatures, sea level rise that will contaminate freshwater supplies, and droughts and floods that are more frequent and more severe (Bates et al., 2008; IPCC, 2014). The more frequent incidents of extreme weather events, be it heat waves or intense and persistent precipitation, have raised concerns that human activity might have caused an alteration of the climate system, which in turn is behind the severity of such events. There is also the belief that the climate system will continue on the same path of change due to human activities and that humanity will have to face an increased number of extreme events (Yang et al., 2012).

Over the last 30 years, 1.8 billion people have experienced abnormal rainfall episodes each year, whether it was an unusually dry or wet year. Over this period, 300 million people every year have suffered destructive rainfall events that were supposed to be rare enough to only happen twice in a century in a given location. From the affected population, more than 85% are living in low to middle income countries. These developing nations usually lack the necessary infrastructure to safeguard them from shocks (Damania et al., 2017). These precipitation extremes, either excess or deficit, can be hazardous to human health, societal infrastructure, and livestock and agriculture. While seasonal fluctuations in precipitation are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), flooding or droughts can have serious negative impacts. These are complex phenomena and often the result of accumulated excesses or deficits of other compounding factors such as spring snowmelt, high tides/storm surges or changes in land use (Met Office, 2011).

Water availability though does not only directly affect humans, but also indirectly by affecting other resources important to humans, like energy. The main challenge of the energy system worldwide is to simultaneously

achieve greenhouse gas (GHG) emissions reduction targets, along with energy security and meeting a growing demand for electricity for modern day living standards (IEA, 2012b; Nogueira et al., 2014). But, the energy sector is vulnerable to water constraints, and the vulnerabilities depend on geography and different types of energy production. The energy industry along with mining account for 19% of the world's water withdrawal (agriculture: 70% and municipal networks: 11%) (UN FAO, 2012). Driven by growing population and economic growth, the energy sector is expected to expand, which will further increase the pressures on fresh water demand in many nations (Zhang, 2013).

Decreasing water availability directly impacts nearly all aspects of energy supply, and namely how electricity is produced, where future capacity might be sited, production cost, types of generation and cooling technologies and their costs, the methods and costs of extraction, production and delivery of fuels (U.S. DOE, 2013). Particularly thermal plants with once-through cooling and hydropower can be exposed to fluctuations in water availability (IEA, 2012a). Bioenergy production can also be affected. As a consequence, in water scarce regions, competition for water between energy production and other uses will also increase, indirectly not allowing for economic development and stability (WEF, 2014). Recent examples of extreme weather events impacting on energy supply are presented in table 2.1.

Location	Weather event	Consequences
Spain (2004-2005)	Drought	Reduced hydroelectric production resulting in losses of $123 million
Germany (2006)	Excess river temperatures and low stream flow in the Isar river	The Isar nuclear power plant cut production by 60% for 14 days
France (July 2009)	Long-lasting heat wave	1/3 of nuclear capacity shut down forcing import electricity from neighbouring countries (estimated damage €300 million)
Brazil/Paraguay (November 2009)	Heavy rains and winds	20 turbines of the world's second largest hydroelectric dam shut down. An estimated 87 million people were affected by power loss
China (2011)	Drought	Limited hydro generation, higher coal demand (affecting prices), forcing implementing strict energy efficiency measures and electricity rationing
USA (2011)	Drought	Power emergencies in Texas due to a large number of unplanned power plant outages
India (2012)	Delayed monsoon	Electricity demand rose and hydro generation reduced, contributing to blackouts lasting two days and affecting 600 million people
Chile (March 2015)	Torrential storms with the equivalent of 7 years worth of rain in 12 hours	Left thousands without electricity due to impact on due to transmission lines and dam flooding

Table 2.1 – Examples of worldwide extreme weather events and their consequences (Adapted from: IEA, 2012a; World Energy Council, 2015)

Currently, over 1.3 billion people worldwide still lack access to electricity (IEA, 2012b). At the same time, 2.8 billion people live in areas of high water stress and 1.2 billion live in areas of physical scarcity, while it is estimated that by 2030 nearly half the world's population will be living in areas of high water stress affecting energy and food security (WWAP, 2012). It was forecasted (IEA, 2008; IEA, 2013) that the world economy will demand 40% more energy in 2030 compared to 2007, whereas the demand for electricity was expected to grow by over 70% between 2010 and 2030 (Granit, 2010). Energy demand in 2018 grew by 2.3%, which was the fastest pace this

decade. Electricity demand grew by 4% in 2018 to more than 23,000TWh, which puts electricity towards a 20% share in total final consumption of energy. The increase of power generation was responsible for half of the growth in primary energy demand, and renewables were a major contributor accounting for nearly half of electricity demand growth (IEA, 2019). At the same time, total global water demand (in terms of water withdrawals) could rise by between 35% and 60% between 2010 and 2025, and could double by 2050 (Foresight, 2011). In figure 2.2 by Walsh et al. (2015) we can see the projections for water demand from 2000 to 2050 for Organisation for Economic Cooperation and Development (OECD) countries, Brazil-Russia-India-Indonesia-China-South Africa (BRIICS), and rest of the world, and the increasing demand of water for electricity. Although it needs to be noted, that these publications do not make any reference to water quality, which is an important issue.

According to World Energy Council estimates (2010), emerging economies like China, India and Brazil will double their energy consumption in the next 40 years. Also, in Latin America in general, it is expected that the increased production will come from non-conventional oil, thermal, and gas sources and the amount of electricity generated is expected to increase fivefold, while the amount of water needed will triple (World Energy Council, 2010).
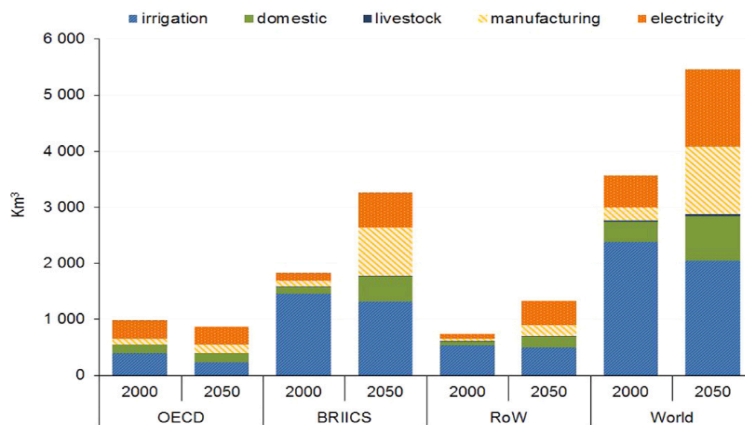
Figure 2.2 – Increase in water demand by 2050 (Source: Walsh et al., 2015)

Particularly for electricity, Davies et al. (2013) in figure 2.3 show in one of their scenarios that global consumptive water use by electric power generation could triple from 2005 to 2095. The main water consumption increase is due to hydroelectricity. At the same time the same does not hold true for water withdrawal, mainly due to decreased coal usage, which even sees a decrease before increasing to similar values to 2005 again.
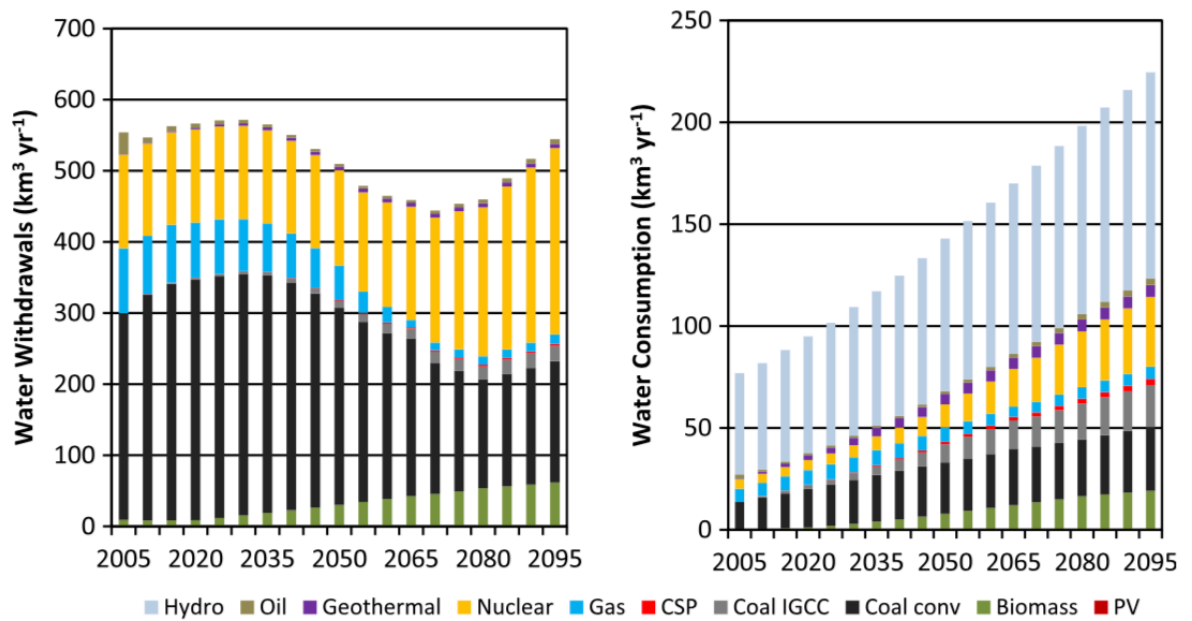
Figure 2.3 – Global water consumption by electricity generation technology (Source: Davies et al., 2013)

2.2. Sustainable Development Goals, other frameworks, and indicators

In September 2015, 193 members of the United Nations (UN) adopted the new 2030 Agenda for Sustainable Development. The Agenda 2030 is the successor of the UN's Millennium Development Goals (MDGs), and it consists of 17 Sustainable Development Goals (SDGs) with 169 targets. The member states of the UN have all committed to implement these by 2030. What is new in the SDGs in comparison to the MDGs is that energy was not explicitly part of the MDGs, whereas it is one the 17 SDGs. Nerini et al. (2018) identified 113 targets that require actions to change energy systems, and 143 targets where there is evidence of some sort of relationship between

them in order to achieve SDG7. 'Energy systems' is a broad term and the actions required are diverse and could refer to addressing climate change, reduce deaths from pollution and end certain human rights abuses. This broad spectrum makes it clear that in order to improve energy systems globally, substantial efforts are required.

Energy systems produce around 60% of anthropogenic emissions of GHGs (IPCC, 2014b) and consequently are one of the main points of focus to combat climate change and its impacts (SDG 13). Investing in low-carbon systems (target 7.2, 7.a) is vital for the effort towards the 1.5-2°C mitigation goal of the 2015 Paris Agreement on climate change. Reliable energy services strengthened by research, technology, and infrastructure (7.1, 7.a, 7.b) can help towards adaptation, natural hazard reduction and resilience (SDG 3, 9, 13). At the same time, use of natural resources by energy systems has impacted on ecosystem services that support food and water security (SDG 2, 6), and human health (SDG 3). The need for more energy supply due to growing demand must be counterbalanced by protection and restoration of critical ecosystems and support development in other sectors. This will depend on technology, behaviour and policy changes that will decrease the natural resource-intensity of energy systems (Target 7.3, SDG 12) in a broader effort to decouple adverse environmental impacts from economic growth (Target 8.4) (Nerini et al., 2018).

In theory, the SDGs are something worth striving for, but there are a few issues with them. Firstly, the SDGs have 232 indicators in total as of mid-2018. Even for western societies it is difficult to calculate so many indicators adequately, let alone for countries that lack the economic capacity to do so. Additionally, not all indicators are necessarily applicable to every country and although all indicators were created for a reason, not all of them are critical, but rather informative. One could also argue that a lot of SDGs are somehow connected to water and energy, but this should not turn into a quest to find links, rather concentrating on critical interlinkages and on how these can be measured adequately in a useful way. The SDGs do a good job

of identifying points of interest in general, but not an equally good job when it comes to methods for measuring specific indicators. When it comes to water in particular, withdrawal is mentioned, but consumption on the other hand is not explicitly mentioned anywhere. Indirectly, it could be said that water consumption is included in indicator 6.4.1. *"Change in water-use efficiency over time"*, but this is only if 'water-use efficiency' is taken to mean specifically water consumption, which is not necessarily the case. Another issue is that most indicators refer to the national level, which is not necessarily useful for water, since water issues are highly localised.

Nevertheless, the natural resource dependencies of water, energy and food systems, intertwined with environmental threats such as biodiversity loss, climate change and local air and water pollution, create a picture with complex trade-offs. The SDGs create a systematic way of looking at a lot of valid problems of our times and by understanding the complex links between the different SDGs and their targets (e.g. Nerini et al., 2018; McCollum et al., 2018), and also thinking and acting in a more systematic way, it will be possible to research how different goals affect each other within and between sectors. This way, researchers could improve their ability of supporting policymakers.

Another interesting framework when it comes to water in particular is the Integrated Water Resources Management (IWRM). This framework has received a lot of attention. IWRM came into light in the 1980s and is an "umbrella concept encompassing multiple principles", which aims at a more coordinated management of water resources (Benson et al., 2014). The IWRM is a process, which can theoretically assist towards the aim of dealing with water issues in a cost-effective and sustainable way. By recognizing all the characteristics of the hydrological cycle and its interactions with other natural resources and ecosystems, it is offering a rather holistic approach to management. It is also recognized that water is required for various purposes, functions and services, thereby making it clear that the demands placed on the resource and the threats to it need to

be taken into consideration. The definition for IWRM is "*a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (GWP, 2000). Such definitions can create discussion regarding specific wording like "equitable", which is not necessarily always defined the same way. This will be further discussed in section 2.3.

Furthermore, Pires et al. (2017) identified 170 indicators related to water use and management and assessed them with the help of an international panel of experts on the base of four sustainability criteria: social, economic, environmental, and institutional. It was argued that indicators could be more useful if organized in a coherent framework instead of individually as a simple collection of elements (something that the SDGs are trying to do). From the 170 indicators taken into account, only 24 complied with the majority of the sustainability criteria. Although these indicators were not assessed with a specific problem in mind, they nevertheless give an overall indication as to how useful they might be. The highest scored indicators in this study were the "water poverty index", the "climate vulnerability index", "water shortages" and "fraction of the burden of ill-health from nutritional deficiencies" (Pires et al., 2017). One of the 24 indicators that received a lot of attention was the "water footprint", because it allows a comprehensive view of the sustainability of water use and can be assessed within the IWRM framework (Pellicer-Martínez & Martínez-Paz, 2016). "Water footprint" is not the same as "water use", which is a general term, and this will be further explained in section 3.3. Pires et al. (2017) recommended further study of this indicator, especially aiming to overcome some calculation methods limitations as mentioned in Lovarelli et al. (2016).

2.3. What makes an indicator useful?

Firstly, it needs to be noted that the terms "indicator" and "metric" though not having the exact same definition, are used interchangeably in literature

meaning the same thing. Consequently, they are also used interchangeably in this thesis.

Generally, designing a more resilient future relies on decision-making that is informed by biophysical, social, and economic factors. The scientific community is a big proponent of the adoption of indicators for the evaluation and monitoring of progress towards sustainable development. In the same vein, international organizations also acknowledge the importance of indicators as influential decision-making tools. At the same time, the quality and reliability of indicators varies a lot and they need to be properly assessed based on appropriate criteria. But, what makes an indicator actually useful? Useful metrics should present relevant data that is summarized and have simplified a complicated system in a way that is easily understood by all decision-makers irrespective of their background. A good metric should not only measure an unsustainable trend, but also define and ensure sustainability (Pires et al., 2017).

Indicators/metrics serve two important purposes, management and accountability. The first one is necessary to sustain resources and stay on course, and the second to hold all stakeholders to the goals. It is also of great importance for indicators to be accurate and frequently reported, ideally at least once per year (Sustainable Development Solutions Network, 2015). When it comes to decision-making, the relevance of indicators is very important, even more so than other types of information, since they can be powerful policy decision tools (Nicholson et al., 2012). Indicators should present attributes that are relevant and comprehensible by decision makers and not only by a specialized audience (Klug & Kmoch, 2014). In a nutshell, indicators should be based on common sense and clear language.

More specifically on the links between water and energy, as the water and energy subsystems dangerously approach limits of some sort (be that biophysical, social, economic, and/or legal), their interactions more often than not become very sensitive and can affect parts of society in various

ways, some unexpected. For example, droughts can force regulators to make decisions that do not necessarily go in line with existing water laws, laws that were appropriate in times of resource affluence, but are inadequate in times of high water stress (King & Carbajales-Dale, 2016). This occurrence shows the discrepancy of critical indicators in times of resource affluence and resource scarcity, and thus the inadequacy of indicators in use.

Water resources management in particular is very complex, since it does not only deal with physical aspects of water, which are complicated enough on their own, but also with social and economic complexities. The management of water does not necessarily have expected outcomes, since small actions can have big outcomes and vice versa (Barbosa et al., 2017). Management of water is mainly dictated based on how scarce it is, either because of actual shortage, or because of poor quality. As long as water is of good quality and sufficient, its management seems to not be of importance, and its value in economic terms is very little. On the contrary, as scarcity appears, competition increases and the value of water increases as well, not only in economic terms (Hassing et al., 2009).

In the case of water management it is possible that the precautionary principle should be taken into account, since although there have been signs of what scarcity, or even abundance in the face of floods, can cause, it seems that a business as usual scenario in terms of management and long-term planning has been the norm. Water needs to be treated more prudently and it should not be wasted on low-value uses, but in the most beneficial way possible. Groenfeldt & Schmidt (2013) also highlight the importance of ethics and values in water management. They remark how water policies and governmental priorities are influenced by value systems, and further note that water scarcity should not only be treated as an economic issue but also as a social, environmental and cultural issue. They argue that ethics have been left out of discussions of water governance (Araújo et al., 2015).

Clearly developed metrics and identification of critical interlinkages are

essential in order to mitigate the consequences of water-energy interdependence and to adequately direct policy action, and the various decision makers, avoiding as much as possible competing arguments for and against water-energy policies that can prove to be calamitous. Metrics are useful when they can be calculated from observed data and then if they are simulated in models that give us insight into future impacts, options, and interactions with feedbacks and constraints. Understanding the scope and being able to categorize metrics derived from different methods and models can prove to be of great value, since we are becoming able to understand the motivation behind various stakeholders on concentrating on certain metrics over others. This knowledge in turn can be useful in allowing us to translate between metrics and models for water-energy planning and stakeholder collaboration (King & Carbajales-Dale, 2016).

In summary, useful indicators should assist in terms of adaptation, mitigation, and resilience. Adaptation is achievable by keeping safe minimum standards, and having contingency measures in place, therefore responding to climate change effects by reducing the vulnerability due to sudden changes of resource availability. Mitigation is attainable by safeguarding the security of supply for the long-term, which means limiting the magnitude and rate of climate change by making choices that are environmentally friendly, thereby acting towards reducing risk associated with human-induced climate change. Finally, resilience is achieved by fulfilling the aforementioned adaptation and mitigation goals, therefore enhancing the capacity of the system in absorbing stresses and maintaining function in the face of external stresses imposed by climate change, while at the same time evolving and preparing further for future impacts. It needs to be mentioned here that resilience differs from adaptation in that it includes both absorbing shock and self-renewal (evolution) functions.

2.4. Water-Energy Nexus

We have seen that water is notably important for energy, and electricity in

particular. Due to increased population and demand for electricity the relationship between these two resources will become even more strained in a matter of a few decades. Therefore, it is important to investigate the interconnections of these two resources in a systematic and comprehensive way.

2.4.1. Resource nexus

There are links that are well known, like the links between agriculture, food, land and water in the production of biofuels. On the other hand, links of fresh water supply in energy production, and mineral and energy extraction and processing have received less attention, although there are studies like Jordaan et al. (2018) and Asdrubali et al. (2015) that through Life-Cycle Assessment (LCA) have contributed towards this goal. Also, environmental challenges and economic volatilities make the relationships even more uncertain and unpredictable, especially given the changing political dynamics of the international system with the rise of powers like China, India and Brazil. Understanding and quantifying these connections between resources can offer opportunities like efficiency gains, substitution, reuse and recycling, reduced consumption, to name but a few, while minimising the risk of governing resource concerns in isolation (Andrews-Speed et al., 2012).

The approach taken and the decisions made in policy-making will reflect the perspective of the policy-maker, which means that if a water perspective is adopted, then food and energy are users of the resource, or from a food perspective energy and water are the inputs, and so on (Bazilian et al., 2011). Ignoring effects in one resource though, can have significant impacts on another and as Lee & Ellinas (2010) note: *The anticipated bottlenecks and constraints in energy, water and other critical natural resources and infrastructure are bringing new political and economic challenges, as well as new and hard-to-manage instabilities.* Single sector policy-making can temporarily have performance improvements in the sector concerned, but it

is highly unlikely they would persist over time. Holistic treatment on the other hand, could lead to a more optimal allocation of resources, improved economic efficiency, lower environmental and health impacts, and better economic development conditions.

Over the past centuries, science has focused on narrow and tightly defined challenges, rather than consider wider problems and their links. This kind of reductionism leads to a lack of adequate knowledge for us to understand the emergence of complex and wicked problems. These problems are ever changing and highly interconnected with each other and actions we take. How we think and manage them is considered part of the larger problem (Kenway, 2013). A systems-thinking approach is required to deal with such a complicated problem. This is not easily translated into government making, or any other processes though. A concept that will be able to deal with the various resource interlinkages is needed, and this concept could well be the resource nexus.

The resource nexus is a framework attempting to integrate the crucial aspects of sustainable development. Only in the past few years has it been recognized as a way of dealing with resource issues, but governments around the world have started to consider it. The resource nexus has its roots in the interconnections between different resources, like the requirement of one resource as an input to produce another or from the substitutability of two or more resources, and as is noted in Andrews-Speed et al. (2012): *"it comprises the numerous linkages between different natural resources and raw materials that arise from economic, political, social, and natural processes."*

Instead of focusing on single elements for efficient resource use and management, the nexus concept highlights the interlinkages among the various elements and their twisted conversion pathways (e.g. extraction, supply, distribution, end use, disposal) via the parallel production and consumption chains in terms of socio-economic sectors. This concept uses a

systematic approach, having as a focal point the dynamic interactions, to optimize the interconnections within the whole system and identify how to obtain the trade-offs and synergies, achieving the system's sustainability over time (Chen & Chen, 2014). By unpicking relationships between resources, it can help us appreciate how various sectors and industries could potentially achieve gains in resource efficiency and build their resilience against future challenges like shocks in resource availability or pricing (WWAP, 2014).

2.4.2. Water for energy and energy for water, or the Water-Energy Nexus

Water and energy interconnections are part of the resource nexus thinking, but they have traditionally been considered as separate and distinct, although they were always considered to be indispensable resources to modern economies. Water and energy security are deeply interlinked. The linkages and interdependencies between them are multiple and they will most likely deepen in coming years, making integration of the two vital. The identification and elimination of tensions and trade-offs between these sectors, and the highlighting of synergies and shared goals between them is something worth investigating (Williams et al., 2014).

The two-way links between water and energy are called the Water-Energy Nexus with the nexus considering the embedded energy in water systems and the embedded water in energy systems, or put more simply energy for water and water for energy. Figure 2.4 shows some of the main interlinkages between water and energy. Here is an appropriate time to explain in the words of Leck et al. (2015) what a nexus is, in order to avoid confusion: *"a nexus is defined as one or more connections linking two or more things"*. The WEN is part of the more broad resource nexus, which was defined earlier.
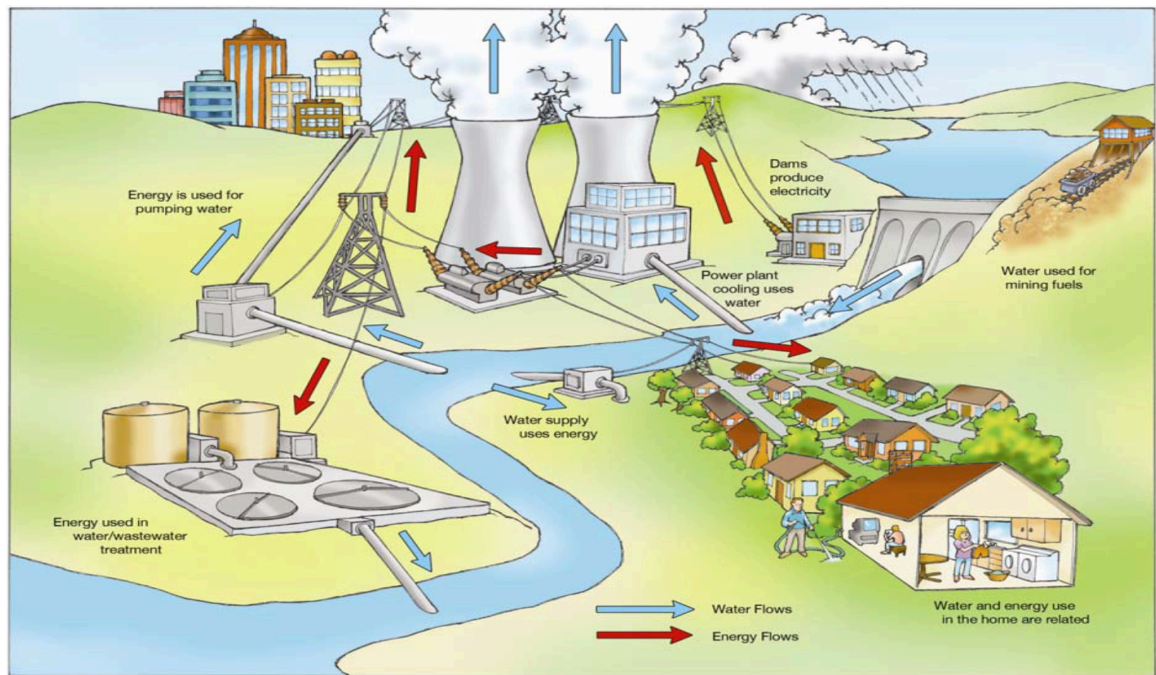
Figure 2.4 – Examples of interrelationships between water and energy
(Source: US DOE, 2006)

To comprehensively understand the WEN though, it is important to consider all spatial and political scales, from technologies, through production and consumption in space and time, to the geopolitical struggles for control of resources (Williams et al., 2014). The nexus approach, in the process of capturing the interconnectedness of resource challenges, may offer additional opportunities to improve efficiency gains, substitution, reuse and recycling, reduced consumption and a number of other options. Simultaneously, it lowers the risks associated with trying to govern resource concerns in isolation (Andrews-Speed et al., 2012).

Interactions of energy and water have long existed (e.g. Gleick, 1994; Harte and El-Gasseir, 1978), but the WEN is becoming increasingly relevant due to the following reasons: growth in total demand for both electricity and water driven by population growth, growth in per capita demand for both electricity and water driven by economic growth, distortion of availability of fresh water due to climate change, and a multitude of drivers for more electricity-intensive water and more water-intensive electricity (e.g. enhanced water treatment standards, water consuming flue gas treatment

at thermal power plants, and ageing infrastructure that incurs greater losses) (Lubega & Farid, 2014).

Though there have been attempts at a technological level to optimize coupling points between electricity and water systems to reduce water and energy intensity of technologies, the discussion of the water-energy nexus from an engineering systems perspective has received little attention (Lubega & Farid, 2014). Bazilian et al. (2011) suggest that an important step in approaching the nexus is to develop robust analytical tools, conceptual models and robust data sets that can supply information on the future use of energy and water, since existing models focus on one resource and ignore interconnections with others. Also, according to Bleischwitz et al. (2013) the resource nexus is not yet built into future policy tools, nor yet properly reflected in research.

Here the work done in LCAs needs to be mentioned, since it is heading towards the same direction as the WEN. LCAs are frequently used to evaluate differences in water consumption across energy technologies, without though capturing the changing spatial patterns of water consumption associated with a product. More specifically, LCAs of electricity generation focusing on water consumption have been thus far insufficient in determining the actual impacts to watersheds. Dynamic, spatially-resolved LCAs are needed to represent this spatial variation in product flows and the heterogeneous patterns of environmental impacts. As an example, Jordaan et al. (2018) have contributed in improving regional detail to better reflect spatial variation, in particular compiling a spatially-resolved inventory of changes in water consumption associated with the coal-to-gas transition in Pennsylvania, USA. This is a very promising start for the improvement of LCAs regarding water consumption estimates.

2.4.3. *Interlinkages, metrics, and definitions*

Before progressing any further, it is important to analyse which exactly the connections between water and energy are and provide definitions for important terms.

Primary fuel production requires water for extraction, refinement and transport. Also, power plants require water for cooling. The actual water consumption can vary significantly for each process due to a number of geographical, physical, and technological factors (Siddiqi & Anadon, 2011; Siddiqi et al., 2013; Bartos & Chester, 2014). In the water chain, energy is needed for abstraction (e.g. pumping surface or ground water), purification (e.g. desalination or wastewater treatment), distribution (e.g. transportation of water over long distances in pipelines or urban supply networks), utilization (e.g. heating of water for domestic or industrial use, irrigation), and disposal (e.g. urban and industrial wastewater) (Siddiqi & Anadon, 2011). Energy use for water depends on many variables and namely water source (e.g. surface water, groundwater, etc.), treatment, intended end-use, distribution, water losses (e.g. evaporation and leakage), and level of wastewater treatment (e.g. stringency of water quality regulations to meet discharge standards). In the same vein, the intensity of energy use for water, which is the relative amount of energy needed for a task like pumping water, varies depending on characteristics like topography, climate, seasonal temperature, and rainfall (Copeland, 2014). Table 2.2 represents where the main interactions between water and energy occur.

Water for energy	Energy for water
Exploration, extraction and processing of fuels	Abstraction and treatment
Transportation and storage	Transportation
Construction and maintenance of energy-generation facilities	Construction and maintenance of water-supply facilities
Electric power generation (thermal, hydro, etc.)	Distribution
Thermal power plant cooling	End use
Waste disposal and emission control	Desalination
End use	Wastewater collection and treatment

Table 2.2 – Water for energy, and energy for water interactions

Water for energy has received a lot more attention than energy for water and this has to do primarily with the fact that water is directly impacted by weather and climate change, and its availability is vital for many functions within society in the micro and macro scale. The amount of water available for a specific use depends on many factors like quality, intended use, laws and regulations, physical nature of the hydrologic system, ecosystems, culture, lifestyle, and societal values of the region. Additionally, it also varies over time as economic, climatic, hydrologic, and environmental conditions change. By accounting all these factors, water availability is best determined on a region-by-region basis with reassessments over time (Healy et al., 2015). Quantification of water resources is commonly done in a hydrologic or water budget context, where water budget describes *"the movement of water into, through, and out of a representative volume, such as a watershed, a state, or the country as* whole" (Healy et al., 2007).

When it comes to water for energy specifically, there have been numerous studies in recent years using a range of measures and methods to quantify the water impacts of energy. Some of the measures that have been developed and used include: water withdrawal and consumption (Macknick et al., 2012a; U.S. DOE/EIA, 2011), water utilization, water use, virtual water content (Galan-del-Castillo & Velasquez, 2010), water footprint (Gerbens-Leenes & Hoekstra, 2011), blue and green water (Gerbens-Leenes

et al., 2012; Mekonnen & Hoekstra, 2012), grey water (Wilson et al., 2012), water abstraction, freshwater use (U.S. DOE/EIA, 2011), water intensity (King & Webber, 2008), and so on. Also, some methods and indexes that have been used for the measurement of the WEN include the following: emergy (Arbault, 2013; Watanabe, 2014), water energy intensity index (Dubreuil et al., 2013), water exploitation index (Walsh et al., 2015), energy return on water invested (EROW) and water returned on energy invested (WROE) (Voinov & Cardwell, 2009), water consumption of energy production (Spang et al., 2014), and net reservoir fill change (Tarroja et al., 2014).

The aforementioned list of methods and measures is by no means exhaustive and what becomes clear when researching the subject is that there is a lack of consistency in the interpretation and use of different measures due to *"a competition for the development of the 'correct' evaluation method"* as Madani & Khatami (2015) argue. These inconsistencies could in theory create uncertainties and confusion to decision makers and academics, because they could obscure the validity of the outcomes, and consequently could lead to inaction, hindering the progress to more sustainable solutions that could solve emergent energy problems, without unintended impacts on water resources. Apart from the large number of measures, there are additional issues. Existing literature mainly assesses the amount of water withdrawn and consumed for energy production, showing a lot less interest in the evaluation of the effects of energy production to the quality and temperature of water.

'Water use' as a general term can be confusing, although it is very widely used from everyday purposes to scientific papers. In engineering for example, water can be used in several functions in a process and each time this will be counted as a use, but this way the water used will be several times larger than the amount of water withdrawn. Macknick et al. (2012a) and Meldrum et al. (2013) both stress out the fact that state agencies and reports fail to specify whether it is withdrawal or consumption that is being

analysed and do not use consistent methods or definitions in measuring water use by the energy sector. Water withdrawal, as the name implies, is a quantification of the amount of water removed from local sources temporarily, independent of its later use (energy production or processing, or other purposes). On the other hand, water consumption is the amount of water that is withdrawn but not returned to the local water basin from which it was abstracted. Consumed water is evaporated, transpired, incorporated into products or crops, or otherwise removed (Williams & Simmons, 2013).

Water consumption is calculated in terms of water intensity, with the units being litres of water consumed per generated kilowatt-hour of electricity (l/kWh). The total water intensity of producing one kilowatt-hour of electricity is calculated according to Healy et al. (2015) *"by adding the water intensity for extracting and processing the fuel that is used in generating that electricity and the water intensity of the electrical power plant"*. Apart from water consumption, water withdrawal is also a key indicator for assessing water use in the energy sector and it is important to understand their difference.

On the other hand, energy consumption is calculated in terms or energy intensity, with the units being kilowatt-hours of electricity consumed per generated litre of water (kWh/l). Energy is consumed throughout the water cycle, and depending on the source of water and the distance and topography over which it is transported, it is possible that large amounts of energy are required to move water from its source to its final destination. The energy intensity of water treatment for example depends on the water source, quality of water, intended use and the chosen treatment process. The age of the water-treatment infrastructure could also affect energy intensity. Similarly, the energy intensity of groundwater pumping depends on pumping depth and the efficiency of the pump. The energy intensity of water conveyance is also dependent on the efficiency of the infrastructure. Leaks from unlined canals and pipelines can be substantial, as can evaporation

from the open water surfaces of large reservoirs (Healy et al., 2015).

Healy et al. (2015) argue that there is need to develop improved methods for measuring or estimating water withdrawal and consumption for energy use, especially in the case of hydroelectricity generation and biofuels production. Furthermore, they argue that current understanding of the WEN is limited due to the uncertainty on issues such as the amount of freshwater that is available and the amount of water that is used in energy development. Provided that this uncertainty is reduced, predictions of future water and energy needs and availability can improve.

2.4.4. Water consumption of electricity generation technologies

Although there have been issues with the definitions of water withdrawal and consumption, as well as with methods for measuring and estimating them, the strain on water resources by electricity generation has been internationally recognised, often in the context of the WEN, and it has been discussed in detail in literature (Cooley et al., 2011; IEA, 2012a; Rodriguez et al., 2013). In recent past there have been publications that provide consolidated estimates of water withdrawal and consumption for the full life cycle of selected electricity generating technologies, with the water usage of cooling in thermoelectric power plants monopolizing these publications. These estimates are drawn from a broad range of sources with publicly available data. The most frequent sources are the United States Geological Survey (USGS, 2010) and the Energy Information Administration (EIA). Some of the publications that address water use across varying degrees of the life cycle include work by Gleick (1994), Fthenakis & Kim (2010), Mielke et al. (2010), Cooley et al. (2011), Averyt et al. (2011), Macknick et al. (2012a) and Meldrum et al. (2013).

Despite extensive collection, screening, and harmonization efforts by these publications, the estimates for most generation technologies and life cycle stages remain few in number and wide in range (Averyt et al., 2011;

Meldrum et al., 2013). Yet, they are widely used in energy and water modelling. An important issue of the estimates of water consumption and withdrawal is that they are presented irrespective of geographic location, although a plant's location and the corresponding climatic conditions affect the overall efficiency and water use rate (Dziegielewski & Bik, 2006; Yang & Dziegielewski, 2007; Rutberg et al., 2011).

In the overall limited water resources management work, water consumption by hydroelectricity generation is one important aspect that may exacerbate regional water scarcity problems (Fthenakis & Kim, 2010; Gerbens-Leenes et al., 2009; Gleick, 1994), making it a matter of great importance to accurately assess it. However, it was not until the "Special Report on Renewable Energy Sources and Climate Change Mitigation" by the Intergovernmental Panel on Climate Change (IPCC) came out in 2012 that the impact of hydroelectricity on water resources received more recognition. The reason for the increased attention was the wide range of estimates on water consumption per unit of energy generated by hydropower plants, but also because these values were considerably greater than all other technologies, as shown in table 2.3 presenting examples from Macknick et al. (2012a).

Technology	Median	Min	Max
Biopower Tower Steam	2.1	1.82	3.65
Nuclear Tower	2.54	2.2	3.2
Nuclear Once-Through	1.02	0.38	1.51
Natural Gas Tower Combined Cycle	0.78	0.49	1.14
Natural Gas Tower Steam	3.13	2.51	4.43
Natural Gas Once-Through Combined Cycle	0.38	0.08	0.38
Natural Gas Once-Through Steam	0.91	0.36	1.1
Coal Tower	2.6	1.82	4.16
Coal Once-Through	0.95	0.38	1.2
Hydro	17	5.39	68.14

Table 2.3 – Water consumption factors for different technologies in m³/MWh

(Source: Macknick et al., 2012a)

Hitherto, this large variability in water consumption from hydroelectricity has been acceptably problematic in literature. The main consumption comes from evaporation from large reservoirs, which though are multi-purpose, storing water for agriculture, industrial or domestic use as well as for power production (Healy et al., 2015). Thus, the water losses cannot only be attributed to power generation purposes alone (Siddiqi & Anadon, 2011). Estimating these evaporative losses and attributing them to hydroelectricity or other uses is a major issue (Dodder, 2014) and there is no commonly accepted methodology for it (Bakken et al., 2013). Many modelling approaches (e.g. ReEDS and GCAM analyses) either excluded (Spang et al., 2014; Elcock, 2010; Macknick et al., 2012b) or treated water consumption of hydropower as a separate category of overall water demand (Dodder, 2014). Torcellini et al. (2003) estimated it to be from 0 to 18,000 gallons per MWh (68.14 m³/MWh).

The uses of a reservoir are important and can affect water consumption, but as is the case in Brazil, most hydropower reservoirs are solely used for this purpose, and in such cases, it all comes down to evaporation. The main reasons why this large variability in literature exists are that, firstly evaporation rates are not constant within an country, nor a region, and they depend a lot on the geomorphology of the reservoir in question, apart from the weather in that specific location. Secondly, and more importantly, the size of the reservoir in relation to the power capacity of the power plant is what makes the biggest difference. The larger the area of the reservoir and the lower the power capacity is, the higher the water consumption becomes. This wide range in values indicates the difficulty to estimate water use factors for hydroelectricity that could be universally applicable, deeming them an issue of great importance when it comes to their use in water demands for energy scenarios in modelling exercises.

2.5. Summary

This chapter offered a first glance at water and energy links, recent popular frameworks to address some of those interlinkages, an introduction into useful indicators, and setting the base of what the Water-Energy Nexus is through definitions, interlinkages, metrics, and finally identifying issues about water consumption of electricity generation.

The rise of population, along with increased living standards and therefore higher consumption rates of resources is fast progressing. Shortages of resources are inevitable, with water and energy being at the forefront of such discussions and concerns. Energy supply requires vast amounts of water, and availability of water dictates decision-making. This is particularly important for emerging economies like China, India and Brazil that will double their energy consumption in the next 40 years. Through recent studies it was shown that most of future water consumption in energy production would be due to hydroelectricity.

Understanding the importance of links between resources is one thing, but doing something about it is another. The recent Sustainable Development Goals have water and energy as goals and they have specific targets for them in order to create a more systematic way of addressing issues globally. This is a very welcome framework, but it does not come without its issues. There are 232 different indicators in total, which is a very large number for any country to deal with, let alone for countries without the appropriate economic capacity. Furthermore, in terms of water in particular, withdrawal is mentioned, but consumption is missing, which has already been identified as being an important indicator in terms of water and energy.

Also, there are other frameworks, more specific about water, like the IWRM, which promotes more coordinated management of water resources, although it is hard to account for all the characteristics of the hydrological cycle and its interactions with other natural resources and ecosystems, so although

trying to systematically give meaning and propose solutions, it is not necessarily translated practically (Sustainable Development Solutions Network, 2015). Finally, Pires et al. (2017) identified 170 indicators related to water use and management, with 24 complying with the sustainability criteria they set. One of the indicators that have drawn a lot of attention is the "water footprint", because it allows a comprehensive view of the sustainability of water use and can be assessed within the IWRM framework. This indicator ought to be investigated further, aiming to overcome some calculation methods limitations.

The interactions of water and energy are many, as shown, and addressing their links is very complicated. A concept like the resource nexus, here in the form of the water-energy nexus, can assist in understanding the multiple faceted issues of the interconnections between the two resources, identifying and eliminating tensions and trade-offs, while highlighting synergies, and it acts complementary to frameworks like the SDGs. Although nexus thinking is a relatively easy concept to understand at first glance, it is complicated and difficult to tackle. The main reason for this is that it needs to be looked at on many different scales and levels, from biophysical to political ones. At the same time, the most direct links in the nexus exist at the resource level. Analysis of the biophysical impacts in space and time is vital to be undertaken in order to set the basis of the problem, which will further assist on the analysis on subsequent levels (WWAP, 2014). Basically, first we need to know how much water there actually is.

As Healy et al. (2015) suggest, estimating water withdrawal and consumption for energy use is of the utmost importance, especially in the case of hydroelectricity generation and biofuels production. Water consumption and water footprint are indicators that are easily understood, irrespective of one's background, while at the same time measuring unsustainable trends and defining and ensuring sustainability. Apart from these two indicators, the quantification of water through a water budget

analysis seems like the next logical step. As Bazilian et al. (2011) suggested, the next important step after identifying important links is to develop robust analytical tools to supply information on the future use of water and energy. A further simulation of these in models would give us insight into future impacts, options, and interactions with feedbacks and constraints.

The introduction of water into energy models would introduce new areas of uncertainty in the face of the variable nature of the underlying weather data projections (mainly evaporation, precipitation and temperature) and their correlation to the energy service demand projections. Water models are frequently used to determine water systems' resilience to weather extremes, whether energy models are more frequently used to find economically optimal investments out of a vast number of options. Therefore, integrating water systems in energy modelling would require careful design of the input data sets (Rodriguez et al., 2013). With these issues in mind, chapter 3 will concentrate more on reviewing existing methods and approaches for water and energy, and particularly investigating water consumption of hydroelectricity, the water footprint, water budget analysis, and assessing if and how energy models are able to address the WEN.

Chapter 3. Review of existing methods and approaches for water and energy

Chapter 2 addressed the links between water and energy, the role of SDGs and other relevant frameworks in water and energy assessments, and what makes for a useful indicator for them. It laid the ground for what the WEN is, its important metrics, and finally identified some important aspects in terms of metrics and modelling of the WEN that deserve to be further investigated. Chapter 3 is going deeper into reviewing the gaps of existing methods and approaches, and reviewing the most important aspects of metrics and methods regarding the WEN of hydroelectricity (evaporation, water footprint, water budget), plus reviewing different energy models and their ability to address the WEN. This review will set the groundwork for chapter 4, where the methodology used in this thesis will be described.

3.1. Gaps of existing methods and approaches

The gaps that exist in literature can be classified into two categories and namely operationalization of the nexus, and metrics. There is general agreement in academia that research has not concentrated on the impacts of water availability on energy and more specifically the electric power sector (e.g. Nogueira et al., 2014; Schaeffer et al., 2012; Chandramowli & Felder, 2014; Wang et al., 2014). At the same time, the WEN from an engineering systems perspective has received little attention (Lubega & Farid, 2014). Finally, as Leck et al. (2015) argue, the operationalization of the WEN has been to date largely a paper exercise. There have been attempts at a technological level to optimize coupling points between electricity and water systems to reduce water and energy intensity of technologies, but the scope has been limited. The reason why operationalization of the WEN has not progressed much is because it is challenging to integrate energy and water system planning models due to their fundamental ideological differences.

Energy systems models are based on physical principles, like conservation of

energy and materials, conversion efficiencies and operational limitations. They are driven by societal demands for energy services, related to standards of living and overall economic activity and growth. They are primarily concerned with siting and cost requirements for energy generation and transmitting the produced energy to population centres. There are several technologies competing to provide the many requirements, and optimization models are frequently used to compare optimal investment strategies for new energy technologies. The models measure the relative costs and benefits for each option (Rodriguez et al., 2013). Similarly to water models, energy models assume an existing supply of water necessary for power generation (with systems dominated by hydropower being an exception) and do not consider it to be a limiting factor in operations. Although energy models focus on generation, they do incorporate estimates of water demand for energy production through coefficients of water utilization per unit of output. What is missing is a consideration of water availability and its dynamic nature or trade-offs among water uses. Also, models do not consider the use of water to generate the electricity needed by water infrastructure. This could potentially be something negligible in regions with abundant supplies of water and energy, but important in the case of resource scarcity (Rodriguez et al., 2013).

On the other hand, water models are primarily dynamic simulations of natural watersheds and their interaction with man-made systems over a period, given actual and projected precipitation and weather patterns. This kind of models are driven by physical principles, like soil permeability, to track interactions between surface water and groundwater. The main concern of most water models is to manage the distribution of water resources over space and time to meet specific objectives or demands. They track water withdrawal and consumption from a system's entry to the exit. The reason simulation is used, is to meet water demands under the most extreme conditions expected. They determine the impact on future water availability under different investment and management options (Rodriguez et al., 2013). The energy supplied to divert, pump, and treat water is

assumed to be adequate and in most cases the energy consumed in the different water demand scenarios is not quantified. This isolated assessment does not represent the dynamic relationship between water and energy. Also, water models typically have a high level of hydrologic detail (e.g. evapotranspiration, stream flows, return flows, exchange between surface and ground water) on particular watersheds, which makes them very data-intensive and complex. If a national water budget is to be assessed, the data intensity rises significantly (Rodriguez et al., 2013).

Apart from the aforementioned problems of both water and energy models, it is also difficult to integrate them. Energy and water models need to agree on spatial boundaries in order to be combined, since water models are primarily applied to watershed boundaries and energy models deal with political boundaries. This is one of the issues when trying to combine such inherently different kinds of models. Some studies have to a certain extent successfully succeeded in this endeavour. This includes Karlberg et al. (2015), Welsch et al. (2013), Hermann et al. (2012), Bartos & Chester (2014), Dubreuil et al. (2013), and Senger & Spataru (2015). The first three of these studies integrated the Water Evaluation and Planning system (WEAP) and the Long-range Energy Alternatives Planning system (LEAP), while the last one added water and land components to an energy model.

At this point it is appropriate to present in more detail what some important recent studies have done in relation to water inputs in energy systems. Firstly, Webster et al. (2013) used a generation expansion planning model to explore trade-offs between CO_2 and water in electricity generation planning in the USA. To put things in context, nearly half of the water withdrawals in the USA are for electricity generation, much of which comes from fossil fuel combustion that emits greenhouse gases. Hence, the USA faces tensions between meeting growing energy demands, while reducing greenhouse gas emissions and water withdrawals, which is part of the WEN. With their research they show that large reductions in CO_2 emissions would likely increase water withdrawals due to absence of limits on water

usage, and also that simultaneous restriction of CO_2 emissions and water withdrawals would require a different than present generation technology mix, but also higher costs in relation to trying to reduce either CO_2 or water usage alone.

For example, solar generation was economic in only 0.1% of scenarios used without water limits, but 4% when both water withdrawal and CO_2 limits were taken into account. Thus renewable sources seem to contribute more when water is considered. Reducing CO_2 emissions as well as water withdrawals help achieve a shift away from coal and nuclear, and in favor of natural gas generation, which mainly uses hybrid or dry cooling systems reducing water withdrawals. Overall, considering water limits along with CO_2 limits could dramatically change the configuration of the electric sector compared to typical predictions from energy-climate models that do not consider water. A future where large reductions in greenhouse gases are desirable and sought after is more likely to occur if water resources are more constrained than they are today. Water restrictions could play a critical role in the optimal generation mix (Webster et al., 2013).

Another seminal publication by Scott et al. (2016) argues that the uncertainty in the future human demand for water, interacts with future impacts of climate change on water supplies, which influence water management decisions at an international to a local level, but until recently tools were not available to assess the uncertainties surrounding these decisions. Scott et al. (2016) demonstrate using a multi-model framework in a structured sensitivity analysis to project and quantify the sensitivity of future deficits in surface water in the context of climate and socioeconomic change for all US states (presenting Georgia). The work used geographically gridded temperature, precipitation, and on occasion water runoff from global-scale general circulation models to drive hydrologic and water management models, and estimate climate change impacts on surface water availability. Due to the amount of inputs and possible combinations, 6,561 downscaled model runs were identified, and 2,187 runs were required to

identify the highest and lowest water demand. Although the high and low demand cases represent reasonable extreme estimates of water demand, the climate-driven water supply aspects apply to one climate model, represent only one interannual variation around a reference case (without including groundwater). This work did not address water supply risks inherent in either inaccuracies or differences between climate models (Scott et al., 2016). This work shows the difficulties of modelling numerous interactions, but also paves the way for such research.

Finally, Hejazi et al. (2014) assess future water demands for agricultural, energy, industrial, and municipal sectors, by incorporating water demands into a technologically-detailed global integrated assessment model of energy, agriculture, and climate change, the Global Change Assessment Model (GCAM). Their socioeconomic scenarios have no constraints imposed by future water supplies, however they indicate that many regions of the world will likely see an increased reliance on non-renewable groundwater, water reuse, and desalinated water, while they highlight the importance of water conservation technologies and practices. This work represented the first incorporation of sectoral water demands into a prominent, technologically-detailed integrated assessment model, which already includes energy, agriculture, land use, and climate within one modelling framework. This study presented an endogenously incorporated water demand model, however with a coarse spatial representation. A dynamic water supply module was not incorporated, but this was not the focus of the study.

The results provided two important outcomes. Firstly, that water is a limiting factor in several scenarios of socio-economic pathways, and secondly investing in irrigation water saving is likely unavoidable. Such attempts in modelling will permit improvements in possible feedbacks between water, energy, land use, agriculture, the economy, and other systems in a complex global structure. The authors pinpoint challenges and suggest future research among other things in the effects of climate change on water use,

capturing the seasonality of water use while shifting from annual to sub-annual temporal scales, and also accounting for evaporative losses from reservoirs. While, they argue that incorporation of climate change effects on water availability, and computation at finer spatial and temporal scales, would improve localized water scarcity estimates (Hejazi et al., 2014).

In general, there are three possible approaches to address the WEN in a modelling framework:

o Incorporate water resources and uses into an existing energy model,
o Incorporate energy production and uses into a water model, or
o Construct a combined framework.

The first option seems to be favoured over the other two due to the fact that energy systems models currently exist in many developing and emerging economies. It needs to be noted here that depending on one's perception of what it is that drives development as a whole (e.g. better resource management, specific direction of growth of the energy sector, etc.), it is possible that the point of view as to which one of these options is the best choice would be different.

Particular attention must be drawn on two issues and namely spatial and temporal scale. Geographic boundaries are important, since energy systems are usually delineated along political boundaries or interconnected regions (national, regional, global), while watersheds and river basins usually outline water systems. There are some exceptions of very small countries, islands, and some African states. Location is more critical to water, since the majority of resource supplies is local. Linkages are strong at the river basin scale, where competing demands for water can sharpen the trade-offs and opportunity costs of water use against agriculture, electricity generation, of which many forms are water intensive (hydropower and cooling), and urban and environmental needs. Therefore, the two kinds of boundaries should be aligned. Another issue would be to produce results in identical time steps. Many energy models produce results for each system in

annual increments, and analyse policies and options with a 20-50 year horizon, or even more. Water models, like WEAP, can generate sub-annual results, sometimes even daily ones. Seasonal variability can have a large impact on water supply, so it is important to model in smaller time steps (Rodriguez et al., 2013). However, it is needs to be noted that energy modelling timescales can vary depending on what a model is trying to achieve. Energy models that include peak and off-peak variation for example, have smaller time steps, whereas other models for long-term planning have annual time steps.

Apart from the modelling issues analysed above, the issues of estimating specific critical metrics like water consumption of hydroelectricity and evaluating the water footprint have already been identified as important issues in chapter 2, and they will be analysed in more detail in this chapter. This is particularly important since as Healy et al. (2015) argue, there is need to develop improved methods for measuring or estimating water withdrawal and consumption for energy use, especially in the case of hydroelectricity generation and biofuels production. Particularly hydroelectricity water consumptive use is an acceptably problematic issue mainly due to evaporation and multi-purpose uses of reservoirs. One of the main reasons why the current understanding of the WEN is limited is the uncertainty on issues like freshwater availability and the amount that is used in energy development.

Consequently, the main gaps when it comes to addressing the WEN for hydroelectricity in a modelling framework can be narrowed down to ways to measure water consumption, and also water availability, in appropriate temporal and spatial scales. This should be done taking into account the precautionary principle, meaning that water should be treated prudently, which can be achieved by setting minimum and maximum limits of usage. Addressing these gaps could provide useful findings in terms of better management of water, higher efficiency of both water and electricity, strategically located power plants, appropriate energy sources per region,

avoiding possible competition for water, and highlighting possible opportunities.

On that account, what follows is a review of aspects identified to be of importance, and namely evaporation (water consumption of hydroelectricity), water footprint (water consumed per unit of energy), water budget (water availability analysis), and the ability of energy systems models to address the WEN.

3.2. Evaporation - issues and methods for its estimation

Evaporation is a very important aspect of assessing hydroelectricity and thus it deserves to be investigated in detail. At this point it is useful to make a clear distinction between evaporation and transpiration. According to the Food and Agriculture Organization of the United Nations (FAO), evaporation is *"the process whereby liquid water is converted to water vapour and removed from the evaporating surface"*. Evaporating surfaces include lakes, rivers, pavements, soils, and wet vegetation. On the other hand, transpiration *"consists of the vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere"*. Crops lose most of the water that they consume through their stomata (small openings on the plant's leafs).

Recent studies (Maestre-Valero et al., 2013; Martínez-Granados et al., 2011; Gallego-Elvira et al., 2013) show that large amounts of water are lost due to evaporation from lakes and reservoirs, leading to huge waste of resources. The hydrologic and economic impacts of this are significant, hence evaporative losses should receive more attention in water management for the formulation of future projections. Yet, the estimation of evaporation from lakes and reservoirs is not a simple task due to the many factors affecting evaporation rate, relating to the climate and physiography of the water body and its surroundings. More specifically, *"The rate of evaporation is mainly controlled by the available energy and the ease with which water*

vapour diffuses into the atmosphere. Where, the available energy is a combination of the net radiation at the lake's surface and the amount of heat stored in the water" (Finch & Calver, 2008).

Consequently, the evaporation of water is directly related to the surface of the body of water and it varies with temperature, wind conditions, and humidity of a region. Differences in evaporative losses can also occur due to the type and size of the hydroelectric plant (IEA, 2012a; Mekonnen & Hoekstra, 2012; OECD/PBL, 2015). It all depends on the hydraulic head and dam height. When the hydraulic head exceeds the dam height, the water losses are smaller than when the hyraulic head is smaller than the dam height (Gleick, 1994). It needs to be taken into account that evaporation is part of the normal hydrological cycle, however since these large reservoir areas would not exist if it were not for the dams built there, evaporation stemming from there is considered to be a consumptive use and it is attributed to the hydroelectric plants.

Before going into more detail about how to estimate evaporation, it is worth understanding the physics behind the phenomenon. During early spring, most large temperate lakes and reservoirs have a uniform temperature distribution with depth. As the year progresses and the weather warms up, the water body receives heat at a rapid rate and the function of heat transportation to deeper layer within the water body does not have the time to cope with the increase in temperature (the thermocline formation), and during the remainder of the heating period the deeper regions of the lake are relatively uninfluenced by changes in surface conditions. The upper layer is called the epilimnion and is dominantly a function of the surface area of the water body and the climate. In autumn, when the water body has attained its maximum heat content, the thermocline moves rapidly into deeper layers of the lake, due to surface cooling. The thermocline keeps moving down rapidly until the whole water body attains homothermal conditions again (Finch & Calver, 2008).

A reverse phenomenon is also possible in winter (mainly continental climates), but the cool layer is much thinner than the epilimnion of the summer. The meaning of this phenomenon is that water temperatures are lower than air temperatures during the summer and higher during the winter. As a consequence, evaporation rates may be higher in winter than in summer. Additionally, the heat transferred into a lake or reservoir by inflows and outflows of water could also be a significant factor in the energy budget of the lake and consequently the evaporation rate. It needs to be noted that tropical water bodies rarely experience this stratification phenomenon (Finch & Calver, 2008).

3.2.1. Multiple uses of reservoirs and other issues

Many reservoirs worldwide have multiple uses (e.g. agricultural, industrial, domestic, etc.) additionally to the generation of electricity (Healy et al., 2015), thus water losses cannot always be attributed to power generation alone (Siddiqi & Anadon, 2011). Despite this fact, there is no commonly accepted methodology for determining how much reservoir evaporation should be attributed to hydroelectricity or other uses (Torcellini et a., 2003; Bakken et al., 2013; Gleick, 1992). Work done by Pasqualetti & Kelley (2007) proposes allocating evaporative water losses to the various uses of the reservoir on the economic value of those different uses. Subsequently, Zhao & Liu (2015) in their study used a new approach to quantify the water footprint of hydroelectric power by developing *"an allocation coefficient estimating the ratio of the ecosystem services value of hydroelectricity to the total ecosystem services value of a reservoir"* and applied it to the Three Gorges Reservoir in China. However, additional research would greatly benefit this kind of thinking. Although there is scope to pursue this analysis for reservoirs that have different uses, the vast majority of reservoirs in Brazil that are used for hydroelectricity are solely used for that purpose (Lehner et al., 2015; AQUASTAT database). Therefore, for the purpose of the present work, all evaporative losses are attributed to hydroelectricity production.

Seepage losses due to porous ground underlying hydroelectric reservoirs can also lead to water consumption, and according to Gleick (1994) that can be up to 5% of the volume of the reservoir annually. However, the opposite is also possible in some cases and it depends entirely on the location of the reservoir and the groundwater level present. This means that each reservoir would need to be investigated individually, and a generic value for regions cannot be used. At the same time though, this water remains in the basin and may become available downstream or recharge ground water resources, thus it is not going to be taken into consideration in the analysis, since it is not considered to be a true loss (Gleick, 1994; Healy et al., 2015).

Furthermore, it needs to be noted that water used to turn the turbines is not considered as consumption since it is returned to the river. Also, possible polluted water from hydropower generation is not considered in this study. Changed temperature, turbidity and chemicals could theoretically pollute water, but this is deemed to be very minimal so it is ignored. Hydropower in general is regarded to be clean and climate-friendly (Huang & Yan, 2009; Sims, 2004; USGS, 2010). Another aspect, which was not taken into consideration, but needs to be noted, is the water consumption during the construction of the dam, but also decommissioning (Herath et al., 2011). This study was limited to a quantity assessment of the operational water consumption and of water resources.

3.2.2. Methods for estimating evaporation

There have been studies that compare and assess evapotranspiration methods for land surfaces or estimating required parameters in limited data conditions around the world, and also Brazil (Carvalho et al., 2013; Mendonca et al., 2013; da Cunha et al., 2015). However, studies that estimate lake or reservoir evaporation under conditions that long-term data are unavailable are a rare occurrence. Consequently, there is no clear consensus as to which methodology is the best one when data like

temperature profiles, radiation, and heat fluxes are missing (Majidi et al., 2015), which are vital for an accurate estimation of evaporation.

Generally, the rate of evaporation from any wet surface is determined by three factors: a) the physical state of the surrounding air, b) the net available heat, and c) the wetness of the evaporating surface (Monteith, 1991). More specifically, evaporation rate is the difference between the vaporization rate (function of temperature) and the condensation rate (function of vapour pressure) (Shuttleworth, 1992). Moreover, in dealing with deep lakes and reservoirs, heat storage of the water body affects the surface energy flux and needs to be taken into account, as is the case in Brazil's hydroelectric reservoirs. Similarly, the effects of salinity, which reduces evaporation, and water-advected energy, need to be addressed as well if they are relevant for the reservoir, although this is not the case for Brazil's reservoirs (McMahon et al., 2013).

There are a variety of methods for estimating open water evaporation, but generally they can be categorized into a few major types: a) pan evaporation, b) mass balance, c) energy budget, d) bulk transfer, and e) combination methods (Finch & Calver, 2008). Each of them has certain advantages and disadvantages, and there are studies that review them in detail (Stephen et al., 2007; Shakir et al., 2008; Gallego-Elvira et al., 2013; McJannet et al., 2012), but their main concept is provided here:

a) Pan evaporation - This method is the most commonly used across the world, especially in less developed countries, chosen because of its simplicity, due to lack of other necessary measurements. A pan filled with water is placed next to the lake/reservoir, which forms a micro representation of the lake/reservoir and it is used to estimate evaporation, deeming it an empirical method. The 2004 ONS study also used this method. Pan evaporation is simply the depth of water evaporated from the pan during a day. There are many different evaporation pans, but the most common one is the US Class A pan. Pan evaporation provides a

measurement of the combined effect of temperature, humidity, wind speed and solar radiation on the evaporation (Kim et al. 2013; Majidi et al., 2015). Although pan evaporation has been used for about 200 years, the measurements can rarely be directly used as estimates of evaporation from a water body because of the differences in size between the pan and the water body, and possibly the difference in the overlying air (Finch & Calver, 2008). Some authors have used pan coefficients to relate pan evaporation to open air evaporation. The problem though is that these coefficients are specific to pan type, location and nature of water body, so calibration is always required. Also, heat storage effects are not accounted for (McJannet et al., 2008).

b) *Mass balance* - This technique calculates evaporation by looking at the differences between storage volume and inflows and outflows for specific water bodies. The problem with this method is the requirement for detailed and accurate measurements of surface and subsurface flows, which are rarely available (McJannet et al., 2008).

c) *Energy budget* - This method estimates evaporation from a water body by the difference between energy inputs and outputs measured at a site. The energy lost through evaporation represents a major part of the energy balance typically, but the problem here is the specialized equipment necessary for each water body if accurate budgets are to be found (McJannet et al., 2008).

d) *Bulk transfer* - Here the evaporation rate can be estimated using measurements of wind speed, vapour pressure, air and water surface temperature, and estimates of measurements of water temperature. Even if all variables are not readily available, it is possible to estimate them, but this technique is best suited to larger water bodies hence having a more limited applicability to the size and range of the water bodies (McJannet et al., 2008).

e) Combination methods - These methods combine bulk transfer and energy budget in a single equation. The most commonly used one (also the one suggested by FAO) is the Penman-Monteith equation (Monteith, 1965). This requires inputs of net radiation, air temperature, vapour pressure, and wind speed. The Penman-Monteith approach allows adjustment to the amount of energy available for evaporation based on changes in heat storage within the water body. The loss of heat through evaporation is an important part of the energy calculation used to calculate temperature (McJannet et al., 2008).

3.3. Water footprint and methods for its estimation

Water footprint has attracted interest as a metric that indicates the use of water resources and its impacts. It is defined as *"the volume of freshwater used directly, or indirectly, in the production of a good or service"* (Hoekstra & Chapagain, 2007), where "used" considers the water consumed and also polluted throughout the production. Taking this definition into consideration, the water footprint of a hydroelectric reservoir, and as a consequence the water footprint of hydroelectricity generation is not different than what the water energy nexus represents. Simply put, the water energy nexus represents the relationship between how much water is used to generate energy (electricity in this case) and how much energy is used to collect, clean, store, move and dispose of water. Since in this case there is no energy used for water, the only relevant part is that of the amount of water used to generate electricity, which is equivalent to the "…*water used to produce the product*…" part of the water footprint definition. Therefore, the methods used to calculate the water footprint for hydroelectricity *(e.g.* Herath et al., 2011; Mekonnen & Hoekstra, 2012) are apt for representing the water energy nexus. It is for this reason that the methods presented in the following subsection do not make a distinction between being used to specifically estimate water footprint or simply methods used to evaluate the water evaporated from the reservoirs as a function of energy produced, since they are one and the same thing.

3.3.1. Methods for estimating water footprint

There are two main methods for estimating the water footprint of a lake/reservoir: a) gross water consumption, and b) net water consumption.

Gross water consumption is the method used by Gleick (1992) and Mekonnen & Hoekstra (2012). More specifically, Mekonnen & Hoekstra (2012) calculate the water footprint of hydropower electricity (WF, m^3/GJ) by dividing the amount of water evaporated from the reservoir annually (WE, m^3/yr) by the amount of energy generated (EG, GJ/yr):

$$WF = \frac{WE}{EG} \quad (Equation\ 3.1)$$

The total volume of evaporated water (WE, m^3/yr) from the hydropower reservoir over the year is calculated by:

$$WE = A \times \sum_{t=1}^{365} E \quad (Equation\ 3.2)$$

where A is the area of the reservoir (km^2) and E is the daily evaporation (mm/day)

The second approach is that used by Herath et al. (2011) and Healy et al. (2015), calculating the net water consumption, subtracting the land surface evaporation that was used before the reservoir was built. More precisely, Healy et al. (2015) calculate the reservoir water consumption rate as:

$$Q_{op} = (ET_0 - ET) \times A \quad (Equation\ 3.3)$$

where Q_{op} is the annual operational consumption of water in m^3/year, ET_0 is the evaporation rate of open water in m/year, ET is the estimated evapotranspiration rate of the impounded area prior to being inundated in m/year, and A is the surface area of the reservoir in m^2.

In the case of net water consumption, the difficulty lies in estimating ET, since evapotranspiration depends on vegetation and available soil-water content. If soil water is unlimited (e.g. humid areas), then ET values will be very similar to ET_0 values. On the other hand, in arid regions, ET is substantially less than ET_0. Nevertheless, a very detailed analysis of the vegetation and soil-water content needs to take place in order to be able to use this method. Due to this difficulty, the gross water consumption seems to be the most commonly used, and therefore most dominant method, for estimating water consumption by hydroelectric power plants (Mekonnen & Hoekstra, 2012; Gerbens-Leenes et al., 2009; Pasqualetti & Kelley, 2007; Torcellini et al., 2003), although the net water consumption method is also used in some cases (Herath et al., 2011; Yesuf, 2012; Arnøy, 2012).

It also needs to be noted that these methods might overestimate the water footprint of hydroelectricity, since they allocate all water consumption to hydroelectricity, even when the reservoirs might be used to provide multiple services (e.g. water supply, flood control). This should theoretically not be a problem in the case of Brazil, since the reservoirs used for hydroelectricity are solely used for that purpose.

3.4. Water budget – its importance and uses

Evaporation estimation is valuable due to its use in the water footprint, which is a valuable indicator for the assessment of hydroelectricity, but it is also valuable because it can be used in a water budget analysis. A water budget analysis is an analysis of water availability, which in the case of hydroelectricity is vital, for operational purposes but also future planning.

3.4.1. Definition of water budget and its use

Before going any further, water budget needs to be properly defined and understood. Perhaps the first instance the term "climatic water budget" was introduced into literature was by Thornthwaite and his fellow researchers

(Thornthwaite, 1948; Thornthwaite & Mather, 1955). At first it was used for analyses of global and regional climatic classification relating to the interactions of energy and moisture, determining humid and dry climatic realms, and generally establishing an orderly structure of climatic types based solely on climatic parameters rather than vegetation characteristics (Carter & Mather, 1966). The data inputs were based on mean monthly temperature and precipitation derived from climatic stations of respective areas (Muller & Grymes III).

Since then, the concept has changed slightly and evolved to be more inclusive of other water issues as well, nevertheless its definition and main equation are simple to comprehend. So, quantification of water resources is commonly done in the context of a hydrologic or water budget, which describes the movement of water in, through and out of a specific volume (e.g. watershed, state, country). The water budget equation for a watershed is:

$$P + Q_{in} = ET + \Delta S + Q_{out} \text{ } (Equation\ 3.4)$$

where P is precipitation, Q_{in} is surface and subsurface flow into the watershed, ET is evapotranspiration, ΔS is change in water storage, and Q_{out} is surface and subsurface flow out of the watershed (including human withdrawals) (Healy et al., 2015). This equation can be refined and customized depending on the goals and scales of a particular study, which will be done for the purpose of this thesis in chapter 4.

In a nutshell, water budgets are a way for evaluating availability and sustainability of water supply. Their concept is simple enough as they attest that the rate of change in water stored in an area is balanced by the rate at which water flows into and out of that area. But, understanding water budgets and other possible underlying hydrologic processes provides insight into complex processes over space and time (Teixeira et al., 2008), and the needed background for effective water resource, but also generally

environmental, planning and management. Human activities affect the hydrological cycle manifold. Examples include land modifications for agriculture, installation of drainage and irrigation systems, runoff, evaporation, and plant transpiration. A water budget can help into assessing how a natural or human-induced change in one part of the hydrologic cycle can affect another part of it. Changes in water budgets of a watershed, state, country, etc. over time can be used to assess the effects of climate variability and human activities on water resources. Furthermore, by comparing water budgets of different areas, it is possible to quantify the effects of factors like geology, soils, vegetation, and land use on the hydrologic cycle (Healy et al., 2007).

The link between the components of a water budget is the basis of how natural or human-induced change to one component may be reflected in other components. In the case of hydroelectric reservoirs, three components have to do with the climate (precipitation, evaporation, river flow), but storage is a human interaction that can be changed if necessary to account from climate change or better management for human needs. The data needed for a water budget can be considerable, let alone when we have to deal with a large study area. For this reason, a water budget can be achieved through hydrologic computer-simulation models, which contribute immensely to our understanding of the hydrology of watersheds, states, countries, etc., but they are also indispensable tools for managing water resources. Water budget equations can vary a lot in complexity, but even the calculations of the simplest version can be impossible to do without the use of a model. The more complex a model gets, the more insight it can give into processes that drive water movement within a volume or area. At the same time though, this further insight comes at the expense of data requirements, accuracy, etc. as well (Healy et al., 2007).

3.4.2. The importance of assessing operation of hydroelectric plants through a water budget analysis

Climate change has an immediate impact on water resources. The temperature rise could increase evaporation and precipitation in different areas, and in turn affect water flows. Consequently, droughts and floods are more frequent and more severe (IPCC, 2013). A decrease in water availability also affects electricity production directly, from generation and cooling technologies, to cost and future capacity siting (U.S. DOE, 2013). Hydroelectricity, along with thermal once-through cooling, is particularly susceptible to fluctuations in water availability (IEA, 2012a). At the United Nations General Assembly thematic debate in 2013, one major outcome was the recognition that rain patterns and irrigation are vital for the reservoir management of hydropower and biofuels.

In addition of depletion of water being highly depended on climate, it is also site specific. This fact, along with the fact that generation of electricity is highly time relevant, makes it clear that an analysis of a hydroelectric system should ideally be done on a maximum daily time step and individually for each power plant/reservoir. Ideally, an analysis of this sort would quantify as accurately as possible the movement of water in, through and out of a specific volume of water, which in turn makes it feasible to be adequately informed about the availability of water in order to make decisions about the future. This type of analysis is achieved through a water budget (or balance).

In order to do a water budget analysis and address the operation of a hydroelectric plant, it is important to treat the process in a dynamic way since the main variables (precipitation, evaporation and river flow) are all dynamic in nature. Consequently, the operation of hydroelectric plants largely depends on climate and its changes through time, which can occur rapidly, within days or even hours sometimes. It is for this purpose that the evaporation (water consumption) of hydro plants, a subject that is

particularly lacking in literature and modelling exercises, is estimated for the case of Brazil and presented in detail in this research in chapter 6, especially taking into account the complexity of the hydroelectric system of Brazil. Although in this instance the subject matter is hydroelectric power, evaporation (or evapotranspiration if the study is broadened to include land surfaces as well) is very important in water resource management, which includes hydroelectric power, drinking-water supply, irrigation, and fishery (Kobiyama, & Chaffe, 2008). As it was already explained, evaporation is a valuable indicator on its own, but it does not hold any information about water availability, which is where a water budget comes in. Adding precipitation and river flow data, it is possible to perform such an analysis and assess operation of hydroelectricity.

Assessing operation through a water budget analysis can have many advantages. It can serve as an indication of which reservoirs and regions are more susceptible to disruptions of electricity generation, but also when and how frequently they are likely to occur. The same holds true for general water availability in time. The results of a water budget can provide minimum and maximum values of water availability, and the estimation of their frequency is aimed at showing critical links between water and energy, which in turn could prove a valuable planning tool in increasing efficiency of both water use and electricity production, in line with water-energy nexus thinking, ultimately helping towards resilience. Using optimization models assisting in operating strategies is important in dealing with issues of critical limits (Güntner et al., 2009).

There are large uncertainties in model applications, mainly in terms of reservoir operation rules that will be discussed in detail later, but reasonable simplifications assessing surface water availability, and consequently also water storage, are of great value. An importance advantage of operation optimization over various other hydraulic and energy efficiency measures is that this is not a structural mediation, which

means that large investments are unnecessary. Moreover, the economic benefits are attainable in the short term (Vilanova & Balesieri, 2014).

A water budget analysis can shed light into how important appropriate operation at the reservoir level is for electricity generation. Through its conceptual simplicity, and despite data complexity and application issues, a water budget analysis of a whole system can provide invaluable results for the present operation through to future operation and planning. In an era where concepts like circular economy gain traction around the world, it would not make sense to discount the importance of making the most out of the water available to us. Healy et al. (2015) argue, and rightly so, that although it is difficult to quantify, water storage is a key metric for determining sustainable water use, since continuous decrease in water storage will eventually result in decreased availability for the environment but also human use. Therefore, it is worth investigating the potential of water storage, and consequently energy storage, of hydroelectricity, which could prove to be valuable in terms of understanding the impact of our actions and how we could possibly better manage it, in a future where water availability could be an important issue we will have to deal with.

As Earth's population rises, so does demand for water. Balancing human water needs with those of ecosystems on Earth will continue being a challenge, but water budgets provide a means for evaluating the availability and sustainability of water supply. The water budget constructed and presented in chapter 4 can be universally applied at any spatial scale (e.g. a reservoir, state, region), and at any temporal scale from minutes to years depending on data provided, thus providing a base for improved water management and future planning.

3.5. Can energy models address the WEN?

Here, and before starting this process, an important disclaimer needs to be stated. The following energy models review is not meant to be a

comprehensive and detailed review, since this is not the goal of this thesis, rather it is a relatively simple review in order to understand the general point and main differences in the conceptual frameworks of a variety of models. It is also important to explain that the definition of a model is a relatively simplified mathematical representation of a system, process or a phenomenon, in order to assist calculations and projections. These models are turned into specific tools in various computer-programming languages, which allows for fast calculations. The words 'model' and 'tool' are thus used interchangeably in literature and also in this thesis. Also, another important thing to keep in mind is that some specific tools mentioned are not necessary mutually exclusive and can very well belong in more than one specific conceptual framework.

Examples in section 3.1 have already shown the complexity of an attempt to investigate energy and water simultaneously. The problem lies in the fact that if for example energy is addressed first, then water is exogenous to the process, and vice versa. Which resource comes first in a modelling perspective determines the whole process, since models are created with specific problems and goals in mind, so issues of one resource will receive priority, due to the theoretical framework. The opposite process would give different results. As explained in section 3.1, the optimal solution would be for both energy and water, in the case of this thesis, to be addressed in parallel, but until very recently this was not a priority, and thus established models that do this do not exist. Consequently, the easy answer to the question of this section would be that: no, energy models cannot address the WEN. However, as the examples presented have already shown, there is scope to pursue this goal, because it can be valuable, and recent examples of trying to achieve this will be presented. Since more work has been done from the energy side, it was deemed valuable to concentrate on the water side in this thesis, having energy in mind, and it is for this reason why it is beneficial to understand what the main general frameworks of energy models are, since if energy is ignored, the WEN cannot truly be addressed.

3.5.1. Types of tools

Before starting the process of selecting a model that is capable of addressing the WEN, it is important to understand what kind of methods and models exist, and categorize them according to their theoretical background, capabilities and limitations. However, it is hard to find a systematic comparative study in literature, so a variety of recent reviews was used, as well as papers reviewing specific methods and models.

Authors	Focus
Bhattacharyya & Timilsina, 2010	A review of energy systems models
Connolly et al., 2010	A review of computer tools for analysing the integration of renewable energy into various energy systems
DeCarolis et al., 2012	The case for repeatable analysis with energy economy optimization models
Herbst et al., 2012	Introduction to energy systems modelling
Manfren et al., 2011	Paradigm shift in urban energy systems through distributed generation: methods and models
Pfenninger et al., 2014	Energy systems modelling for twenty-first century energy challenges
Urban et al., 2007	Modelling energy systems for developing countries

Table 3.1 – Recent reviews of energy systems and related work

Classifying energy models is a difficult task, as there are many ways in which this can be done, with most models belonging to several categories. The diversity of modelling approaches developed through the years is significant and they depend on the target group (scientific community, policy makers, energy supply companies, etc.), the kind of use (forecasting, simulation, optimization, etc.), regional coverage (local, national, regional, worldwide), conceptual framework (top-down: underlying economic theory, bottom-up: underlying engineering, technical focus) and the availability of data (Herbst et al., 2012). Following the paradigm of the reviews in table 3.1, they are categorised based on their conceptual framework and therefore

divided mainly in top-down and bottom-up tools, and then their kind of use.

Top-down analysis is preferred by economists and it relies on historical market data to estimate aggregate relationships between the relative costs and the relative market shares of energy and other inputs to the economy (Jaccard et al., 2003). These models try to depict the economy as a whole on a national or regional level and to assess the aggregated effects of energy and climate change policies in monetary units. They are driven by economic growth, inter-industrial structural change, demographic development, and price trends, and they try to equilibrate markets by maximizing consumer welfare (Herbst et al., 2012).

Bottom-up analysis is preferred by engineers, physicists and environmental scientists and it estimates how changes in energy efficiency, fuel types, infrastructure, land practices, etc. might lead to different levels of Greenhouse Gas (GHG) emissions (Jaccard et al., 2003). The main characteristic of bottom-up models is the high degree of technological detail used to assess future energy demand and supply. They are driven by energy-related technological progress, innovations, and intra-industrial structural change, and they use a business economics approach for the economic evaluation of the technologies simulated (Herbst et al., 2012). Hybrid models also exist and they are an innovation of the nineties, which saw the linkage of technologically rich bottom-up models with top-down general equilibrium economic models (Pfenninger et al., 2014).

3.5.2. Limitations of top-down and bottom-up models

Both top-down and bottom-up models have significant limitations. Top-down models suffer from the lack of technological detail and deliver generalized information, thus not being able to provide an appropriate indication on technological progress, non-monetary barriers to energy efficiency or specific policies for certain technologies or branches. Technological change is treated as an exogenous trend, sometimes explicitly related to energy consumption,

affecting the productivity of the homogeneous capital input. Especially in the long run, where technological change, saturation, and intra-sectoral structural change are inevitably expected, they are ill suited to provide credible technology futures. Also, the capital is treated as a homogeneous input related to energy only through a degree of substitutability with energy inputs in production. Another limitation is the conception of the nature of markets. Most top-down models do not admit the possibility of market imperfections, disregarding costless opportunities and alternative technological scenarios that have not been taken up in the economy yet. They assume perfect markets, thus underestimating the complexity of obstacles and their non-monetary forms, like lack of knowledge, inadequate decision routines, or group-specific interests of technology producers. Computable General Equilibrium (CGE) models, for example, assume that any policy implies additional cost, although highly profitable investments in energy efficiency may actually reduce cost and increase profits and tax income (E3ME, 2014; Herbst et al., 2012). Finally, since they are focused on monetary terms, they tend to favour monetary related policies, like price-based policies or emission certificates and regulatory policies (Hourcade et al., 2006).

Though the high degree of detail is a great advantage for bottom-up models, it is also their greatest disadvantage, since they are heavily dependent on data availability and credibility with regard to their many assumptions on technology diffusion, investments and operating cost. Other criticisms include the neglect of the feedback of energy policies, the macro-effects of the presumed technological change on overall economic activity, structural changes, employment, and prices (Herbst et al., 2012). In bottom-up models, the capital is given an empirical content and is related to energy either in terms of generating equipment, other energy-related capital, or public infrastructure. Technological change is treated as a variety of options presently or soon to be available that enjoy increasing market penetration. Also, they attribute the inability of the economy to reach a technologically efficient supply chain in terms of the provision of energy services to market

imperfections, but do not explore the relationship between these imperfections and decision making (E3ME, 2014).

Additionally, both types of analysis cannot address long-term issues satisfactorily. In one case, after a certain number of years it is the engineering characteristics of a technology that are important in the carbon-energy-output relationship and not the behavioural relations, deeming top-down models unsatisfactory. On the other hand, the path of technological change is unknown, so the models cannot be dynamic, deeming bottom-down models unsuitable for long-term analysis as well (E3ME, 2014).

Lastly, there are some more general, but important challenges, which energy models irrelevant of their categorization, will need to deal with in the future and these were summarized by Pfenninger et al. (2014) in four themes: 1) temporal and spatial detail, 2) balancing uncertainty, transparency and reproducibility, 3) developing methods to address the growing complexity of the energy system, and 4) integrating human behaviour. All of them are at the forefront of modelling concerns and research in many institutes is undertaken constantly to deal with them.

3.5.3. Categorisation of top-down and bottom-up models

Generally, top-down models could be further categorized in a) Econometric, b) CGE, c) Input-Output, and d) System Dynamics models and a brief overview of each one follows:

a) Econometric models - At first, they were aimed at testing economic theory using empirical evidence, but that moved on to highly complex open-ended, growth-driven macro econometric models using/analysing time series data on a higher level of aggregation. Their major disadvantage is their heavy reliance on data (needed for long time periods), to be able to generate credible results (Herbst et al., 2012).

b) Computable General Equilibrium (CGE) models - They analyse policy implications for economies, assuming that all markets are in perfect equilibrium, and are used for long-term simulations. They rule out energy efficiency gaps, adjustment delays and generally neglect market failures and obstacles. Additionally, they do not take technological details into account that may be important for assessing certain policy measures (Herbst et al., 2012; Hourcade et al., 2006).

c) Input-output models - They describe the total flow of goods and services of a country subdivided into different sectors and users in terms of value added and specific input/output coefficients. They are best suited for short-term evaluation of energy policies, because they can only give a current picture of the underlying economic structure based on historical data (Catenazzi, 2012; Herbst et al., 2012).

d) System Dynamics models - They analyse the long-term behaviour of social systems (e.g. from companies to cities) as a result of the assumed interdependencies considering dynamic changes over time among the various components that constitute the defined system. They have some drawbacks in the validation and calibration of the assumed feedback loops, in particular in long-term developments in the energy systems, and are also unable to make detailed analyses and projections of sectoral technologies (Fichtner et al., 2003; Herbst et al., 2012).

In the same way, bottom-up models could be further categorized in a) Optimization, b) Simulation, c) Partial Equilibrium and d) Multi-Agent models and a brief overview of each one follows:

a) Optimization models - They try to define the optimal set of technology choices to achieve a specific target at minimized costs under certain constraints. They support policy makers by providing them with detailed information about energy technologies on the demand and supply sides and are used for overall and single-sector analysis of the energy market. Their

use is limited to discrete energy conversion technologies and typified energy uses as information on investment and operating cost are needed for the optimization. Also, severe market imperfections and obstacles are not accounted for, leading to unrealistically low projections of energy demand (Herbst et al., 2012; Schade et al., 2009).

b) *Simulation models* - They attempt to provide a descriptive, quantitative illustration of energy demand and conversion based on exogenously determined drivers and technical data with the objective to model observed and expected decision-making. They are flexible and allow aspects like strategic behaviour or the absence of complete information to be integrated, helping in mirroring market imperfections and failures. System dynamics and agent-based models can be said to belong in simulation (Herbst et al., 2012).

c) *Partial Equilibrium models* - They are similar to CGE models framework-wise, but they only assess one sector or certain subset of sectors at a time. They focus on energy demand and supply, and by neglecting interrelations and effects on the broader economy they can include many more technological details than conventional CGE models (Herbst et al., 2012).

d) *Multi-Agent models* - They have a simulation approach and consider market imperfections, like strategic behaviour, asymmetric information, etc. Apart from research tools, they are also used to improve decision-making as well as to test specific policies and project alternative scenarios and futures. So far, they are limited to applications of the energy converting technologies and a few applications on final energy sectors. One major obstacle to developing and using them is the enormous demand on additional empirical data in order to simulate the behaviour of the different agents (Alexandridis & Pijanowski, 2006; Herbst et al., 2012).

As it has already been mentioned, a lot of tools do not only belong in one of

the above categories, hence they are not mutually exclusive. For example E3ME is considered a macro-econometric model, IREDSS is also an econometric model, GTAP and GEM-E3 are CGE models, ASTRA is a system dynamics model, and TIMES is a bottom-up optimization model. However, as models progress and improve with time, distinctions become more difficult. For example MARKAL/TIMES is an optimization/simulation model with rich detail, and POLES is a partial equilibrium simulation model. Although it is valuable to somewhat understand the difference between different frameworks, it is neither vital nor restrictive. What is more important is to choose the right model to address specific problems in the most appropriate way, while at the same time trying to not ignore important variables.

3.5.4. Tools that have been used to address the WEN

There is an increasing number of researchers that are trying to address the WEN in energy modelling, with most of the modelling exercises being in their first stages of application. There are three examples though that were some of the first and most cited ones, and namely the models OSeMOSYS, MARKAL/TIMES and LEAP. These examples are by no means restrictive, and there are plenty more examples of models trying to address the WEN, one of which (IDA3) will also be used for the purposes of this thesis.

OSeMOSYS (Open Source Energy System Model) is an energy systems optimization model for long-term energy planning. In 2013, Weirich developed a global model incorporating Climate Land Energy and Water (CLEW) parameters and interconnections using OSeMOSYS. The model was created to be a simplistic representation of the nexus systems and include the most relevant mechanisms between them. The existing energy model was combined with two separately created modules on land use and materials. Water and climate parameters were added to all modules and they were combined to the global CLEW model. Results from the comparison of the separate and combined modules showed that this

approach is applicable even on a simplistic, highly aggregated scale (Weirich, 2013). It is argued that apart from climate, energy, water and food, materials play an important role and should be added to the nexus. In this particular study and in order to limit the model's scope, six material sectors were included and namely: aluminium, cement, iron & steel, pulp & paper, chemicals & petrochemicals, and fertiliser. It was further argued that rare earths or precious metals could be an interesting addition. The model could not be implemented as desired in some cases due to lack of required data, especially in the materials section. For the interconnections and materials sections, a comprehensive review including technical, production and demand data on a global level was not found. Also, the data on materials was expensive and difficult to aggregate, with a further problem being conflicting information in some cases. Finally, the representation of water in the combined model was not sufficient (Welsch et al., 2014).

MARKAL/TIMES (Market Allocation/The Integrated MARKAL EFOM System) are energy-economic-environmental tools for national energy systems, providing a technology-rich basis for the estimation of energy dynamics. Bhatt (2013) used US MARKAL to research the WEN in the US, separating the country in 10 regions. It accounted for water withdrawals and water consumption for electricity production from fossil fuels, nuclear power and renewable energy. Detailed water use factors were applied to the technology-rich base of the model. The model allowed for the analysis of which technology investment and policy choices related to the development of the energy system affect water use (Bhatt, 2013).

Rodriguez (2013) also presents work done with the South Africa TIMES (SATIM) model, which improved integration of water dynamics and economy of water. The model addressed the WEN, running different scenarios of how energy sector development strategies change relative to a reference scenario depending on different kinds of changes to water. At first, a CGE model (E-SAGE) was ran to establish reference scenario demand projections for energy. Then SATIM using these demand projections

produced a reference case and then ran a new WEN case that allowed for reduced energy demands from economy-wide adjustments when energy prices rise to reflect water scarcity. The SATIM findings were further fed back to the CGE model to evaluate the economy-wide impact of accounting for water scarcity in energy sector development. Finally, after comparisons, the increased demands on water sources from the energy sector were identified (Rodriguez, 2013).

LEAP (Long-range Energy Alternatives Planning) is a well-known and widely adopted tool, which does user-friendly analysis for energy systems at the city, state, national, regional and global scale in the medium to long-term. Karlberg et al. (2015) used LEAP in conjunction with WEAP to evaluate the impacts of alternative development trajectories pertaining to agriculture, energy and environment for Lake Tana Sub-basin, Ethiopia, accounting for cross-sector interlinkages and competing resource use within the food-energy-environment nexus. Three future scenarios were developed, compared and evaluated: Business As Usual, National Plan and Nexus. Also, stakeholder perceptions on the outcomes of the different pathways were assessed. The final objective of the research was to develop, test and apply a nexus toolkit in joint dialogue with stakeholders. The study identified the strong link between agricultural transformation and energy transitions (Karlberg et al., 2015).

Welsch et al. (2014) also used an integrated analytical assessment approach to analyse CLEW, by valuing various interdependencies and interactions, primarily from an energy sector perspective. The energy system was assessed with the LEAP tool, which was set up to reflect the extraction, conversion and demand of energy. For the climate part, they used GCMs and their corresponding climate projections to derive temperature and rainfall assumptions. For land-use, the Agro-Ecological Zones land production planning model (AEZ) was used to derive the production potential of the farmland used for ethanol production, calculate irrigation requirements under different climate conditions, and fertilizer input

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required for different crops under different conditions like crop cycles. Finally, the water system was modelled using WEAP, which was applied to assess the implications of local municipal and agricultural water requirements on the national water supply schemes. This approach highlighted important dynamics that would have been overlooked otherwise, like for example, when rainfall reductions are taken into account, and where future land-use changes might occur (Welsch et al., 2014).

Finally, IDA3, which is a dynamic energy-water-land model developed by Spataru at University College London (Spataru, 2017; Spataru, 2014), was used to address the three aforementioned resources in parallel for the case studies of France, Egypt, and Brazil. The model captures trade-offs between these resources and aims to assess the long-term effects of electricity generation on the energy-water-land system. Scenarios are used to assess different generation technology compositions and to account for climatic changes and data uncertainties. The model uses capacity factors of hydropower (among other technologies) as input to account for it. It has already been validated for Brazil, which is positive concerning this thesis, and the fact that the framework of the model takes resource trade-offs into account is important. Due to these reasons, this model was deemed to be of great value towards incorporating the detailed water availability data output of the water model presented in this thesis, and thus the model's equations will be presented in more detail in chapter 4. Although the water availability data will be incorporated exogenously through the use of capacity factors, nevertheless, the fact that IDA3's conceptual framework is based on resource trade-offs will allow for improved results about Brazil's electricity sector.

3.6. Summary

This chapter reviewed the gaps of existing methods and approaches, the most important aspects of metrics and methods regarding the WEN of

hydroelectricity (evaporation, water footprint, water budget), and finally the different energy models and their ability to address the WEN.

The main conceptual gaps identified are operationalization of the nexus, and metrics. The operationalization of the WEN is a challenge and until recently there were no modelling attempts to address it, mainly because of the challenges to integrate energy and water systems due to their fundamental differences. Energy models are based on physical principles like conservation of energy and materials, conversion efficiencies and operational limitations, frequently comparing optimal investment strategies for new energy technologies. On the other hand, water models are mainly simulations of natural watersheds and their interaction with man-made systems over a period given actual and projected precipitation and weather patterns, and they are driven by physical principles. Additionally, there are spatial and temporal disparities between them, which makes linking of the two problematic. Energy models have political boundaries, whereas water models have hydrological boundaries. Location is very critical to water, since the majority of resource supplies is local. The two kinds of boundaries need to be aligned in order to make any sense of the results.

The water consumptive use of hydroelectricity has been a particularly problematic issue in literature due to evaporation estimation methods and multi-purpose uses of reservoirs, and therefore it is an issue that deserves a lot of attention. Hence, evaporation issues and methods for its estimation are reviewed. Evaporation can be further used to estimate the water footprint of hydroelectricity (water consumed per unit of energy), which is an important and valuable metric, and thus it was reviewed along with methods for its estimation. Furthermore, evaporation is part of estimating water availability using a water budget analysis, which was also reviewed, analysing the importance of assessing the operation of hydroelectric plants. The importance of treating operation of hydroelectricity dynamically is stressed out, and water budget is defined and its use for evaluating availability and sustainability of water supply is explained.

A detailed review of energy models followed. Energy modelling tools have been used in the past and it could be argued that they cover aspects of the nexus, but at the same time none of them is able to deal holistically with all interlinkages between resources. Therefore, before deciding which tool is more adequate to deal with the nexus, it is important to understand what kind of models exist and what their limitations are. Classifying them and finding their limitations is no easy task. For the purpose of this thesis, they were categorised according to their conceptual framework in top-down and bottom-up models. They were further categorised in econometric, CGE, system dynamics, input-output, optimisation, simulation, partial equilibrium and multi-agent tools. The main limitations of top-down models are their lack of technological detail and the inability to acknowledge market imperfections. On the other hand, bottom-up models depend heavily on data availability and their assumptions on technology diffusion. Additionally, both types of analysis cannot address long-term issues satisfactorily.

Finally, four specific recent examples of tools that have been used to address the WEN were presented. This list is not restrictive and as time goes by, more and more researchers are attempting similar work. The first three examples use the models OSeMOSYS, MARKAL/TIMES and LEAP respectively. Each of them has helped regarding progress in the field, but they still need improvement. The same holds true for the fourth example, the IDA3 model, however where this defers from the rest is that it is designed with the nexus in mind, therefore being a closer approximation to a resource trade-off model. Furthermore, it has been used for Brazil already, which is useful for the purposes of this thesis. For these reasons, this model was deemed to be appropriate for the present work and it will be presented in more detail in chapter 4.

Summarising, the main gaps identified in terms of addressing the WEN of hydroelectricity in a modelling framework are measuring water consumption and availability in appropriate temporal and spatial scales.

Following the review of methods and approaches in this chapter, chapter 4 will describe the specific methodology that will be used in this thesis to address these issues and perform a novel analysis of the WEN for a specific case study.

Chapter 4. **Methodology**

Chapter 3 reviewed the gaps of existing methods and approaches, as well as the importance of metrics and methods in regards to addressing the WEN for hydropower. The critical metrics and methods included evaporation, water footprint, and water budget analysis. Following these findings, this chapter introduces the modelling framework that will be used, and it includes the determination of the nearest meteorological stations, evaporation and water footprint estimation, and the water budget analysis equations used. Finally, IDA3's main equations (Spataru, 2014) are presented.

4.1. An integrated research framework for the WEN

As discussed in chapter 3, water and energy integration in a modelling framework is impaired by their fundamental conceptual differences. This is translated in spatial and temporal disparities, which makes linking an issue. The smaller the time step of the water model, the more useful it could be to energy models, since the results of water availability will be more accurate, and as it has been discussed already, water availability for electricity generation operation-wise is a highly temporal issue. Energy-water-land models like IDA3 do not look into depth at capacity factors, and modelling detailed capacity factors thanks to detailed water modelling will strengthen the outputs for this kind of models. Furthermore, and possibly more importantly, there is need to align the political boundaries of energy models with the hydrological boundaries of water models, always keeping in mind that locality is very critical for water.

Apart from the issues mentioned above, useful metrics has been another important issue when it comes to water and energy integration in modelling terms. In particular the consumptive use of water by hydropower has been an issue that has only recently been recognised being of importance and its detailed estimation is predominantly lacking, although very valuable. To

achieve estimating it, evaporation needs to be estimated at a small time step and at a small spatial scale, preferably for every reservoir taking part in a modelling exercise. Evaporation is further useful since it takes part in a water budget analysis and improving accuracy of water availability estimation. Finally, a water budget analysis is vital for hydropower, since water availability is of the essence, especially in a highly uncertain climatic future.

From the three possible ways of addressing the WEN in a modelling framework, it would be ideal to construct a combined framework. Nevertheless, it is very time and resource consuming to achieve something like this in a limited timeframe. Hence, since the main gaps identified in literature concern water issues, it was deemed that this thesis and the ensuing analysis would be predominantly based on water modelling and analysis for electricity generation. However, it will be demonstrated how the water model can be linked to an energy model, since the water model is constructed particularly taking energy models and their needs into account, without ever discounting the importance of issues revolving around water.

In the analysis in chapter 3 we have seen that all energy models are not properly equipped to take water issues into consideration. Attempts have taken place in recent years, as shown in chapter 3, to alleviate these issues, but more work is needed towards this direction. It is for this reason, that the model IDA3 developed by Spataru at University College London was chosen to be linked with the water model developed in this thesis. IDA3 models energy-water-land and the trade-offs between these resources, which could help in policy making and planning (Spataru, 2017). Integrating the water model's realistic capacity factors into IDA3, improves its results. However, it needs to be noted that the water model is performed for specific reservoirs and provides hourly results for evaporation and water footprint, and daily results for the water budget analysis, whereas IDA3 in its present form operates regionally and on an annual basis. It has the capacity to be used in different time steps, but this was deemed too time consuming for the

purposes of this thesis, where the goal was to show the two models could be linked. This was the main limitation of this specific link, however the results will shed light in terms of Brazil's hydropower future. It will be further demonstrated how the water model created here can assist in improving results from IDA3, and consequently in theory also of other models that take energy into account.

Figure 4.1 presents the modelling framework adopted for this thesis, presenting the main inputs, outputs, and processes. Each one of them will be discussed in more detail in subsequent subsections of chapters 4 and 5. In general, the methodology consists of the following steps: a) determining the nearest meteorological stations to the reservoirs, b) estimating the evaporation for each reservoir, c) estimating the water footprint of the hydropower plants, and d) performing a water budget analysis to estimate water availability in space and time. Finally, the outputs of the water model are used as inputs for the IDA3 model, although they could be used for other models in the same way.
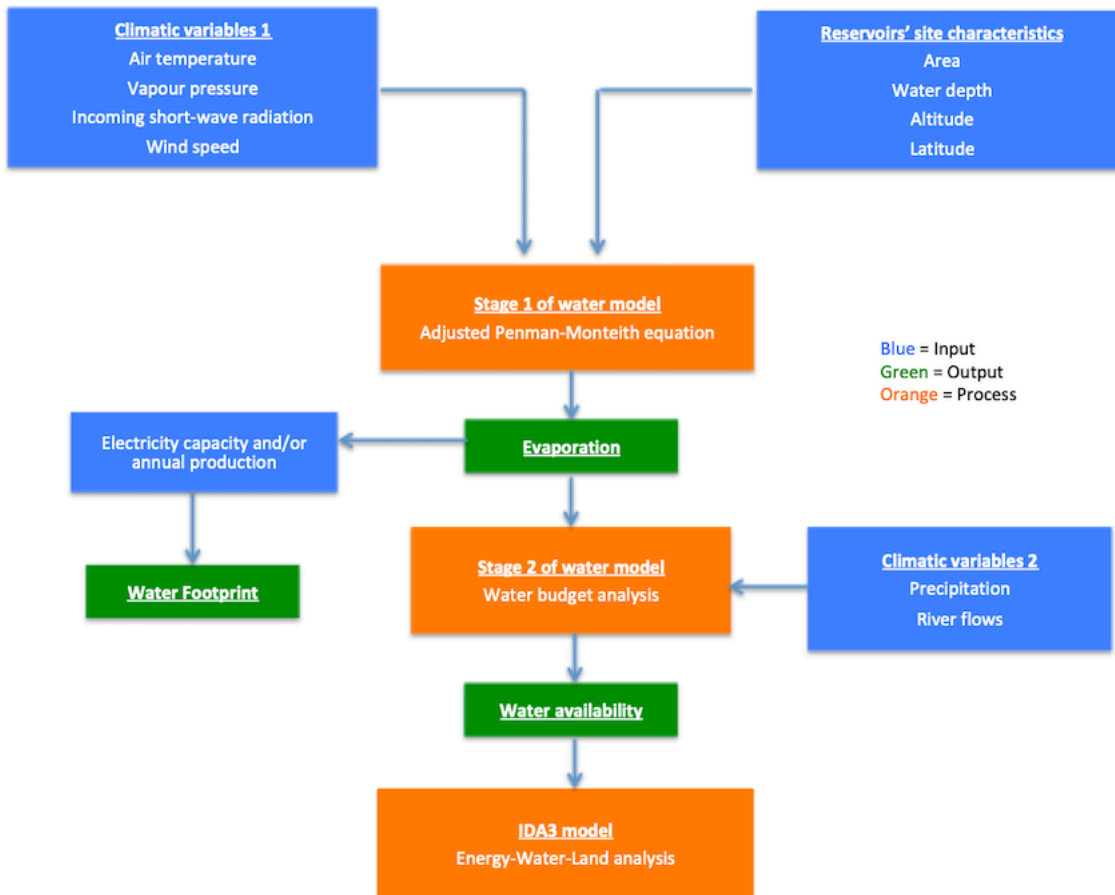
Figure 4.1 – The water model framework, with inputs, outputs and processes

4.2. Determination of nearest meteorological stations

To find the nearest meteorological stations to the reservoirs, the spherical law of cosines was used, which is described by the following equation:

$$d = \mathrm{acos}(sin\varphi1 \times sin\varphi2 + cos\varphi1 \times cos\varphi2 \times cos\Delta\lambda) \times R \; (\textit{Equation 4.1})$$

where φ is latitude, λ is longitude and R is the earth's radius (mean radius = 6,371 km)

4.3. Estimation of water evaporation

McMahon et al. (2013) conclude that the Penman-Monteith model that incorporates a seasonal heat storage component and a water advection

component, and the Morton CRLE model are the most suitable ones to estimate evaporation from deep lakes and large voids. Since the Penman-Monteith method has not been used to estimate evaporation for the whole of Brazil before (unlike the Morton method, which ONS used in 2004), and since it is the method suggested by FAO, it was deemed suitable to use the Penman-Monteith equation (Equation 4.2), adjusted by McJannet et al. (2008) to account for deep lakes. This equation requires eight inputs, which are presented later on in detail. All other variables are calculated within the accompanying equations, and the physics behind them are explained in detail in the papers referenced. The equations of the method are the following:

$$E = \frac{1}{\lambda} \left(\frac{\Delta_w (Q-N) + 86400 \, \rho_a \, C_a \frac{(e_w - e_a)}{r_a}}{\Delta_w + \gamma} \right) \; (Equation \; 4.2)$$

where E = evaporation (mm/d)

λ = latent heat of vaporization (MJ/kg)

Δ_w = slope of the temperature saturation water vapour curve at water temperature (kPa/°C)

Q = net radiation (MJ/m^2 d)

N = change in heat storage in the water body (MJ/m^2 d)

ρ_a = density of air (1.2 kg/m^3)

C_a = specific heat of air (0.001013 MJ/kg °K)

e_w = saturation vapour pressure at water temperature (kPa)

e_a = daily vapour pressure (taken at 9:00 am) (kPa)

r_a = aerodynamic resistance (s/m)

γ = psychometric constant (kPa/°C)

$$\lambda = 2.501 - T_a \, 2.361 \, 10^{-3} \; (Equation \; 4.3)$$

where T_a = mean daily air temperature (°C)

$$\gamma = \frac{C_a \, 100}{0.622 \, \lambda} \; (Equation \; 4.4)$$

$$r_a = \frac{\rho_a \, C_a}{\gamma \left(\frac{f(u)}{86400}\right)} \ (Equation \ 4.5) \ (\text{Calder \& Neal, 1984})$$

where f(u) = wind function (MJ/m² d kPa)

$$f(u) = \left(\frac{5}{A}\right)^{0.05} (3.80 + 1.57 \, U_{10}) \ (Equation \ 4.6) \ (\text{Sweers, 1976})$$

where A = water body area (km²)

U$_{10}$ = average daily wind speed at 10m (m/s)

$$Q = K \downarrow (1 - a) + (L \downarrow - L \uparrow) \ (Equation \ 4.7)$$

where K⇓ = total daily incoming short-wave radiation (MJ/m² d)

α = albedo of water (0.08)

L⇓ = incoming long-wave radiation (MJ/m² d)

L⇑ = outgoing long-wave radiation (MJ/m² d)

$$L \downarrow = \left(C_f + (1 - C_f)\left(1 - \left(0.261 \, e^{-7.77 \, 10^{-4} \, T_a{}^2}\right)\right)\right) \sigma \, (T_a + 273.15)^4$$

(*Equation 4.8*) (Oke, 1987; Idso & Jackson, 1969)

where σ = Stefan-Boltzmann constant (4.9 E-09 MJ/m² °K⁴ d)

C$_f$ = Fraction of cloud cover (value from 0 to 1, with 1 being 100%
cover)

Equations 4.9 to 4.16 are all for the calculation of L⇓.

$$if \ K_{ratio} \leq 0.9 \ then \ use \ C_f = 1.1 - \ K_{ratio}$$
$$if \ K_{ratio} > 0.9 \ then \ use \ C_f = 2 \, (1 - \ K_{ratio}) \ (Equation \ 4.9)$$

(Jegede et al., 2006)

where K$_{ratio}$ = ratio of incoming short-wave radiation to clear sky short-wave
radiation

$$K_{ratio} = \frac{K\downarrow}{K_{clear}} \ (\textit{Equation 4.10})$$

where K_clear = clear sky short-wave radiation (MJ/m² d)

$$K_{clear} = (0.75 + 2 \ 10^{-5} \ \psi) \ K_{ET} \ (\textit{Equation 4.11})$$

(Allen et al., 1998)

where ψ = water body altitude (m)

K_ET = extraterrestrial short-wave radiation (MJ/m² d)

$$K_{ET} = \frac{24 \ (60)}{\pi} \ 0.082 \ d_r \ (\varpi_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\varpi_s)) \ (\textit{Equation 4.12})$$

where d_r = inverse relative distance Earth-Sun

ϖ_s = sunset hour angle

φ = latitude (radians)

δ = solar decimation

$$\varpi_s = \frac{\pi}{2} - \arctan \left(\frac{-\tan(\varphi) \tan(\delta)}{X^{0.5}}\right) \ (\textit{Equation 4.13})$$

where X = X-factor

$$X = 1 - \ (\tan(\varphi))^2 \ (\tan(\delta))^2 \ (\textit{Equation 4.14})$$

$$\delta = 0.409 \sin \left(\frac{2\pi}{365} \ J - 1.39\right) \ (\textit{Equation 4.15})$$

where J = day of the year

$$d_r = 1 + 0.033 \cos \left(\frac{2\pi}{365} \ J\right) \ (\textit{Equation 4.16})$$

$$L\uparrow = 0.97 \ \sigma \ (T_w + 273.15)^4 \ (\textit{Equation 4.17})$$

where T_w = water temperature (°C)

Equations 4.18 to 4.25 are all for the calculation of L⇑.

$$T_w = T_e + (T_{w0} - T_e)e^{\frac{-1}{\tau}} \ (Equation \ 4.18)$$

(de Bruin, 1982)

where T_e = equilibrium temperature (°C)

T_{w0} = water temperature at the previous time step

τ = time constant (days)

$$T_e = T_n + \frac{Q_n}{4 \ \sigma \ (T_n+273.15)^3+f(u)(\Delta_n+\gamma)} \ (Equation \ 4.19)$$

(de Bruin, 1982)

where T_n = wet-bulb temperature (°C)

Q_n = net radiation at wet-bulb temperature (MJ/m² d)

Δ_n = slope of the temperature saturation water vapour curve at
wet-bulb temperature (kPa/°C)

$$T_n = \frac{0.00066 \ 100 \ T_a+\left(\frac{4098 \ e_a}{(T_d+237.3)^2}\right)T_d}{0.00066 \ 100+\frac{4098 \ e_a}{(T_d+237.3)^2}} \ (Equation \ 4.20)$$

(Jensen et al., 1990)

where T_d = dew point temperature

$$T_d = \frac{116.9+237.3 \ \ln(e_a)}{16.78- \ \ln(e_a)} \ (Equation \ 4.21)$$

$$\Delta_n = \frac{4098 \ (0.6108 \ e^{\frac{17.27 \ T_n}{T_n+237.3}})}{(T_n+237.3)^2} \ (Equation \ 4.22)$$

$$Q_n = K \downarrow (1-a) + (L \downarrow -L \uparrow_n) \ (Equation \ 4.23)$$

where $L\Uparrow_n$ = outgoing long-wave radiation at wet-bulb temperature
$(MJ/m^2 d)$

$$L\uparrow_n = \sigma\,(T_a + 273.15)^4 + 4\,\sigma\,(T_a + 273.15)^3\,(T_n - T_a) \quad (\textit{Equation 4.24})$$

$$\tau = \frac{\rho_w\,C_w\,Z}{4\,\sigma\,(T_n+273.15)^3 + f(u)(\Delta_n + \gamma)} \quad (\textit{Equation 4.25})$$

(de Bruin, 1982)

where ρ_w = density of water $(1000\ kg/m^3)$

C_w = specific heat of water $(0.004185\ MJ/kg\ °K)$

Z = water depth (m) (could be a time series, although due to lack of such data, an average depth was calculated and used)

$$N = \rho_w\,C_w\,Z\,(T_w - T_{w0}) \quad (\textit{Equation 4.26})$$

$$e_w = 0.6108\ e^{\frac{17.27\,T_w}{T_w+237.3}} \quad (\textit{Equation 4.27})$$

$$\Delta_w = \frac{4098\,(0.6108\ e^{\frac{17.27\,T_w}{T_w+237.3}})}{(T_w+237.3)^2} \quad (\textit{Equation 4.28})$$

Apart from the ability to take depth of the reservoir, and therefore water body heat storage into account, a further reason why the Penman-Monteith method was selected includes the fact that the kind of data needed for evaporation estimation are becoming increasingly available throughout the world, thus deeming the model appropriate to be used for a variety of water bodies anywhere in the world.

Using the adjusted Penman-Monteith equation requires hourly data, which were not collected in Brazil before circa 2006. To the best of my knowledge, there is no nationwide network for monitoring reservoir evaporation in Brazil, so it is important to have actual values of the aforementioned inputs for this equation (net radiation, air temperature, vapour pressure, and wind

speed). It is recommended that evaporation estimates be based on data from a nearby weather station that is considered to have a similar climate to the site in question (McMahon et al., 2013). In recent years with the introduction of a number of new weather stations, it has become feasible to have a good proximity of weather stations and reservoirs, making in turn calculations feasible and more reliable.

The method requires eight different inputs, which are separated into site characteristics and time series inputs. Table 4.1 presents these inputs and the source for the data required.

Site characteristics		Time series	
Input	Source	Input	Source
A = water body area (km^2)	ANEEL (The Brazilian Electricity Regulatory Agency) and power station websites	T_a = mean daily air temperature (°C)	Provided by INMET (The Brazilian National Institute of Meteorology) after personal communication
Z = water depth (m)	Calculated using reservoir capacity data from ONS and AQUASTAT (FAO's information system on water and agriculture)	e_a = daily vapour pressure (taken at 9:00 am) (kPa)	Calculated by knowing the air temperature at 09:00 am of each day
ψ = water body altitude (m)	Google Earth Pro and power station websites	$K\Downarrow$ = total daily incoming short-wave radiation (MJ/m^2 d)	Provided by INMET after personal communication
φ = latitude (radians)	Google Earth Pro and power station websites	U_{10} = average daily wind speed at 10m (m/s)	Provided by INMET after personal communication

Table 4.1 – Inputs for the modified Penman-Monteith equation for calculation of evaporation

4.4. Estimation of the water footprint

It could be argued that using the net water consumption method for calculating the water footprint of a reservoir would be more appropriate, since evapotranspiration (river evaporation, and evapotranspiration from land and vegetation) took place in the same area nevertheless. There are two counter arguments though.

Firstly, as noted by Mekonnen & Hoekstra (2012), the water footprint is not meant to refer to additional evaporation compared to a reference situation, but rather to quantify the volume of water consumption that can be associated with a specific human purpose, the generation of electricity in this case. If the area presently inundated were previously used for agricultural purposes or any other human activity, then the evapotranspiration taking place would be attributed to agricultural or other activities. In the same way in this case, since the water is solely used for the generation of electricity, it makes sense to attribute the ensuing evaporation to electricity generation. Secondly, as explained earlier, the estimation of evapotranspiration from vegetation and land from 163 different areas would be extremely difficult, taking into account that most of the reservoirs are many decades old, and data for the river surface and vegetation present at those moments in time does not exist in most cases. Hence, many heavy assumptions would need to take place.

With these things in mind, and since it is the most commonly used method in literature, the gross water consumption method for the estimation of water footprint was used in this analysis, which is based on Gleick (1992) and Mekonnen & Hoekstra (2012):

$$WF \ = \ \frac{WE}{EG} \quad (Equation \ 4.29)$$

where WF = water footprint (m^3/GJ)

WE = water evaporated (m³/yr)

EG = energy generated (GJ/yr)

The total volume of evaporated water from the hydropower reservoir over the year is calculated by:

$$WE = A \times \sum_{t=1}^{365} E \quad (Equation\ 4.30)$$

where A = area of the reservoir (km²)

E = daily evaporation (mm/day)

It needs to be noted that the water footprint was calculated in this thesis on an hourly basis, so E in equation 4.30 was actually mm/hour.

4.5. Water budget analysis equations

As it was explained in section 3.4, quantification of water resources is done in the context of a water budget, describing the movement of water in, through and out of a specific volume, which in this case study is a hydroelectric reservoir. The main water budget according to Healy et al. (2015) is:

$$P + Q_{in} = ET + \Delta S + Q_{out}\ (Equation\ 4.31)$$

where P = precipitation

Q_{in} = surface and subsurface flow into the watershed

ET = evapotranspiration (in this particular case of reservoirs there is no transpiration taking place, due to lack of vegetation, so it is just evaporation from the reservoir surface)

ΔS = change in water storage

Q_{out} = surface and subsurface flow out of the watershed (including human withdrawals)

Availability of water in reservoirs is highly depended on the weather and also it is site specific. The fact that availability of water is site specific, and also the fact that generation of electricity is highly time relevant, makes it helpful to analyse the hydroelectric electricity on the smallest time step possible (daily in this case due to flow data), and each of the power plants/reservoirs individually. In this study, a water budget analysis for 151 hydropower plants in Brazil for the period 2010-2015 (2016 data for flow were not available) has been performed, in order to assess availability of water for electricity generation or other uses, and as shown above, river flow, precipitation, and evaporation data will be used to achieve this.

Water availability calculations in time and space, indicate which regions and specific reservoirs in the country are most at risk in regards to electricity production, and additionally the difference between precipitation and evaporation will also be presented for the study period. This analysis is based upon actual detailed estimations of evaporation for each reservoir, while the methodology used provides an approach on minimum standards and critical interlinkages, and a management system that could potentially increase the efficiency of both water use and electricity production, which is in line with water-energy nexus thinking. The use of these evaporation estimates, along with the specific water budget method used (including the specific algorithms, created in this thesis) for the whole hydroelectric system in Brazil in this much detail, has never been attempted in literature according to my knowledge, therefore providing a novel contribution to knowledge.

Equation 4.31 can be refined and customized depending on the goals and scales of a particular study. In this case, the goal is to reach the maximum water storage level possible at all times, without compromising the minimum safe outflow values. Thus, the main priority of the model is to keep the outflow value (Q_{out}) above the minimum restriction value, according to inflow plus precipitation minus evaporation. The second priority is to fill the reservoir up to its maximum capacity if there is

sufficient inflow plus precipitation minus evaporation. Finally, the reservoir is not allowed to fill more than its maximum capacity, in which case excess water is all flowing out of the reservoir.

The main period of interest for this research is from the 1st of January 2010 until 31st of December 2015. Nevertheless, the level values of the reservoirs on the 31st December 2009 do not exist, therefore based on the assumption that each reservoir was full the day the power plant started running, the analysis will take place in two parts. The first part is aimed at calculating the value of S_0, which is the level of the reservoir specifically on the 31st of December 2009 using equation 4.33, and the second part of the analysis uses equation 4.32, which is the actual water budget analysis of the whole hydroelectric system in Brazil for the period 2010-2015 with actual weather data and inflow values.

$$P + Q_{in} + S_0 = E + S + Q_{out} \ (Equation \ 4.32)$$

where S = storage (in million m³) at any given day, starting on the 1st of
        January 2010, or the second day of whenever Q_{in} data was
        available from, according to when the power plant was opened
    S_0 = storage (in million m³) on the 31st of December 2009, or
        maximum reservoir capacity on day the power plant was opened
    Q_{in} = the water inflow (in million m³) at any given day
    P = precipitation (in million m³) at any given day
    E = evaporation (in million m³) at any given day
    Q_{out} = the water outflow (in million m³) at any given day, which can
        take different values according to the restrictions set

Since actual detailed precipitation data (and consequently evaporation data) from the 1st of January 1931 do not exist, and the analysis period is 2010-2015, equation 4.32 is simplified and until the 31st of December 2009 becomes:

$$S_a + Q_{in} = S + Q_{out} \ (\textit{Equation 4.33})$$

where S = storage (in million m³) at any given day, starting on the 2nd of
January 1931, or the second day of whenever Q_{in} data was
available from, according to when the power plant was
opened. S becomes S_0 on the 31st of December 2009, to
be used in the next phase

S_a = storage (in million m³) on the day the power plant was opened,
which is taken as the maximum reservoir capacity

And we check:

1. If S ≥ max reservoir capacity ⟹
   $Q_{out} = S_a + Q_{in} - max \ reservoir \ capacity$, since we cannot let the
   reservoir overfill

2. If max reservoir capacity > S ≥ 0 ⟹ $Q_{out} = Q_{out}min$, since we want to
   keep a maximum reservoir capacity, but without causing problems
   downstream, thus always keeping the outflow above a minimum
   value

3. If S < 0 ⟹ $Q_{out} = S_a + Q_{in}$ and S = 0, this was put in place in case the
   values for storage became negative in the model

It is acknowledged that the level of reservoir values on the 31st of December
2009 would assist the process, but in order to not make a wild assumption,
it was decided to do the analysis in two parts as explained to get more
realistic reservoir values, using actual flow data. There is a small margin of
error in this estimation, but it was deemed being within reason, since as it
will be shown later on, the volume of water from flows greatly exceeds the
difference between precipitation and evaporation.

From the 1st of January 2010 until the 31st of December 2015, we have
precipitation and other weather data (thus the ability to calculate
evaporation as well), and the water budget equation becomes equation 4.32.

And we check:

1. If S ≥ max reservoir capacity ⇒
    $$Q_{out} = S_0 + Q_{in} + P - E - max\ reservoir\ capacity$$
2. If max reservoir capacity > S ≥ 0 ⇒ $Q_{out} = Q_{out}min$
3. If S < 0 ⇒ $Q_{out} = S_0 + Q_{in} + P - E$ and S = 0 (In case Q_{out} becomes negative, we take Q_{out} = 0)

Water inflow to reservoirs data (Q_{in}) exists on a daily basis starting from the 1st of January 1931, or from when the power plant started its operation, until the 31st of December 2015, taken from ONS. Hourly precipitation data (P) for each of the reservoirs exists from 1st January 2010 until 31st December 2016, which was provided by INMET after personal communication with them. Hourly evaporation data (E) for each reservoir will be calculated in chapter 6. ΔS values and Q_{out} values change according to what is happening to Q_{in}, P and E, but values of maximum reservoir capacity, minimum useful capacity, maximum safe outflow, and minimum safe outflow values (ONS, 2016) act as restrictions for the water budget equation. Although precipitation and evaporation values exist until 2016, the same does not hold true for flow data, so the study period is until 2015.

The model's results, which are performed for each reservoir, state, and region in the country on a daily basis, include the following:

*   Number of days the reservoir's volume is less than or equal to minimum useful capacity
*   Number of days the reservoir's volume is less than or equal to maximum reservoir capacity and greater than minimum useful capacity
*   Number of days the outflow volume is less than or equal to minimum outflow limit volume
*   Number of days the outflow volume is less than or equal to maximum outflow limit volume and greater than minimum outflow limit volume

- Number of days the outflow volume is greater than maximum outflow limit volume
- Number of days the inflow volume is less than the outflow limit volume
- Number of days the evaporation volume is greater than the precipitation plus inflow volume
- Volume of water present in the reservoir in million m^3
- Volume of inflow in million m^3
- Volume of outflow in million m^3
- Volume of minimum outflow in million m^3
- Volume of precipitation in million m^3
- Volume of evaporation in million m^3

The methodology presented here can theoretically be used for any reservoir, hydroelectric or other. Although, the main priorities, which are also restrictions for the model, are made specifically for hydroelectric reservoirs, and also the maximum and minimum limits used are specific for individual reservoirs in Brazil. If this method is to be replicated, these limits, and possibly priorities will need to be adjusted accordingly.

4.6. IDA3 model equations

The IDA3 model was developed by Spataru at University College London (Spataru, 2017; Spataru, 2014) and it is a dynamic energy-water-land model. The model captures trade-offs between energy, water, and land, and therefore it was deemed to be a good choice for the purposes of this thesis, since the link between water and energy is inherent. What is meant by trade-off is that the model takes into account the simultaneous existence of these resources and models their interactions, which is more evident from the following equations. The model also takes land into account, but this part was omitted for the purposes of this exercise, since the focal point was the WEN. The reason behind the model selection also had to do with the fact that it has already been validated for other case studies like France and

Egypt, but also more importantly Brazil, and the code has been made available, along with assumptions and limitations.

Equation 4.34 calculates the electricity supply requirements of each water supply category and the amount of treated wastewater.

$$WS_{c,a,i+1} = WS_{c,i} * (1 + gr_{c,a}) \text{ (\textit{Equation 4.34})}$$

where c = water supply category (agricultural, industrial, domestic)

i = time step

a = sub-area

gr = growth rate

Equation 4.35 calculates the energy demand for each service (PCW).

$$PCW_{c,a,i} = WS_{c,a,i} * fp_{c,a} \text{ (\textit{Equation 4.35})}$$

where fp = area-specific energy requirements

The total energy requirements for water services result from the sum of all assessed categories and sub-areas.

Equation 4.36 calculates the total power supply requirements (TPSR).

$$TPSR_i = PC_i / (1 - Leg_i) \text{ (\textit{Equation 4.36})}$$

where PC = power demand (comprised of base demand and the calculated demand for water services)

Leg = percentage grid losses

Equation 4.37 calculates power supply (PS). The 5 technologies include photovoltaic, hydro, wind, nuclear and thermoelectric generation.

Thermoelectric generation consists of oil, gas, coal and biomass as sub-categories. Storage is not part of the equations, which could be a future improvement of the model.

$$PS_{t,a,i} = GC_{t,a,i} * fc_{t,a,i} * ft \text{ (\textit{Equation 4.37})}$$

where t = technology

      GC = installed capacity

      fc = area and time specific capacity factors, accounting for seasonal variations and long-term climatic changes

      ft = time factor

The model has certain preferences in terms of generation in place. Firstly, photovoltaic, wind and nuclear capacities are to supply power. Secondly, hydropower is used, and lastly, thermoelectric capacity supplies the remaining demand. The prioritisation was made in accordance with other energy models and also environmental, economic and social concerns. These are not restrictive and it is possible to change them, however this would require researching further into various country issues, which goes beyond the scope of this thesis, where this exercise is just an example showing that it is possible to include detailed water availability data in a resource trade-off model.

Finally, equation 4.38 calculates water withdrawal (WW) for each technology and sub-area.

$$WW_{t,a,i} = PS_{t,a,i} * fww_t \text{ (\textit{Equation 4.38})}$$

where PS = energy supplied by the technology

      fww = technology-specific water withdrawal factor

It is recognised that the approach of prioritizing generation technologies is a simplification of complex electricity trading markets. The results are

reasonable as long as the amount of fluctuating generation capacity, like wind and PV, do not endanger grid stability (Spataru, 2014; Spataru, 2017; Senger & Spataru, 2015). It also needs to be noted that in the case of the link achieved in this thesis, the only important technology is hydropower, however other technologies are present in the Brazilian system and will play a role in the future too. Apart from showing that it is possible to include detailed water availability data through capacity factors in IDA3, the model was also ran to provide future projections (to 2050) of the national Brazilian generation capacity and power supply under different climate scenarios, which were devised in this thesis in chapter 7. This way it is possible to investigate if water availability affects different generation capacity futures, and allowing making better decisions about future capacity.

The important novelty in this case was that very detailed water model outputs (through capacity factors) are used as an input for the IDA3 model, substituting generic literature values that do not change through time. In its original run, IDA3 had a constant rate of capacity factor changes through time until 2050. The annual growth rates were the same for the North and the Northeast, and the same for the Midwest, Southeast and South. To achieve the link between the water model of this thesis and IDA3, some modifications regarding this took place. Since the results of IDA3 for this exercise were annual, a progression of annual capacity factors until 2050 was created for each of the five regions, thanks to water availability output data from the water model. Doing this, the five regions become distinct in regards of their water availability, and also the rate of growth of the capacity factors changes every year, based on detailed possible future climatic changes, that allows for more realistic changes of water availability through time.

Finally, it is important to note that this link between the models is a first step towards creating a combined method for addressing the WEN, and it serves merely as an example for the purposes of this thesis. However, it is

shown that such links are possible, and also that they can be useful.

4.7. Summary

This chapter was about the methods used that comprise the water model, whose results will be presented and analysed in chapters 6 and 7. Firstly, the framework is analysed, which is mainly based on water, since this is where the main gaps for the WEN were identified. Water and energy integration in a single framework has long been impaired by their fundamental conceptual differences, which have to do with spatial and temporal disparities. A smaller time step, and most importantly alignment of boundaries of the water and energy models is a significant contribution towards their linking. Also, certain useful metrics are missing to better comprehend water-energy issues, and the main one proposed to be analysed is the consumptive use of water by hydropower. Therefore, evaporation needs to be estimated in a small time step and appropriate spatial scale. Consequently, evaporation needs to be used to perform a water budget analysis to analyse water availability for electricity generation. Although the concentration of interest is on water modelling, nevertheless, the water model will be linked to the energy-water-land IDA3 model, in order to show what detailed water availability results can offer in an energy modelling context. In general, the novelty of this research lies on the detailed spatiotemporal modelling and analysis of water evaporation, water footprint, and water budget for 163 reservoirs/power plants in Brazil.

At first, the equation to determine the nearest metrological stations to the reservoirs was presented, which is an important first step for the best possible sources of data. Subsequently, the main equation, along with its secondary equations, for the estimation of evaporation was presented. The equation is the Penman-Monteith equation adjusted to account for deep lakes. This equation is the one suggested by FAO and it has not been used before to estimate evaporation for all hydropower reservoirs in Brazil. Also, before circa 2006, it was impossible to use such a method for a small time

step, since Brazil was lacking the number of weather stations it currently possesses. The introduction of a large number of weather stations in recent times allows for the estimation of evaporation to be very detailed and reliable. Ultimately, the water model is concluded by a water budget analysis. The main equation is presented, followed by the algorithms used to dictate operation. This water budget method, in this detail, for the whole hydroelectric system of Brazil, has also never been attempted in literature. In the case of evaporation estimation, the time step used was hourly, whereas for the water budget analysis it was daily. Spatially, each reservoir in the Brazilian system was treated separately, so there are no averages used anywhere in the analysis, accounting for the locality of each reservoir. These temporal and spatial scales allow for the water model to be linked with an energy model.

The final part of this chapter presented the main equations of the IDA3 model, which will be used as an example to show what detailed water availability results can actually offer to such a resource trade-off model. The linking of the models will be achieved through capacity factors for hydropower, which is the way most energy models get linked to water, as do the ones discussed in section 3.5.4, however not using detailed water availability data. The specifics of the linking will be analysed further in section 6.4, where it will be shown exactly how outflow values from the reservoirs can be used to estimate capacity factors, therefore achieving the necessary link. Finally, the specific capacity factors for hydropower used for the future scenarios will be presented in section 7.2.3.

The next chapter will set the scene for the analysis that will ensue in chapters 6 and 7, presenting the case study of Brazil. Furthermore, chapter 5 contains all the input data and assumptions that were used for the evaporation and water budget analyses, specific for Brazil, in detail in sections 5.6 and 5.7.

Chapter 5. Case study - Brazil

Chapter 4 described the methodology that will be used in the thesis, and now it is time to set the context of the analysis, which is the case study of Brazil. Firstly, some general information about the country and its climate will be presented, followed by the issues the country is facing regarding water and electricity. Then, the energy and water sectors will be analysed in order to gain a detailed understanding of them, but also pinpointing hazards. Furthermore, hydroelectric power plants/reservoirs are analysed in terms of capacity and reservoir area for both political and hydrographic regions. Moreover, methods and models used in literature to address WEN issues in Brazil are presented. Finally, input data and assumptions for the evaporation and water budget analyses are presented in detail, advocating transparency of the analysis to follow in chapters 6 and 7.

5.1. General information about Brazil

	1990	2000	2010	2017
Population (millions)	149.35	175.29	196.8	209.29
Population growth (%)	1.8	1.5	1.0	0.8
Surface area (km²)	8,515.8	8,515.8	8,515.8	8,515.8
Population density (people per km² of land area)	17.9	21	23.5	25
Income share by lowest 20% (%)	2.3	2.5	3.3	3.6
Forest area (thousand km²)	5,467.1	5,212.7	4,984.6	4,935.4
Energy use (kg of oil equivalent per capita)	939	1,069	1,351	1,485
CO_2 emissions (metric tons per capita)	1.4	1.87	2.13	2.59
Electric power consumption (kWh per capita)	1,457	1,892	2,361	2,601
GDP (Gross Domestic Product) (billion $US)	461.95	655.42	2,208.87	2,055.51

Table 5.1 – Brazil indicators from 1990 to 2017 (Source: World Bank databank)

Table 5.1 presents several indicators in order to create a context of Brazil as a country. Firstly, the population of the country as of 2017 was more than 209 million inhabitants making it the fifth most populous country on Earth after China, India, the United States, and Indonesia. The population is constantly growing, although the percentage of growth has halved since 1990. The surface area is 8,515.8km^2, which again makes Brazil the country with the fifth largest area on Earth after Russia, Canada, China, and the United States. The income share of the lowest 20% of the population is particularly low showing income disparities in the country. Environment-wise, Brazil is home to 60% of the Amazon rainforest, although the forest area in the country has been decreasing, with a percentage of 10% of total forest area lost since 1990. The energy usage per capita has increased from 939 to 1,485kg of oil equivalent from 1990 to 2017, which is almost a 60% increase. At the same time, the CO_2 emissions per capita have increased from 1.4 to 2.59 metric tons from 1990 to 2017, which is an 85% increase. Also, electric power consumption per capita has risen from 1,457 to 2,601kWh in the same period, which is a 78.5% increase. Finally, the GDP skyrocketed from 2000 to 2010 from 655.42 to 2,208.87 $US billions, while it dropped to 2,055.51 in 2017.

Brazil spans latitudes 5°N to 32°S, which are mostly tropical latitudes and the altitude of the midday sun is always close to vertical. Because of this, the climate is very warm throughout the year in the whole country, with some changes occurring in the southern parts. The seasonal variations in temperature are small and the daily maxima on low ground are typically 30-34°C. The mean annual temperature at low ground stations in most of the country is ~26-27°C, although much of central and southern Brazil is on a high plateau, which means a drop of ~6°C per 1000m of ascent. As an example, the country's capital, Brasília, has a mean temperature of ~21°C. Mean low ground temperature gradually falls to ~20°C near the borders. There is more seasonal change in temperature that far south, with lower winter temperatures, while the mean temperature of the warmest month remains to about 26°C. Frosts and snow are a rare occurrence, but a

possibility during invasions of cold air from the Antarctic. Furthermore, most of Brazil has high rainfall, which is partly attributed to the Inter-Tropical Convergence Zone (ITCZ). The Amazon Basin sees an annual average rainfall that exceeds 2000mm, and even the "dry" season of June-October has typically 60-120mm per month. The "wet" months can have even 400mm on average. Brasília receives about 1550mm of annual rainfall. In contrast to the rest of the country, the Northeast is relatively dry, averaging 750mm per year in places, and there are large variations from year to year, which frequently result in prolonged droughts (Met Office, 2011). The climate of Brazil will be discussed in more detail in chapter 7.

5.2. The main issues Brazil is facing in regards to water and electricity

Brazil recently faced its worst drought in 40 years, which resulted in hydropower consumption decrease of 7% in 2013 and 5.5% in 2014 (BP, 2015). In December 2014 the biggest dams were at only 16.1% capacity (Morales, 2014). Inhabitants and the agriculture sector suffered due to the lack of water, while cities were hit by blackouts due to weak hydroelectricity generation and high demand for services (e.g. use of air conditioning due to high temperatures). To partly alleviate the problem, the assistance of burning more fossil fuels was required. Brazil faced several droughts in the past years, and it is anticipated that this trend will continue and increase in intensity and frequency, mainly in the Northeast of Brazil due to climate change (World Bank, 2013). Water availability in general is recognized as being an issue for Brazil, which is alarming for the electricity sector, since the hydroelectric production in Brazil historically accounts for more than 70% of the country's electricity supply matrix, with a capacity of 91.348GW in 2014. An additional 31.7GW of capacity was expected to be installed, as of 2014, in the northern region to match with the country's growing economy (Westin et al., 2014).

As seen in table 5.1, the population has increased by 34 millions since 2000. Economic and social development invariably leads to urbanization and increased standards of living. In turn these changes require increased amounts of energy and water, among other resources. While at the same time, climate change is affecting temperature and precipitation. Rising temperatures accelerate water movement, increasing both evaporation and possibly precipitation. Also, there are falling average surface water flows, higher surface water temperatures, sea level rise that will contaminate freshwater supplies, and droughts, heat waves and floods that are more frequent and more severe (IPCC, 2008; IPCC, 2014). Hence, climate change has an immediate effect on water resources and the energy industry in general, creating a vicious circle.

Decreasing water availability directly impacts nearly all aspects of energy supply, and namely how electricity is produced, where future capacity might be sited, production costs, types of generation and cooling technologies and their costs, the methods and costs of extraction, production and delivery of fuels (U.S. DOE, 2013). Thermal plants with once-through cooling and hydropower can be particularly exposed to fluctuations in water availability (IEA, 2012a). Bioenergy production can also be affected. Consequently, in water scarce regions, competition for water between energy production and other uses will also increase, indirectly not allowing for economic development and stability (WEF, 2014). At the United Nations General Assembly thematic debate in 2013, it was recognized that rain patterns and irrigation would play an important role for the reservoir management of hydropower and also biofuels.

Brazil started taking water issues more seriously in 1997, when law No. 9433 (also known as the "water law") came into force, establishing the National Policy of Water Resources (PNRH) and creating the National Water Resources Management System (SINGREH) and the National Water Agency (ANA). The water law produced a decentralized and participative management style and one of the main foundations upon which it was based

is that *"in situations of water resources scarcity, priority of use will be given to human consumption and quenching animal thirst"*, which gives an indication as to what should be prioritized in times of drought. Also, it is ANA's aim to make sure different water usages are complementary, without one hindering another, but also to prevent critical water-related events (ANA, 2014).

Energy wise, in 2006, the Ten Year Plan for Energy (PDE) 2006-2015 was approved by the Ministry of Mines and Energy (MME), which was a design for policies for the energy sector. As part of this initiative, in 2007, the National Energy Plan (PNE) 2030 was released, which was to be used for long-term planning, directing trends and underlain energy supply alternatives in the subsequent decades. In this report, the state-run Energy Research Company (EPE) predicts that by 2030 the country will generate 1,056TWh of energy, of which 77% from hydro, 9% natural gas, 5% from nuclear power plants, 4% biomass, 3% coal and derivatives, 1% of oil and 1% wind power (Instituto Escholhas, 2015).

After the PNE 2030 in 2007, EPE/MME conducted the second long-term study PNE 2050, presenting the evolution of the demands of the acceding energy to long-term economic scenario. The PNE 2030 was used in various ministerial spheres as an economic and energy baseline scenario of long-term federal government, and also from various stakeholders in the energy sector. It was crucial in strengthening and prioritizing hydroelectricity, for indicating natural gas as a complement to the generation matrix, the consolidation of ethanol in the matrix fuels, and also indicating the high potential of oil and natural gas in the country. PNE 2050 is a response to new events that have happened since 2006 and have an impact on the energy sector, like the competitiveness of wind energy, the rise of oil and natural gas supply, and global events like Fukushima, the extension of the economic crisis and the growing concern over climate change (EPE, 2016).

The main strategy of the Brazilian government for energy supply expansion so far has consisted of the construction of the large-scale hydropower plants in Santo Antonio (3,150MW) and Jirau (3,300MW) on Madeira River, and Belo Monte (11,233MW) on Xingu River, all three being in the Amazon Basin (Andrade Guerra et al., 2015). This existing power policy of mainly hydropower expansion (predominantly in the Amazon region) and also future plans for "run-of-the-river" plants, with small or no reservoirs at all, creates issues on many levels, since decisions to build large power plants are made long before consulting locals, which indicates a lack of nexus thinking in the planning process, while at the same time leaving the power supply system highly susceptible to events like droughts, which is a fact recognised in recent work done for Brazil by Nogueira et al. (2014) and Lucena et al. (2016). As of 2013, thermal power generation in Brazil mostly fuelled by natural gas and sugarcane bagasse, acts as a complementary source to hydropower, in an attempt to optimize the system's operation (Nogueira et al., 2014), which causes further concerns.

5.3. Analysis of the water and energy sectors in Brazil

In order to identify the main points of interest in relation to the WEN in Brazil, the first step is to look at the two sectors in more detail. This analysis presents a general picture of the water and energy sectors in Brazil, based on the year 2014 or whenever the latest data were available for.

5.3.1. Analysis of the energy sector
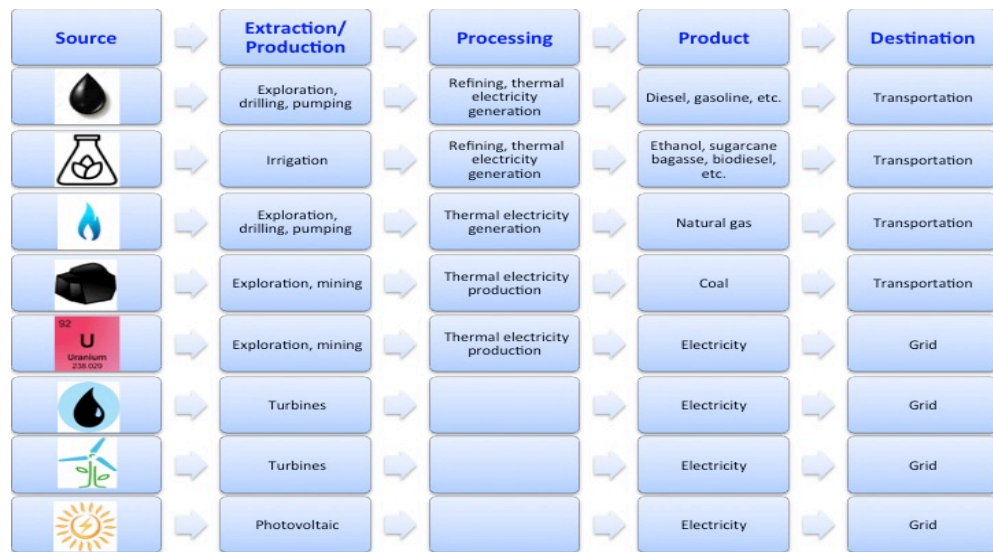
Figure 5.1 – Energy pathways

Figure 5.1 shows the main energy sources of Brazil and the processing they go through. Water is used in most of those steps in various ways. For example, in the oil pathway, water is used in drilling, hydraulic fracturing, water floods, steam heat, cooling, steam for turbines, and refinery. For biomass, water is used in irrigation of the crops, cooling, steam heat, steam for turbines and refinery. Natural gas uses water in drilling, hydraulic fracturing, cooling and steam for turbines. Coal uses water in drilling, irrigation, coal washing, dust suppression and cooling, cooling and steam for turbines. Uranium processes use water in drilling, dust suppression, uranium enrichment, cooling and steam for turbines. Wind and solar water uses are deemed negligible. The consumption of water by hydroelectricity for Brazil will be discussed in detail in chapter 6.
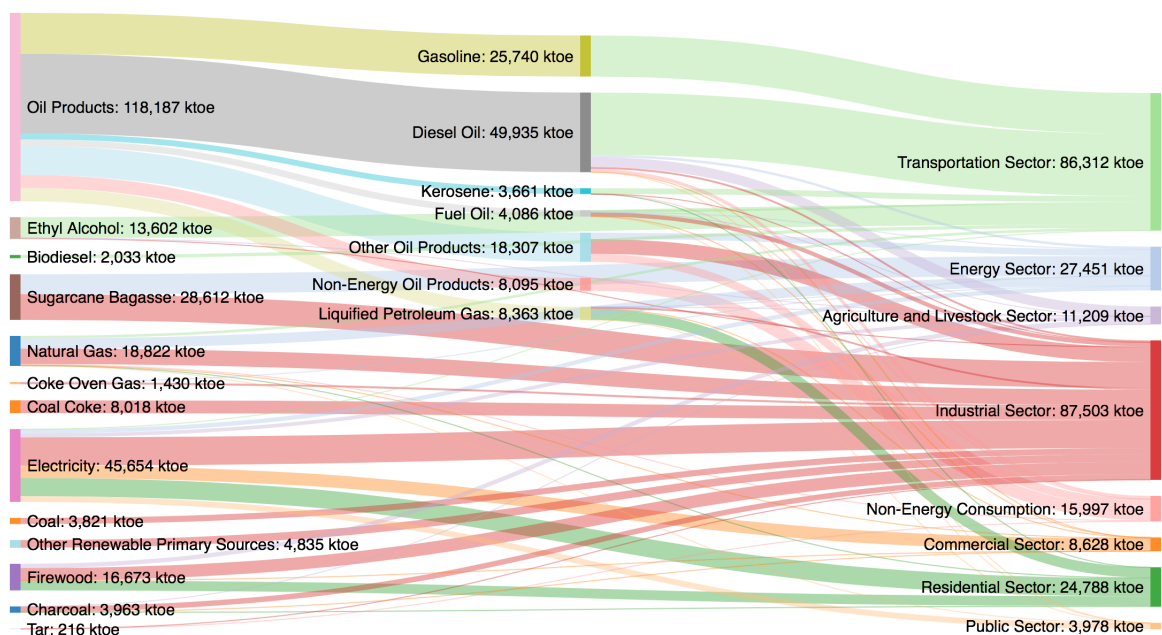
Figure 5.2 – Energy consumption by source and sector in Brazil in 2014

(Data source: EPE, 2015a)

Figure 5.2 shows the flow of energy consumption in Brazil by source and sector for the year 2014. The total amount of energy consumed was 265,864ktoe. The most important source of energy is oil products with 118,187ktoe, from which most consists of gasoline and diesel oil for the transportation sector. Electricity comes second with 45,654ktoe, with most of it going to the industrial, residential, and commercial sectors. Sugarcane products (ethyl alcohol and sugarcane bagasse) come third with 42,214ktoe, with ethanol being used almost solely in the transportation sector and sugarcane bagasse being split between the energy and industrial sector. These three sectors are the ones that in all likelihood ought to be investigated more closely.
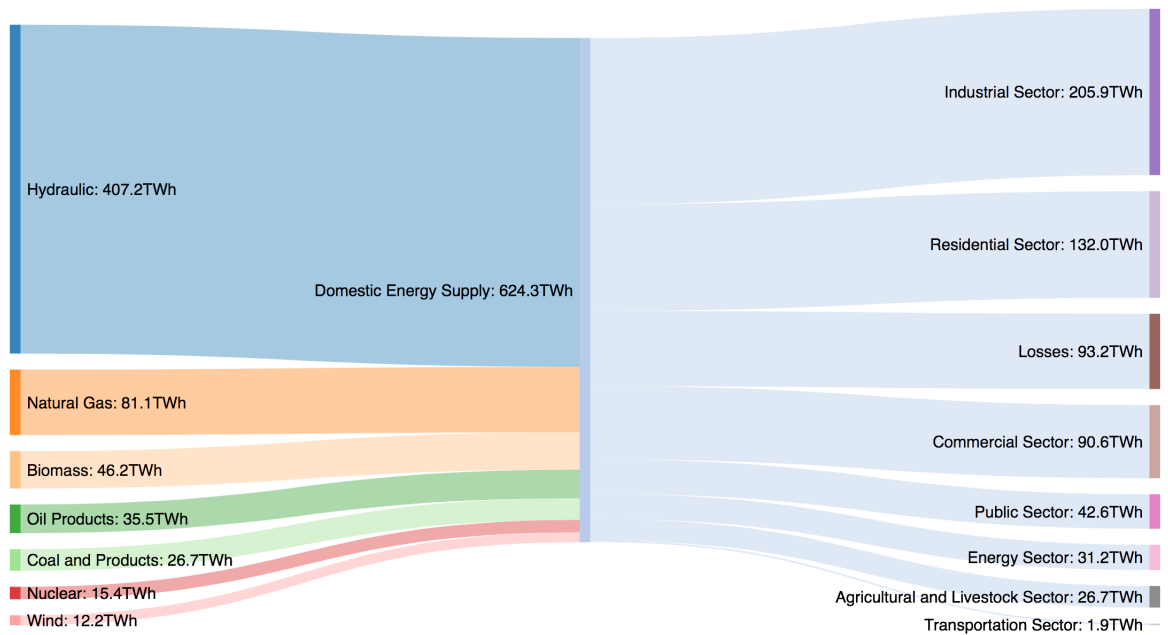
Figure 5.3 – Domestic electricity supply in Brazil in 2014 (Data source: EPE, 2015a)

Electricity supply is presented in more detail in figure 5.3. Most of Brazil's electricity is produced by hydroelectric power plants, followed by natural gas, biomass and oil products. The percentage of hydraulic energy supply has decreased in recent years, mainly due to increased overall demand and frequent droughts. Nevertheless, this percentage exceeds 60-65% on a constant basis, making hydropower the obvious main focus of analysis in a WEN context. Additionally, analysis of thermoelectric power plants and their efficiencies could prove beneficial, since their usage has been increasing in recent years.

Source	2005	2014	Change (%)
Natural Gas	13,410	18,822	+28.8
Firewood	16,119	16,672	+3.3
Sugarcane Bagasse	21,147	28,612	+26.1
Electricity	32,267	45,655	+29.3
Ethyl Alcohol	7,324	13,602	+46.1
Oil Products	83,954	118,186	+29.0
Diesel Oil	32,643	49,935	+34.6
Gasoline	13,638	25,740	+47.0
Total (*including sources not in the list*)	195,491	265,864	+26.5

Table 5.2 – Final energy consumption by sector in ktoe in 2005 and 2014

(Data source: EPE, 2015a)

Table 5.2 presents final energy consumption by source for the most prominent sources in 2005 and 2014. Unsurprisingly, due to a population and living standards increase, the overall energy consumption goes up by 26.5% within 10 years. Gasoline and ethyl alcohol saw huge increases of a bit less than 50%, diesel oil also increased by about 35%, with electricity coming fourth with an almost 30% increase. Generally, all the main sources of energy saw a considerable increase. The only sources that saw a decrease (although not in the table since they are relatively insignificant) are charcoal, fuel oil and naphtha.

	Population	Oil (10^6 m^3)	Natural Gas (10^6 m^3)	Hydraulic Potential (MW)	% of hydraulic potential being operated or being built
North	17,231,027	13	52,383	100,370	31 (19+12)
Northeast	56,186,190	146	45,329	22,102	52
Midwest	15,219,608	0	0	39,663	31 (28+3)
Southeast	85,115,623	2,414	373,383	43,757	59
South	29,016,114	0	0	41,351	59
Brazil Total	202,768,562	2,573	471,095	247,242	42 (37+5)

Table 5.3 – Proven reserves and hydraulic potential in 2014 (Data sources: IBGE, 2016; EPE, 2015a)

Brazil is a very large country and the resources within it are not evenly distributed. Table 5.3 shows the population (in 2014) and the reserves of oil, natural gas and hydraulic potential divided in the five main geographical areas of Brazil. Most of the population is concentrated in the Southeast and Northeast of the country. The Southeast has most of the country's oil and natural gas reserves, and also good hydraulic potential. The Northeast has some natural gas potential, while it has the least hydraulic potential. Most of the hydraulic potential is concentrated in the North, although environmental reservations as to the exploitation of this potential are high due to the ecological importance of the Amazon rainforest and river. However, this is where most of the planned hydroelectric plants are being built, due to the potential of the area.

	Hydro (MW)	Thermo (MW)	Wind (MW)	Solar (MW)	Nuclear (MW)	Total (MW)	Oil Refineries (m³/day)	Natural Gas plants (10³ m³/day)
North	16,070	3,684	0	0	0	19,754	7,300	9,706
Northeast	11,553	9,530	3,904	7	0	24,993	79,353	24,500
Midwest	11,895	4,244	0	0	0	16,139	0	0
Southeast	25,129	15,981	28	4	1,990	43,131	210,056	62,490
South	24,546	4,389	956	4	0	29,895	67,700	0
Brazil total	89,193	37,827	4,888	15	1,990	133,913	364,409	96,696

Table 5.4 – Installed capacity of electrical generation, oil refineries and

natural gas plants in Brazil in 2014 (Data source: EPE, 2015a)

Table 5.4 shows the installed capacity of electrical generation in each region of Brazil, along with the oil refineries and natural gas plants. Most of the hydro capacity is in the Southeast and South, while most of the thermoelectric plants are located in the Southeast and the Northeast. The Northeast has the most wind capacity, followed by the South. The two sole nuclear plants of the country are located in the Southeast, while solar capacity is a non-factor in comparison with the rest. The Southeast also has the most oil refineries and natural gas plants. This concentration of capacity in the Southeast could pose a risk for the future of the system in the country. At the same time, the Northeast with its historical water availability issues is most likely not ideal for hydro or thermo plants, however it could be ideal for wind and solar energy.

	Consumption (GWh)	Consumption per capita (kWh/capita)
North	32,364	1,865
Northeast	80,746	1,432
Midwest	34,381	2,243
Southeast	243,123	2,846
South	84,819	2,912
Brazil	475,432	2,630

Table 5.5 – Consumption of electricity by geographic region and per capita

in Brazil in 2014 (Data Source: EPE, 2015b)

Table 5.5 shows the total and per capita consumption by geographic region. The Southeast has the largest population, which is evident from the total consumption, followed by the South and the Northeast. The per capita values indicate that the South is the most affluent region, followed closely by the Southeast, whereas the Northeast that has the second largest population within the Brazilian regions has by far the lowest per capita value. If the Northeast's per capita consumption was to follow other regions' trends, it would need a lot of additional capacity.

	Consumption (GWh)	Percentage (%)
Residential	132,399	27.8
Industrial	179,618	37.8
Commercial	81,840	18.9
Rural	25,671	5.4
Public sector	15,354	3.2
Public lighting	14,043	3.0
Public service	15,242	3.2
Own use	3,265	0.7
Total	475,432	100

Table 5.6 – Consumption by sector in Brazil in 2014 (Data Source: EPE, 2015b)

Finally, table 5.6 shows in which sectors consumption of electricity occurs within Brazil. The most "electricity hungry" sectors are the industrial and residential with 37.8 and 27.8% respectively, followed by the commercial sector with 18.9%.

5.3.2. Analysis of the water sector

After the analysis of the energy sector and having an idea as to where attention needs to be drawn, it would be beneficial to analyse the water sector, since water is of the highest importance in Brazil due to its hydropower share, and also its large population. It will furthermore make the WEN connections clearer. Here it needs to be mentioned that water data in Brazil does not have the same availability nor is it of the same quality as

that for energy. Unlike the energy sector, the national water agency in the country (ANA) does not have the funds, nor consequently the capacity to produce detailed datasets. ANA produces a detailed report, alas with very little data, every four years (last one available at time of analysis in 2013) and a smaller one every year (last one available at time of analysis in 2015). They do however provide some useful data like the ones presented in the following tables.

	Water demand (m³/s)	Percentage (%)
North	156.98	6.6
Northeast	604.08	25.5
Midwest	297.58	12.5
Southeast	789.74	33.3
South	524.45	22.1
Brazil	2,372.83	100

Table 5.7 – Regional water demand in m³/s in Brazil in 2010 (Data source: ANA, 2013)

Table 5.7 shows that unsurprisingly the Southeast has the highest water demand, followed by the Northeast and the South, following a similar trend as to where population is located, but also electricity capacity.

	2006				2010				2014			
	Withdrawal		Consumption		Withdrawal		Consumption		Withdrawal		Consumption	
Brazil	1,842 m³/s	%	986 m³/s	%	2,373 m³/s	%	1,161 m³/s	%	2,275.07 m³/s	%	1,209.64 m³/s	%
Industrial	313	17	69	7	395	17	78	7	346.28	15	69.26	6
Animal	147	8	118.4	12	151.5	6	125	11	135.38	6	108.30	9
Urban	479	26	98.7	10	522	22	104	9	503.27	22	100.65	8
Rural	37	2	19.8	2	34.5	1	18	1	37.61	2	18.80	2
Irrigation	865.5	47	680.5	69	1,270	54	836	72	1,252.73	55	912.63	75

Table 5.8 – Total withdrawal and consumption of water in Brazil (Data source: ANA, 2013; ANA, 2009; ANA, 2015)

Table 5.8 shows the withdrawal and consumption of water in Brazil by different sectors, as is recorded by ANA, which is not the same as energy data for the country. Nevertheless, we can see that the irrigation in the country accounts for most withdrawal, about 50%, but also most of the

consumption as well, passing 75% in 2014. Animal water withdrawal and consumption could be added to irrigation, as is done with energy data, which would make these percentages even higher. An important trend is that withdrawal and consumption have risen through the years for irrigation, which means that there is a trend of rising agriculture economy, and/or more water-dependent crops in the country.

Brazil, as it was shown earlier, is a large bioethanol producer. The main crop used for the production of bioethanol is sugarcane, which is for the most part rainfed, so it does not require irrigation in theory. However, a change in climate in the future could deem precipitation not enough to satisfy the water requirements of sugarcane cultivation. In this case, the water required by these crops is significant to say the least, as is shown in table 5.9, which is something to keep in mind. For comparative purposes, the average consumptive water intensity of unconventional oil is 100 m^3/TJ (data source: Williams & Simmons, 2013) and that of sugarcane 4400 m^3/TJ.

	Average crop water use	Average irrigation calculated	Withdrawal intensity of ethanol
Rainfed	9,627	0	0
Irrigated	15,942	7,402	4.4

Table 5.9 – Sugarcane average water use and average irrigation (m^3/ha/yr), and withdrawal intensity (1,000 m^3/TJ) (Data source: Williams & Simmons, 2013)

Table 5.10 shows the average flows and water availability for the 12 hydrographic regions of Brazil. It becomes immediately apparent that most of the flow exists in the Amazon, and the other two regions with large average flows are the Tocantins-Araguaia and Paraná.

Hydrographic region	Average flow (m³/s)	Water availability (m³/s)
Amazônica	132,145	73,748
Tocantins-Araguaia	13,799	5,447
Atlântico Nordeste Ocidental	2,608	320
Parnaíba	767	379
Atlântico Nordeste Oriental	774	91
São Francisco	2,846	1,886
Atlântico Leste	1,484	305
Atlântico Sudeste	3,167	1,145
Atlântico Sul	4,055	647
Paraná	11,831	5,956
Uruguai	4,103	565
Paraguai	2,359	782
Brazil	179,938	91,271

Table 5.10 – Average flow and water availability of the 12 hydrographic regions of Brazil (Source: ANA, 2013)

Finally, figure 5.4 is a map of Brazil, by the Brazilian Institute of Geography and Statistics (IBGE), providing a geographical reference of the distribution of population per hydrographic region in the country. The map shows that most of the population is located in regions of relatively low river flows and water availability, with the exception of the Paraná region, which though is also the region where most of the population of the country is located.
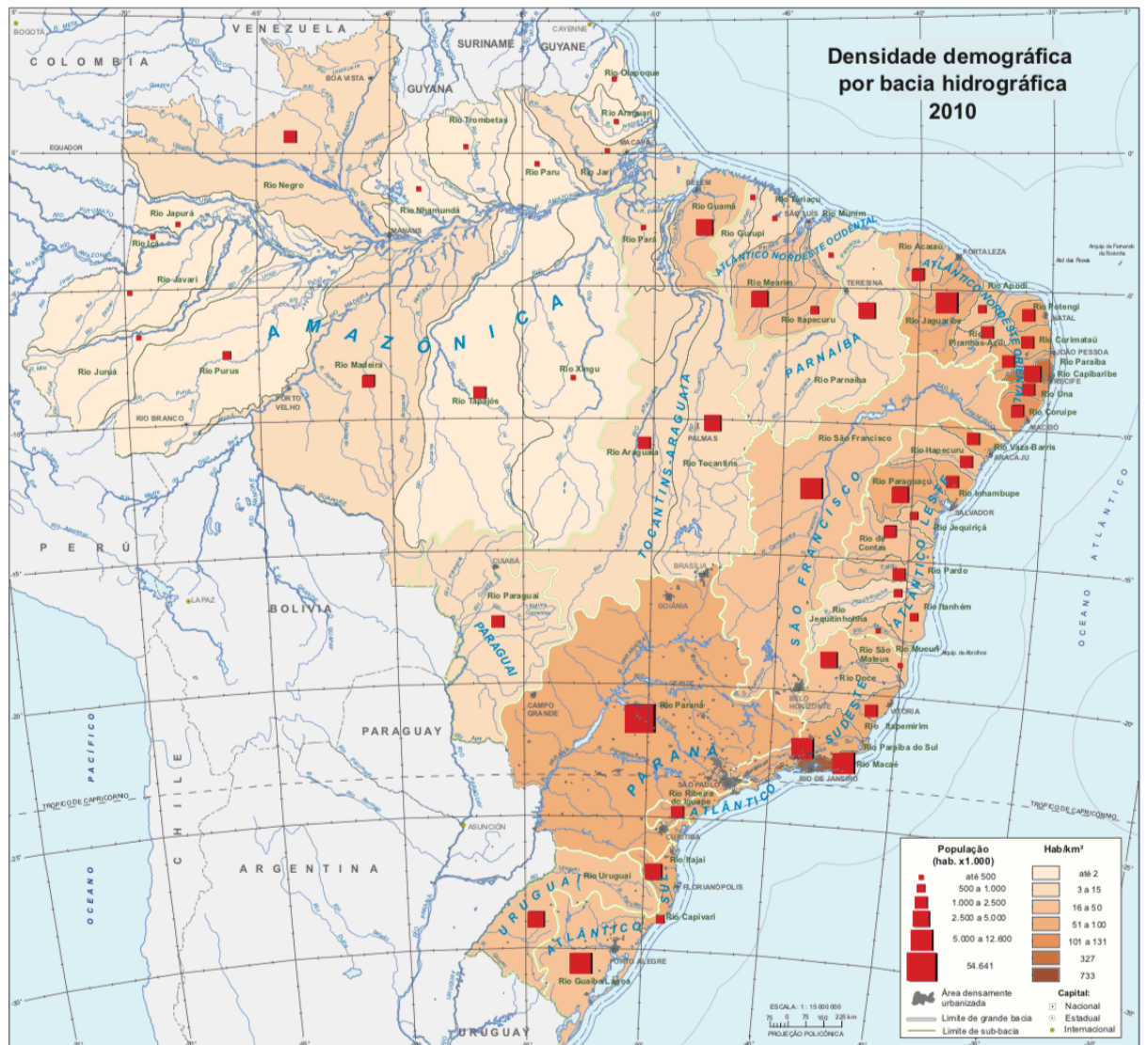
Figure 5.4 – Distribution of population per hydrographic region in 2010
(Source: IBGE, 2010)

Both the energy and water analyses were done to create a general picture of energy and water in the country, which helps to better understand the issue at hand. The rest of the chapter will concentrate on hydroelectricity in Brazil, firstly by analysing the Brazilian system in terms of hydroelectric capacity and reservoir area.

5.4. Hydroelectric analysis of Brazil in terms of capacity and reservoir area

Before going into methods and models that have been used to address WEN issues of hydropower in Brazil, and presenting specific input data and

assumptions made for the main analysis of the thesis that will follow in chapters 6 and 7, it is important to have a clear idea about where most of the capacity and reservoir area of hydropower is located within the country. The following analysis is done both for political and hydrographic regions. Figure 5.5 shows where the 220 reservoirs that were used for the analysis of this thesis are located.

Map of Hydroelectric Plants in Brazil

Created using Google Earth data in QGIS
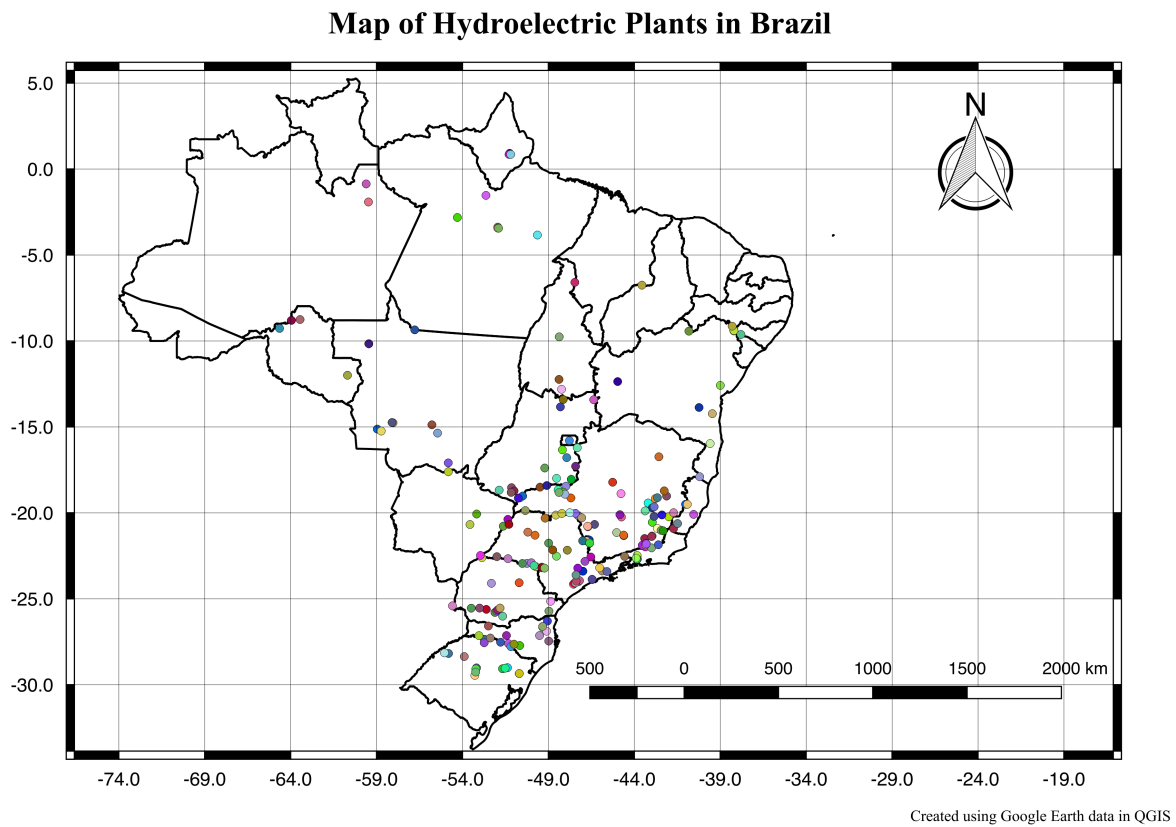
Figure 5.5 – Map of hydroelectric plants in Brazil
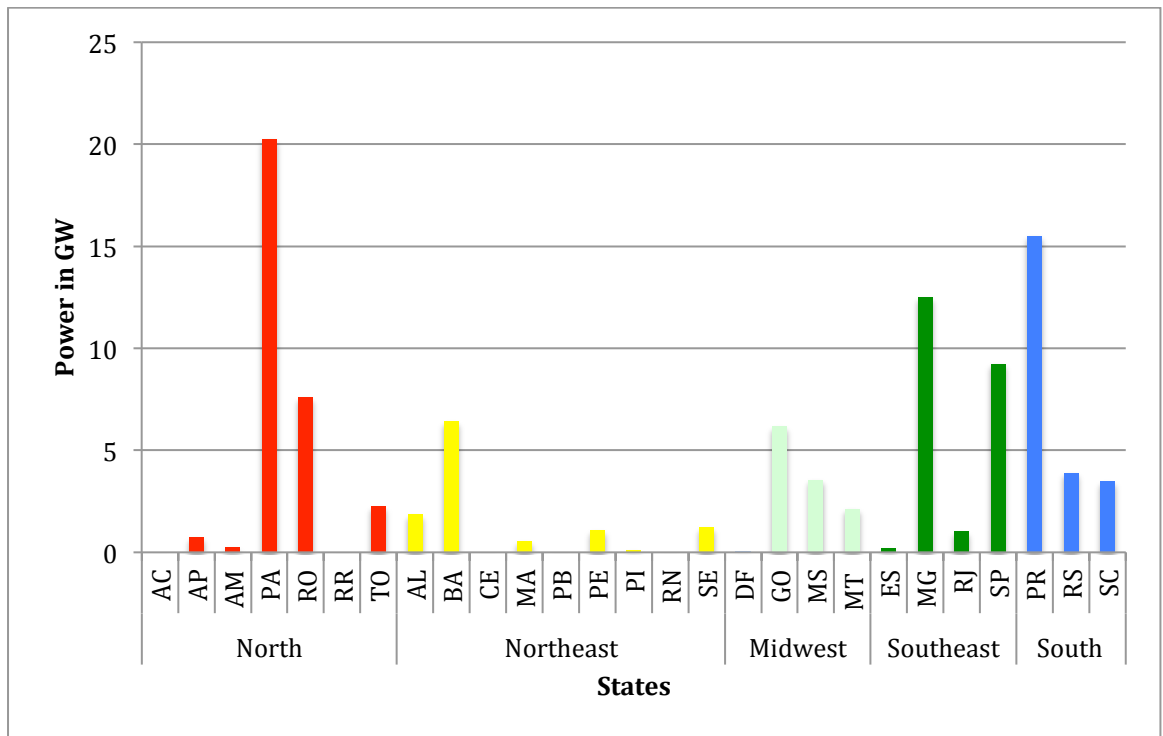
Figure 5.6 – Electricity capacity in GW per state in Brazil

Figure 5.6 shows that most of the hydroelectric capacity is located in the North, and then the Southeast and the South. Although, the Northeast and the Midwest also have considerable capacities. Some states do not have any capacity, whereas some other ones are very important for the system of the country. The state of Pará is the only one that exceeds 20GW with 20.3GW capacity, with Paraná coming second with 15.5GW, and Minas Gerais coming third with 12.5GW. The state of São Paulo, which is also the most populated state, is in fourth place with 9.2GW capacity, and the states of Rondônia (7.6GW), Bahia (6.4GW), and Goiás (6.2GW) are the rest that exceed 5GW.
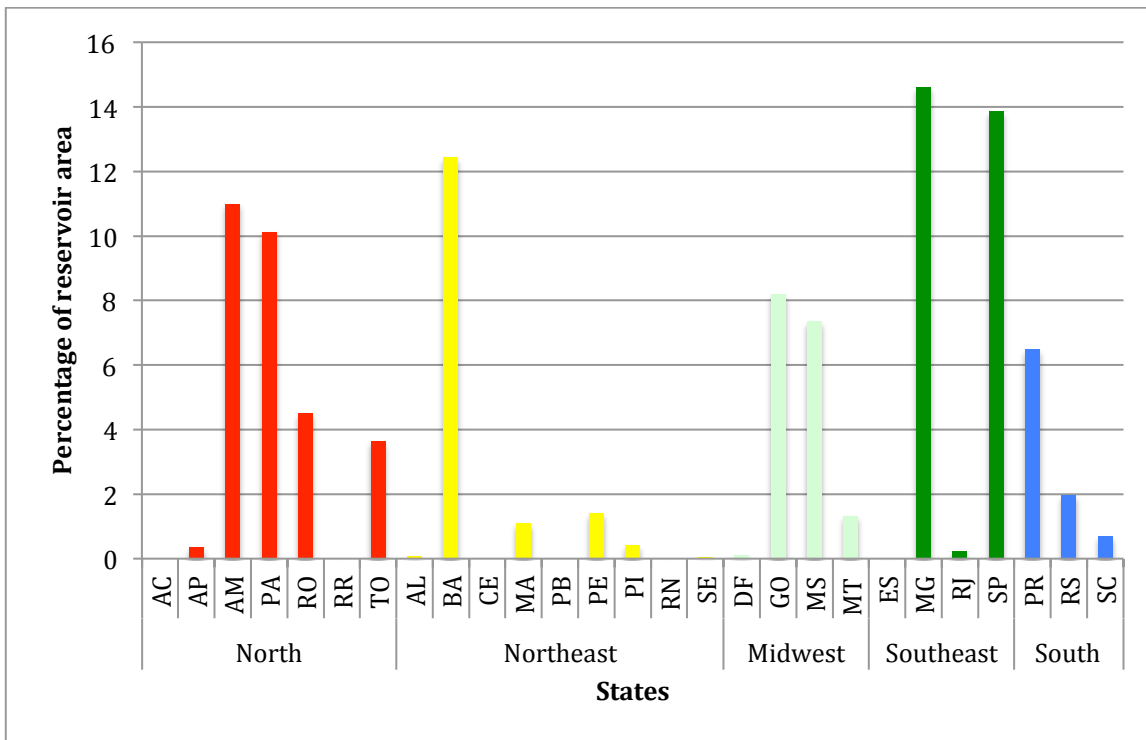
Figure 5.7 – Percentage of hydroelectric reservoir area per state in Brazil

In Figure 5.7 we can see that most of the hydroelectric reservoir area is located in the North and the Southeast. The states of Minas Gerais and São Paulo are in first and second place with 14.6% and 13.9% respectively. In third place is the state of Bahia in the Northeast with 12.4%, followed by the states of Amazônas (11%) and Pará (10.1%) in the North. Other states with high percentages are the states of Goiás (8.2%), Mato Grosso do Sul (7.4%), and Paraná (6.5%).

It is interesting to look at figures 5.6 and 5.7 in conjunction, in order to get a first indication of which states might be susceptible to water availability in relation to electricity generation. The state of Amazônas has a capacity of 0.3GW with an 11% of total reservoir area of the country. The state of Bahia is another not ideal example with a capacity of 6.4GW and a 12.4% reservoir area. The Midwest does not fare very well since the states of Goiás and Mato Grosso do Sul have 6.2 and 3.5GW capacities and their respective reservoir areas are 8.2% and 7.4%. The same holds true for the states of Minas Gerais and São Paulo in the Southeast, which have 12.5 and 9.2GW capacities and the highest percentages of reservoir area in the country with

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14.6% and 13.9%. On the other hand, the state of Pará is a great example with a 20.3GW capacity and 10.1% of total reservoir area, while the state of Paraná also fares very well with a 15.5GW capacity and a 6.5% of the total reservoir area.

There are different reasons as to why some states fare much worse than others, which have to do with their specific locality. Reservoir areas in the North are understandably very large, since they are located on tributaries of the Amazon River. Although they could have a higher capacity, the fact that they do not, does not necessarily mean that the reservoir areas should be smaller, although this is a big issue that will be further discussed in chapter 8. The Northeast and the Midwest, which historically have the harshest weather, do not have high capacities as a rule, since the production of electricity through hydro is highly unreliable. Furthermore, the Southeast is where most of the population of the country is located and also the most hydropower plants and reservoirs, with very variable capacities between them. The South in general is the region with the highest efficiency when it comes to this capacity and reservoir area comparison.
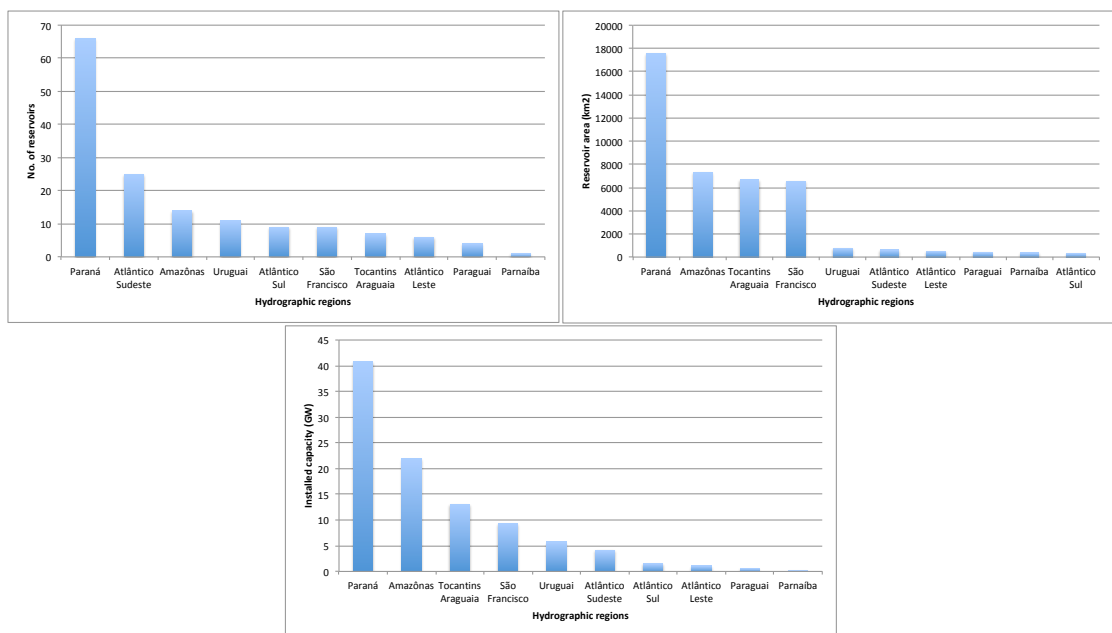
Figure 5.8 – Hydrographic regions in Brazil ranked by no. of reservoirs, reservoir area, and installed capacity

Figure 5.8 shows the 10 hydrographic regions of Brazil that have hydropower stations ranked by number of reservoirs, their accumulated reservoir area, and their accumulated electricity capacity. In all three graphs, Paraná comes first with 66 reservoirs, an area of 17,532.6km², and 44.885GW. This shows clearly that the electricity system of the country is highly dependent on this one hydrographic region, and low water availability there is a huge hazard. The Amazônas region has the second largest area (7,286.75km²) and capacity (22GW), although the third most reservoirs (14). Tocantins Araguaia has the third largest area (6664.9km²) and capacity (13GW), with the seventh most reservoirs (9). São Francisco has the fourth largest area (6546.94km²) and capacity (9.32GW) and the fifth most reservoirs (9) along with Atlântico Sul. Finally, the only other one that has a capacity larger than 5GW is Uruguai, which has the fifth largest area (781.25km²) and capacity (5.755GW), and also the fourth most reservoirs (11).
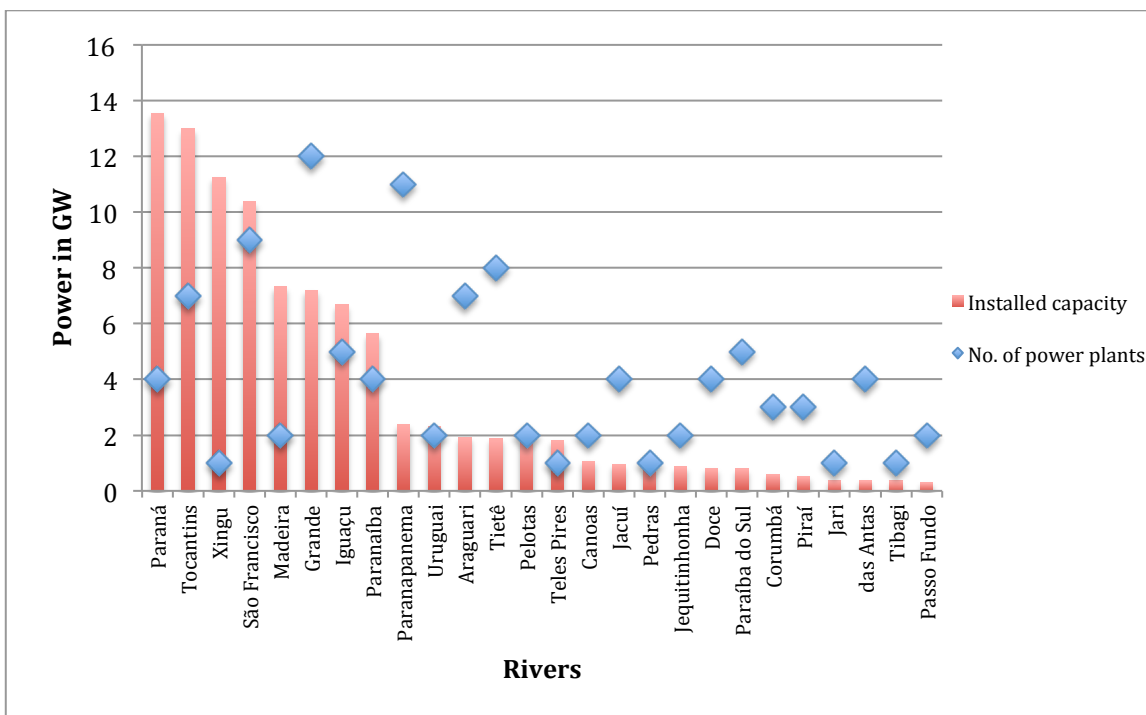
Figure 5.9 – Installed capacity (minimum 0.3GW) per river

Figure 5.9 provides another interesting early indicator, by showing which rivers have the most installed capacity and the largest number of power

plants/reservoirs. These are the 26 rivers that along them there is a minimum of 0.3GW of capacity. The Paraná, Tocantins, Xingu, and São Francisco rivers are the ones with the highest capacity along them with 13.5, 13, 11.2, and 10.4GW respectively. What is interesting is that for example Paraná achieves its capacity with 4 power plants, Xingu with only 1, and Madeira with 2. On the other hand, Grande has 12 power plants with a high capacity, Paranapanema 11 with a lower capacity, and São Francisco 9 with also a high capacity. The flow of especially the first 8 rivers is vital for the hydroelectric sector of Brazil.

Regions	Early plan		Latest plan	
	Installed capacity (GW)	Average capacity factor	Installed capacity (GW)	Average capacity factor
North	32.65	0.565	15.12	0.476
Northeast	0.8	0.729	0.45	0.714
Midwest	9.41	0.553	4.39	0.557
Southeast	1.88	0.516	1.19	0.521
South	4.17	0.569	4.17	0.569

Table 5.11 – Future expansion of hydropower in Brazil by region by 2050

Finally, table 5.11 shows the former and most current (as of February 2018) plans for hydropower in Brazil. This information is based upon information by ANEEL and the federal University of Rio de Janeiro. Brazil was planning to install another 48.91GW by 2050, but as of February 2018 the plan had changed and the overall expansion plan had fallen to 25.32GW by 2050. The rest of the capacity expansion was either cancelled entirely, or postponed to after 2050, while all these plants were only a paper exercise. It is possible, due to various difficulties surrounding the accomplishment of such large plans, that the 25.32GW until 2050 will diminish further, which is something that will be discussed in chapter 8. With the existing plans, most of the future capacity will be situated in the North, with the Midwest and the South also having a considerable expansion in their capacity. On the other hand, the Southeast and the Northeast will not see a significant rise, nor was there a plan for it. Although most of the capacity factor values are within reason, what is striking is that the majority of the expansion,

located in the North will have an average of 0.476, which is low compared to the rest of the country, and low compared to South American values. One of the biggest criticisms the new Belo Monte power plant has faced is its low capacity factor of just over 0.4, so it comes as a surprise that the average capacity factor expected in the North is below 0.5. Keeping this in mind, along with political instability, and the upheaval concerning such large plans in the country in the recent past, it would not be surprising if much of the capacity discussed here will not come to be, or it will be further delayed to after 2050.

5.5. Methods and models used in literature to address WEN issues in Brazil

Having analysed the current capacity and reservoir areas of all political and hydrographic regions, but also future capacity within Brazil, it is now time to see what kind of research has taken place in literature addressing specifically evaporation, water footprint, and water budget within the country.

Until the 2012 "Special Report on Renewable Energy Sources and Climate Change Mitigation" by the IPCC, the impact of hydroelectricity on water resources hadn't received the attention it deserves. However, despite the report by IPCC and others that preceded or followed it, water use from dams for energy generation has traditionally been considered a non-consumptive use in Brazil (ANA, 2013). Nevertheless, ONS prepared a report on evaporative losses from hydroelectric reservoirs in operation in the country in 2004 (ONS, 2004), although these are not considered in water resources planning and management on a river basin level, nor has there any extensive research been carried out since (Bueno et al., 2016). Due to the multiple recent drought events, the debate has slowly started to resurface.

For example, in 2012 Mekonnen & Hoekstra estimated the water footprint of hydroelectricity for 35 power stations around the world, including 8 from

Brazil, using a modified Penman-Monteith equation for the estimation of evaporation. More recently, in 2016, Fischmann & Chaffe published a study estimating the water footprint of hydroelectricity in the Santa Catarina State in Southern Brazil. They used algorithms proposed by Morton (1983) in an attempt to avoid a large amount of input data and to be able to apply the method to varying contexts without needing locally optimized coefficients. They used time series data of weather parameters retrieved from the website of the Brazilian National Institute of Meteorology (INMET, 2016). The lack of data regarding reservoir properties and electricity generation, especially that of smaller facilities, constrained their study (Fthenakis & Kim, 2010), which is an issue that all similar studies had.

Likewise in 2016, Bueno et al. published a study calculating the monthly water footprint of the Camargos reservoir (Southeast Brazil), using the water footprint definition by Mekonnen & Hoekstra (2012). They used four methods (Linacre, Penman, Penman-Monteith, and the ONS method) to calculate evaporation for the period 2010-2014. The average evaporation estimated was 1329 mm/year, and 2014 had higher values due to the severe dry season that affected the region. This also shows the importance of calculating evaporation from hydroelectric reservoirs.

There have also been various papers that have attempted water budget analyses or other hydrologic research in Brazil in the past few years. Lopes et al. (2017) developed the flow regionalization in the Teles Pires Basin in Brazil using historical series and probabilistic models. In cases where the cost of a hydrometric network is too high, regionalization improves the estimates of hydrologic variables and allows for a check on the consistency of hydrological data series. Ho et al. (2016) did an uncertainty assessment of hydrology projections for the Tocantins-Araguaia Basin. Oliveira et al. (2014) assessed the water balance of the Brazilian Cerraso based on remotely sensed estimates of precipitation, evapotranspiration and terrestrial water storage for the period 2003-2010. Kobiyama & Chaffe (2008) did a water assessment in Cubatão-Sul in Santa Catarina, using the

storage model HYCYMODEL both for water balance and evapotranspiration analyses. Leite & Fujaco (2010) did a long-term annual water balance of the Araçuaí River Basin. They found that evaporation is extremely high, higher than precipitation for most of the year, which leaves no water for infiltration (aquifer recharge) and runoff.

Furthermore, Güntner et al. (2009) did a simple water balance modelling of surface reservoir systems in the State of Ceará in the Northeast of Brazil, to represent water availability in a large system of hydroelectricity reservoirs. This research also comments on the scarce data availability, and trying to retain enough detail to capture the most important aspects of reservoir dynamics like interactions and varying storage behaviour as a function of size and water use. The water balance model for reservoirs used here is part of the hydrological model WASA (Model of Water Availability in Semi-Arid Environments), and water use in the area (required for the water balance model) was determined by a data survey-based assessment at the scale of municipalities in the irrigation, livestock, domestic, industrial and tourist water use sectors.

Finally, Teixeira et al. (2008) performed a long-term analysis of the annual water balance of the Araçuaí River Basin, using satellite images, hydrometeorological and river discharge data. This research was done from an agriculture perspective, but the results are interesting and the knowledge gained applicable in research done for reservoirs only as well. For example, one of the findings agrees with Leite & Fujaco (2010) in that evaporation was higher than precipitation during most of the year in the area, leaving no water for infiltration and runoff. This has serious implications when it comes to research done about groundwater.

All the above exercises are useful in their own right and towards showcasing the importance of water in relation to electricity. However, none of them performs a comprehensive analysis for the whole Brazilian system neither in terms of evaporation estimation nor water budget. This is precisely what

follows in chapters 6 and 7, a comprehensive analysis of evaporation, water footprint and water budget both for recent years and for the future, while using improved methodologies. However, before dwelling further into the analysis, it is important to present and discuss the various input data and assumptions, specifically for the case of Brazil, that were made in order to do the analysis in chapters 6 and 7.

5.6. Input data and assumptions for evaporation calculations

Although it may not be possible to eliminate assumptions, care was taken to minimise them as much as possible, and in order to avoid incomplete or misguided information, all the assumptions made are presented here in detail to assist transparency and the ethical aspect of the work done.

5.6.1. Number of reservoirs taken into consideration in the analysis

According to ANEEL, at the end of 2016, 218 hydroelectric plants were used for the generation of electricity. From these, 55 were run-of-the-river with no reservoir, or they had a small sized reservoir of a maximum $3.12km^2$, and were not used in the analysis. The reason why the 13 of the 55 that had even a very small reservoir were not taken into account is because they were missing information on area, volume, and coordinates. The combined area of the reservoirs not taken into account is 19.45 km^2 out of a total of $41,108.37km^2$, which is a percentage of 0.047%, therefore not making any significant difference to any results of evaporation. The electricity capacity of the 55 stations is 0.797GW out of 101.063GW overall, which is a percentage of 0.788%. The electricity capacity will be taken into account when calculating the water footprint. Furthermore, some reservoirs belonged to more than one state and sometimes more than one region. The percentages as to where these belong were taken from ANEEL and evaporation from each of those reservoirs belonging in more than one state and one region was attributed percentagewise in each of those states and regions.

5.6.2. Assigning meteorological stations to reservoirs

INMET had 522 active weather stations throughout Brazil by the start of 2017, that collected the needed input data for this analysis. The number of weather stations has seen a great increase in the past decade, however for a country with an area of 8,515,767km², this means that there is a weather station for every 16,313km². At the same time, these weather stations are not randomly or equally and analogically located throughout the country, rather they are located in places of interest.

To assign the nearest meteorological station to each reservoir, the spherical law of cosines was used, but there were two criteria for this. Firstly and most importantly, the weather stations needed to have started operating before the 1st of January 2010, which is the start date for the subsequent analysis, and they needed to measure all needed inputs (some did not) for the estimation of evaporation (Table 4.1). Secondly, the difference in altitude needed to not be significant.

Through this data cleaning process, 98 weather stations were selected that met the criteria and they provided the necessary weather data input for the analysis of 163 reservoirs across Brazil. The distances between the weather stations and the reservoirs varied from a minimum of 3km to a maximum of 223km. Only eight reservoirs were further than 100km (7 between 101 and 161km, and 1 which was 223km) from a weather station. The average distance of the rest was about 40km. Although these few large distances might seem significant, the weather in these areas (the Amazon region) does not vary significantly, therefore making the assumption logical.

5.6.3. Site characteristics data for evaporation estimation

There are four kinds of data that needed to be collected: a) water body altitude, b) water body latitude, c) water body area, and d) water depth. The altitudes and latitudes of the power stations/reservoirs were collected with

the use of Google Earth Pro and information from various sources including AQUASTAT, ONS, ANEEL, and official websites of the various power stations. Only 7 power plants from the 218 were not found on the map, although they were the ones with the smallest electricity capacities, and also they did not have a reservoir, therefore not taking part in the calculation of evaporation. Similarly, data from AQUASTAT, ONS, ANEEL, and official websites of power stations were used to find the water body areas. The water depth needed to be calculated, thus the capacity of each reservoir needed to be known. Most of the capacity data existed in ONS and AQUASTAT databases, but for seven reservoirs that were used in the analysis there was no volume data to calculate the depth. For these seven, an assumption was made as to their capacity, based on other reservoirs with a similar area in similar locations. Apart from one reservoir that was nearly 80km^2, the other six were smaller than 25km^2, therefore even if the assumptions were wrong, the overall results would not be affected significantly.

Although altitude and latitude of the reservoirs can be very accurate and they do not change with time, the same cannot be said for the area and depth. For the analysis to be as accurate as possible, the reservoir area and the volume of water needs to exist at least on a daily basis. The volume can be estimated by doing a water budget analysis, however such measurements and data do not exist for the areas of the reservoirs. Although water body areas through time are important for a better analysis, it would be dangerous to make general assumptions, as the area is highly dependent upon location and the geological features of each reservoir. This is the single most important unsolved issue when it comes to evaporation estimation, but there is no study done that takes it into account. All studies of evaporation, including this one, use a fixed reservoir area, which is the one reported in official documents, and it is presumably in most cases the maximum possible area of a reservoir. This has implications in the final results of evaporation presented, by overestimating values, which is something that needs to be noted.

5.6.4. Meteorological time series data for evaporation estimation

There are four kinds of time series data that needed to be collected: a) mean daily air temperature, b) total daily incoming short-wave radiation, c) average daily wind speed at 10m, and d) daily vapour pressure (taken at 9:00 am). The first three kinds of data are available online by INMET for the past 12 months at each time. After personal communication with them, they kindly offered me this hourly data from 1st of January 2010 to 31st December 2016. The daily vapour pressure needed to be calculated, which can be done if the air temperature at 9:00am of each day is known. The values of water vapour for each possible temperature from -10 to 62.5°C were taken by Lange's handbook of chemistry (Dean, 1999) and converted from mm Hg to kPa.

The problem with this data is that there were missing entries. The data is hourly, so for all the parameters needed there are hundreds of thousands of data entries for the 7-year period of the analysis. These missing entries can occur due to human error during the process of observation, and/or in the transcription and digitization of data (Reek et al., 1992). Moreover, measurements at a weather station can be problematic due to instrument deterioration or replacement, variations in the time of observations, and changes in the surrounding environment. All these factors can lead to the data not being homogeneous (Peterson et al., 1998; Beaulieu et al., 2007).

In order to alleviate this problem and end up with the best possible data, a reconstruction process needs to take place, along with a quality control to make sure there are no negative or zero values that would decrease the overall value of the data. There are a few methodologies as to how to complete the missing entries, but there are three methodologies that have been used relatively widely: a) nearest neighbouring weather station to obtain missing values, b) inverse distance weighting methods, and c) the linear regression method. The first one depends on data from nearby stations, and for example Vicente-Serrano et al. (2010) used this method to

create a homogeneous database for daily precipitation, although it can be used for other variables in the same way. The second method is a more complicated version of the first, which again depends on data from nearby stations, but a cluster of them. For instance, de Mesnard (2013) used this method for evaluating the impact of pollution and discussed various issues that could be improved. The third method fills the missing gaps using linear regression projections of existing data around the missing entries. This method is very widely used for future projections. Recently, Bagirov et al. (2017) used a more advanced version of this method to predict monthly rainfall in Victoria, Australia. Finally, using a different path, Mekonnen & Hoekstra (2012) in their study replaced missing entries of days/months with averages of the equivalent days/months from the rest of the years of their analysis period.

At first, it was attempted to use the first method in this analysis, but there were two important issues. Firstly, as was explained earlier, the weather stations are quite sparsely located, so in some cases the neighbouring station was hundreds of kilometres away, rendering any comparison pointless. Secondly, it was the case that even for weather stations that had neighbouring stations relatively nearby, sometimes they were missing the same values. For this reason, this method was discarded. The second method is a more complicated version of the first one that can give very accurate estimations of missing data, but at the same time it depends even more on the presence of neighbouring stations, therefore it was also discarded. The linear regression method could be used in most cases, but also there were cases that many consecutive days, even months in some cases were missing, so a linear assumption about weather data would not necessarily be very accurate, especially since the data from INMET is hourly and the estimation of evaporation is done on an hourly basis. The methodology Mekonnen & Hoekstra (2012) used could be used more easily, since the data allowed it. Nevertheless, it was deemed preferable to make a slight improvement to this method.

Firstly, the missing entries were filled with the average values for the same hours from the rest of the years of the analysis period. For example, if the value for 11:00am on the 1st of January 2010 was missing, then the gap was filled with the average value for 11:00am on the 1st of January from the years 2011-2016, assuming that these values are available. In most cases, only one gap exists, so the average value comes from taking into account values from six years. It was very rarely the case that only values for two years were available, so the average would come from those two, and it was never the case that data from only one year existed. This way, all gaps were filled and the data was checked for inconsistencies and possible negative or zero values as part of the quality control.

The problem with using this method is that it does not account for specific changes (e.g. in temperature) of a specific month or year. To improve this aspect, the weighted arithmetic mean method (Equation 5.1) was used.

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i\, x_i}{\sum_{i=1}^{n} w_i} \ (Equation\ 5.1)$$

$\bar{x}$ = new value of temperature, radiation, wind speed, or vapour pressure
x = average value of temperature, radiation, wind speed, or vapour pressure based on existing values of other years
w = weight, which is either the monthly average of a year or annual average (only taken into account when data from a whole month is missing), divided by the average of all existing averages for that month or the year for the period 2010-2016

In most cases, the data did not change a lot and the weights applied to the newly filled entries were close to 1, but in some cases it seems that there were some variations in that time of year, which were accounted for, therefore making the data represent reality better than before. This part of the analysis could potentially be improved if there were more weather stations present. Nevertheless, the data gaps were filled to a satisfactory

degree, taking into account differences in the weather in specific months and years, and the quality control did not show any negative or zero values that would decrease the quality of the data. The difference the weighted arithmetic mean made to the results of evaporation will be exhibited in the evaporation analysis section.

5.6.5. Water footprint

Although there is an ongoing argument in literature as to which one is the most appropriate method, as mentioned earlier, in the present analysis the gross water consumption was used to calculate evaporation, and not net water consumption. Apart from the reasons given for this choice, the Water Footprint Manual also suggests using the gross evaporation values in water consumption assessments (Hoekstra et al., 2011). Secondly, as was also explained earlier, all evaporative losses from reservoirs were allocated to the production of electricity, which raises its water footprint. Lastly, in the calculation of the Water Footprint, the maximum theoretical capacity of each hydro-plant was used, which means that the estimated values are an underestimation of the actual water footprint, since the plants do not actually reach this maximum theoretical capacity. Nevertheless, the Water Footprint estimations are there as a point of reference for the differences between power stations and areas. If the actual production of each power plant for each day is known, it is possible to calculate the Water Footprint on a daily basis.

5.7. Input data and assumptions for the water budget analysis

Problems relating to the processing of data required for model applications have been mentioned in various papers (Paim & Menezes, 2009; Carvalho Neto et al., 2011; Meira Neto et al., 2011; Fernandes et al., 2012; Bonumá et al., 2013). As mentioned in Bressiani et al. (2015), much of the existing data is not well organized and not accessible via centralized databases. Precision, quality and resolution is particularly acute in some regions like Amazonia

(Bressiani et al., 2015) in Brazil for example. Although data availability can be a barrier, a lot of countries, including Brazil, have enough data to capture the most important aspects of reservoir dynamics for the majority of reservoirs in a country (Güntner et al., 2009), to be able to perform a meaningful analysis. In cases of missing data, one possible and widespread way to deal with the problem, if the local particularities permit it, would be regionalization, which transfers information from one location to another (Lopes et al., 2017).

Furthermore, the seasonal and spatiotemporal variability of precipitation, evaporation and river flows result in challenges regarding accurate representation of systems and hydrologic simulations in models (Bressiani et al., 2015). The uncertainty in annual flow and seasonal distribution of river discharge is a problem that has been identified in literature (Arnell, 2011; Hughes et al., 2011; Kingston et al., 2011; Xu et al., 2010). Finally, important uncertainties also exist in reservoir operation rules, and adapted integrated measures of water management are required to secure water availability from reservoirs in the future (Güntner et al., 2009). Understanding water balance in relation to climate and catchment characteristics provides valuable information on complex processes spatially and temporally (Leite & Fujaco, 2010).

When it comes to modelling, especially of such a large system of reservoirs like is the case in Brazil, certain assumptions are necessary due to lack of data for various variables. However, care was taken to minimise assumptions as much as possible by checking data meticulously. In order to avoid incomplete or misguided information, all the assumptions made, in data preparation and in modelling, are presented here in detail to assist transparency and the ethical aspect of the work done.

5.7.1. Number of reservoirs taken into consideration in the analysis

According to ANEEL, at the end of 2016, 218 hydroelectric plants were used for the generation of electricity. As explained earlier, 55 of them were not used for the estimation of water consumption. The reason being that some were run-of-the-river thus having no reservoirs, and some were too small and/or missing information needed for calculations. From the 163 reservoirs that took part in the water consumption estimations, 151 were considered in the water budget analysis. The reason for excluding a further 12 reservoirs is because they were missing important data, and more specifically they did not have river flow data, nor minimum and maximum limits of reservoir capacity and flows. However, the reservoirs not taken into account have an accumulated area of 36 km², which compared to the total of 41,108km² of all reservoirs is a very small fraction of less than 0.09%. The electricity capacity of the 67 stations not taken into account is 1.211GW out of 101.063GW overall, which is a percentage of 1.2% and again does change the overall results by much. Also, as was the case with water consumption as well, some reservoirs belonged to more than one state and sometimes more than one region. The percentages as to where these belong were taken from ANEEL.

5.7.2. Maximum reservoir capacity and minimum useful capacity of reservoirs

These two values are vital for a water budget analysis, since the maximum reservoir capacity, as the name suggests is the maximum volume of water that a reservoir can withhold, whereas the minimum useful capacity is the volume of water below which the power plant does not operate. The maximum value is more straightforward to understand, but the minimum value can work differently in different reservoirs. Sometimes the minimum and maximum values are one and the same, meaning that the reservoir needs to be full for the power plant to operate, and it solely depends on the inflow of water. When it comes to larger power plants/reservoirs, the

minimum useful capacity is such that it would allow the power plant to operate even if the inflow of water is not enough, since the stored water would help alleviate the problem for a period of time. ONS (ONS, 2016) provides in its databases the maximum reservoir capacities and the minimum useful capacities for almost all the reservoirs. There were 14 cases though where the minimum useful capacity was missing. For those cases, reservoirs with a similar area were found, and their maximum reservoir capacity and depth of the reservoir were taken into account in order to estimate an average minimum useful capacity and use it to fill the gaps.

5.7.3. River flow data

From the 151 plants/reservoirs that were part of the analysis, 135 had river inflow values (taken from ONS databases), but 16 did not. 14 of the 16 without inflow data were the same ones that were also missing minimum useful capacity values. In this case, regionalisation was used, transferring information from one location to another based on several principles. The flow data needed to come from rivers that were similar to the one with the missing values, so they belong in the same watershed, they are as close as possible (in order to have similar weather conditions), and they have similar maximum reservoir capacities, inundated areas, and electricity capacities, which all point towards similar inflows.

5.7.4. Maximum and minimum river outflow limits

These two values are necessary for the water budget to be performed, since they are very important parameters of the reservoirs' operation. From the 151 reservoirs, only 65 had values for both maximum and minimum limits of outflow. 30 had a minimum value but had no maximum value, 14 had a maximum value but no minimum, and 42 had neither a minimum nor a maximum value. This was the biggest assumption that needed to be made in the water budget process, since the values missing were a lot, and this shows a very clear omission from the entities responsible to provide this

information. The existing data was taken from ONS (ONS, 2016), but this data should be provided in each and every Environmental Impact Assessment for each reservoir since it is vital information whether a river is particularly susceptible to problems or not. The larger reservoirs more often than not do have these values, but as the reservoirs get smaller, the gaps in data become more prominent. Nevertheless, the missing values needed to be estimated for the water budget model to work.

In the ONS document (ONS, 2016), all the limits and the reasons behind them for each case can be found, but some of the reasons why these values are important and also need to be respected include the following:

- Protect environmental conditions downstream
- Keep water oxygenated enough for life to be sustained in it
- Preservation of flora and fauna downstream, especially that of ichthyofauna (fish life of a region)
- Have at least a certain minimum outflow due to other reservoirs' needs downstream, since many rivers have more than one reservoirs located along them
- Avoid turbine damage
- Prevent flooding of the powerhouse, which is usually downstream
- Avoid affecting river morphology
- Protect bridges that could be threatened and deemed unsafe to be used
- Avoid affecting transportation between some villages
- Preserving navigation, which can be affected with either too little or too much flow
- Prevent damage to cultivated areas
- Service downstream users (there are occasional concession agreements in place)
- Control filling and emptying of floodplains in order to give enough time to riverside populations to evacuate if need be
- Avoid damage to the banks and some fishermen's ranches

- Avoid removal of landfills, which could be located downstream and could cause pollution

River flow data exists on a daily basis since 1931 (or whenever a power plant started operating), and the minimum, maximum, and average values for the whole period of existing data was either recorded or estimated. Then the existing minimum and maximum values by ONS were divided by the average flow of each plant/reservoir. This showed that on average the maximum outflow was 4.382 the average outflow, and that the minimum outflow was 0.232 the average outflow. To be on the safe side, these factors were taken as 4 and 0.25, and they were multiplied with the average outflow for all plants/reservoirs. This process took place for the plants with existing values as well for a check, serving as a sensitivity analysis. Apart from 13 exceptions, the other 138 values very closely resembled existing values. In the case where the minimum and maximum values estimated were lower or higher respectively from existing values, the existing values were used, but in the case the estimated values were higher and lower than the existing values, then the estimated values were used to be on the safe side. Overall, 16 times it was the case that estimated values were used instead of the existing ones. Factors other than 4 and 0.25 were also considered to check their sensitivity and the more the change, the more illogical the estimated values, hence deeming the 4 and 0.25 factors a fair assumption.

It is difficult to estimate such values, since they depend on a very high degree on the specific site, the geography, different ecosystems, human settlements, etc. Since the reasons behind having upper and lower limits of river flows are all of imperative importance, care was taken to not make assumptions that could potentially prove to be harmful, so it is likely that some of the estimated values are safer than they need to be.

5.7.5. Meteorological time series data

Apart from the river flow data that was already mentioned, there are two more time series data sets that were needed, and namely evaporation and precipitation. There is no available time series data for evaporation that could be collected from anywhere, but it was estimated in detail for each hydroelectric reservoir in Brazil in operation at the end of 2016 and will be presented in chapter 6, which helped fill a gap in knowledge. What remained was the precipitation series data that was collected after personal communication with INMET, who kindly offered to provide hourly data from 1st January 2010 to 31st December 2016.

As was the case with the time series data that was used to calculate evaporation, there were missing entries in the data. Since the data is hourly, there were thousands of gaps, due to a variety of reasons like human error, transcription and digitization of data, or problems due to instrument deterioration, replacement, etc. There are various methods that can be used to alleviate this problem and they are explained in more detail in section 5.6.4. The method used to fill the missing data is an improvement to the method Mekonnen & Hoekstra (2012) used of replacing missing entries of days/months with averages of the equivalent days/months from the rest of the years of their analysis period, which is also a novel contribution to knowledge. The weighted arithmetic mean method was used to account for specific variations within specific months or even years, therefore making data represent reality better. The method is presented in more detail in section 5.6.4.

5.7.6. Other issues

Watershed models are most likely the most complete form of water budget models, which account for snowmelt, and groundwater movement and storage. Groundwater in particular is the largest reservoir of extractable freshwater on Earth, although its importance is more often than not

overlooked due to it not being visible to the naked eye. However, groundwater recharge is a very important part of aquifer water budgets. Despite its importance, it is very hard to quantify because it largely varies in space and time, and the data requirements in the physical and hydrologic properties of earth materials required is extremely large (Healy et al., 2007). For the purposes of this work, it is assumed that seepage losses due to porous ground underlying hydroelectric reservoirs remains in the basin and can become available downstream or recharge ground water, thus not being a true loss (Gleick, 1994; Healy et al., 2015). On the other hand, depending on the reservoir, the opposite, a recharging of the reservoir, is also possible. Since there is a complete lack of data on this matter, the assumption is that this exchange of water is minimal and not changing the operation of the reservoirs significantly.

Another aspect that was not taken into account in the model, due to lack of data and conflicting studies on the matter, is sedimentation. Sedimentation can reduce the volume of water stored in a reservoir, obstruct irrigation canals and navigation, raise difficulty of water entering hydraulic structures of uptake systems, and possibly alter or destroy aquatic ecosystems. Also, the inactive capacity and the possible electromechanical equipment wear can reduce the supplier's revenue (de Miranda & Mauad, 2015). Generally, the more the river flow slows down, the more possible sedimentation is, so in the case of reduced flows in the future, it could become a much more important problem and it is something that needs to be taken into account. Bathymetric surveys are of great importance for better future planning of the Brazilian electricity sector. They would assist in monitoring sedimentation in order to know when preventive and/or corrective actions would be needed, especially when it comes to small or medium sized reservoirs, where the problem tends to be more exaggerated.

As mentioned in de Miranda & Mauad (2015), the only known study conducted in Brazil that proposes an average value of sedimentation for the whole country is from 1994 when the Institute of Hydraulic Research for

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Eletrobras Company concluded that the annual loss of reservoirs' storage volume in the country was about 0.5%. At the same time, another study conducted for the Sobradinho reservoir stated that the reservoir would be completely silted within 80 years, when other studies calculated that in a 100-year period sedimentation would reach only 5% of the reservoir (de Miranda & Mauad, 2015). Another study (de Araújo et al., 2006) estimated that the reduction in storage capacity in the state of Ceará in particular is 0.2% per year, which could be three times more than the projected increase in evaporation in the area would cause. Due to conflicting values from studies, which exist due to the lack of observatory data, and because sedimentation is a matter that is extremely local in nature, it was deemed that the inclusion of sedimentation in the model was not possible, since the assumptions would be too large. Nevertheless, it is recognised that it is an important issue and a big gap in knowledge.

Despite the two above-mentioned issues not taken into account in the water budget model, it does nevertheless perform a reservoir dynamics analysis in fine space and time detail that assesses water availability for electricity production (or other uses) and can serve for better water and energy management in Brazil. Although the methodology is applicable everywhere, it needs to be tailored for particular case studies, since the existence and detail of data is very important.

5.8. Summary

This chapter set the context of the analysis to follow, and namely the case study of Brazil. Brazil is the fifth largest country on Earth in terms of population and area. The income disparities are large within the country that is home to 60% of the Amazon rainforest. Electric power consumption per capita has risen in 2017 by 78.5% since 1990. The climate in Brazil can be characterised as mostly tropical, which means it is warm and has high rainfall rates, mainly attributed to the ITCZ. Recently Brazil faced its worst drought in 40 years, which meant that inhabitants and agriculture suffered

due to lack of water, while cities faced blackouts due to weak hydroelectricity generation. Fossil fuels were used to deal with this problem. The country has faced droughts in the past, and it is anticipated that this trend will continue with increased intensity and frequency, which is alarming for the electricity sector, since water availability is of the utmost importance for hydropower, which historically accounts for more than 70% of the country's electricity supply matrix.

The analysis of the Brazilian energy sector showed that electricity consumption has been rising in the whole country, while the importance of hydropower in the system is undeniable. At the same time, the Northeast would be particularly susceptible in a low water availability future, due to its large population, high dependence on hydroelectricity and the possibility of consumption per capita rising significantly if the living standards were to increase. Also, the Southeast has a very high concentration of both hydro and thermal capacity, which both consume large amounts of water, as will be shown later, and along with its large population would also be particularly in jeopardy in a low water availability future.

The analysis of water in Brazil showed that, unsurprisingly, the water demand is highest where most of the population resides, and where most of the electricity capacity is situated. This would primarily be the Southeast, and then the Northeast and the South. At the same time, most of the water withdrawal and consumption comes from agriculture. An important note is that although sugarcane crops are rainfed, climate change could transform them into irrigated crops, which require considerable amounts of water. Finally, by looking at figure 5.4, we can see that only the Paraná hydrographic region has considerable river flows near very populated areas.

The hydroelectric analysis in terms of capacity and reservoir area showed that most of the hydroelectric capacity is located in the North, and then the Southeast and the South. The states of Pará (20.3GW), Paraná (15.5GW), Minas Gerais (12.5GW), São Paulo (9.2GW), Rondônia (7.6GW), Bahia

(6.4GW), and Goiás (6.2GW) are the ones that exceed a 5GW capacity and so are of particular importance. At the same time, the states Minas Gerais (14.6%), São Paulo (13.9%), Bahia (12.4%), Amazônas (11%), Pará (10.1%), Goiás (8.2%), Mato Grosso do Sul (7.4%), and Paraná (6.5%) are the states with the highest percentage of hydropower reservoir areas. What is interesting is that for example the state of Amazônas has a capacity of 0.3GW with an 11% of total reservoir area of the country, while Bahia is another such example with a capacity of 6.4GW and a 12.4% reservoir area. The analysis done by hydrographic regions showed that Paraná has 66 reservoirs, a reservoir area of 17,532.6 km², and 44.885GW capacity, making it by the far the most important hydrographic region in the country, and also the most hazardous one. Other important regions include Amazônas, Tocantins Araguaia, and São Francisco in this order. The analysis done by river showed that the Paraná (13.5GW), Tocantins (13GW), Xingu (11.2GW), and São Francisco (10.4GW) rivers are the ones with the most capacity along them.

Table 5.11 showed the former and most current plans for hydropower expansion in Brazil. The projected capacity expansion to 2050 saw an almost 50% decrease, from 48.91GW to 25.32GW, in planning in recent years, which could further rise due to the country's political turmoil. The existing plans show that most of the capacity will be installed in the North, with the Midwest and the South also having a considerable expansion. Although it needs to be noted that the expansion in the North will come with capacity factors that are not satisfactory and raise further concerns as to the fruition of the plans.

Finally, methods and models used in literature to address WEN issues in Brazil were examined, which showed the rising concerns about hydroelectricity in the country, but also that there is scope to perform a more detailed, comprehensive analysis for the whole Brazilian system. It is to this end that input data and assumptions for evaporation and water budget analyses were presented in great detail, in order to adhere to

transparency and assist in possible future research. The input data and assumptions included the number of reservoirs used in the analysis, the choosing of meteorological stations for the collection of data, analysis of the site characteristics and time series data, maximum and minimum capacities of reservoirs, and maximum and minimum river outflow limits among others.

After the presentation of input data and assumptions in this chapter, what follows in chapter 6 is the analysis of hydroelectricity in Brazil separated into evaporation, water footprint, water budget, and outflow and capacity factor - link with energy models, performed for the period 2010-2015.

Chapter 6. Historical results and analysis

Following the methodology description, and the analysis of the water and electricity sectors in Brazil in order to understand the main issues of these resources in the country, it is time to present the results of the first part of the modelling exercise. This chapter is separated into four parts and namely evaporation, water footprint, water budget, and outflow and capacity factor - link with energy models. The analysis period for the first two parts is from 2010 to 2016, and for the next two parts from 2010 to 2015. The reason for 2016 missing in the third and fourth parts of the analysis is that river flow data was not available after 2015 at the time the analysis took place. All four parts have results for the five regions of the country, and the first three parts also have results for the country's 27 states, and for specific reservoirs of particular significance. The evaporation part also includes a comparison of results with the only other existing similar study by ONS, and a sensitivity analysis. The results presented here for evaporation for regions, states and most reservoirs, are the only ones in existence in literature, apart from the ONS study that was performed in 2004 with a different methodology. The same holds true for the water footprint results for regions, states and most reservoirs. Finally, the water budget analysis is also unique mainly due to the specific restrictions applied to the reservoirs through the model's algorithms.

6.1. Evaporation results and analysis

This part of the chapter is dedicated to evaporation results and analysis done per region, state and specific reservoirs of interest for the period 2010-2016. The results presented are on an annual level and separately on a monthly level. The reason for this is that the differences of evaporation per year are in some cases not significant and in a monthly/annual graph they would not be visible. Also, the most important part of these results is the evaporation per month, where the variation between months offers significant insight and needs to be shown clearly.

6.1.1. Evaporation per region
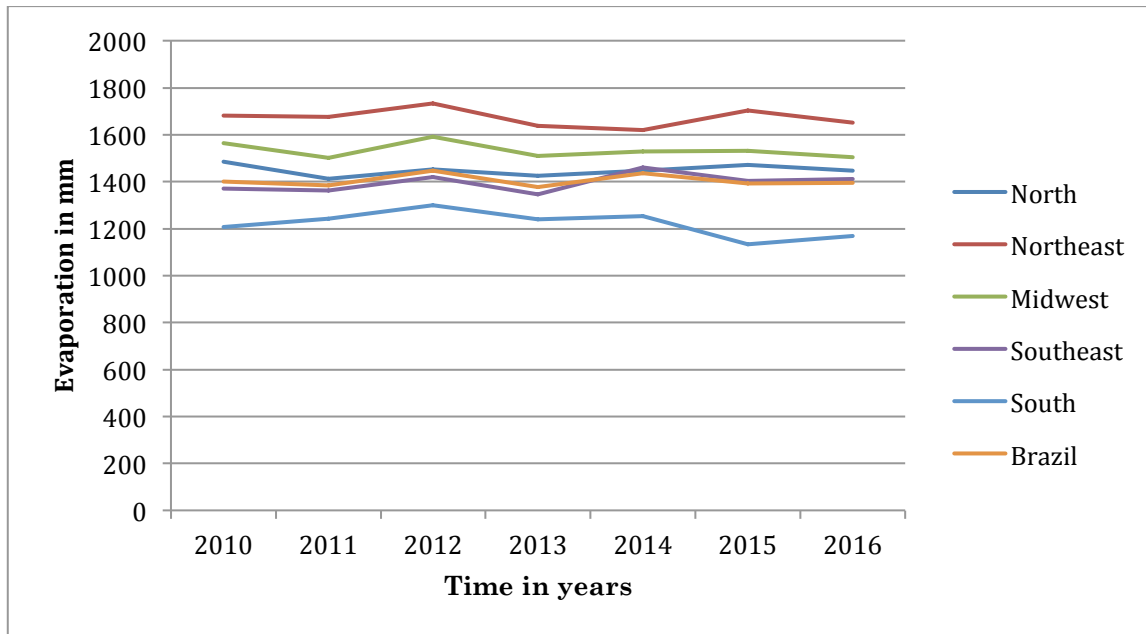
Figure 6.1 – Average annual evaporation per region and country for the period 2010-2016

As is shown in Figure 6.1, evaporation does not change drastically through the years at first glance, although a change in evaporation is noticeable at times of droughts, like the one in 2014-2015 in the Southeast. The Northeast is the region with the most evaporation every year. In the 7-year period, the Northeastern reservoirs never had an average evaporation less than 1618mm per year (in 2014), reaching the highest average in 2012 with 1732mm per year, when the region suffered severe drought problems. Midwest is the region with the second highest evaporation overall, with a minimum of 1500mm in 2011, and a maximum of 1590mm in 2012. The North is third when it comes to average evaporation with a minimum of 1412mm in 2011, and a maximum of 1486mm in 2010. The Southeast is the region with the most reservoirs in the country (about 74), so its evaporation affects the overall Brazilian results a lot. The minimum overall evaporation occurred in 2013 with 1345mm, whereas in 2014 the overall average evaporation was 1459mm, which was the highest in the 7-year analysis period, and also when the region suffered its worst drought in many years. The South is the region with the lowest overall average evaporation with a

minimum of 1133mm in 2015, and a maximum of 1301mm in 2012, when they faced some drought issues as well. The Brazilian minimum evaporation in the 7-year period occurred in 2013 with 1377mm, and the maximum came in 2012 with 1447mm.
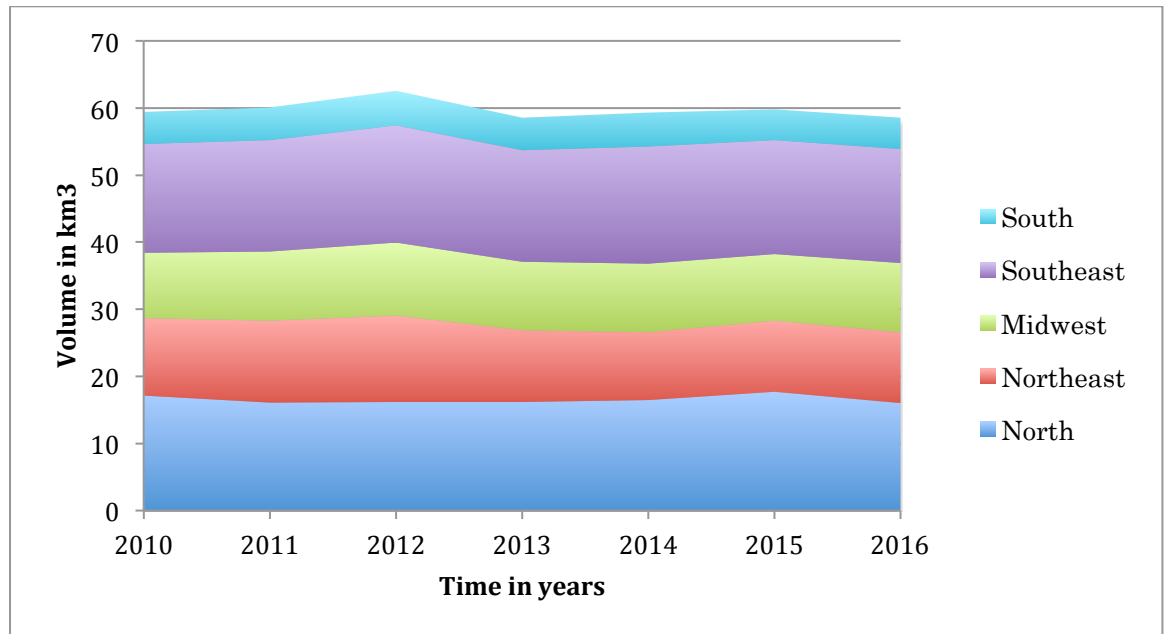
Figure 6.2 – Volume of water evaporated per region and country for the period 2010-2016

To have an idea about how much water evaporation actually accounts for, it is worth looking at figure 6.2. The volume of water evaporated is a relation between the overall reservoir area and the rate of evaporation. We can see that the reservoirs in the North and the Southeast lose around 16-17km³ per year, the ones in the Midwest and the Northeast about 10km³, and the ones in the South a little less than 5km³ every year. The total Brazilian evaporation is about 60km³ every year. Taking into account that Lake Constance (Germany, Austria, Switzerland) has a volume of 48km³ and Lake Geneva (France, Switzerland) a volume of 89km³, we can see that the amount evaporated from hydroelectric reservoirs in Brazil every year is actually considerable.
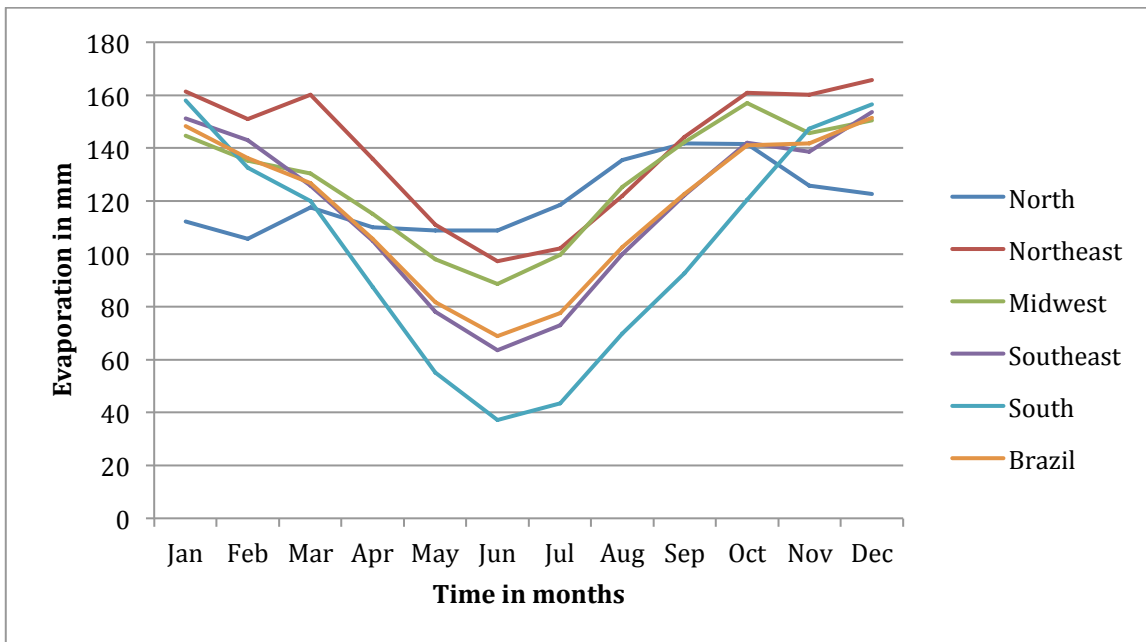
Figure 6.3 – Average monthly evaporation per region and country for the period 2010-2016

Something important to keep in mind when analysing and taking evaporation into account is that it is not uniform throughout the year. Depending on the climate and weather conditions at specific sites, there can be considerable differences and that can make a big difference for future planning purposes. Brazil, due to its sheer size does not have one kind of climate throughout its territory, which also shows in Figure 6.3. The North has the most uniform evaporation with a minimum of 106mm in February and a maximum of 142mm in September. In contrast, the South is the one that has the largest change through the seasons, with a minimum evaporation in June with 37mm and a maximum in January with 158mm. The Northeast and the Midwest have relatively high minimums with 97 and 89mm respectively in June, and high maximums of 142 and 157mm in September and October respectively. The Southeast is the region with the second lowest evaporation overall and has a minimum of 63mm in June and a maximum of 154mm in December. The Southeast heavily affects the Brazilian overall values, which has a minimum of 69mm in June and a maximum of 151mm of evaporation in December.

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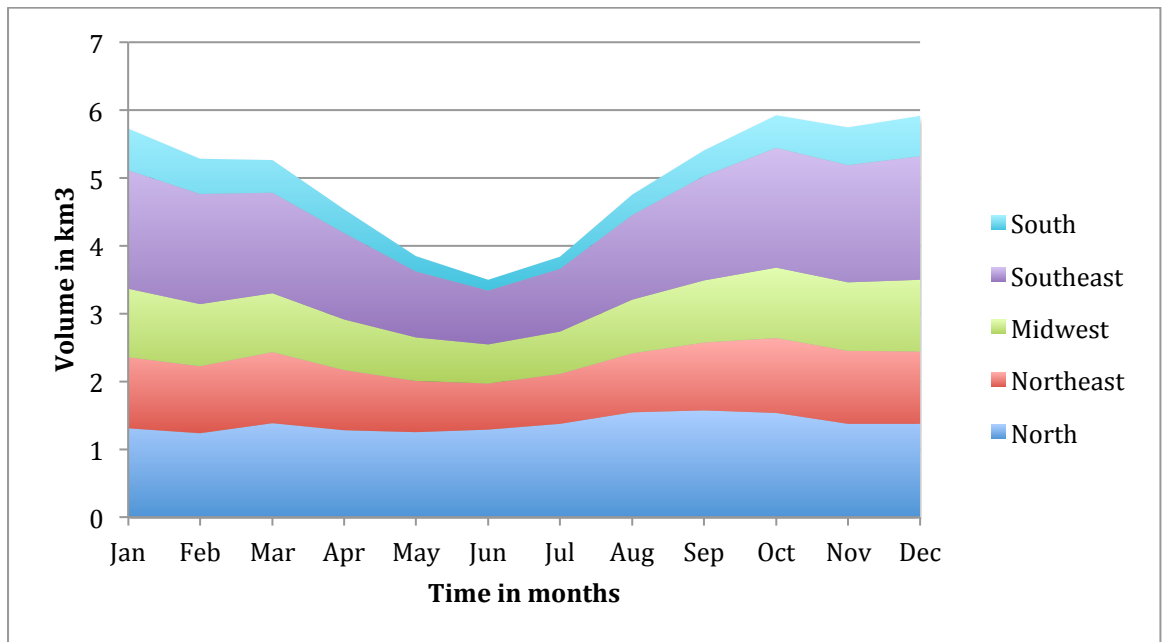
Figure 6.4 – Average monthly volume of water evaporated per region and country for the period 2010-2016

One again, to have an idea as to how much water is actually evaporated in total, it is worth looking at figure 6.4. The Southeast and the North alternate during the year being the region with the largest volume of evaporated water, with the South always clearly losing the least water through evaporation. Again, we can see that the Southeast with 45.5% of all reservoirs affects the overall Brazilian values quite a lot. June sees the least lost water with 3.5km^3, and October and December the most with 5.9km^3.

6.1.2. Evaporation per state
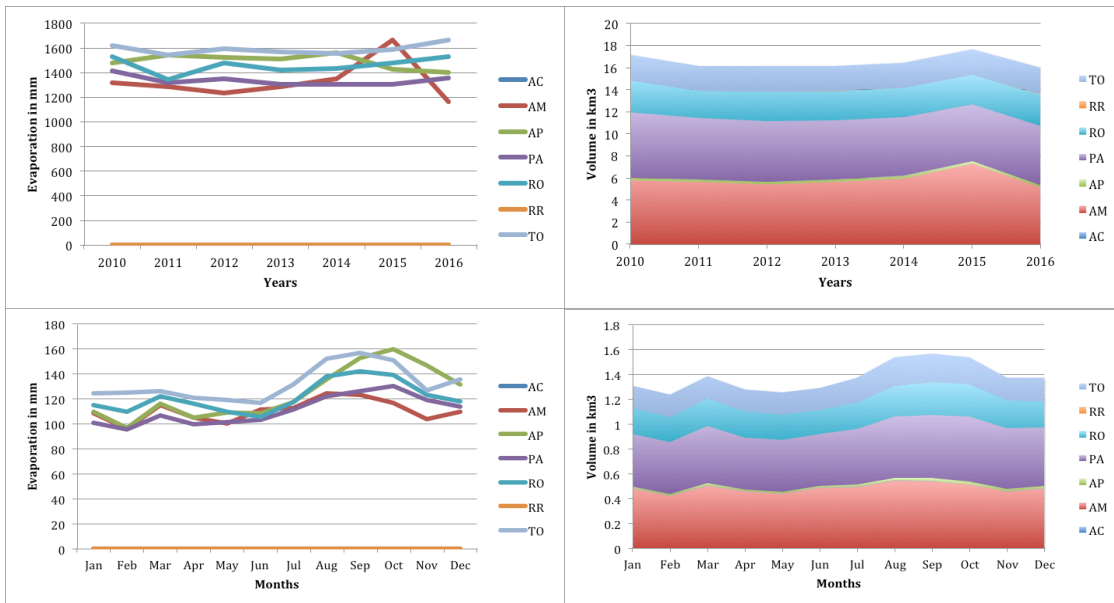
Figure 6.5 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, per state in the North for the period 2010-2016

The North has 7 states, of which 2 do not have any reservoirs. The other 5 states have an accumulated 16.71 reservoirs (some reservoirs belong in more than one state and some in more than one region), with Rondônia (RO) having the most with 4. As can be seen in figure 6.5, the state of Amazonas (AM) normally has the lowest rate of evaporation, apart from 2015 where it had the highest, followed by a huge drop in 2016. Tocantíns (TO) normally has the highest evaporation. The evaporation in the North for any state is usually from just below 1200 to just above 1600mm per year. Most of the evaporated water occurs in the state of Amazonas (AM), followed by the state of Pará (PA). The pattern of evaporation per month is different to the rest of the country, since from January to June evaporation is more or less uniform, then there is an increase to about October, with the values decreasing again until December. The volume of water evaporated from reservoirs in the North is always above $1.2km^3$ per month and could be as high as $1.6km^3$. The total volume evaporated was between 16 and $18km^3$.

Figure 6.6 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, per state in the Northeast for the period 2010-2016

The Northeast has 9 states, of which 3 do not have any reservoirs. The other 6 states have an accumulated 11.34 reservoirs, with Bahia (BA) having 7.79 of them. As can be seen in figure 6.6, the state with the highest evaporation is Pernambuco (PE), but it only has 1 reservoir. Piauí (PI) and Maranhão (MA) have the lowest evaporation rates. The evaporation in the Northeast for any state is from about 1400 to almost 2000mm per year, which is the highest rate for any region in Brazil. The Northeast has two patterns of evaporation. The states of Maranhão (MA) and Piauí (PI) are similar to the Northern region of the country, whereas the other 4 states that have reservoirs show a different seasonal change in evaporation. They have a decline of evaporation from March until June-July and an increase from then until December. Not surprisingly, almost all the evaporated water in the region occurs in Bahia (BA), since this is where about 70% of the reservoirs are located. The volume of water evaporated in the region is from about 0.6km^3 per month in June to about 1.1km^3 in October, and the total volume evaporated is between 10 and 13km^3 per year.

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Figure 6.7 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, per state in the Midwest for the period 2010-2016

The Midwest had 4 states, all of which have reservoirs with a total of 25.75. The one that has the most is Goiás (GO) with 15.08. In figure 6.7, we can see that the state of Goiás (GO) is also the one with clearly the highest evaporation rate, with Mato Grosso (MT) usually being the one with the lowest. The evaporation in the Midwest for any state is from about 1400 to a little over 1600mm per year. All states in the region have a similar pattern of evaporation through the seasons, with a decrease from January until June and an increase to about October. This is comparable to the Northeast of the country. Most of the evaporation occurs in Goiás (GO) and Mato Grosso do Sul (MS). Although Mato Grosso do Sul (MS) only has 5.3 reservoirs, these are quite large in comparison to the ones in Goiás (GO), so the total volume evaporated in these two states is similar. The volume evaporated per month is from just below $0.6km^3$ in June to just over $1km^3$ in December, and the total volume evaporated is between just below 10 to about $11km^3$ per year.

Figure 6.8 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, per state in the Southeast for the period 2010-2016

The Southeast has 4 states, all of which have reservoirs with a total of 74.19. São Paulo (SP) and Minas Gerais (MG) have 33.92 and 32.79 respectively, making them the two states with the most reservoirs in Brazil. As shown in figure 6.8, the state of Espírito Santo (ES) is the one with the highest evaporation rate, whereas the other three states have a similar rate, with São Paulo (SP) having the lowest half of the time and Rio de Janeiro (RJ) having the lowest rest of the time. The evaporation in the Southeast for any state is from a little over 1200 to about 1700mm per year. The seasonal evaporation pattern is very similar for all states, although Espírito Santo (ES) has a higher rate. From January until June there is a decrease, which changes from July to December. This is similar to the Midwest and most parts of the Northeast, although in the case of the Southeast, it is more prominent. With the amount of reservoirs in the two states of São Paulo (SP) and Minas Gerais (MG), it comes as no surprise that apart from a tiny fraction, all of the evaporation occurs there. The volume evaporated per month is from about $0.8km^3$ in June to just over

1.8km³ in December, and the total volume evaporated is between 16 to just below 18km³ per year.

Figure 6.9 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, per state in the South for the period 2010-2016

The South is the region with the fewest states, 3, all of which have reservoirs with a total of 35.01. Rio Grande do Sul (RS) and Paraná (PR) have 15.02 and 13.99 respectively. As we can see in figure 6.9, the rate of evaporation is very similar for all three states, although Paraná (PR) usually has a slightly higher one. The evaporation in the South for any state is from a little over 1000 to a little over 1300mm per year, which is the lowest rate for any region in Brazil. The seasonal evaporation pattern is very similar for all states, although Paraná (PR) has a rate a little lower from March to October. There is a decrease from January to June and then an increase through to December. Although evaporation rates are quite high in December and January, they are very low in June and July. The change of the seasons is quite obvious in the South, a lot more than anywhere else in the country. Although Rio Grande do Sul (RS) has more reservoirs, Paraná (PR) has clearly the largest ones, so more than 60% of the

evaporation of water occurs in this state. The volume evaporated per month is from about 0.15km^3 in June to about 0.6km^3 in December and January, and the total volume evaporated is between 4.5 to just over 5km^3 per year, making South the region with the most prominent extremes within the year and also the one with the least total evaporation.

6.1.3. Examples of evaporation in specific reservoirs

In this section, the results from three reservoirs per region are presented. Their selection was based on their average annual evaporation, and secondarily on their inundated area, trying to select ones with as large a reservoir as possible. There is one example with a close to minimum, one with a close to maximum, and one with a close to the average evaporation for each region. The selected reservoirs are presented in table 6.1.

Region	Region's average evaporation (mm) 2010-2016	Reservoir	State	Area (km²)	Average evaporation (mm) 2010-2016
North	1450.51	Balbina	Amazonas	4437.72	1289.86
		Samuel	Rondônia	679.51	1455.43
		Peixe Angical	Tocantins	318.45	1652.43
Northeast	1662.33	Pedra	Bahia	89.17	1247.14
		Sobradinho	Bahia	4380.79	1795.29
		Apolônio Sales	Alagoas, Bahia, and Pernambuco	94.96	1916.71
Midwest	1527.16	Manso	Mato Grosso	401.8	1066
		Corumbá IV	Goiás	186.51	1553.14
		Serra da Mesa	Goiás	1254.09	1660
Southeast	1387.53	Henry Borden	São Paulo	135.59	1187.29
		Furnas	Minas Gerais	1406.26	1391.86
		Água Vermelha	São Paulo and Minas Gerais	673.63	1579.71
South	1192.1	Governador Bento Munhoz da Rocha Neto	Paraná and Santa Catarina	159.87	980
		Itá	Rio Grande do Sul and Santa Catarina	126.32	1187.71
		Governador José Richa	Paraná	144.2	1436.29

Table 6.1 – Reservoir examples
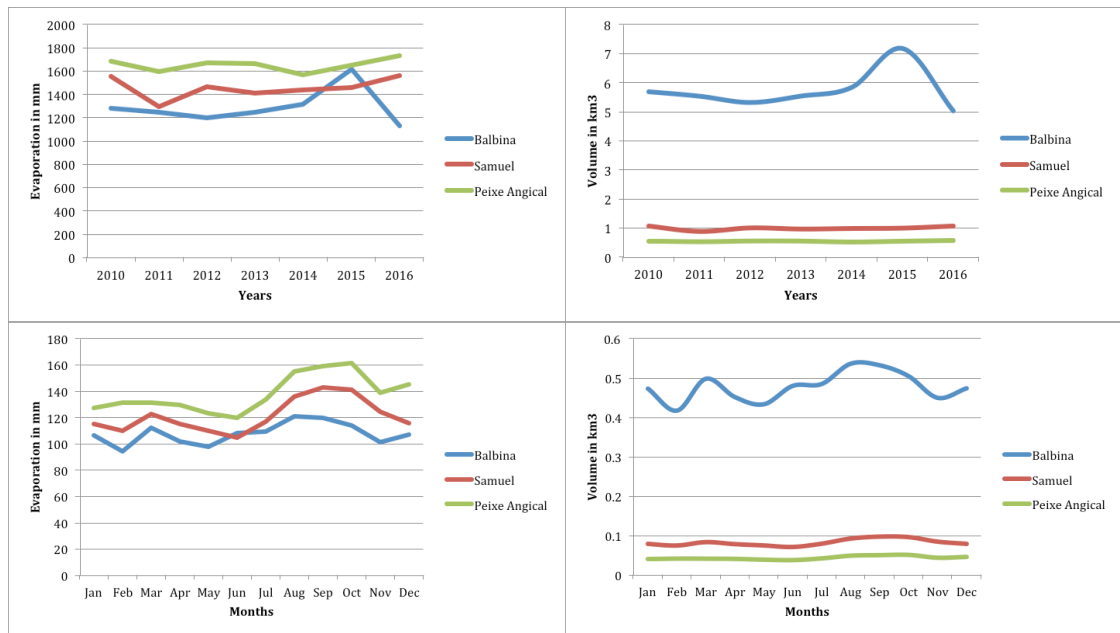
Figure 6.10 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for 3 example reservoirs in the North for the period 2010-2016

As seen in table 6.1, the average evaporation in the North is 1450.51mm. Balbina is the largest reservoir in Brazil with an area of 4437.72km² and it also has the least evaporation from any reservoir in the North of the country. As it is shown in figure 6.10, normally it is between 1200 and 1300mm per year, apart from 2015 when it was around 1600mm, and 2016 when it was about 1100mm. Samuel has almost exactly the northern average with 1455.43mm evaporation per year, and apart from 2010 and 2011 when it had a maximum of about 1600mm and a minimum of about 1300mm respectively, the rest of the period evaporation is relatively constant. Peixe Angical has the second highest evaporation of any reservoir in the North with 1652.43mm, and the values vary from just below 1600 to a little lower than 1800mm per year. The pattern of evaporation through the seasons for all three reservoirs is similar, although it is obvious that the rate is different, which could be attributed to them being in different states. Due to the substantial difference in size, the volume evaporated every year from Balbina is a lot higher than the other two reservoirs and it has an average of about 6km³ evaporation every year.

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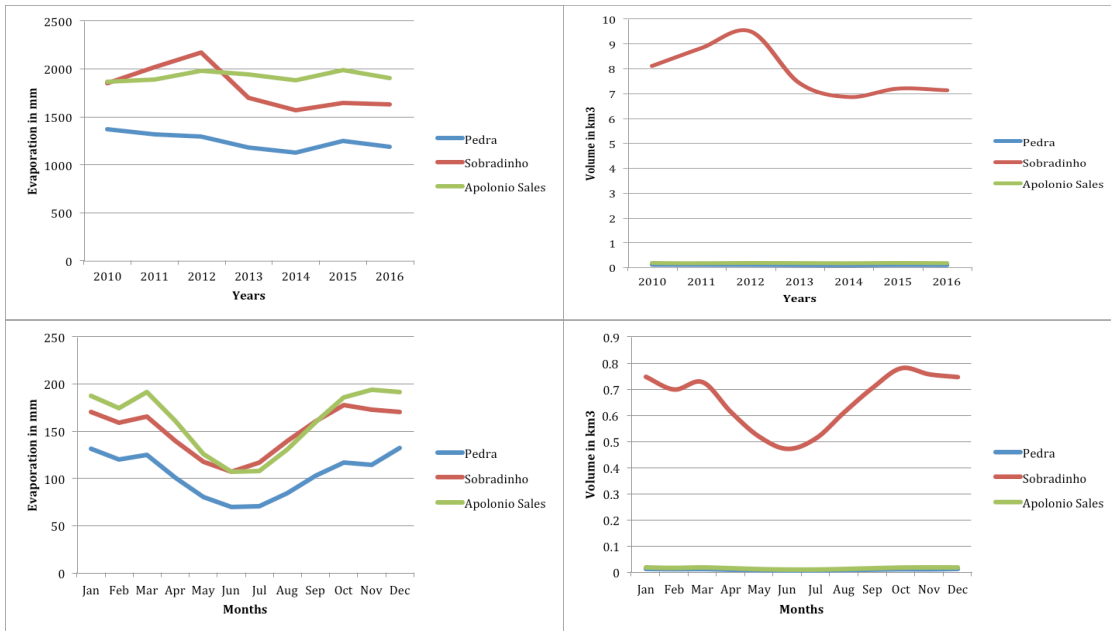
Figure 6.11 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for 3 example reservoirs in the Northeast for the period 2010-2016

The average evaporation in the Northeast is 1662.33mm, which is the highest in the country. Pedra has the lowest evaporation with 1247.14mm per year, which is quite a lot lower than the average in the region. There are a few more small reservoirs with low evaporation rates that bring the average down. Sobradinho, although above the average, was chosen as an example because it is the second largest reservoir in the country and it has a relatively high evaporation rate with 1795.29mm per year, with 2011 having about 2000mm, and 2012 when there was a drought in the area, having about 2200mm. Its average evaporation the rest of the time is closer to the region's average, as is seen in figure 6.11. Finally, Apolônio Sales has a very high evaporation rate, which is relatively constant and 1916.71mm on average for the 7-year period. These three reservoirs are also a good example, because they are either wholly or partly in the same state and we can see the massive differences of evaporation rates they have. The pattern of evaporation for all three is almost identical, but the rate differs a lot. From this, we can see that the geology and the size of a reservoir can make a significant difference. Due to Sobradinho being about 50 times larger than

the other two reservoirs, they cannot really be compared, but firstly the Northeast does not have other large reservoirs, and secondly evaporation from Sobradinho alone is about 8km³ per year, which is by far the largest volume evaporated from any other in Brazil. Balbina in the North with a very similar size is losing 2km³ less every year.
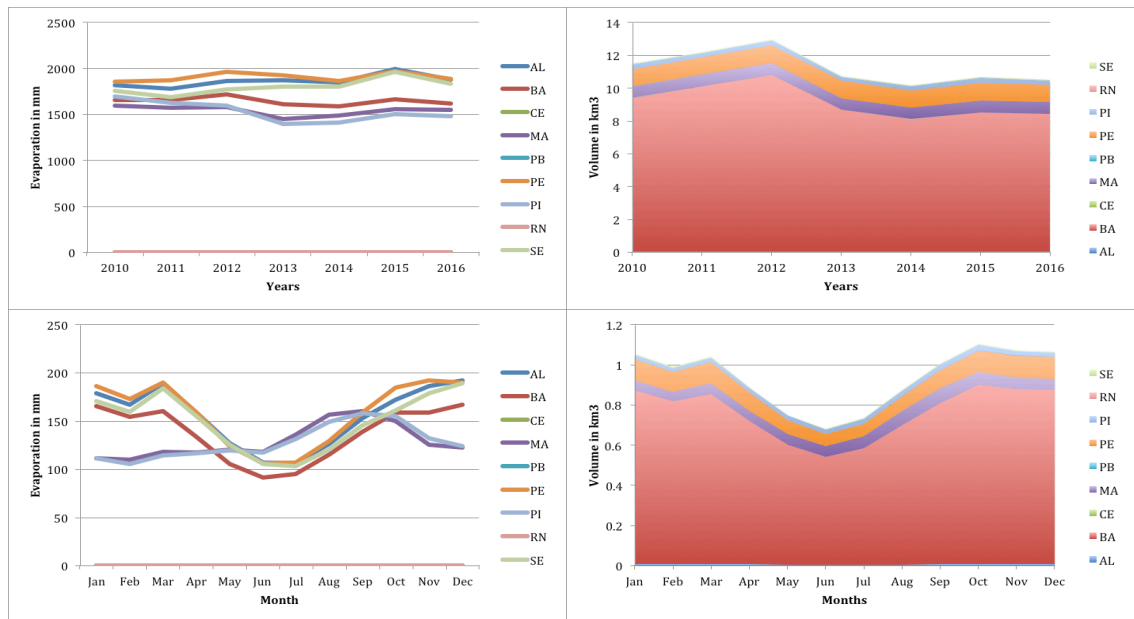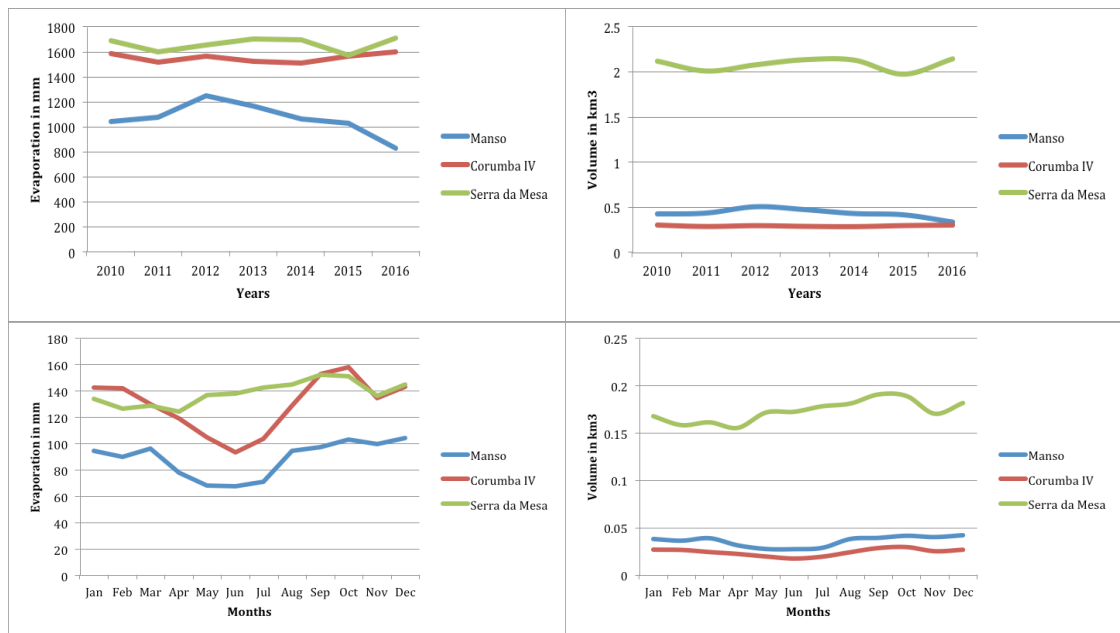

Figure 6.12 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for 3 example reservoirs in the Midwest for the period 2010-2016

The average evaporation in the Midwest is 1527.16mm, which is the second highest in the country. Serra da Mesa is the second largest reservoir in the region and also the one with the second highest evaporation rate with 1660mm per year, which is comparable to the average northeastern reservoir where the highest evaporation rates occur. As is seen in figure 6.12, its evaporation rate sometimes drops to just below 1600 and sometimes it's a little over 1700mm per year. Corumbá IV follows a similar pattern through the years, although its average evaporation rate is 1553.14mm, which is interesting because they both belong in the same state. Finally, Manso has a considerably lower average evaporation rate with 1066mm per year, although it was about 1250mm in 2012 and just

over 800mm in 2016, showing a wide variation of values, due to weather extremes. The evaporation pattern through the seasons is similar for all 3 reservoirs, although Serra da Mesa has an increase in June-August unlike the other two, showing again that specific location makes a difference, since Corumbá IV and Serra da Mesa belong in the same state. Although the sizes of the reservoirs are not comparable, it is interesting that the volume evaporated from Manso and Corumbá IV is comparable. Corumbá IV is not even half the size of Manso, yet its evaporation rate is 50% higher, and in 2016 when the rate was double, the evaporation volume was the same.

Figure 6.13 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for 3 example reservoirs in the Southeast for the period 2010-2016

The average evaporation in the Southeast is 1387.53mm, which is the second lowest in the country. Henry Borden has one of the lowest evaporation rates in the region with 1187.29mm per year, which has been relatively constant throughout this 7-year period, from just below to just above 1200mm, as is shown in figure 6.13, which is comparable to evaporation rates in the South of the country. Furnas, which is the fifth largest reservoir in Brazil, has an average evaporation of 1391.86mm per

year, almost the exact average of the region. Again the evaporation rate is fairly constant from 1350 to 1500mm. Finally, Água Vermelha has one of the highest evaporation rates in the Southeast with 1579.71mm, which is comparable to values in the Midwest. Its rates are also relatively constant, like the other two examples as well, with a minimum of a bit over 1500 to a maximum of a bit over 1600mm. The evaporation patterns through the seasons are almost identical, showing that the weather patterns in the two states where the reservoirs belong are fairly similar. Due to their constant evaporation, the volumes evaporated do not change much every year, but there is a considerable change through the seasons, which is unlike the previous 3 regions of the country presented, but in similar fashion to the South.
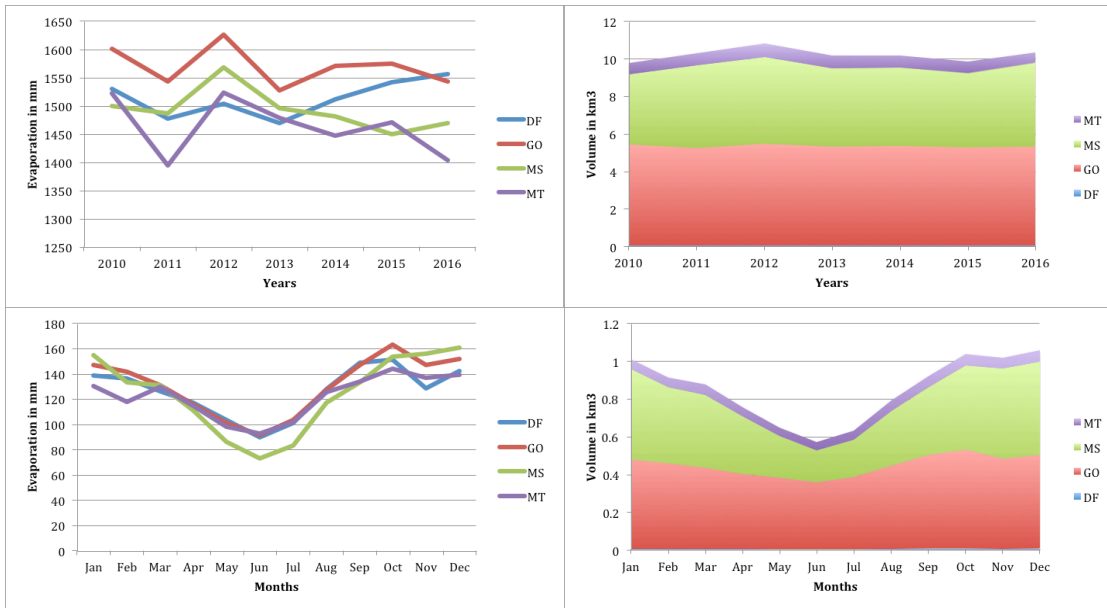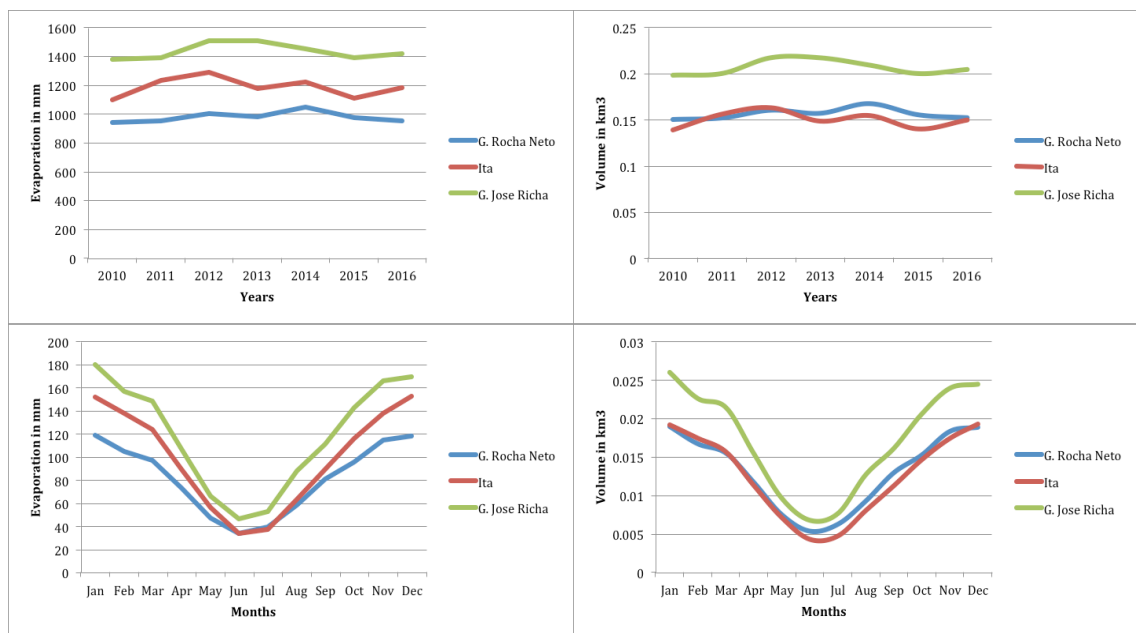

Figure 6.14 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for 3 example reservoirs in the South for the period 2010-2016

The average evaporation in the South is 1192.1mm, which is the lowest in the country. Governador Bento Munhoz da Rocha Neto is the reservoir with the lowest evaporation rate in the South with 980mm per year on average, which is also quite constant in this 7-year period, as shown in figure 6.14.

Itá is almost exactly the average reservoir in the region with 1187.71mm, with its values of evaporation rate being between 1100 and 1300mm every year. Finally, Governador José Richa has the highest evaporation rate in the South with 1436.29mm per year, which is comparable to reservoirs in the Southeast. Its values vary from just below 1400 to just over 1500mm per year. The pattern of evaporation through the years is quite similar for all reservoirs. The pattern of evaporation rates through the seasons is almost identical as well, which is logical since the reservoirs are relatively close to each other, so having very similar weather patterns. The volumes evaporated are very similar for Governador Munhoz and Itá, whereas Governador Richa's evaporated volume is about 33% more than the other two. Nevertheless, all 3 reservoirs are not of considerable size compared to other reservoirs presented earlier, and since the evaporation rate is lower as well, the total volume of evaporated water is relatively low and about 0.15-0.2 for all 3 of them. As was the case in the Southeast as well, there is a large variation of evaporation rate and volumes evaporated through the seasons.

Another interesting comparison would be that of the 5 largest reservoirs in Brazil irrespective of their location. The North has a lot of large reservoirs, the Northeast has only 4 above 100km², the Midwest also has a few large ones, the Southeast has both a lot of large ones and a lot of small ones, and the South has 6 over 100km², but none very large ones. The 5 largest reservoirs are shown in table 6.2.

Region	Reservoir	State	Area (km²)	Average evaporation (mm) 2010-2016
North	Balbina	Amazonas	4437.72	1289.86
Northeast	Sobradinho	Bahia	4380.79	1795.29
North	Tucuruí I & II	Paraná	3513.29	1319
Midwest and Southeast	Porto Primavera	Mato Grosso do Sul and São Paulo	2976.98	1384.71
Southeast	Furnas	Minas Gerais	1406.26	1391.86

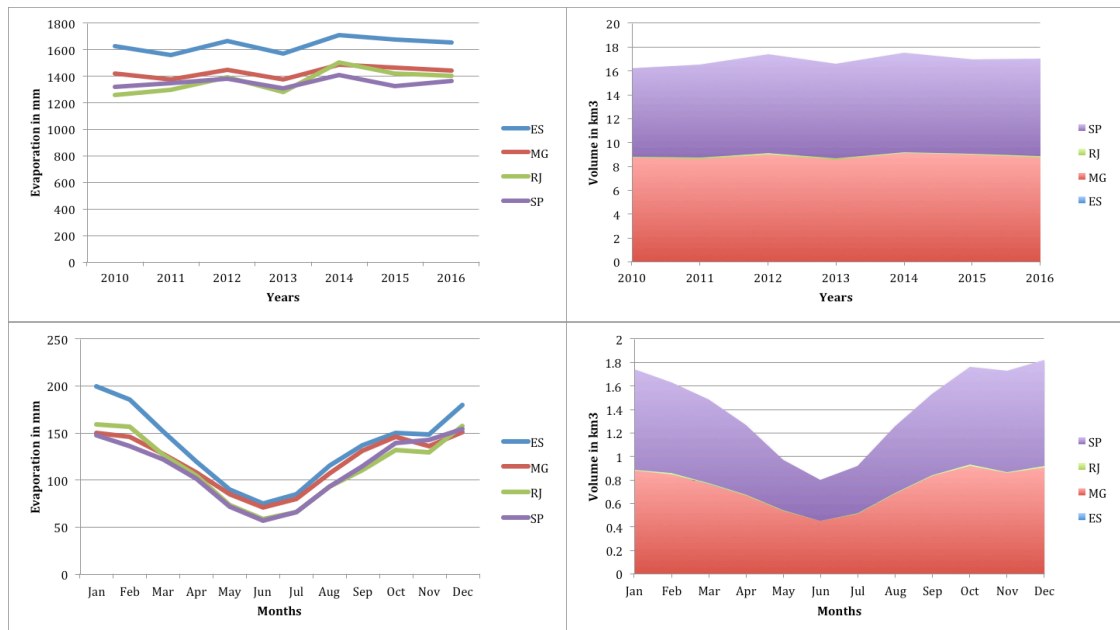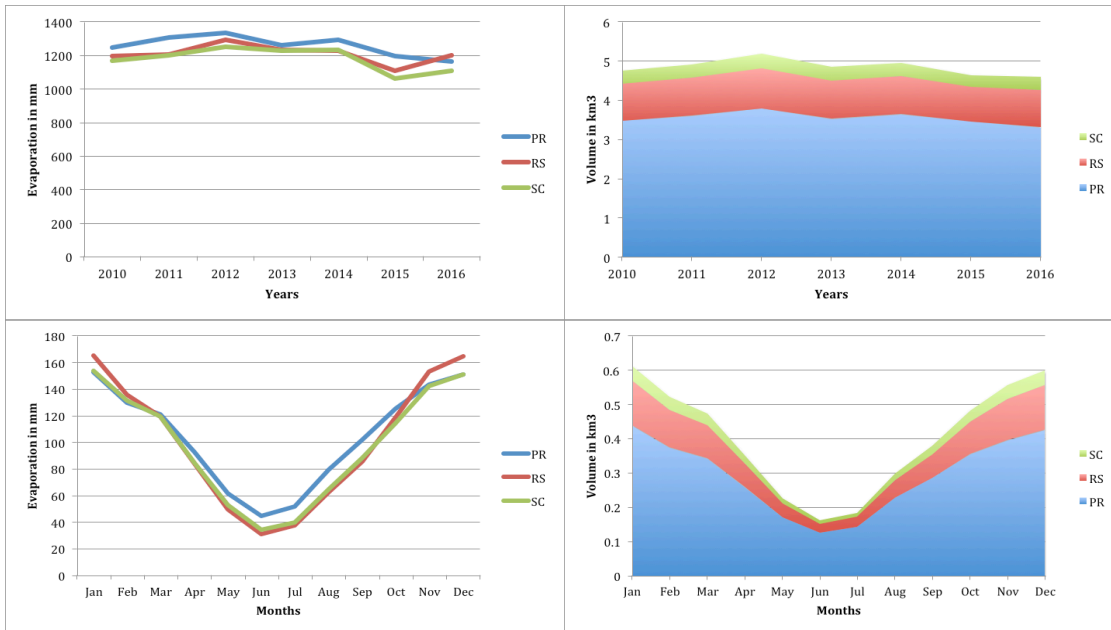Table 6.2 – 5 largest reservoirs in Brazil
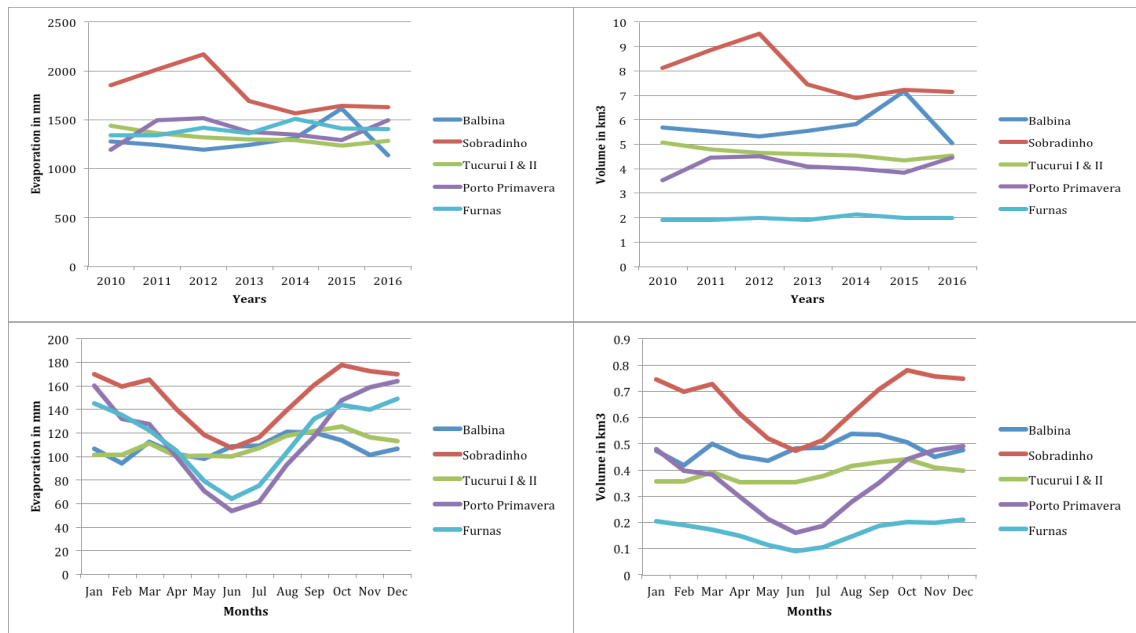
Figure 6.15 - a) (top-left) average annual evaporation, b) (bottom-left) average monthly evaporation, c) (top-right) annual volume of water evaporated, d) (bottom-right) monthly volume of water evaporated, for the 5 largest reservoirs in Brazil for the period 2010-2016

The average evaporation rates of 4 of the reservoirs is relatively similar, with only 100mm per year difference between them, but the fifth one, Sobradinho, has a 400mm difference and a 500mm difference from the second and fifth in the list respectively. This difference is also obvious in figure 6.15, since only in 2015 Balbina was close to it. The volumes evaporated are in line with the evaporation rates, although for example in 2012 and 2016 Porto Primavera had a similar evaporated volume to Tucuruí despite the over 500km² difference in size. As far as the evaporation rate is concerned, Balbina and Tucuruí, and Porto Primavera and Furnas have similar patterns compared to the other reservoirs, since they belong in the same region. An interesting fact is that these 5 reservoirs have a total of about 25km³ evaporated volume of water from them every year, when the Brazilian total is about 60km³ per year.

From the evaporation analysis performed, there are a few important lessons learned: a) the Southeast of the country has the most reservoirs and so it greatly affects the overall results, b) the total volume of water evaporated

from the country's hydroelectric reservoirs every year is equal to a relatively large European lake, c) the Northeast has the largest evaporation rate, while the South has the lowest, d) depending on the climate and weather conditions at specific sites, there can be considerable differences on evaporation rates even within the same region, and finally e) the more south we move within Brazil, the more the evaporation rate is changing through the seasons, which is especially the case in the South and the Southeast where most of the reservoirs are located.

The aforementioned facts have certain important implications:

- Firstly, the volume of water evaporated each year in the country shows that evaporation cannot be taken lightly, but needs to be part of the investigated water cycle.
- Secondly, not all regions have the same evaporation rates, and perhaps even more importantly even within a region some reservoirs perform much better than others. This shows clearly that Brazil, being such a large country, cannot be investigated as a whole, rather analysis needs to be done at the very least regionally, and when it comes to making decisions about new reservoirs the investigation would need to take place for the specific area where the future reservoir is to be located.
- Furthermore, seasonality is important when it comes to evaporation and the more south we move in Brazil, the more evident seasonality becomes and needs to be taken into account.
- Finally, from this first analysis, we can see that the Southeast has a lot of reservoirs and that alone can potentially cause problems in times of droughts, while the Northeast already from this first evaporation analysis shows signs of not being an ideal place for hydroelectric reservoirs, unlike the South.

All these aspects are in one or another degree important, and their importance will become more obvious in the water footprint and water budget analyses.

6.1.4. Comparison of evaporation results with ONS study

As mentioned in the methodology chapter, the Penman-Monteith model that incorporates a seasonal heat storage component and a water advection component, and the Morton CRLE model are the most suitable ones to estimate evaporation from deep lakes and large voids. ONS used the Morton method in 2004 to calculate evaporation from reservoirs in operation at that time. Since the Penman-Monteith method is suggested by FAO, it was deemed appropriate to use for the analysis of the Brazilian reservoirs, in conjunction with the fact that this method had not been used before for the whole hydroelectricity system in the country. One important difference between this research/analysis compared to the one by ONS, apart from the different methods employed, is the different data used for the calculation of evaporation. The ONS study estimated average monthly evaporation values based on average climate data for several locations for the years 1931 to 1990, from a limited number of meteorological stations. The difference from 2004 to 2017 is that in 2017 Brazil, through INMET, have a much better nationwide network of weather stations for collecting actual data from several places, in close proximity to reservoirs, which is something that did not exist in 2004. Hence, evaporation calculations have become much more feasible and reliable than before. Consequently, although the results presented here and the results by ONS are not directly comparable, it is nevertheless interesting to see how closely related they are.

Hydroelectric power plant	State	Region	ONS - Evaporation (mm/year) – 1931-1990	This study – Evaporation (mm/year) – 2010-2016
Tucuruí I e II	PA	North	1652	1319
Luís Eduardo Magalhães (Lajeado)	TO	North	1751	1475
Luiz Gonzaga (Itaparica)	BA	Northeast	1862	1878
Sobradinho	PE	Northeast	1909	1795
Emborcação	GO	Midwest	1556	1445
Itumbiara	GO	Midwest	1597	1529
São Simão	GO	Midwest	1603	1537
Serra da Mesa	GO	Midwest	1660	1660
Ilha Solteira	MS	Midwest	1597	1417
Três Irmãos	MS	Midwest	1577	1429
Furnas	MG	Southeast	1413	1392
Nova Ponte	MG	Southeast	1498	1446
Três Marias	MG	Southeast	1526	1511
Água Vermelha (Antiga José Ermírio de Moraes)	SP	Southeast	1579	1580
Capivara (Escola de Engenharia Mackenzie)	SP	Southeast	1429	1349
Marimbondo	SP	Southeast	1536	1446
Governador Bento Munhoz da Rocha Neto (Foz do Areia)	PR	South	1118	980
Itaipu	PR	South	1305	1400
Porto Primavera (Eng° Sérgio Motta)	PR	South	1461	1385
Salto Santiago	PR	South	1163	1252

Table 6.3 – Comparison of evaporation rates between this and ONS's studies

ONS in their 2004 report only report the net evaporation, which is not very useful on its own since precipitation data was not included, but Bueno & de Mello (2015) in their paper provide a table with 20 examples that also includes gross evaporation, and this table was used as a reference for the comparison presented in table 6.3. Evaporation values for the 2 reservoirs in the North are quite different, about 300mm different on average. The 2 reservoirs in the Northeast have more similar values, since the results for Luiz Gonzaga are almost identical, and results for Sobradinho have a difference of just over 100mm. For the Midwest reservoirs there is a mix of differences. Serra da Mesa had the exact same outcome, Itumbiara and São Simão about 70mm difference, Emborcação about 100mm, and the other 2 an average of 165mm difference. In the Southeast, the results for Água

Vermelha were identical, and very closely related for Furnas and Três Marias. For the other 3, the differences were 50, 80, and 90mm. The results in the South were mixed. The largest difference was for the values for Governador Munhoz, which was about 140mm. An interesting fact is that for most of the reservoirs, 15 of them, the evaporation rates found in this study were lower than the ones found by ONS, 2 of the results were identical, and 3 were higher.

The average evaporation rate for these 20 examples was 1539.6mm in the ONS study and 1461.25mm in this study, hence a 78.35mm difference per year. There are two reasons for the difference, firstly the different methods applied, and secondly the different data used. The relatively small difference in values in most of the cases shows that the two methods are comparable and/or the weather has not been substantially different the past almost 90 years. In general, as has already been partly shown in the evaporation results for the 2010-2016 period, evaporation does not fluctuate too much between years. This will become even more evident in chapter 7 and the evaporation projections to 2050. Hence, it is logical that evaporation rates between this and ONS's studies are not very different.

Nevertheless, if we are talking in terms of water availability for electricity and other uses that require planning in matter of hours or days at the most, it is not logical to depend on average values calculated from data for many years. As was shown earlier, evaporation rates can change through the years, and even more importantly through the seasons. It is important to be as precise as possible on how much water is evaporated in small time steps, because this way it is actually possible to perform a water budget analysis, so as to know the availability of water at any given day, and to be able to plan accordingly. Hence, although values for a 60-year and a 7-year period are compared here, none of these values should be used in modeling terms for the future, because they disregard the change of evaporation through the seasons and years, which means they disregard weather and possible climate change. Evaporation and in turn water availability, is a dynamic

process and it needs to be treated as such, so evaporation needs to be calculated within a model dynamically as time progresses in future scenarios depending on the specific locations' weather variables.

The contribution to knowledge of the evaporation results presented so far is that a) they are estimated using a modified for deep lakes Penman-Monteith equation, which is also the suggested method by FAO for evaporation estimation, b) they are estimated on an hourly basis, c) independently for each reservoir present in the Brazilian system at the end of 2016, and d) using actual weather data from weather stations in close proximity to the reservoirs. This is the first such attempt in literature for all hydroelectric reservoirs in Brazil since ONS's attempt in 2004, which also improves on the methodology used then in various ways that were described in more detail in the methodology section. The evaporation estimates will be used in the water footprint and water budget analyses and improve the accuracy of past research.

6.1.5. Sensitivity analysis of evaporation

The calculations for evaporation rely on eight kinds of data: water body area, water depth, water body altitude, latitude, mean daily air temperature, total daily incoming short-wave radiation, average daily wind speed, and daily vapour pressure. The altitude and latitude are constant, so they are not considered in the sensitivity analysis. The area and depth affect evaporation, since the larger the area, the more the evaporation, and also the depth could play a role as well, which is the reason the adjusted Penman-Monteith method was employed. Nevertheless, area and depth are both heavily dependent upon the geological morphology of each reservoir's inundated area. It is also for this reason that a reasonable assumption as to how these change in time is very hard. For the purposes of the analysis, and due to lack of such data, area and depth were considered constant, as is the case with all similar hydrological models. Although, it is recognised that

data on them would be of great assistance and it would be a good idea for countries to start collecting such data.

A sensitivity analysis of water area would be interesting, but as explained, the area change depends a lot on the geomorphology of each individual reservoir, therefore for such an analysis to take place, an individual assumption would need to be made for each reservoir, since a general assumption for all cannot provide any meaningful insight. This would need to be based upon some knowledge of the geomorphology of each area, which is very time consuming. Also, the results presented in this thesis are per state/region/country, hence it is beyond the scope of the research to perform such an analysis heavily based upon assumptions.

Daily vapour pressure is fully dependent upon temperature, so it was omitted from the sensitivity analysis as well. This analysis was concentrated on mean daily air temperature, daily wind speed, and total daily incoming short-wave radiation. Although this is not the case in reality, the effect of each of the three factors is presented as if they were changing individually and keeping the other factors constant, to have an idea of how sensitive evaporation is to their effect alone.

Temperature change (°C)	-2	-1	+1	+2	+3	+4
States	% Change of evaporation					
North						
AC	0	0	0	0	0	0
AP	-4.73	-2.38	+2.4	+4.83	+7.27	+9.72
AM	-5.1	-2.57	+2.6	+5.24	+7.9	+10.58
PA	-5.09	-2.57	+2.6	+5.24	+7.91	+10.59
RO	-5.05	-2.54	+2.58	+5.2	+7.84	+10.51
RR	0	0	0	0	0	0
TO	-5.15	-2.59	+2.62	+5.26	+7.92	+10.6
Northeast						
AL	-4.76	-2.39	+2.41	+4.84	+7.28	+9.73
BA	-4.72	-2.38	+2.4	+4.83	+7.28	+9.74
CE	0	0	0	0	0	0
MA	-4.95	-2.5	+2.52	+5.05	+7.6	+10.16
PB	0	0	0	0	0	0
PE	-4.61	-2.31	+2.34	+4.69	+7.05	+9.43
PI	-4.83	-2.42	+2.44	+4.89	+7.35	+9.84
RN	0	0	0	0	0	0
SE	-4.89	-2.46	+2.5	+5.01	+7.53	+10.06
Midwest						
DF	-5.1	-2.57	+2.63	+5.3	+8	+10.75
GO	-5.19	-2.62	+2.66	+5.35	+8.08	+10.84
MS	-5.21	-2.63	+2.68	+5.39	+8.14	+10.92
MT	-4.99	-2.51	+2.55	+5.12	+7.72	+10.34
Southeast						
ES	-4.94	-2.49	+2.52	+5.06	+7.62	+10.21
MG	-5.16	-2.6	+2.65	+5.34	+8.07	+10.83
RJ	-5.04	-2.54	+2.57	+5.18	+7.82	+10.47
SP	-5.2	-2.63	+2.68	+5.4	+8.17	+10.97
South						
PR	-5.23	-2.65	+2.71	+5.48	+8.29	+11.16
RS	-5.01	-2.54	+2.61	+5.28	+8.01	+10.81
SC	-5.07	-2.57	+2.65	+5.37	+8.15	+10.99

Table 6.4 – Percentage change of evaporation due to temperature change

Table 6.4 presents the percentage of change for evaporation if temperature went up 1-4 degrees Celsius, and also if it went down 1-2 degrees, from the average temperature of the 7-year analysis. States that have no reservoirs have no results. Most temperature change future projections to 2050-2100 (IPCC, World Bank, etc.) are within the range of plus 1-4°C, therefore these values were selected to create a perception as to what would such theoretical temperature changes mean to evaporation. The minus 1-2°C values are also presented, once again to have an idea of what would happen to evaporation in a scenario where temperature went down. Firstly, we can see that states within a region do not necessarily have similar results and as the temperature increases, so do the differences. Although the percentage

increase in evaporation across the whole country is quite similar and never more than about 1% from the minimum to the maximum. Another important finding is that the more temperature rises, the regions that will feel the effects of evaporation rise the most, are the regions that have the least rate of evaporation at present, although the differences are not big. Generally, it seems that for every 1 degree Celsius, there is an increase of about 2.5% in evaporation.

Wind speed change (m/s)	+0.5	+1	+2
States	% Change of evaporation		
North			
AC	0	0	0
AP	+2.61	+4.84	+8.48
AM	+4.48	+8.18	+13.97
PA	+4.41	+8.05	+13.75
RO	+3.28	+6.05	+10.53
RR	0	0	0
TO	+3.65	+6.72	+11.65
Northeast			
AL	+2.29	+4.24	+7.48
BA	+1.93	+3.63	+6.53
CE	0	0	0
MA	+3.63	+6.68	+11.57
PB	0	0	0
PE	+1.45	+2.76	+5.05
PI	+3.38	+6.24	+10.85
RN	0	0	0
SE	2.83	+5.21	+9.1
Midwest			
DF	+2.43	+4.56	+8.13
GO	+2.85	+5.3	+9.36
MS	+3.04	+5.64	+9.87
MT	+3.27	+6.01	+10.42
Southeast			
ES	+2.36	+4.38	+7.7
MG	+2.82	+5.24	+9.25
RJ	+2.53	+4.71	+8.32
SP	+3	+5.58	+9.84
South			
PR	+3.2	+5.94	+10.43
RS	+2.38	+4.47	+7.99
SC	+2.82	+5.23	+9.21

Table 6.5 – Percentage change of evaporation due to wind speed change

Table 6.5 presents the percentage of change for evaporation if wind speed went up 0.5, 1, and 2 m/s. The reason these specific values (0.5-2 m/s) were selected is based on the observation of past data. Wind speed does not

change too much through time, however some changes are possible. Climate change has already given rise to more extreme weather and for this reason a rise in wind speed is investigated here, to give a perception as to what such a change would entail in relation to evaporation. Although almost always temperature change is dominating future scenarios analyses, wind speed can increase evaporation quite a lot. With an increase of 2 m/s per year, evaporation can increase from as little as 5% to 14%. There is no real pattern as to which region would be mostly affected by wind speed, which means that this is highly locally, and hence morphologically, dependent. The relatively large increase of evaporation due to wind speed is potentially a good reason to recognise its impact and for it to further be included as an important factor to hydroelectricity planning.

Daily incoming short-wave radiation change (MJ/m² d)	+1	+2
States	% Change of evaporation	
North		
AC	0	0
AP	+4.7	+9.39
AM	+4.74	+9.47
PA	+4.71	+9.42
RO	+4.46	+8.91
RR	0	0
TO	+4.15	+8.31
Northeast		
AL	+3.87	+7.75
BA	+4.2	+8.39
CE	0	0
MA	+4.36	+8.72
PB	0	0
PE	+3.9	+7.8
PI	+4.47	+8.94
RN	0	0
SE	+3.89	+7.78
Midwest		
DF	+4.23	+8.46
GO	+4.07	+8.14
MS	+4.14	+8.28
MT	+4.51	+9.02
Southeast		
ES	+4.01	+8.03
MG	+4.32	+8.63
RJ	+4.66	+9.32
SP	+4.41	+8.83
South		
PR	+4.47	+8.93
RS	+4.55	+9.1
SC	+4.54	+9.08

Table 6.6 – Percentage change of evaporation due to daily incoming short-wave radiation change

Table 6.6 presents the percentage of change for evaporation if the daily incoming short-wave radiation would go up 1 and 2 MJ/m². The selection of these values (1-2 MJ/m²d) was based on observation of past data. Short-wave radiation had not changed significantly, therefore is was difficult to make a selection. Short-wave radiation changes happen in relation to temperature changes, although they are not linearly related, and hence their effect was investigated irrespective of each other in this sensitivity analysis. However, a change of 1-2 MJ/m²d was deemed logical, when comparing past temperature and short-wave radiation changes. Like with wind speed, it is not abundantly clear which regions are mostly affected by

an increase in short-wave radiation. Values within a region, apart from the South, vary. Generally, it appears that for each 1 MJ/m³ the evaporation rate increases by 4-4.5%.

Although the analysis per region and state provides information that could be useful in the building of scenarios, it would be interesting to see results for the 10 largest reservoirs in Brazil and how their evaporation rate is affected from each of the 3 factors.

Temperature change (°C)		-2	-1	+1	+2	+3	+4
Reservoirs	Area (km²)	% Change of evaporation					
Balbina	4437	-5.21	-2.62	+2.66	+5.36	+8.09	+10.84
Furnas	1406	-5.51	-2.79	+2.83	+5.74	+8.69	+11.68
IIha Solteira	1357	-5.32	-2.68	+2.74	+5.51	+8.32	+11.16
Itaipu	1049	-5.24	-2.64	+2.71	+5.47	+8.27	+11.13
Luis Gonzaga	839	-4.63	-2.33	+2.35	+4.72	+7.10	+9.49
Porto Primavera	2976	-5.33	-2.69	+2.75	+5.56	+8.42	+11.32
Sera da Mesa	1254	-5.56	-2.80	+2.85	+5.75	+8.69	+11.67
Sobrandinho	4380	-4.68	-2.36	+2.37	+4.77	+7.19	+9.60
Tres Marias	1087	-5.25	-2.66	+2.70	+5.46	+8.26	+11.10
Tucurui	3513	-5.14	-2.60	+2.63	+5.30	+7.98	+10.70

Table 6.7 – Percentage change of evaporation due to temperature change for the 10 largest reservoirs in Brazil

From table 6.7, we can see that the size of the reservoir is not necessarily an important factor, since from these 10 examples the largest reservoirs did not have the highest or the lowest rate of evaporation percentage change according to the increase from temperature. Nevertheless, all these values are higher than the averages in table 6.4, so size of the reservoir must make a difference when compared to much smaller reservoirs.

Wind speed change (m/s)		+0.5	+1	+2
Reservoirs	Area (km²)	% Change of evaporation		
Balbina	4437	+4.74	+8.68	+14.87
Furnas	1406	+3.60	+6.70	+11.78
IIha Solteira	1357	+3.95	+7.28	+12.64
Itaipu	1049	+2.72	+5.08	+9.03
Luis Gonzaga	839	+1.48	+2.82	+5.16
Porto Primavera	2976	+3.56	+6.58	+11.51
Sera da Mesa	1254	+3.13	+5.82	+10.22
Sobrandinho	4380	+1.83	+3.46	+6.28
Tres Marias	1087	+2.40	+4.50	+8.04
Tucurui	3513	+4.34	+7.95	+13.65

Table 6.8 – Percentage change of evaporation due to wind speed change for the 10 largest reservoirs in Brazil

Table 6.8 shows that for example a 2 m/s increase in wind speed, the percentage change in evaporation rate can be anything from about 5% to just shy of 15%. In the case of wind speed, it seems that size of the reservoir plays an even more insignificant role, as the 2 largest reservoirs had the highest and second lowest percentage change in the presented examples. In the case of wind speed, the morphology of the location is key.

Daily incoming short-wave radiation (MJ/m² d)		+1	+2
Reservoirs	Area (km²)	% Change of evaporation	
Balbina	4437	+4.68	+9.37
Furnas	1406	+4.06	+8.13
IIha Solteira	1357	+4.16	+8.32
Itaipu	1049	+4.09	+8.19
Luis Gonzaga	839	+3.90	+7.81
Porto Primavera	2976	+4.10	+8.19
Sera da Mesa	1254	+3.84	+7.69
Sobrandinho	4380	+4.02	+8.04
Tres Marias	1087	+4.08	+8.18
Tucurui	3513	+4.73	+9.46

Table 6.9 – Percentage change of evaporation due to daily incoming short-wave radiation change for the 10 largest reservoirs in Brazil

Finally, table 6.9 also shows that once again size of the reservoir does not mean higher evaporation rate changes due to higher incoming short-wave radiation. All values here are within the same range of values shown in table 6.6.

All in all, we can see that mean daily air temperature, daily wind speed, and total daily incoming short-wave radiation do not necessarily affect certain reservoirs more according to their size, or geographical location, rather their morphological geography is key. Furthermore, the combination of effects from these three factors could potentially increase evaporation rates anywhere from 10 to 15% for each degree Celsius, which is something that needs to be taken into account for future planning. With this in mind it becomes clearer that an analysis for hydroelectric reservoirs needs to be done separately for each reservoir, as is done here, and not through averages for regions or even states. How much of a difference an increase of these three factors makes for future planning of hydroelectricity and the electricity sector in general will be further explored and presented in chapter 7, where they are taken into account in the development of climate scenarios.

6.2. Water footprint results and analysis

This part of the chapter is dedicated to water footprint results and analysis done per region, state and specific reservoirs of interest for the period 2010-2016. As was the case with evaporation, also with water footprint results presented here, they are on an annual level and separately on a monthly level. This way it is easier to notice differences in more detail between years and also months, since this offers significant insight on variations of water footprint.

Before going ahead with results and analysis, an important aspect needs to be noticed. The water footprint has units of m^3/MWh, therefore it is the volume of water used to produce a certain amount of electricity. In the case of hydroelectric reservoirs, the water used is solely the volume of water evaporated from those reservoirs. Although data for the electricity produced for the period 2010-2016 exists for most hydroelectric plants and it was used for the analysis, the main issue with the estimation of evaporation persists in the water footprint estimations as well. As it has already been

mentioned, the area of the reservoir changes through time in reality. Data on how the area changes do not exist, and this could not possibly be estimated since it depends solely on the geological morphology of each reservoir. For the purposes of the evaporation and also the water footprint analysis, area was taken as being constant, which is something normal for water modelling, although it is recognised that advances in this respect are needed in order to better represent reality in models.

The constant area has repercussions for evaporation and water footprint estimations. When a reservoir gets depleted of water its area diminishes, but this is not taken into account in the model, so the volume of water evaporated is overestimated. Also, when the hydro plant is not operated due to maintenance or any other reason, it does not produce electricity but water still gets evaporated, which counts towards water footprint. At the same time, using values for the potential capacity of the hydro plants is an exaggeration, since the plants never actually reach their full potential. For the reasons mentioned, in some of the following results both actual electricity generation and potential capacity of the hydro plants are used, which could act as an indirect indicator of efficiency as well.

Although there are no limits set in policy or otherwise for what "normal" values for water footprint are, nevertheless comparison between reservoirs can be useful. By observing the values of different reservoirs, one develops an understanding of what is too much, too little, or about average. Thus, increases of water footprint can serve as an early warning indicator for the efficiency of plants, but also possibly the criticality of water availability for a certain reservoir/area/region. Reservoirs with a high water footprint value are either underutilised or the water availability issues are so critical in the area, that perhaps even electricity generation from the plant/reservoir is deemed impractical. According to extensive literature review, a water footprint analysis for all hydroelectric reservoirs in Brazil was not found, so the results presented here are novel and should aid in the better understanding of the water-energy nexus of hydroelectricity in the country.

The water footprint provides a clearer idea as an indicator when presented and analysed for individual reservoirs. However, by presenting results by region we can actually notice some trends. It needs to be noted that the power plants/reservoirs considered for the water footprint analysis were the ones that were already in operation on the 1st of January 2010, so that the values would not change significantly in some regions, rendering comparisons between years impossible. Overall, 18 reservoirs whose evaporation was calculated earlier, did not take part in the water footprint analysis because they started operating sometime within the 2010-2016 period.

Furthermore, the results presented here are separated into ones taking into account all reservoirs per region, but also results discounting the reservoirs with extreme values in order to find possible trends that would otherwise be invisible. As explained earlier, water footprint values depend on the water evaporated per reservoir in relation to electricity produced. Some reservoirs are very large and/or they produce very little electricity, so their water footprint values are extremely high in relation to others and also an average reservoir. These values are so high that alone they change the regional averages in some cases, so it was deemed more insightful to perform the analysis both with and without taking these few reservoirs (15 in total) into account. Firstly, so that they would not affect the average results by too much, and secondly to have an idea of how much they actually affect the averages if they are taken into account in the analysis.
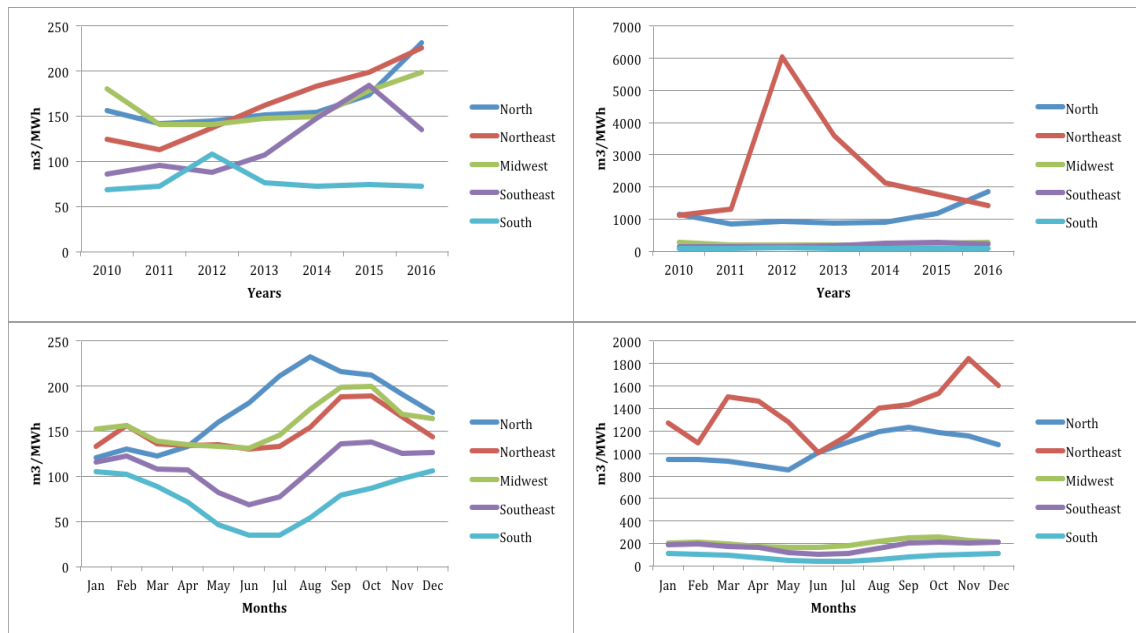
Figure 6.16 – Average annual water footprint a) (top-left) without and b) (top-right) with reservoirs with extreme values, and average monthly water footprint c) (bottom-left) without and d) (bottom-right) with reservoirs with extreme values, per region for the period 2010-2016

The first two parts of figure 6.16 present the water footprint of each region with and without taking account of 15 power plants/reservoirs that had extreme values. The results for these will be presented separately. We can see that the water footprint in the South is very constant through time, just above 70 m³/MWh, apart from an increase to over 100 m³/MWh in 2012. The values for the Southeast are around 90 m³/MWh until 2012 and then they are increasing every year until 2015, reaching over 180 m³/MWh, and finally they have a decrease in 2016 to 135 m³/MWh, which is still high compared to values until 2012. The Southeast suffered a big drought from 2014 to 2015, which is evident from these results. The Northeast had values of about 125 m³/MWh for the period 2010-2011, but an increase until 2016. The region has had a prolonged drought since 2012. The Midwest and the North historically have a relatively large water footprint of about 150 m³/MWh, which has worsened the last 2 years. The second part of the figure shows how different the results would be if the 15 power plants/reservoirs with the largest footprint values for this period were taken into account, showing that the Northeast and the North have been far from ideal

regarding the water-energy nexus. The c) and d) parts of figure 6.16 show that the patterns of the water footprint change within the year, differently for each region. The Southeast and the South follow a similar pattern, and so do the Midwest and the Northeast. When the 15 extreme value reservoirs are taken into account, the patterns differentiate slightly. Both in annual and monthly results, when extreme values are taken into account, results go from hundreds to thousands.

Region	Water footprint (m³/MWh) without reservoirs with extreme values	Water footprint (m³/MWh) with reservoirs with extreme values
North	91.81	517.73
Northeast	61.04	186.49
Midwest	74.38	92.35
Southeast	47.57	76.02
South	42.75	42.75

Table 6.10 – Average annual water footprint per region for the period 2010-2016, based on potential capacity of plants

Table 6.10 shows that the water footprint values change a lot in some cases, compared with figure 6.16, if we take the potential capacity of the power plants into account. The water footprint in the North changes from 91.81 to 150-220 m³/MWh, in the Northeast from 61.04 to 120-220 m³/MWh, in the Midwest from 74.38 to 145-200 m³/MWh, in the Southeast from 47.57 to 90-180 m³/MWh, and in the South from 42.75 to 70-105 m³/MWh. The value differences will become even more exaggerated (apart from the South's) if we consider the top-15 water footprint power plants/reservoirs as well, which are presented in the third column of table 6.10.

6.2.2. Water footprint per state

Unlike the regional results, the per state results are presented accounting for power plants/reservoirs with extreme water footprint values. The reason for this is that some states only have 1-2 reservoirs and they would not be taken into account in the graphs otherwise.
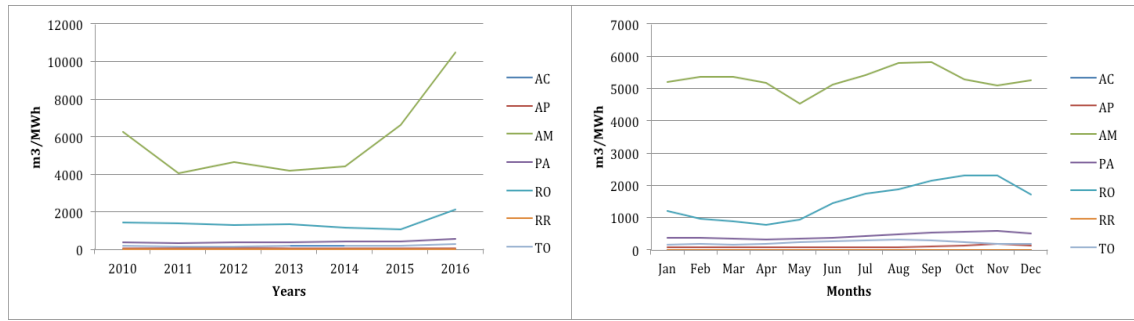
Figure 6.17– Average annual and monthly water footprint per state for the North for the period 2010-2016

We can see in Figure 6.17 that in the North, the state with the largest footprint is Amazonas (AM). The reason for this is that there is only one reservoir there, Balbina, which is one of the ones with the highest footprints in the country. Its potential capacity is very low in comparison to its inundated area, and this was exaggerated in 2010, 2015, and 2016, when the values exceeded 6000 m^3/MWh and even reached 10500 m^3/MWh in 2016. The state with the second largest footprint is Rondônia (RO), again with only one reservoir, Samuel, with values from just above 1000 to just above 2000 m^3/MWh per year. Third with two reservoirs is the state of Pará (PA), and values from just above 300 to just below 600 m^3/MWh. Fourth and fifth were the states of Tocantíns (TO) and Amapá (AP) with values from 160 to 300 m^3/MWh, and from 75 to 120 m^3/MWh respectively. Two states have no reservoirs. The pattern of footprint change is decreasing in the first half of the year and increasing in the second half in 3 states, apart from the state of Tocantíns (TO) where the increase stops in September and then the footprint drops again, and also Amazonas (AM) that has a big drop in May and another after September again.
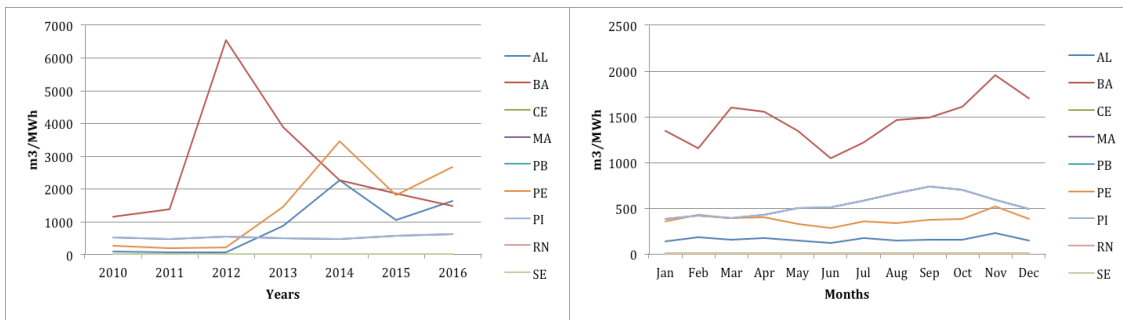
Figure 6.18 – Average annual and monthly water footprint per state for the Northeast for the period 2010-2016

In the Northeast, shown in Figure 6.18, the state that is the most prominent is Bahia (BA). Bahia (BA) has 11 power stations/reservoirs within its limits, but one of them, Pedra, is the one that changes the average values quite a lot, especially in 2012. Another two reservoirs, Pedra do Cavalo and Sobradinho, keep the water footprint values of the state quite high for the whole 7-year period, which are from a minimum of just above 1000 to 6500 m³/MWh. The state with the second highest footprint, and two reservoirs, is Pernambuco (PE), which even has the largest footprint in 2014 and 2016, mainly due to the reservoir Apolônio Sales. Although it has a footprint of less than 200 m³/MWh in 2012, it is almost 3500 m³/MWh in 2014. A similar trend is followed by the state with the third largest footprint, Alagoas (AL), mainly because Apolônio Sales also belongs within its boundaries. Fourth are the states of Piauí (PI) and Maranhão (MA) together, because they share the reservoir Boa Esperança, with an average footprint around 500 m³/MWh. Finally, the state of Sergipe (SE), with one reservoir, has a very small footprint between 5 and 13 m³/MWh per year. 3 states have no reservoirs. The pattern of footprint change through the year is relatively constant for most states, apart from Bahia (BA), Piauí (PI), and Maranhão (MA). In Bahia (BA) there is a drop from November to February, then elevated values to April, with a drop following to June, and an increase until November. The other two states follow an increase pattern from January to September and then a decrease.
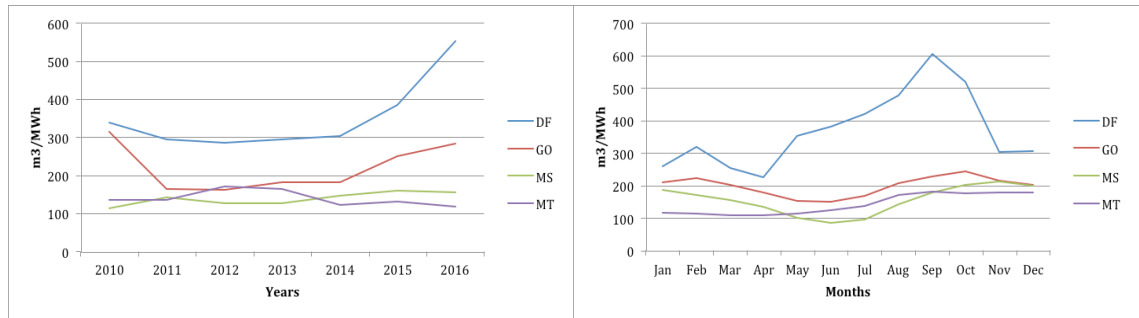
Figure 6.19 – Average annual and monthly water footprint per state for the
Midwest for the period 2010-2016

In the Midwest, shown in Figure 6.19, the state with the largest water
footprint is Distrito Federal (DF), which only has two reservoirs, but one of
them, Paranoá, has quite high values, so the average is from just below 300
to about 550 m³/MWh. The state with the second largest footprint is Goiás
(GO) with 19 reservoirs present. 2 of them, Corumbá IV and Serra do Facão,
are the ones that cause the more elevated values in 2010, 2014, and 2015,
from about 170 to 250-300 m³/MWh. Mato Grosso (MT), with 5 reservoirs,
would fare far better if it wasn't for Manso, which increases the average of
the state to 120-170 m³/MWh. Finally, Mato Grosso do Sul (MS), with 6
reservoirs, although it is the state with the smallest footprint in the
Midwest, would also fare better without Porto Primavera, which raises the
average to 110-160 m³/MWh. The pattern of footprint is similar for Goiás
(GO) and Mato Grosso do Sul (MS) with a decrease from January to June
and an increase to October or December. The values for Mato Grosso (MT)
are relatively constant to April, then increase until September and remain
constant until December. For the Distrito Federal (DF) the pattern is more
exaggerated, with an increase from April to October and then a sudden
large decrease in a month.
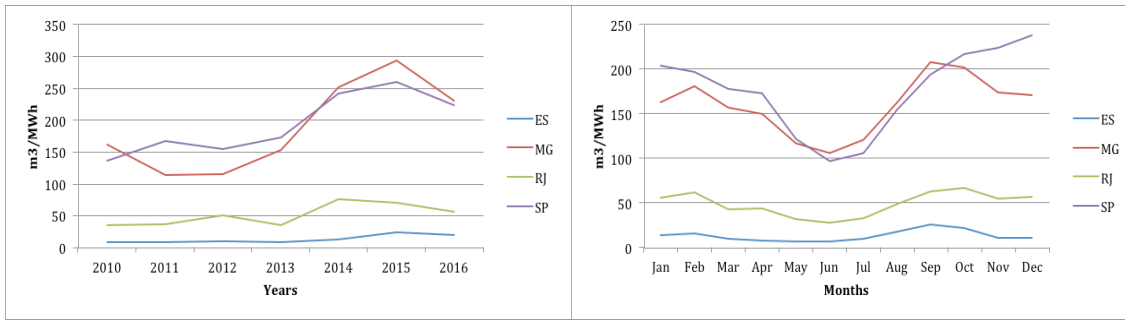
Figure 6.20 – Average annual and monthly water footprint per state for the
Southeast for the period 2010-2016

In the Southeast, Figure 6.20, we have the two most significant states in
Brazil, since Minas Gerais (MG) and São Paulo (SP) have 40 and 44
reservoirs respectively. São Paulo (SP) has on average a slightly larger
footprint than Minas Gerais (MG), with values ranging from 135 to 260
m³/MWh. It has 4 reservoirs with high footprint values (Jurumirim,
Paraibuna, Promissão, and Porto Primavera), but because of the amount of
reservoirs present, the footprint values do not become extreme, as is the
case with states in the previous 3 regions. Minas Gerais (MG) has values
from 113 to 293 m³/MWh, and also two reservoirs with extreme values
(Camargos and Três Marias), although they do not affect the state average
too much. Rio de Janeiro (RJ), with 6 reservoirs, has a much smaller
footprint that the other two states, with values ranging from 35 to 75
m³/MWh. Fontes Nova is the reservoir that brings the average up here, with
Funil also contributing in 2014 and 2015. Espírito Santo (ES) only has 3
reservoirs, none of which have any extreme values, so the average is 9-24
m³/MWh. The pattern of footprint for Minas Gerais (MG) and São Paulo
(SP) is similar from February to September, but then the footprint continues
to increase in São Paulo (SP) until December, with Minas Gerais (MG)
following the opposite direction. Rio de Janeiro (RJ) and Espírito Santo (ES)
also have a similar pattern from January to September. Then, the footprint
in Espírito Santo (ES) decreases, whereas this decrease in Rio de Janeiro
(RJ) starts in October.
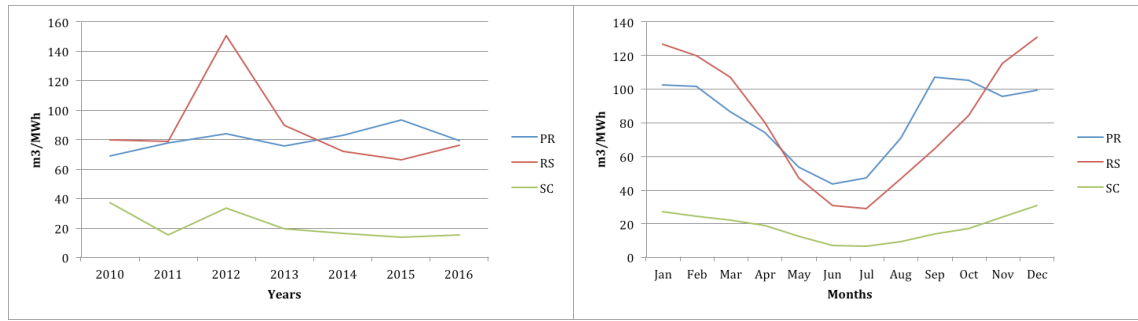
Figure 6.21 – Average annual and monthly water footprint per state for the
South for the period 2010-2016

Finally, in the South, Figure 6.21, we have even fewer extreme values than all the other regions, making the South the region that fares by far the best compared to the others. Rio Grande do Sul (RS), with 16 reservoirs, is the state with the highest average water footprint, with values ranging from 66 to 150 m³/MWh. The high value of 2012 is mainly because of the reservoir Passo Real. Paraná (PR), with 17 reservoirs, has the second largest footprint with 68-93 m³/MWh, and it doesn't have a reservoir that had an extreme footprint at any one year. Lastly, Santa Catarina (SC), with 8 reservoirs, has values from 14 to 37 m³/MWh, and it has no reservoirs with extreme values. The pattern of footprint for Rio Grande do Sul (RS) and Santa Catarina (SC) are similar, decrease from January to July and increase from there to December, although it is more exaggerated for the first. The pattern for Paraná (PR) is also similar to the other 2 up to September, but then it is slowly decreasing.

States	Water footprint (m³/MWh) based on potential generation	Water footprint (m³/MWh) based on actual generation
North		
AC	0	0
AP	67.336	88.233
AM	2613.779	5812.015
PA	305.071	416.874
RO	520.905	1396.8
RR	0	0
TO	109.903	201.805
Northeast		
AL	18.861	870.339
BA	178.011	2643.849
CE	0	0
MA	279.775	523.974
PB	0	0
PE	86.79	1427.991
PI	279.775	523.974
RN	0	0
SE	3.809	8.537
Midwest		
DF	145.096	351.522
GO	90.595	219.403
MS	90.364	138.728
MT	54.089	140.656
Southeast		
ES	4.851	13.509
MG	63.729	188.513
RJ	15.317	51.769
SP	90.375	193.245
South		
PR	45.008	80.341
RS	47.535	87.753
SC	9.95	21.391

Table 6.11 – Average annual water footprint per state for the period 2010-2016, based on potential capacity and actual generation of plants

Table 6.11 shows the average water footprint of each state, both based on capacity and actual electricity generation values. Although as explained earlier these results should be taken with a degree of scepticism, nevertheless they also show where the water-energy nexus is particularly an issue. When a reservoir has a very large area and has a relatively small electricity capacity, the water footprint will be quite large. If the actual

electricity generation is taken into account, the results can potentially skyrocket for a large reservoir, as was the case with quite a few reservoirs in this analysis. In Table 6.11 we can see that the values of the water footprint are always larger if the actual generation is used. Sometimes this difference can be extreme, as is the case for Amazonas (AM), Bahia (BA), and Pernambuco (PE). As it was explained, these extremes are mainly because of specific power plants that remained almost idle or produced very little electricity for months at a time, or even a whole year, therefore producing extreme values. There were also cases where the two values do not differ too much like in Amapá (AP), Sergipe (SE), Espírito Santo (ES), and Santa Catarina (SC), showing that power plants there firstly have a capacity relative to the inundated area of the reservoirs, and also they do actually produce electricity close to their capacity. Attention therefore should be drawn to states and specific reservoirs that do not fare well in their water footprint values based on their potential capacity, and even more so to states and reservoirs that fare even worse in their water footprint values based on actual generation.

It needs to be noted that this difference between potential and actual generation is due to capacity factors, water availability, turbine efficiency, maintenance, regulation, etc. (as will be discussed in chapter 8). Generally speaking, most of the times, these changes will occur due to water availability, but an investigation would need to take place for each reservoir specifically, since this can vary a lot, especially in a country as large and diverse as Brazil. This was deemed to be outside of the scope of the present analysis.

6.2.3. Examples of water footprint of specific reservoirs

As seen in the water footprint results for both regions and states, some values obtained are greatly influenced by specific power plants/reservoirs. Table 6.12 presents all the important information of reservoirs, which have the top-10 water footprint values, based on their potential annual capacity.

Reservoir	Region	State	Area (km²)	Evaporation (mm)	Potential annual electricity production (GWh)	Water Footprint (m³/MWh)
Balbina	North	AM	4437.72	1289.89	2190	2613.78
Curuá-Una	North	PA	106.25	1369.39	265.4	548.16
Jurumirim	Southeast	SP	470.4	1313.13	884.4	698.46
Paraibuna	Southeast	SP	197.62	1213.22	762.3	314.52
Pedra	Northeast	BA	89.17	1247.25	175.3	634.58
Porto Primavera	78.39% Midwest & 21.61% Southeast	78.39% MS & 21.62% SP	2976.98	1384.83	13490.4	305.6
Promissão	Southeast	SP	572.72	1548.33	2312.6	383.44
Samuel	North	RO	679.51	1455.55	1898.7	520.91
Sobradinho	Northeast	BA	4380.79	1795.31	9200.6	854.82
Três Marias	Southeast	MG	1087.77	1511.2	3469	473.87

Table 6.12 – Information of reservoirs with the top-10 water footprints

The top-10 reservoirs belong in all regions, apart from the South, which actually fares very well in terms of water footprint. The inundated areas of the reservoirs vary a lot, going from the largest reservoirs in Brazil (Balbina and Sobradinho) to some that can be considered to be relatively small (Pedra), although their inundated area is fairly significant as well. The evaporation rates also vary from a minimum of 1289.89 to 1795.31mm, which by coincidence also happen to come from the two largest reservoirs. The potential electricity production per year varies a lot as well, from 175.3 to 13490.4GWh. At once, we can see by comparing the top-3 largest reservoirs (Balbina, Sobradinho, and Porto Primavera), that although Balbina has the largest inundated area, it is only capable of producing 2190GWh, whereas Porto Primavera is capable of producing more than 5 times that much. This has an immediate large effect on the water footprint. Evaporation is important in order to calculate the water footprint, but in terms of variations in water footprint values it does not make a big difference since it does not change too much from year to year. It is almost entirely the relationship between area and electricity capacity that is important. Although as explained earlier it is extremely difficult to find a way to calculate the changing area through time, which would be a factor in the water footprint, nevertheless even this maximum area provides a pretty

clear picture as to which reservoirs are far too large for the amount of electricity they produce.

Figure 6.22 – Water footprint of the top-3 a) annually (top-left), and b) monthly (top-right), and water footprint of the rest of the top-10 c) (bottom-left) annually, and d) (bottom-right) monthly for the period 2010-2016

Figure 6.22 presents the water footprint values of the top-10 power plants/reservoirs based on actual electricity they produced for the period 2010-2016. Compared with values from table 6.12, we can see that the actual footprints are greatly elevated, being at least about 500 m³/MWh per year and reaching extreme values for some reservoirs. Pedra for example has a high water footprint anyway, but it produced so little electricity during most of the 7-year period that its footprint in 2012 was 100 times larger than what it would be in theory using its potential capacity. Balbina was also between 4000 and 10000 m³/MWh, which is larger than its theoretical footprint using potential capacity, although not as extreme as Pedra's values. The same holds true for Sobradinho, which had values between 2000 and 5000 m³/MWh. The rest of the top-10 also fares quite badly compared to their water footprint based on their potential capacities with values varying between around 500 to 2500 m³/MWh. What is interesting is that with the exception of Pedra, the rest are showing an

increased water footprint after 2013, which is just after and just before the country suffered serious droughts in different regions. Another interesting fact is that most of the reservoirs presented here have water footprints that drop in June-August and increase afterwards. This is a trend that is also present in evaporation results, which is also the cause for the trend here and it shows that during those months water availability could be or become critical.
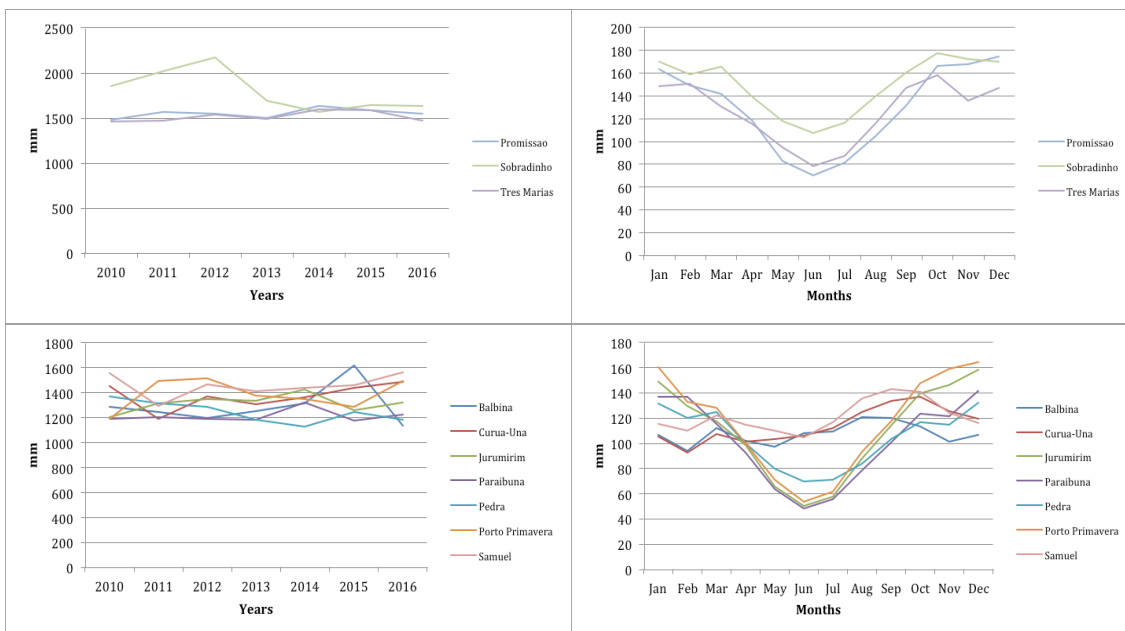
Figure 6.23 – Evaporation rate of the top-3 a) (top-left) annually, and b) (top-right) monthly, and evaporation rate of the rest of the top-10 c) (bottom-left) annually, and d) (bottom-right) monthly for the period 2010-2016

As explained earlier, evaporation rate on its own does not make a big difference in water footprint values, but a reservoir with a large inundated area and a high evaporation rate does not fare well in terms of water footprint. Figure 6.23 shows the evaporation rates of the top-10 power plants/reservoirs, which range from about 1100 to 2200mm. The top-3 in this case is not the same as in the water footprint graphs, although Sobradinho actually has a very high evaporation rate, and the changes in evaporation rates do actually go along with the changes in water footprint values. As mentioned earlier, an interesting observation is that the water

footprint values through the year decrease at the same time as evaporation rate values decrease, which is mostly June-August.
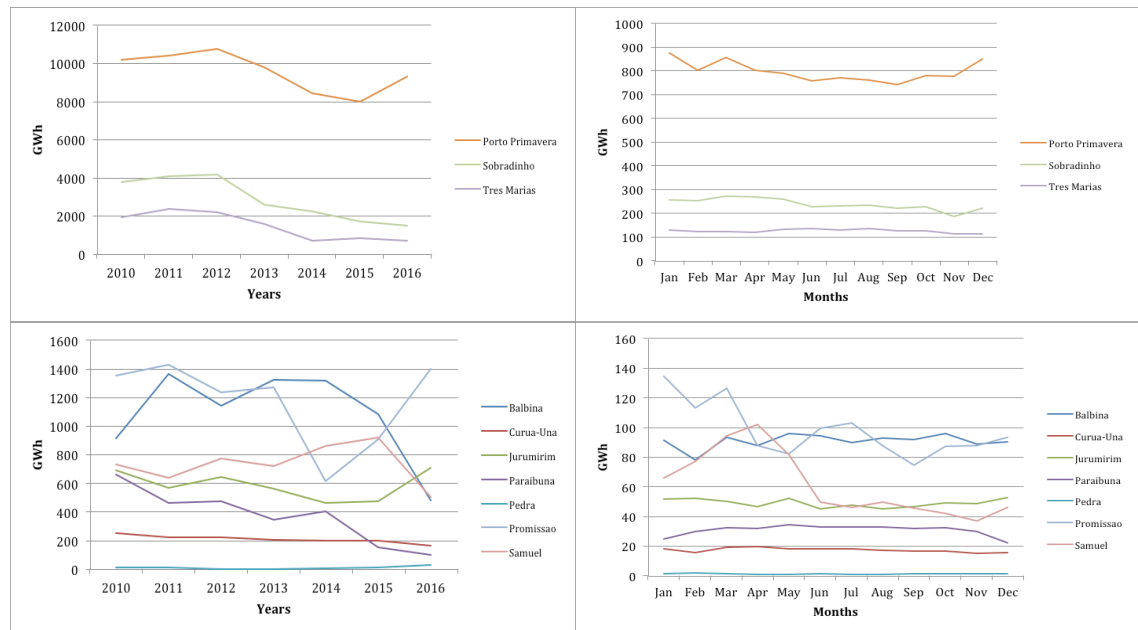
Figure 6.24 – Electricity generation of the top-3 a) (top-left) annually, and b) (top-right) monthly, and electricity generation of the rest of the top-10 c) (bottom-left) annually, and d) (bottom-right) monthly for the period 2010-2016

Apart from the inundated area that remains constant in calculations throughout the time in the analysis, the other factor that is important is the change in electricity generation, which is presented in figure 6.24. Porto Primavera produces by far the most electricity, between 8000 and 11000GWh per year, which is quite good compared to its 13490GWh capacity, and this is why it fares better than the rest of the top-10. Sobradinho, which has the second largest production with 1500-4100GWh, is quite a lot below its 9200GWh capacity and that is why it is in the top-3 worst-faring power plants/reservoirs. The same holds more or less true for the rest of the power plants/reservoirs, with Pedra producing between 2-30GWh, which is extremely low compared to its capacity of 175GWh. The changes through the year do not really follow a very specific pattern, but they do allow us to notice that although the evaporation rate does not make a huge difference in the overall results, it nevertheless plays a role in when

the water footprint increases or decreases, which is useful for future planning purposes, since it might become an issue if and when water availability decreases.

From the water footprint analysis performed, the first of its kind for all hydroelectric reservoirs in use by the end of 2016 in the country, there are a few important lessons learned: a) there are no "normal" values for water footprint, but comparison between reservoirs can be useful, and increased water footprint values can serve as an early warning indicator for efficiency of plants and criticality of water availability, b) the South of the country fares by far the best in terms of water footprint, the Southeast also normally fares well, although the 2014-2015 drought is evident in the results, and the North and Northeast are not faring very well in comparison to the rest of the country, c) the states of Minas Gerais (MG) and São Paulo (SP) have 40 and 44 reservoirs respectively and are thus very important, d) the relationship between inundated area and electricity production is key for water footprint, and e) most water footprint values in the country drop in June-August, which shows that during those months water availability is not an issue for the time being.

The aforementioned facts have certain important implications:

- Firstly, there is no "normal" water footprint value. This means that it does not make sense to choose an average and use it as the basis for decisions; rather each reservoir should be assessed individually. Since, a "normal" value does not exist, performing a study as in this thesis for all reservoirs in the country, allows for comparisons, which could provide useful information.
- Water footprint is an indicator regarding the efficiency of power plants, and as such it shows in this case that the South fares ideally compared to all other regions and should perhaps be considered the golden standard.
- The Southeast also performs well unless it goes through a drought

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like in 2014-2015, in which case the high concentration of power plants in the region can potentially cause problems for the whole country.

- Additionally, the North and the Northeast do not have good water footprint values compared to other regions, which means that potential future plants would need to undergo thorough assessment.

- The inundated area in relation to electricity produced is the key to such an assessment.

- Finally, the water footprint for most of the country drops in June-August, which is a time of the year with potential for water to be used for other purposes.

All these aspects are important as indicators on their own, and their importance will be further examined in the water budget analysis.

6.3. Water budget results and analysis

This part of the chapter is dedicated to water budget results and analysis done per region, state and specific reservoirs of interest for the period 2010-2015. The results presented come in the form of 4 different kinds of graphs and namely: a) volume level of reservoirs, b) percentage of days per month when the reservoir level was lower than the minimum useful capacity, c) difference of actual outflow and minimum safe outflow, and d) difference between precipitation and evaporation. It needs to be noted that 16 reservoirs that took part in the water footprint analysis, did not take part in the water budget analysis because of lack of data.

6.3.1. Results per region
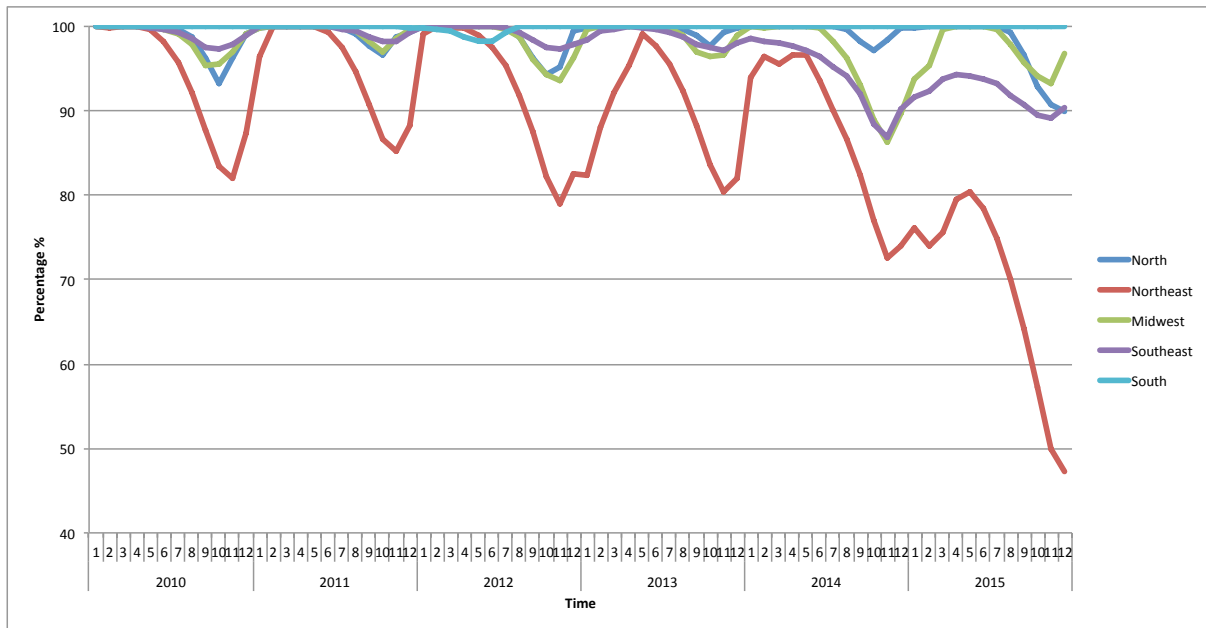
Figure 6.25 – Aggregated volume level of reservoirs per region per month for the period 2010-2015

Firstly, it needs to be highlighted that the values presented in figure 6.25 are aggregated. This means that it is as though each region of Brazil has a single large reservoir with an aggregated maximum volume and what is seen is the level difference each month for this single reservoir. In reality this is not the case since each region has dozens of reservoirs, most of which are not on the same river, sometimes not even in the same hydrographical region. Nevertheless, it is a first sign of the larger picture of what is going on in the country, which is also a first kind of indication of the state of the reservoirs in each region. At first glance we can see that the reservoir levels in the South never drop below 98%, which shows that water availability has not really been an issue in the region. On the other hand, the reservoir levels in the Northeast start dropping after June-August until the end of the year each year, and that in 2014 the levels dropped so low that they never fully recovered in 2015, which meant that they dropped even further in the last months of 2015, showing that the region's reservoirs' water availability is suffering intensely. The North is faring relatively well, with the levels dropping around October every year, but going up fast afterwards, with an

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exception in 2015 when the levels dropped further after October to reach a low of about 90% in December 2015. The Southeast and the Midwest also fare generally well with only a small drop after June-August, but in 2014, especially the Southeast never fully recovered its levels and reached a low of 87% in November in 2014 and 89% in November 2015, while the Midwest had a low of 86% in November 2015 as well. The Midwest can recover faster than the Southeast, although it also reaches lower values faster. It is worth keeping in mind the drought that hit the Southeast part of the country in 2014-2015.
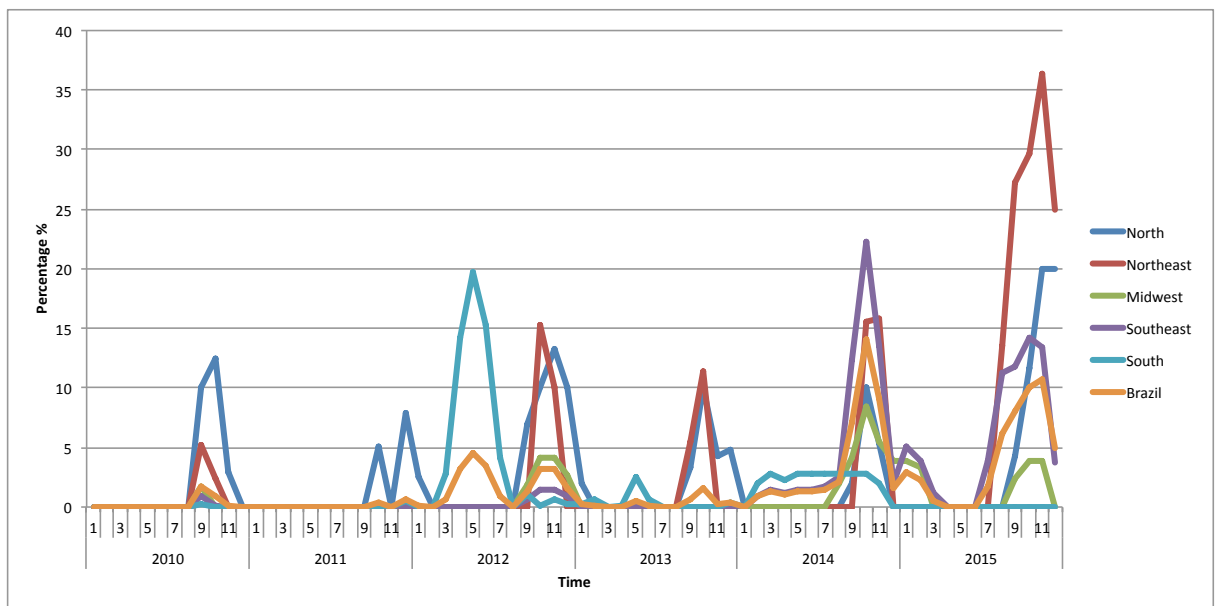
Figure 6.26 – Aggregated percentage of days when the reservoir level was lower than the minimum useful capacity per region per month in the period 2010-2015

Figure 6.26 is complementary to figure 6.25, as together they better tell the whole story of reservoir levels since we are dealing with aggregated regional results. The figure presents how many days in total there were per month that a plant/reservoir in the region could not produce electricity because its level was lower than its minimum useful capacity. It is worth noting at this point that each reservoir has a minimum useful capacity, which can vary a lot from about 10% to even 100% of the maximum capacity for run-of-the-river plants. What is at once obvious is that the months that problems occur

is when the levels were the lowest as shown in figure 6.25. We can see that even though the North's aggregated level of reservoirs is high throughout the year, only dropping by 5% around October every year, at the same time there's a 5 to about 15% chance that electricity cannot be produced. The South has very rarely issues, always either being at 0% or below 4%, apart from 3 months in the middle of 2012 when some particular reservoirs caused this elevated percentage. The Northeast has usually the most pronounced problems after June-August, reaching 10-15% of days of no electricity production, with 2015 being particularly bad and reaching 36% in November. The Southeast usually fares very well and the Midwest is always below 5%, but in the months after June-August of 2014 and 2015, both regions passed 10% of days with no electricity production, with the Southeast reaching a maximum of 22% in October 2014. The country averages are not surprisingly greatly affected by the Southeast, since this is where most of the country's reservoirs are located.
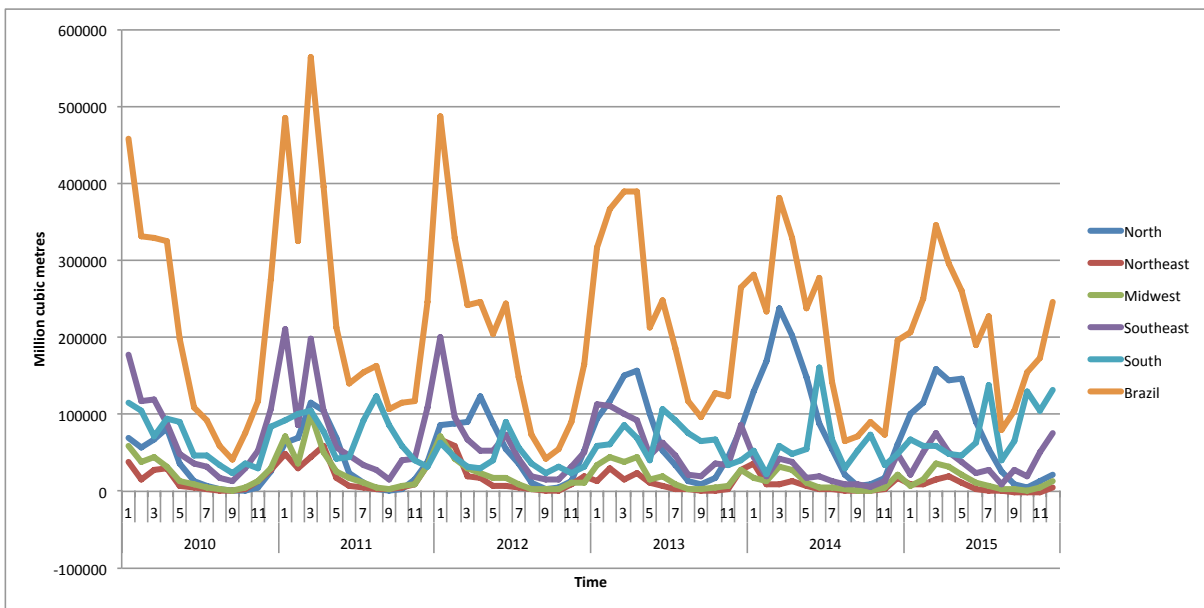
Figure 6.27 – Aggregated difference of actual outflow and minimum safe outflow per region per month in the period 2010-2015

As it has been mentioned before in the methodology section, each reservoir has a minimum outflow, which is either provided by official Brazilian documents, or was attributed to them for the purposes of the water model.

Figure 6.27 shows what the aggregated difference is between the actual outflow from reservoirs in each region to the minimum outflow needed for various environmental/operational reasons. In theory, this difference could be used for other purposes without harming the environment, the population or other hydropower plants downstream. Practically, great attention and strict rules and regulations would be needed to properly utilise this potential. All regions have potential for alternative water utilisation, with the Southeast, South, and North having the most potential. The Northeast and the Midwest rarely have enough water for other purposes and the Northeast at the end of 2015 even had negative values, which means water availability was at extreme lows. It can be noted that the water availability drops fast after June-August and is rising again by the end of each year. Another important observation is that the water available each year is dropping from 2010 to 2015 every single year, with March-May of 2015 being at about 60% of the levels of March-May 2011.
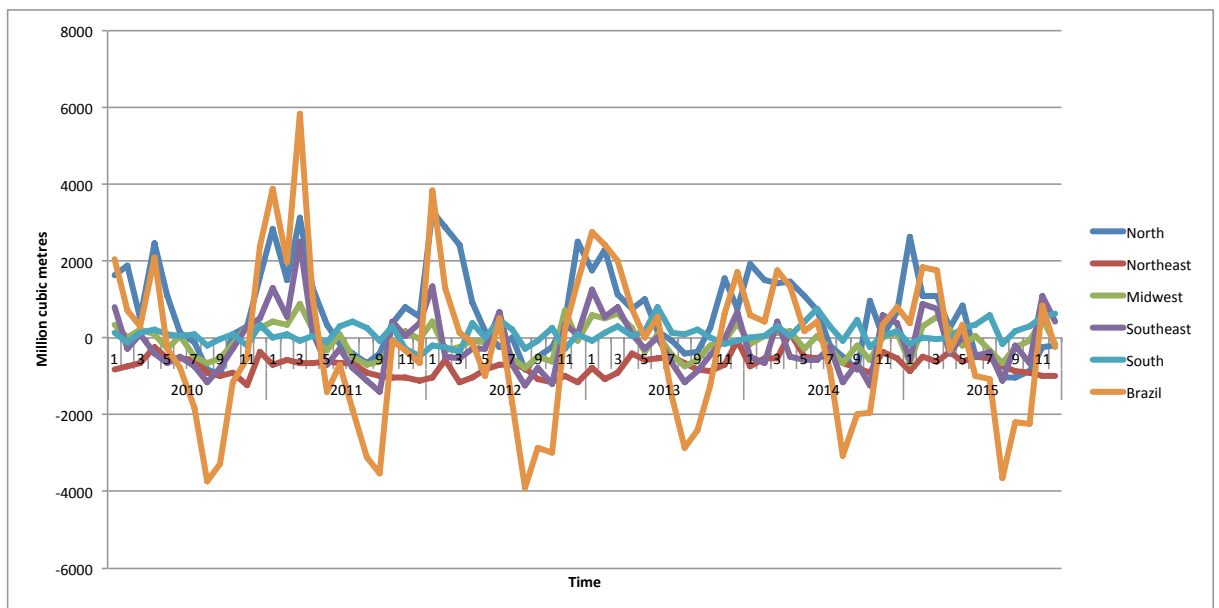
Figure 6.28 – Aggregated difference between precipitation and evaporation per region per month in the period 2010-2015

Figure 6.28 shows the difference between precipitation and evaporation for every region and it serves as an extra indicator in addition to the other graphs. As has been previously shown and discussed, evaporation in the

country is always a little bit higher than precipitation in total in this 2010-2015 period. The highest precipitation occurs in the North, where the Amazon rainforest lies. The Southeast also sees a lot of rain during the first half of the year each year. The South never has too much precipitation or evaporation, and the Midwest shows patterns somewhat between the Southeast and the South. On the other hand, the Northeast always has more evaporation than precipitation throughout the year, every year. The overall high precipitation values for the country every March-May have been dropping every year reaching lows in 2014 and 2015, whereas the evaporation highs every September-November are more constant throughout the whole 6-year period. By comparing values in figures 6.27 and 6.28 we can see that the volume of water of the difference between precipitation and evaporation, and the volume of water available as outflow have a relationship of about 1 in a 100. This does not mean that precipitation or evaporation from the surface of reservoirs is insignificant though, since it could make a difference in the operation of the reservoirs.

Figure 6.29 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per state per month for the period 2010-2015 in the North

Figure 6.29 shows the 4 main graphs of the water budget analysis for the North region of the country. The region has 7 states, but 2 of them do not have any reservoirs. What becomes immediately evident is that the state Amapá (AP) at the end of each year has extremely low reservoir levels, even almost drying up. This means that the production of electricity is impossible, but also this lack of water causes problems unrelated to electricity that have to do with environmental and social issues. Only one reservoir belongs in this state, Coaracy Nunes, which fares extremely bad in this analysis, and it will be one of the reservoirs examined in section 6.3.3. The state of Rondônia (RO) reached levels of below 80% and 90% twice, but it never had days when electricity generation was at risk thanks to the low minimum useful capacities of its reservoirs. On the other hand, Tocantins (TO) with 2 reservoirs reaches about 90% capacity in September-November and every year it can reach 10-50% of days when electricity generation was

not possible. Furthermore, as shown in part c) the states of Rondônia (RO) and Pará (PA) have a lot of water availability in March-May, unlike the other states in the region. The North is the region with by far the most precipitation in the country, which is shown in part d) when precipitation is high for most of the year and evaporation never reaches high values in September-November when it surpasses precipitation.

Figure 6.30 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per state per month for the period 2010-2015 in the Northeast

Figure 6.30 shows the 4 main graphs of the water budget analysis for the Northeast region of the country. The region has 5 states with reservoirs taking part in the analysis. We can see that each year the level of the reservoirs is decreasing to below 80% in September-November, but the reservoirs get filled up again by the start of each new year. The state that dictates how the region fares is Bahia (BA) that has 11 reservoirs. Since 2013, when the levels in the state dropped, they never filled up to 100% again and in 2015 they were at a maximum just above 70%, reaching about 35% at the end of 2015. The other states, although not in the same degree,

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followed a similar path of reduced levels in September-November, with Alagoas (AL) that has 2 reservoirs faring extremely badly at the end of 2015. Although the levels of the reservoirs have dropped considerably, only Alagoas (AL) had elevated days of no electricity production in September-November, but 2014 saw elevated percentages for all states, apart from Piauí (PI), from 20 to even 100%, which shows that the region is suffering by severe droughts that affect electricity production profusely. This is also visible in part c) of the figure, where Bahia (BA) that has the most water availability potential, has less water each and every year, reaching very low levels of availability in 2015. Finally, we can see that all states have more evaporation than precipitation every month of the year, even though not by much, with the exception of Bahia (BA) that has the most elevated evaporation rates in the whole country.

Figure 6.31 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per state per month for the period 2010-2015 in the Midwest

Figure 6.31 shows the 4 main graphs of the water budget analysis for the Midwest region of the country. The region has 4 states and only Mato

Grosso do Sul (MS) fares badly in September-November since it reached 75% in November 2012, 38% in November 2014, and 77% in November 2015. The other states always remain above 90 or even 95%. This can also be seen in part b) of the graphs, since Mato Grosso do Sul (MS) had some issues of electricity production in November 2012, and more prolonged periods in 2014 and 2015, when it reached 15-20% days with no possibility of electricity production. In 2014 it was the only year when Goiás (GO) and Mato Grosso (MT) also had issues with 5 and 10% respectively. Also, in this region we can see that water availability goes down every year, mainly due to Mato Grosso do Sul (MS) and Goiás (GO), which also have the most reservoirs and therefore the most water availability in general. The Midwest has almost equally as much precipitation in March-May, as it has evaporation in September-November.

Figure 6.32 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per state per month for the period 2010-2015 in the Southeast

Figure 6.32 shows the 4 main graphs of the water budget analysis for the Southeast region of the country. The first noticeable thing is that until 2013

none of the states had any particular problem and this is due to the fact that precipitation and river flows are normally adequate in the region. The 2014-2015 drought though affected the whole region. The Espírito Santo (ES) state seems to have suffered the most with levels even reaching below 10% in September-November 2014 and 2015, but it only has 2 reservoirs that are not large. On the other hand, Minas Gerais (MG) and São Paulo (SP) have the most reservoirs in the country and we can see that their levels started dropping in June-August of 2014, they never fully recovered in Minas Gerais (MG) and then they dropped again in September-November 2015. This prolonged drop affected electricity production and it reached highs of days of no possibility of electricity production in October 2014 for Mina Gerais (MG) with 27% and São Paulo (SP) with 16%. Espírito Santo (ES) reached almost 100% in both 2014 and 2015, while Rio de Janeiro (RJ) reached highs of 41% in 2014 and 47% in 2015, but with only 3 relatively small reservoirs. The water availability, which is almost entirely dictated by Minas Gerais (MG) and São Paulo (SP) has been decreasing since 2013, reaching in 2014-2015 an availability that was about 60% less than in the 2010-2012 period. Evaporation has been gaining ground in March-May compared to precipitation, while maintaining its levels in the September-November.

Figure 6.33 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per state per month for the period 2010-2015 in the South

Figure 6.33 shows the 4 main graphs of the water budget analysis for the South region of the country. The South is the region with the least issues in Brazil and apart from a period in the middle of 2012 when the Rio Grande do Sul (RS) state reached a 90% level of reservoirs, the rest of the analysis period the levels were close to 100% for all 3 states. In the middle of 2012, Rio Grande do Sul (RS) had slightly less than 50% days with no possibility of electricity production, while Santa Catarina (SC) reached about 15%. Santa Catarina (SC) had some issues from 2012 to 2013, but always less than 10% and usually just 2-3%. In 2014, and for most of the year, Paraná (PR) had about 5% of days of no electricity production. Paraná (PR) is the only state that has elevated water availability more or less throughout the year, which is unlike any other state in the country. The difference of precipitation and evaporation is usually positive in the whole region and precipitation reaches higher levels when its positive than the levels evaporation reaches. The only time that evaporation was constantly higher

than precipitation was at the end of 2011 and start of 2012, immediately before the region had its only instance of issues of electricity production.

6.3.3. Results for specific reservoirs

In this section, the results from 5 reservoirs per region are presented. Their selection was based on their installed capacity, maximum and minimum useful reservoir capacity, and location. The selected reservoirs are presented in table 6.13. Some reservoirs belong in more than one region, but they are important due to size and capacity, so they are included as examples.

Power plant/reservoir	Region	State	Installed capacity (MW)	Maximum reservoir capacity (million m³)	Minimum useful capacity (million m³)
Balbina	North	AM	250	20006.22	9711.9
Coaracy Nunes	North	AP	78	138.8	24.57
Luís Eduardo Magalhães	North	TO	902.5	4940	4711.11
Peixe Angical	North	TO	498.75	2741	2223.73
Tucuruí I & II	North	PA	8535	50275	11292.78
Apolônio Sales	Northeast	BA, PE, AL	400	1226	1068
Luiz Gonzaga	Northeast	PE, BA	1479.6	10782	7233
Paulo Afonso IV	Northeast	BA	2462.4	121	75.39
Pedra	Northeast	BA	20	1640	1558.86
Sobradinho	Northeast	BA	1050.3	34116	5448
Cachoeira Dourada	Midwest & Southeast	MG, GO	658	460	300.81
Itumbiara	Midwest & Southeast	GO, MG	2082	17027	4573
Manso	Midwest	MT	210	7337	4386
Porto Primavera	Midwest & Southeast	MS, SP	1540	20000	15707
Serra da Mesa	Midwest	GO	1275	54400	11150
Água Vermelha	Southeast	SP, MG	1396.2	11025	5858.27
Estreito	Southeast	MG, SP	1050	1423	1245
Furnas	Southeast	MG	1216	22950	5733
Porto Colômbia	Southeast	MG, SP	320	1524	1291
Três Marias	Southeast	MG	396	19528	4250
Capivara	South & Southeast	PR, SP	619	10540	4816.83
Dona Francisca	South	RS	125	330	267.44
Itaipu	South & Midwest	PR, MS	7000	14702	5000
Itaúba	South	RS	500.4	620	461.8
Passo Real	South	RS	158	3646	289

Table 6.13 – Information of 5 example reservoirs per region used in the
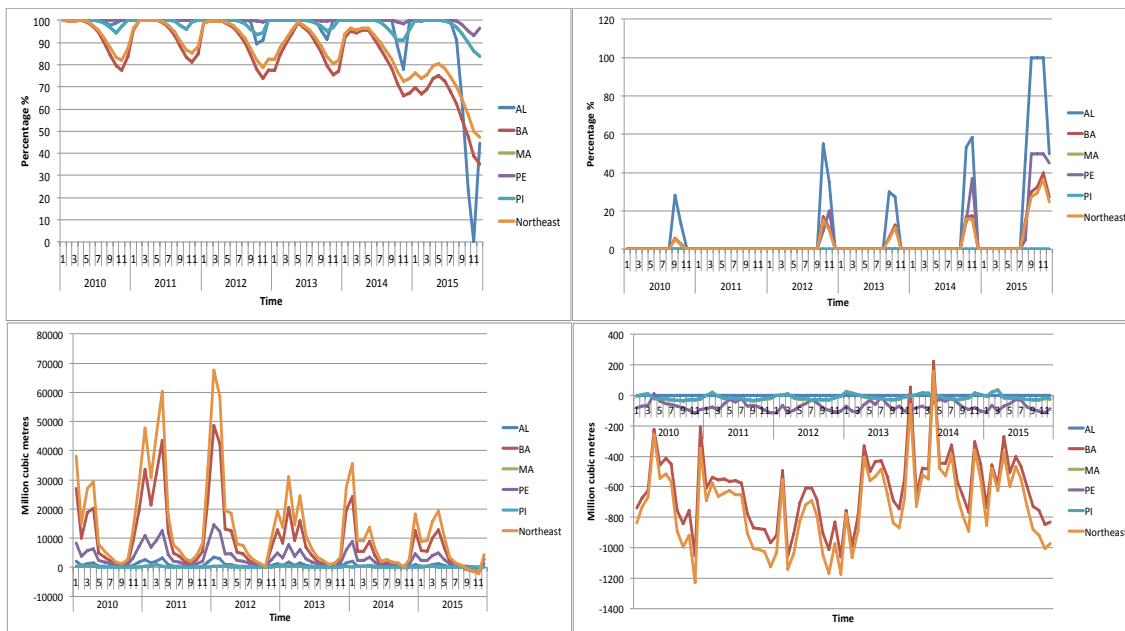
water budget analysis
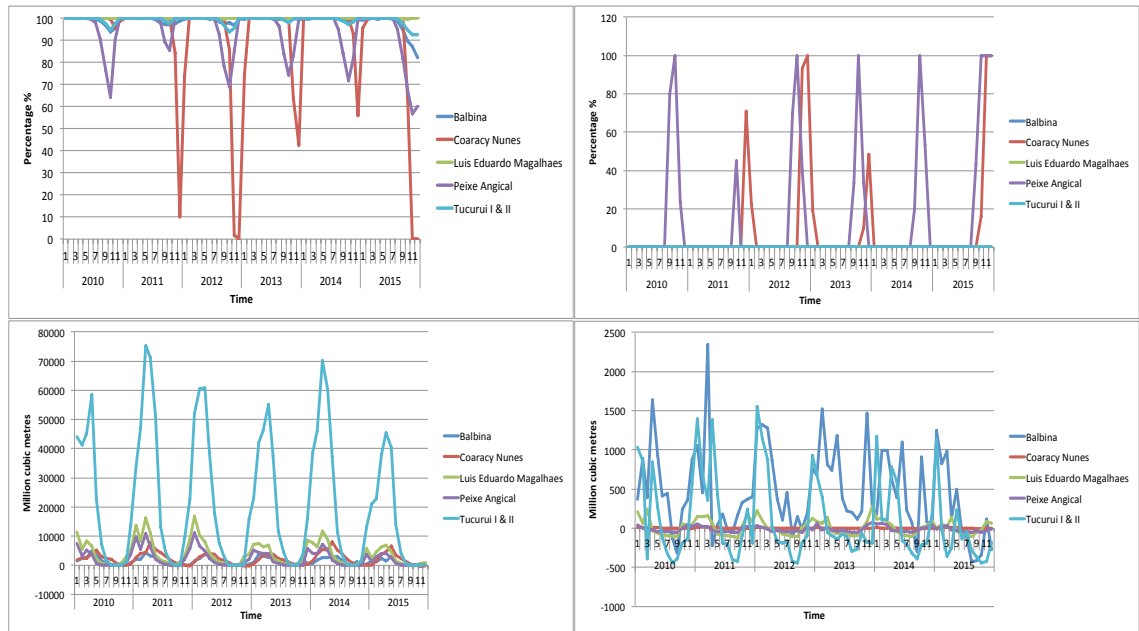
Figure 6.34 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per reservoir per month for the period 2010-2015 in the North

Figure 6.34 shows the 4 main graphs of the water budget analysis for 5 example reservoirs in the North of Brazil. Here we can see 2 examples, Coaracy Nunes and Peixe Angical that do not fare well in the analysis and are 2 of the main reasons why the North is having issues with electricity production sometimes. The level of Coaracy Nunes drops to about 0% at the end of 2012 and 2015, 20% in 2011 and 40% in 2014. Due to its low minimum useful capacity though, the 40% level in 2014 is enough to not cause more than 42% days of no electricity production, whereas in 2011, 2012, and 2015 that percentage is between 70 and 100% at the end of those years. Peixe Angical on the other hand, has a much higher minimum useful capacity, so it reaches 100% days of no electricity production every October apart from 2011. The other 3 reservoirs fare very well throughout the 6-year period. Tucuruí even has great water availability potential every March-May, whereas the other 4 have much less in comparison. Balbina and Tucuruí have very elevated precipitation compared to evaporation every December-February and March-May, with Balbina sometimes having a lot

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of precipitation even in September-November. The difference between precipitation and evaporation for the other 3 reservoirs is close to zero throughout the year every year.
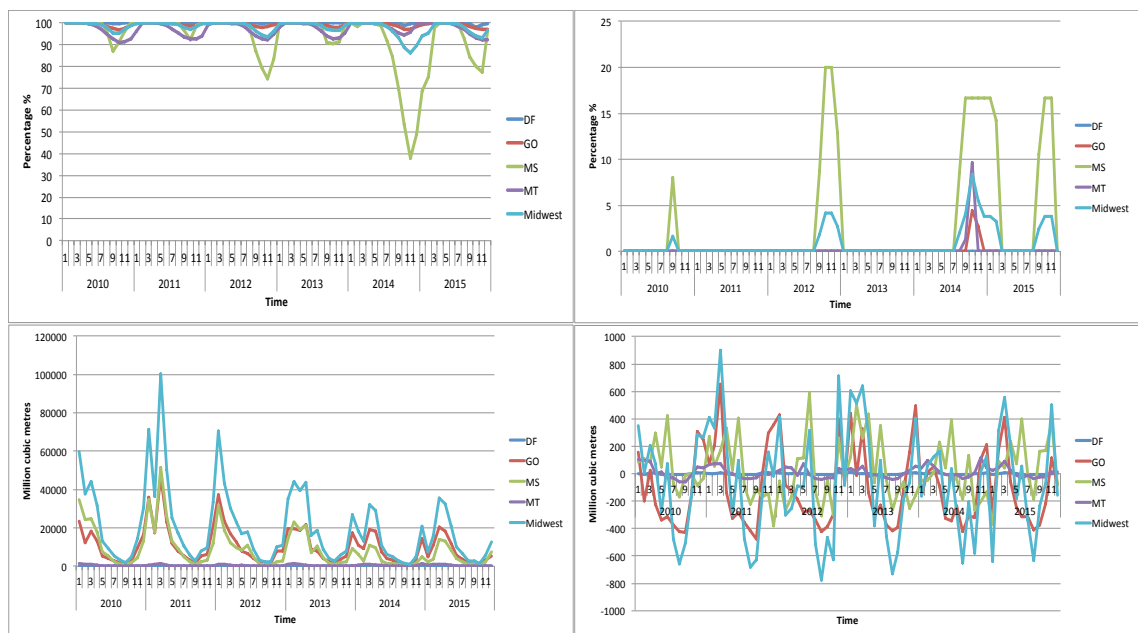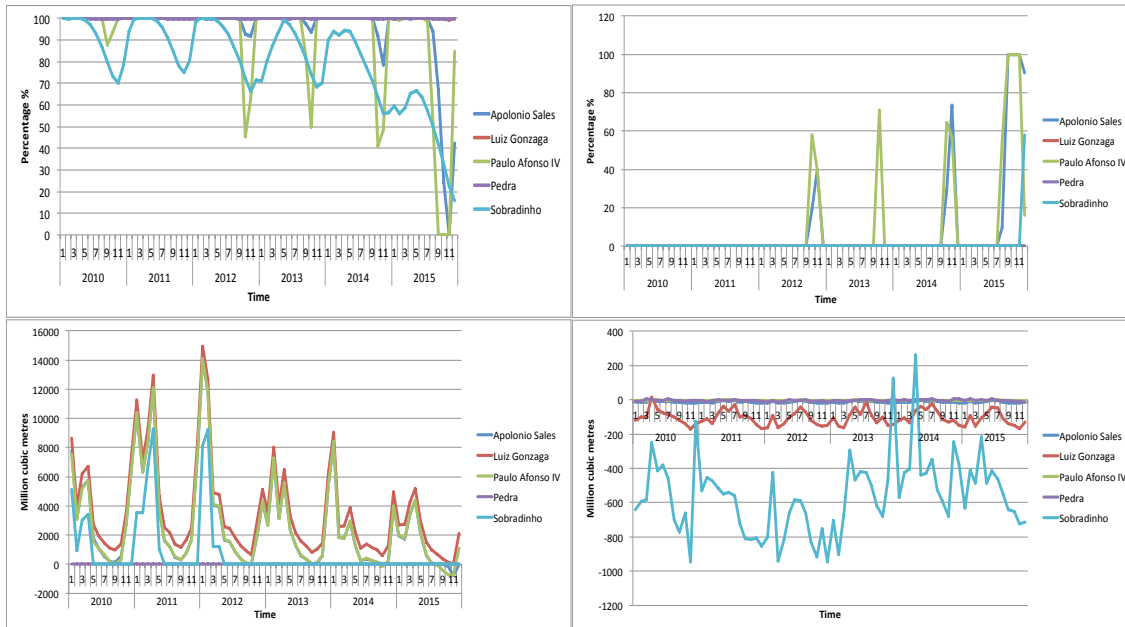

Figure 6.35 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per reservoir per month for the period 2010-2015 in the Northeast

Figure 6.35 shows the 4 main graphs of the water budget analysis for 5 example reservoirs in the Northeast of Brazil. The Northeast is the most problematic region in the country, which can be seen in the examples here. Although 2 reservoirs fare well, the other 3 do not. Since 2012, the levels of Paulo Afonso and Apolônio Sales started falling every September-November, with the first being below 50% that season and the second about 80-90% from 2012 to 2014. In 2015 they both reached almost 0% in September-November. Sobradinho's reservoir level drops every September-November since 2010 to about 70%, but then gets replenished. This did not happen in 2014 and 2015 though, so the level of the reservoir dropped below 60% and 20% in September-November of 2014 and 2015. Paulo Afonso has about 60% of days with no possibility of electricity production every October in 2012-

2014 and 100% in 2015. Apolônio Sales has issues the same month in 2012, 2014 and 2015. Sobradinho though, fares very well with the exception of 2015, which has to do with its very low minimum useful capacity. Luiz Gonzaga and Paulo Afonso have good water availability potential from the end of each year to about the middle of the next from 2010 to 2012, but that decreases from 2013 to 2015. Sobradinho also had potential from 2010 to 2012, but not at all since then. Sobradinho has a very high evaporation rate and evaporation is quite higher than precipitation throughout the year every year, a trend also followed to a lesser extent by Luiz Gonzaga. The other 3 reservoirs have almost as much precipitation as evaporation throughout the whole 6-year period.
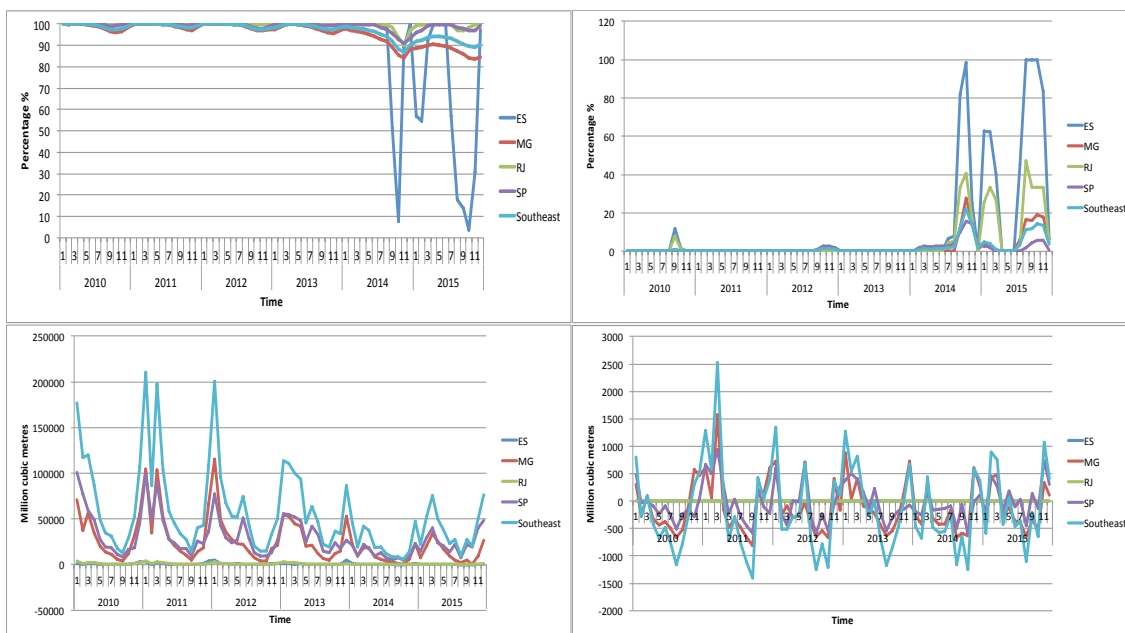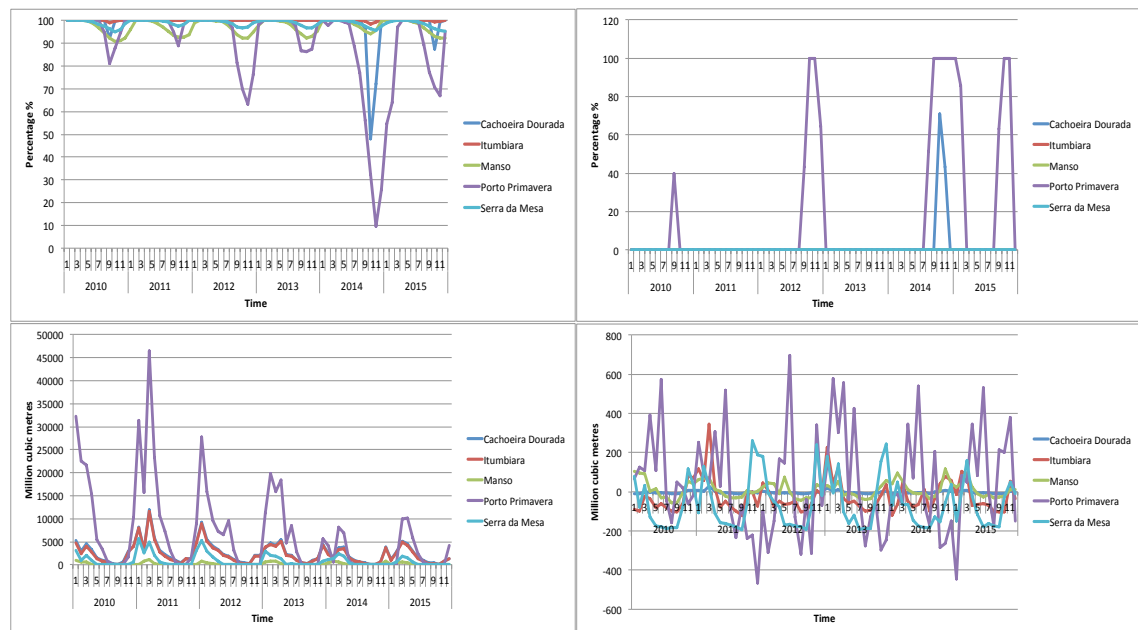

Figure 6.36 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per reservoir per month for the period 2010-2015 in the Midwest

Figure 6.36 shows the 4 main graphs of the water budget analysis for 5 example reservoirs in the Midwest of Brazil. 3 of the reservoirs have levels of more than 90% in the whole 6-year period. Cachoeira Dourada falls to 48% in October 2014 and 88% in October 2015. On the other hand, Porto

Primavera is always below 90% in September-November, twice below 70% in 2012 and 2015, and finally in 2014 it was below 60% from September until January 2015, even reaching 10% in November. Both Cachoeira Dourada and Porto Primavera have issues with electricity production once their level drops below 65 and 78% respectively, so Cachoeira Dourada was unable to produce electricity in September-November 2014, reaching 71% of days of no electricity production in October, and Porto Primavera had issues in 2010, 2012, 2014 and 2015, with 2014 being particularly bad. Porto Primavera was the only reservoir with good water availability in the early months of the years 2010-2012, but 2014 and 2015 have significantly dropped the levels of availability to the levels of the rest of the reservoirs. Porto Primavera is the only reservoir that has pronounced differences between precipitation and evaporation through the year, since it has high precipitation in March-May and high evaporation in September-November. Serra da Mesa has a somewhat different pattern of precipitation and evaporation compared to the rest of the reservoirs, since particularly in 2011 and 2013 it had more precipitation than evaporation in September-November.
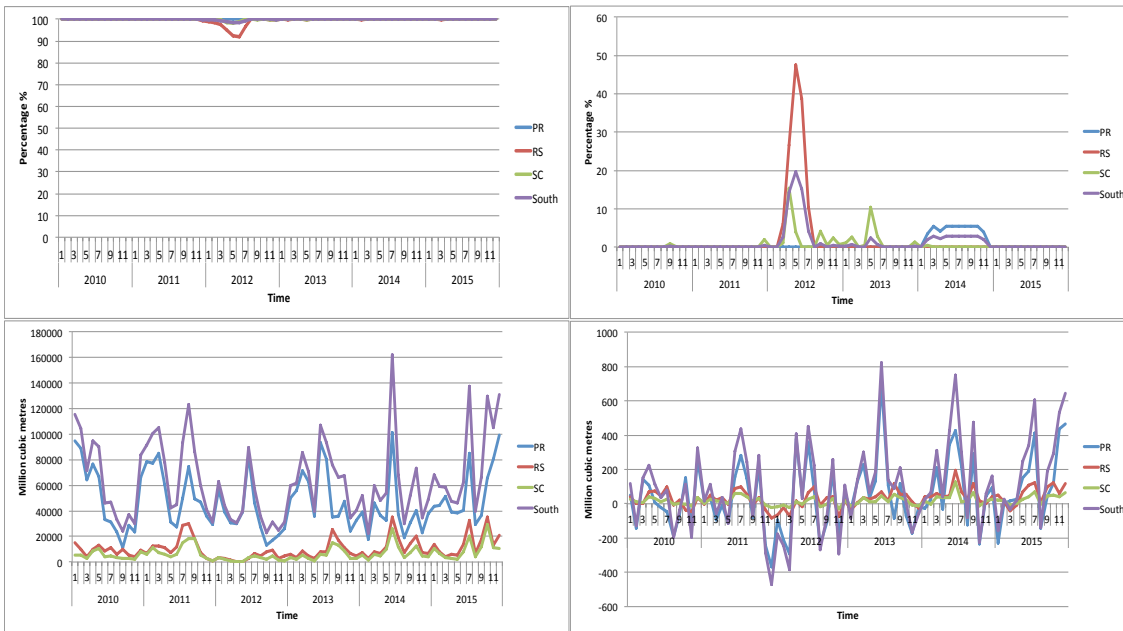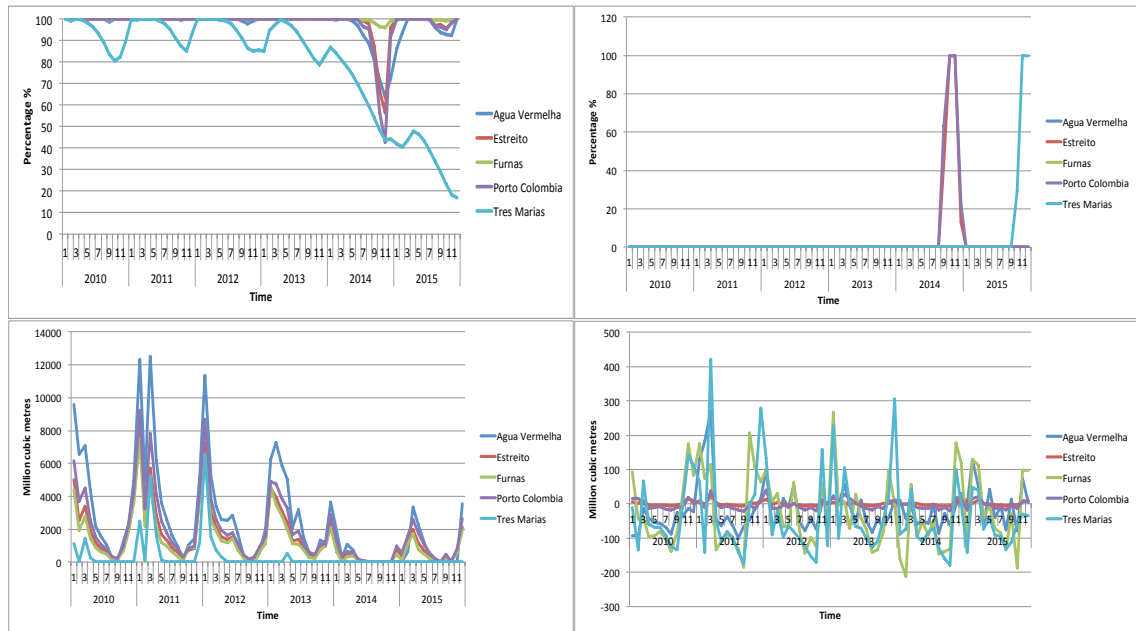
Figure 6.37 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per reservoir per month for the period 2010-2015 in the Southeast

Figure 6.37 shows the 4 main graphs of the water budget analysis for 5 example reservoirs in the Southeast of Brazil. From 2010 to 2013, only Três Marias has reservoir levels that drop from the end of August to December, reaching about 80% each year. The rest of the reservoirs fare very well, being constantly almost full. In 2014 though all reservoirs, with the exception of Furnas, had low levels from the end of August until December. Água Vermelha had a low of 64%, Estreito 56%, Porto Colômbia 43%, and Três Marias 44% in November. The first 3 of those reservoirs filled up adequately by December 2014, and then had another drop to about 90% in the same period in 2015. Três Marias never really recovered and dropped even further in 2015 to a low of 17% in December 2015. The only 2 reservoirs that had electricity production issues in 2014 were Estreito and Porto Colômbia due to their high minimum useful capacities of 87.5 and 85%, so the days of no electricity production started rising in September, reached almost 100% in October and November, and were 0% in January 2015 again. On the other hand, Três Marias did not have such issues until

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October 2015, reaching almost 100% in November-December, due to its low minimum useful capacity of 22%. All reservoirs, apart from Três Marias, had good water availability in March-May of 2010-2012, dropped a lot in 2013, finally reaching very low levels in 2014-2015. Estreito and Porto Colômbia have very equal precipitation and evaporation throughout the whole period, whereas the other 3 reservoirs have elevated precipitation in September-February and then higher evaporation than precipitation in March-August. Through the years we can see precipitation losing ground, while evaporation is gaining some.
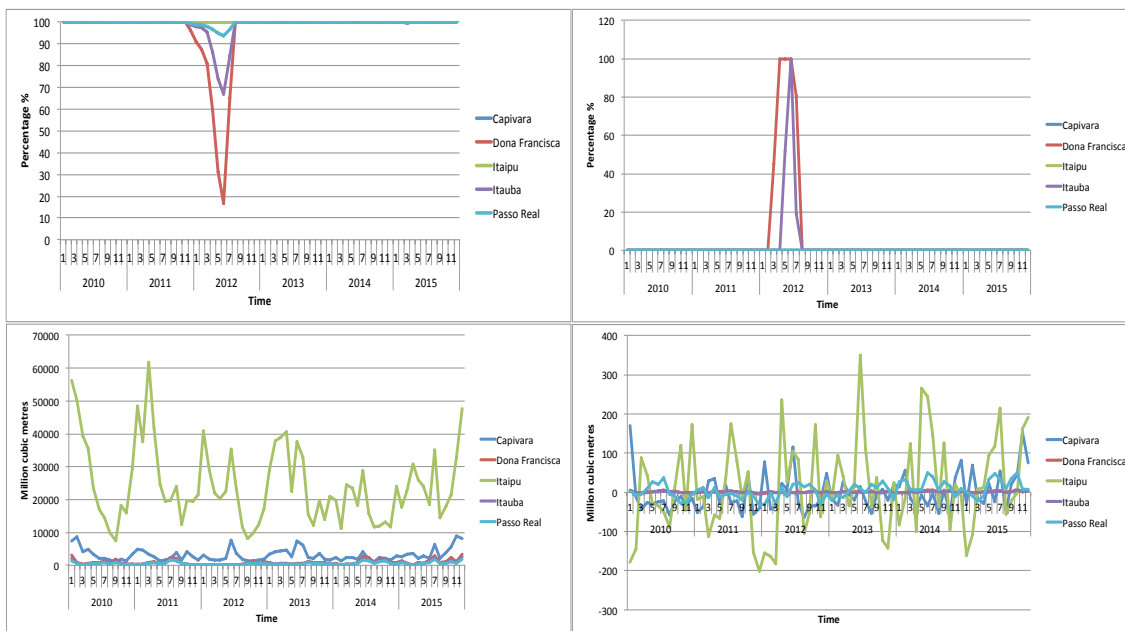
Figure 6.38 – a) (top-left) volume level of reservoirs, b) (top-right) days reservoirs' level is lower than minimum useful capacity, c) (bottom-left) difference of actual outflow and minimum safe outflow, d) (bottom-right) difference of precipitation and evaporation per reservoir per month for the period 2010-2015 in the South

Figure 6.38 shows the 4 main graphs of the water budget analysis for 5 example reservoirs in the South of Brazil. The reservoirs in the South generally fare very well, with an exception in the middle of 2012, where the level of Dona Francisca fell to 17% and Itaúba's to 67%. The only time when electricity production was an issue was in March-August for both these reservoirs, with the first reaching almost 100% of days with no electricity

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production in April-June and the second in June. Despite these reservoirs never really having any water availability issues, only Itaipu has a very high potential throughout the year, and to a lesser extent Capivara. What is interesting in the South is that water availability is never too close to zero, as is the case in the rest of the country's regions. 4 of the reservoirs have very similar precipitation and evaporation throughout the year and never have too high extremes either end. Only Itaipu sometimes has a lot more precipitation than evaporation and vice versa, although there is not an actual pattern to this, since the highs and lows are never in a particular season of the year.

From this novel water budget analysis performed for most hydroelectric plants/reservoirs (data permitting) in Brazil, these are the most important lessons learned: a) The years 2014 and 2015 were particularly bad regarding water availability and electricity generation for the whole country, especially for the Southeast, which is where most of the hydroelectric reservoirs are located, affecting the system of the whole country, b) The Northeast has been in an extended drought, which by the end of 2015 has started to seriously affect nearly all reservoirs in the region, c) The useful outflow is decreasing every year in the 6-year analysis period for the whole country apart from the South, with 2014 and 2015 having very low values, d) Precipitation in relation to evaporation in March-May (the main rainy season) is decreasing in the Northeast, Midwest and the Southeast, which affects the country averages as well, whereas evaporation in relation to precipitation in September-November has remained constant, e) In times of reduced water availability the minimum useful capacity of reservoirs plays a very important role regarding electricity generation.

The aforementioned facts have certain important implications:

- Firstly, the 2014-2015 drought showed the criticality of the Southeast in the country's electricity system and although the region fares well

in general, in times of drought it is in danger, along with the rest of the country in terms of electricity generation.

- Secondly, the Northeast has serious water availability issues, which along with the region's water footprint values show that it is not an ideal region in general for hydropower plants. This is true to a certain extent for all hydropower plants in the region, meaning that potential future hydropower plans in the region either require thorough assessment and planning, or to be abandoned all together.

- Furthermore, the useful outflow has been decreasing for the 6-year examination period, and although this could change in the future, it is nevertheless an indication that care should be taken when making hydropower or other plans that require water in general.

- Also, evaporation is becoming more prominent in comparison with precipitation as time goes by, showing even further the importance of accurate evaporation estimation.

- Finally, in times of drought the minimum useful capacity of reservoirs plays an important role since it allows for electricity generation for a prolonged time, whereas power plants that are run-of-the-river for example, would immediately suffer in times of drought and not be able to produce electricity as soon as water levels drop. This last fact could be an indication that despite elevated evaporation as time goes by, it would perhaps make sense to have stored water in reservoirs for times of need, therefore favouring reservoir plants to run-of-the-river plants.

6.4. Outflow and capacity factor - Link with energy models

The results of the water budget analysis all serve as standalone indicators of the water-energy nexus, but it is also possible and desirable to create a more direct link with energy models. Availability of water has an effect on electricity generation, but even more specifically, the outflow from the reservoirs directly affects capacity factors of the power plants.

Capacity factor is the ratio of the actual energy produced in a given period, to the hypothetical maximum possible. Capacity factors vary due to resource, technology, and purpose. Typical hydro capacity factors are in the range of 30-80% (RERL). Generally, a capacity factor of 100% is not possible due to many reasons, which include efficiency of turbines, time the plant is out of service, or it is operating at reduced output due to a variety of reasons like equipment failure, routine maintenance, etc. For hydroelectric plants, the most common reasons of lower capacity factors are availability of water, and to a lesser extent, requirements of water downstream. However, when hydroelectric plants have high availability factors, they are almost always able to produce electricity. Although, managers of the power plants have the ability to store water and process it at the most economically opportune time, and they can also adjust usage based on expected shortages (Solaun & Cerdá, 2017).

ANEEL has data on the production of electricity of all hydroelectric power plants and the capacity factors for all of them individually and per region were calculated based on this data. The volume of outflow is one of the variables estimated through the water budget analysis, and the relationship between capacity factors and outflow will be presented here.

The capacity factor of a region is not estimated by averaging the capacity factors of all power plants in that region, because some plants produce a lot more electricity, and so they are a lot more important for the region. Alternatively, the capacity factor of each power plant is multiplied by a factor that is the potential annual electricity production of each plant divided by the total potential annual electricity production of the whole region, and the addition of the values provides the actual capacity factor of the region. These values are presented in table 6.14. The first column of each year shows the average values of the regional capacity factor, and the second column of each year shows the capacity factor factored by potential electricity production of each plant.

	2010		2011		2012		2013		2014		2015	
North	0.61	0.51	0.63	0.56	0.59	0.54	0.62	0.53	0.62	0.54	0.57	0.48
Northeast	0.41	0.43	0.46	0.47	0.38	0.48	0.32	0.32	0.32	0.28	0.30	0.24
Midwest	0.53	0.61	0.58	0.63	0.64	0.69	0.56	0.61	0.55	0.55	0.48	0.50
Southeast	0.59	0.57	0.57	0.56	0.58	0.60	0.50	0.46	0.40	0.38	0.34	0.31
South	0.60	0.63	0.62	0.69	0.44	0.54	0.58	0.64	0.64	0.66	0.63	0.67

Table 6.14 – Average and factored by potential electricity production capacity factors by region for the period 2010-2015

As is shown, the difference is not consistent and either of the two values could be higher than the other, depending in the second case how the largest power plants performed that specific year, which is more logical since they are the ones that produce most of the electricity and so the capacity factor of the second column of each year gives a more realistic regional capacity factor. In such cases of aggregation, care needs to be taken in order to not make assumptions that could potentially harm the modelling process. For example in 2012 the capacity factor for the South is either 0.44 or 0.54, which is a 22.73% difference and could alter the results of the model a lot. The same process takes place for the outflow values, since some of them, the larger power plants, will affect the regional capacity factor a lot more than others.
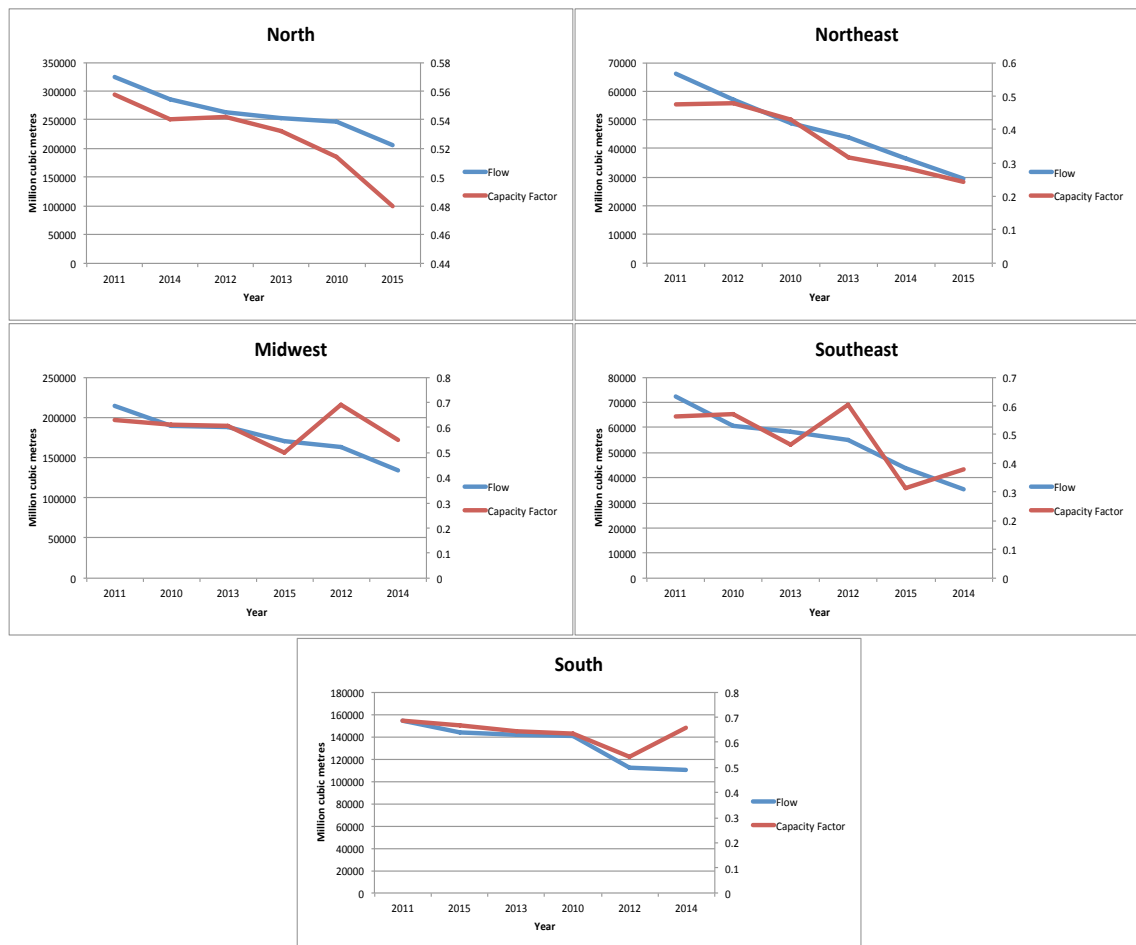
Figure 6.39 – Capacity factor of each region against river outflow for the period 2010-2015, presented by descending outflow volume

Figure 6.39 presents the average factored capacity factor of each region against the average factored outflow, presented by descending outflow volume and not by ascending year, to better show what is happening when the outflow decreases. It becomes obvious that there is a large correlation between the two variables, since as outflow decreases capacity factor decreases as well. In most cases the decrease is uniform, but there are years that do not follow the pattern. For example in 2012 the capacity factor in the Midwest was 0.69 although the outflow would not justify this. The same is true for 2012 in the Southeast when the capacity factor was 0.6 and the outflow was less than 2010 and 2013 for example. And again in 2014, the capacity factor in the South is 0.66, although the outflow was the least of any year in the 6-year period of the analysis.

As it was explained earlier, the factor that affects capacity factor the most is availability of water, which here is represented by the outflow. However, there are other factors affecting capacity factor, like out-of-service time of plants, various failures, producing electricity in more economically opportune times, but also perhaps more importantly other uses of the reservoirs. As it has been mentioned before, the vast majority of hydroelectric reservoirs in Brazil are solely used for this purpose, at least in theory because practically this is not the case. Unfortunately, other uses are not regulated and consequently there is no data regarding other uses of the reservoirs.

To link the water model, presented in the methodology chapter, with energy models, it is important to have a rule regarding the relationship between outflow and capacity factor. Chapter 7 presents in detail the future scenarios creation (climate and energy scenarios) and the ensuing results, but the relationship between outflow and capacity factor that will be used in the scenarios will be shown in this part because it is based on actual historical data. Generally, hydropower production and capacity factor can be estimated with the following equations:

$$P = \eta \times \rho \times g \times H \times Q \text{ (Equation 6.1)}$$

$$CF = P \div (C \times T) \text{ (Equation 6.2)}$$

where P = hydropower production (MWh)

η = plant efficiency

ρ = water density (997 kg/m³)

g = gravitational acceleration (9.81 m/s)

H = hydraulic head (m)

Q = inflow into the turbine (m³/s)

CF = capacity factor

C = nominal capacity of the hydropower station (MWh)

T = number of hours in the timeframe in question (h)

Hydropower plant efficiency can normally be anything between 80% and 95%, but the exact efficiencies for most of the Brazilian hydropower plants are not readily available. This also partly explains the variability and difference between footprint values based on actual and potential electricity production. Furthermore, the hydraulic head values are missing for a number of plants. It is for these reasons, that it was deemed too much of an assumption to calculate capacity factors with this method. Nevertheless, the method was used for the power plants that did have all the values known, but some of the results were far from reality as is shown in table 6.15. The year 2010 and a power plant for each region were chosen as examples. The actual capacity factor for each of them was calculated, since for 2010 (also for years until 2015) the electricity production data exists for all power plants, and the results are presented in the first column. For the purpose of the following calculations, plant efficiency was taken as 90% for all 5 examples. The second column presents the capacity factors calculated with equations 6.1 and 6.2.

	Actual produced electricity / nominal capacity of hydropower station	Hydropower production and capacity factor equations
North – Balbina	0.42	0.99
Northeast - Sobradinho	0.41	0.49
Midwest – Serra da Mesa	0.57	0.54
Southeast - Furnas	0.58	0.64
South – Campos Novos	0.57	0.93

Table 6.15 – Capacity factor results by two methods for one example power plant per region for 2010

As can be seen for Balbina, the two values are far off, which also holds true for Campos Novos. On the other hand, Sobradinho, Serra da Mesa, and Furnas had values for their capacity factors that were not far from reality, however there was a difference. This is a trend for all other power plants as well, since sometimes the values are quite close, but other times they are

very different. As it was discussed above, there are a lot of missing values to use this method for all reservoirs, but another issue lies in the fact that a lot of the existing data is also not verifiable and is most likely wrong for a variety of reasons. It is not possible to know exactly which values are the incorrect ones, and how much these would affect a potential analysis of this sort for each region/state. However, it is possible to avoid this obstacle by using a different method. For the abovementioned reasons, the decision was made to try and use a different method of calculating capacity factors for the future.

As was seen in figure 6.39, there is a relationship between the outflow values and capacity factors, but sometimes there are variations. These variations need to be homogenised in order to create a rule, so regression was used to alleviate this issue. Firstly, there should be an upper limit to which values a capacity factor can take. The average capacity factor of a region depends on the capacity factors of many power plants, and their capacity factor depends a lot on availability of water, which in turn depends on weather conditions, which can be quite different even within the same region as has been showed in earlier results. For this reason it is difficult to set a maximum value, but for the purposes of the model, the maximum value selected was 5% higher that the maximum observed regional capacity factor in the 2010-2015 period. Thus, the maximum capacity factors of the regions are 0.59 for the North, 0.5 for the Northeast, 0.73 for the Midwest, 0.63 for the Southeast, and 0.72 for the South.

According to the values of the actual capacities for the period 2010-2015 in relation to outflow values, a linear regression was performed, providing maximum and minimum values of capacity factors for each year of the study period. The new average values for the capacity factors alongside their respective outflow values are presented in figure 6.40. The lines are a lot more homogeneous than in figure 6.39, showing more clearly the relationship between the two variables and allowing for the creation of a rule.

This part could be improved if more years were available to take part in the regression, but outflow values were not available, since these values are calculated from the evaporation part of the water model and the climatic data available for the analysis start in 2010. The relationships between outflows and capacity factors in each region of Brazil, shown in figure 6.40, will be used to calculate capacity factors until 2049 in chapter 7.
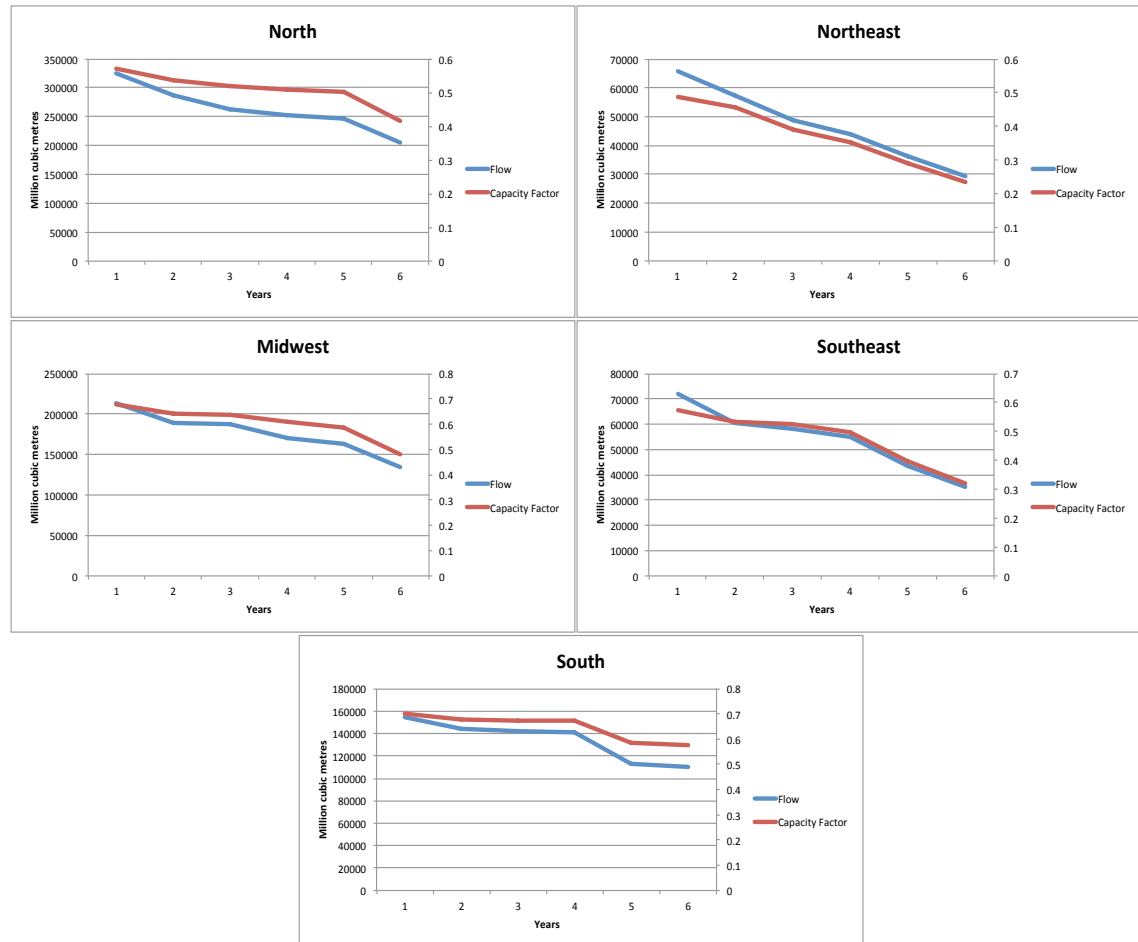
Figure 6.40 – Average capacity factor of each region against river outflow using 2010-2015 values not in chronological order, presented by descending outflow volume

6.5. Summary

This chapter presented the results and analysis of the water model that was presented in the methodology chapter, performing evaporation, water footprint, water budget, and finally capacity factor estimation calculations

based on climatic data for the period 2010-2016 for the first two parts and 2010-2015 for the next two parts. The water budget analysis in particular provides information about a) the volume level of reservoirs, b) the percentage of days per month when the reservoir level was lower than the minimum useful capacity, c) the useful water outflow (difference of actual outflow and minimum safe outflow), and d) the difference between precipitation and evaporation. The results presented for the first three parts of the analysis included regional, state and specific reservoir analysis. All parts of the analysis are novel either thanks to the methodology used and because they were performed for all hydroelectric reservoirs in operation in Brazil by the end of 2016, and the main outcomes are summarised here.

The water-energy analysis revealed some important outcomes that could prove to be useful for operation purposes and also future planning. The evaporation part showed that the Southeast affects the overall country results significantly, due to the amount of reservoirs located there. The Northeast has the highest evaporation rate, while the South has the lowest. Also generally, the more south we move within Brazil, the more the evaporation rate is changing through the seasons, which is especially the case in the South and the Southeast where most of the reservoirs are located. Although, depending on the climate and weather conditions at specific sites, there can be considerable differences on evaporation rates even within the same region. Keeping this in mind, it becomes more evident that an analysis for hydroelectric reservoirs needs to be done separately for each reservoir and not through averages for regions or even states, to account for these differences. Finally, the total volume of water evaporated from the country's hydroelectric reservoirs every year is equal to a relatively large European lake. This is not just a trivial fact; since it shows that hydroelectric generation is not a non-consumptive water use as it has been historically treated in Brazil and worldwide. The loss of water through evaporation is significant and it has also been increasing in relation to precipitation rates. Evaporation is of course a natural phenomenon and it cannot be stopped entirely even using cutting edge ideas and technology,

nor is it suggested that it should be stopped. Rather, it needs to be taken into account and measured or estimated in detail when assessing the pros and cons of constructing dams for hydroelectricity, and also for operation purposes. Some sites with high evaporation rates could potentially be unsuitable for the construction of a dam, since the power plant will be highly susceptible to reduced water availability.

The importance of evaporation as an indicator is further shown through the water footprint analysis. This part of the analysis showed that although there are no "normal" values for water footprint in literature, the comparison between reservoirs can be useful, and increased water footprint values can serve as an early warning indicator for efficiency of plants and criticality of water availability. Water footprint as an indicator shows which plants/reservoirs are underutilised or perhaps even misused, meaning that alternative uses would be more beneficial. Hydropower plants that inundate a large area per unit of installed capacity have in general a larger water footprint than those that flood a small area. This becomes even more of an issue the less electricity a plant produces. The relationship between inundated area and electricity production is key for water footprint. In general, the South of Brazil fares by far the best in terms of water footprint and maybe the values obtained there should set the standard for the country. The Southeast also normally fares well, although the drought of 2014-2015 raised the water footprint values. The Southeast is very important for the whole country since the states of Minas Gerais (MG) and São Paulo (SP) have 40 and 44 reservoirs respectively, which is by far the most in the country. The North due to the extremely large inundated areas of the reservoirs in the middle of forested and environmentally protected areas, and the Northeast due to its low precipitation and high evaporation levels do not fare as well as the rest of the country. An important finding is also that most water footprint values in the country drop in June-August, which shows that during those months water availability is such that it creates opportunities for alternative uses.

Evaporation and in extension water footprint are good indicators by themselves, but detailed and accurate evaporation estimations also serve in improving water budget analyses. The water budget analysis showed that the years 2014 and 2015 were particularly bad regarding water availability and electricity generation for the whole country. This was mainly due to the Southeast, and to a lesser extent the Midwest, because this is where most of the hydroelectric reservoirs are located. The Northeast has been in an extended drought, which by the end of 2015 seriously affected nearly all reservoirs present in the region. On a more general note, the useful water outflow has been decreasing every year in the 6-year analysis period for the whole country apart from the South, with 2014 and 2015 having particularly low values. Additionally, precipitation in relation to evaporation has decreased in March-May (the main rainy season) in the Northeast, the Midwest and the Southeast, which greatly affects the country averages. On the other hand, evaporation in relation to precipitation in September-November (the least rainy season) has remained more or less constant. An important observation is that the minimum useful capacity of reservoirs plays a very important role regarding electricity generation, especially in times of reduced water availability, since if river flows are low and the minimum useful capacity is also low, stored water will allow for electricity to be produced for a longer period of time. One important disclaimer is that almost all of Brazil's hydroelectric reservoirs are reportedly used solely for the production of electricity and for this analysis this was assumed to be true. However, in a general context of hydroelectric reservoirs it is a subject that needs to be investigated further in order to improve analysis and in turn improve the operation of a system.

An important aspect of this analysis was that the work was based on the fact that water availability is highly site specific and that electricity generation is highly time specific, thus the water budget analysis was performed for each reservoir and on a daily time step. More specifically, the results are based on daily water flows and actual hourly climatic data for each reservoir in the Brazilian system, capturing the real operation of the

system. Evaporation in particular has a central role in this analysis, compared to existing work, since as shown in the results it is actually higher than precipitation, and generally an important factor in water analyses of this sort. Additionally, the results for the reservoirs are aligned to political boundaries as opposed to watershed/river basin boundaries. Thanks to the small time step and the spatial alignment, this evaporation/water budget model can be used in conjunction with various energy systems models, which is partly the subject of chapter 7.

What follows is a presentation of the development of future climate and energy scenarios, and then the presentation of regional results and analysis for evaporation, water footprint, water budget, and the IDA3 model for the period 2015-2049.

Chapter 7. Future scenarios results and analysis

Following the detailed historical analysis of results for the period 2010-2016 for evaporation and water footprint, and for the period 2010-2015 for the water budget, this chapter is about future scenarios. Firstly, the meteorological phenomena in Brazil, along with global and Brazilian climate projections will be investigated. This will be followed by analysing GCMs and the importance of downscaling, before presenting the climate scenario projections used for the analysis. What follows is an investigation of scenario work used for Brazil in the past and the presentation of the energy scenarios that will be used, based on work by Senger & Spataru (2015). After the presentation of both climatic and energy scenarios, the results and analysis of evaporation, water footprint, and water budget will be presented for the five regions of Brazil for the period 2015-2049. Finally, the results of the IDA3 model will be presented and analysed. The way the climatic scenarios were constructed is a novel method that takes into account the locality and past climatic conditions of individual reservoirs in a daily time step, following downscaling of GCM projections.

7.1. Development of climate scenarios

This part of the chapter is dedicated to the development of the climate scenarios that will be used for the future analysis of evaporation, water footprint, and the water budget, which will further feed the IDA3 model. Firstly, the background to meteorological phenomena in Brazil, projections for the country, and climate models will be presented, followed by the process followed for building detailed climate scenarios for reservoirs in Brazil.

7.1.1. Meteorological phenomena in Brazil

Water availability, and climate change more generally, is typically portrayed through a lens of averages and trends. However, this is seldom an

adequate representation of water availability, where deviations from trends are frequent, as illustrated by the recent droughts in Brazil (Damania et al., 2017). Adapting to rainfall variability is challenging due to the unpredictable duration of a deviation, its uncertain magnitude, and its unknown frequency (Adams et al., 2013). Due to climate change, deviations from trends are projected to become more prominent and frequent, with inter-annual variability in particular posing a threat in particularly dry regions (Hall et al., 2014). Furthermore, rainfall variability is not something that will become a problem in the future; on the contrary it already is a problem, since much of the world suffers from inter-annual variation in rainfall (Damania et al., 2017).

Before going any further, it would be useful to understand why it is difficult to make any useful projections for the future climate in Brazil. The El Niño Southern Oscillation (ENSO) controls the inter-annual variability of the spatial distribution of precipitation in the Amazon basin. El Niño and La Niña conditions mainly affect the northern and central parts of the basin. El Niño has negative precipitation effects, while La Niña has positive (e.g. Costa & Foley, 1999; Marengo et al., 2011). Inter-annual variability of river flows is strongly influenced by large-scale atmospheric circulation patterns, which are associated with ENSO, North Atlantic Oscillations (NAO) and other oceanic–atmospheric variability systems that operate within decadal and multi-decadal time scales (Kundzewicz & Döll, 2009). Although global and regional studies of future drought and water stress are uncertain due to the role of ENSO under climate change (Met Office, 2011), ENSO only partly explains the rainfall variability in the Northeast for example. As shown by Kane (1997), from 46 El Niño events during 1849-1992, only 21 were associated with droughts in the Northeast. More recently, only the 2015 drought has been during ENSO years (Marengo et al., 2016).

Furthermore, the inter-annual variability of precipitation and runoff are controlled by the tropical North Atlantic Sea Surface Temperature (SST) anomalies (Moura & Shukla, 1981; Enfield, 1996; Enfield et al., 1999;

Marengo et al., 2008; Yoon & Zheng, 2010). Annual precipitation and total river discharge of the northern basins are anti-correlated with the tropical North Atlantic SST anomalies (e.g. Gloor et al., 2013). Tropical and North Atlantic SSTs have increased rapidly and steadily since 1990, while the Pacific SSTs have shifted during the 1990s from a positive Pacific Decadal Oscillation (PDO) phase with warm eastern Pacific temperatures to a negative phase with cold eastern Pacific temperatures. These SST conditions might be associated with an increase in precipitation over most of the Amazon save the south and southwest (Gloor et al., 2015).

Drought events in the north-eastern region have been also attributed to an anomalously northward position of the Inter-Tropical Convergence Zone (ITCZ) over the Atlantic sector, due to a warmer tropical North Atlantic Ocean (e.g. Moura & Shukla 1981; Kousky et al. 1984; Aceituno 1988; Marengo et al. 2013; Amorim et al. 2014). The ITCZ is the main meteorological system responsible for the rainy season over most of the Northeast. ITCZ is *a semi-permanent low-pressure band of clouds that circle the Earth near the equator on the confluence region of the south-easterly and north-easterly trade winds from the Southern and Northern Hemispheres, respectively*" (da Silva & Mendes, 2015). A crucial factor for Brazil's climate is the position of the ITCZ, which oscillates southwards and then northwards across much of the country each year, lagging behind the latitude of overhead midday sun. The axis of convective-type rainfall lies to the north of Brazil in May-October and somewhere over Brazil for the rest of the year (Met Office, 2011).

Warmer than average tropical North Atlantic SSTs lock in the ITCZ more to the north than usual, which leads to less overall basin-wide precipitation (Gloor et al., 2015). Also, this effect is concentrated in the Amazon dry season (July-October), while ENSO primarily affects the wet season (December-April) (Yoon & Zheng, 2010). Additionally, the Northeast of Brazil, an important agricultural area, is also affected by the relationship of ITCZ and the North Atlantic SSTs (e.g. Uvo & Nobre, 1989; Uvo et al.,

1998). The correlation between all these phenomena is too intricate to be adequately understood, let alone allow for any future projections of the climate in Brazil or other countries in South America, something that becomes evident when researching projections in literature. However, following precautionary steps, it is possible to perform such an analysis.

7.1.2. Global and Brazilian climate projections

According to IPCC (2013, 2014), droughts are likely to become more severe and with a longer duration by the second half of the 21st century, but such projections for the first half of the century are made with low confidence (Marengo et al., 2016). At a large scale, there is evidence of a broadly coherent pattern of change in annual river runoff driven by precipitation change (Milly et al., 2005). Generally, climate models project that frequency of heavy precipitation and maximum number of consecutive days without precipitation will increase in the future, even for regions where mean precipitation is supposed to decrease (Kundzewicz & Döll, 2009). There are studies that have found that in certain geographies, areas with a water surplus are becoming drier and vice versa some drier areas are becoming wetter (Ashfaq et al. 2009; Chaturvedi et al. 2012; Donat et al. 2016; Ghosh et al. 2016; Greve et al. 2014; Hu et al. 2000; Krishnan et al. 2016). However, most models suggest that rainfall variability will increase (Hall et al. 2014).

Patterns of precipitation change are more spatially and temporally variable than temperature change and evapotranspiration change, which is directly temperature-driven. According to Trenberth et al. (2007), there is no statistically significant long-term trend in the time series of global precipitation in the period 1900-2005, which makes precipitation future projections extremely difficult (Kundzewicz & Döll, 2009). Since the 1970s, precipitation variability has risen and more intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics. Also, precipitation intensity has increased over most land areas,

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and particularly at middle and high latitudes where mean precipitation also increased (Tebaldi et al., 2006; Meehl et al., 2007). The increase of heavy precipitation and higher water temperatures could also exacerbate water quality problems, particularly by flushing pathogens and other pollutants (Kundzewicz et al., 2007), although this is not the subject of this research.

Different climate models do not agree for most areas of the globe, not even regarding the direction of change. As a general rule, for high latitudes and parts of the tropics climate models project increases in precipitation, whereas for some subtropical and lower mid-latitude regions they project decreases. Nevertheless, it needs to be noted that even if most models agree regarding specific trends, it is not proof that the results are credible (Kundzewicz & Döll, 2009). In conclusion, unlike the case of temperature where almost all models are in agreement, with precipitation most models disagree over whether precipitation is increasing or decreasing in different regions and there is no consensus among studies concerning water stress (Met Office, 2011; IPCC, 2014). As a consequence, constructing reliable scenarios of future climate extremes has been a challenge so far and tropical and subtropical regions are difficult to project due to inconsistent weather patterns (Yang et al., 2012).

Recent analyses of runoff and precipitation data suggest that wet season precipitation and peak river runoff have been increasing since 1980, as well as annual mean precipitation since 1990. At the same time, dry season precipitation and minimum runoff have decreased, and there has been an increase in the frequency of severe droughts and floods (Gloor et al., 2015). Specific analyses of discharge and precipitation data of the Amazon River have pointed out that the hydrological cycle of the Amazon basin has become more variable in the past 30-40 years with more frequent floods and droughts than in previous decades (Gloor et al., 2013). This increase of extreme events is compatible with the upward trend in the seasonal amplitude of the Amazon basin discharge, which drains 77% of the basin (Callède et al., 2004). Additionally, there has been an increase in net annual

precipitation as a result of increase during the wet season in the northern, north-western, and central parts of the basin, despite a small decrease during the dry season (Gloor et al., 2013). The exception to this trend has been the south-western part, which has become drier and the dry periods have become marginally longer (Marengo et al., 2011; Fu et al., 2013).

At the same time, the IPCC AR4 noted projections of reduced precipitation in northern Brazil, and potential increases over other parts of the country, but not much into changing precipitation extremes (Met Office, 2011). More specifically about discharge, Ho et al. (2016) suggest that most climate models suggest declines in mean annual discharge, although some predict increases in the Tocantins-Araguaia basin (south-eastern part of the North). It is projected that the dry season will experience large declines in discharge, with more than 75% of the models suggesting declines in annual minimum flows. It needs to be noted that the projections from 41 GCMs clearly show very large uncertainties regarding river discharge (Ho et al., 2016).

Water resources in many semi-arid areas, like the Northeast, are projected to experience a decrease due to climate change (Kundzewicz & Döll, 2009). The Northeast has had a drought from 2012 to 2015, with an intensity not seen in several decades, which has destroyed cropland, affected feeding and watering of cattle, and affected hundreds of cities in the region. Future climate projections for the region show large temperature increases and rainfall reductions. Along with a tendency for longer periods of consecutive dry days, droughts are set to occur more frequently and be more intense, leading to aridification of the region. These conditions lead to an increase of evaporation from lakes and reservoirs, which would affect irrigation and agriculture, along with hydropower, industry and the overall welfare of residents (Marengo et al., 2016).

In the Amazon Basin, annual average rainfall exceeds 2000mm and even between June and October, the dry season, it typically rains 60-120mm per

month. By contrast, the Northeast is a relatively dry zone averaging less than 750mm per year and with large variations from year to year, resulting in frequent droughts. Concerning annual precipitation changes, it is projected that the west will have an increase of about 5% in precipitation, with the central, northern and south-eastern regions seeing a decrease of about 5% (Met Office, 2011).

As found by Marengo et al. (2016) for the Northeast, in the whole 2010-2015 period, only 2011 has historically above average rainfall, but 2012 was particularly bad. The February-May rainy season in 2012 was the driest between 1961 and 2012. The mean observed peak of the rainy season varies from 5 to 6 mm/day, while in June-August and September-November it is up to 4 mm/day. For the Northeast there is a spread among rainfall projections from -1.5 to +1.5 mm/day by 2100, while most models project increases or decreases from 0.5 to 1.0 mm/day.

Reboita et al. (2014) showed climate projections of air temperature and precipitation over South America from the Regional Climate Model version 3 (RegCM3) nested in ECHAM5 and HadCM3 global models. Their results projected general warming throughout South America, with more pronounced results in the far-future period (2070-2100). In this period, there are projected trends of negative precipitation in the North (-1.5 to -2.5 mm/day) and an increase in the Southeast (~1.5 mm/day).

As will be later shown in the results and analysis part, precipitation change directly affects hydroelectricity, since it affects the river flows, which in turn are the most prominent variable in a water budget analysis. It is for this reason that the above information is concentrated on precipitation trends. Nevertheless, temperature is a variable directly considered in evaporation estimation. The global average temperature has risen by about 0.7°C over the past century, a trend that will continue as a result of ongoing GHG emissions over the coming century (IPCC, 2007; IPCC, 2014). Brazil as well has warmed by about 0.7°C in the past 50 years. Specifically in the Amazon

region that has available observations, increasing temperature have been measured in day and night time temperatures and although the trends vary, all records show a detectable increase (Victoria et al.1998; Marengo, 2003). The IPCC's estimate for temperature increase between the end of the 20th century (1908-1999) and the end of the 21st century (2090-2099) for the low emission scenario (SRES B1) is 2.2°C (range 1.8 to 2.6°C), and for the high emission scenario (SRES A2) is 4.5°C (range 3.9 to 5.1°C). Although for Brazil in particular there is a range described by individual models, all models project increasing temperatures. In South America and its tropical regions, temperature is projected to rise from 1-2°C in 2010-2040 to 6-8°C by 2071-2100, with increases being largest in the Amazon region (Marengo et al., 2011).

7.1.3. General Circulation Models (GCMs) and downscaling

The models mentioned previously are GCMs. GCMs are the most important and effective tools for climate impact studies. Their sophistication has increased during the years and their ability to simulate present and past, global and continental scale climates has substantially improved. However, despite the improvements, the resolution of GCMs remains relatively coarse and does not produce a direct estimation of hydrological responses to climate change (Yang et al., 2012; Palomino-Lemus et al., 2017). GCMs provide output at nodes of grid-boxes that are tens of thousands of square kilometres in size, when the scale of interest to hydrologists is of the order of a few hundred square kilometres (Yang et al., 2012). While GCMs have good projecting capabilities, model parameters may have large uncertainties depending not only on space but also forecast time horizon. The uncertainties are due to the nature of the climate system itself, which is based on complex behaviours and large internal variability (Xue et al., 2017), as explained earlier. Finally, recent simulations by the AVOID programme showed that exposure to increased or decreased water stress with climate change is not simulated by most GCMs (Met Office, 2011).

The gap between resolution of climate models and more local-scale processes is a problem for climate change studies, which includes the application of climate change scenarios to hydrological models (Yang et al., 2012). It is for this reason that downscaling techniques are required to provide high-resolution climate change scenarios (Christensen et al., 2007; IPCC, 2013).

Downscaling methods are generally classified into two categories (Xu, 1999): dynamic downscaling and statistical downscaling. In dynamic downscaling, the GCM outputs are used as boundary conditions to usually drive Regional Climate Models (RCM) and they produce regional-scale information up to 5-50km. Although this method has superior capability in complex terrains, it entails high computation costs and it relies on boundary conditions provided by GCMs and the accompanying uncertainties. On the other hand, statistical downscaling has more station-scale meteorological time series detail by appropriate statistical or empirical relationships with surface or troposphere atmospheric features. Also, being computationally inexpensive they can be easily applied to different GCMs, parameters and regions (Wilby et al., 2004). Statistical downscaling techniques have been described in three categories (Wilby & Wigley, 2000): regression methods, weather pattern based approaches, and stochastic weather generators. No matter the complexity of the method used, there is always some kind of regression relationship (Yang et al., 2012). One issue with statistical downscaling is that longer historical time series are needed to build the appropriate statistical relationship. However, due to its advantages, statistical downscaling has been widely used in climate change impact assessments (e.g. Wilby et al., 1999; Huth, 2002; Tripathi et al., 2006; Ghosh & Mujumdar, 2008). The method used for the purposes of this work will be further discussed in section 7.1.4.

In conclusion, reliance on gridded weather data and downscaling could result in incorrect flows for regions with complex topography where there are sharp changes in rainfall and runoff over short distances. Nevertheless, for the analysis of impacts of climate change, GCMs are the only credible

tools available that simulate physical processes of global climate, and they are used as the basis for assessing climate change impacts on natural and human systems (Schaeffer et al. 2013).

7.1.4. Devising climate scenarios for future projections

First of all, the period 2015-2049 was chosen for the future analysis. 2015 was the last year for which all actual climatic data existed and so it serves as the base year, and 2049 was chosen to have a 35-year period of analysis in total, until the middle of this century. The main inputs for the overall water model presented in chapter 4 are: temperature, incoming short-wave radiation, wind speed, precipitation, and river flow. These five inputs are separated into two parts in order to devise the scenarios. This is done because evaporation is temperature driven, and precipitation depends on the meteorological phenomena explained earlier. River flows are directly correlated to precipitation as explained earlier.

Based on projections by IPCC and Marengo et al. (2011), temperature in Brazil will rise within a range of 1 to about 4°C until 2050. The exact increase is difficult to project and so are the variations within the country itself and from season to season. Based on these projections, it was decided to create two different scenarios for evaporation estimation, using an increase of 2°C and another of 3°C until 2049, which lie in the middle of the aforementioned projections. At the same time, projections for incoming short-wave radiation and wind speed do not exist in literature, hence they were based upon empirical observation and analysis of past data. Based on the sensitivity analysis of evaporation in chapter 6, it was decided that the 2°C scenario will be accompanied by an increase of 0.5 MJ/m² for incoming short-wave radiation and an increase of 0.5 m/s for wind speed, while the 3°C scenario by an increase of 1 MJ/m² for incoming short-wave radiation and an increase of 1 m/s for wind speed. The scenarios are presented in table 7.1.

The projections for precipitation are more difficult than the ones about temperature, since as seen earlier, climate models do not even agree about the direction of change, let alone the exact change, especially since the weather patterns in Brazil are so inconsistent due to the meteorological phenomena present in the region. Generally, the IPCC projected reduced precipitation in the North, with potential increase over other parts of the country. Also, the Northeast will have decreases according to Marengo et al. (2016). Finally, Reboita et al. (2014) projected trends of negative precipitation in the more northern region of the country of -1.5 to -2.5 mm/day and increases in the Southeast and South of ~1.5 mm/day in the period 2070-2100. These values are in agreement with Marengo et al. (2016).

Since precipitation projections are difficult, it was decided to have four different scenarios of precipitation/river flows. The first one is based on the GCM miroc5 (World Bank Climate Change Knowledge Portal), which projects an extreme upward precipitation future of 1858mm (from 1439mm in the period 2010-2015) for the period 2016-2039 and 1865mm for the period 2040-2049. The second one is based on the GCM ipsl_cm5a_mr (World Bank Climate Change Knowledge Portal), which projects an extreme downward precipitation future of 1190mm (from 1439mm in the period 2010-2015) for the period 2016-2039 and 1225mm for the period 2040-2049. The third and fourth scenarios are based on projections by Reboita et al. (2014) and Marengo et al. (2016), projecting an increase of 1mm and 0.5mm precipitation per day until 2049 in the South and Southeast of Brazil, and a decrease of 1mm and 0.5mm precipitation respectively in the North, Northeast, and Midwest. The scenarios are presented in table 7.1.

Evaporation Precipitation	Increase of temperature by 2°C, increase of incoming short-wave radiation by 0.5 MJ/m², and increase of wind speed by 0.5 m/s	Increase of temperature by 3°C, increase of incoming short-wave radiation by 1 MJ/m², and increase of wind speed by 1 m/s
Increase to 1858mm by 2039 and 1865mm by 2049	E1P1	E2P1
Decrease to 1190mm by 2039 and 1225mm by 2049	E1P2	E2P2
Increase of 1 mm/day in the South and Southeast by 2049, decrease of 1 mm/day in the North, Northeast and Midwest by 2049	E1P3	E2P3
Increase of 0.5 mm/day in the South and Southeast by 2049, decrease of 0.5 mm/day in the North, Northeast and Midwest by 2049	E1P4	E2P4

Table 7.1 – The 8 climatic scenarios

Apart from the aforementioned difficulties of temperature and precipitation projections, another issue is capturing spatial and temporal patterns mainly of precipitation, but also temperature. At the same time, the availability of historical data for precipitation and temperature is poor, which is why the historical analysis was done for the period 2010-2015, unlike the good availability of historical flow data by ONS. Because of the poor availability of data, but also because of the detail required, it was decided to create a sequence of data for future projections, based on the spatially and temporally detailed 2010-2015 data, but at the same time accounting for changes due to climate change. As discussed earlier, the 2014-2015 drought in Brazil has had serious consequences for the electricity sector and also such droughts will occur more frequently in the future. For this reason the

sequence of the data used was created to account for droughts in the future. The sequence of years is presented in table 7.2.

2015	2016	2017	2018	2019	2020	2021
2015	2010	2011	2012	2013	2010	2011
2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
2012	2013	2010	2011	2012	2013	2014
2029	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
2015	2010	2011	2012	2013	2010	2011
2036	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**
2012	2013	2014	2015	2010	2011	2012
2043	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**
2013	2014	2015	2010	2011	2014	2015

Table 7.2 – Sequence of years used for future projections

As seen in table 7.2, 2015 was used as the base year, and then 2016 used 2010 data as its basis, 2017 used 2011 data as its basis, and so on. Then, the basis data for each year accounts for changes in temperature, precipitation, wind speed, and incoming short-wave radiation, and eight scenarios for each year are created as per table 7.1. The reason for deciding to create such a sequence of data is because hydropower has an inherent risk of experiencing high and low flows of incoming water due to climatic variations, and it is important to simulate real conditions of all input variables in the best possible way. Furthermore, this sequence data includes a period of drought that affected most of the country (2014-2015), which as time progresses becomes more frequent. In this way, it is possible to investigate the behaviour of specific reservoirs to more frequent drought events combined with climate change effects. It is only the results of the Northeast that could be exaggerated, since the region has been in a continuous drought since 2012, but also the years 2010-2011 were used more frequently for this reason.

It is on these grounds that each reservoir/power plant has been simulated in isolation, meaning that each reservoir has its own datasets created, which is not the norm for this kind of future projection work, and this is a novel contribution to research. By also researching and analysing different

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scenarios based on the sequences of data created this way, the analysis combines mean climate changes with actual observed variability, which is another novel contribution.

There were two main steps in devising the needed sequence of data. Firstly, evaporation for the period 2015-2049 needed to be calculated. Evaporation is dependent on temperature, short-wave radiation, and wind speed. As seen on table 7.1, two scenarios for evaporation were created. The increments for all three parameters occurred uniformly during the 35-year period, taking differences within a year into account.

Devising the four scenarios of precipitation and river flow for each reservoir was a more complicated affair partly due to reasons explained earlier, as was the variability in precipitation projections and the need to downscale these for use in specific reservoirs, but also because in order to devise river flow projections based on precipitation, it needs to be done on a hydrographic region basis.

Two scenarios were based on GCM precipitation projections, as shown in table 7.1, whereas the other two scenarios were based on projections from literature. The historical values for each region per month for the period 2010-2015 were estimated from the hourly dataset from INMET (acquired after personal communication). Since the precipitation values are available after calculations for both country and regions for 2010-2015, and for the country for 2015-2049 from GCM projections, the values for the regions for 2015-2049 were estimated by correlation. It is at this point that downscaling from region to the reservoir level is required, thus a weather-scale based approach of statistical downscaling was followed to estimate average precipitation for each month and specific reservoir until 2049. Here it needs to be noted that the projections from the GCM models were until 2039 and then until 2049. For this reason the estimation process was done in two steps, first until 2039 and then 2049. The same process was followed for all scenarios, and the data was checked for inconsistencies and in order to not

have negative precipitation values or gaps.

The next step was to create river flow datasets for each reservoir, but water movement in hydrographic regions affects these river flows, so it was needed to produce the datasets taking hydrographic regions into account. As mentioned earlier, precipitation and river flows are directly correlated. Also, it is known in which hydrographic region and at what percentage each reservoir belongs to. Hence, the next step was to produce precipitation datasets for all 10 hydrographic regions of the country until 2049. After producing these datasets, it was possible to estimate river flow data for each hydrographic region as well until 2049. At this point, downscaling correlation was used again to produce a river flow dataset for each individual reservoir until 2049. Once reservoir-scale river flow time series data were ready, the averages for each geographical region were estimated in order to proceed to the water budget analysis.

It is important to note here that the goal of devising climate scenarios was not necessarily to follow the most plausible projections in literature. Care was taken to do this, but the main goal was to create daily time series of climatic data for each reservoir that took part in the water budget analysis, simulating in the best possible way a plausible setting of how climate actually affects reservoirs and not just following general trends for regions from global climate models. The way climate scenarios were devised here, makes it possible to understand how specific reservoirs and in extension whole regions will fare in futures of different climatic conditions and an increase of dry periods that highly affect hydropower, and in extension the whole electricity sector in the country.

7.2. Introduction of energy scenarios

This part of the chapter is dedicated to the introduction of the energy scenarios that will be used for the future analysis of the energy system of Brazil using the model IDA3, based on water availability and capacity factor

projections. Firstly, a background to some important scenario work for Brazil is given, followed by the presentation of scenarios to be used in this chapter, and finally presenting the regional capacity factors for hydroelectricity in particular, highlighting the difference between literature values against actual calculated values.

7.2.1. Background to literature scenario work for Brazil

In 2006 MME in Brazil approved the Ten Year Plan for Energy (PDE) 2006-2015 (EPE, 2006), which was a design for policies for the energy sector. A year later, as part of the same initiative, the PNE 2030 (EPE, 2007) was released that was more about long-term planning. In this report the Energy Research Company (EPE) predicted that in 2030 the country would generate 1,056TWh of energy, of which 77% from hydro, 9% natural gas, 5% from nuclear power plants, 4% biomass, 3% coal and derivatives, 1% of oil and 1% wind power (Instituto Escolhas, 2015). The PNE 2030 has been used in various ministerial spheres as economic and energy baseline scenario of long-term federal government, and also from various stakeholders in the energy sector. It was crucial in strengthening and prioritizing hydroelectricity, for indicating natural gas as a complement to the generation matrix, the consolidation of ethanol in the matrix fuels, and also indicating the high potential of oil and natural gas in the country (EPE, 2016).

Subsequently, EPE/MME conducted the second long-term study PNE 2050, presenting the evolution of the demands of energy to long-term economic scenarios. PNE 2050 is a response to newer events that happened since 2006 and have an impact on the energy sector, like the competitiveness of wind energy, the rise of oil and natural gas supply, and global events like Fukushima, the extension of the economic crisis and the growing concern over climate change (EPE, 2016). In general, PDE 2024 (EPE, 2015c) expects that in the future the national electricity system will expand in such a way as to guarantee the participation of renewable sources as the main

means of meeting the growth of demand for electricity, but also as the PDE 2024 (EPE, 2015c) states, there is a marginal increase of non-renewable thermoelectric sources for balancing renewable variable sources.

Apart from studies within Brazil, there have been others. For example, the IEA in their 2013 World Energy Outlook (IEA, 2013) presented three scenarios for the different paths of expansion of the Brazilian electricity sector. Generally, the IEA believes it is plausible that Brazil might decrease its reliance on hydroelectricity due to the remoteness and environmental sensitivity of most of the potential, which finds itself in the Amazon region. For example, the New Policies Scenario projects a 70GW increase in hydropower capacity by 2035, assuming that the projects will not be of high social and environmental sensitivity and they will somehow be accepted. In this case, hydropower would reach 110GW in 2020 and 151GW in 2035, keeping hydropower as the predominant source of power generation, although the percentage would fall from 71% in 2012 to 58% in 2035. Since this might not be feasible, there is also a low-hydro case where the growth is limited to 50GW, and other technologies compensate for this shortfall (IEA, 2013). It is stressed in the IEA report that the development of large hydropower in Brazil is subject to lengthy planning periods, evaluation, consultation, authorization and construction, alongside legal challenges and obstruction.

The PDE 2024 (EPE, 2015c) presents an accurate picture of the Brazilian electricity system for 2020, but one issue is that it combines all renewable sources (biomass, wind, PV, etc.), apart from hydropower, in a single category. Also, it is impossible to disaggregate these sources of generation within the 5 different Brazilian regions. The IEA data (IEA, 2013) present the same issues (Saporta, 2017). For this reason, the water analysis was done using information from ANEEL, and also it is for this reason that Senger & Spataru (2015) used information by EPE, but the scenarios of PDE 2024 for example were not used to the letter.

7.2.2. Presentation of scenarios to be used

Unlike the climate scenarios, which were developed specifically for the purposes of this thesis, the energy scenarios were adopted by work done by Senger & Spataru (2015), and applied to the model IDA3 developed by Spataru. The reason the same energy scenarios were adopted was to be able to draw comparisons between the results based on the original water availability assumptions made by the authors for the future, and the projections devised in this thesis.

The power generation capacity mix was based on the publication by EPE (EPE, 2014a) "Brazilian Energy Balance 2014", where the base year was 2013, and the values are presented in table 7.3. The Southeast and the South have most of the hydro capacity, with more than 56% of it, whereas regarding thermo capacity, the Northeast had the most with about 35% and the Southeast was second with about 27%. Wind capacity was mostly concentrated in the Northeast with more than 66% of the country's capacity being located there, while the rest was in the South, and the Southeast had a small contribution as well. PV capacity was insignificant and located in the Northeast and Southeast. Finally, the only two nuclear plants are located in the Southeast.

Region	Hydro	Thermo	Wind	PV	Nuclear
North	12,805	3,236	0	0	0
Northeast	11,044	7,460	1,464	1	0
Midwest	11,500	1,640	0	0	0
Southeast	22,939	5,872	28	1	1,990
South	22,926	3,216	708	0	0
Brazil	81,214	21,424	2,200	2	1,990

Table 7.3 – Installed power generation capacity in Brazil in 2013, excluding self-producers (MW) (Source: EPE 2014a)

Based on installed power generation capacity values by MME/EPE (table 7.3) and official projections until 2023 again by EPE (EPE 2014b), four scenarios were devised projecting different directions of development until

2050. The first scenario (GenH) simulates the full exploitation of Brazil's hydropower potential, estimated to be 245GW. By doing so, hydropower accounts for nearly 60% of installed capacity in 2050, while additional investments result in 77GW thermo, 53GW wind, and 25GW PV in the same period. The second scenario (GenW) concentrates on the expansion of wind and PV capacity, which results in 168GW wind, and 98GW PV capacity by 2050, while at the same time hydro falls to 162GW, which is about 37% in total, and finally thermo is at 65GW. The third scenario (GenB) sees the rise of thermo, with a growing proportion of biomass. In total, thermo capacity accounts for 172GW by 2050, of which 80% comes from biomass. In addition, nuclear capacity is extended to 11GW. As was the case with scenario GenW, hydro falls to about 40%, while wind and PV are at 48 and 14GW respectively by 2050. Finally, the fourth scenario (GenM) is a mix of the previous three scenarios, assuming that all available technologies will expand, which sees hydro reaching 162GW, thermo 131GW, wind 61GW, and PV 46GW capacity by 2050.

When it comes to water use for power generation, as has been mentioned earlier, water withdrawal and consumption factors of electricity generation technologies vary in literature. The fundamental reasoning for this has to do with the specificity of each and every power station and the many variables that surround it. Concerning specifically the Brazilian power plants, it is very difficult to get any data about water usage, which is the main reason the main scope of this thesis was an in depth analysis and estimation of water usage of hydropower. Nevertheless, water withdrawal and consumption factors were needed to run the IDA3 model, and these factors were obtained from power stations outside Brazil. Three of the original scenarios of IDA3 (WuL, WuH, WuA1) are based on withdrawal and consumption factors from McMahon and Price (2011). WuL uses the lowest limits of the available range, WuH the highest, while WuA1 uses average ones. Additionally, there was a fourth scenario (WuA2) based again on values by McMahon & Price (2011) but with biomass factors taken from Gerbens-Leenes et al. (2009) in order to assess the sensitivity of the results

to this factor. Finally, the fifth scenario (WuG) is based on data by Macknick et al. (2012a) and it solely considers the generation step, without water use for fuel cultivation/extraction and processing. The withdrawal and consumption factors used in the original run of the IDA3 model are presented in tables 7.4 and 7.5.

Scenario	Nuclear	PV	Wind	Hydro	Coal	Gas	Biomass	Oil
WuL								
Extraction	0.04	0	0	0	0.06	0	267.8[2,4]	0.26
Production	0.24	0	0	0	1.68	0.05	-	0.3
Generation	0[1]	0	0	0	50.13	17.25	50.13[3]	50.13[3]
WuH								
Extraction	0	0	0	0	0.84	0	267.8[2,4]	43.25
Production	0	0	0	0	2.64	0.05	-	0.78
Generation	0[1]	0	0	0	112.29	133.83	112.29[3]	112.29[3]
WuA1								
Extraction	0.1	0	0	0	0.5	0	267.8[2,4]	21.8
Production	0.3	0	0	0	2.2	0.1	-	0.5
Generation	0[1]	0	0	0	81.2	75.5	81.2[3]	81.2[3]
WuA2								
Extraction	0.1	0	0	0	0.5	0	156.3[2,4]	21.8
Production	0.3	0	0	0	2.2	0.1	-	0.5
Generation	0[1]	0	0	0	81.2	75.5	81.2[3]	81.2[3]
WuG								
Generation	0[1]	0	0	0	81.85	1.15	78.67	77.29
Notes	[1]Nuclear power station uses sea water, [2]Includes extraction and production, [3]Factor from coal, [4]Assuming 42% irrigation (Gerbens-Leenes et al., 2009)							

Table 7.4 – Water withdrawal factors of power generation (m^3/MWh) assuming 42% closed-loop cooling systems and 58% once-through cooling systems (Source: Senger & Spataru, 2015)

Scenario	Nuclear	PV	Wind	Hydro	Coal	Gas	Biomass	Oil
WuL								
Extraction	0.04	0	0	0	0.06	0	637.71[2]	0.26
Production	0.24	0	0	0	1.68	0.05	-	0.30
Generation	0[1]	0	0	17.0	0.58	0.71	0.58[3]	0.58[3]
WuH								
Extraction	0.21	0	0	0	0.84	0	637.71[2]	43.25
Production	0.28	0	0	0	2.64	0.05	-	0.78
Generation	0[1]	0	0	17.0	2.39	1.82	2.39[3]	2.39[3]
WuA1								
Extraction	0.1	0	0	0	0.5	0	637.71[2]	21.8
Production	0.3	0	0	0	2.2	0.1	-	0.5
Generation	0[1]	0	0	17.0	1.5	1.3	1.5[3]	1.5[3]
WuA2								
Extraction	0.1	0	0	0	0.5	0	372.2[2]	21.8
Production	0.3	0	0	0	2.2	0.1	-	0.5
Generation	0[1]	0	0	17.0	1.5	1.3	1.5[3]	1.5[3]
WuG								
Generation	0[1]	0	0	17.0	1.64	0.81	1.54	1.48
Notes	[1]Nuclear power station uses sea water, [2]Includes extraction and production, [3]Factor from coal							

Table 7.5 – Water consumption factors of power generation (m³/MWh) assuming 42% closed-loop cooling systems and 58% once-through cooling systems (Source: Senger & Spataru, 2015)

7.2.3. Regional capacity factors for hydropower

In the original run of the IDA3 model, water availability was assumed either to stay constant or decline in all four scenarios used, which was simulated by declining capacity factors. Scenario CfC was the base scenario, in which the capacity factors remain constant throughout the examination period until 2050. In scenario CfD it was assumed that water availability would decline rapidly in the Midwest and the Southeast (the regions that suffered the most in the 2014-2015 drought), while the other regions would remain unaffected. Finally, scenarios CfA2 and CfB2 were based on a study by Lucena et al. (2010) on the impact of climate change on Brazil's hydropower production. Scenario CfA2 was further based on results of the IPCC SRES A2. The assumptions of the four scenarios are presented in table 7.6.

Region	Historical	Annual Growth Rate (%)			
		CfC	CfD	CfA2	CfB2
North	0.601	0	0	-0.72	-0.65
Northeast	0.626	0	0	-0.72	-0.65
Midwest	0.604	0	-2	-0.66	-0.60
Southeast	0.554	0	-2	-0.66	-0.60
South	0.514	0	0	-0.66	-0.60

Table 7.6 – Hydropower capacity factor assumptions for 4 different scenarios of original analysis (Source: Senger & Spataru, 2015)

As explained in section 6.4, the link between the water model developed in this thesis and the IDA3 model will occur by changing capacity factors, which are based on water availability analysis performed by the water model. More specifically, based on the relationship between outflow from the reservoirs and capacity factor (presented in section 6.4), the projected capacity factors for scenarios E1P1-E1P4 are presented in figure 7.1.
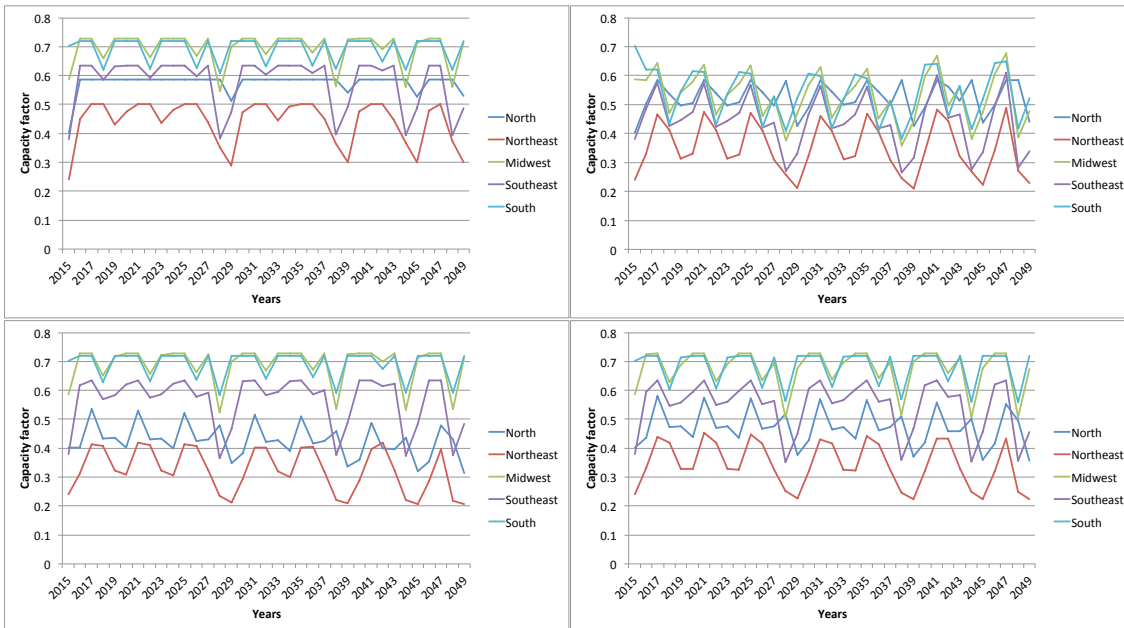
Figure 7.1 – Projected hydropower capacity factors based on scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Firstly, it needs to be mentioned that only scenarios E1P1-E1P4 are presented here, since scenarios E2P1-E2P4, where only evaporation changes while precipitation and river flows remain constant in relation to scenarios

E1P1-E1P4, do not affect capacity factors by much. In fact, the difference evaporation makes in relation to capacity factors between scenarios E1P1 and E2P1 is from 0 to 4% in any given year, with the average being a 1% difference for all regions for the period 2015-2049. The same comparison between E1P2 and E2P2, E1P3 and E2P3, and E1P4 and E2P4 gives a difference of 0 to 5% in capacity factors in any given year, with the average being about 2% for all three comparisons. Secondly, as it was shown in section 6.4, the capacity factor for the regions mentioned in table 7.6 is not exactly the same as the values presented in table 6.14. Although the values for the North, the Midwest, and the Southeast are similar, there is a discrepancy in the values for the Northeast and the South. The values for the Northeast are exaggerated in table 7.6, and they are lower for the South than they have been historically and also for the period 2010-2015.

In scenario E1P1, which projects a very high precipitation future, the capacity factors for all regions reach their maximum set values and do not drop by too much at any given year. Even in such a scenario with high precipitation and flows though, there are some years that capacity factors might drop by about 0.2 in the Northeast and the Southeast, about 0.1-0.15 in the Midwest and the South, and about 0.05 in the North. In scenario E1P2, which projects a very low precipitation future, the capacity factors for all regions are well below their theoretical maximum throughout the whole period. The South that historically has good capacity factor values is between 0.4 and 0.65 at best, the North is above and below 0.5, the Southeast has some good years of about 0.6, but also some very bad ones of about 0.3, the Midwest also some good ones with above 0.6, but also a few below 0.4, while the Northeast never above 0.5 and some years close to 0.2. Even in such a low precipitation future though, we can see that some years will have high enough precipitation and river flows to allow for decent capacity factors in all regions.

Scenarios E1P3 and E1P4 represent a mix of precipitation within the country, with the Southeast and the South having elevated precipitation

values and the rest of the regions seeing less precipitation. They show that the Northeast is particularly suffering with capacity factors being between just above 0.2 minimum and just below 0.45 maximum, the North from just above 0.3 minimum and just above 0.55 in good years, the Midwest not suffering particularly and remaining to about 0.5 in bad years, the South staying at minimum to just below 0.6 and most of the time close to its maximum, while finally the Southeast it between 0.5 and 0.6 most of the years, but suffering some particular years where droughts might occur and dropping to below 0.4. The reason the Midwest is not suffering much in these scenarios is that it shares hydrological regions with the Southeast and the South and river flows are more important than precipitation over the reservoirs.

7.3. Evaporation results and analysis

This part of the chapter is dedicated to evaporation results and analysis done for the 5 regions of Brazil for the period 2015-2049.
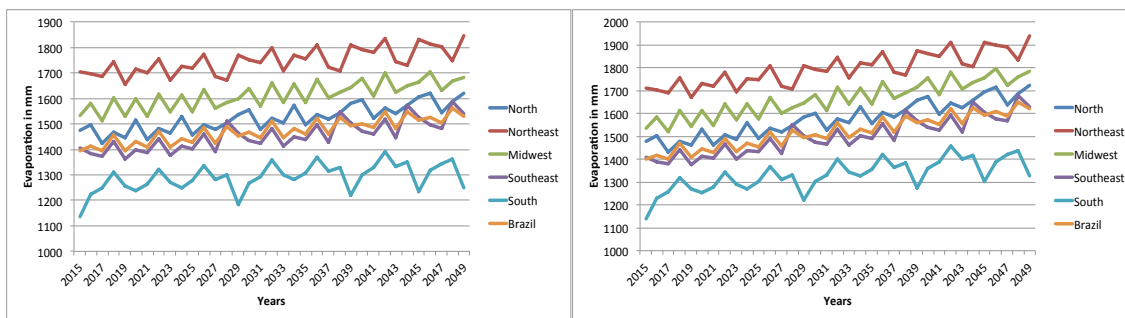
Figure 7.2 – Annual evaporation results from scenarios E1 (left) and E2 (right) for the period 2015-2049

Figure 7.2 shows the annual progression of evaporation from 2015 through to 2049 for the two scenarios created. As we can see, there is an increasing trend for evaporation for both scenarios, which is logical since temperature increases, along with incoming short-wave radiation and wind speed. The progression of the lines in both scenarios is similar, but the difference lies in the values themselves. Both scenarios share the same values for 2015,

which is the base year, and then there is a 3-4mm upward difference every year, except for the South that has 2-4mm, from scenario E1 to E2. In the 35-year period, the increase of evaporation has been most prominent in the North with an overall increase of about 103mm more for scenario E2 than E1. The least increase was in the South with 77mm. Overall, for a 1°C increase in temperature, a 0.5 MJ/m^2 increase in incoming short-wave radiation, and a 0.5 m/s increase in wind speed, the average difference between the two scenarios for the country was just over 90mm in total.

	North	Northeast	Midwest	Southeast	South	Brazil
2010-2015	1449.4	1675	1537.7	1393.3	1229.4	1406.3
2015-2049 E1	1522.9	1748.2	1612.9	1455.2	1290.6	1472.1
2015-2049 E2	1575.9	1795.5	1664	1501.8	1331.1	1518.8

Table 7.7 – Average annual evaporation (in mm) for the period 2010-2015 and for scenarios E1 and E2 for the period 2015-2049

When comparing the average evaporation for all regions in the period 2010-2015 and the two scenarios for the period 2015-2049, shown in table 7.7, we can see that for a 2°C increase in temperature, a 0.5 MJ/m^2 increase in incoming short-wave radiation, and a 0.5 m/s increase in wind speed (scenario E1), evaporation increases by a maximum 75mm in the Midwest, to a minimum 61mm in the South. The average increase for the country is about 66mm. On the other hand, for a further 1°C increase in temperature, a 0.5 MJ/m^2 increase in incoming short-wave radiation, and a 0.5 m/s increase in wind speed (scenario E2), the maximum change is both in the North and Midwest with over 126mm, while the lowest increase is again in the South with just less than 102mm. The average increase for the country in this case is just less than 113mm. Hence, for this extra rise in temperature, etc., evaporation rises from a maximum extra 53mm in the North, a minimum extra 41mm in the South, and an average 47mm in the country as a whole.
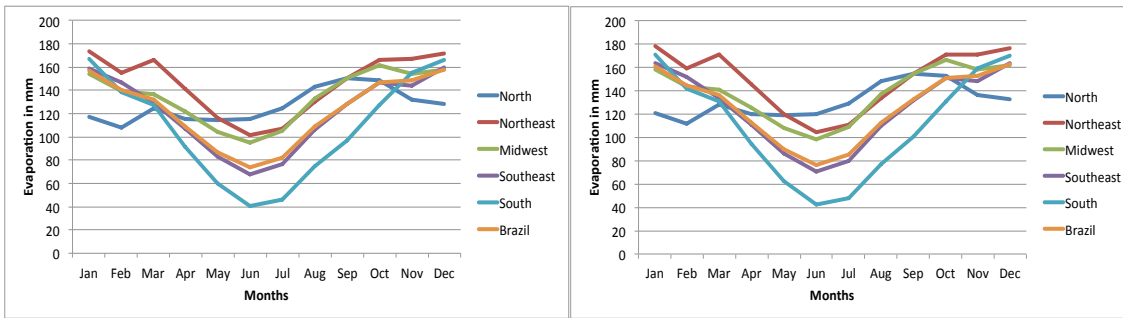
Figure 7.3 – Monthly evaporation results from scenarios E1 (left) and E2 (right) for the period 2015-2049

Figure 7.3 shows the monthly evaporation for the period 2015-2049 for scenarios E1 and E2. The graphs for both scenarios are similar, with the difference lying in small increments throughout the year. Evaporation is rising for every month of the year, with September-February seeing the largest rise in both cases. The average rise per month of the year is from 3.38mm per month in the South to 4.41mm in the North, with the country's average being 3.9mm. The North had increases from 3.7mm in February to 5mm in August, while the South from 1.75mm in June to 4.6mm in February. An interesting observation is that all regions have their minimum evaporation in June, except the North that has it in February. Also, the maximum evaporation occurs in December or January for the Northeast, Southeast and South, October for the Midwest, and September for the North.

		North	Northeast	Midwest	Southeast	South	Brazil
2010-2015	Max	141.8	165.8	157.1	153.6	158.1	151.5
	Av.	120.7	139.3	127.7	116.3	101.7	117
	Min	105.7	97.1	88.6	63.5	37.2	68.8
2015-2049 E1	Max	150.1	173.9	161.9	159.4	166.7	158.3
	Av.	126.9	145.7	134.4	121.3	107.5	122.7
	Min	107.9	101.3	94.7	67.8	40.4	73.4
2015-2049 E2	Max	155.1	178.3	166.5	164	171.3	162.8
	Av.	131.3	149.6	138.7	125.2	110.9	126.6
	Min	111.6	104.5	98.4	70.7	42.2	76.4

Table 7.8 – Average, minimum, and maximum monthly evaporation (in mm) for the period 2010-2015 and for scenarios E1 and E2 for the period 2015-2049

In the comparison of average monthly evaporation between 2010-2015 values and those from scenarios E1 and E2, shown in table 7.8, we can see that the Midwest sees the highest increase in evaporation in the future with 6.7mm overall increase for scenario E1 and 10.9mm for scenario E2. The South sees the lowest evaporation increase with 4.9 and 8.8mm in scenarios E1 and E2 respectively. The country as a whole sees increases of 5.6 and 9.5mm of evaporation in scenarios E1 and E2 respectively. These range for Brazil from a minimum of 3.8 and 7.5mm in April to a maximum of 8.3 and 12.8mm in January for scenarios E1 and E2. As a general rule, evaporation increases more in December-February and less in March-May.

From the future evaporation analysis performed, there are a few important lessons learned: a) evaporation will likely rise throughout the country due to increased temperature, assisted by incoming short-wave radiation and wind speed, b) the North, the Northeast, and the Midwest will likely see a higher rise than the Southeast and the South, c) the North will likely have the highest rise per month, while the South the lowest, d) the North has its lowest evaporation in February, while the other four regions in June. Also, the North has its highest evaporation in September, the Midwest in October, and the other three regions in December and January, e) the Midwest has the highest increase for a single month, while the South the lowest, and f) evaporation increases more in December-February and less in March-May.

The aforementioned facts have certain important implications:

- Firstly, the rise of evaporation due to temperature increase once again shows that it should not be ignored in assessments of the water cycle of hydroelectric reservoirs, since it can make a difference.
- Evaporation rates are increasing more in the North and the Northeast, which is something that needs to be taken into consideration in the plans for new hydropower plants. Particularly,

the Northeast is already underperforming and this increase will only worsen the situation.

- Seasonality once again seems to be of importance and showing the differences within the country, since the highs and lows appear months apart, meaning that the country cannot be assessed as a whole, rather at the very least regionally.

- Finally, the evaporation rate is not going to increase uniformly throughout the year, which means that certain extremes within the year will likely become more extreme, which is a climate change trend.

7.4. Water footprint results and analysis

This part of the chapter is dedicated to water footprint results and analysis done for the five regions of Brazil for the period 2015-2049. It needs to be noted that some reservoirs with extreme water footprints are excluded from the graphs and analysis below, since they change averages by too much. The magnitude of the change is seen in results in chapter 6.
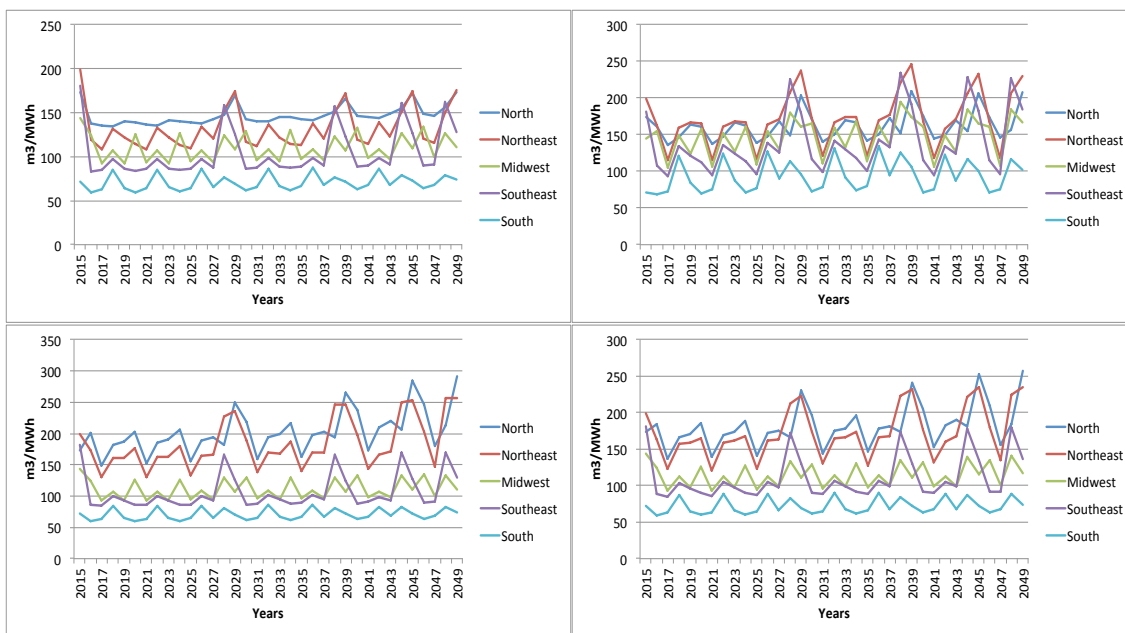
Figure 7.4 - Annual water footprint results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.4 shows the water footprint per region for the four different scenarios of precipitation (and river flows) for the period 2015-2049. The general trend in all four scenarios is that there is an increase in water footprint values for years with similar conditions, and this is due to the steady increase of evaporation, which in turn increases the consumption of water. In all scenarios the North has the highest water footprint, except for E1P2 where the Northeast has a higher one. Also, the Midwest's footprint is comparable to the Southeast's in all scenarios, even if in the third and fourth scenario the Midwest is experiencing a decrease in precipitation whereas the Southeast an increase. The reason why this is happening is because these two regions share hydrographic regions and river flow is more important that precipitation above the reservoirs. The South has in all four scenarios the lowest footprint.

	North	Northeast	Midwest	Southeast	South
2010-2015	153.2	153	156.3	117.5	78.5
2015-2049 E1P1	147	132.5	110.6	104.5	70.7
2015-2049 E1P2	162.1	171.5	147.1	139.9	93.9
2015-2049 E1P3	201.9	183.7	111.4	107.2	70.9
2015-2049 E1P4	181.6	172.9	114.2	111.2	72.1

Table 7.9 – Average annual water footprint (m^3/MWh) for the period 2010-2015 and for scenarios E1P1-E1P4 for the period 2015-2049

When comparing the average water footprint values for 2010-2015 and the four scenarios, shown in table 7.9, we can see that there are no drastic changes no matter the future of the climatic conditions. In scenario E1P1 where we have a drastic increase of precipitation in all regions, the water footprint of all regions decreases, especially in the Northeast and the Midwest, but the other regions have only mild decreases. In the rather

drastic decrease of precipitation E1P2 scenario for all regions, all footprints, apart from the Midwest, increase above the 2010-2015 period values. The reason the Midwest does not have a higher value is because the 2010-2015 period has not been great in the region, since it shares hydrographic regions with both the northern and the southern parts of the country, which suffered droughts at different times in the study period. In scenarios E1P3 and E1P4, the Midwest, Southeast and South have footprints similar to scenario E1P1 with elevated precipitation, which is logical at one hand since they are scenarios of elevated precipitation for these regions as well, but it also shows that after a point, the increase in precipitation does not make a big difference in water footprint values. The footprint values for the North and Northeast rise in these scenarios in correlation to precipitation decrease.

Figure 7.5 - Monthly water footprint results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.5 shows the monthly water footprint for the four scenarios for the 2015-2049 period. In general, the graphs have similar shaped lines. In the first two scenarios, water footprint values of all regions are closer in December-February than the second two scenarios, and in the second two

scenarios the values of all regions are further apart during June-August than in the first two scenarios. As was shown in figure 7.4 as well, the North and the Northeast have the highest footprint values throughout the year, with the Midwest and the Southeast following, and the South having the lowest values all year round. The Northeast, the Midwest and the Southeast have their lowest footprint values in June, the South in June and July, and the North in March. On the other hand, the highest values occur in September for the Northeast and the Southeast, in October for the Midwest, in December for the South, and in August for the North.

		North	Northeast	Midwest	Southeast	South
2010-2015	Max	232.6	188.5	199.3	126.6	106.2
	Av.	173.6	149.4	157.8	109.1	75.6
	Min	120.8	130.1	131.2	68.2	34.2
2015-2049 E1P1	Max	213	160.3	132.7	130	95.8
	Av.	158.7	126.8	109.6	99.3	68.5
	Min	112.4	111.4	83.4	64.5	33
2015-2049 E1P2	Max	232.8	203.8	174.2	170	123.1
	Av.	173.5	161.1	143.7	130	87.9
	Min	122.9	141.7	109.4	84.4	42.4
2015-2049 E1P3	Max	287	219.9	133.6	133	96
	Av.	213.9	173.8	110.2	101.6	68.6
	Min	151.5	152.9	83.9	66	33.1
2015-2049 E1P4	Max	258.7	207.3	136.9	137.6	97.2
	Av.	192.8	163.9	113	105.1	69.5
	Min	136.6	144.1	86	68.2	33.5

Table 7.10 – Average, minimum, and maximum monthly water footprint (m^3/MWh) for the period 2010-2015 and for scenarios E1P1-E1P4 for the period 2015-2049

In table 7.10 we can see, as was also shown in table 7.9, that the North and the Northeast have the highest water footprints per month in all scenarios, with the Midwest following, then the Southeast, and finally South with the lowest footprint. The North has in all scenarios the month with the highest footprint (August), whereas the South has the month with the lowest footprint (July). On the other hand, the North has its lowest footprint in March, whereas the South has its highest in December-January. This is interesting since these two regions reach their best and worst performances

in almost opposite months of the year. The Northeast has usually the month with the highest minimum footprint, followed closely by the North. The Midwest and the Southeast have very similar maximum footprints, and relatively similar averages as well, although the minimum values in the Southeast are lower. This happens because the change of seasons is more prominent in the Southeast. At the same time, the South has the lowest values altogether, with particularly low minimum values, faring by far the best than any other region. In general, the Northeast, the Midwest, and the Southeast have low values in March-May and June-July, reaching their highest values in September-February. The South follows a similar pattern delayed by 1-2 months. The North seems to follow its own pattern with high values in June-November and low in December-May.

From the future water footprint analysis performed, there are a few important lessons learned: a) there is a likely overall increase of water footprint in three scenarios, with a decrease only in the first scenario of extreme precipitation all over the country, b) the North and the Northeast have the highest water footprint values in all scenarios, and the South the lowest, c) the North has its lowest footprint in March, while the other four regions in June-July. Also, the North has its highest footprint in August, the South in December, and the other three regions in September-October, d) the North has the month with the highest footprint in all scenarios (August), while the South has the month with the lowest footprint (July), and e) the change of seasons is apparent in the South and the Southeast, to a lesser extent in the Midwest and the Northeast, while the North follows a different pattern than the other regions in March-August.

The aforementioned facts have certain important implications:

- Firstly, in all scenarios apart from the extreme precipitation one, the water footprint values seem to rise in all regions, which means that power plants become more inefficient as time goes by. For some that already have very high values, it should perhaps be assessed whether

to either increase the capacity of the plants or to use the water in different ways, investing at the same time in different electricity generation sources.

- Following the results of chapter 6, also in this analysis in all four scenarios the North and the Northeast have the highest water footprint values. The Northeast has traditionally had such issues due to water availability, but the power plants in the North are also underperforming, which means that if Brazil insists on building dams in the region, they need to be much better planned. On the other hand, the South once again shows to be the "golden standard".

- Once again, seasonality shows its value, which is something important to consider and plan around. Capacity would need to be distributed in such a way so as the system as a whole would not suffer during particular seasons due to concentration of capacity in a region.

7.5. Water budget results and analysis

This part of the chapter is dedicated to water budget results and analysis done for the five regions of Brazil for the period 2015-2049.
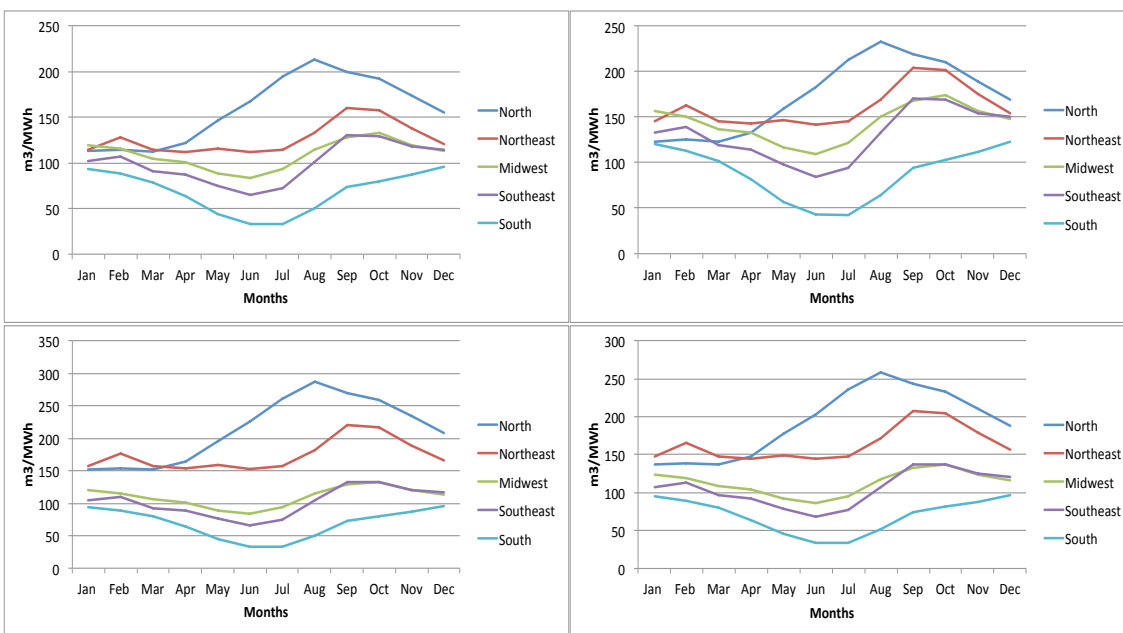
7.5.1. Volume level of reservoirs
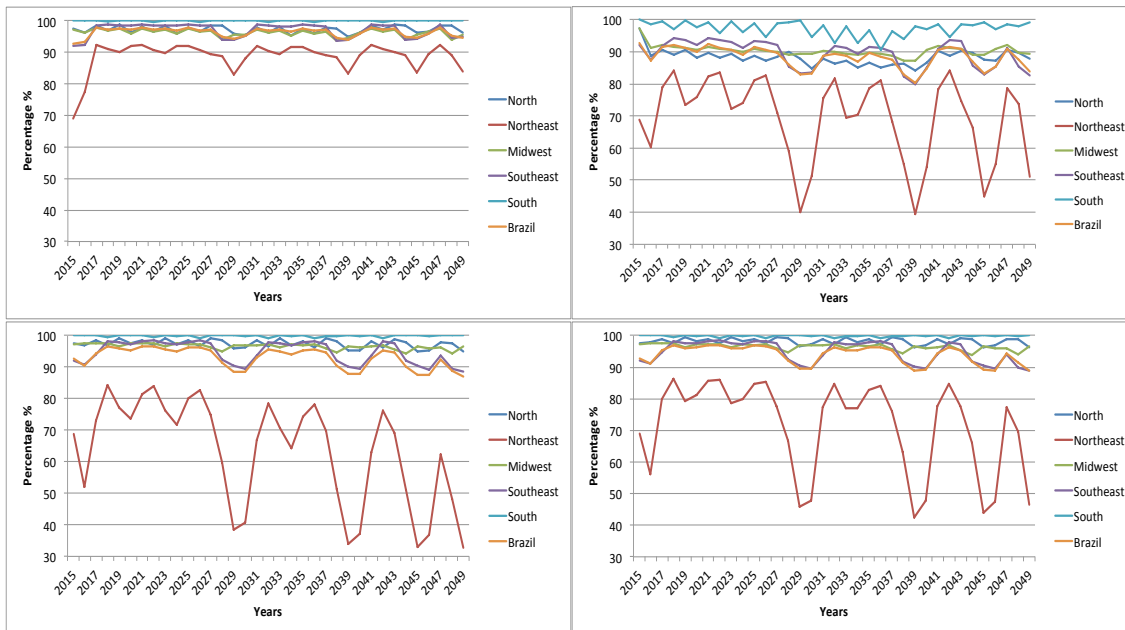
Figure 7.6 – Annual volume level of reservoirs results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.6 shows the progression of the overall level of the reservoirs in each region of Brazil for the period 2015-2049. As it was mentioned in the analysis in chapter 6 as well, the results here show regions as if they had a single reservoir each, so it should not necessarily be taken as a good indication if the levels seem high. Each region has several reservoirs and they all behave very differently to climatic changes. Nevertheless, these results in conjunction with results presented in figure 7.8, act as a first indicator about how much climate change would affect whole regions. In scenario E1P1, precipitation and river flows are very high, thus the volume level of the reservoirs is always equally high. All regions have levels well above 90% for the whole period, while the Northeast ranges from 83 to 93% from 2017 onwards. Scenario E1P2 has low levels of precipitation and river flows, so the levels of the regional reservoirs are decreased. The South does not suffer particularly, since the lowest annual value is 91%. The same holds true for the Midwest with a minimum of 87%. The North and the Southeast follow with 84 and 80% respectively. The Northeast in this

scenario suffers since it has values between 39 and 84%. After particularly bad years, the reservoirs need time to fill up (1-2 years). In scenarios E1P3 and E1P4, the North although it has decreased precipitation and river flows, it fares well with minimums of 95 and 96%. The Midwest and Southeast also fare well with 94 and 89% minimums. The Midwest has reduced precipitation, but the river flows that come from the South help in keeping the levels high. The Northeast fares once again badly in both scenarios with 33-84% and 42-86% levels respectively in the two scenarios. The South has levels of almost 100% with the slightest increase of precipitation. The increase of temperature, and hence evaporation, does not have much of an effect on this level of analysis, but rather more from an operational day to day standpoint.
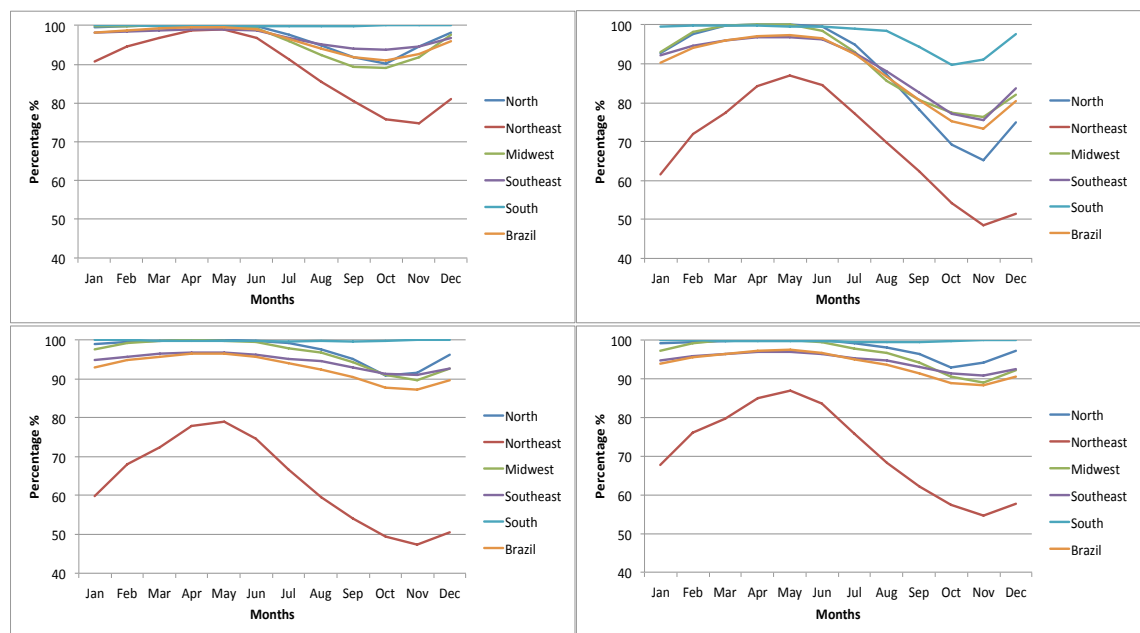
Figure 7.7 – Monthly volume level of reservoirs results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.7 shows the monthly progression of the overall level of the reservoirs in each region of Brazil for the period 2015-2049. In scenario E1P1, precipitation levels and river flows are very high, but even in this case, the level of the reservoirs can fall within the year itself. The North has a minimum of 90%, the Midwest 89%, and the Southeast 94% in the month

of October. The Northeast has the lowest values in October and November with 75 and 76%. The South is always close to 100%. In scenario E1P2, precipitation and river flows are decreased in the whole country, and so all regions have lower reservoir levels mainly in September-November, and to a lesser extent in December-February. In this case the lowest values occur in November for the North with 65%, for the Northeast with 49%, for the Midwest and the Southeast with 76%. Even the South has decreased reservoir levels, with the minimum occurring in October with 90%. In scenarios E1P3 and E1P4, the South is almost at 100% throughout the year. The North has a minimum in October with 91 and 93% respectively, and the Midwest and the Southeast have minimums with about 90% in November. The Northeast fares the worst in November with 47 and 55%, while never reaching 80% in scenario E1P3.

7.5.2. Percentage of days reservoir levels will likely be below minimum useful capacities
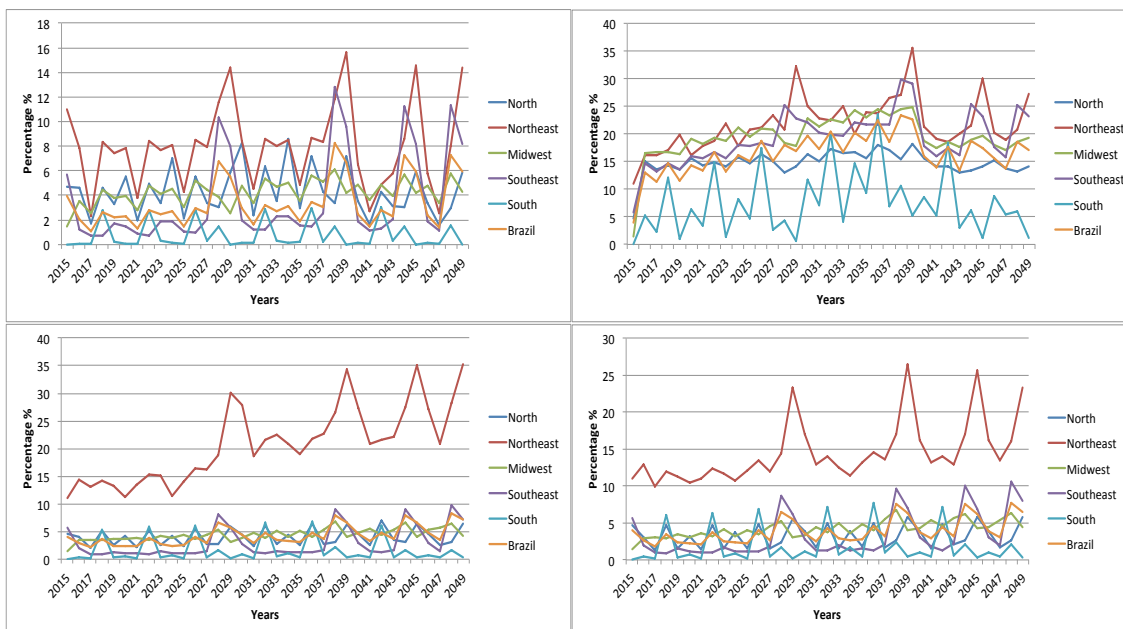
Figure 7.8 – Percentage of days reservoir levels will likely be below minimum useful capacity results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.8 shows the percentage of days within each year in the period 2015-2049 that the reservoir levels will likely be below the minimum useful capacity. This figure in conjunction with figure 7.6, acts as an indicator on how much climate change actually affects regions in the country. Although in figure 7.6 results show regions as if they had a single reservoir, in this case the number of days comes individually from reservoirs, therefore giving a better overall picture as to what is happening, taking into account the variability of effects on reservoirs within the same region. In scenario E1P1 of high precipitation, the North has a minimum value of 1.5% and a maximum of 8.5%, the Northeast 2.5-14.5%, the Midwest 2.5-6%, the Southeast 0.7-11.3%, and the South 0-3%. Unlike the case of reservoir levels, the percentage of days when reservoir levels will likely be below minimum useful capacities does progressively increase through the years, although not by a significant amount. In scenario E1P2 of low precipitation throughout the country, the minimum and maximum percentages are 13-18% for the North, 16-35% for the Northeast, 16-25% for the Midwest, 13-30% for the Southeast, and 1-18% in the South. These results show that the Northeast and the Southeast are the regions that would suffer the most in a scenario with low precipitation, and hence lower river flows. In scenarios E1P3 and E1P4, the percentages become 2-7% and 1-5% for the North, 11-35% and 10-26% for the Northeast, 3.5-6.5% and 3-7% for the Midwest, 1-10% in both cases for the Southeast, and 0-7% in both cases for the South. The increase of precipitation in the Southeast and South does not really change the percentages, so higher water availability of this magnitude does not improve the situation, which is at good levels. The difference of precipitation in the 2 scenarios does not largely affect the Midwest and the North either. The North has a slight change, whereas the Midwest due to its river flows even slightly improves. The Northeast however can suffer almost a 10% increase in particularly bad years due to a 0.5mm decrease in precipitation.
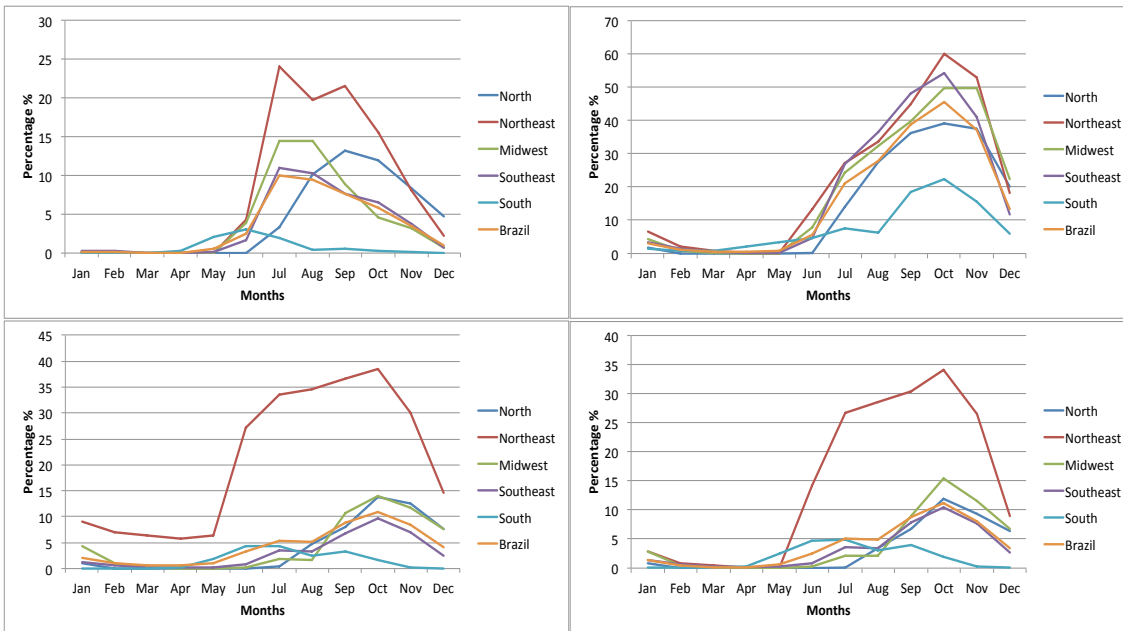
Figure 7.9 – Monthly percentage of days reservoir levels will likely be below minimum useful capacity results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.9 shows the monthly percentage of days within each year in the period 2015-2049 that the reservoir levels will likely be below the minimum useful capacity. The first observation here is that problems start occurring in June-August, getting worse in September-November and then dissipating in December-February. March-May is the season where all regions fare the best. In scenario E1P1, the North fares the worst in September with 13%, the Northeast in July with 24%, the Midwest in July and August with 14.5%, the Southeast in July with 11%, and the South in June with 3%. What becomes apparent from these results is that even if precipitation increases drastically in the whole country, that will not happen uniformly throughout all the seasons and there will be months in which reservoirs will not be full enough to produce electricity. In scenario E1P2, the drastic decrease or precipitation throughout the whole country causes big changes in the percentages with a maximum of 39% in the North, 60% in the Northeast, 50% in the Midwest, 54% in the Southeast, and 22% in the South. This increase also shifted the maximum observed values from June-August to October. This theme with October being the most prone month for reduced water availability is also the case with scenarios E1P3 and E1P4,

with the exception of the South, where July is the worst month. The highest respective to each scenario percentages are 14 and 12% for the North, 38.5 and 34% for the Northeast, 14 and 15.5% for the Midwest, 9.5 and 10.5% for the Southeast, and 4.5 and 5% for the South.

7.5.3. Difference of actual outflow and minimum safe outflow
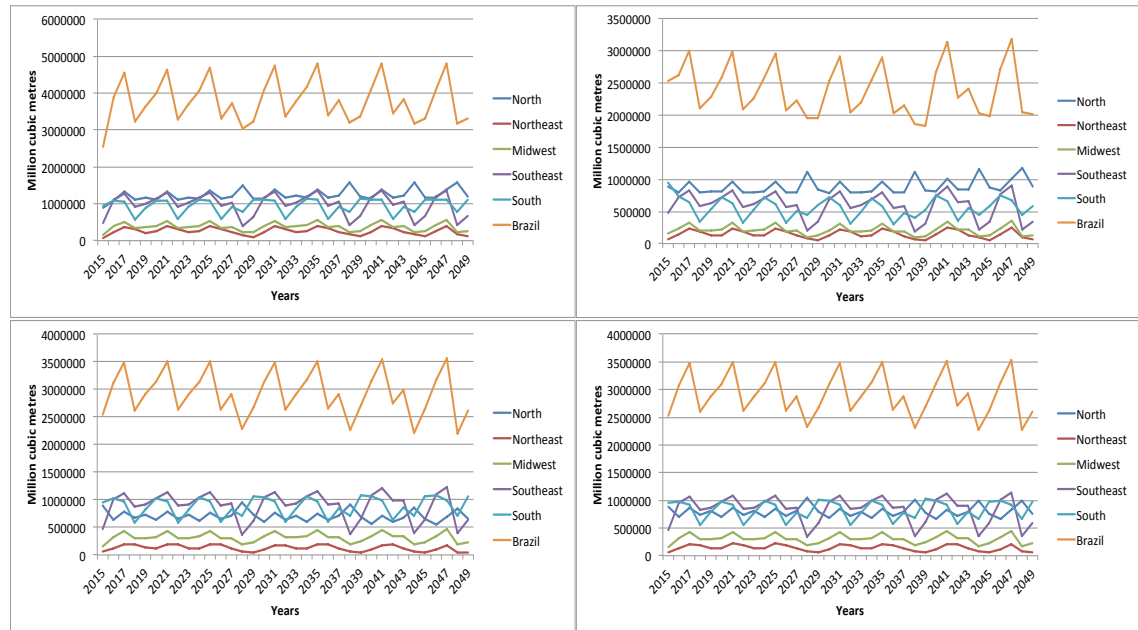
Figure 7.10 – Difference of actual outflow and minimum safe outflow results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.10 shows the difference between actual outflow from reservoirs and the minimum safe outflow for all regions of Brazil in the period 2015-2049. The accumulated minimum safe outflows exist in order to prevent a variety of issues downstream like affecting other hydropower plants, harming the environment, or affecting human populations. In theory, although with a high degree of reservation and although the values in these results are overestimated due to a number of reservoirs being on the same rivers, the difference of these two values is an indication as to when water availability for other purposes would be an issue, or when it is possible to perhaps utilize the excess water. In scenario E1P1, the water availability would be between 1,100 and 1,600km³ for the North, 105-400km³ for the Northeast,

220-550km³ for the Midwest, 400-1350km³ for the Southeast, and 570-1,140km³ for the South. In scenario E1P2, the values become 785-1,175km³ for the North, 45-245km³ for the Northeast, 90-355km³ for the Midwest, 200-895km³ for the Southeast, and 300-750km³ for the South. As explained, these values on their own are not very useful, but they do serve well for comparative purposes. Comparing the first two scenarios, we can see that regarding water availability changes, precipitation change does make a difference, although water is available even in an extremely low precipitation scenario for the whole country. The values in scenarios E1P3 and E1P4 range from 550-950 and 660-1040km³ respectively for the North, 37-195 and 53-215km³ for the Northeast, 190-460 and 175-440km³ for the Midwest, 365-1,225 and 345-1,135km³ for the Southeast, and 590-1,075 and 555-1,010km³ for the South.
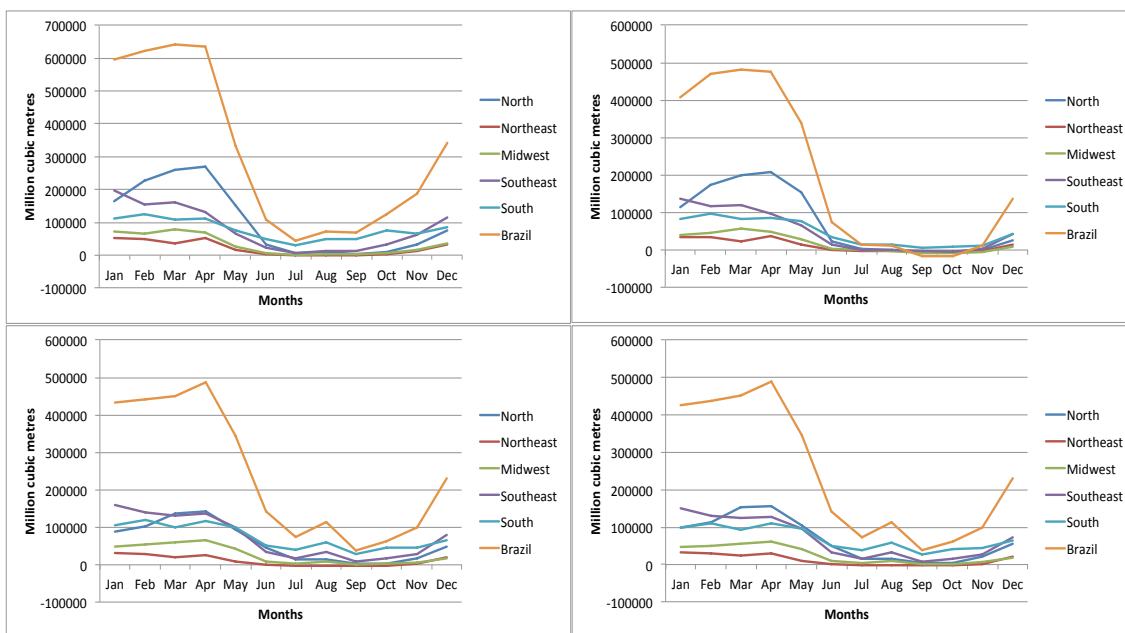
Figure 7.11 – Monthly difference of actual outflow and minimum safe outflow results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.11 shows the monthly difference between actual outflow from reservoirs and the minimum safe outflow for all regions of Brazil in the period 2015-2049. Although the results presented in figures 7.10 and 7.11 are exaggerated since some reservoirs are on the same river and restrictions

might apply, figure 7.11 nevertheless makes it clear that in June-November, water availability is a big issue for the whole country and it would not be wise to use it for other purposes, since this would put electricity generation in jeopardy, not mentioning other environmental and social issues that might occur. This only applies for reservoirs that are in theory only used for the purpose of electricity production. For reservoirs that are not solely used for this purpose, the debate is difficult, since prioritisations will need to be made, which is perhaps even an ethical matter, or at the very least a political one. In scenario E1P1, the water availability would be between 3 and 33km^3 respectively in September and November for the North, -0.8 and 53km^3 in July and April for the Northeast, 0.5 and 78km^3 in July and March for the Midwest, 6 and 160km^3 in July and March for the Southeast, and 30 and 125km^3 in July and February for the South. In scenario E1P2, the values become -6.5 and 208km^3 in October and April for the North, -4.2 and 35km^3 in October and April for the Northeast, -8.7 and 58km^3 in October and March for the Midwest, -4.6 and 137km^3 in October and January for the Southeast, and 5.7 and 97km^3 in September and February for the South. The negative values show that in this period there will not be enough water to satisfy the needs downstream. In scenario E1P3, the values become 3 and 140km^3 in October and April for the North, -3.8 and 27km^3 in August and February for the Northeast, 0.7 and 59km^3 in September and March for the Midwest, 8.5 and 160km^3 in September and January for the Southeast, and 28 and 119km^3 in September and February for the South. Finally, in scenario E1P4, the values become 4.2 and 157km^3 in September and April for the North, -2.6 and 33km^3 in July and January for the Northeast, 0.7 and 62km^3 in September and April for the Midwest, 7.5 and 150km^3 in September and January for the Southeast, and 25 and 111km^3 in September and February for the South.

7.5.4. Difference between precipitation and evaporation
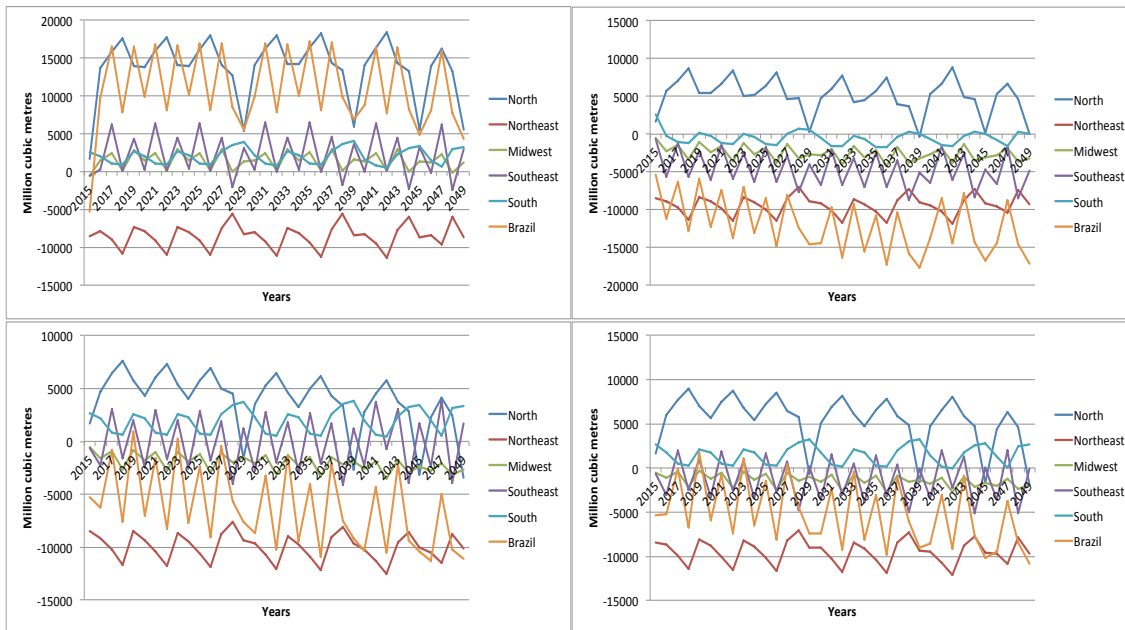
Figure 7.12 – Difference between precipitation and evaporation results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.12 shows the difference between precipitation and evaporation for all regions of Brazil in the period 2015-2049. Although the volume of water from precipitation above a reservoir and evaporation from a reservoir cannot be compared with the volume of water coming from river flows in the long-term, their importance cannot be overlooked for the short-term every day operation of the reservoirs/power plants. Evaporation as already shown can serve as an indicator for the efficiency of hydroelectric power plants through the water footprint, but also the difference between precipitation and evaporation can show trends that could prove to be valuable for operation purposes. In scenario E1P1, precipitation values increase every year, but at the same time, due to the increase of temperature, evaporation increases at a slightly higher rate. So, although precipitation is always higher that evaporation in the country, precipitation is not gaining traction after a first surge in values. Northeast has higher evaporation throughout the whole period, and even the Southeast and the Midwest have years that evaporation is higher than precipitation despite a general large increase of

precipitation during the 35-year period. In scenario E1P2, which is based on low precipitation all over the country, we can see that the Midwest, Southeast, and the Northeast have higher evaporation than precipitation every year for 35 years. Also, the South has higher evaporation for most of the period and those values are more elevated than when precipitation is higher. Only the North has higher precipitation, apart from 1 year when evaporation is higher. The general trend is that precipitation is losing ground in comparison with evaporation, which could mean more days when hydro plants would have operational issues. In scenarios E1P3 and E1P4, there is also a trend where precipitation is losing ground compared to evaporation overall, due to the North and the Northeast. The South manages to have higher precipitation throughout the period in both scenarios, whereas the Southeast in the 35-year period has a trend where evaporation is growing faster than precipitation, and so especially in scenario E1P4, there are fewer years where precipitation is higher as time goes by.
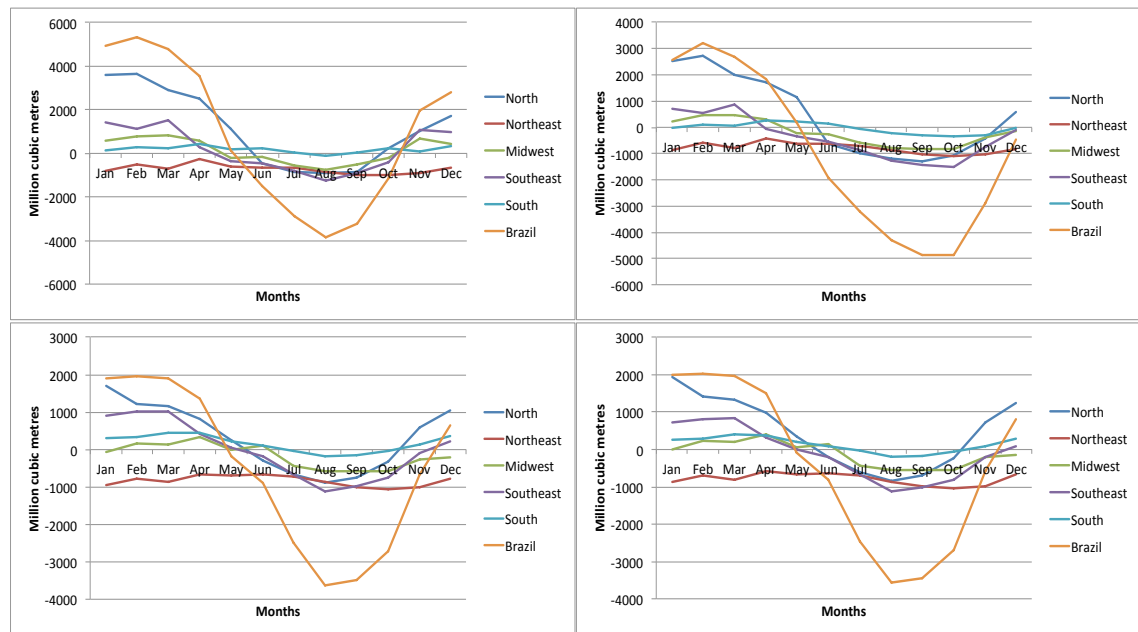
Figure 7.13 – Monthly difference between precipitation and evaporation results from scenarios E1P1 (top-left), E1P2 (top-right), E1P3 (bottom-left), and E1P4 (bottom-right) for the period 2015-2049

Figure 7.13 shows the monthly difference between precipitation and evaporation for all regions of Brazil in the period 2015-2049. This figure is yet another indication that seasonality plays an important role for hydropower. In all scenarios from May to at least October evaporation is higher than precipitation in the country as a whole, with August and September having particularly elevated evaporation in relation to precipitation. In scenario E1P1, the North, the Midwest and the Southeast have high precipitation in December-February and come May, evaporation takes over until October. The South's values are very stable throughout the year, with precipitation being slightly above evaporation, apart from August. The Northeast has also stable values throughout the year, where evaporation is always higher. In scenario E1P2, the North, the Midwest, and the Southeast follow a similar trend as in E1P1, but with values of precipitation being lower overall and values of evaporation being slightly higher. The difference is that precipitation does not take over until November or even December. The South does not have large differentiations throughout the year, although in this case, evaporation is slightly higher from July to December. The Northeast has a similar trend with slightly elevated evaporation. Scenarios E1P3 and E1P4 show very similar seasonality patterns, with the North and the Southeast having higher evaporation from June to October and November respectively, while the Midwest has higher precipitation in January again in this case. The South has once again a very uniform trend and slightly higher evaporation from July to October. The Northeast follows a similar trend in all scenarios, with uniformly higher evaporation in relation to precipitation.

From this future water budget analysis performed for most hydroelectric plants/reservoirs (data permitting) in Brazil, these are the most important lessons learned: a) the South would not suffer much in a decreased precipitation future, while the Northeast has water and electricity issues even if precipitation increases in the region. The Northeast and the Southeast are the regions that would suffer the most in a scenario with low precipitation. Also, an increase of precipitation in the Southeast and the

South does not significantly improve adequate water availability levels for electricity production, since these two regions fare well in general anyway, b) seasonal water availability is important, since even precipitation increase will not occur uniformly through the seasons and some months will not fare well. Annual availability can be deceiving in results and for modelling purposes, c) the days when reservoir levels are likely to be below minimum useful capacity progressively increase through the years, even for an increased precipitation future (although not significantly), which has to do with seasonal water availability, d) issues start occurring in June-August, getting worse in September-November and then dissipating in December-February, while in March-May all regions fare well. October is the month most prone to reduced water availability for four regions, while for the South it is July, and e) evaporation and precipitation from and to the reservoirs do not make a big difference for long-term analysis, but rather for short-term, operational purposes. Precipitation is losing traction in comparison to evaporation in all scenarios, even in the scenarios where it increases, which could make a difference operation-wise, especially in June-November.

The aforementioned facts have certain important implications:

- Firstly, the South performs very well under all precipitation projections, and along with its very good water footprint values, it means that the region's hydropower potential could and probably should be further exploited.
- Following the opposite direction, the Northeast seems to continue to struggle and along with its bad water footprint values, it means that apart from possible exceptions, plans for hydropower plants in the regions should be abandoned and investment should be directed towards wind and solar.
- During a drought, it seems that apart from the Northeast, the other region that can suffer the most is the Southeast. Taking into account the region's population and importance for the country's economy, it

would perhaps be a good idea for the region to be better connected to the rest of Brazil's regions and also invest in wind and solar to a certain extent.

- Annual values of water availability can be very deceiving, since even in years where precipitation increases, there are months that will see a precipitation decrease. This is represented well by the days when reservoir levels are likely to be below minimum useful capacity, which increase as time goes by, even in an increased precipitation future. This is very important for modelling purposes and it shows the need for fine temporal analysis.

- March-May are the months that water is affluent enough to consider other uses, while October seems to be the month where the whole country, apart from the South, will need to be in a state of caution in terms of water availability for hydropower, and possibly in general.

- Evaporation rates are at present higher than precipitation rates, with the gap widening in the future. In terms of modelling this is important, especially in June-November when the river flows slow down and the difference between evaporation and precipitation is becoming more evident and can make a difference in terms of reservoir operation.

7.6. IDA3 model results and analysis

Section 7.6 is the final part of the analysis and it is an example of linking the water model presented in this thesis with an energy-water-land model (IDA3). The link was based upon changing capacity factors for hydroelectricity, which in turn were based on future water availability changes. To achieve this, IDA3 was modified to account for new hydropower capacity factors. There are many possible combinations for scenarios, and three of them will be presented here in order to assist with the discussion in chapter 8. It needs to be noted that this link between the models is a first step towards creating a combined method for addressing the WEN, and it serves merely as an example for the purposes of this thesis. Also, it needs to

be taken into account that the detail of the water model's results is not well represented in this example, since regional data was used, although IDA3 is able if modified to account for finer scale data. Nevertheless, IDA3 results will provide a different and much needed angle in the WEN discussion of Brazil's hydropower. Finally, it needs to be mentioned again that energy storage in regards to hydropower is inherently taken into account in the water model, which is done in the water budget part, hence it is indirectly present in these results.
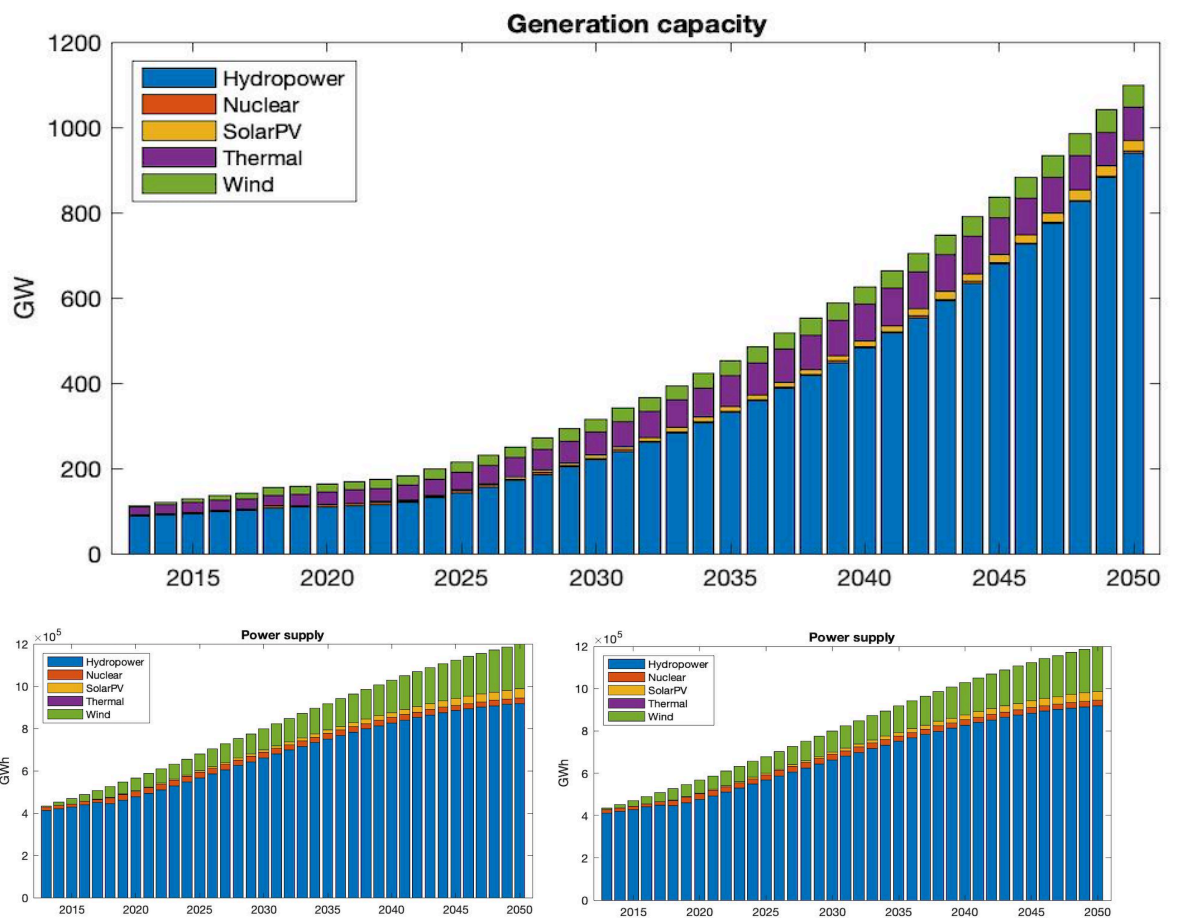
Figure 7.14 – National generation capacity, and power supply under climate scenarios E1P1 (bottom-left) and E1P2 (bottom-right) for the period 2013-2050, under an energy scenario of maximum hydropower exploitation and investment in wind and solar energy

Figure 7.14 presents a future where hydropower is exploited as much as possible, increasing its generation capacity fourfold, while at the same time

there is some investment towards mainly wind, but also solar energy. Thermal energy remains in the mix, but its capacity does not increase much until 2050. The bottom-left and bottom-right parts of the figure present the power supply until 2050 under a climate of heavy precipitation (and therefore high water availability) and under a climate of low precipitation. We can see that the power supply does not change almost at all visibly and the actual data changes are minimal. This has to do with the fact that the capacity of hydropower is so high that although it is affected by water availability, nevertheless it never loses the ability to satisfy demand, especially since as time goes by the system is assisted by wind and to a lesser extent by solar energy. Due to the rules set by the model, thermo plants do not need to operate due to sufficient supply by hydropower, wind, solar, and the country's two new nuclear power stations that remain in operation and steadily supply electricity.
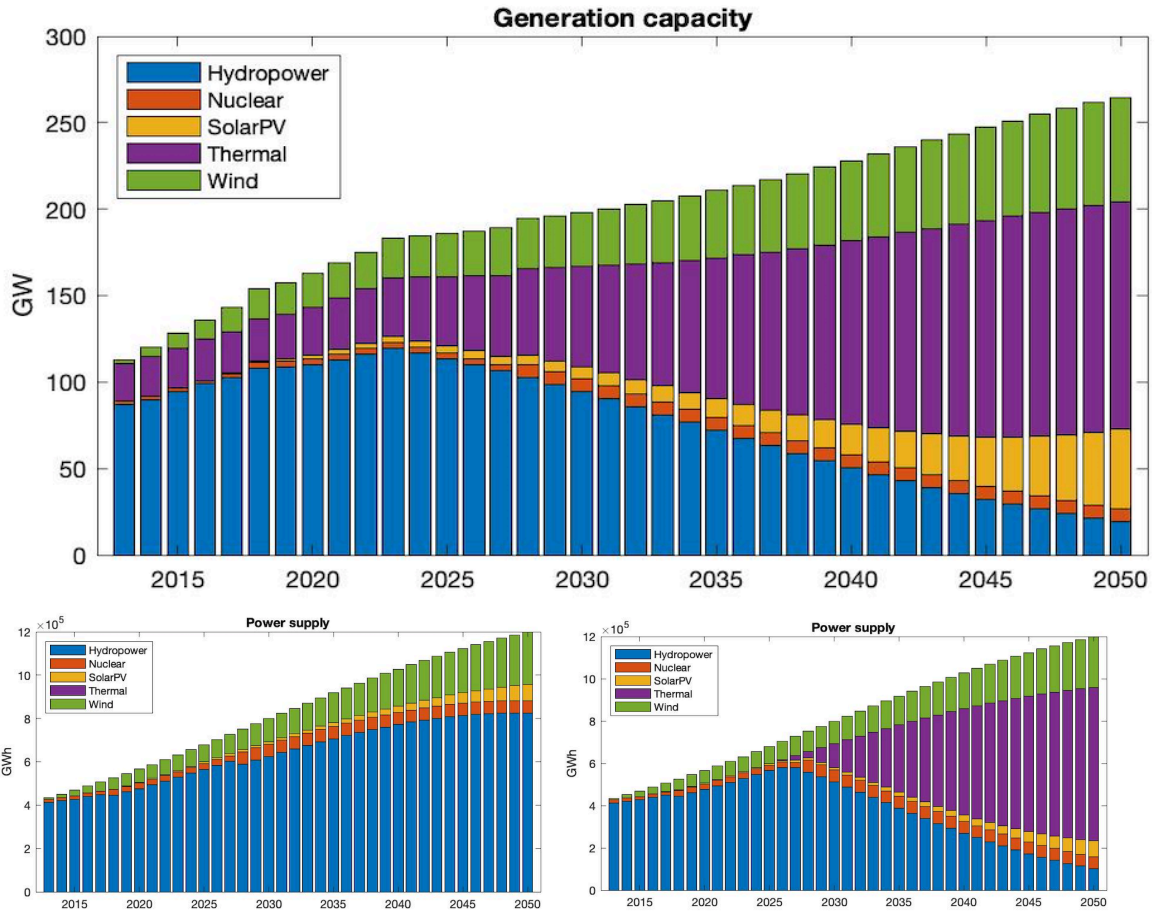
Figure 7.15 – National generation capacity, and power supply under climate scenarios E1P1 (bottom-left) and E1P2 (bottom-right) for the period 2013-2050, under an energy scenario of balanced mix that accounts for water availability

Figure 7.15 presents a future where there is a more balanced mix of capacity, with a slight increase of hydropower at first, but a steady decrease until 2050. At the same time there is a steady increase of wind, solar picking up after 2030, and an increase in thermal power to account for the loss of hydropower. The power supply under the high precipitation scenario shows that although hydropower is losing capacity, it still provides most of the electricity for the country, stabilizing around 2040, while wind is steadily supporting the system more and more. At the same time solar power is picking up after 2030, as does nuclear in 2028 with the introduction of more capacity, and both of them steadily assist the system from about 2040 onwards. On the other hand, the power supply picture

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under a low precipitation scenario is completely different. As hydropower capacity goes down, so does its power supply, which means that thermal capacity picks up to satisfy demand. Wind, solar, and nuclear do not see any change.
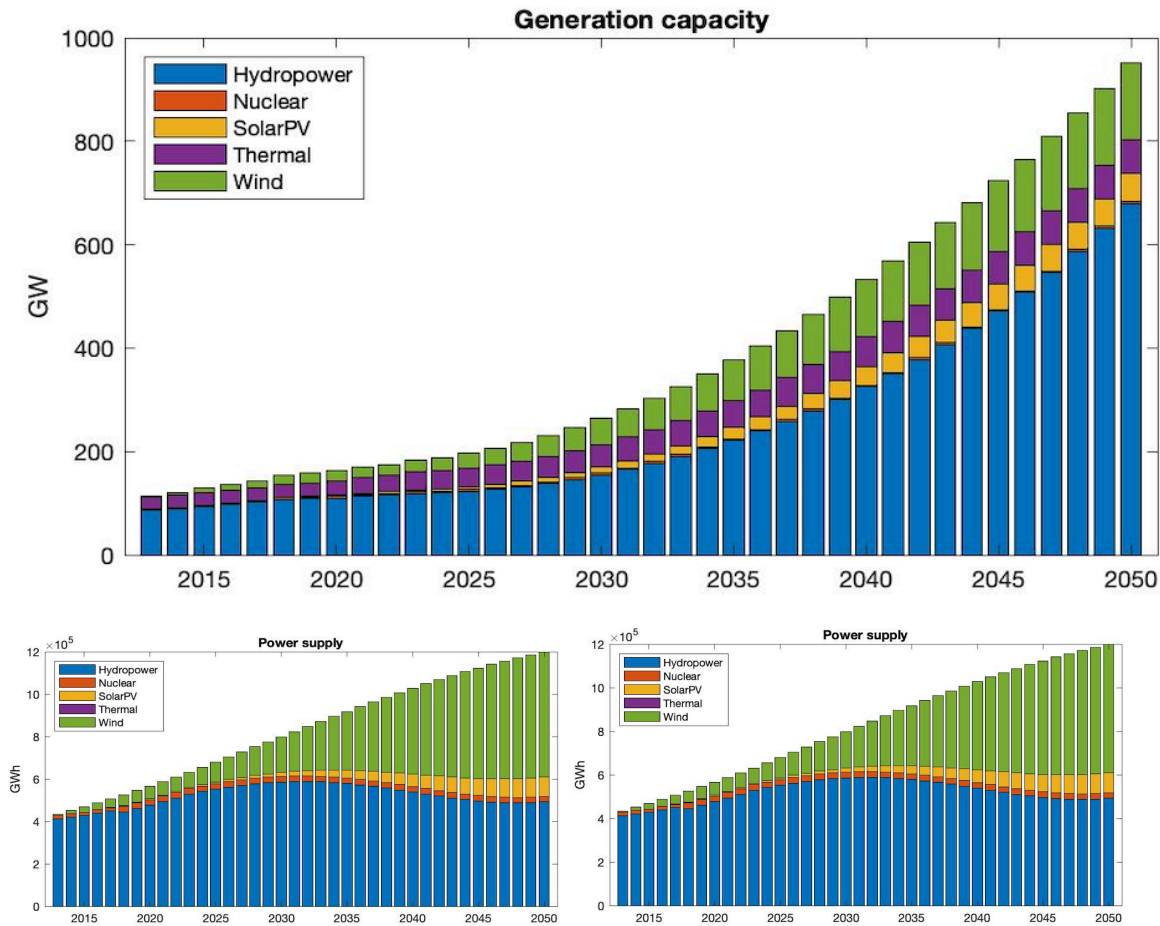
Figure 7.16 – National generation capacity, and power supply under climate scenarios E1P1 (bottom-left) and E1P2 (bottom-right) for the period 2013-2050, under an energy scenario of heavy investment on wind and solar, and an increase of moderate increase of hydropower, with a simultaneous shift to biomass

Finally, figure 7.16 presents a future where there is an increase of hydropower, although more moderate than in figure 7.14, and a high increase of wind generation capacity, as well as a solar generation capacity increase after 2030. The thermal power capacity remains constant, as does nuclear. Here, both high and low precipitation futures are again, as in

figure 7.14, almost identical with minimal data changes. The reasons are similar to the first case, since the increase of hydropower capacity, along with the high increase of wind power allow for the system to not have a problem under a low precipitation future. In the model, wind and solar generation have priority in producing power, therefore the remaining demand can adequately be filled by hydropower and nuclear, while thermal power is not required at all.

In conclusion, it seems that the system does not suffer from water availability when the capacity of hydropower increases while at the same time it is assisted by mainly wind, but also solar energy. Wind and solar have priority in generation, assisted by hydropower. In such scenarios, water availability seems to not be an issue, and thermal power is usually not required. It needs to be of course noted that a scenario with such a high increase of hydropower capacity is not practically achievable for a variety of financial, environmental, and political reasons that will be discussed in chapter 8. On the other hand, if hydro capacity remains constant (or decreases as shown here), it would not necessarily be a problem in a high precipitation future (which is unlikely though), but under low precipitation hydropower plants would not produce adequate electricity, and thermal energy would be required. In this case, there are issues that will be raised like CO_2 emissions, but also elevated water withdrawal, which might not be possible in times of drought, which in turn would cause a lot of problems, and finally demand will not be met.

This energy analysis has certain important implications:

- Firstly, these energy scenarios showed that Brazil would not have serious electricity supply issues if investments are targeted towards more hydropower, assisted by wind and solar. It seems that the country is more susceptible to electricity disruptions under a future where there isn't investment on hydropower and the investment on wind and solar is minimal. However, it needs to be noted that wind

generation is not stable, and also high investments are needed. Incentives for wind investment have been the case in recent times (as is discussed in chapter 8), but even more incentives are required to account for a future of low water availability.

- Taking into account the results from the water model as well, it becomes clear that even in scenarios where investments are made towards more hydropower, this would need to be done taking seasonality into account, the potential of regions, but also the interconnections between regions. The Northeast is far from ideal in terms of hydropower, the North has potential in theory but thorough planning is required, the Southeast already has a high concentration of supply but also has the highest demand, while the South is the region with the best hydropower potential in terms of water availability.

- A more detailed analysis by an energy model coupled with the detailed results by the water model would provide more specific recommendations, but this goes beyond the scope of this thesis. However, it was shown that it is possible to link the water model designed in this thesis with a model mainly concentrated on energy.

7.7. Summary

This chapter in the first instance revolved around the development of climate scenarios in order to develop future projections for the water model analysis. Then the energy scenarios to be used were introduced, based on work by Senger & Spataru (2015), which included analysis for the regional capacity factors for hydropower in Brazil. What ensued the climate and energy scenarios were the evaporation, water footprint, and water budget analyses for the period 2015-2049. The analysis presented is for the regional level, although the model can also estimate values in a state and individual reservoir level. Eight climatic scenarios were devised, of which four were used for the water model analysis presented. The way the climatic scenarios were constructed is a novel way in order to account for climatic variations at

a daily time step, droughts, and individual reservoir variability. Finally, three different energy scenarios produced by the linking of the water model with IDA3 are presented and future capacity and power supply are discussed.

The development of climate scenarios is a difficult process, and water availability in particular is normally portrayed through a lens of averages and trends, which is an inadequate representation and does not account for extreme events like droughts. This is in part understandable due to the meteorological phenomena in Brazil, which include the ENSO, the La Niña, the tropical North Atlantic SST, and the ITCZ. These phenomena deem climate scenarios in Brazil a near impossibility, and projections for the South American region in general show that. Nevertheless, GCMs were used and extreme examples of them were chosen to devise the climate scenarios for this thesis. At the same time, projections from literature were also used to account for different possibilities. All the projection data needed to be downscaled in order to be used in the model analysis at a reservoir level. The projections were done in two steps, firstly changing temperature, wind speed and incoming short-wave radiation, and secondly changing precipitation and river flows. In total, there were eight different scenarios, of which four were used in the analysis.

Although the main focus and also analysis of this thesis revolves around the water model, it was nevertheless deemed important to show how exactly a link of the water model with another model that accounts for energy is achievable. For this purpose, energy scenario work done in literature is presented, followed by the scenarios to be used in this analysis. The link between the water model and IDA3 is accomplished through capacity factors, and so this subsection includes a comparison of regional capacity factors for hydropower used in the original run of the IDA3 model, as well as the capacity factors stemming from the water model. This comparison shows that if analysis and projections for the future are to be done at minimum annually, it is not logical to assume a declining capacity factor for a

prolonged period of time, since nature does not work like this and water availability (and hence capacity factors) are fluctuating a lot through the years, which is something that needs to be taken into account no matter the difficulty this can pose for the purposes of energy models.

The first part of analysis showed that evaporation will likely rise in the whole country, due to temperature, incoming short-wave radiation, and possibly wind speed increases. The highest increases will likely occur in the North, the Northeast, and the Midwest of the country, with the North having the highest monthly increase and the South the lowest. The time of the year when evaporation has its highest and lowest rates is important in terms of water footprint and for the water budget analysis, and the projections show that the North has its highest evaporation in September and the lowest in February, the Midwest its highest in October and its lowest in June, while the other three regions have their highest in December and January and their lowest in June. Compared to 2010-2015 values, the Midwest in the 2015-2049 period saw the highest increase for a single month, while the South the lowest. Finally, the increase of evaporation does not occur uniformly throughout the year, it increases more in December-February and less in March-May, which means that it could accentuate extreme weather events in December-February.

The second part of the analysis was the estimation of water footprint, and it showed that due to the rise of evaporation, and also the climate in general, the overall water footprint will likely rise in three of the scenarios, with a decrease only occurring in the first scenario because of the extreme precipitation, which also means more power generated. In all scenarios, the North and the Northeast had the highest water footprint, while the South had the lowest. Perhaps even more importantly than the evaporation analysis, in the case of the water footprint the seasonal variation shows clearly when electricity generation is more efficient in terms of water. The North has a low footprint in March and a high one in August, while the other regions have a low footprint in June-July and a high one in

September-October. This shows that August-October are the months that the hydropower plants are the least efficient all over the country, since they consume the most water per electricity generated. August is the month that sees the highest footprint in the country, occurring in the North, while the lowest occurs in July in the South. This drop in efficiency poses serious energy security risks, as the water budget analysis shows.

The third part, water budget analysis, showed that the South fares relatively well even in a future with decreased precipitation, while on the contrary the Northeast is problematic even if precipitation increases. In a scenario where precipitation, and therefore river flows, decreases, the Northeast and the Southeast are the regions that would suffer the most. On the other hand, even if precipitation increases on average in the Southeast and the South, it would not necessarily significantly improve water availability for electricity generation, since these regions fare well most years, and increase in average precipitation will not stop droughts all together, so some years this can affect the Southeast in particular. Once again, seasonal water availability is a more important indicator than annual availability, since the increase and decrease of precipitation does not occur uniformly throughout the year, affecting some months more than others. This is something that needs to be taken into account when modelling water availability in energy models. It is also for this reason that the days when reservoir levels are below minimum useful capacity progressively increase in the 35-year study period, even in the increased precipitation scenarios. Although these changes are not significant, they cannot be ignored entirely. In general, issues with water availability start occurring in June-August, aggravating in September-November, with October being the most prone month for all regions apart from the South, and dissipating in December-February. In March-May all regions fare well. Finally, precipitation is losing traction compared to evaporation, and although the difference between the two does not make a big difference for long-term modelling purposes, it is important for operational purposes, especially in June-November.

The final part of the future analysis was the presentation of generation capacity and power supply under three different energy scenarios. The analysis showed that the Brazilian system would not suffer particularly in the case where investments were made towards hydropower (as has been the case historically), while at the same time investing mainly in wind, but also in solar energy. The increase in hydropower capacity would to a certain extent alleviate water availability issues, because it is unlikely that the whole country will suffer from droughts at the same time, therefore capacity in other regions will be able to account for water availability issues elsewhere. At the same time, when this is not possible, wind and solar energy, which also would have priority in terms of generation, would greatly assist the system by taking away some of the burden laid upon hydropower. In such a case, where investments on hydropower, wind and solar continue, the need for thermal power production could be greatly minimized. However, in a scenario where hydropower capacity decreases, while there is minimal investment in wind and solar, thermal plants would slowly take over, especially in times of decreased water availability, which means that CO_2 emissions would greatly increase. At the same time, it is possible that decreased water availability would cause water withdrawal issues for thermal plants, which means that blackouts will be a common phenomenon. Overall, it seems that investment in hydropower, wind and solar is the solution in dealing with water availability issues, although further research on various aspects is required.

The way the scenarios were constructed, allowed for an analysis of different future projections that are based on detailed climatic data, specific for each reservoir in the analysis based on their locality and past behaviour. Both political and hydrographic boundaries were employed wherever necessary, and the final results are presented in political boundaries in order to allow for a link with energy models. The downscaling of projections at this scale (all hydropower plants in Brazil) is a novel contribution, and the analysis that followed presents results that shine a light in issues that are important

for the future of the Brazilian electricity and water sectors. The following chapter is an in detail discussion about issues that have been raised in chapters 6 and 7, and what their significance is for Brazil, but also in general.

Chapter 8. **Discussion**

After the detailed analysis of chapters 6 and 7, it is time to discuss in more detail about some important results, methods and data issues, issues that can affect hydroelectricity but were not included in the analysis, and finally conclude with a policy discussion about the vulnerabilities and potential of the country in terms of water and electricity and formulate more specific recommendations.

8.1. Discussion of important results

8.1.1. Evaporation results discussion

As of early 2019, the only existing analysis for all hydroelectric plants/reservoirs in Brazil is that of ONS from 2004. Since the climate is changing and evaporation is a dynamic process, the importance of estimating it anew was of great importance. The results showed that the evaporation of some reservoirs estimated in this research was closely related to that by ONS, however other reservoirs had a significant difference of even 300mm per year, which shows the importance of having frequent evaporation estimations.

Based on the 2010-2016 analysis performed, the Northeast of Brazil experienced the highest rate of evaporation per year, with values of 1618-1732mm. The Midwest had the second highest rate with 1500-1590mm, the North was third with 1412-1486mm, the Southeast fourth with 1345-1459 mm, and the South was fifth with 1133-1301mm. The values for Brazil were 1377-1447mm. The values for the Southeast and Brazil are similar, which is understandable, since half of the reservoirs of the country are in the Southeast, so the country's values are affected.

These values give an indication as to where evaporation is more of an issue, but even more importantly, seasonality is something that needs to be taken

into account when analysing evaporation, and in extension water availability. Evaporation is not uniform within the year, nor is it uniform at all sites. The size of a country like Brazil cannot be discounted when analysing water availability. The North experiences monthly evaporation rates of 106-142mm, the Northeast 97-142mm, the Midwest 89-157mm, the Southeast 69-151mm, and the South 37-158mm. Brazil's average values are 69-151mm. The further south we move, the more seasonality plays a role, which is an important aspect to be taken into account. Also, the highs and lows in different regions appear months apart, which means that the country cannot be assessed as a whole, rather at least regionally, and if possible each reservoir individually, since even within a region reservoirs can have quite different evaporation rates.

In the future analysis performed, both scenarios for evaporation were based on an increase of temperature, wind speed and incoming short-wave radiation. Consequently, evaporation also increased, since it is affected by the aforementioned factors. The difference of evaporation of scenario E2 compared to E1 is in the order of 3-4mm every year for all regions except the South, where the increase was 2-4mm. In the 35-year period projection, evaporation increases the most in the North, and the overall difference between the two scenarios is 103mm. On the other hand, the least increase between scenarios occurs in the South with 77mm. In general, for a 1°C increase in temperature, a 0.5 MJ/m^2 increase in incoming short-wave radiation, and a 0.5 m/s increase in wind speed, the average increase of evaporation is 90mm.

Evaporation was expected to rise, but the interesting aspect is the seasonal changes. The average rise per month varies from a minimum of 3.38mm in the South to a 4.41mm in the North, while the country average is 3.9mm. The North had increases from 3.7mm in February to 5mm in August, while the South from 1.75mm in June to 4.6mm in February. Also, the maximum evaporation occurs in December or January for the Northeast, Southeast and South, October for the Midwest, and September for the North.

The evaporation results showed that evaporation is an important aspect of the water cycle, and especially for the purpose of hydropower analyses it needs to be estimated in detail. Seasonality is an important aspect that needs to be taken into account when deciding when future plants will be sited, especially taking into account that the evaporation rate is not going to increase uniformly throughout the year, making extremes through the seasons more prominent. As the situation stands for the time being in Brazil, the Southeast seems to have a lot of reservoirs, which alone is an important factor in times of droughts. Also, the Northeast even with just an evaporation analysis seems to not be ideal for the existence of hydropower plants. On the other hand, the South seems to be an ideal region. The North's and the Northeast's evaporation rates will likely increase more than in other regions, a factor that needs to be taken seriously into account for future planning, especially for the Northeast.

8.1.2. Water footprint results discussion

Based on the 2010-2016 analysis performed, the average water footprint for the North is about 150 m³/MWh, while reaching a high in 2016 with about 235 m³/MWh. The values for the Northeast were around 125 m³/MWh in 2010-2011, but have risen since to a high of 230 m³/MWh in 2016. The Midwest also has an average close to 150 m³/MWh, reaching a high in 2016 with 200 m³/MWh. The Southeast has an average of about 90 m³/MWh until 2012, and reaching a high in 2015 with 180 m³/MWh. Finally, the South has a relatively constant average with about 70 m³/MWh, reaching a high in 2012 with 100 m³/MWh. Some reservoirs have extreme water footprints, as shown in chapter 6, which has to do with the relationship between reservoir area and installed capacity. As was the case with evaporation, consequently seasonality is important in water footprint as well.

Since the temperature, along with wind speed and incoming short-wave radiation, is set to increase in the future scenarios used, the same holds true for water footprint. In all scenarios investigated the North had the highest

water footprint values with 147-201 m³/MWh, except for scenario E1P2 where the Northeast surpassed it. The Northeast has values of 132-184 m³/MWh, the Midwest 110-147 m³/MWh, the Southeast 105-140 m³/MWh, and the South has in all four scenarios the lowest footprint with 71-94 m³/MWh. Once again, seasonality is important and the Northeast, the Midwest and the Southeast have their lowest footprint values in June, the South in June and July, and the North in March. On the other hand, the highest values occur in September for the Northeast and the Southeast, in October for the Midwest, in December for the South, and in August for the North. Only if precipitation increases drastically could water footprint values decrease in the future.

The water footprint results showed that there is no "normal" footprint value that can be used for all reservoirs. On the contrary, each reservoir should be assessed individually, which has the hidden advantage of making it possible to make accurate comparisons with similar plants and their performance. One important finding was that the inundated area in relation to electricity produced is the key to designing an efficient reservoir/power plant. The South's footprint values are ideal compared to all other regions in Brazil and they should be taken as the golden standard and something to strive for. The Southeast also normally performs well, but in times of droughts, water availability causes a large increase in footprint values, which also affects the country as a whole. The North and the Northeast do not have good water footprint values compared to other regions, which means that they suffer during times of reduced water availability, but also that the plants themselves were not built to be particularly efficient. Future plans should undergo more strict assessment. Furthermore, except in an extreme precipitation future, water footprint values for existing plants will most likely rise in all regions, which can magnify problems that some plants already have, hence it would be a good idea to assess whether to increase capacity of some plants if possible, or perhaps invest in other electricity sources in the area and use the existing water otherwise. Finally, once again seasonality is important and extremes within the year will become more extreme. New

capacity within the country should be sited in order to avoid as much as possible for too many reservoirs being affected at the same time.

8.1.3. Water budget results discussion

The South's reservoir level did not drop below 98% in the 2010-2015 period, and meanwhile the region's hydropower plants did not suffer from water availability. Contrarily, the Northeast's level drops after June until December every year, and in 2014 the drop was so big, to just over 70%, that the level did not fully recover within 2015, which meant a further drop to less than 50% by the end of 2015, and meanwhile hydropower plants suffered substantially. The Southeast that normally fares well, due to the 2014-2015 drought had its levels drop to 87% in November 2014 and 89% in November 2015, with the overall level not recovering fully in between. The Midwest's level also dropped to 86% in November 2015.

For the 2010-2013 period, the percentage of days within a month that reservoir levels were below minimum useful capacity occurred 6-13% for the North, 5-15% for the Northeast, 0-5% for the Midwest, 0-3% for the Southeast, and 0-3% for the South. However, in 2015 this percentage rose to 20% for the North, to 35% for the Northeast, to 10% for the Midwest in 2014, and to 22% in 2014 for the Southeast and 14% in 2015. The highest percentages usually occur around October. Specifically for affected areas of the 2014-2015 drought, the states of Minas Gerais and São Paulo reached percentages of 27 and 16% respectively in October 2014.

From the four future scenarios ran, the E1P1 was a high overall precipitation one, in which none of the regions would face any significant water availability issues for electricity generation. For example, the North would have a minimum reservoir level of 90%, the Midwest 89%, and the Southeast 94% in the month of October. The Northeast has the lowest values in October and November with 75 and 76%. The second scenario (E1P2) was one of low overall precipitation, in which all regions would suffer to a certain extent. For

example, the lowest values would occur in November for the North with 65%, for the Northeast with 49%, for the Midwest and the Southeast with 76%. Even the South would have decreased reservoir levels, with the minimum occurring in October with 90%.

In scenarios E1P3 and E1P4, the South is almost at 100% throughout the year. The North has a minimum in October with 91 and 93% respectively, and the Midwest and the Southeast have minimums with about 90% in November. The Northeast fares the worst in November with 47 and 55%, while never reaching 80% in scenario E1P3. In general, the region faring the best would be the South, with the other four regions having low to moderate problems on a good year, but significant issues on a bad year, especially after June. After particularly bad years, some reservoirs need significant time to fill up, which in some cases can reach 1-2 years.

As far as the percentage of days within a year that reservoir levels were below minimum useful capacity (meaning that electricity generation was impossible), in scenario E1P1, the North would have values of 1.5-8.5%, the Northeast 2.5-14.5%, the Midwest 2.5-6%, the Southeast 0.7-11.3%, and the South 0-3%. This percentage increases marginally as time progresses. In scenario E1P2, the percentages become 13-18% for the North, 16-35% for the Northeast, 16-25% for the Midwest, 13-30% for the Southeast, and 1-18% for the South. Such a low precipitation future would cause significant problems to the Northeast, the Southeast, and the Midwest, but also to the North to a slightly lesser extent. The South would fare well most of the years, but extended droughts could affect this region as well. In scenarios E1P3 and E1P4, the percentages become 1-7% for the North, 10-35% for the Northeast, 3-7% for the Midwest, 1-10% for the Southeast, and 0-7% for the South.

The water budget analysis showed that the Southeast usually fares well in terms of water availability, but in times of drought the entire region is in danger in regards of electricity generation, which also affects the large population of the region. The Northeast has and in all likelihood will continue

having serious water availability issues, which along with the water footprint values for the region makes it clear that the region is far from ideal for hydropower plants. In case of future planned power plants, there needs to be a thorough assessment to determine whether other sources are better suited. The useful outflow from reservoirs has been decreasing from to 2010 to 2015, and although this might change in the future, it is concerning in terms of any plans that involve water. Precipitation is losing ground compared to evaporation (a trend also noticed in the future analysis), showing that detailed modelling including more precise evaporation estimation is becoming more important. Also, in terms of designing reservoirs to better deal with reduced water availability, the minimum useful capacity of reservoirs is important, since it is better to allow for storage of water that could be used in times of need than to invest in run-of-the-river plants that immediately suffer when water availability becomes an issue.

The future analysis showed that the South performs well under all precipitation scenarios, which along with the very good footprint values, means that the region's hydropower potential could be further exploited if possible. On the other hand, the Northeast will most likely continue to struggle, which is a clear indication that if new electricity capacity is to be sited in the region it should be of a different form that does not need water, favouring wind and solar energy. Although the Southeast most years has no immediate problems in terms of electricity generation through hydropower, in times of water availability strains, the region's immense population can face many days of no electricity. The region should possibly invest in other forms of electricity production as well (wind and solar) if applicable, but also investments should be made towards better interconnection to the rest of the country. March-May seem to be the months that water is affluent enough to consider further implementations, while October is the month when the whole country should be more cautious with water being used. Finally, in terms of modelling, annual values of water availability can be very deceiving, since even in years when precipitation increases, there are months that will

see a precipitation decrease, making it clear that modelling needs to be done at a fine temporal, apart from spatial, scale.

8.1.4. Energy model results discussion

There is the possibility to run a lot of different scenarios based on the different climate scenarios, along with the different energy scenarios within the energy-water-land IDA3 model. Three different energy scenarios, under two different climate scenarios were presented in section 7.6. The link between the two models was achieved through capacity factors for hydroelectricity. In the first energy scenario, hydropower is fully exploited, along with investments in wind and solar. In this case, water availability does not seem to cause any problems until 2050, deeming thermal power unnecessary. In the second scenario, there is a more balanced mix to start with, while hydropower capacity is decreasing until 2050, while thermal capacity mainly, but also wind, is increasing. In this scenario, when water availability is adequate, power supply is still mainly achieved by hydropower. However, when water availability is low due to low precipitation, thermal power plants take over. In this case, the national system is under serious threat and blackouts would be expected. The third scenario is one where wind and solar see more investments, while hydropower sees an increase as well. In this case, as in the first scenario, the system does not suffer under a low water availability future, while once again thermal power is more or less unnecessary.

It is important to note that although a link between the water model and IDA3 is possible and was achieved, nevertheless the detail of the present IDA3 configuration does not match that of the water model. IDA3 has the capacity for finer scale analysis, but that would be much more time consuming. This exercise was mostly aimed at proving such a link is possible, rather than providing detailed results by the energy-water-land model. Even if a more detailed energy model, coupled with the detailed results by the water model, would provide more comprehensive recommendations, some

interesting results were achieved. The energy scenarios showed that Brazil would not have serious electricity supply issues if significant investments were made towards more hydropower all over the country, assisted by wind and solar. It seems that the country is more susceptible to electricity disruptions under a future where investment towards hydro, wind, and solar is minimal. Of course investing heavily in hydropower is most likely not realistic, which is why better management of water in hydro plants is needed, and it can be achieved by continuing to perform an analysis, as was shown in the water model, continuously, while also investing in wind and solar energy. Specifically further investment towards new hydropower plants needs to be based upon taking seasonality into account, the potential of regions, but also the interconnections between regions.

8.2. Discussion of methods and data

As Healy et al. (2015) argued, there is need to develop improved methods for measuring or estimating water withdrawal and consumption for energy use, with hydropower being at the top of this list. This thesis concentrated mostly on the water aspect of the WEN, because this is where most of the gaps were identified, thus contributing to relevant literature.

8.2.1. Methods and improvements

There are three ways of addressing the WEN in a modelling framework, incorporating water resources into an energy model, incorporating energy into a water model, and a combined framework. Most approaches choose incorporating water resources in existing energy models. In theory, it would be ideal to construct a combined framework in order to not miss out any important parameter of either water or energy. To build such a model is very time and resource consuming and cannot be done in a limited timeframe. As it has already been mentioned, this thesis concentrated on the water part, but at the same time the water model was constructed with energy issues in mind and able to be linked to energy models spatially and temporally, without

compromising the necessary detail water needs. The evaporation and water budget parts were performed using geopolitical boundaries and the temporal scale was hourly and daily, data allowing. The alignment of political and hydrographic boundaries is something that most water models are lacking in order to be meaningfully linked to energy models, which is something that was overcome in this thesis, and is one of the main contributions of this work.

When it comes to the evaporation estimation method used, it was based on the Penman-Monteith equation that is suggested by FAO, but also taking into account deep lakes, which was adjusted by McJannet et al. (2008). The estimation was done hourly, which can be useful when performing operation kind modelling. Furthermore, the analysis was done individually for all reservoirs present in the Brazilian system at the end of 2016, and actual weather data was used, provided after personal communication with INMET. This method used along with the extent of it (whole of Brazil) is the first of its kind.

The times series data for evaporation estimation had missing entries, something logical for hourly data from meteorological stations in secluded areas. Since the missing data entries were in the hundreds of thousands for the 7-year period of analysis, a reconstruction process was necessary. From three identified methods to do this, the only suited one was that of Mekonnen & Hoekstra (2012), due to data allowing it as explained in chapter 5. However, it was deemed preferable to make an improvement to this method, by using the arithmetic mean method to fill in the gaps, which takes into account specific changes (e.g. in temperature) of a specific month or year, therefore providing more realistic results. The same method was used for precipitation data in the water budget analysis. This improvement of data is another major contribution to literature of the present work.

Concerning water footprint estimation, as it has been mentioned there is an ongoing argument as to which is the most appropriate method. In this thesis, the gross water consumption was used instead of net water consumption. The

reason for this is that the Water Footprint Manual suggests it, but also it was deemed that since these reservoirs would not exist if it were not for the production of electricity, all evaporative losses should be allocated to the production of electricity.

Furthermore, the water budget equation by Healy et al. (2015) was used to perform the water budget analysis, which is also a very basic equation of movement of water in, through and out of a specific volume, in this case a hydropower reservoir. There are no disputes regarding this equation in literature, and the difference in its use relies mostly in the regulations set for the reservoirs. Firstly though, this analysis used new evaporation estimations for each reservoir individually, presented in this thesis, which already makes this a novel application. Additionally, the method is based on minimum standards and a management system in order to increase efficiency of both water use and electricity production, without compromising environmental stability. The goal of the regulations set for the main equation, and also the operation of the reservoirs, was to reach the maximum water storage level possible at all times, without compromising safe outflow values, which are prioritised. This improvement concludes the contributions to existing work in relation to water models alone.

One of the most common ways, if not the most common, to link water to energy models is through capacity factors. Since water availability is projected into the future, so can the capacity factors for each hydro plant. In theory, the most appropriate method for the estimation of capacity factors for hydropower would be to use equations 6.1 and 6.2. However, a number of hydraulic head values for hydro plants are missing, and exact plant efficiencies (normally 80-95%) are not readily available. Despite the assumptions, this method was tried but as shown in table 6.15, although some estimated values come close to actual values, some other ones are far from being correct. In order not to use such values that are clearly wrong, and in consequence possibly change the overall capacity factors of a region significantly, a different method needed to be applied.

As seen in figure 6.39, although there are variations from year to year, there is a relationship between outflow and capacity factors. These variations needed to be homogenised so that a rule can be created, and linear regression was used in order to achieve this. Doing this, a direct relationship between water availability and capacity factors is created, which closely resembles reality, so large assumptions are avoided and the results are improved. The results of this process could be improved if more years were taken into consideration in the regression, but outflow values were not available, since these partly depend on the evaporation part of the water model, which only had climatic data available for analysis from 2010 to 2016. However, this method is the first of its kind, and provides an alternative in case other options are unavailable.

8.2.2. Future scenarios and downscaling

The climate scenarios needed to be devised in such a way as to take locality and actual past climatic conditions of individual reservoirs into account. Also, the projected data needed to be in the same temporal and spatial scales as the historical analysis. However, there were two important issues with achieving this. Firstly, due to the various climatic phenomena in Brazil, it is difficult to find useful future climate projections that are generally accepted by the scientific community. Secondly, the resolution of the existing projections is not detailed enough to provide the water model with the needed data to run projections.

Concerning the first issue, in general the likelihood of droughts becoming more frequent is very high according to the IPCC (2013, 2014) and Marengo et al. (2016). Unlike temperature, which can be projected with a relatively high degree of probability, the same cannot be said about precipitation (and consequently river flows), because there is no statistically significant long-term trend in the time series of global precipitation in the period 1900–2005 (Trenberth et al., 2007; Kundzewicz & Döll, 2009). As a consequence,

different climate models do not agree for most areas of the globe, not even regarding the direction of change. For example, analyses of discharge and precipitation data for the Amazon River have shown that the hydrological cycle of the Amazon basin has become more variable in the last 40 years, with an increase of both floods and droughts (Gloor et al., 2013).

As for the second issue, in a similar vein, the gap between resolution of climate models and more local-scale processes is a problem for climate change studies, with their application to hydrological models being no exception (Yang et al., 2012). As a consequence, downscaling is required to provide high-resolution scenarios (Palomino-Lemus et al., 2017). The goal of this thesis and analysis was not necessarily to use the most plausible climatic future projections, rather to see what would happen water availability-wise in different more extreme scenarios. For this reason, the scenarios chosen are based on high precipitation for the whole country, low precipitation for the whole country, and a mix of futures for different regions in the country.

Due to the detail required, a sequence of data for future projections was used, based on the spatially and temporally detailed 2010-2015 data, but at the same time accounting for changes due to climate change. This way, real conditions of all the input variables are captured in cases of extreme weather, like in 2014-2015, and it is possible to investigate the behaviour of specific reservoirs to more frequent drought events combined with climate change effects. Furthermore, each reservoir/power plant was simulated in isolation, which is not the norm for this kind of future projection work, which is also a novel contribution. The GCM precipitation projections were downscaled down to individual reservoirs, by using the available hourly dataset from INMET, and the GCM future country and regional projections. Although most of the modelling and analysis is done using geopolitical boundaries, river flows are influenced by the river basin's conditions, which are not in line with political boundaries. For this reason, the analysis for river flows was performed for hydrological boundaries and then translated into political boundaries, thus taking hydrological conditions into account. The way the climate scenarios

were devised, along with their spatiotemporal detail is another contribution to literature, and a way to deal with lack of fine scale datasets.

The IDA3 model and its results, presented in chapter 7, were an example of how the results of the water model presented in this thesis could be linked to an energy-water-land model. As a consequence, the future projections for energy presented, were not devised specifically for this thesis, rather the same ones that were used in Senger & Spataru (2015) were also used in this thesis.

8.2.3. Data needs and limitations

Firstly, the whole analysis would benefit from longer historical time series data, but it was impossible to perform such an analysis to this degree of detail until recently, since there were not enough meteorological stations present in Brazil to allow for this. As time goes by, this kind of analysis will improve. Also something that needs to be taken into consideration is that the data needed as input for the evaporation estimation and water budget analysis can be considerable, let alone when we have to deal with a large study area like Brazil.

There have been issues with climatic data, which have been discussed elsewhere, and these issues can be overcome without compromising the quality and accuracy of the results. However, there is other data, whose absence could potentially be problematic, since they cannot adequately be assumed. Such data include the maximum reservoir capacity and minimum useful capacity of reservoirs, which are vital for a water budget analysis. ONS provides these values in its databases for almost all reservoirs, however there were 14 cases where this was not the case. This problem was overcome by using values from similar reservoirs, however the actual values would be useful for operation purposes results of those specific reservoirs. Another important dataset is that of river flows. From the 151 reservoirs used in the water budget analysis, 135 had river flow time series, but 16 did not, with 14

that did not being the same as before. In this case, regionalisation was used, transferring information from one location to another based on several principles. However, once again this data should exist for all reservoirs.

Additionally, another set of important data is the maximum and minimum river outflow limits from reservoirs. These limits are important due to operational and most importantly downstream environmental limitations. From the 151 reservoirs used in the water budget analysis, only 65 had both values available, while 30 had a minimum value, 14 a maximum value, and 42 neither. As a consequence, this was the biggest assumption that needed to be made in the whole modelling process. This issue was overcome by taking other reservoirs with similar conditions (same river basin, similar historical flow) into consideration and keeping values higher than what is possibly needed to be on the safe side. However, it is difficult to estimate such values since they depend on the specific sites, ecosystems, human settlements, etc. The lack of this kind of data is a clear omission from the entities responsible to provide it.

Furthermore, in general water losses from a reservoir cannot be attributed to power generation purposes alone (Siddiqi & Anadon, 2011). The vast majority of hydropower reservoirs in Brazil are used solely for this purpose, and so this was assumed to be true for the analytical purposes of this thesis. Additionally, an accepted methodology attributing the evaporative losses to different uses does not exist (Bakken et al., 2013), however there is scope to pursue such an analysis of reservoirs, since in many cases, reservoirs in Brazil should not (and in truth are not) be used solely for electricity production. This is a very interesting subject for a continued development of the model presented in this thesis.

Finally, as is also mentioned in section 8.1.2, water body areas were taken as being constant, although this is not so. This is most likely the single most important unsolved issue when it comes to this sort of analysis, but unfortunately, only very recently has this started to be measured, and only

for specific large reservoirs. Consequently, there is not enough data to take into account. In the near future, it will be possible to improve analysis and it is of value to do so when this data will become available.

8.3. Other important issues that affect, or could be affected by, hydroelectricity

Before attempting to discuss policy implications, it would be valuable to briefly discuss issues that are not part of the analysis performed in the thesis, nevertheless, they are part of the whole discussion and should be taken into account.

It has already been mentioned, but biodiversity issues are extremely important for rivers, especially when we are talking about the Amazon, which is perhaps the most bio-diverse river basin in the world (along with Congo and Mekong), and it could suffer from the construction of large hydropower dams, no matter the care taken. Cumulative impacts on hydrology and ecosystem services are largely ignored in such projects, which can become problematic the more dams are built in specific watersheds. Attempts to achieve true sustainability should include assessments of new dams that go beyond local impacts and account for synergies of existing infrastructure, land cover changes and possible climatic shifts (Winemiller et al., 2016).

In the same way as far-reaching effects on biodiversity are underestimated, such large projects often also overestimate economic benefits. The true benefits and costs of large hydropower projects have largely been miscalculated and returns have fallen short of expectations. 75% of large dams have suffered cost overruns, averaging 96% above figures used to justify their construction (Ansar et al., 2014). In addition, economic projections, more often than not, underestimate or ignore costs of environmental mitigation, like the Three Gorges Dam example where China spent ~$26 million to moderate ecological impacts (Winemiller et al., 2016).

Apart from various issues that directly revolve around hydropower issues, which are plenty, Brazil has great renewable potential overall, and this potential is explored in publications like the IEA World Energy Outlook (WEO) (IEA, 2013), where in the New Policies Scenario, Brazil's variable renewables (including wind, solar, small hydro and excluding large hydro) increase from 14TWh in 2011 to 140TWh in 2035. This increase is mostly based on the amount of energy storage of hydropower reservoirs, capable of providing balance in times of short-term variations in supply and demand, but also on wind and solar (IEA, 2013).

In recent years, research related to the integration of wind and solar sources of the grid has started to develop, due to the increased participation of these sources in the national generation. This expansion was achieved through incentives created in the ANEEL auctions that made them more competitive, since especially wind generation has level costs able to compete with other traditional forms of generation (IRENA, 2017). However, despite economic incentives and competitiveness, there are certain issues that need addressing. These renewable energy sources are highly variable and at the same time Brazil is a vast country with different generation potentials within its borders in different regions throughout the year, since the climates of these regions have different characteristics. As shown in chapters 6 and 7, and discussed in section 8.1, the precipitation patterns and river flows are not constant throughout Brazil and seasonality plays an important role, especially in the southernmost parts of the country.

So far, most of the expansion of wind power generation is concentrated in the Northeast and the South, but these regions also have transmission limitations. Even with the planned investments described in PDE 2024 (EPE, 2015c), interregional transmission is the key in establishing the penetration limit of renewable sources like wind and solar. The potential of wind, hydro, but also biomass generation in remote areas with low transmission capacity will depend a lot on seasonal variation and how this can be taken advantage of, or the competition problems eliminated before they even start. A factor

that differentiates Brazil from other countries when it comes to penetration of renewables is its traditional dependence on large reservoir hydropower, which means capacity to store water and energy. This can greatly help in the quest for renewables expansion, along with the transmission system that will need to optimize its dispatches throughout the year (Saporta, 2017).

In general, transmission is important in ensuring the safety of the national interconnected system, since it connects the different submarkets, allowing for a high degree of equalization of electricity prices, minimizing imbalances between demand and supply in different regions. This imbalance between regions is important, since most of the population of the country is located in the Southeast and Midwest regions (which ONS sees as a single submarket), and there is an imbalance between demand of electricity and generation capacity in these regions. In 2016, the average share of demand of these 2 regions was 60% of the national total, and the average share of generation was about 40% of the national total. This is a permanent imbalance and since they are the main economic regions of Brazil, transmission capacity to account for this with excess generation from other regions needs to be in place (Saporta, 2017).

Furthermore, an important aspect to be taken into consideration when discussing hydroelectricity in Brazil is biofuels. For example, IEA WEO (IEA, 2013) projects that Brazilian produced biofuels account for about one third of domestic demand for road transport fuel in 2035, which shows the importance of biofuels in the future. As it has been shown in chapter 5, Brazil is a large bioethanol producer. The main crop used for bioethanol production is sugarcane, which is mainly rainfed, thus not requiring irrigation. Nevertheless, as has also been shown and discussed, the climate has been changing and there are variations within the country, which are only increasing in frequency. It is possible that areas that had little to no problems regarding water for sugarcane will start having issues, in which case irrigation of the crops will be required, if they keep cultivating this crop in those areas. In this case though, the water required is significant, since

sugarcane needs large amounts of water as is shown in table 5.9. Brazil has more than enough cultivation areas to accommodate an increase of ethanol, without intruding on environmentally sensitive areas, and if and where sugarcane will be cultivated is an important factor when it comes to hydroelectricity too, since it is possible that water from hydro reservoirs might be required.

Since sugarcane crops were mentioned, it is worth including other important agricultural products in the discussion. As was the case with precipitation projections that vary greatly depending on the climatological models used, the same holds true for crop yields. Due to different models, assumptions, and emissions scenarios, quantitative crop yield projections under climate change for Brazil vary across studies. However, most studies project yield losses for maize, rice, and soybean (three of Brazil's major crops) due to climate change, while there is a chance that sugarcane yields might increase overall. These yield losses could possibly be offset thanks to CO_2 fertilisation, or other advancements is science, but there are still knowledge gaps to include this as an actual possibility. Nevertheless, Brazil is a country with low levels of undernourishment, with its food security not being under threat in the next 40 years due to climate change according to studies (Met Office, 2011). A simultaneous electricity and food crisis though would most likely strain the ability of the country to satisfy its citizens' needs.

Finally, something that should be taken into consideration is that Brazil, according to the IEA WEO (2013), is set to become a major exporter of oil and a leading global energy producer. This is mainly due to offshore discoveries, which will triple the country's oil production to reach 6 mb/d in 2035, accounting for one third of global growth and making Brazil the sixth largest producer. At the same time, natural gas grows more than fivefold, which is enough to cover the country's domestic needs by 2030, even with a significant expansion. Such increases in oil and gas production will undoubtedly affect environmental, social, and economic security, which will also affect decision-making regarding hydropower.

8.4. Policy discussion and recommendations

Brazil started taking water issues seriously after 1997 with the "water law" (law No. 9433), also establishing a National Water Agency (ANA). One of the main foundations of this law was that it gave priority of use of water to human and animal consumption in times of drought. Also, it was left up to ANA to make sure different water uses are complementary, without competition between them, and to prevent critical water-related events. Additionally, In December 2009, law No. 12,187 was approved, the "National Policy on Climate Change". This law was about stimulating efficiency increases, keeping a high share of renewable energy (which the country is proud of), encouraging the increase of biofuels, reducing deforestation rates, reduce the vulnerabilities of populations, identifying environmental impacts of climate change, and stimulating scientific research to develop strategies of minimizing socio-economic costs of adaptation (Clarke et al., 2016).

Finally, a European Commission strategy of preparing the EU for current and future consequences, including implementation of IWRM, has gained attention in Brazil, failing though to actually become a core concern for Brazilian authorities and society so far (Araújo et al., 2015; Barbosa et al., 2017). To achieve the aforementioned goals, first and foremost a lot of research is needed and in turn, instruments that will regulate water and enforce policy recommendations made by ANA. However, although Brazil is mostly aligned with international trends and has seen improvements, the implementation of many instruments is at an early stage and requires more effort (Veiga & Magrini, 2013).

Ignoring effects in one resource can have significant impacts on another and single sector policy-making cannot support long-term performance improvements. A more holistic treatment could lead to more optimal allocation of resources, improved economic efficiency, and lower environmental impacts. The laws discussed hint towards improvements that could be perceived as taking more than one resource into consideration at

once, but practically it seems this is not the case. The relatively recent internationally recognized SDGs could help implement a more holistic approach towards water and energy issues in the country, although care needs to be taken.

The SDGs have water and energy as separate goals, and although there are some clear links between them, there are also some important omissions. Water consumption of energy is not included, and the focus seems to be national, whereas water availability is a highly local issue. Nevertheless, the framework itself allows for different aspects of various resources to be taken into account, which helps pinpointing synergies and avoiding competitions. For example, the need for more energy due to increased demand should be counterbalanced by protection and restoration of critical ecosystems, while supporting development in other sectors. This depends on technology, behaviour, and policy changes to decrease natural resource-intensity of energy systems, while trying to decouple environmental impacts from economic growth (Nerini et al., 2017).

Although the SDGs do have a scope, it is important to not get lost in them. They have 232 indicators in total as of mid-2018, which is an extremely large number for any country to take into account, especially for countries that are as large as Brazil and most of the indicators could be applicable for them. Prioritising is important, but also difficult. The criticality of the indicators for the country needs to be properly assessed. Furthermore, even though the SDGs are good at identifying critical points, they are not yet equally good at quantifying the suggested indicators. The omission of water consumption and the locality factor is something that could be improved by employing water-energy nexus thinking in the case of Brazil's electricity future (which is heavily hydropower influenced) and keeping other resources in mind as well, in ways similar to the ones shown in this thesis with the water and energy modelling.

8.4.1. Brazil's future energy plans and useful considerations

In 2006, Brazil approved the Ten Year Plan for Energy (PDE) 2006-2015, which was a policy design for the energy sector, with the National Energy Plan (PNE) 2030 following in 2007, which directed trends and energy supply alternatives for the coming decades. Their prediction was that by 2030 the country would depend 77% on hydroelectricity. The PNE 2030 was used in various ministerial spheres as an economic and energy baseline scenario, and was crucial in strengthening and prioritising hydroelectricity. In the next instalment of long-term planning, the PNE 2050 was released, which presented the evolution and competitiveness of wind energy, the rise of oil and natural gas supply, and the growing concern over climate change. The use of these documents for policymaking, make it clear that evidence-based research could in theory provide the government with a powerful tool towards achieving the goals set by law No. 12,187.

Although the plans for hydropower expansion have changed numerous times in recent years, it is nevertheless clear that hydropower will continue playing an incredibly important role for the country. But, Brazil's plan to invest further into hydropower, and especially in the North, does not come without considerable questions. In planning an expansion to a power system, the reliability of a source is of imperative importance. Hydroelectric-based systems must be dimensioned or complemented to guarantee supply in the worst hydrological conditions (Lucena et al., 2010). Furthermore, the development of large hydropower projects in Brazil is subject to lengthy periods of planning, evaluation, consultation, authorization and construction, which are all subject to legal challenges and obstruction (IEA, 2013). And lastly, it cannot be ignored that such large projects usually overestimate economic benefits, since figures have shown that 75% of large dams have suffered cost overruns, averaging 96% above figures used to justify their construction (Ansar et al., 2014).

The Brazilian government invested a lot on large hydropower plants like Santo Antonio (3,150MW), Jirau (3,300MW), and Belo Monte (11,233MW), all located in the Amazon. Originally, the plan was for an additional 48.91GW until 2050, but opposition forced this plan to go on hold and investigate "run-of-the-river" plants, and the expansion falling to 25.32GW until 2050, mainly due to not going forward with power plants in the Amazon. The decisions for future capacity seem to be based mainly on environmental reasons in one hand and on expansion where there is in theory a lot of potential on the other hand. However, Brazil has a new government as of October 2018, and their plan, at least in paper, is to go through with the expansion of hydroelectricity in the North and in general, which was the original plan.

On one hand a plan of run-of-the-river plants could decrease local environmental issues, on the other hand large reservoirs can withhold more water for times when it is needed, which improves resilience. Smaller, or no, reservoirs are a direct contradiction to energy security, whereas large reservoirs in most cases are a direct contradiction to environmental security. Both sides have valid reasons to support their agendas in theory, however the most important factor could be the climate, which neither of the sides seems to be taking into account. Another important factor that needs to be taken into account is that the capacity factors of the potential future power plants in the North are on average 0.476, which is low compared to the rest of the country and also South American values. Additionally, as the energy model results showed, the system would perform better, when wind and solar power generation assist hydropower.

8.4.2. Water model findings in relation to Brazil's future energy plans

The climate is changing, and with it water availability will also be affected. Temperature is rising and with it so will evaporation. The research conducted in this thesis showed that evaporation, which is dynamic and needs to be estimated regularly, will increase on average in the country by 90mm for a 1°C increase in temperature, a 0.5 MJ/m² increase in incoming short-wave

radiation, and a 0.5 m/s increase in wind speed, which is an increase of 10-15% for every degree Celsius. The North in particular will most likely see the largest increase in evaporation with about 103mm on average for a 1°C increase in temperature, whereas the South will see the least increase with 77mm. At the same time, this increase will not happen uniformly within the year, it will mainly occur in December-February and less in June-August. Consequently, seasonality is important in terms of evaporation and it needs to be taken into account for planning purposes, without forgetting that location is very important for evaporation rates.

Since evaporation is increasing, the same will hold true for water footprint values of hydropower plants. Only if precipitation increases drastically is it possible for water footprint values to see a small decrease in the future, which is an unlikely scenario. In the case of water footprint, the relationship of inundated area of a reservoir and electricity capacity (and generation) of the power plant is key to good water footprint values. The larger the capacity and generation while at the same time having smaller reservoir areas, the better and more efficient the use of water will be. This relationship is very important for future planning and something that needs to be taken into account, while not overlooking or discounting certain factors, such as potential capacity factors of the plants, present ecosystems, and human settlements, which all should be in the equation when deciding for ideal sites. At the same time, locations that could potentially have issues with water availability in the future and do not perfectly meet these criteria, should be avoided at all costs.

At the time of the analysis presented in this thesis, data to account for changes in inundated areas in time for all reservoirs did not exist, which is something that needs to change in order to have accurate measurements that will greatly assist future estimations of water footprint values. However, recently there was a study (Andrade Vieira et al., 2018) that attempted to take the change of inundated area into account, performed for one reservoir (Sobradinho), albeit the method used to estimate evaporation (water balance),

is a simple one and far from ideal. The flaw exists in not using climatological variables; rather they assume a perfect system (reservoir) of input and output of a resource (water), discounting other possible uses of the reservoir. A water balance should be the final step of such an analysis as was done in the analysis in this thesis, and not be used in order to estimate evaporation. Nevertheless, taking into account the variation of the reservoir's flooded area is useful, since a constant area has repercussions for evaporation volume and water footprint estimations. Such work is a definite step towards the right direction, deeming it valuable.

Finally, there are no standards as to which water footprint values are "normal" and acceptable and perhaps it would not make sense to have such values that would be a countrywide fit, let alone a global fit. Nevertheless, the analysis performed in this thesis shows that the South of Brazil has good water footprint values compared to the rest of the country, and although it would be perhaps impossible for other regions and specific future reservoirs to achieve these values, it would be of value to strive for similar ones if possible.

Most likely the most important part of the analysis in terms of future planning is the water budget analysis. The results showed that in the 2010-2015 period, all regions apart from the South had water availability issues at some point and had percentages of no possibility of producing electricity up to 20% in the North, 35% in the Northeast, 10% in the Midwest, 22% in the Southeast, and 3% in the South. The highest percentages usually occurred around October. The future analysis showed that a slight increase of precipitation overall would not change the situation by much, since bad years with droughts are a possibility and they can create water availability problems.

Overall, the Southeast affects the Brazilian system a lot since a lot of hydropower plants are located there, and at the same time as the analysis showed, the Southeast and the Northeast were the more susceptible to a low

precipitation future. As discussed in section 8.3, the electricity demand of the Southeast and the Midwest (60%) is higher than their average share of generation (40%), creating an imbalance. The Northeast on the other hand has different problems, since it has historically had water availability issues, which will not dissipate even if precipitation increases in the future. However, the region has wind potential and the country's additions of wind generation have mainly been in the Northeast. With the region's water availability issues, wind power generation seems to be a logical solution that needs to be further exploited in order to increase the region's energy security. Furthermore, the South would fare well even if precipitation decreased, and there is scope for additional hydropower capacity to be located there. Additionally, the region has wind potential, which should also be exploited. Once again, both the Northeast and the South have transmission limitations, which it something that will need to be taken into consideration in future planning of the electricity system.

Seasonality is important for hydropower, since some months every year, it is possible that water does not suffice to produce electricity. Problems with water availability start occurring in June-August, getting worse in September-November, and dissipating in December-February. March-May are the months when all regions fare the best. Even in a scenario with high overall precipitation increase, there will still be times in specific years that water availability will be an issue for hydropower, which is something that cannot entirely be avoided in any climatic future. The days when reservoir levels will be below useful capacity levels increase in the future, even if precipitation increases, which means that water availability issues will not dissipate in any climatic future. Additionally, due to temperature increase, evaporation is gaining traction in relation to precipitation, which will make a difference in terms of operation of plants by increasing the days when water availability won't be adequate, even if this is a small fraction of the overall possible changes. Finally, the water budget analysis also showed that the useful minimum capacity of reservoirs plays an important role in a low water

availability future, since a power plant could continue operating even with less available water in the reservoir.

Finally, water from large reservoirs could theoretically be used for other purposes (e.g. sugarcane crops), depending on their location and the needs of the area. What needs to be made clear before even starting such a conversation though, is that all environmental and social functions downstream are kept intact and out of danger. All regions have potential for alternative water utilisation to a certain extent, with the Southeast, South, and North having the most potential. The Northeast and the Midwest rarely have enough water for other purposes. Water availability drops fast after June and rises again by the end of the year. Although, it needs to be noted that the excess water available had been dropping every year from 2010 to 2015, and the same holds true for the most part in the future scenarios until 2049, since even in a high precipitation future, some years will be bad enough in order to not sustain other uses of the reservoirs' water. Further research would be needed regarding other uses of the reservoirs, which would need to be local.

8.5. Summary

The research and discussion have helped into identifying certain specific points that could prove to be valuable for future planning and policy making. These can be summarised into the next four points:

a) Data collection
b) Holistic methods and models
c) Model results and climate change
d) Brazilian future electricity plans

a) First and foremost it is important to collect appropriate data consistently, and make sure they are transparent, with integrity, and available to researchers. As mentioned in the SDGs (Sustainable Development Solutions

Network, 2015), it is of great importance for indicators to be accurate and frequently reported, ideally at least once per year. The lack of data on water resources management puts water at a political disadvantage in terms of priority decision-making, which is not the case for energy, and this fact is reflected in economic, social and political aspects. A water availability assessment for hydropower is possible as it has been showed in this thesis, however, analysis would greatly benefit from longer historical time series data, and some missing data like area changes of reservoirs. It would also be of use to have this time series data complete, without gaps in order to avoid assumptions, which are small but could be avoided. The present work contributed in literature in the fact that it improved existing datasets and improved on a method to fill gaps in datasets. Furthermore, since some climatic data do not exist in fine spatiotemporal scale, the present work suggests ways in which to downscale data, without discounting climate change or other local issues.

b) Secondly, better data will give the opportunity to improve results from already existing models, but also further analysis will be possible. Water is a very volatile resource and the climate makes it even more so, thus models need to be updated ideally more than once per year. More precise analysis will reduce uncertainty of future projections of water availability for energy, deeming planning and decision making more foreseeable. There is also scope to improve existing models, with the water model presented in this thesis included. Ideally, when it comes to the WEN, a combined water-energy framework is needed to not miss out any important parameters of either resource. Such an attempt is time and resource consuming, and should be backed up by the government as much as possible. However, the water model presented in this thesis was created with energy spatial and temporal scales in mind, and a novel method of providing detailed capacity factors based on water availability was suggested in order to assist in links between water and energy models.

c) The water model results showed that evaporation could increase by 10-15% for every increase of 1 degree Celsius in the future. Also, although there is no standard as to water footprint values, the values of the South of the country could be considered as the "golden standard" as to what is attainable in theory. Furthermore, all regions apart from the South had water availability issues in the 2010-2015 period, but also in every single scenario investigated, since even if precipitation increases, some years will be bad for water resources. Another important finding was that seasonality plays an important role. Most of the water availability issues, which were translated into percentages of no possibility of producing electricity, were observed in October. Generally, increases/decreases of water availability do not occur uniformly throughout the year, and annual availability values can be deceiving. Additionally, precipitation is losing ground compared to evaporation in all scenarios, which could make a difference in June-November.

Also, the future analysis showed that a slight increase of precipitation overall would not change the situation by much, since droughts are more of an inevitability rather than a possibility in the future. Water availability will not cease to be an issue in any scenario, even for an increased precipitation future. As was discussed by the Met office (2011) though, there is consensus that temperature is not the only important metric for impacts, with human activity playing an important role. Human activities deserve to be taken more into account in modelling. Finally, changes in the relationship between storage capacity, affluent flow and demand are key variables in establishing the penetration limit of variable renewable sources as well. The evaporation analysis of this thesis for the whole of Brazil is the first of its kind, after an ONS attempt in 2004, which also provides new and more accurate water footprint values for all reservoirs present in the country. Finally, the water budget analysis part of the model provides very detailed water availability values that are important for modelling purposes, but also serve as indicators by themselves.

d) The plans for hydropower have changed numerous times in the recent past in Brazil, however it is clear that hydropower will continue playing an incredibly important role for the country. The two most prominent plans have been to either invest further into expansion in the North (Amazon), or more on smaller run-of-the-river plants all over the country. Both options have positives and negatives. Run-of-the-river plants cause significantly fewer environmental problems, but on the other hand decrease the resilience of the whole system since they cannot withhold any water for times of need. Run-of-the-river plants are a direct contradiction to energy security. That is not to say that environmental concerns are to be taken lightly, since constructing and operating a hydropower plant/reservoir needs to be done under strict regulations to protect the environment and human settlements. Plans need to be devised with adaptation in mind as well, and continuing with large reservoirs in the North of the country is also in direct contradiction with adaptation principles, because there is an overwhelming reliance to hydropower, with water being highly volatile due to climate change. Additionally, capacity factors in the North seem to be well below national averages, which is not hopeful.

The electricity system of the country needs to take advantage of its potential, which includes the wind capacities of the Northeast and the South, and further investigation into solar energy. A further investment in hydropower, assisted by wind and solar is the right path for Brazil, if done assisted by appropriate analysis and planning, in order to adapt to decreased water availability. Concentration of capacity in any one region poses a huge risk for the country's future. Other and complementary uses of water need to be investigated by taking into account more resources like food and materials important for the country's economy. Adapting to climate and social changes, while maintaining security of supply of water and electricity are the keys for long-term resilience.

Chapter 9. Conclusions

In this final chapter, the hypothesis made in the first chapter will be verified, while the strengths of the work done and its contribution to research will be briefly discussed. Finally, certain limitations of the work done will be discussed, along with suggestions for future work that could provide further contributions to research.

9.1. Hypothesis verification

The hypothesis of this thesis was that a detailed spatiotemporal analysis of water availability and water consumption of hydropower could pinpoint the criticality of the links between water and electricity. Furthermore, that this knowledge could allow for better management of water, and improve efficiency of both resources in Brazil. Finally, the analysis performed aimed at informing policy towards a more resilient future for both water and energy in relation to hydropower.

Firstly, the first part of a water model was created in order to estimate the water consumption of hydropower individually for 163 plants/reservoirs in Brazil on an hourly time step. The model also allows for results on a state and regional scale. Secondly, the second part of a water model was created, performing an individual water budget analysis for 151 plants/reservoirs in Brazil, estimating water availability on a daily time step. This part of the model also allows for results on a state and regional scale. These first two parts of the analysis performed for this number of reservoirs is the only such existing study. Subsequently, detailed climatic scenarios taking locality and actual climatic conditions of individual reservoirs into account were devised in order to investigate future water availability in the country. Consequently, the relation of outflow from reservoirs and capacity factors allowed for a link to be created between the water model and energy models through future capacity factor estimations. The estimated future capacity factors were used

in an example run of the energy-water-land IDA3 model, proving the success of such an attempt.

It was shown that spatial and temporal issues of linking water and energy models can successfully be overcome. Finally, the results were discussed in relation to Brazil's future energy plans and more specific recommendations for policy were provided, in order to secure supply for both water and energy resources. The identification of critical links between water and energy in hydropower and the way to estimate them, shown in this thesis, can be performed in other locations as well, as long as the necessary data is available, although the discussion mainly concentrated on Brazil, since no two cases are exactly the same and they would need further investigation. In conclusion, the analysis displayed that evaporation and water availability are important metrics for hydropower that do not only measure an unsustainable trend, but they can also define what is sustainable and ensure resilience.

9.2. Strengths of work and contribution to research

The main novel contributions of this thesis were investigating hydropower (163 reservoirs) in Brazil under the prism of the WEN, estimating evaporation, water consumption, and water availability for hydropower, creating climatic scenarios and a link to energy models, while improving on existing methodologies, and finally analysing what the results mean in terms of Brazil's electricity future. The strengths of the work done also coincide with the novel contribution to research, and they can be summarized more specifically in the next seven points: a) water model construction with energy in mind, b) identification, application to a country (Brazil), and analysis of critical metrics for the WEN of hydroelectricity, c) setting priorities for a water budget analysis and filling gaps in important datasets, d) climatic data improvements, e) creating an alternative link to energy models through capacity factors, f) constructing detailed climatic scenarios through downscaling for future projections, and g) implications and lessons learned for Brazil.

9.2.1. Water model construction with energy in mind

One of the two main gaps identified in literature in terms of the WEN was operationalization of the nexus. There are three possible approaches to addressing the WEN in a modelling framework, with the ideal one being to construct a combined framework. To achieve this there are certain obstacles due to fundamental conceptual differences between water and energy models. These are spatial and temporal disparities, which hinder their linking. In the model presented in this thesis, the first part was done on an hourly basis, which helps provide detailed water footprint values, and the second part was done on a daily basis, which provides important information for operation purposes. Furthermore, and possibly more importantly, the political boundaries of energy models are perfectly aligned to the hydrological boundaries of water models. This was achieved by doing the analysis individually for each reservoir present in the Brazilian system, which also made it possible to translate future projections from hydrological to political boundaries.

9.2.2. Critical metrics for the WEN of hydroelectricity

The second main gap identified in literature in terms of the WEN was metrics for the nexus. Water consumption of energy uses in general and hydroelectricity in particular, have been acceptably problematic in literature, deserving more research. WEN analysis has been limited due to uncertainty on issues like freshwater availability and the amount used for energy. The Penman-Monteith evaporation estimation method is the preferred method of FAO, and in this thesis a modified version of it (McJannet et al., 2008) accounting for deep lakes has been used. This evaporation estimation method was not possible in the past, due to the lack of data from meteorological stations. The analysis performed in this thesis is based upon actual weather data from weather stations in close proximity to the reservoirs (which was also estimated), and it is performed on an hourly basis and individually for each reservoir. Results are also presented on a state and regional basis.

This is the first application of this method for the entirety of the large hydropower plants/reservoirs operating in Brazil by the end of 2016, in literature. The results showed the importance of evaporation estimation to be done individually for reservoirs and not using generic values from literature, since reality can be quite different depending on the location and characteristics of the reservoir. Additionally, the detailed evaporation estimation helped in the only existing detailed estimation of water footprint values for all hydropower plants/reservoirs in the country by the end of 2016, since never before was such detailed data of evaporation available. The results showed that there are no "normal" values for water footprint, but the South of Brazil has values the whole country should be striving to have in case new plants are to be built. Also, it was shown that the relationship between inundated area and electricity production is key for water footprint, and the importance of seasonality for the present and future was presented. Finally, the model can be used to estimate evaporation and water footprint on an hourly basis anywhere in the world, as long as there is available data for it.

9.2.3. Priorities for the water budget analysis

The detailed evaporation estimation made it possible to perform a water budget analysis for the entirety of the large Brazilian hydropower plants and estimate water availability, which is something sorely missing in literature. The main water budget equation can be customised depending on the goals of a study or system. In this case, the main priority was to keep outflow values above the minimum restriction values, the second priority was to fill the reservoirs up to their maximum capacity when inflow was sufficient, and finally not allowing the reservoirs to fill up more than their maximum capacity. The methodology can be used for any hydropower reservoir in the world with the same priorities, although it is also possible to make adjustments to priorities to better suit the particular local needs and expectations.

9.2.4. Climatic data improvements

As it is logical with such meteorological stations, there were gaps in the datasets due to faults, etc. of the various instruments present. There are three main methods used to fill in data in such cases. Two of those methods could not be applied due to lack of other data, but the third method could. Mekonnen & Hoekstra (2012) used this third method, but it did not account for specific changes (e.g. in temperature) of a specific month or year. In order to improve on this, the method used in this thesis used the weighted arithmetic mean method to account for specific variations within particular months or even years, therefore making data represent reality better.

9.2.5. Alternative link to energy models through capacity factors

There are equations with which capacity factors can be directly calculated, but in the case of Brazil, as is the case with a lot of emerging or developing countries, some data is either not available or of doubtful quality. The exact efficiency values for most hydropower plants in Brazil are not available, nor are the hydraulic head values for a large number of plants. Hence, the estimation of capacity factors in this way was not feasible and a different method was needed. As it was shown in this thesis, there is a direct relationship between capacity factors and outflow. However, the relationship is not stable and there are variations. In order to deal with these variations, a homogenisation process needed to be performed. Firstly, upper limits for capacity factors were set according to historical values. Subsequently, based on values of actual capacities for the period 2010-2015 in relation to actual outflow values, a linear regression was performed, providing a range of possible capacity factors for the future depending on climatic variables, which is a novel way of dealing with such issues of lacking data. This data was used to link the water model presented in this thesis with IDA3 and some example results were presented, which show that such a link was possible and successful.

9.2.6. Detailed climatic scenarios through downscaling for future projections

Future projections of climatic data from GCMs do not possess the detail required for them to be used in the water model presented in this thesis. In order to have climatic data projections at this scale (individual hydropower plants) downscaling was required. Firstly, a sequence of data for future projections was created, based on the spatially and temporally detailed 2010-2015 data, accounting for the inherent risk of experiencing high and low flows of incoming water due to climatic variations. The sequence of data also includes the 2014-2015 drought, so it was possible to investigate the behaviour of specific reservoirs to more frequent drought events combined with climate change effects. Both political and hydrographic boundaries were employed in the downscaling and creation of databases, wherever this was necessary, and the final results are once again presented in political boundaries in order to assist with the energy model link. The way climatic scenarios were constructed in the thesis is a novel way in order to account for climatic variations at a daily time step, extreme weather, and individual reservoir variability.

9.2.7. Implications and lessons learned for Brazil

Assessments of evaporation, water footprint, and water availability need to be performed individually for each reservoir, as Brazil is a very large country and values can be very different in different regions, but also within regions. The individual assessment of 163 reservoirs in this thesis is a novel contribution and something that all such analyses ought to be doing. Seasonality is an important aspect of such analyses in general, but specifically for Brazil it is something that needs to be taken seriously into account when planning for the future (especially siting of new hydropower plants), since it presents opportunities in regards to seasons that water is available in different regions, but also seasons in which care is needed in order to avoid problems due to lack of water. Also, run-of-the-river plants for most of the country (apart from the South) do not seem to be a good idea,

since the disability of storing water (and hence energy) can mean that electricity security is not achieved.

In terms of regional lessons learned, the North is a region with question marks regarding future water availability, since evaporation rates will likely increase in the future more than in other regions, and its current water footprint values are not great, nor are they going to change in the future. Despite water availability, the efficiency of power plants in the region is not good. Future plants require strict assessment and better design. The Northeast in all analyses performed in this thesis showed that it is a far from ideal place for hydropower, and future plans should concentrate more on wind and solar. Some reservoirs in the region could even possibly be better suited for different uses, other than hydropower. The Southeast's (and to a lesser extent the Midwest's) many reservoirs is a factor that needs to be taken into account, since the region can have serious problems in times of droughts, although it otherwise fares fine. Nevertheless, the Southeast should invest in other electricity sources, but also better interconnections to the rest of the country, since due to its population and importance for the country's economy, they cannot afford to be affected by water availability. Finally, the South, which performed well in all analyses, seems to be an ideal region for hydropower, hence investments should be made for further hydropower, and the country should consider the South as their golden standard as to the design and operation of hydroelectric reservoirs.

9.3. Limitations and future work

9.3.1. Missing Brazilian data

The historical analysis was performed for the years 2010-2015. As it has been previously explained, before 2006 it would be impossible to have the data required for the kind of analysis presented in this thesis, since Brazil did not have the meteorological stations in place measuring the appropriate variables. Nevertheless, the data was enough to perform the analysis and it

even included a period of drought in the country, which is very valuable in terms of future projections. The time series data from the meteorological stations had missing entries, and although this is logical, it would be helpful for the authorities responsible to have processes in place to fill in the missing entries, since they have all the data available, and not just parts of it. The analysis would benefit from longer historical time series data, which would make all parts more precise. This will be able in the future, as long as the meteorological stations in Brazil keep operating properly and even more are installed, since Brazil is a country with a very large area.

Apart from the climatic data, there is other data, of more operational nature, like the maximum reservoir capacity and minimum useful capacity of reservoirs, river flows for specific reservoirs, and maximum and minimum river outflow limits for reservoirs, which are vital for a water budget analysis. Most of these exist and provided by ONS, but especially the last set of data has very serious gaps. It is understandable for some small run-of-the-river plants to not have these values assigned to them by environmental studies, but the same does not hold true for larger plants/reservoirs, especially if they are in areas that are environmentally important.

Furthermore, the link of the water model to energy models has been explained in detail, but although the novel alternative method proposed in this thesis is of value, it would be an easier process if detailed data on hydraulic heads, plant efficiencies, etc. were available and correct. Another set of data that would greatly assist the analysis done in this thesis is a dataset of continuous change of the water body areas, which were taken as being constant in the analysis. Although steps have been taken towards this, this data needs to nevertheless be available for all reservoirs. Lastly, in order to assist with WEN studies and analyses, there is further data that needs to be available and does not currently exist, like water abstracted for cooling and losses of water by utilities, among others.

9.3.2. Better climate future projections

The goal of devising detailed climate scenarios was not necessarily to find the most plausible projections in literature and follow them, rather to see how the system would react under certain extremes, as well as under more plausible futures. Meteorological phenomena in the Brazilian geographical area deem future climate projections very difficult. GCMs are the best available tools, but even their data needs to be downscaled. Locality and actual past climatic conditions of individual reservoirs need to be taken into account. It is important to understand how specific reservoirs act, which then would inform regional results. In this way the locality of issues, which is extremely important, as it has extensively been discussed in the thesis, is taken into account and not ignored as in the case of regional averages, as is the case with most models. A lens of averages and trends could be deceiving and harm future planning and should be avoided as much as possible. The downscaling process suggested and performed in this thesis is a solution to this problem, since real conditions are captured, however it would be helpful if in the future downscaling would cease to be necessary.

9.3.3. Multi-purpose uses of reservoirs

As it has already been discussed, all evaporation losses from hydropower reservoirs have been attributed to the production of electricity in the analysis performed in this thesis. On one hand this is logical, since reportedly the vast majority of the reservoirs in the country is solely used for the purpose of electricity generation. This assumption is therefore logical to make, however by investigating the locations of certain reservoirs it is easy to observe that they are located right next to agricultural fields with no other water reservoir present nearby, which deems the reports claiming the reservoirs are solely used for electricity generation questionable. This could not be investigated in detail and it was not the point of this thesis, nevertheless attributing water losses from the reservoirs to different purposes would greatly assist future planning. Additionally, an accepted methodology to performing this analysis

does not exist, and although it is an issue that is once again highly local, it is an area of research that is very interesting for future work and one of the steps that could improve the water model presented in this thesis.

9.3.4. Model improvements and new applications

Attributing water losses from reservoirs to different uses is not the only way the water model presented in this thesis could be improved. The model presented is taking into account water in terms of electricity, hence performing a WEN analysis, but the nexus includes more resources that should not be ignored. Food, land, and materials should in theory be included in a holistic analysis of a specific location. Therefore, the propositions made in chapter 8 are based on a partial understanding of the complex relationships between all these systems, and they are questionably sustainable and do not prevent unintended consequences in other sectors and systems. Also, water supply is a regional stressor, but water trade and virtual water trade also play a role, which should be further investigated. Hence, it could perhaps be useful to use a CGE model to get a global picture of the various links of water in this way. Also, the link achieved with IDA3 is a first step towards such exercises.

Furthermore, economic variables, political and social aspects are not really represented in the model, and they are important for future plans. However, it needs to be noted that the main goal of the thesis was to understand links at the biophysical level. Finally, although anthropogenic greenhouse gas emissions and the ensuing climate change can alter water availability and this needs to be investigated and taken into account, nevertheless, a more direct human influence seems to be a larger hazard, and this is the reason why investigating different uses of hydropower reservoirs seems to be the first step towards improving on what has been done in this thesis. In conclusion, other areas of research that could be performed to improve on the work done here include adding food and land in the analysis (e.g. biofuels), a more detailed economic analysis, investigating complementary uses of wind

and solar energy, transmission requirements, and finally an investigation into legal instruments to assist with the implementation of the necessary steps to ensure a resilient future in terms of resources.

9.4. Final word

The climate will change in the future, global population will rise, and human activities will continue being resource hungry. These seem to be inevitabilities, but at the same time they are not reasons to despair. This research has shown that it is possible to adapt in new climate conditions and mitigate the problems that might arise in regards to water and electricity issues in Brazil, with careful planning based on good results. Certain important functions of water need to be better measured. These measurements will assist in improved research and results. And these results can be used as the basis of important decisions. Elaborate thinking and models are not needed to devise a good future plan. What is needed is to understand simple functions of resources and work around them. Hence, the indicators chosen and pursued in this thesis are simple to understand, yet important, and it has been shown that it is crucial for them to be estimated as precisely as possible and respect the locality of issues. If simple indicators as these are not estimated properly and taken into account, it is inevitable for water to remain at a political disadvantage. The methods and indicators used in this thesis are applicable everywhere, as long as data exists. First and foremost, emerging and developing societies need to invest in measurements of vital factors, which is only a small price to pay for a sustainable future. What it all comes down to is the value we give to these resources, like water. We ought to be appreciative of what they offer us and treat them ethically.

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