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Energy and hydrology modeling for the Paraná basin

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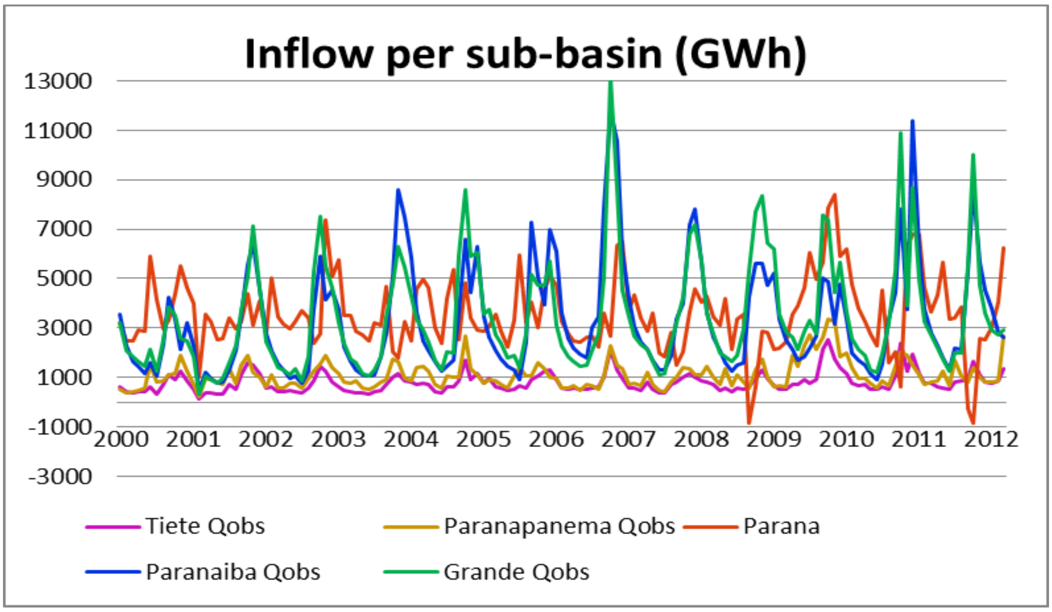

Karin Olsson and Agnieszka Duma
Spring 2013

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Prof. Cintia Bertacchi Uvo
Stefan Söderberg

Abstract

Hydropower in Brazil stands for 64.5% of all energy sources in the country. The largest number of hydropower plants are located in the Paraná basin, which together have an installed capacity of approximately 40 GW including the world's largest producing hydropower plant, Itaipu.

The wet season during Brazilian summer (January-March) is the most important for hydropower. Occasionally, extreme, such as El Niño and La Niña, which are connected to variability of the sea surface temperature in the Tropical Pacific Ocean affect climate patterns. These events could lead to drought and result in dramatic consequences for hydropower production. Rain patterns within the basin reflect the flows during different seasons so that the largest flows in the Paraná River basin occur between January and March. The rivers Paranaíba and Grande are the main tributaries of Paraná with the largest energy inflows.

The objective of this project includes the adaption of the Scania-HBV model for the Paraná basin and its evaluation. Thomson Reuters Point Carbon provided the model, which uses precipitation and temperature as input data, and through simplified hydrological processes, simulates inflow to the basin in energy units. Limitations were mainly connected to measurements and calculations of input data. Thomson Reuters Point Carbon uses information about energy inflow for prediction of future hydropower production and prices on the energy market. Severe peaks in prices seem to be connected to long-term droughts in the wet season and technical problems in the hydropower system.

Natural energy inflow was the target data used for calibration of the model. The Paraná basin was divided into five sub-basins: Paraná, Grande, Paranaíba, Tietê and Paranapanema. Scania-HBV model was adapted for each sub-basin and the calibration period was chosen from 2005 to 2012. Objective functions were used to find the best fit between observed and calculated energy inflow. Evaluation was done by simulating energy inflow for a validation period from 2000 to 2005. Finally the results from the five models were put together to receive information of energy inflow for the whole basin.

Model results were generally satisfying. The model captured common characteristic patterns of energy inflow for each sub-basin and peak events. All sub-basins, except one, exhibited high values of the Coefficient of determination (r2); weekly r2 values of approximately 0.8 (monthly 0.9) in calibration and 0.7 (monthly 0.8) in validation. The final result was satisfying validation showed weekly r2 0.87 (monthly 0.92) for the calibration, and 0.75 (monthly 0.82) for the validation and with a relative low Accumulated difference of -2106 GWh. These objective functions, together with the evaluation of input data, give the conclusion that the model is reliable and probably useful for future predictions of hydropower production at the Paraná River basin.

Keywords

Brazil, Paraná basin, Hydropower, HBV model, Natural energy inflow, El Niño/La Niña

Preface

This project is not unique in that sense that it has already from the beginning being like a rollercoaster, with its continuously ups and downs but during this process we have realized that we have also learnt a great deal about ourselves, Brazilian hydropower as well as HBV modeling.

Acknowledgements

There are many persons we would like to send our appreciation to. Especially thanks to our supervisor at Thomson Reuters Point Carbon Stefan Söderberg and our supervisor at Lund University Professor Cíntia Bertacchi Uvo. Warm regards and thanks to Stefan's colleagues Marion Guegan and Marc Pearson and Cíntia's colleague Fabio Pereira. Thanks to all nice and helpful Brazilians from different institutions that we have come in contact with during our search for data and information. Also thanks to our dear families and friends for your support and encouragement.

Lund 7/6- 2013

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Acronyms

Types of power plants
CGH Central Hydroelectric Generating
PCH Small Hydropower
UHE Hydroelectric power

Actors in the Brazilian energy sector and climate institutions
ANEEL National power agency
ANA/Hidroweb National water agency
CCEE (before MAE) Electric Power Commercialization Chamber
CPTEC Centre for Weather Forecasting and Climate Research
EPE Energy Research Company
ELETROBRAS Brazilian Electric Central, S.A.
FURNAS Furnas Electric Central, S.A.
BIG Bank of Generation information
INMET National Institution of Meteorology
MMA Ministry of the Environment
MME Ministry of Mines and Energy
NOAA National Oceanic and Atmospheric Administration
ONS National Electrical System Operator
SIMEPAR Information centre of environmental technology
SIN National Interconnected System

Hydrological and political divisions used in this project
Total basin: Paraná basin
Sub-basins: Paranaíba, Grande, Tietê, Paranapanema, and Paraná
Regions connected to Paraná basin: Central (CO), SouthEast (SE) and South (S)
Obs! See section Climate variability (Grimm, 1998) divides regions into: CentralWest (CW), CentralEast (CE), SouthEast (SE) and South (S).
States connected to Paraná basin: Mato Grosso do Sul, Goiás, Minas Gerais, São Paulo and Paraná

1. Introduction

Brazil is a country with huge amount of water resources, which are used extensively for hydropower production. Dominant part (64.5%) of the electricity supply comes from this natural and renewable resource. The Paraná basin has the largest installed capacity in Brazil of approximately 40 GW, including the impressive power plant Itaipu. Dependency on electricity from hydropower influences decisions and prices on the energy market.

The hydrological cycle is connected with hydropower production; thus, weather and availability of water in a river basin affects with time the production. A model with precipitation and temperature as the main inputs and basic concepts of transport and transformation of water resulting in inflow to a basin could act as a simplification of the hydrological system, which will in the end affect hydropower.

This thesis project aim is to calibrate and validate an energy based HBV model, the Scania-HBV model; by using energy inflow target series for the Paraná basin, Brazil see further Aim below. Information about energy inflow from this project and changes in reservoir storage could be used later on by Thomson Reuters Point Carbon to interpret future hydropower production and its connection to prices. Knowledge that is valuable for all actors on the energy market.

1.1 Aim

- Adapt the Scania-HBV model to the Paraná basin and simulate historical and current energy inflow.
- Make the model as reliable as possible and evaluate it so that Thomson Reuters can use it to predict future energy production and prices.

1.2 Limitations

Although this project was accomplished with a carefully and precisely chosen method and has reached its aims, it has some unavoidable limitations.
To begin with, shortcomings due to simplification of the hydrological situation in the model compared to reality. It is the first time when Scania-HBV is tested on the area without any snowmelt. Secondly, input related limitations are of importance. Even though quality of precipitation and temperature data, together with their source, was thoroughly verified, single errors in the series are inescapable due to human inaccuracy of measurements, operations on the series, change of technology and conditions in surroundings of stations. Furthermore, significant part of natural energy inflow target was not straightforwardly provided, but created artificially yet with best workable approach.

2. Background

2.1 Thomson Reuters

The project task was provided by Thomson Reuter Point Carbon, a price analytic company on the energy market. The usefulness of this project can be better understood with a brief overview of the energy market, and how Thomson Reuters acts in it and the services they offer. Note that Figures shown in section 2.1 are taken as example of how results from the Scania-HBV model can be used; in this case, energy inflow and system prices are for Norway.

There are two main components to the energy market, the **physical** and the **financial one**. The **physical** market includes power generation, transmission and distribution, environmental laws etc. An important part of the physical market is the spot market, which deals with the immediate trade of electricity. Actors on the market receive daily or one-day-prior pricing information from the market place.

The **financial** market includes short-term agreements on future prices, system prices, and speculation, which secure prices. Contracts on agreements are of varying lengths and no delivery is included. Thomson Reuters forecasts prices on the financial energy market. The company offers analysis, consulting services and news for energy, gas and, carbon dioxide markets. They do risk assessments and forecasts that show how the climate conditions will affect supply and prices from different energy sources. Clients, energy producers and power companies for example, can receive daily updated information to support purchasing and energy source selection (Söderberg, 2012).

2.1.1 Forecasting prices on the energy market

The Scania model is the hydrological energy model used at Thomson Reuters' hydrological department. This model includes parameters for storage, as well as the physical movement and transformation processes for water. The balance generates a hydrograph in energy units of GigaWatt hours (GWh) and is calibrated against observed energy inflow values (target values). Receiving as trustworthy predictions from the HBV model as possible is of great importance. Results are continuously compared with observed values and with other hydrological models. The more predictive the models are, the more valuable the information Thomson Reuter can deliver is.

A reliable model is used to create forecasts, both short- and long-term. Short-term forecasts are run based on the most recently state of the soil, groundwater, and snow together with observed precipitation and temperature. Nevertheless, the main goal for Thomson Reuters is to create a model that can be used to predict energy prices on the market at least one year ahead. Initially, a model is created corresponding to a short-term forecast, often 14 days, provided from an institution. The result is then used together with historical data to simulate a long- term prognosis. To compensate for the uncertainties in the future forecasts, several scenarios are modeled for the long-term prognosis. An average is calculated for the different scenarios and the distance between the curves gives a picture of the probability of different scenarios occurring (Söderberg, 2012).

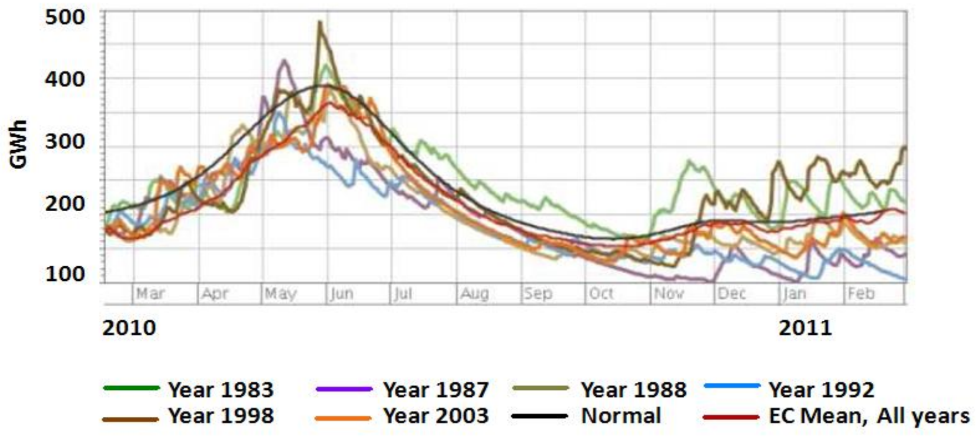

Figure 1 Weekly inflow simulated for different weather scenario inputs (Söderberg, 2013)

Figure 1 shows model results forecasting energy inflow in Norway for 2010 and 2011. The model is run multiple times using data from various years as input, each reflecting different meteorological scenarios (e.g. El Niño year 1983), and this observed meteorological data is combined with current state of soil, groundwater, and snow. The different scenarios are compared to a normal curve (black) which is the modeling result for a long-term meteorological data series; 1981-2005 and the mean forecast for the six individually selected years (Söderberg, 2012). Figure 2 also presents the weekly inflow long-term forecast, including the normal situation (black) in comparison with the mean (red) of different scenarios. The uncertainty range is shown in two shades of grey for 10, 25, 75 and 90 percentile values of uncertainty (Söderberg, 2012).

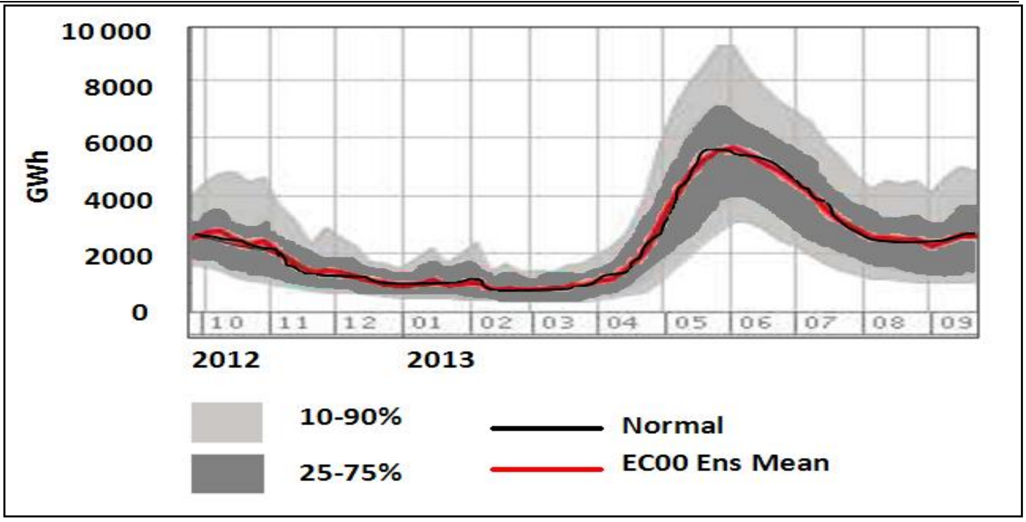

Figure 2 Long-term forecast including the normal situation, mean, and uncertainty (Söderberg, 2013)

Energy prices in countries with a high degree of hydropower dependency correlate strongly with water availability. Hence, the concept of hydrological balance can be used to describe the energy situation for hydropower and to compare it with the system price in a region. If a change in the hydrological balance is, for example, positive (e.g. increase of water in the reservoirs), the price decreases see Figure 3.

$$\boldsymbol{Hydrological\ balance\ (GWh)} = \boldsymbol{Hydrological\ situation} - \boldsymbol{Normal\ situation}$$

Where: Hydrological situation = snow&soil + reservoir = total reservoir
Normal situation = snow&soil+reservoir

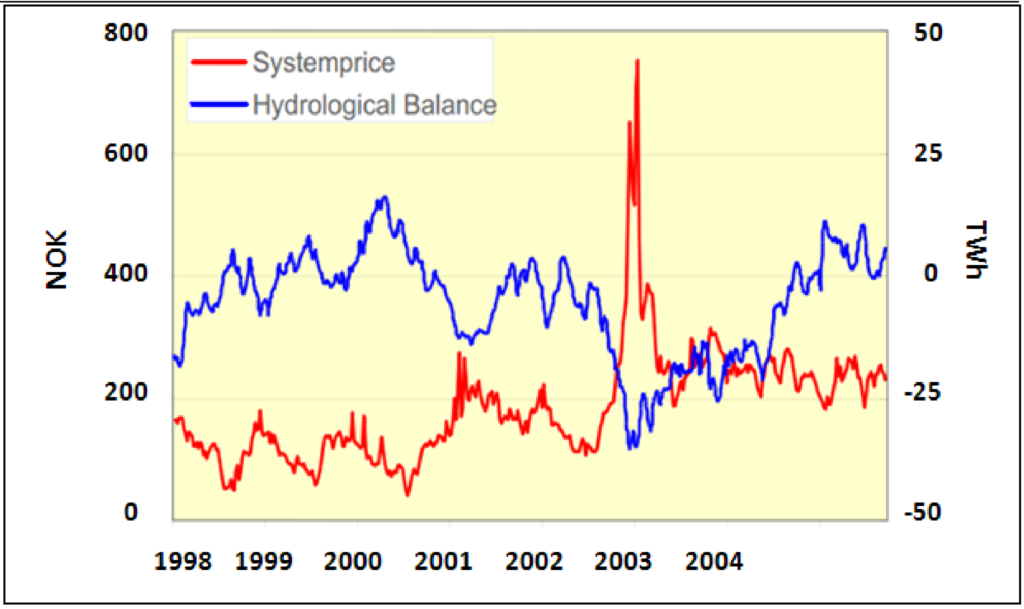

Figure 3 Connection between system price (NOK) and hydrological balance in unit TWh (Söderberg, 2012)

2.2 Brazilian energy market

Hydropower is the major source of electrical power in Brazil and consequently dominates the energy market. More than 64.5% of the electricity supply and 82.8% of consumer energy needs are met by hydropower (ANEEL, 2013), (Bermann, 2007). Production from hydropower in 2011 was 472 TWh, according to the EPE this number will probably increase to 736 TWh by 2021 (Lobão, et al., 2011). The abundance of hydropower in the Brazilian energy market results in lower energy prices compared to countries with a larger variety of energy sources, but sudden disruptions in the system caused by e.g. climate anomalies show the system vulnerability see Figure 4 (Schwieger, et al., 2009).

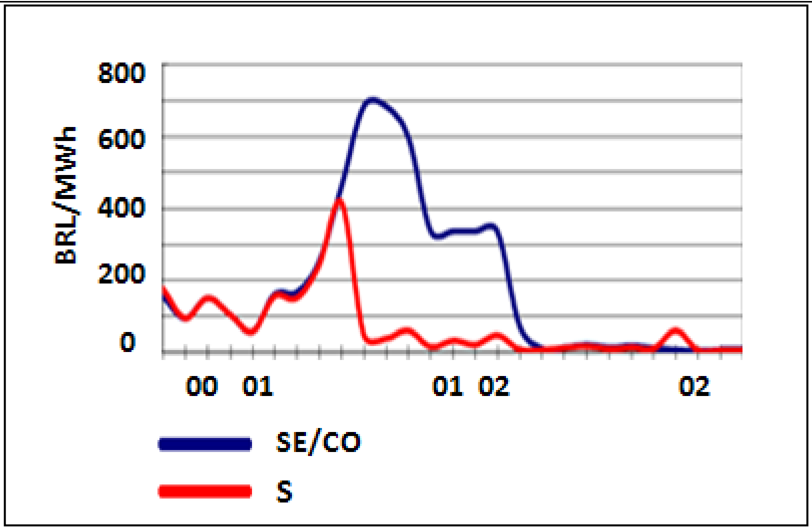

Figure 4 Drought event and failure of distribution system year 2001 effect on energy prices in the South and Southeast/Central region ((Bardelin, 2004)

The dominant control of the Brazilian government over the energy sector decreased in the beginning of 1990s, when the privatization of generation and distribution of electricity started. The aim of the privatization was to create a self-regulated spot market for electric power. ANEEL, independent of the government, was founded and ONS became responsible for the management of SIN.

The production and transmission of hydro electricity in Brazil is large and complex with many actors. SIN was formed by companies all over Brazil and today, only 3.4% of production capacity is not part of SIN. CCE, a private non-profit association for companies involved in generation, transmission, and distribution of electricity was formed in 2001. Today, the electricity market is not yet totally liberalized. The state owned company ELETROBRAS owns a large share (~40%) of the installed capacity and transmission systems, but most of the energy distribution system is privately owned. (Schwieger, et al., 2009).

The federal government established a new market model for the power sector in 2003/2004, including two general markets for selling and purchasing electricity contracts, the Free Contracting Environment (ACL) and the Regulated Contract Environment (ACR). Free negotiations and bilateral contract agreements between generators, traders, importers/exporters and free consumers define the ACL market section. Only generators are involved in both environments, where they can freely sell their energy. (Anon., 2010). The electricity distributers in the SIN system only act in the ACR segment. To ensure optimized generation and transmission costs, consumers with a consumption of over 500 GWh/year are required to participate in auctions organized by CCEE and regulated by ANEEL. EPE together with MME start the auction process by investigating the lowest-cost source for generation on the market. Generation actors compete in the auction to offer the lowest price per MWh, and to reach the forecasted energy demand from the distributors. Finally, bilateral contracts formalize the purchase and sale of energy. The auction system was created to ensure a low price tariff and secure electrical supply for consumers, and to guarantee the sale of generation capacity (Anon., 2010).

CCEE sets the spot prices on the market and arranges the electric power auctions. Another obligation for the institute is the registration of contracts from both markets and the regulation of differences in the short-term market. (Anon., 2010) CCEE divide the market into four pricing areas, South (S), Southeast (SE) (including CO), North (N), and Northeast (NE). These areas are split into three loads (heavy, medium, light). The spot price is in units of Brazilian real per megawatt hour BRL/MWh. Energy prices on the spot market are generally low except when there is lack of energy. It is always in the energy producer's interest to generate more electricity when prices increase but there is a dominant governmental control, which regulates production and prices. Production is regulated by the governmental institution ONS and their demands depends mainly on consumption needs from society (Freire, 2013). The average spot price in Brazil was, 62 BRL/MWh in 2002 (CEE, 2002).

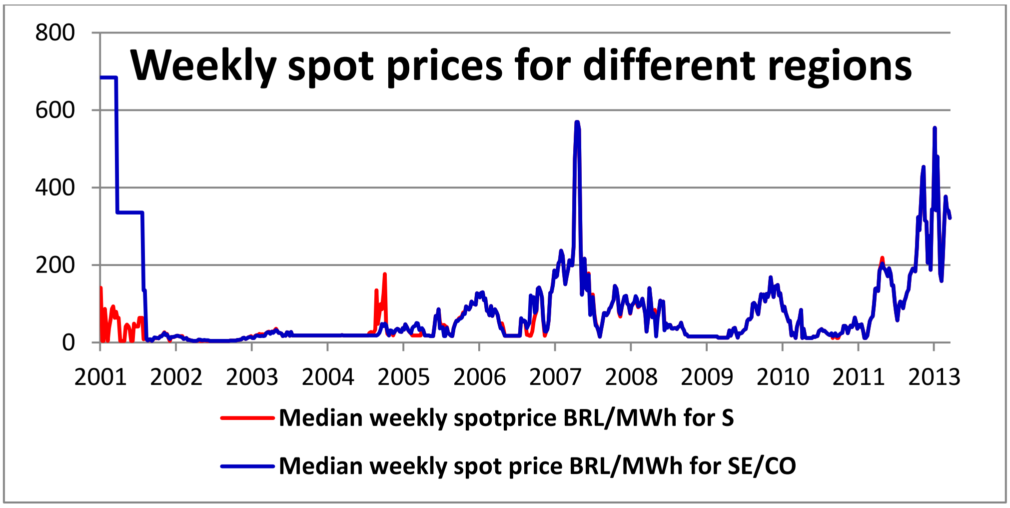

Figure 5 Median weekly spot prices in BRL/MWh in the price regions S and SE/CO from 2001 to 2013 (Freire, 2013)

The average weekly spot price from 2001-2012 was 67 BRL/MWh in S and 88 BRL/MWh in SE/CO. These prices could be compared with average weekly spot prices in Sweden e.g. in 2011 it was approximately 140 BRL/MWh (~50 EUR/MWh) (NordPoolSpot, 2013).The Brazilian spot prices are generally low except for some years when prices peak. In 2002-2004, 2009 and 2011 the prices stayed consistently low but there were peaks, especially in 2001, 2005-2008, 2010 and 2012-2013. The extreme peaks could be connected to many different causes.

The extreme price peak in year 2001 for the SE/CO regions was a consequence of severe drop in reservoirs water level due to drought and lack of planning and investment (Freneda, 2010). This resulted in cut down of energy generation, nevertheless south part was not affected at same extent since reservoirs in this region were full and investments in the energy sector had already been made, therefore prices in south region were less affected see Figure 5. In a report from Audit Court (TCU) published in 2009 calculation for economical loss due to the crisis in 2001 was estimated to £ 45.2 billion. There could be multiple reasons for extremes in prices. Generally, the market is governmental controlled and prices are fluctuating due to the involved institutions decisions but impact due to long-term technical problems or due to climate variability could in the end influence prices as well. In September 2007 there was a power shut down in two states due to technical problems in the power plant Furnas, problems that led to the blackout could be one of many reason for peak prices in 2007. In November 2009 complete shutdown of Itaipu, SE region was most affected for ex. Mato Grosso do Sul, Paraná, Goiás, São Paulo and Rio de Janeiro. In October 2012 there was a transformer failure in Itaipu, affected e.g. Paraná, Rio de Janeiro, Minas Gerais, the outcome was power outage in hydropower plant Furnas, which affected Southern Brazil (DefesaNet, 2012).

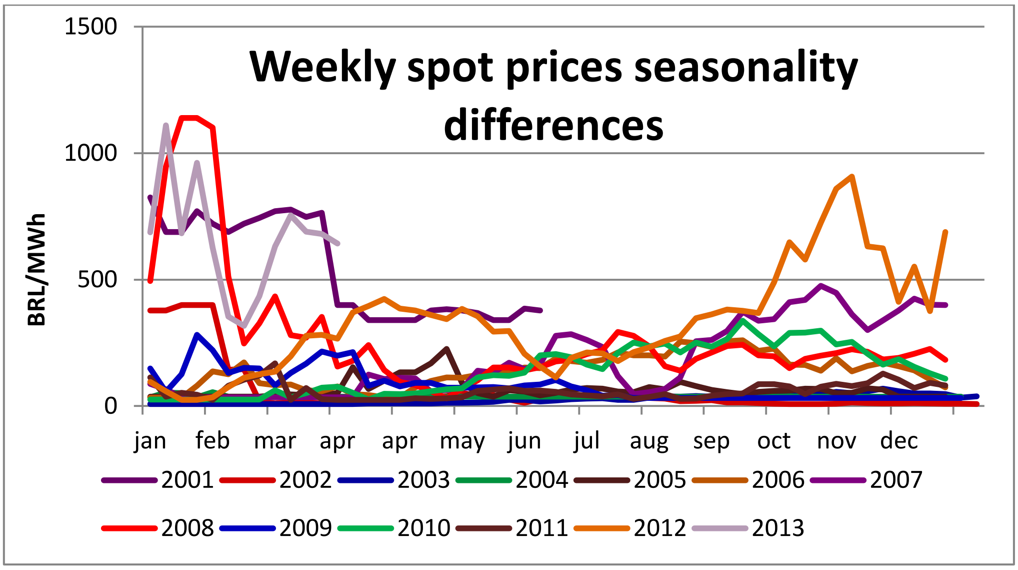

Figure 6 Median weekly spot price in BRL/MWh for SE/CO and S regions for different years (Freire, 2013) *Note: Currency BRL to SEK and EUR (1 BRL=3.21 SEK and 1BRL=0.36 EUR)*

During spring and summer in 2001, 2008 and 2012/2013 the energy prices on the market were extremely high Figure 6. Explanations for these extremes could be found in the market section above combined with the section of abnormal climate events. Any occasion of long-term drought effecting hydropower system during wet periods might be the reason for increased prices, since this is the most important period for collecting storage of water for production (ThomsonReuters, 2013). Other years also show variations in prices during the seasons but the general trend is that during summer and spring the prices are low and during the drier winter season the prices increase a bit or the prices are on a constant low level throughout the year.

2.3 Climate

2.3.1 Precipitation and Temperature

There are two main seasons in central Brazil including most of the Paraná basin, wet and dry. The Brazilian summer in December - March coincides with the rainy season. The South American Summer Monsoon (SAMS) is responsible for most of the precipitation during the rainy season in Brazil. In the Paraná basin, experiences 400-700 mm of rainfall in this season and temperatures stay on average between 21-26°C. Figure 7 and 9 show average data during these months from 1961-1990. Brazilian winter is in June- August and is the dry season because it is characterized by lower amounts of rain, on average 50-300 mm, and temperatures are on average between 16-22°C see Figure 8 and 10.

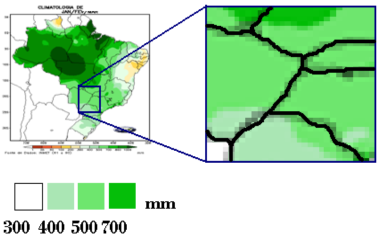

Figure 7 Precipitation (mm) in Paraná basin during Brazilian summer, J-F-M, (CPTEC/INPE, 2013)

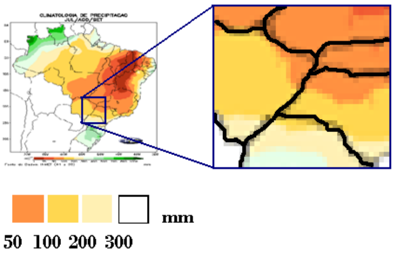

Figure 8 Precipitation (mm) in Paraná basin during Brazilian winter, J-J-A, (CPTEC/INPE, 2013)

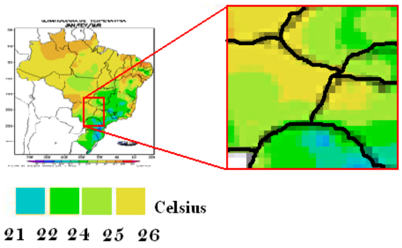

Figure 9 Temperature (°C) in Paraná basin during Brazilian summer, J-F-M, (CPTEC/INPE, 2013)

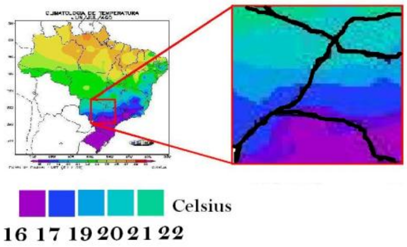

Figure 10 Temperature (°C) in Paraná basin during Brazilian winter, J-J-A, (CPTEC/INPE, 2013)

The above figures show that the North and Central parts of the Paraná basin have the largest variations in rainfall between the seasons and receive the largest amount of rain during the wet season and the least amount in dry season. The temperature figure shows that the North West and Central West parts of the Paraná basin have the highest temperatures during both the wet season and dry season. Typical seasonal differences and climate variations can also be shown by studying annual distributions of precipitation. Figure 7 is calculated from historical data for the years 1956-1992 (AMS, 1993).

In the northern part of the Paraná basin there is a distinct difference between the rainy and dry seasons. Further south the difference decreases and that region receives a more constant amount of rain throughout the year.

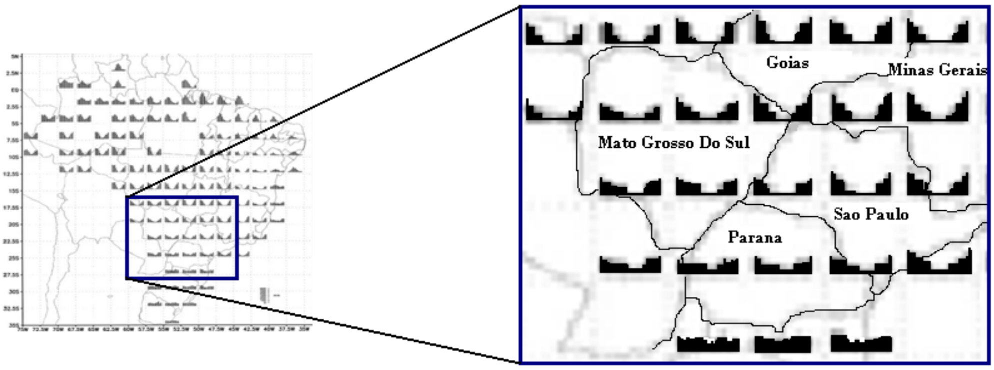

Figure 7 Precipitation distribution in the Paraná basin (AMS, 1993)

2.3.3 Climate variability

2.3.3.1 ENSO cycle

Nearly annual unexpected temperature variations of cold and warm fronts occur across the equatorial Pacific Ocean. These anomalies are connected to the El Niño Southern Oscillation (ENSO), which is a natural phenomenon that can result in very strong year-to-year variation in sea surface temperature (SST), surface air pressure, convective rainfall and atmospheric circulation (ATMOS, 1998). Two extremes are included in the ENSO cycle, the warm episode is called El Niño and the cold episode is called La Niña. These events occur every 2-7 years and El Niño often lasts less than one year while La Niña lasts between 1-3 years. Interactions between SST and the air pressure affect wind systems between the Eastern and Western Tropical Pacific Ocean and are known as known as Southern Oscillations. During El Niño events there is a warming of the SST which leads to the heating and rising of air above the sea, resulting occasionally in clouds with heavy rains. La Niña is connected with the opposite effect (NOAA, 2012).

ONI stands for Oceanic Nino Index and is based on observed monthly averages of fluctuations in SST in the 3.4 region; see Figure 46 in Appendix, between Tahiti and Darwin across the Tropical Pacific. An ONI index that is above or below +/-0.5$°C$ for more than five seasons (e.g. JFM, FMA, MAJ, AJJ, JJA) indicates an extreme event. If the index is more than +0.5 $°C$ during a period of more than five seasons indicate a El Niño event and is the index -0.5 $°C$ during a period of more than five seasons indicate a La Niña event see Figure 8 (NOAA, 2013).

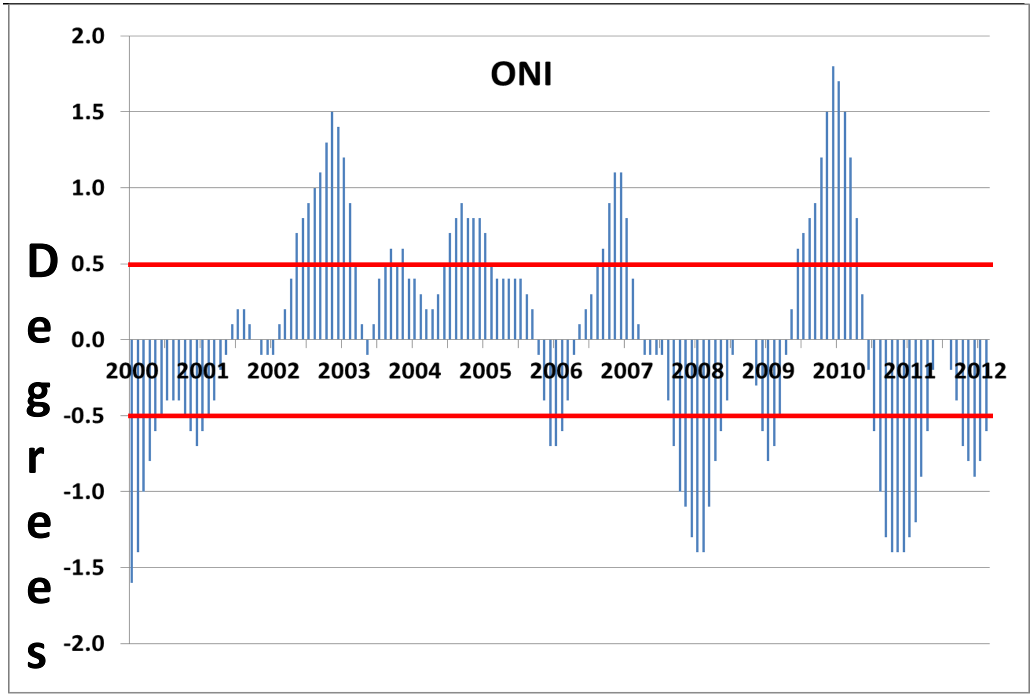

Figure 8 ONI based on sea surface temperature variability view when there is a El Niño event (above +0.5°C) respectively La Niña event (below -0.5°C) after a period of five seasons (NOAA, 2013).

Interactions between ocean surface and atmosphere in the Pacific Ocean affect rainfall and temperature patterns and can result in abnormally wet or dry conditions. A study by Grimm from 2003 showed the effect of El Niño on the summer monsoon (during the wet season) in Brazil. Most of the rain falls during the wet season making this period very important since lots of economic activity (e.g. hydroelectricity) is dependent on the amount of water generated. In the beginning of the summer monsoon season, Central East had a heat period which led to negative precipitation anomalies in central Brazil while a positive one with cyclonic circulation occurred in the South due to moisture inflow from the Atlantic. In January, increased precipitation in the Central East and anomalies in the South almost disappeared. In February, there were negative anomalies in the Central East and positive in South. Another study showed the same results from an El Niño event and noted also an indication of increased dryness in the Southeast regions the year before a warm event (Grimm, 1998). Within a single season, there are changes in temperature and precipitation patterns connected with a La Niña event. In the spring of a La Niña event, the precipitation anomalies are often positive in the Central East and negative in the South. In December-January, wet flux anomalies occur in the South and Central West but not in the Central East. At the same time, precipitation below normal occurs in Southeast. In February, positive sea temperature anomalies in the Southeast and positive rainfall anomalies in the South Atlantic convergence zone and negative in south see also simplified summary in Table 1 (Grimm, 2003).

Table 1 Change in rain patterns, positive (+) and negative (-) caused by climate anomalies from sources used above are summarized to get a clearer overview.

+/- Precipitation anomalies	CW (≈West of Paraná basin)			CE (≈Mid/East of Paraná basin)			SE (≈East part of Paraná basin) - Year before El Niño			S (≈South of Paraná basin)		
*spring-early summer **Dec./Jan.	Dec.	Jan.	Feb.	Dec.	Jan.	Feb.	Dec.	Jan.	Feb.	Dec.	Jan.	Feb.
El Niño	-*			-*	+	-				+	0	+
La Niña	+	+		+*				-	+	-*	+ **	-

Note that climate system is very complex and it is impossible to generalize exact change of patterns. Paraná basin is according to Grimm division situated in four different regions; central east, central west, southeast and south.

2.3.3.2 Extreme events

The ENSO cycle occasionally results in extreme events, like droughts and flooding which can have a devastating impact on the society. Knowledge about the yearly anomalies variability is important for economic activity such as hydroelectricity and agriculture. In 1983, several abnormal events occurred throughout Brazil connected with an El Niño event. In May- July extensive flooding was experienced in the South of Brazil (Magrin, 2007). In the years 2000 and 2001, Brazil suffered a major crisis due to a severe and long-lasting drought. The drought caused a drop of 60 % in some reservoir levels and the subsequent reduction in power output. The energy prices reached historical peaks and there was a struggle to cover even the basic demands. Governmental institutions introduced sanctions to be able to decrease energy usage to avoid long-term blackouts (Schwieger, 2009). Recent anomalous climate patterns have also had a huge impact on society. The Southern part of Brazil experienced heavy rainfall and flooding in November 2008 and in the following year (2009), the region suffered from a severe drought.

2.4 Topography and Geology

The Paraná basin is mainly sedimentary with various types of faulting in the crystalline rock due to tectonic movements. Deformations and faulting are important for occurrences of groundwater. The high lands surrounding the Paraná basin disconnect it from the ocean. As a result of this geological feature of the basin, most of the water flowing from higher elevations will end up in the main drain of the Paraná river (MMA, 2006).

Figure 9 shows that within the Paraná basin altitudes vary from 100 to higher than 1000 meters above sea level. In the Central basin, in the surroundings of the Paraná River and its tributaries, the land is flatter, with an approximate elevation of 100-300 meters whereas the elevation increases closer to the outskirts of the basin. Towards the sea in the East part of the basin, the highest altitudes are found. In the states of Minas Gerais and Paraná, there are highland areas with elevations from 600 to above 1000 meters.

Topography has a local and regional impact on rainfall and temperature patterns. On the windward side of higher-elevation regions the moist air rises, condenses, and falls down as precipitation, resulting in drier air on the leeward side (National Geographic, 2012). Dry periods regularly occur in the river valleys during winter time. The temperature is also affected by changes in altitude and often decreases with height (Seo, 2005). The lowest temperatures, reaching below zero, can be found in the Eastern mountainous areas of the Paraná basin. Nevertheless, a dramatic change in temperature from day to night can take place. Hot temperatures are more common in the lowlands (Carvalho, 2006).

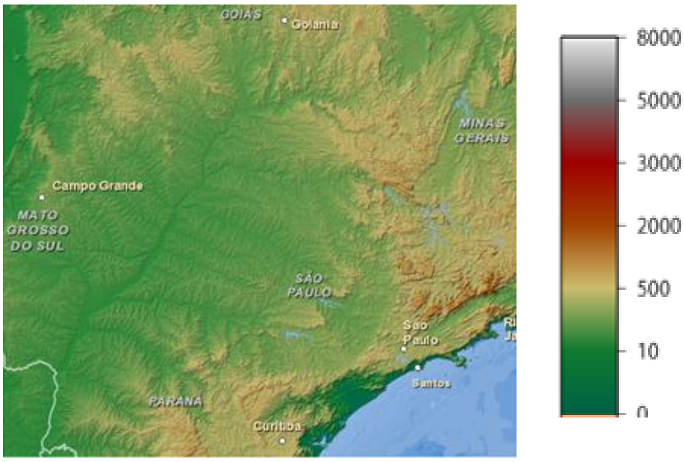

Figure 9 Topography map over Paraná basin (NOAA, 2012)

2.5 Hydrology

2.5.1 Hydrological cycle

Understanding the hydrological cycle and water balance is valuable to be able to understand the basic concepts of a Rainfall runoff model and to realize the simplifications compared to the complex natural system. This knowledge is useful when the connection between hydrological balance, production and energy prices are investigated.

Water in the natural system is transformed and transported by different physical processes driven by the energy from the sun (see Figure 10). In this system, there is no difference between the amounts of water entering and leaving, resulting in a water balance.

$$\mathit{Runoff}=\mathit{Precipitation}-\mathit{Evapotranspiration}-\Delta \mathit{Snow}-\Delta \mathit{Soil\ water}-\Delta \mathit{Groundwater} \quad \textbf{(1)}$$

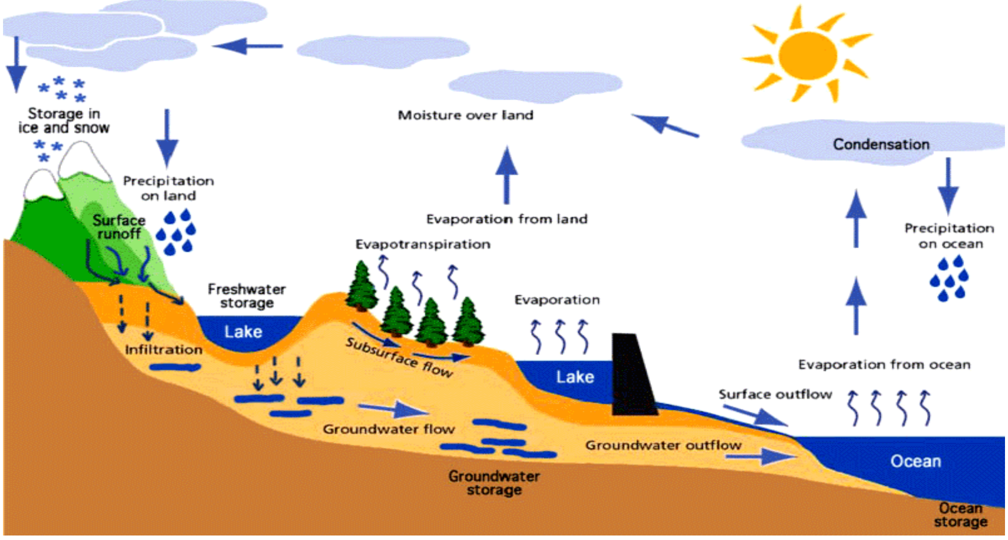

Figure 10 Hydrological cycle including the physical processes (Merritt, 2011)

Physical processes include evapotranspiration, condensation, precipitation and infiltration which move the water between different inland storages; unsaturated and saturated zones in the soil and snow magazines (Fetter, 2001).

2.5.2 Hydrology in Paraná

Brazil is a country rich in water resources as it accumulates 12% of the world's available freshwater resources (ANA, 2007). The Hydrographic Region of Paraná covers 10% of the total Brazilian territory, but 32% of the national population lives in the region, which results in the highest demand for water resources in the country, (about 736 m^3/s). Most of the water resources in the Paraná basin are used for irrigation (42%) and industrial supply (27%) (ANA, 2001), even though the average flow rate of the river basin is only 6.5% of the country's total (GOV, 1999).

The sedimentary intracratonic to the Paraná basin has the largest volume of subsurface fresh water reserves in Brazil, estimated to be 50 km^3 due to the Bauru aquifer (Campos, 2004). The Hydrographic region of Paraná holds about 45% of the groundwater reserves of the country (Borguetti, et al., 2002). The distribution of recharge areas of aquifers in the river basin are as follows: porous, semi-confined Bauru-Caiuá (38%), fractured Serra Geral (23.9%), confined Guarani (3.1%), Bambuí (0,6%), Furnas (0,5%) and Ponta Grossa (0,2%) (ANA, 2007). However, due to the large quantity of surface water and the limitations of this study, the importance and presence of groundwater have not been investigated.

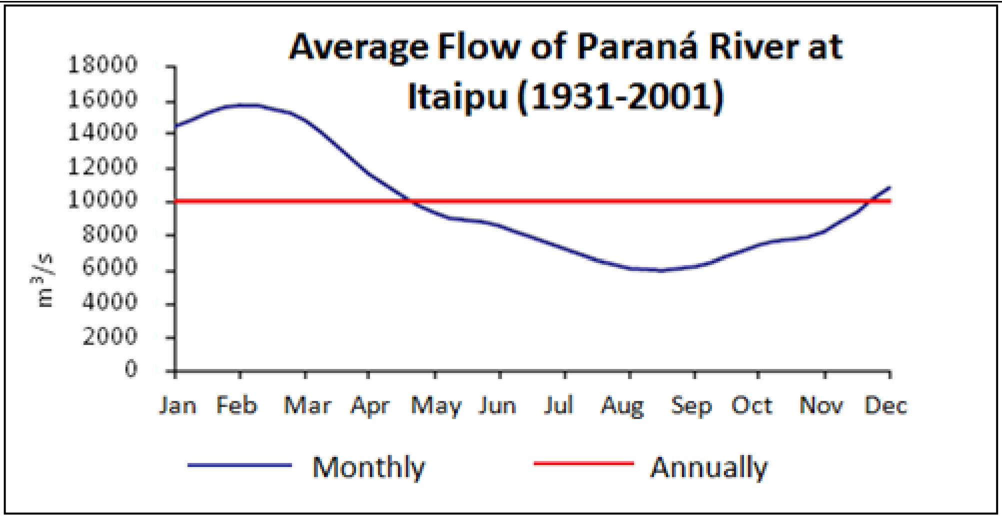

Figure 11 Average monthly and yearly flow in the Paraná basin at Itaipu (ANA, 2005)

Rainfall is a main source of water supply to all rivers in Brazil with an exception of the Amazon, which is supplied with water from glaciers and snowmelt from the Andes (ANA, 2007). The rivers of the Paraná basin flow year-round, however it is important to highlight the seasonal flow variations due to rainfall patterns during different seasons. The largest flows in the Paraná river basin of 15000 m^3/s occur between January and March and the lowest, amounting to 6200 m^3/s, between August and September as shown in Figure 11 (ANA, 2005).

2.5.3 Rivers and Reservoirs

A drainage area of the Paraná river basin till Itaipu dam is 820 000 km^2. The Paraná River originates from a confluence of Paranaíba and Grande and after Itaipu continues to the confluence with Iguaçu to further South become a natural border between Argentina and Paraguay (Binacional, 2006). The main tributaries to Paraná are namely Grande, Paranaíba, Tietê, Paranapanema and Iguaçu (Binacional, 1999) and originate from East or North-East however there are a number of West-originated tributaries as well. Figure 12 displays the main rivers of the Paraná basin.

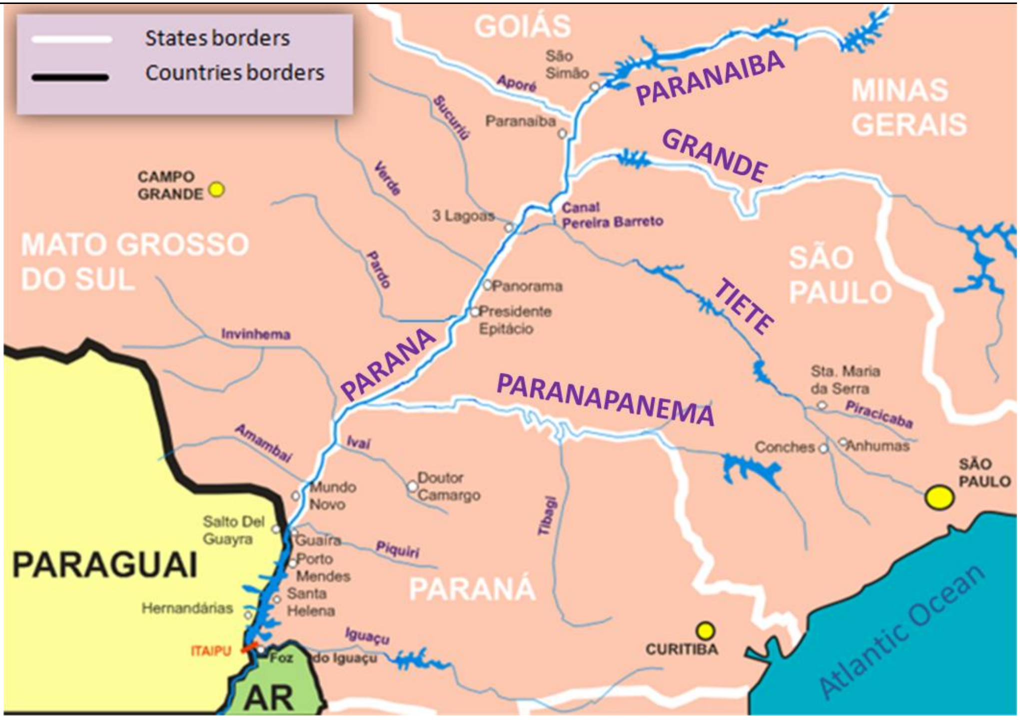

Figure 12 Main rivers in Paraná basin together with political regions of the basin; adapted and translated from (AÇÃO, 2004)

Figure 13 displays variation among tributaries of the Paraná basin in terms of inflow. Tributaries situated in the North of the basin, namely Grande and Paranaíba, carry the largest volumes of water representing a monthly natural energy inflow of over 8000 GWh during the wet season. Additionally, their pattern from year-to-year differentiates clearly seasonality in those sub-basins. Paraná is in the middle range and holds some negative values of natural energy inflow due to a building up the target series elucidated in chapter 4.1.1. Tietê and Paranapanema have the smallest monthly natural energy inflow infrequently exceeding 2000 GWh, and owing to their rather smooth horizontal pattern, the difference between wet and dry season is less clear. Inflow patterns of Paraná tributaries presented on the hydrograph reflect exclusively the precipitation distribution in the basin described in chapter 2.3.1 Precipitation and Temperature

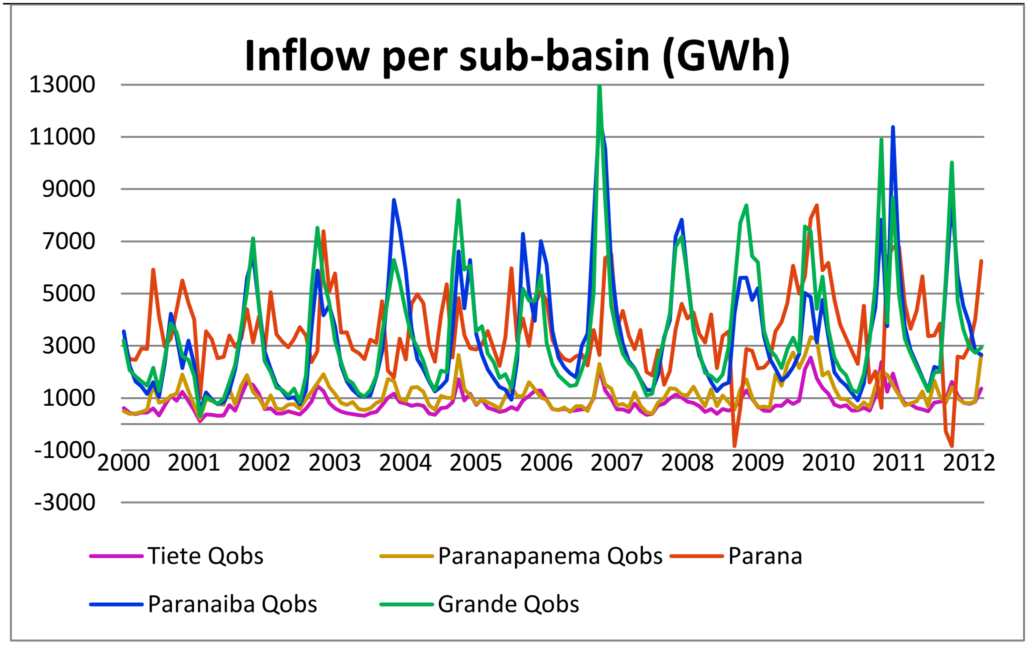

Figure 13 Monthly energy natural inflow to rivers of Paraná basin during period 2000-2012

In total 23 036 water bodies with water surfaces of minimum 20 ha were mapped in Brazil, 16 108 of them are natural water bodies (lakes and ponds) and 6 928 artificial reservoirs. In the Northeast and South of Brazil, hence in Paraná basin as well, artificial water bodies are predominant due to numerous constructed hydropower plants, as shown in Figure 14 (Benício, et al., 2009).

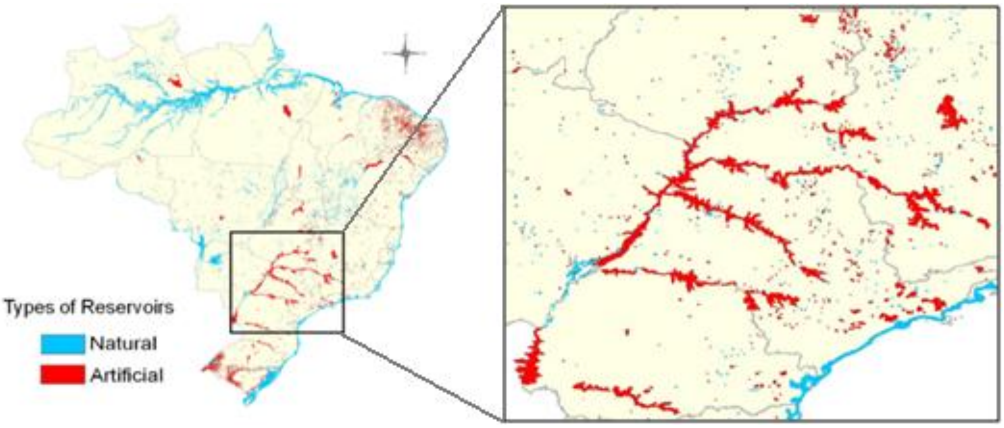

Figure 14 Spatial distribution of reservoirs with minimum surface area of 20 ha in Brazil; adapted from Benício, et al., (2009)

There are 57 major reservoirs in the Paraná basin (Binacional, 1999). The Itaipu reservoir is the seventh largest reservoir in Brazil but has the highest rate of water use for energy with a production index of 10.4 MW per km^2. Its normal surface area is 1350 km^2 and the useful volume is 19 km^3 (Binacional, 1999). Other than Itaipu, the major water bodies of the watershed are São Simão, Nova Ponte, Emborcação, Itumbiara in the Paranaíba basin, Furnas, Água Vermelha, Marimbondo in Grande basin, Capaivara and Chavantes in the Paranapanema basin, lha Solteira on Paraná River (ONS, 2013).

2.6 Hydropower plants

Hydroelectricity in Brazil accounts for 64.5% of the country's installed capacity (ANEEL, 2013) and 82.8% of the total electricity consumed in the country (Bermann, 2007). Paraná Hydrographic region stands out among all the basins in Brazil in terms of installed capacity holding 60% of the national total. The river basin has the highest electricity demand in the country and 75% of national electricity consumption is used within this basin (Filho, et al., 2005).

Data collected from numerous hydropower plants and total installed capacities for both the Paraná basin and whole Brazil diverge depending on the source of information, see Table 3 and Table 4 in chapter 2.6.3 Installed capacity.

The largest hydropower plant in the basin is Itaipu with a total installed capacity of 14000 MW (7000 MW for the Brazilian part and 7000 MW for the Paragyanan part) (Binacional, 2012). Among other power plants operating in the basin the largest are Ilha Solteira with installed capacity of 3444 MW, Itumbiara with 2082 MW and São Simão with 1710 MW (ANEEL, 2013).

2.6.1 Geographical location

Water resources are plentiful in Brazil, and the Paraná River basin, where 32.1% of the national population resides, has the most developed economy and the largest demand for water resources in the country (ANA, 2001). Moreover, the Paraná basin is a typical plateau basin contributing to the formation of many waterfalls, which is optimal for hydropower. These factors could be the reason why the Paraná basin is the area where the most hydropower plants are located. Figure 15 is a screen shot from Google Earth displaying subdivisions of the Paraná basin and the distribution of hydropower plants based on an ANEEL (2013) list. Itaipu is located on the border between Brazil and Paraguay, thus the countries share its energy generation.

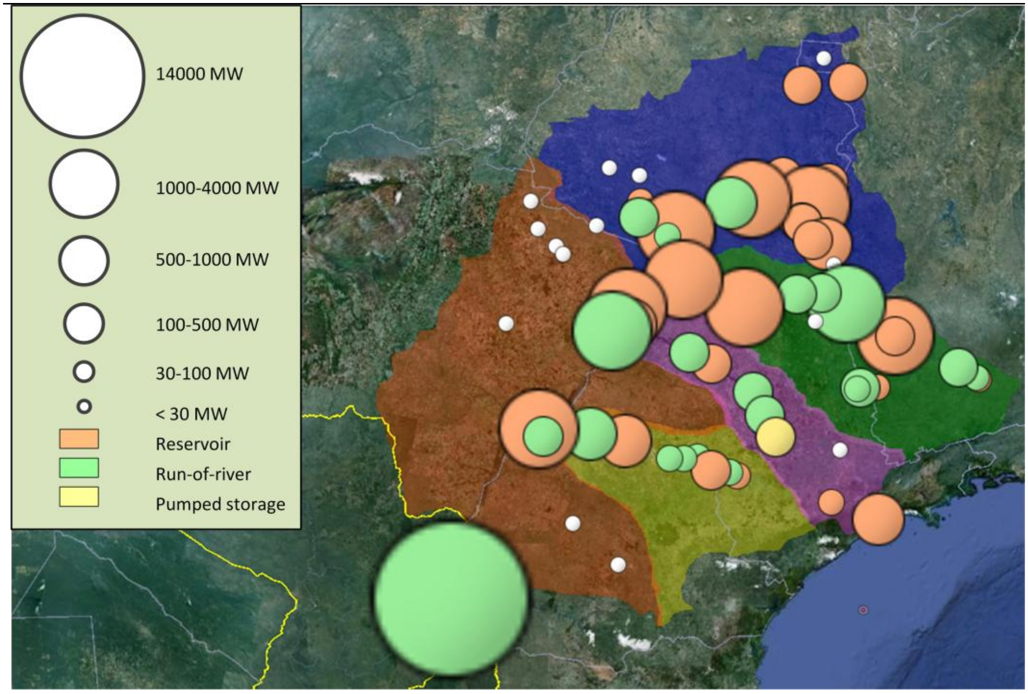

Figure 15 Geographical location of hydropower plants in Paraná basin and their installed capacities

Distribution of hydropower plants and total installed capacities for the Paraná sub-basins are presented in Table 2. Owing to varying sizes of hydropower plants, the larger amount of power plants does not necessarily imply larger total installed capacity in a sub-basin. The Paraná sub-basin, having the least number of hydroelectricity generation units due to Itaipu, holds 49% of total installed capacity of the Paraná basin. This division has been made based on the ANEEL operational power plants list (2013) and it's worth mentioning that all plants of unknown type are small hydropower plants, which means of an installed capacity smaller than 30 MW.

Table 2 Types of hydropower plants in Paraná basin (ANEEL, 2013)

	Grande		**Paraná**		**Paranaíba**		**Paranápanema**		**Tietê**	
Power Plant Type	No. of Plants	Installed Capacity (MW)	No. of Plants	Installed Capacity (MW)	No. of Plants	Installed Capacity (MW)	No. of Plants	Installed Capacity (MW)	No. of Plants	Installed Capacity (MW)
Pumped Storage	0	0	0	0	0	0	0	0	1	141
Reservoir	6	4655	2	4984	13	7135	3	1152	2	1556
RoR*	9	2757	2	15551	5	1145	7	1268	3	622
Unknown	33	221	18	231	15	252	19	107	24	191
Total	**48**	**7632**	**22**	**20767**	**33**	**8532**	**29**	**2527**	**30**	**2510**

*RoR – run-of-river hydropower plants

2.6.2 Different types of hydropower plants

In terms of types of hydropower plant, among known hydroelectricity generation units, predominant in the river basin are run-of-river (RoR) plants, followed by hydropower plants of type reservoir, whereas there is only one hydroelectricity generation unit defined as pumped storage, as shown in Table 2 in chapter 2.6.1 Geographical location.

For the energy market, it makes difference if the electricity is produced by a run-of-river (RoR) plant or a reservoir one. Reservoir power plants allow for flexibility in the timing of energy generation as water can be stored during off-peak times, when demand for energy is low, and released at peak times, during drier periods of the year (Jager & Bevelhimer, 2007). Run-of-river operation involves energy production more proportional to the hydrological situation as water is diverted directly from a river or stored shortly. Therefore, run-of-river power plants are of less value for the energy market. In addition, these facilities do not require the flooding of large land areas hence they have smaller environmental footprint (Ragheb, 2010).

2.6.3 Installed capacity

Daily updated bank of generation information BIG amounts total installed capacity of operating hydroelectricity generation units in Brazil to 84.766 GW where 0.28% is CGH, 5.1% is PCH and 94.6% is UHE (ANEEL, 2013).

According to data (the IIR database) provided by Thomson Reuters Point Carbon total installed capacity of Brazil is 87.381 GW and from the ONS list of power plants it is 90.724 GW (ONS, 2012). The Table 3 below displays those differences.

Table 3 Power plants and installed capacity in Brazil

Number of hydropower plants	Total installed capacity (GW)	Source
1014	84.766	ANEEL
266	87.381	IIR database
644	90.724	ONS

Total capacity installed in hydropower for the Paraná basin, according to collected databases, is in a range of 50% of entire installed capacity for the whole country, totaling 41.968 GW (ANEEL, 2013). Table 4 presents also two other sources for installed capacity and a number of power plants for the Paraná River basin.

Table 4 Power plants and installed capacity in Paraná basin

HPPs Paraná basin	Total installed capacity (GW)	Source	Comment
162	41.968	ANEEL	Based on river names, many rivers of small HPPs not found
72	41.570	IIR database	Based on location (state, region, coordinates)
52	36.518	ONS	Plants > 30 MW collected from a chart

It is interesting to observe how the installed capacity of hydropower was changed throughout the years and to compare it with historical installed capacity values of other renewable energy sources in Brazil. Figure 16 presents a significant increase of installed capacity in hydropower from 1974 to 2010.

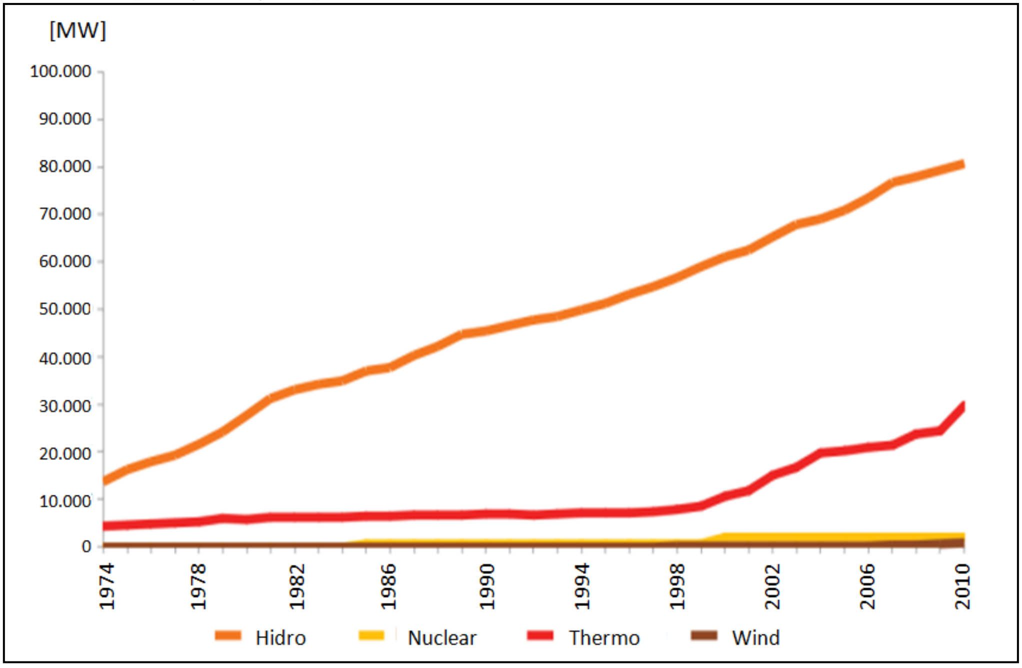

Figure 16 Installed capacity of electric energy generation in Brazil (Lobão & Tolmasquim, 2011)

2.6.4 Generation

In terms of electricity generation, Itaipu is the largest dam in the world, having produced 98 287 GWh of energy in 2012 (Binacional, 2012). The historical annual electricity production of Itaipu from its opening in 1984 to 2012 is shown in Figure 17 and it is in 2007 since installed capacity of Itaipu is invariable due to last units installed. The annual hydroproduction for the Paranapanema, Grande, Tietê, Paranaíba and Paraná is presented in Figure 18 and shows an overall increase in electricity generation for the time period 2002-2011 for all basins except the Paraná. This is due to the documentation from ONS where the Brazilian part of Itaipu is considered as part of the SE region, hence a sub-basin of Paraná until 2007. From 2008 and onwards no information about Itaipu is provided in this production data. The largest yearly production was in 2006 when the 5 sub-basins of the Paraná basin produced 222 881 GWh of energy. No information about hydroelectricity production in 2003 per sub-basin is given, so for the purposes of the graph in this project, generation in 2003 was assumed to be equal to the generation in 2002.

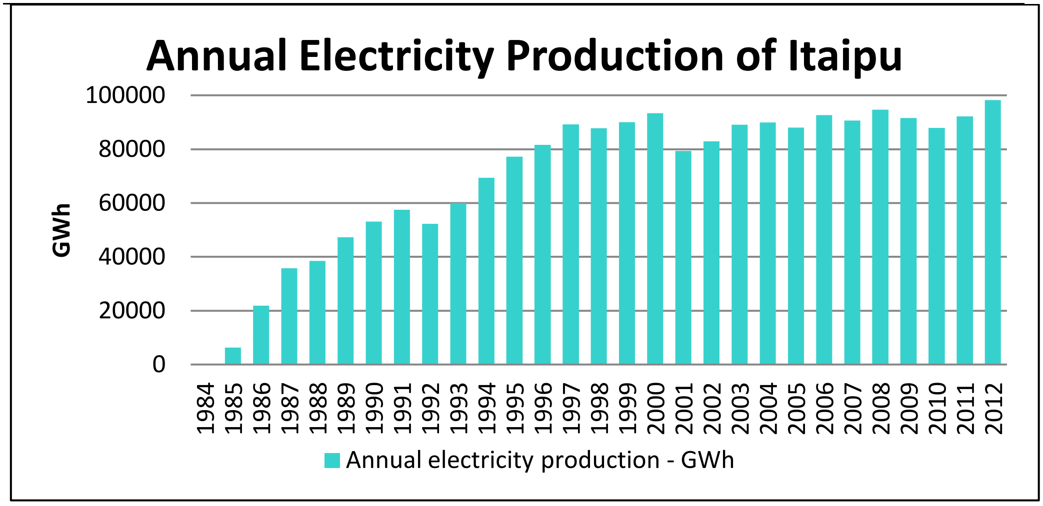

Figure 17 Annual total hydroelectricity production of Itaipu in GWh for Brazilian and Paraguayan part (Binacional, 2012)

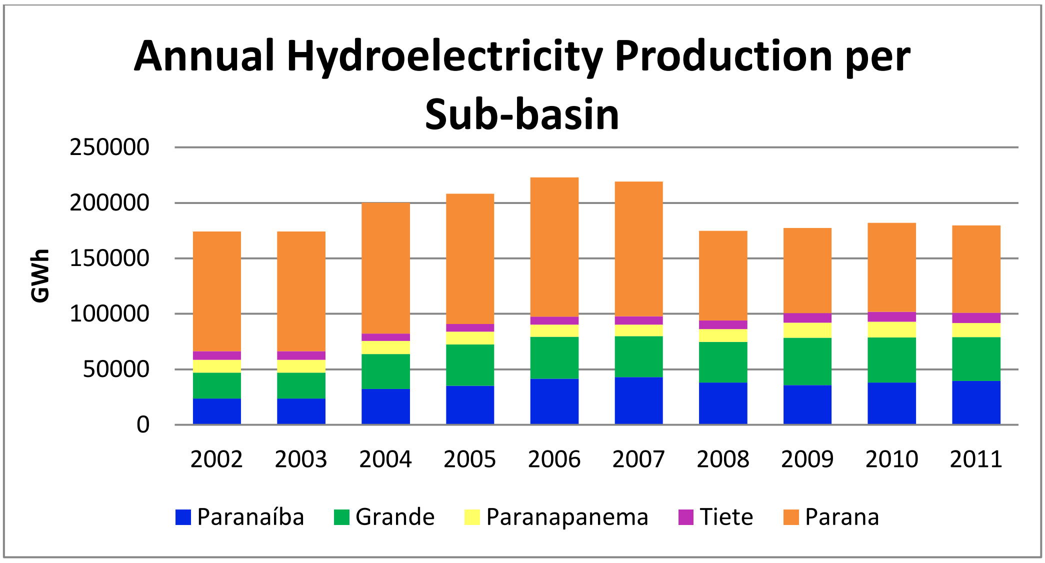

Figure 18 Annual hydroelectricity production for sub-basins of the Paraná basin (ONS, 2013)

The highest inflow to reservoir systems in the Paraná basin occurs in January, February and March, thus one can expect that this is the period when the most energy from hydropower is produced. However, in the long run the producers together with ONS regulating production are what decides when, and how much, electricity to produce for a certain demand. The limitations are storage capacity and amount of available water. Figure 19 below displays an average monthly hydroelectricity production for the SE/CO region from 2000 to 2012.

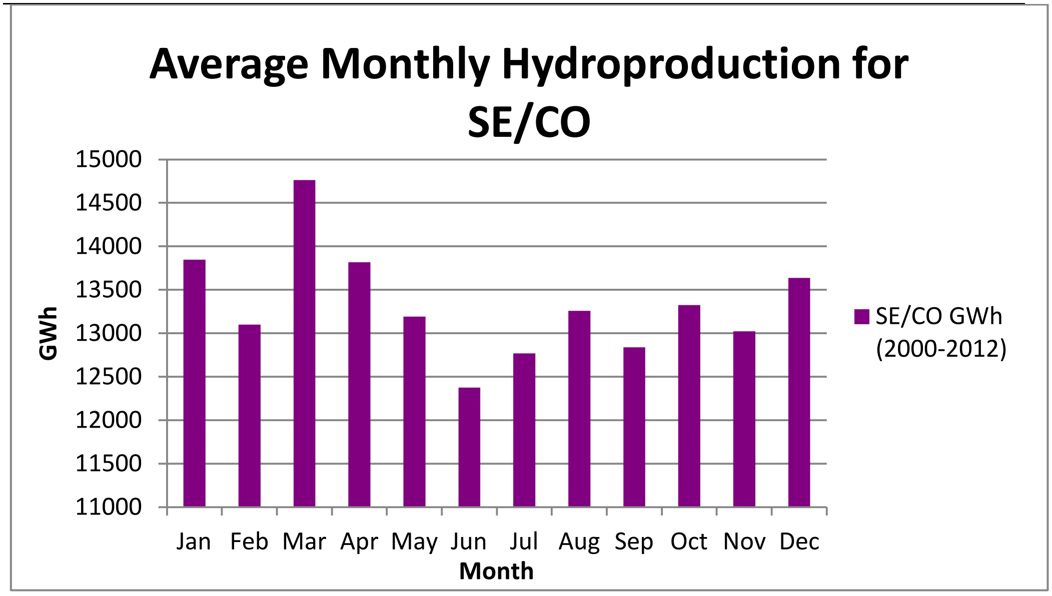

Figure 19 Monthly averages of hydro production for SE/CO region based on years 2000-2012 collected from ONS (ONS, 2013)

2.6.5 Natural energy inflow

Inflow is water entering rivers and reservoirs from soil, groundwater and direct precipitation that becomes available for hydro production. It is important to note that not necessarily all available water is used for production straight away; some of it is stored. Inflow is not a parameter that is measured directly; instead, it is calculated as shown in Equation 2:

$$\boldsymbol{Qin} = \boldsymbol{Qout} - \boldsymbol{\Delta\, Storage} \qquad (2)$$

$\boldsymbol{Q_{in}}$ - Inflow
$\boldsymbol{\Delta\, Storage}$ – Change in reservoir level
For run-of-river hydropower it is assumed that $\boldsymbol{Q_{in}} \approx \boldsymbol{Q_{out}}$ since little to no water is stored due to the small storage capacity of this type of power plants (Söderberg, 2013).

Natural Energy Inflow (Affluent) is the energy producible from the natural flow of a tributary entering to a reservoir system. In other words, it is energy from natural river flow available for production if the power plants cascade was not there (Junior, 2012).

2.6.6 Comparative advantages of hydropower

In terms of electricity generation, hydropower is typically introduced as renewable energy supply alternative. However, obtaining electricity from hydropower often involves the formation of a reservoir and regulation of the natural river flow. In Brazil, electricity generation takes priority over all else for water use. It is crucial to ensure that environmental and social aspects of hydropower are sustainable (Bermann, 2007).

2.7 Model explanation

2.7.1 HBV model

Rainfall- Runoff models are useful tools when space and time limit the number of measurements that can be taken. These models can give further understanding of the hydrological system and provide information about future hydrological scenarios. The rainfall-runoff models consist of boxes with inputs and outputs, picturing parts of the catchment where different hydrological processes occur. Internal processes within the boxes are excluded but a physical understanding of the system can still be gained if knowledge of natural response, e.g. transformation of rainfall to runoff, is known (Beven, 2001).

There are several types of rainfall- runoff models; one of them is the conceptual and numerical HBV model developed by Sten Bergström at the Swedish Meteorological and Hydrological Institute (SMHI) in the 1970s. Today, different versions of the model are used worldwide and the one introduced by SMHI is commonly used in the Nordic countries (Bergström, 1992). The HBV model is built up by subroutines, which illustrate hydrological systems in the catchment area. Examples of subroutines included in the model are meteorological interpolation, snow (accumulation and melt), evapotranspiration, soil moisture, runoff and the connection between sub-basins, and lakes. The inputs are observed data including precipitation, air temperature, and evapotranspiration (SMHI, 2006). The continuity equation for general water balance in the model is:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes] \qquad \textbf{(3)}$$

$P = Precipitation$
$E = Evapotranspiration$
$Q = Runoff$
$SP = Snow\ pack$
$SM = Soil\ moisture$
$UZ = Upper\ groundwater\ zone$
$LZ = Lower\ groundwater\ zone$
$Lakes = Lake\ volume$

2.7.2 Scania-HBV

The Scania-HBV model was developed by Thomson Reuter’s hydrological department. Main features of the HBV are included in the Scania model but there are some additions and simplifications. There is no land use classification and the area-elevation distribution is simplified. All results from the model (precipitation, evaporation, flow etc., except temperature) are shown in energy units, GWh and less of data is required. The model shows results of the energy inflow and not the production which means that the models does not give information about when the energy inflow is utilized, historical production in the catchment and there is no linear conversion between mm rainfall and GWh. The following subroutines (similar to those explained by Bergström) and some of parameters in Scania-HBV are carefully explained in text and Figure 20.

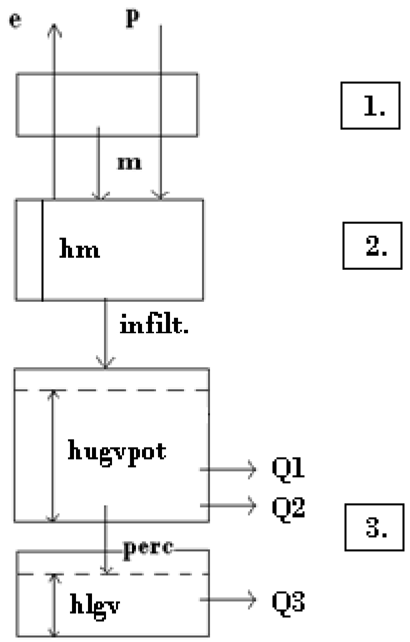

Figure 20 HBV box model with inflow, outflow and thresholds

1. **Snow routine**
   Equations for snow accumulation and snow melt, **m**.
   (In the model for the Paraná basin no snow routine was included)
2. **Soil moisture routine**
   Precipitation, **p** adds water to the box and evapotranspiration, **e** and infiltration, **infilt.** are flow of water from the box. Evapotranspiration is dependent on water amount in the box and the temperature. There will be an infiltration of rain to the upper ground water box.
3. **Runoff routine**
   The upper ground water box includes the quick, **Q1** and medium, **Q2** runoff response. When a certain threshold is reached the quick runoff begins.
   The lower ground water box gives the slow runoff response, **Q3** which should picture the natural systems baseflow. Baseflow often occurrs during dry periods in summer.

Table 5 Objective functions (Söderberg, 2013)

Name	Explanation	Formula
r2	Coefficient of determination of daily inflow	$1 - \frac{\sum(Q_{obs} - Q_{cal})^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2}$
r2_w	Coefficient of determination of weekly inflow	$1 - \frac{\sum(Q_{obsw} - Q_{calw})^2}{\sum(Q_{obsw} - \bar{Q}_{obsw})^2}$
r2_m	Coefficient of determination of monthly inflow	$1 - \frac{\sum(\mathrm{Q_{obsm}} - \mathrm{Q_{calm}})^2}{\sum(\mathrm{Q_{obsm}} - \bar{\mathrm{Q}}_{\mathrm{obsm}})^2}$
AccDiff	Accumulated difference between the observed and simulated daily inflow	$\sum(Q_{obs} - Q_{cal})$
$Qobs, Qobsw, Qobsm$ $Qcal, Qcalw, Qcalm$ $\bar{Q}obs, \bar{Q}obsw, \bar{Q}obsm$	Daily, weekly, monthly: Observed inflow Simulated inflow Average of the observed inflow	

During calibration different objective functions are used to find as close of fit as possible between the observed and simulated energy inflow, see Table 5 Objective functions (Söderberg, 2013). The model result for a certain combination of parameters and start values is assumed to be good and picture the hydrological and meteorological processes if the fit is close enough. A determination coefficient or Nash and Sutcliffe coefficient, r2 with value 1 implies a perfect fit (the closer 1 the better) but a value of already 0.8 would be regarded as good fit as well (Sælthun, 1995). With regard to Accumulated difference, it should preferably be zero. Nevertheless one cannot only rely on the objective functions; some experience is needed to attain an appropriate parameter set up for a certain basin.

3. Method

Literary study of the hydropower situation in Brazil and the accessibility of data determined an area of focus for this project to become the basin of the Paraná River. The basin was then divided into five sub-basins.

Data was collected from databases available on the websites of Brazilian national organizations and institutions. The method of building up a target to HBV model was selected to include precipitation data, temperature data, and natural energy inflow data. Target components were downloaded and extracted using Matlab.

Subsequently, inputs to the HBV model were created by structuring precipitation, temperature, and energy inflow data to a format readable for the model. Calibration and validation periods were chosen based on data accessibility where the main limiting factor was energy inflow data. Thus the calibration period was April 1st , 2005 to June 30th , 2012 and the validation period from April 1st, 2000 to March 31st , 2005. Furthermore, other elements integrated into the model such as lake percentage and evaporation rates for areas were determined. Finally, each sub-basin was calibrated and validated with the Scania-HBV model.

3.1 Division of area to sub-basins

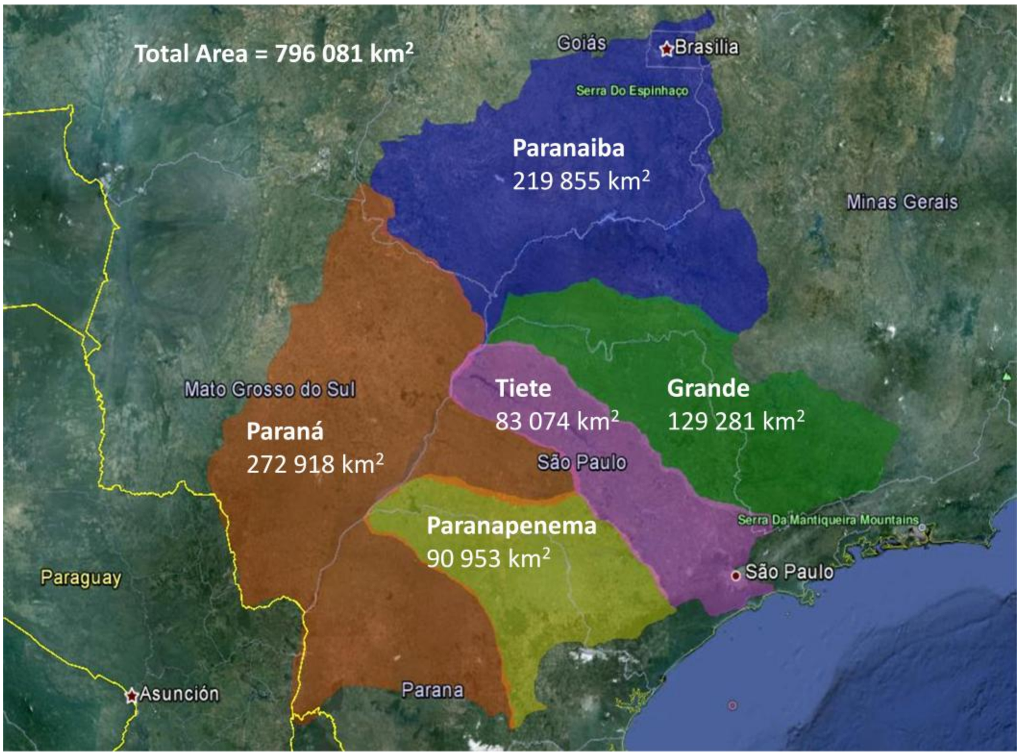

Figure 21 Division of Paraná basin to sub-basins and their areas in km^2 (created with Google Earth)

The basin of the Paraná River with a total area of 796 081 km^2, as obtained from polygons in Google Earth Pro, is too large to be modeled with HBV in real terms simultaneously. This is because of varying meteorological and hydrological conditions and slightly different climate zones. Additionally, rivers of the basin hold a wide range of natural energy inflow. Thus, the basin of Paraná was divided into five sub-basins; four of them were sub-basins of the Paraná's tributaries and a remaining one was a watershed of the Paraná River itself extending on south till Itaipu, as shown in Figure 21. Each region was built up into a separate HBV model and calibrated.

4. Collection and treatment of data

Data is a substantial element of this project as it will determine the final results of modeling and its reliability. Consequently, data collection and data treatment are the biggest and most time-consuming parts of this project. The HBV model operates best with daily values, and thus the collection of daily data was the main focus.

4.1 Energy inflow data

Energy inflow data was acquired from ONS, which provides an online diary with daily monitoring of hydropower, OPHEN (Acompanhamento Diário da Operação Hidroenergética). The diary consists of documents with information about the hydropower situation in Brazil for national electrical regions and for the major river basins. Information is obtained by monitoring natural energy flows and stored energy (ONS, 2013).

4.1.1 Calibration and validation data

- Data availability check

First, OPHEN documents were checked concerning the availability of formats as well as information and dates they contain. OPHEN documents are issued in pdf or word formats on weekdays, generating five documents per week. Natural energy inflow daily data per river basin is presented only from 2004, which limits the choice of period for modeling (calibration and validation). All 2046 available files were downloaded in the original formats.

- Extraction of downloaded data

Matlab code was written to parse documents for the required information, natural energy inflow for the five major basins in a watershed of Itaipu (Paranapanema, Grande, Tietê, Paranaíba, Paraná) together with dates. Due to the large amount of files, different inputs were processed by the Matlab code and information was structured, extracted and saved as .mat or .xlsx file.

- Creation daily values and estimations

Although documents are published on daily basis, natural energy inflow data is not provided as daily values but as two-day to six-day. Therefore, Excel scripts were written to extract the desirable daily data.

For the first value in a series, the following assumption was made to get daily values for the two first days:

$$\mathbf{A1} = \frac{\mathrm{x_1+x_2}}{2} \qquad (4)$$

$$\text{for } x_1 = x_2 \ , A1 = x_1 = x_2$$

A1 - First “Several-days-average data”

x_1, x_2 - Energy inflow for day 1 and 2

Formula to transfer other “Several-days-average data” from OPHEN to daily data:

$$\mathbf{An} = \frac{\mathbf{x_1+x_2+\cdots+x_n}}{\mathbf{n}} \qquad (5)$$

$$\mathbf{x_n} = \mathbf{An \times n - (x_1 + x_2 + \cdots + x_{n-1})} \qquad (6)$$

An - Average “Several-days-average data” for n number of days
x_n - Daily value number n
n - Number of days
The next step was to fill in the missing gaps by doing more estimation. Documents are only published Monday-Friday with the “Several-days-average data” average from Saturday - Sunday (2 days average) to an average Saturday - Thursday (6 days average). Averages from day number one and seven are always missing therefore in each week out of seven days there were at least two days of missing data, creating gaps. Those gaps were filled in using another estimation: they were assumed to be equal to a previous non missing daily value. For most of weeks that method was used for two days out of seven, however the same technique was used when more days than that was missing. The numbers of days with estimated daily values in the target series were 30-40%. In the period 2007-2009, over 40 % of daily values were estimated, see Table 18 in Appendix.

- Check of estimations on monthly basis

Creating a daily data series required a great deal of estimation, so validation of the estimations and assumptions used for calculation was fundamental. An average for each month of newly created daily data series was calculated and compared with the monthly averages of natural energy inflow published in an interactive database by ONS in the section “History of Operation – Energia Natural Affluente”. Before that, monthly averages of ENAs (Natural Energy Inflow) from ONS interactive database were compared to monthly averages of ENAs from OPHEN documents, which are shown in Figure 22.

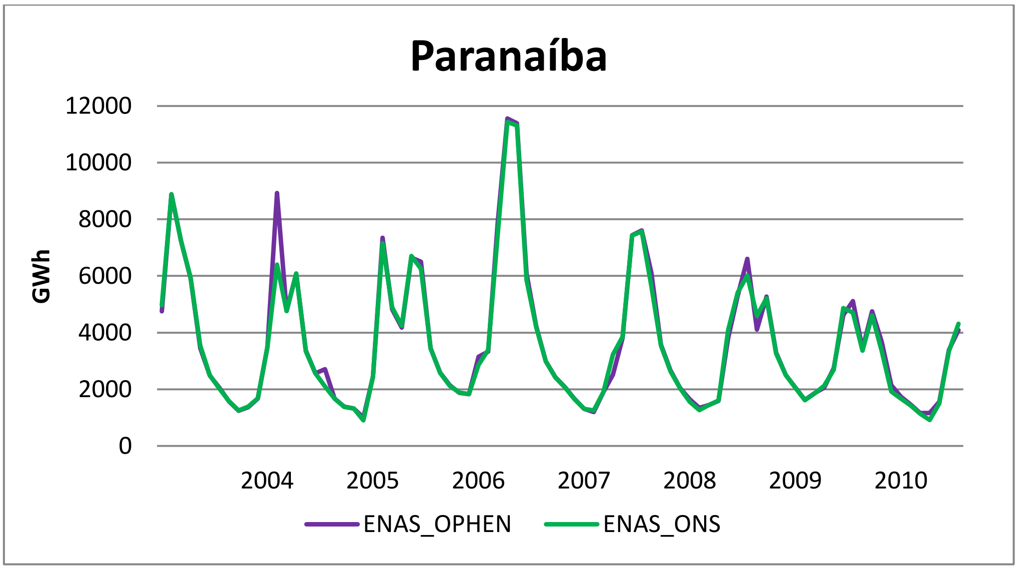

Figure 22 Comparison of natural energy inflow for Paranaíba from ONS OPHEN documents and ONS interactive database

No significant difference in values between the sources was established. However, depending on a date of the last published OPHEN document in a month, many documents do not present an average for the whole month. Additionally, taking into consideration the availability of monthly averages of ENA's interactive database for a longer time period than OPHEN, the former was chosen for validation of implemented estimations.

The differences between monthly averages of the created target data and ENA's source were calculated for each month. The daily data was adjusted by using ENA's monthly values as a normalizing factor.

- Creation a target for the Paraná River

Energy inflow data specified by ONS, such as Paraná, already included data for the other four basins. Therefore, to avoid duplicating work and to model the energy of the Paraná sub-basin only, daily energy targets for the Paraná sub-basin were generated. Energy inflow data for Paranaíba, Grande, Tietê and Paranápanema was subtracted from the energy data set given as Paraná creating a desirable target for the Paraná sub-basin.

- Adaptation data for Scania-HBV model

Units of daily data were changed from MWmed, which are used by ONS, to GWh, which are applicable for the model, by multiplying the number of hours per day and dividing by 1000. Thereafter, energy inflow data sets for five basins together with dates were combined into one data set and structured to a format readable for Scania-HBV.

- Manipulation of estimated values after first calibration

At this point energy inflow data was suitable and ready for use as input target for Scania-HBV. The first calibration attempt for all five basins was performed; however a number of unreasonably looking picks appeared on the hydrograph. Since a number of assumptions were made while creating a daily energy inflow data set, the input data set was likely the problem. In order to add more credibility to the created data set and improve the calibration results, further manipulation of input data was necessary. Observed extreme values were adjusted to more reasonable values based on additional investigation of surrounding days. This manipulation was performed only for estimated values and none of the measured values were changed. Differences in monthly averages were checked again and the following steps repeated.

4.1.2 Validation data

Daily energy inflow data for 2004 was collected as described in chapter 4.1.1 Calibration and validation data and combined with average monthly energy inflow data (ENAs_ONS) for 2000-2003, building up an input data set for validation. Monthly data was changed to daily data by proportional division over each month making it suitable for the model. Creation of the data set for the Paraná sub-basin, changing of units, and structuring for HBV were completed in the same way as in chapter 4.1.1 Calibration and validation data.

4.2 Meteorological data

The emphasis was on obtaining meteorological data of good quality for a period from 1981 to 2012 with one-day resolution. For both precipitation and temperature data, only stations with time series during this period were selected since this is how Thomson Reuters Point Carbon makes their long-term hydrological predictions.

4.2.1 Precipitation data

Historical daily precipitation data were collected from two sources: INMET and HidroWeb. For subscribed users INMET provides the BMDEP (Banco de Dados Meteorológicos para Ensino e Pesquisa) database of historical meteorological data and location of meteorological stations for the whole of Brazil. The second source was the HidroWeb database owned by ANA combined with the SNIRH database which is ANA’s national information system on water resources.

Initially, location and lengths of time series of stations were validated. Precipitation daily data for selected stations were downloaded from HidroWeb by inserting stations’ codes previously found at SNIRH and from INMET by accessing an interactive map at BMDEP.

As the format of the data was not suitable to be treated further in Matlab, all files were parsed with software called Manejo de dados Hidroweb 4.2 provided at the MGB-IPH website (MGB-IPH, 2010).

4.2.2 Temperature data

Historical daily temperature data was collected from the NOAA database available at the National Climatic Data Center at the U.S. Department of Commerce. Data sets for stations with desirable location and length of time series became candidates and the data was downloaded.

4.2.3 Quality data analysis

Meteorological data being an input to HBV plays an important role in the process of modeling. Its quality is a crucial factor affecting the final results of projects so historical data for each station were plotted in Matlab to evaluate an overall profile and exclude errors in the series, such as unfeasibly extreme values. Besides, the overall amount of missing data for the whole 1981-2012 time period was detected. Only stations of the best quality became candidates for further investigation.

The HBV model runs on daily basis therefore another important criteria, fillness of data series was calculated. The number of missing daily values of precipitation or temperature was divided by the total number of days in the series resulting in percentage ratio of fillness. This was done for two time periods: the calibration and validation periods. The fuller the time series is the better, however minimum required fillness for precipitation data is 80% and stations of fillness above 90% are expected to bring the best results.

Based on the quality and fillness of data, 51 precipitation stations were selected, that is 23 from INMET and 28 from ANA HidroWeb. Among the temperature stations, 15 were selected. The location of the candidate stations was plotted in Google Earth as shown in Figure 23.

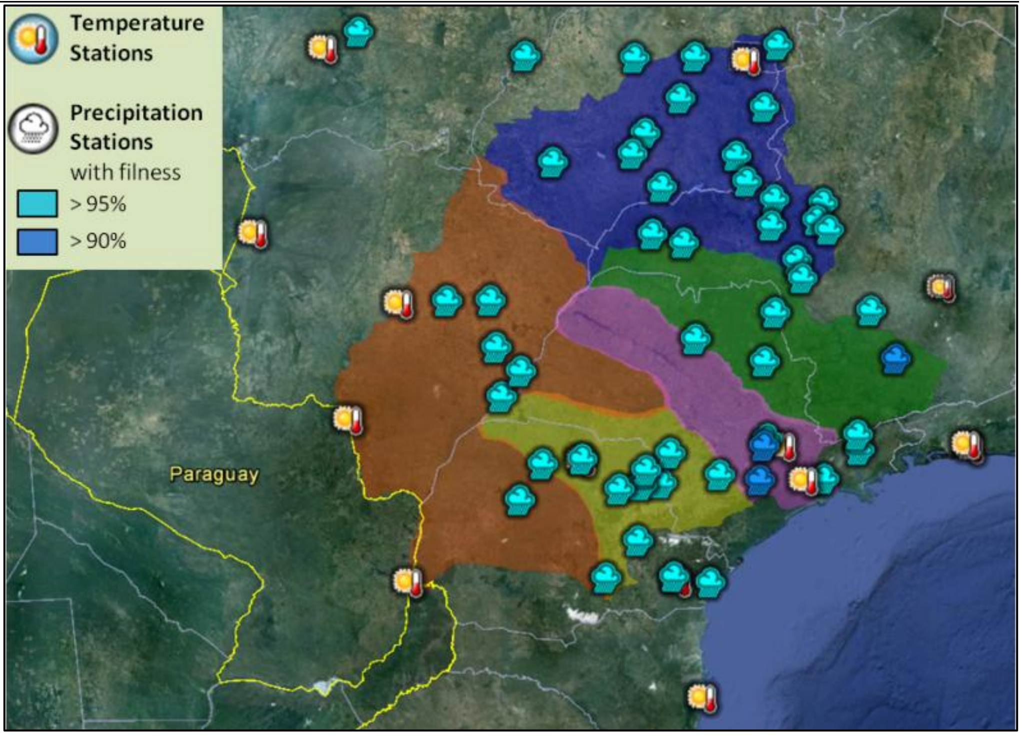

Figure 23 Temperature and precipitation stations of best quality. Fillness of minimum 95% for temperature stations and 90% for precipitation stations

4.3 Evaporation data

Evaporation is one of the outputs from calibration of Scania-HBV; hence, it is one way of validating how close to reality a calibrated model is. Therefore, monthly historical data of evaporation in millimeters were collected from INMET (see chapter 2.7.2). In total, 17 meteorological stations evenly spread out over the basin, from different altitudes with records for both evaporation and precipitation were selected.

Each sub-basin was accredited by 5 meteorological stations from its sub-basin or nearby. Annual averages of monthly evaporation values were compared to annual averages of monthly precipitation values from INMET giving a ratio E/P in a range of 60-65%. They were then compared with a ratio of annual averages from the model during calibration. The evaporation ratio from Scania-HBV for each sub-basin was always too low to represent real hydrological situation. That was improved by manipulation of the two main responsible for evaporation parameters: Thorn and hp in further calibration, see final E/P result in Figure 24 .

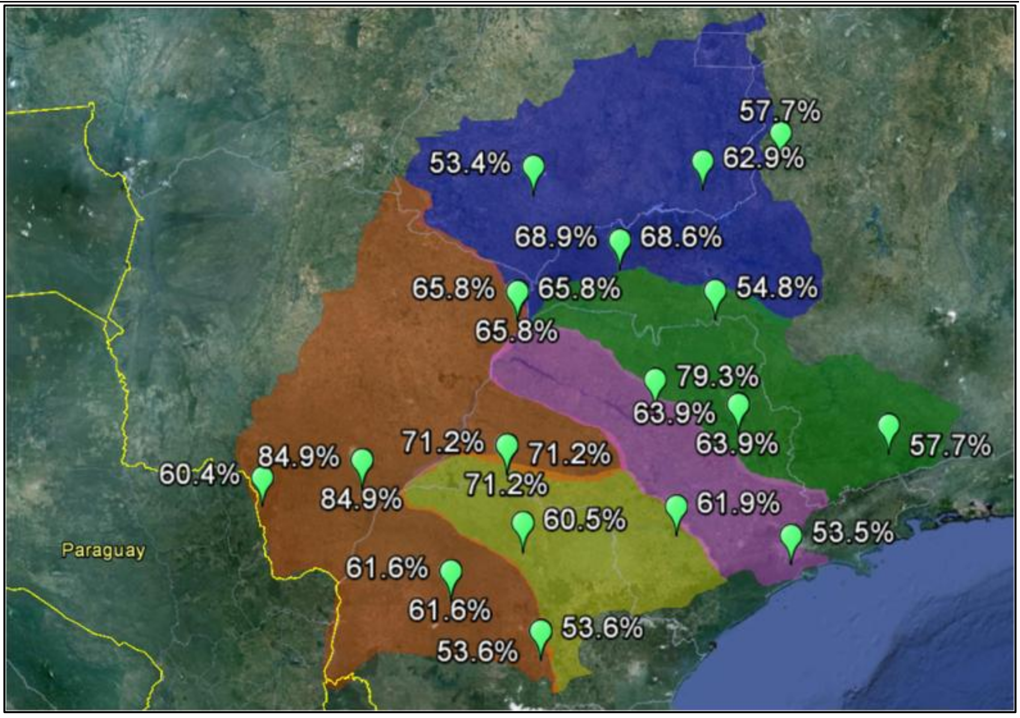

Figure 24 Meteorological stations with E/P (%) ratio calculated from annual averages of monthly evaporation compared with annual averages of monthly precipitation

5. Result and Discussion

5.1 Calibration and Validation

Scania-HBV was applied to five sub-basins individually with records from different meteorological stations. Calibration was performed on a daily basis for the period from 2005-2012 and validation for 2000-2004, where 2000-2003 uses monthly values for energy natural inflow.

The quality of simulation calculated by the model energy inflow against observed inflow can be verified with a hydrograph, which provides a visual impression of an agreement between simulated and observed inflow. Other criteria include objective functions like the coefficient of determination, r^2, or accumulated difference, described in chapter 2.7.2 Scania-HBV, which gives numerical evaluation of the result. Although, where possible, simulations were made on daily basis, it is weekly and monthly results that are more relevant for this project and only those are presented in the results. This is due to significant part in the artificially created values of observed inflow on daily basis. A monthly hydrograph gives a clearer visualization.

Table 6 Comparison of observed evapotranspiration to calculated evapotranspiration per sub-basin

Evapotranspiration	Observed (%)	Calculated (%)
Paranaíba	62	60
Grande	62	63
Tietê	66	65
Paranapanema	65	65
Paraná	66	65

Calculated evapotranspiration values were verified by observed values to ensure realistic simulation results. Observed evapotranspiration data was collected from a number of stations in each sub-basin and an average percentage was calculated. After calibration, the results presented in Table 6 show that calculated evapotranspiration corresponds to the observed data. This serves to verify that the evapotranspiration is within a valid range for the basin.

5.1.1 Paranaíba

The Paranaíba is the largest tributary to the Paraná River in terms of basin area and hydropower capacity, and at the same time the second, after Paraná, the largest among the five models involved in this project. It is located in the northernmost part of the Paraná basin. Calibration of Scania-HBV for the Paranaíba River was performed with a contribution of four temperature and five precipitation stations mostly located at altitudes above 700 m. The position of meteorological stations together with their codes, weights, and other important simulation inputs are presented in Figure 25 and Table 7 below.

Figure 25 Distribution of meteorological stations in Paranaíba sub-basin

Table 7 Basic information about meteorological stations for Paranaíba

Code	Name	Latitude	Longitude	Altitude (m)	Fillness (%)	Weight (%)	Source
Temperature Stations							
835870	Belo Horizonte	-19.93	-43.93	828	100	10	NOAA
833780	Brasilia Aero	-15.87	-47.93	1060	100	60	NOAA
837800	São Paulo Aero	-23.62	-46.65	802	99.9	10	NOAA
837680	Londrina Aero	-23.33	-51.13	569	99.6	20	NOAA
Precipitation Stations							
83526	Catalao	-18.18	-47.95	840	99.7	20	INMET
83579	Araxa	-19.60	-46.94	1023	99.7	40	INMET
1847003	Abadia dos Dourados	-18.49	-47.41	784	97.2	10	ANA
1849016	Ponte Meia Ponte	-18.34	-49.61	500	100	20	ANA
1946022	Carmo do Paraná iba	-19.00	-46.31	1067	96.1	10	ANA

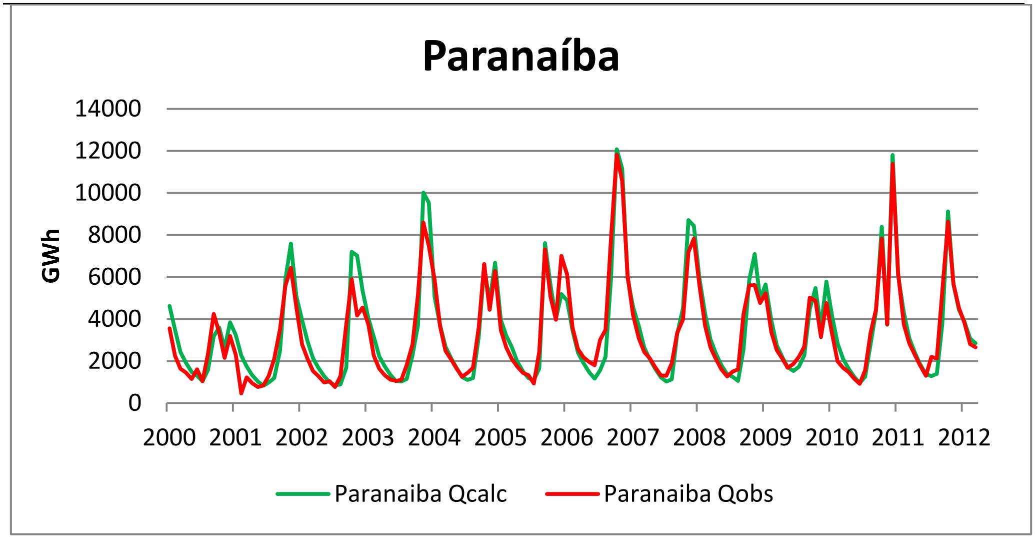

Figure 26 Hydrograph of calculated and observed monthly inflow for Paranaíba

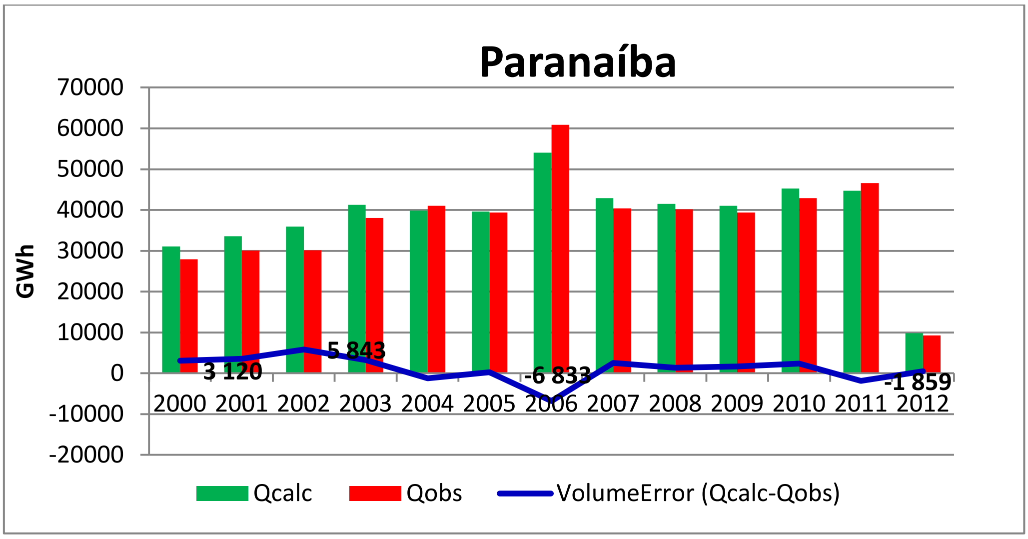

Figure 27 Annual volume differences between calculated and observed inflow for Paranaíba together with volume errors

Table 8 Results of calibration and validation for Paranaíba

Objective function	**r2_w**	**r2_m**	**AccDiff (GWh)**
Calibration	0.87	0.92	0.2
Validation	0.69	0.80	14560

Looking at the coefficient of determination, r^2, the result of runoff simulations is above average, compared to results from other basins, both for calibration and validation as displayed in Figure 26, Figure 27 and Table 8. The coefficient of determination is 0.87 for weekly inflow and 0.92 for monthly inflow for calibration. For validation, the objective function, r^2, decreased and became 0.69 on a weekly basis and 0.80 on a monthly basis. Moreover, the accumulated difference between simulated and observed inflow after the total period of validation is calculated by the model to be 14 560 GWh as shown in Table 8. Between 2000 and 2004, that is during the period when monthly target series is used, high values of volume difference between Qcalc and Qobs occur. This accumulates annually and causes big accumulated difference for validation period, as illustrated in Figure 27. Year 2006 was the weakest in terms of volume error since the model underestimated annual energy inflow by –6 833 GWh, although selected temperature stations showed the highest annual precipitation in 2006.

5.1.2 Grande

The sub-basin of Grande is similar to the Paranaíba in terms of meteorological and hydrological conditions; however it is distinguished by the greatest number of power plants among all the Paraná sub-basins. The simulation was carried out using four temperature and six precipitation stations as illustrated in Figure 28. The details of meteorological stations are listed in Table 9.

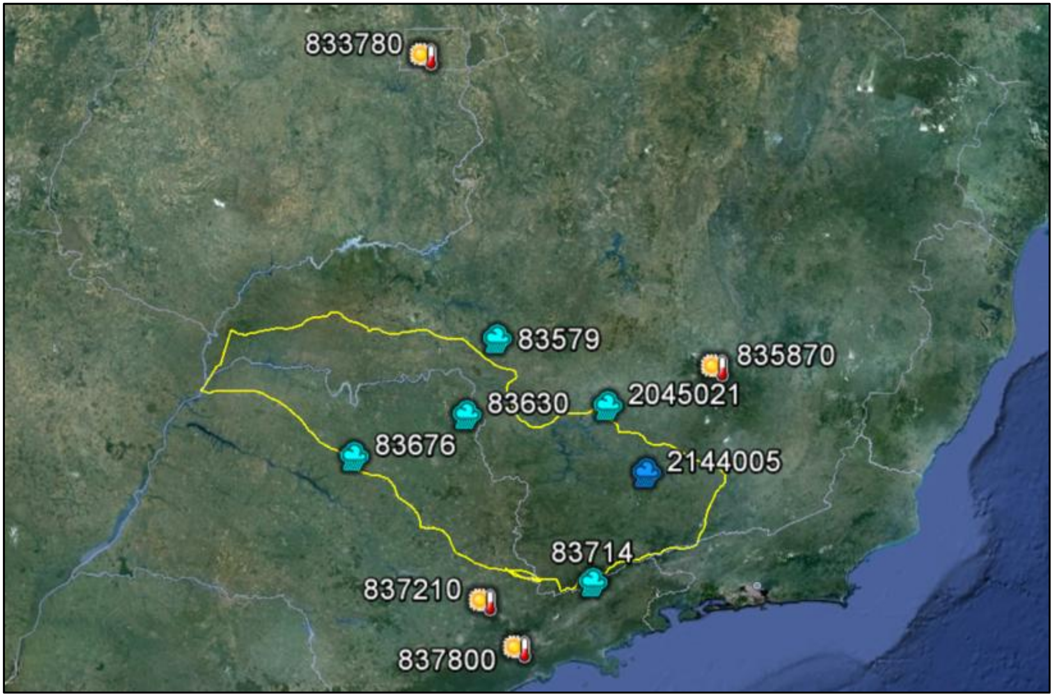

Figure 28 Distribution of meteorological stations in Grande sub-basin

Table 9 Basic information about meteorological stations for Grande

Code	Name	Latitude	Longitude	Altitude (m)	Fillness (%)	Weight (%)	Source
Temperature Stations							
835870	Belo Horizonte	-19.93	-43.93	828	100	40	NOAA
833780	Brasilia Aero	-15.87	-47.93	1060	100	40	NOAA
837800	São Paulo Aero	-23.62	-46.65	802	99.9	10	NOAA
837210	Campo Grande Aero	-20.47	-54.67	559	100	10	NOAA
Precipitation Stations							
2045021	Formiga	-20.46	-45.42	-	98.5	10	ANA
83714	Campos do Jordao	-22.75	-45.60	1642	99.5	30	INMET
2144005	Itumirim	-21.32	-44.87	807	94.2	30	ANA
83579	Araxa	-19.60	-46.94	1023	99.7	10	INMET
83630	Franca	-20.58	-47.36	1026	99.7	10	INMET
83676	Catanduva	-21.11	-48.93	570	95.3	10	INMET

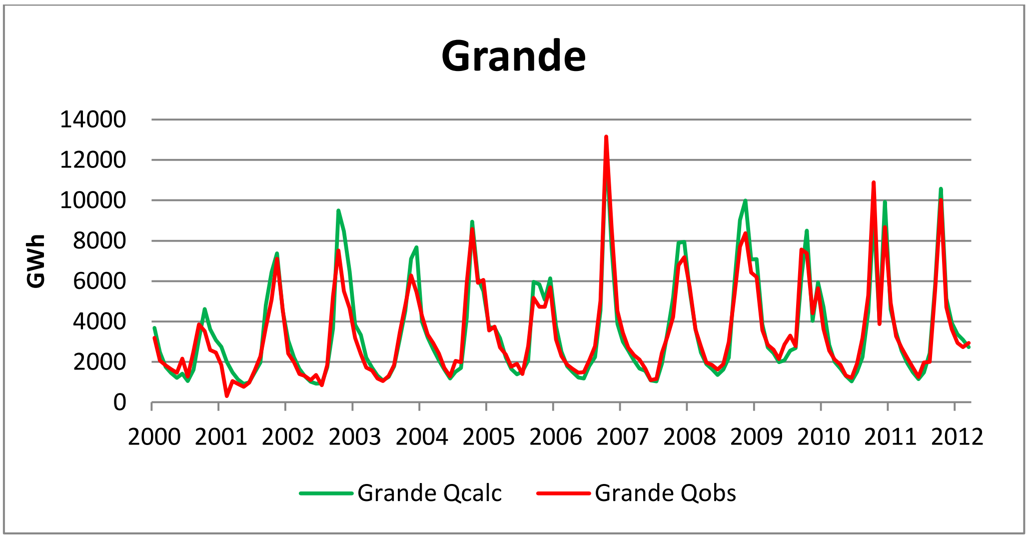

Figure 29 Hydrograph of calculated and observed monthly inflow for Grande

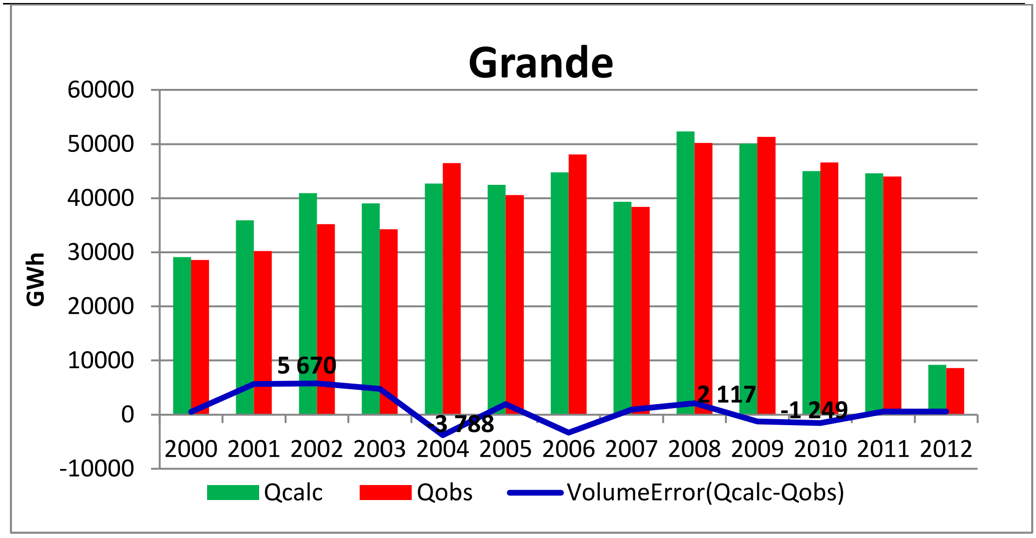

Figure 30 Annual volume differences between calculated and observed inflow for Grande together with volume errors

Table 10 Results of calibration and validation for Grande

Objective function	**r2_w**	**r2_m**	**AccDiff (GWh)**
Calibration	0.90	0.94	0.2
Validation	0.69	0.80	12907

It is worth noting that the Paranaíba and the Grande share similar hydrographs. The calculated inflow for the Grande agrees well with the observed value in calibration and validation as illustrated in Figure 29 and Figure 30 resulting in the greatest r^2 values of all sub-basins as presented in Table 10. The coefficient of determination is 0.90 for weekly inflow and 0.94 for monthly inflow, and for calibration and validation it is 0.69 and 0.80 respectively. The accumulated difference amounts to 12 907 GWh after validation, and the significant annual volume differences between simulated and observed inflow occur mainly from 2000 to 2004 with a volume error of 5 607 GWh in 2002 as shown in Figure 30 Annual volume differences between calculated and observed inflow for Grande together with volume errors

Also worth mentioning is the similarity between the Grande and the Paranaíba in the observed inflow during simulation. For both basins, the pattern of accumulated difference builds up during the dry season and decreases in a wet season. At the same time after the total period accumulated difference is overestimated.

5.1.3 Tietê

The Tietê sub-basin is the smallest in terms of area, total installed capacity and average annual hydropower production among all sub-basins of the Paraná River. Runoff simulations in this sub-basin were done with records of four temperature and six high quality, uneven distributed precipitation stations, as illustrated in Figure 31. Most of precipitation stations are concentrated with in the area of river origin, leaving the middle and mouth parts of the basin empty. Furthermore, precipitation stations are located at altitudes of about 600 m which is much lower than the altitudes of the stations in the basins of Paranaíba and Grande. Their exact altitudes together with other details of the meteorological stations are listed in Table 11.

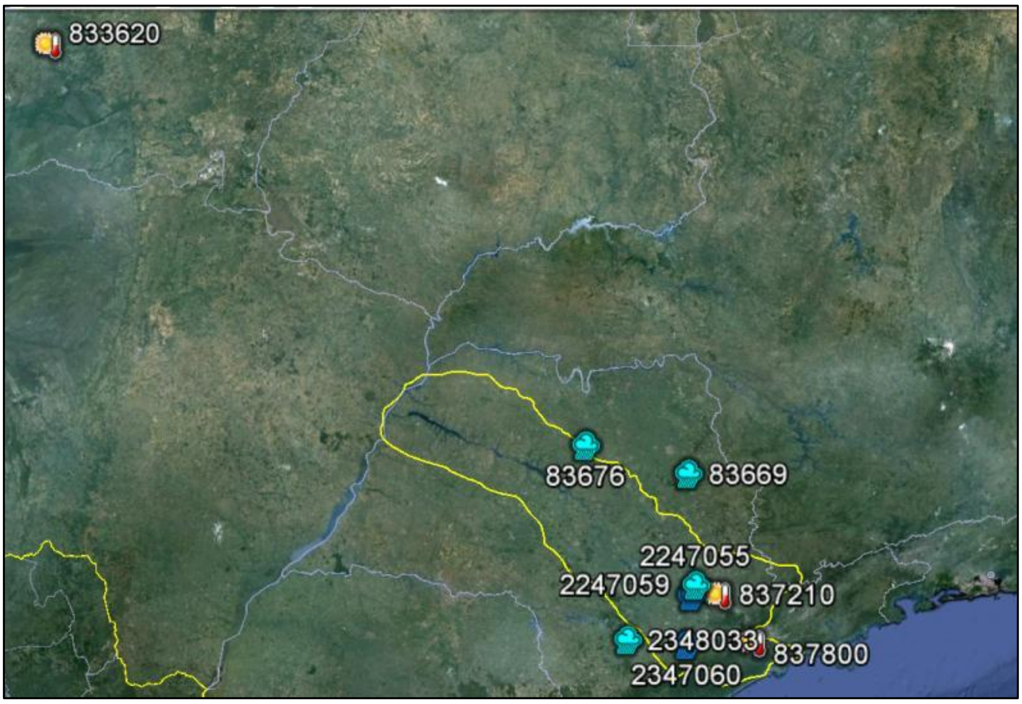

Figure 31 Distribution of meteorological stations in Tietê sub-basin

Table 11 Basic information about meteorological stations for Tietê

Code	Name	Latitude	Longitude	Altitude (m)	Fillness (%)	Weight (%)	Source
Temperature Stations							
833620	Cuiaba	-15.65	-56.10	188	99.6	40	NOAA
837800	São Paulo Aero	-23.62	-46.65	802	99.9	30	NOAA
837210	Campo Grande Aero	-20.47	-54.67	559	100	30	NOAA
Precipitation Stations							
83676	Catanduva	-21.11	-48.93	570	95.3	10	INMET
2247055	Jaguariuna	-22.88	-47.45	570	97.0	10	ANA
2247059	Capivari	-23.02	-47.51	500	91.0	30	ANA
2347060	Salto de Pirapora	-23.64	-47.57	590	93.1	20	ANA
2348033	Angatuba	-23.56	-48.39	580	95.2	20	ANA
83669	Sao Simao	-21.48	-47.55	617	100	10	INMET

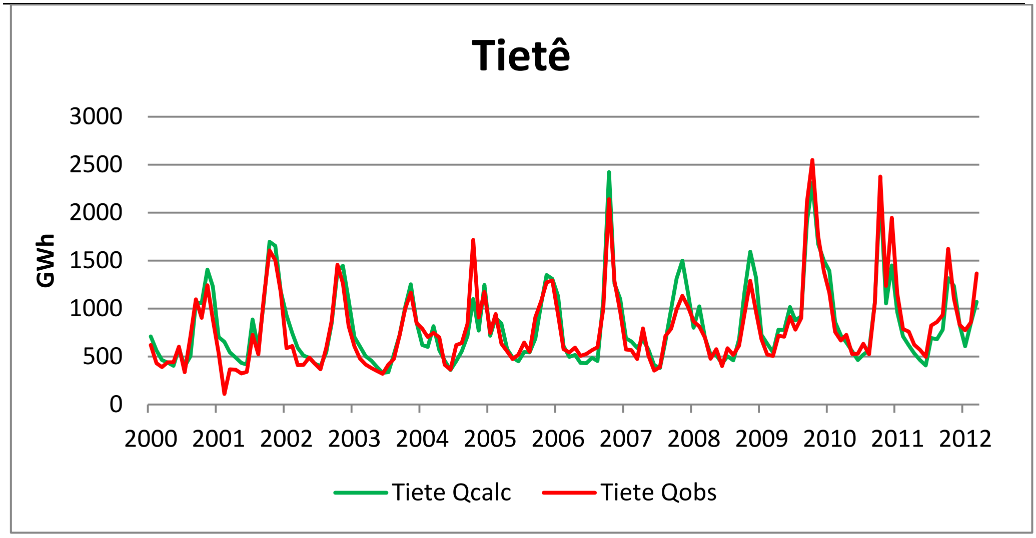

Figure 32 Hydrograph of calculated and observed monthly inflow for Tietê

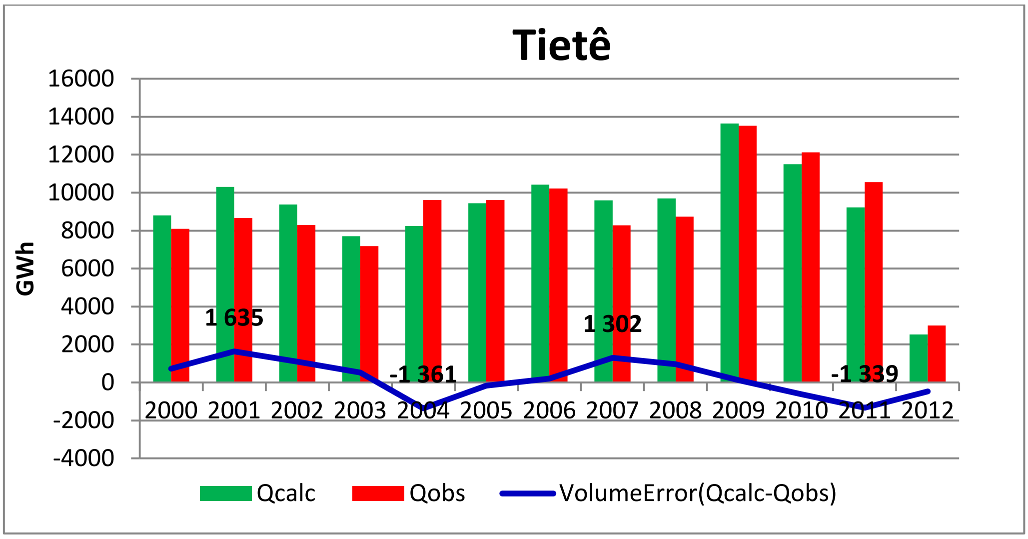

Figure 33 Annual volume differences between calculated and observed inflow for Tietê together with volume errors

Table 12 Results of calibration and validation for Tietê

Objective function	**r2_w**	**r2_m**	**AccDiff (GWh)**
Calibration	0.80	0.88	0.3
Validation	0.66	0.79	2607

The model results for Tietê based on objective functions are satisfactory, yet poorer as compared to those for Paranaíba and Grande. The hydrograph in Figure 32 illustrates a good general fit of simulated monthly inflow of Tietê against observed inflow with few timing and volume defects. On weekly basis, the coefficient of determination is 0.80 and 0.66 for calibration and validation respectively, on a monthly basis it is 0.88 and 0.79 as listed in Table 12. The difference between calculated and observed inflow accumulated after the period of validation is 2607 GWh which is low compared to other models. This is due to the relatively small local natural energy inflow to Tietê.

5.1.4 Paranapanema

The Paranapanema sub-basin, which is the last main tributary to the Paraná River before the Itaipu dam, has similar volumes of local inflow as Tietê. The simulation of inflow in Paranapanema was performed with the largest number of temperature and precipitation stations of varied altitudes illustrated in Figure 34. That may have contributed to more reliable simulation results. Almost evenly distributed weights of precipitation stations along with other details of meteorological stations are presented in Table 13.

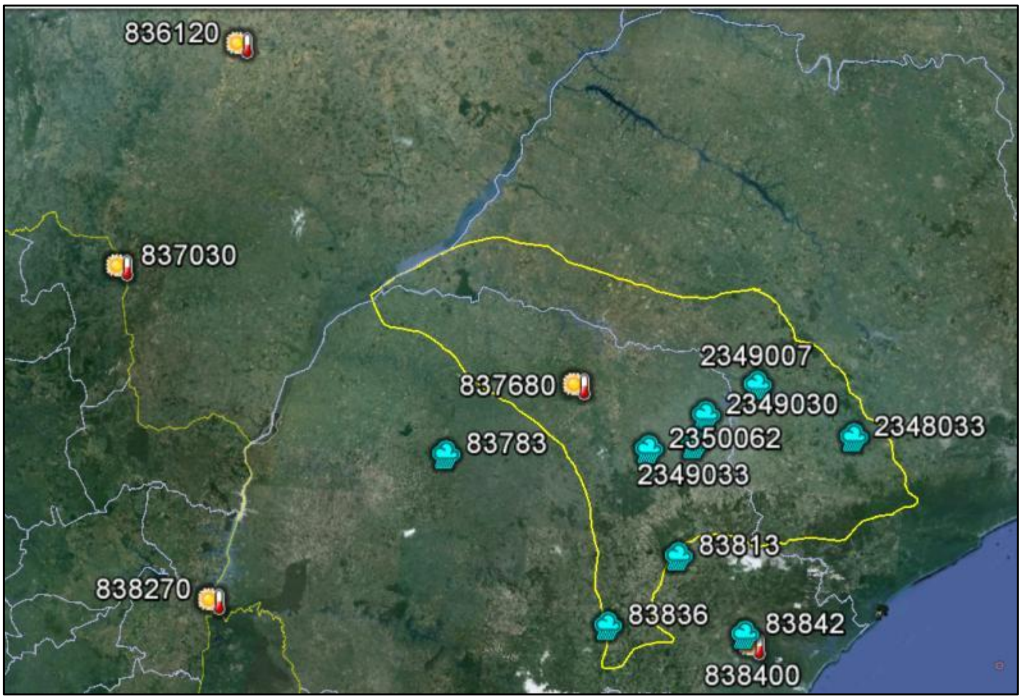

Figure 34 Distribution of meteorological stations in Paranapanema sub-basin

Table 13 Basic information about meteorological stations for Paranapanema

Code	Name	Latitude	Longitude	Altitude (m)	Fillness (%)	Weight (%)	Source
Temperature Stations							
838270	Foz DoIguacu Aero	-25.52	-54.58	240	100	20	NOAA
836120	Campo Grande	-20.47	-54.67	559	100	10	NOAA
838400	Curitiba	-25.52	-49.17	911	100	30	NOAA
837680	Londrina Aero	-23.33	-51.13	569	99.6	30	NOAA
837030	Ponta Pora Aero	-22.55	-55.70	657	99.9	10	NOAA
Precipitation Stations							
2348033	Angatuba	-23.56	-48.39	580	95.2	20	ANA
2350062	Usina Figueira	-23.85	-50.39	526	99.1	10	ANA
2349007	Piraju	-23.19	-49.39	500	95.2	10	ANA
2349030	Joaquim Tavora	-23.50	-49.87	512	97.2	10	ANA
2349033	Tomazina	-23.77	-49.95	483	100.0	10	ANA
83783	Campo Mourao	-24.05	-52.36	616	99.4	10	INMET
83836	Irati	-25.46	-50.63	837	99.7	10	INMET
83842	Curitiba	-25.43	-49.26	923	99.0	10	INMET
83813	Castro	-24.78	-50.00	1008	99.0	10	INMET

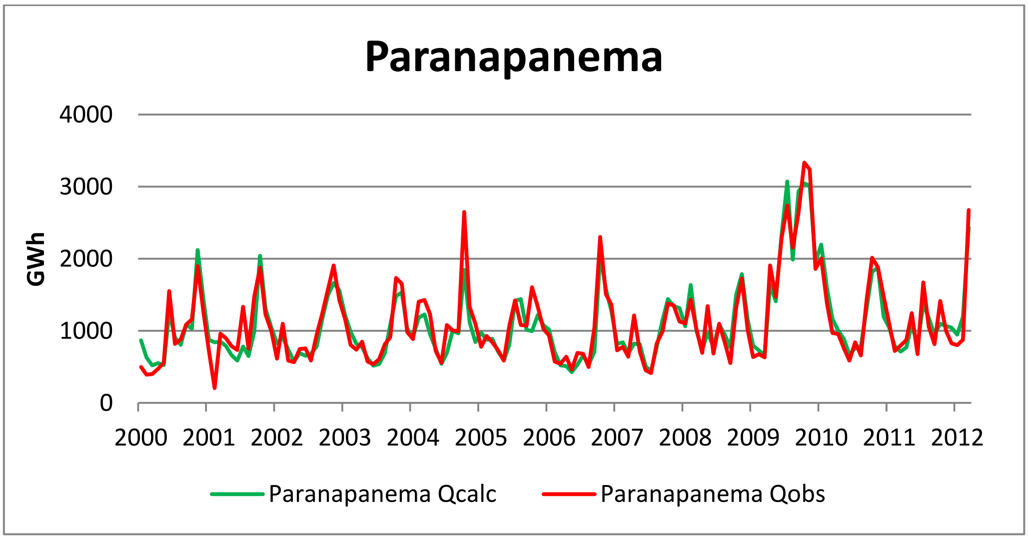

Figure 35 Hydrograph of calculated and observed monthly inflow for Paranapanema

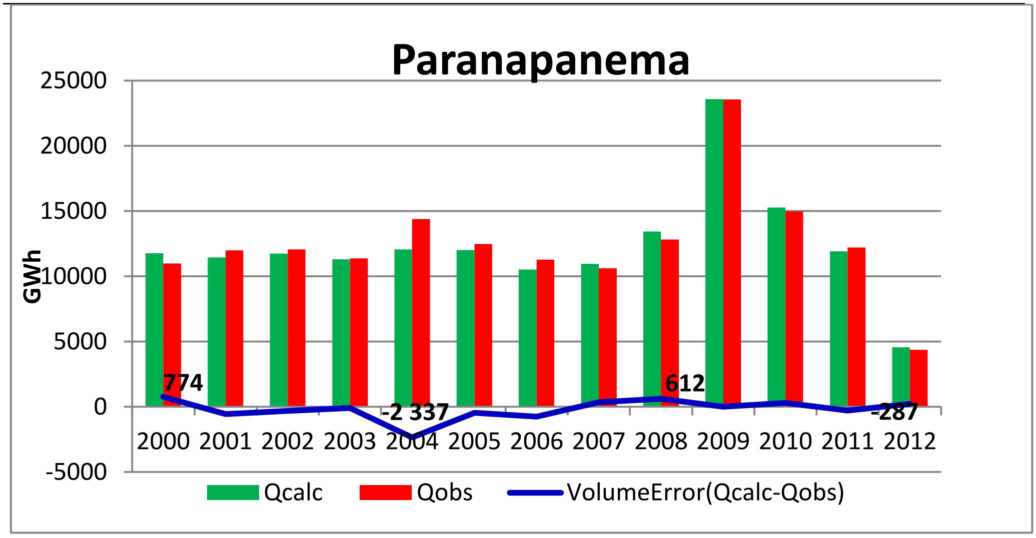

Figure 36 Annual volume differences between calculated and observed inflow for Paranapanema together with volume errors

Table 14 Results of calibration and validation for Paranapanema

Objective function	**r2_w**	**r2_m**	**AccDiff (GWh)**
Calibration	0.83	0.92	-0.1
Validation	0.63	0.75	-2729

It is interesting to note how different the seasonal annual pattern is for the Paranapanema hydrograph, Figure 35, compared to the northern basins. The pattern is generally not very distinct from season to season. The result of runoff simulations is satisfactory especially for calibration when the coefficient of determination is 0.83 for weekly inflow and 0.92 for monthly inflow, as listed in Table 14. For validation, r2 is 0.63 for weekly and 0.75 for monthly. Paranapanema is the most excellent in terms of annual volume differences (see Figure 36), with an exception of 2004 when the volume error between simulated and observed inflow amounts to -2337 GWh. Accumulated difference for validation became -2729 GWh. Noteworthy is the way Scania-HBV handles an extra reach in Qobs inflow during 2009. That is due to properly chosen precipitation stations with high amounts of rain in 2009, which are representative for Qobs in the Paranapanema sub-basin.

5.1.5 Paraná

The Paraná is a unique sub-basin in many aspects. First, due to the created target series and second, this is the only basin where all temperature and precipitation stations used are placed within the basin’s borders. This is clearly illustrated in Figure 37. The simulation of inflow in Paraná was performed with the use of only high quality meteorological stations and a temperature station, with code 837030 was of great importance for the development of the result. Details about this and other meteorological stations considered in the simulation are listed in Table 15.

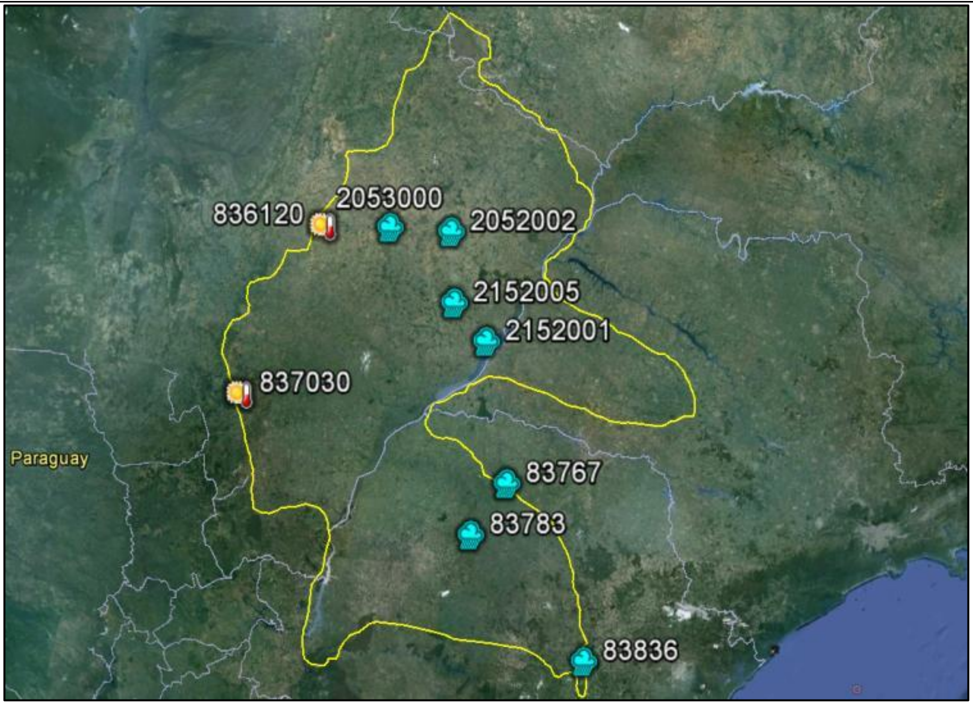

Figure 37 Distribution of meteorological stations in Paraná sub-basin

Table 15 Basic information about meteorological stations for Paraná

Code	Name	Latitude	Longitude	Altitude (m)	Fillness (%)	Weight (%)	Source
Temperature Stations							
837030	Ponta Pora Aero	-22.55	-55.70	657	99.9	90	NOAA
836120	Campo Grande Aero	-20.47	-54.67	559	100	10	NOAA
Precipitation Stations							
2053000	Ribas do Rio Pardo	-20.44	-53.76	373	98.1	10	ANA
2152001	Porto Uere	-21.73	-52.33	293	99.1	10	ANA
2152005	Xavantina do Sul	-21.30	-52.81	393	98.2	10	ANA
83767	Londrina	-23.40	-51.91	542	99.2	15	INMET
83836	Irati	-25.46	-50.63	837	99.7	40	INMET
83783	Campo Mourao	-24.05	-52.36	616	99.4	15	INMET

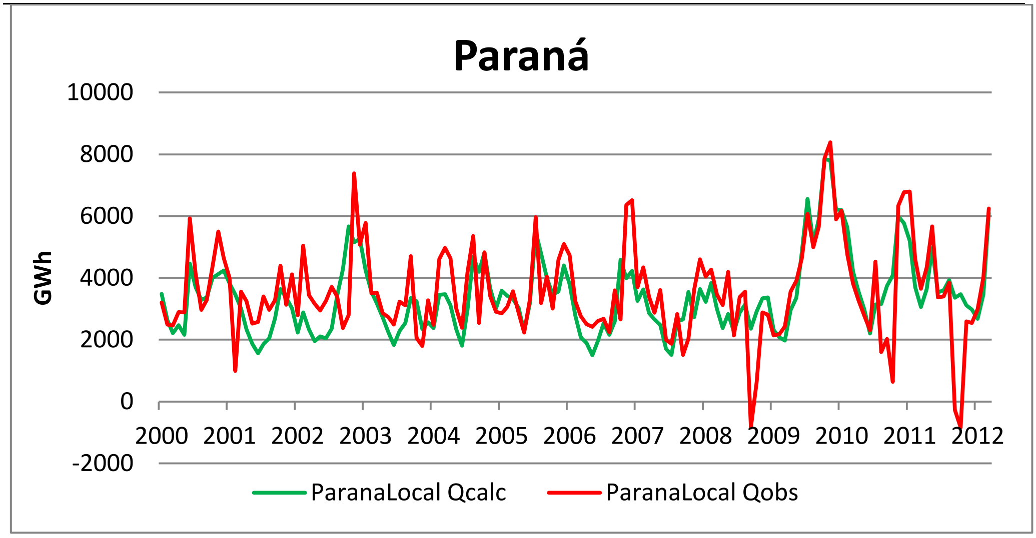

Figure 38 Hydrograph of calculated and observed monthly inflow for Paraná

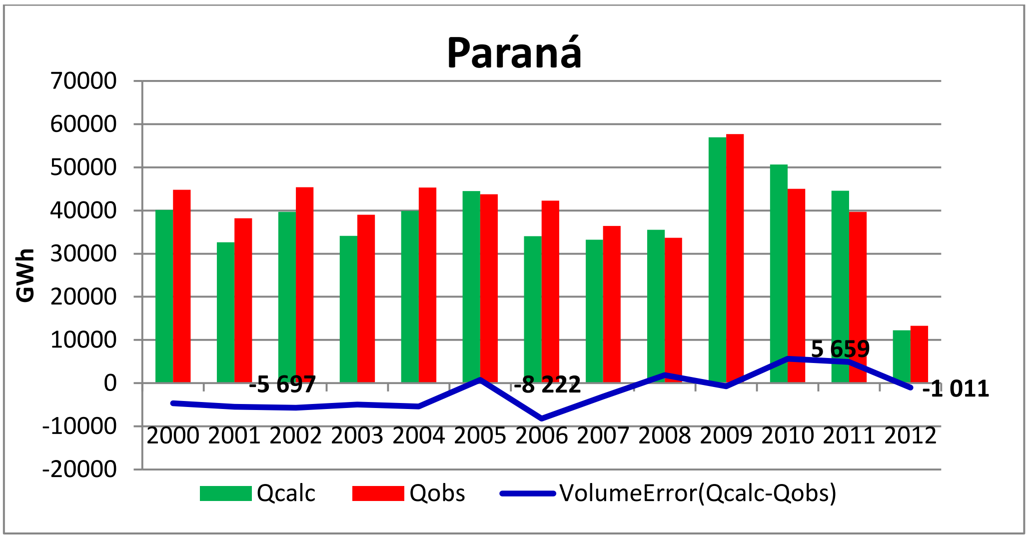

Figure 39 Annual volume differences between calculated and observed inflow for Paraná together with volume errors

Table 16 Results of calibration and validation for Paraná

Objective function	r2_w	r2_m	AccDiff (GWh)
Calibration	0.32	0.56	-0.1
Validation	0.11	0.08	-29451

The modeled inflow matches poorly with the observed inflow as visualized in Figure 38. This happens due to the artificial negative values present in the target series of observed natural energy inflow. Coefficients of determination for calibration are 0.32 on a weekly basis and 0.56 on a monthly basis as presented in Table 16. For validation, it is close to zero but still positive resulting in values of 0.11 and 0.08 on a weekly and a monthly basis respectively. Overall, the model underestimates the inflow to Paraná for a period of validation with an accumulated difference of -29 451 GWh.

5.2 Final results

Application of Scania-HBV to separate basins is of great importance; however, evaluation of the model for the total basin of Paraná is even more crucial (for this project). Hence, contributions from the Paranaíba, Grande, Tietê, Paranapanema and Paraná sub-basin were added together. Based on a sum of calculated and observed inflow for each of five sub-basins on a weekly and monthly basis, objective functions were calculated and are listed in Table 17. Moreover, the hydrograph of aggregated natural energy inflow to the Paraná basin was created as presented in Figure 40, and a graph showing annual volume differences between calculated and observed inflow is shown in Figure 41.

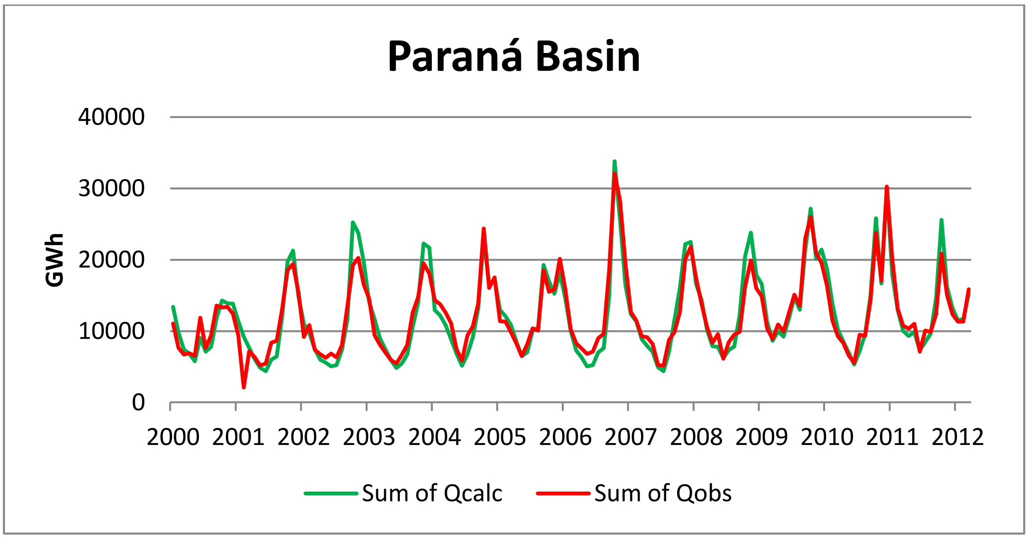

Figure 40 Hydrograph of calculated and observed monthly inflow for all Paraná sub-basins

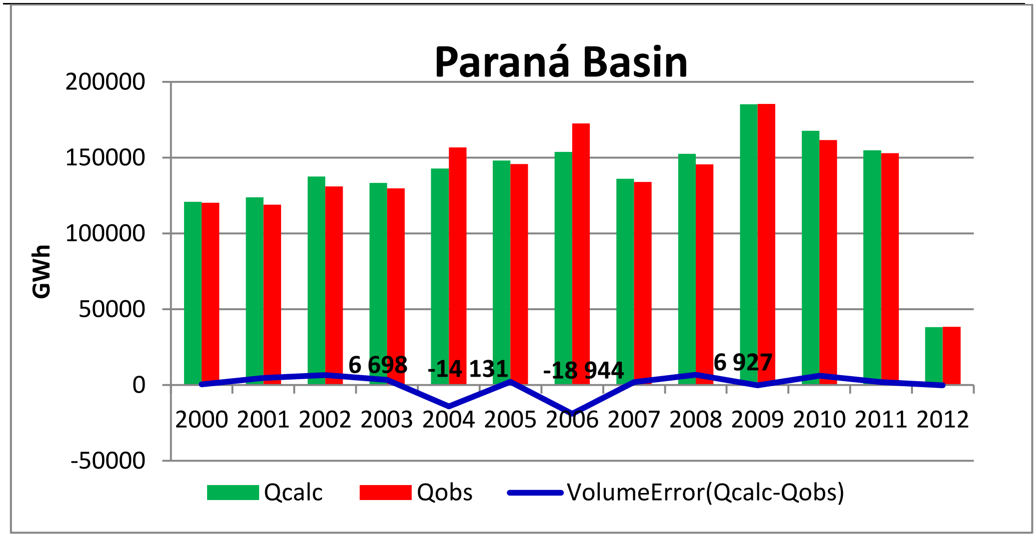

Figure 41 Annual volume differences between calculated and observed inflow for all Paraná sub-basins together with volume errors

Table 17 Results of calibration and validation for Paraná total basin

Objective function	**r2_w**	**r2_m**	**AccDiff (GWh)**
Calibration	0.87	0.92	0.5
Validation	0.75	0.82	-2106

All values in Table 17, together with the hydrograph in Figure 40, indicate that with records of 28 precipitation and 11 temperature stations located within and around the Paraná basin, the Scania-HBV simulated energy inflow satisfactorily agrees with the observed inflow for the period of 2000 to 2012.

The coefficient of determination for the Paraná basin is the second highest value for calibration, amounting to 0.87 on a weekly basis and 0.92 on a monthly basis. In addition, it is certainly the best among all the validation results with a value of 0.75 weekly and 0.82 monthly. This is partly because of a contribution of individual sub-basins to the total basin depending on their weight. Thus, Paranaíba and Grande, having the largest share of inflow, are the most influential sub-basins for the Paraná basin result. Since simulations of those two sub-basins resulted in the highest r^2 it is reasonable that the coefficient of determination of the Paraná basin benefits from them. Another reason is that energy inflow of individual basins can compensate each other when they are put together for the total basin, for example if trends of sub-basins are opposite. This could remove errors and other strange patterns in the different sub-basin model results. The good final result also indicates that negative values of observed natural energy inflow for the Paraná sub-basin are of little consequence to the inflow simulated for the whole basin.

In terms of volume, see Figure 41, annual differences are lesser and the accumulated difference amounts only to -2106 GWh. This quantity is arguably small considering the large total runoff volume in the Paraná basin and significant values of accumulated difference for individual sub-basins.

5.3 Common Discussion

5.3.1 Meteorological Data

- Overall, out of all precipitation stations used, only three of them had a fillness quality between 90 and 95%, the rest had fillness of above 95%. That shows the importance of not missing data in the input series, especially during the wet season since the missing values of precipitation in the series are treated as dry days (no precipitation).
- Meteorological stations spread across and around the Paraná basin had the records sufficient to adapt the model for individual sub-basins. However, more stations are desirable especially in areas currently vacant to get an even better picture of the meteorological situation over the basin.
- The yearly temperature does not vary much within sub-basins during the whole period 2000-2012, as shown in Table 19 in Appendix. This means that temperatures in the calibration and validation period are almost the same. Grande and Paranaíba have the lowest yearly average temperature of 25-26 degrees, Tietê and Paranapanema 27-28 degrees, and Paraná has the highest of 31-32 degrees. All stations chosen are of high quality, with a fillness of above 99%. Fewer T stations (and none of them is situated in the center of the basin) may influence the model to some extent (less high temperature data since the valley areas could have periods with higher temperatures), but at the same time, temperature does not seem to fluctuate much within a year within a sub-basin.

5.3.2 Target Data

- One can conclude that the model has a good fit to the observed data, since an r^2 value of 0.8 in calibration is a good fit according to Saelthun (1995) and project results show weekly coefficients of determination of about 0.8 (monthly r^2 0.9) in calibration and 0.7 (monthly r^2 0.8), in validation for all sub-basins except the Paraná sub-basin. Results also show satisfying values of r^2 weekly were above 0.8 (monthly above 0.9) in calibration and above 0.7 (monthly above 0.8) in validation. Even though r^2 values are lowered during validation as expected, they are still within an acceptable range. The Paraná sub-basin has the least satisfying result but since it is not a big contributor to the total inflow, the results for the whole of the Paraná basin turned out to be good regardless.
- The model cannot capture the exact pattern in the Paraná sub-basin, since it is the result of subtracting the whole basin with the other sub-basins. This leads to odd values (e.g. negative ones) in the target series as well as comparable large negative AccDiff in validation period. An explanation could be the exclusion of local features and routing effects along the river as well as the impact of inflow from western tributaries. The most important thing is to capture the general pattern with the model and not the extreme peaks and negative values. For example, deep negative peaks in the target series should correspond to low values in the simulated inflow. The general yearly negative volume error could be explained by the choice of stations drier than is

representative of the whole sub-basin, “long-term” data demand, and also since it is hard to capture whole Paraná sub-basin (272 918 km^2) weather conditions. Furthermore, the selected stations were not evenly distributed as shown in Figure 37.

- Depending on the year, approximately 30 to 40% of daily natural energy inflow was estimated for each sub-basin, the exact percentage is presented in Table 19 in Appendix. Therefore, the daily energy inflow series included uncertainties depending on whether the estimations captured the real values or not. However, estimations in daily target data will not affect the monthly energy inflow presented above since it was corrected with observed monthly data from ENAS.
- Hydrographs for all the sub-basins show an abnormal pattern of natural energy inflow in May 2001. It is not an error in the target series but a consequence of hydrological situation in some parts of Brazil (e.g. SE/CO, São Paulo). During June 2001 to September 2002, the blackout crisis took place in Brazil and the government established a rationing program. Energy consumption decreased drastically, with 24% in SE/CO, and long electricity cuts were introduced. In addition, electricity from other sources became important. The reason for the blackout was mismanagement of the energy sector and lack of precipitation, which led to low levels in hydroelectric reservoirs.
- Paranaíba, Tietê, Grande, the northern-most sub-basins, overestimate inflow for 2000-2003 (Qcalc>Qobs). The same pattern is evident on hydrographs showing significantly increasing AccDiff during the first four years. The precipitation and temperature stations in Paranaíba, Grande and Tietê are situated at higher altitudes (see Table 7, Table 9 and Table 11). For each sub-basin, the lower elevated areas where there is a connection to the Paraná sub-basin, very few or no high quality stations with long-term data collection were found. Therefore, the stations selected capture mostly the highland climate, that means generally lower temperatures and less evapotranspiration, see chapter 2.3.1 and Figure 28. Another reason could be that wetter stations than is representative for the rainfall of the northern sub-basins were chosen. This could also explain the positive AccDiff and general positive volume error for these three sub-basins. The drought event in 2000-2001, which is shown by less observed energy inflow, might not be captured well by the model since the flatlands are often affected the most. This could be a reason for overestimated model values.
- Collected precipitation and flow pattern data in the Paraná basin correspond to the energy inflow results for Paranaíba, Grande and Tietê for which yearly patterns are clear and diversified contrary to rivers on the south, Paranapanema and Paraná, which have less varied precipitation throughout the year, see climate and hydrology chapters 2.3.1 and 2.5.3.
- In the wet year of 2009, there is a good fit between Qcalc and Qobs for Paranapanema, Tietê, Paraná (rather south). November 2008 is considered an extreme event due to heavy rains in South. Computed runoff captures a peak in 2009 by accurately chosen meteorological stations representative of the real hydro situation in those regions.

5.3.3 Model

- Peaks during dry season are not captured as it was not our focus. Instead, we aimed to build an overall good model with a focus on peaks during wet seasons when most of energy is produced.
- The model is not tested for countries without any snowmelt and this could affect interpretation of results.

5.3.4 Energy market

- There are several different causes for occasionally extreme peak prices on the Brazilian energy market. They might be governmental control through ONS on producers, the need for more planning and maintenance, lack of investment and new technology which could lead to technical problems in power plants, transmission lines and relay stations, as well as natural changes in climate and regulations. Often it is a combination of impacts from several of these things. The drought in 2001 connected to an extreme ENSO event, La Niña, combined with an insufficient energy system seems to be the cause for less energy inflow during wet season in the northern basins (Paranaíba, Grande and total basin), leading to increased prices in the SE/CO regions. Since the S region reservoirs by that time were filled and the energy system was upgraded, it did not result in a peak price. Other peaks in prices might also be explained by governmental regulation due to severe droughts and technical problems.

6. Conclusions and Future Work

All steps including validation, evaluation of meteorological and target data, and quality checks ensure a trustworthy model. The evaluation of source data, together with good values for different objective functions (r^2 and AccDiff), and the fact that the calculated energy inflows that capture observed extreme weather conditions, verify that the model accurately reflects reality. Overall, the Scania-HBV model was successfully adapted to the Paraná basin and together with satisfying final results one can conclude that it is generally a reliable model that probably can be used for prediction of future hydropower production.

Improvements

- It might be useful to check simulated E/P ratio not only for calibration but for the period of validation as well. This could be the reason for the large AccDiff and annual volume errors during validation.
- A relatively large part of daily energy natural inflow (30-40%) was estimated. If simulation on a daily basis is to be presented, further improvements might be needed by collecting real time daily Qobs to fill the gaps. Changes like those could result in better agreement between daily Qobs and Qcalc. On the other hand, with such a large share of estimations in target series, results are very satisfying. This could be due to the good methodology used for estimation of daily values, reliable data and correction of monthly averages.
- Other suggestions for improvements include using other models to verify results, collecting larger quantities of high quality observed data and statistical data and using automatic calibration tools to receive optimal parameter combinations.
- The hydrological year was chosen according to sources about the hydrological year in the Southern hemisphere. Choosing another source which gives region-specific hydrological years might improve the results.

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Appendix

Estimations of daily energy inflow

Table 18 Estimations of daily energy inflow per year for calibration (red) and validation (green)

Year	Number of estimated days in daily target series (%)
2000-2003	Monthly target values
2004	32.9
2005	34.8
2006	34.0
2007	42.7
2008	40.0
2009	41.9
2010	39.5
2011	35.9
2012	33.7
Average	**37.3**

Yearly average of temperatures in the sub-basins

Table 19 Yearly average temperatures from model results

Sub-basins in Paraná basin	Yearly average temperatures ($°C$)
Grande and Paranaíba	25-26
Tietê and Paranapanema	27-28
Paraná	31-32

ONI 3.4 region

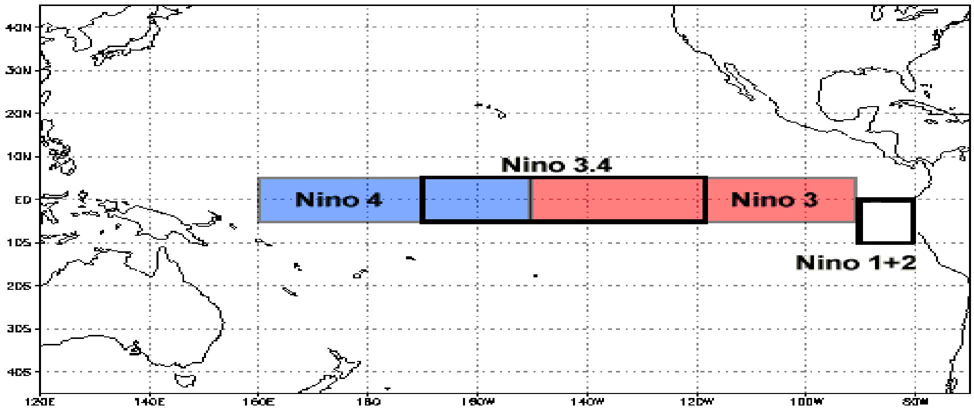

Figure 42 ONI 3.4 region between Tahiti and Darwin across the Tropical Pacific(Enloe, 2012)