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Energy and Hydrology Modelling of Argentina

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Abstract

The Scania-HBV model has been used to model the natural energy inflow to the hydropower plants in Argentina. The installed generation capacity of hydropower in Argentina is a total of 11095 MW and holds 36% of Argentina's total capacity. By successfully modelling the inflow it is possible to yield profits in the energy market with the possibility to estimate the energy available for hydropower production. The model needs to be calibrated and validated for the specific area and to measure the accuracy of the model the Nash-Sutcliffe Efficiency (NSE) coefficient has been used. Meteorological and hydrological data was collected from 1999-05-23 to 2014-05-23 and a total of four models have been calibrated. The calibration result varies from 0.9 to 0.5 and the validation gave NSE coefficient values of 0.74 to -3. For aggregation of the models representing Argentina the calibration ended with 0.77 on a weekly basis and 0.8 on a monthly basis and the validation resulted in -1 on a weekly basis and -0.9 on a monthly basis. A simple double mass curve analysis concluded that the quality of the precipitation data used (CPCp) might not be as good as expected and needs further analysis.

Sammanfattning

För att beskriva det naturliga energiflödet till vattenkraftverken i Argentina har man kalibrerat modellen Scania-HBV. I Argentina är vattenkraftverkens installerade elproduktionskapacitet 11095 MW och står för 36 % av den totala kapaciteten. Det är möjligt att göra vinster i elmarknaden genom att modellera inflödet av energi eftersom man bättre kan förutspå hur mycket energi som är tillgängligt för vattenkraften. Modellen behöver kalibreras och valideras för de områden den används för och resultatet har säkerställs med Nash-Sutcliffe Efficiency (NSE) koefficient. Metereologiska och hydrologiska data har samlats in från 1999-05-23 till 2014-05-23 och fyra olika områden har modellerats. Resultatet har varierat, för kalibreringen mellan 0.9 och 0.5 och för valideringen mellan 0.7 och -3. Summan av alla modeller, som tillsammans representerar hela Argentina, gav för kalibreringen NSE koefficienterna 0.77 på veckovis basis och 0.8 på en månadsvis basis och för valideringen -1 på veckovis och -0.9 på en månadsvis basis. En enkel double mass curve analys visade på att de nederbördsdata som används inte är helt enhetliga över längre perioder och behöver analyseras mer.

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Abbreviations and Acronyms

ENSO – El Niño/Southern Oscillation

EN – El Niño

LN – La Niña

MEM - Mercado Eléctrico Mayorista

MEMSP - Mercado Eléctrico Mayorista del Sur de Patagonia

TR – Thomson Reuter

NSE - Nash-Sutcliffe Efficiency

SMHI – Swedish Meteorological and Hydrological Institute

1 Introduction

Countries have their electrical energy generated by different sources depending on what is available to them. Hydropower is a major contributor to the generation of electricity in Argentina as 36% of the installed capacity in the country is hydropower. (CAMMESA, 2013). With water as its resource, hydropower will not provide complete stability to the generation as the access to water changes from year to year.

As of 1990 Argentina started to privatise the energy market and with that the price is now decided by supply and demand. In a privatised energy market with a substantial dependency on hydropower there will be a correlation between the price and the amount of available water supply. For a market where this dependency is strong, it is of interest to study how the availability of water for the hydropower plants changes. Such a study would make it easier to predict price changes, give a deeper insight in how hydropower affects the market, as well as a possibility to take precautions for possible effects caused by lack or overabundance of hydropower.

This thesis aim to calibrate and validate an energy based box model, similar to the HBV-model, for Argentina. The model will show the available supply of water usable for hydropower and could be used to provide estimates for future prognoses.

1.1 Aim

The main purpose for this thesis is to evaluate the result of a model calculating the natural energy inflow in Argentine hydropower system and if there is a profit for investing in such a model for the market.

This aim will be reached by answering the following questions:

- Is there a seasonal variation of the inflow to the hydropower plant?
- Is the available data good enough to use with the model?
- How does the market price correlate with the results from the model?

1.2 Limitations

Smaller plants are not considered in the model and the studies are therefore limited to power plants with at least 50 MW installed capacity.

2 Background

2.1 Argentina

Argentina with 43 million inhabitants is located in southern Latin America and has a total area of 2.740 million km^2 which is about six times as large as Sweden (CIA, 2014). Hydropower has an installed production capacity of 11095 MW which is about 36% of the total Argentine capacity and generated 31.1% of the total 129.5 TWh electricity generated during 2013. Most of the electricity generated comes from thermal power plants of which combined cycle power plants using natural gas is the most common (CAMMESA, 2013). Of all the energy generated by hydropower plants, three of the plants contribute to around 50 % (Secretaría de Energía, 2008). The hydropower potential is far from completely developed as it is estimated to be 24% of the theoretically feasible potential hydraulic energy available to utilize (Ortega, 2009). The climate is mostly temperate with subtropical areas in the north, arid areas in the centre and southeast, and subantarctic in south west (Gov. of Argentina, 2014). The terrain is generally described as plains in the northern half (Pampas), plateau in the south (Patagonia) and mountainous areas along the western border (Andes) (CIA, 2014).

2.2 Climate

The climate changes in both latitudinal and longitudinal directions. The latitudinal change is more due to the great distance that Argentina covers than any other geographical phenomenon. Argentina is the second largest country in Latin America and from north to south it crosses four major climatic zones viewed and further divided in Figure 2.1. The zones are the subtropics, the temperate Pampas, the arid Patagonia and the most southern subantarctic. The change with longitude is largely due to the ENSO cycle and the heights of Andes. These two influences mainly shape the distribution of precipitation across the country. As seen in Figure 2.3, the Andes (along the western border of Argentina) reach very high heights in the north, making it difficult for clouds to carry water across the mountain range from the west (Greenland, 2005). This effect can be seen in Figure *2.2* as the annual precipitation decreases drastically over the mountains in the north.

Figure 2.1: Climatic zones in Argentina (Gov. of Argentina, 2014).

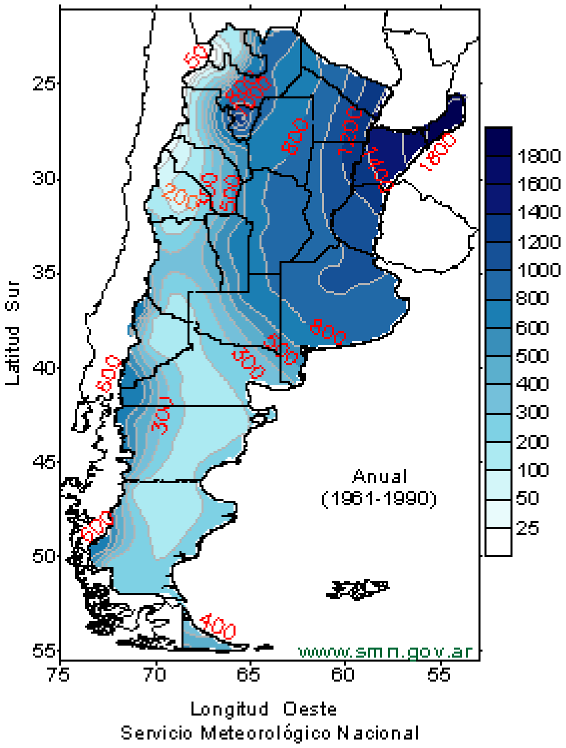


Figure 2.2: Annual precipitation over Argentina in mm (SMN, 1990b).

Further south, the effect of clouds losing water as they cross the range is still present. However, the Andes are not as high as in the north and the higher peaks are east of the border and therefore parts of the precipitation is able to cross the border. Figure 2.4 tells us that this occurs as Chile receives a lot more precipitation. The precipitation will give the south mountain region a comparable larger supply of precipitation while the area close to the mountain might not be as dry. Naturally, the winds crossing the mountain range from the west will be dry when they reach the lower land in Argentina, bringing dust from the mountain and turn this land to arid regions. However, the mountain range is not the only factor that affects the climate. Figure 2.2 shows that there is a significant variation in the precipitation along the east coast as well. For the northern inland and northeast of Argentina the tropical rainstorms coming from the northeast reducing the spread of the arid lands in the north resulting in the temperate zone Pampas. The south however, does not have close to the same amount of precipitation. These areas are supplied with precipitation by the Antarctic winds which do not carry as much water, giving the arid plateau of Patagonia. (Greenland, 2005)

Figure 2.3: Topography over Argentina (Anon, 2009a)

Argentina has four seasons throughout the year. Autumn starts in March and lasts until June when winter comes. The spring begins in September and lasts until December when summer arrives. When looking at data from 1961 to 1990 presented by SMN, the warmest month during the year is January which can have median temperatures of 26 in the north and 14 in the south. The coldest month is July where the median temperature drops to 14 in the north and 2 in the south. The lowest median temperature is generally 4 degrees lower than this, meaning that southern Patagonia as well as the Andes will have snowfall during the winter as the temperature drops below zero. When looking at the absolute minimum, all of Argentina has experienced temperatures below zero. (SMN, 1990a)

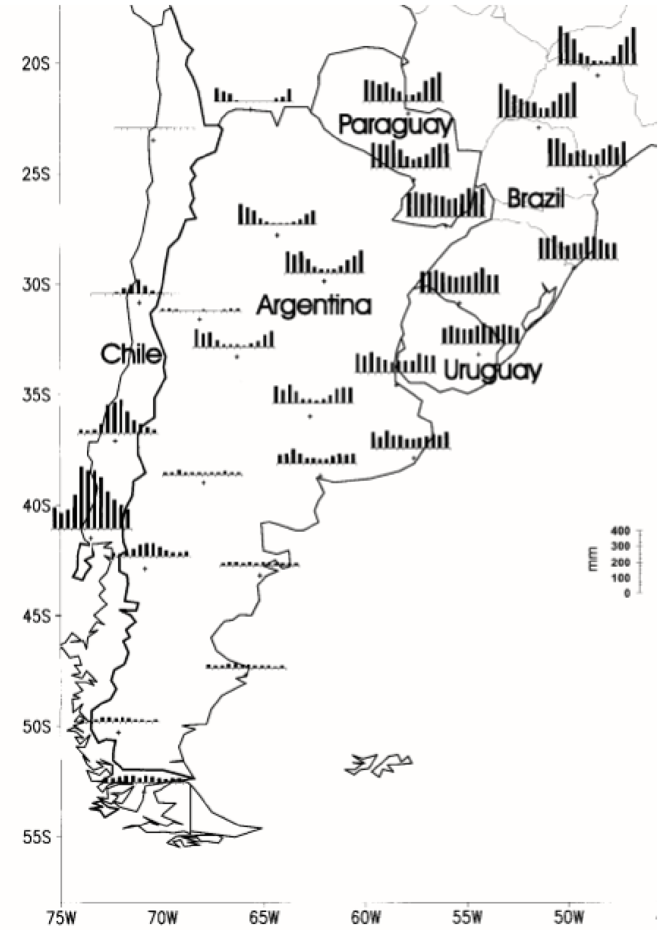


Figure 2.4: Precipitation per month at different locations in southern Latin America. Each bar is one month and they are ordered as they are in a year starting with January to the left. (Grimm, et al., 2000)

When it comes to the precipitation distribution over the months the whole country does not, as seen in Figure 2.4, follow the same pattern. In the northeast there is an almost even distribution with a drop during the winter months. Central and northwest regions have a much larger difference between the summer- and winter months where most of the water comes during the summer. In the south region it shifts to having more precipitation during the winter months and less during the summer. This trend becomes obvious closer to the Andes while some regions in the Patagonia and along the coast have no clear tendency and receives around 10-20 mm monthly. (Worldbank, 1990; Grimm, et al., 2000)

For the whole of southern Latin America, viewed in Figure 2.4, it has been concluded that there is a connection between precipitation anomalies and the events El Niño (EN) and La Niña (LN) (Grimm, et al., 2000). For the region the strongest connection can be found in southern Brazil, meaning that for Argentina the rivers Paraná and Uruguay will show the strongest connection in terms of flow (See Figure 2.5). Both events are part of the ENSO cycle where EN can be defined by warmer surface water from the western part of the Pacific Ocean close to the equator entering the central and eastern part of the Pacific basin along the western boarder of Latin America. This region is usually a cooler region and when the warmer surface water enters, the water balance will shift causing draughts and heavy rainfalls all around the Pacific. LN can be seen as the counterpart to EN as it is caused by colder water entering instead. (Glantz, 2005)

In Argentina the events EN and LN seem to have opposite effects during almost the same timeframe of the events. EN has a tendency to register lower median precipitation the year before the event, nondependent on whether LN occurred that year or not. During the year of EN the tendency is to have a period with more than the usual precipitation starting during the spring, which later on disappears during January and then reappears in February. For LN the year of the event gives lower amounts of percipitation while the year before gives higher. (Grimm, et al., 2000)

2.3 Hydrological conditions

The river network can generally be described as rivers flowing from west to east mostly from the Andes to the Atlantic Ocean as seen in Figure 2.5. However, there is an area between Desaguadero River and Salado River that is endorheic, meaning it does not flow to any ocean, and has Mar Chiquita Lake, Argentina's largest lake as one of its recipients (Anon, 2009b;2014). The origins of Paraná River and Uruguay River are different, thus those rivers do not flow in similar fashion. They come from northeast from other countries flowing more in a north to south pattern. Other exceptions are a few rivers like Futaleufú River which origins from the Andes but flows to the west to the Pacific Ocean (Anon, 2009b).

Figure 2.5: Overview of major Rivers (Anon, 2009b). Picture taken using Google Earth

The major rivers that are being exploited for hydropower today are Paraná, Uruguay, Futaleufú and Negro in the sense that its tributaries, Limay and Neuquén, have power plants (Secretaría de Energía, 2003). The discharges of all these rivers can be found in Table 2.1. Most noticeable is that the Paraná River and Uruguay River carry a lot more water which correlates well with the information about precipitation presented in chapter 2.2, given the location of the river basins. Another noticeable fact is the discharge of Negro compared to its tributaries as it has a lower discharge than the sum of the tributaries. Given the location of the three rivers (seen in Figure 2.5), the tributaries are located on the mountain side while Negro runs of the Patagonian plateau which is described as an arid region with low precipitation, the loss of discharge seems so be a likely scenario as the arid lands probably has a high evapotranspiration. (GRDB, 2014)

By identifying the loss of water in Negro River it is clear that it is not an optimal location for hydropower, at least not close to the outlet. The main inflow of water to Negro River seems to occur in the mountains which is good for hydropower plants. The reason for this is the natural height differences that gives a larger energy potential as power plants can be constructed with a higher elevation head. As for Paraná and Uruguay River there is a smaller height difference that could be used, but on the other hand the shear amount of water flowing in the rivers reduces the need of high potential energy. It is instead possible to make large reservoirs and provide a large steady flow to run the power plant with.

Table 2.1: Average river discharge for major rivers in Argentina (GRDB, 2014)

River	Discharge in m^3/s	Average of period
Paraná	12100	1901 - 1986
Uruguay	5220	1968 - 1979
Negro	850	1927 - 1994
Limay	750	1903 - 1980
Neuquén	310	1903 - 1980
Futaleufú	290	1948 - 1980

2.4 Hydropower system

As the energy market was privatized during the 1990s, all the power plants were to be sold by the government and since then the power plants, new and old, are owned by share companies (Sociedad Anónima, S.A) (Amden, 2010; Secretaría de Energía, 2003). Since 1992 the installed capacity has increased from 5721 to 11095 MW in 2013 (see Figure 2.6) mainly induced by the binational co-operation with Paraguay resulting in the plant Yacyretá with the total capacity of 3100 MW. Yacyretá was installed during the 1990s and is almost all of the potential installed between 1992 and 1999. No new power plants were installed between 1999 and 2001, and from then until 2013 around 2000 MW have been installed (CAMMESA, 2014). This shows a decline in new investments in the 2010s compared with the 1990s. While the capacity of hydropower has not increased drastically in later years, 8000 MW is planned to be installed from 2015 to 2020 according to IIR’s database.

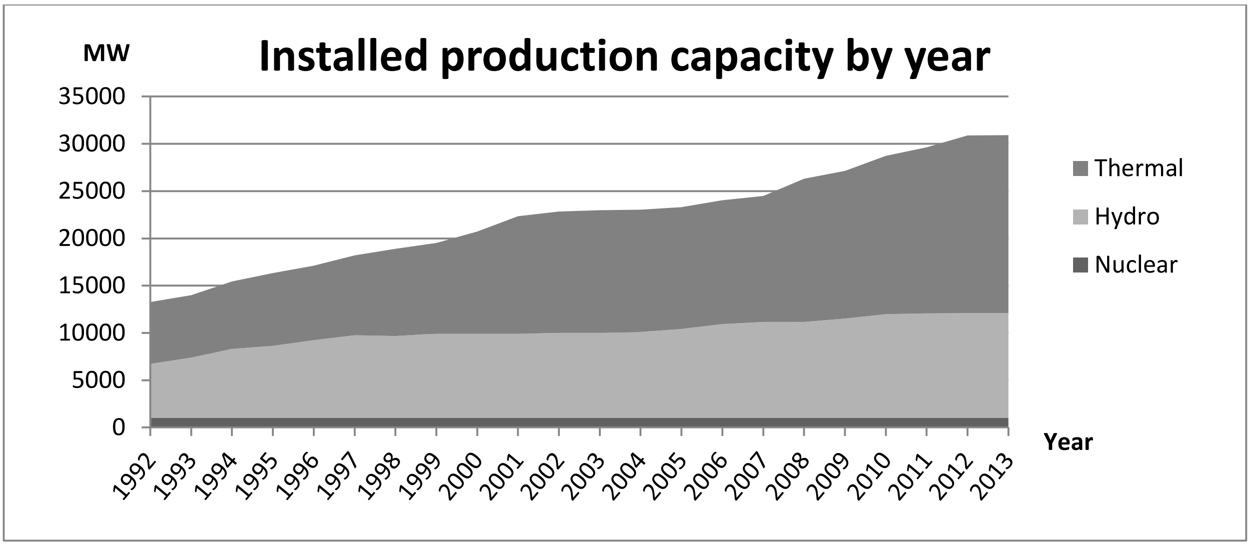


Figure 2.6: Evolution of installed potential in MW by year, lightest grey area represents hydropower (CAMMESA, 2014)

To get an overview of the hydropower system, the rivers were grouped as shown in Table 2.2 to study their contribution and capacity. The river system that has most power plants is the Limay & Neuquén with 6 power plants with a total of 4431 MW installed capacity. The system contributes to almost 30% of the average production, with Piedra Del Aquila as the main contributor with 5500 GWh per year, making it the third largest hydropower production in Argentina. The largest generating plant is found in Paraná River with only one power plant, Yacyretá, generating around 40% of the hydro energy on its own, making Paraná a main river for hydropower production. The third river system in both generation and installed capacity is Uruguay River with the Salto Grande plant generating 6800 GWh per year.

Table 2.2: Installed capacity and average yearly production per river and their tributaries. (Secretaría de Energía, 2003)

River	Installed Capacity [MW]	Average Yearly production [GWh/year]
Limay & Neuquén	4431	13541
Paraná	3100	20000
Uruguay	1890	6800
Colorado & Desaguadero	1043	3270
Salado & Rio Grande	852	1126
Futaleufú	448	2700

With the planned installations of 8000 MW the hydropower production is supposed to increase its contribution to 41% of the total production by 2025 (Républica Argentina, 2014). Currently under construction is Punta Negra Dam, which with 61.6 MW will supply 705 GWh annually and is planned to be completed in 2015, and a few other plants are under way (Panedile, 2014). A big soon to be constructed project, which recently got funding from China, is the construction of Néstor Kichner Dam and Jorge Cepernic Dam with the potential capacities 1140 and 600 MW respectively in the Santa Cruz River. They are estimated to provide 5000 GWh annually and cover 4% of the demand (Secretería de Obras Públicas, 2014). Another big plant to be constructed soon is

Chihuido I in Neuquén River with 637 MW, expecting to give 1750 GWh per year (Répulica Argentina, 2014). In Figure 2.7 the location of larger power plants that have either been constructed and have begun the process of bidding (proceso de licitación) by 2014. As seen Chihuido I is the first of a series of power plants planned in Neuquén River as its bidding process began in 2013.

Not only new plants are to be constructed. It has been decided to increase the capacity at Yacyretá power plant with 10 % by putting generators at one of the dam's spillways (BN Americas, 2013). The statement of a 10 % increase of capacity has also been made for Salto Grande (BN Americas, 2011)

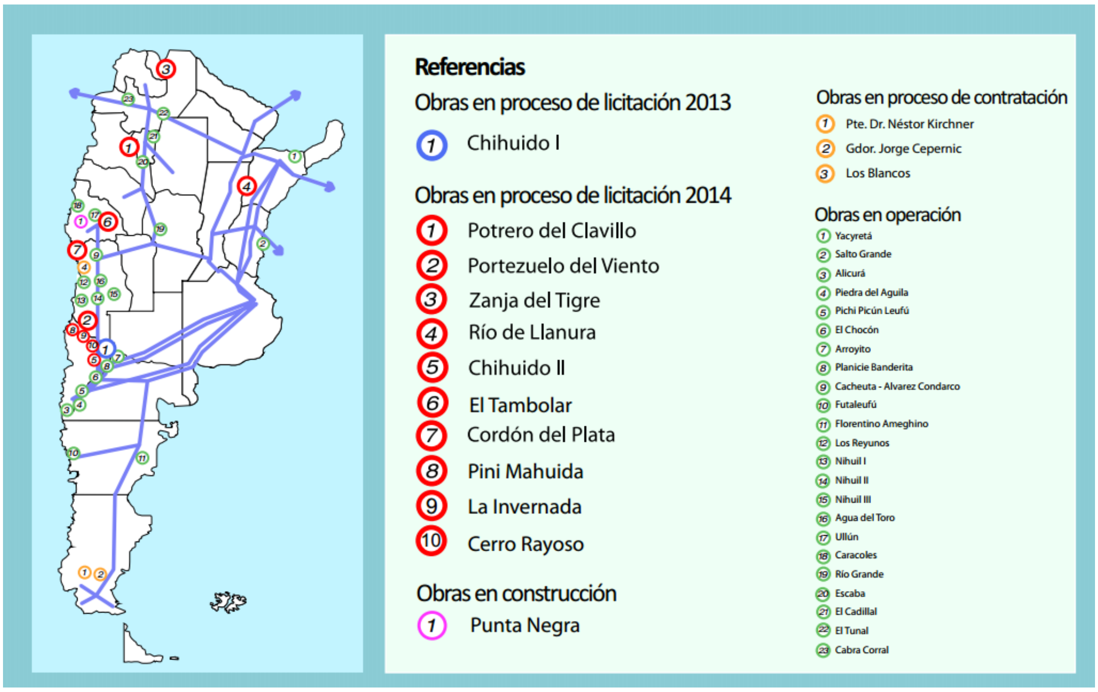


Figure 2.7: Current and soon to be constructed hydropower plants in Argentina. "Obras en proceso de licitación" means "Works in bidding process" (Répulica Argentina, 2014)

2.5 Energy market

The energy market in Argentina is a privatized wholesale priced market which is operated by CAMMESA. The market was privatized during the 1990s as a result of a government led industrial reform, which declared privatization of state-owned companies dealing with commercial activities (Beretta Gody, 2014). The market was divided in two parts, MEM (Mercado Eléctrico Mayorista) and MEMSP (Mercado Eléctrico Mayorista Del Sur de Patagonia) until 2006 as Argentina was operating on two separated power grids (Perczyk, 2009). As of March 2006 the two markets became linked together and are no longer statistically separated by CAMMESA and are continually only presented as MEM (AGEERA, 2013). MEMSP was a fraction of the size of MEM with a total potential capacity of 780 MW in 2004 compared to MEM with 23000 MW at the same given year (Rudnick, 2004). 97.3% of the generated hydropower in MEM was from plants associated with AGEERA in 2013 (AGEERA, 2013).

The market has during its existing time gone through a few changes regarding the pricing. In late 2001 and early 2002 Argentina experienced an economic crisis, which resulted in radical changes by the government in many sectors. Some of these changes dealt with the energy market effecting how the pricing of electricity was to be calculated. The spot price, or short-term marginal cost, was to be calculated based on the cost of production with natural gas from available generation units, disregarding whether natural gas was actually used or available. Any additional cost for producing electricity is called a temporary dispatch surcharge (Pampa Energía, 2014). The spot price was in that sense artificial, reducing the electricity price for the people while the National Treasury paid the surcharge to CAMMESA to cover the expenses (Estudio Beccar Varela, 2014). The price of natural gas in Argentina is decided by the government and their pricing limits the cost of electricity generation to 120 Argentinean pesos per MWh, which is almost 14 US dollar (in 2015). As the government sets a limit to how high the price of natural gas can be, it will cap the cost of electricity. (Pampa Energía, 2014)

Using the natural gas, with a capped price, as a way of pricing has not provided a healthy environment, as the electric consumption has outgrown the generation and not enough new investments in capacity has been done (Kozuji, 2010). A recent act to improve the conditions for the market was made in 2013 when a new generation capacity remuneration scheme (SE Resolution 95/13) was put in place changing the pricing of the short-term marginal cost (Pampa Energía, 2014). Based on available capacity of the power plants, availability and type of fuel, CAMMESA sets the prices which are afterwards approved by the Secretariat of Energy (Estudio Beccar Varela, 2014). Capacity remuneration schemes are used when the existing market does not prove good enough environments for investments (Höschle, 2014). The new scheme affects the entire power generation sector with the exception of binational hydropower plants, nuclear power plants and power plants already under contracts with SE giving them a differential price. (Pampa Energía, 2014)

The new capacity scheme is divided into three parts, fixed cost remuneration, variable cost remuneration and additional remuneration. All parts give a price either per MW or MWh based on type and size of power plant, for example a power plant with a capacity over a certain level of MW will have a lower price per MW. The fixed cost remuneration considers the capacity (MW) made available for production while the variable cost remuneration considers the power generated and is calculated on a monthly basis depending on the production of each generation type. The additional remuneration is paid directly to the generator and also has a part which goes to a trust fund made to support new infrastructure projects within the energy sectors. (Pampa Energía, 2014)

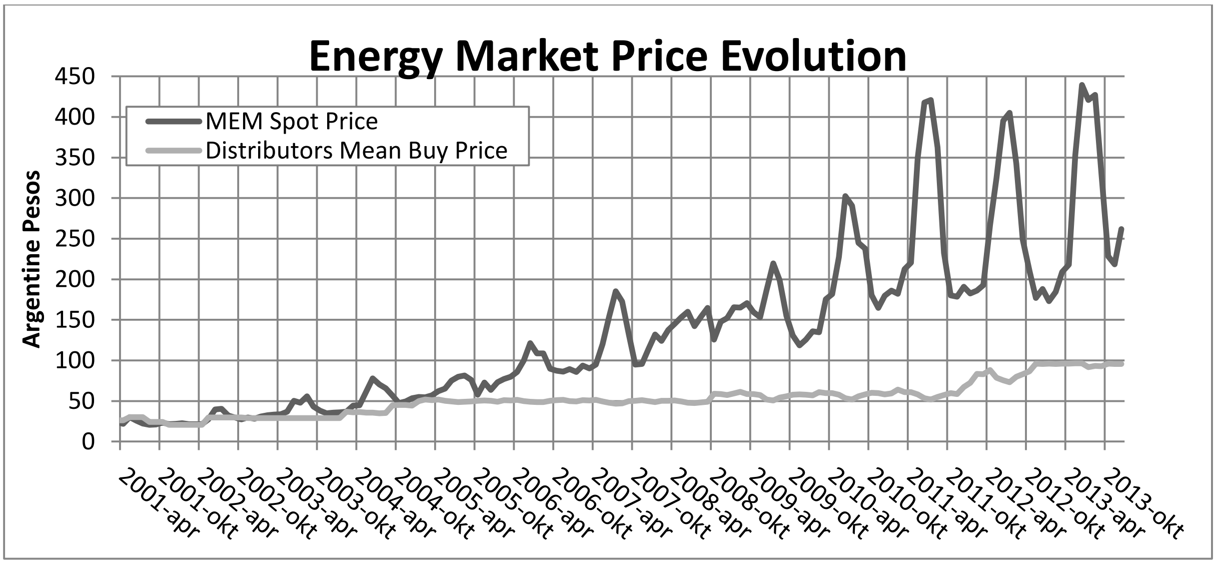


Figure 2.8: Monthly spot price and mean buyer price on the Argentine energy market (CAMMESA, 2014)

The spot price together with the temporary dispatch surcharge is plotted in Figure 2.8 along with the mean buyer's price for the distributors. The price varies seasonally with higher price during the winter. The price has steadily increased since 2001 and as of 2011 the peak price during winter is more than twice as high as the summer prices. (CAMMESA, 2014)

2.6 Box model

The model to be used in this report is a box model similar to the HBV model which is a simple version of a rainfall-runoff model developed by SMHI (Bergström, 1992). A box model is based on the continuity equation, where difference in inflows and outflows is set equal to the change in storage. For a catchment the continuity equation is described as Equation 2.1 below with the storage divided into 5 parts:

$$\frac{d}{dt}(SP + SM + UG + LG + Lakes) = P - E - Q$$ *Equation 2.1*

Where left hand side is the total change in the storages describing

SP = snow pack
SM = soil moisture
UG = upper groundwater zone
LG = lower groundwater zone
Lakes = lakes

The right hand side consists of the inflow P which is the precipitation and the outflows E, describing the evaporation and Q, describing the run off.

The concept behind the model is to divide the soil into different layers, also called boxes, of which there is usually a soil box, an upper and a lower groundwater box and if needed a snow box. The degree of details and physiological processes described by the model is decided by the maker of the model. Examples of different decisions can be how to calculate the evapotranspiration and if there should be an area distribution within the model. (Beven, 2001)

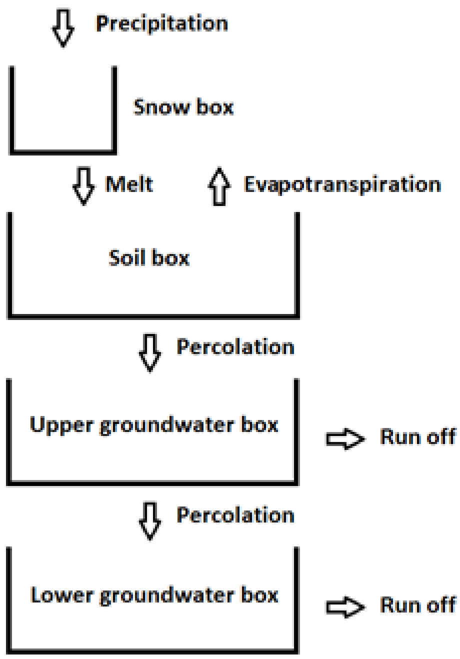


Figure 2.9: Basic overview of a box model

The input for a box model is usually a time series of precipitation and temperature data and gives the run off as output. A general overview of how flows are between the different boxes can be found in Figure 2.9. The boxes serve to operate different routines. The snow box calculates how the snow accumulates and melts. If the temperature is below a decided value, around 0°C, the precipitation is assumed to be snow and commonly the melt is described with a degree day method as Equation 2.2 where C is the degree day coefficient and T_E is the parameter regulating if the precipitation should be seen as snow or rainfall. (Bengtsson, 1996)

$$melt = \begin{cases} C(T - T_E; if\ T > T_E \\ 0 \quad ; if\ T < T_E \end{cases}$$ *Equation 2.2*

The soil box models how the snow melt and rainfall enters and infiltrates the groundwater. The infiltration is based on the precipitation, P, reaching the soil and the current saturation in the soil, h, and can be described with Equation 2.3 with the usage of the parameters FC and b regulating the correlation between soil saturation and infiltration. (Bengtsson, 1996)

$$Infiltration = P * \left(\frac{h}{FC}\right)^b$$ *Equation 2.3*

It also calculates the evapotranspiration which is usually modelled as evaporation. The evaporation is based on the saturation of the soil and the potential evaporation, pe, with only occurs if the saturation is above the level h_p as described in Equation 2.4. The potential evaporation can be described in different ways, for example is can be seen as a fixed value or it could be described with a degree day coefficient as for the snow melt. (Bengtsson, 1996)

$$Evaporation = \begin{cases} pe * \frac{h}{h_p} & ; if\ h > h_p \\ 0 & ; if\ h < h_p \end{cases}$$ *Equation 2.4*

The two groundwater boxes performs a runoff routine calculating how much run off there will be proportional to the water stored in the ground water boxes. (Bengtsson, 1996)

2.6.1 HBV-Scania model

The HBV-Scania model uses the principles and concept of box models, to suit a simulation for energy inflow better the output is expressed in energy (GWh) instead of volume (m^3). The unit makes it easier to analyse storage volumes and the flows in the model with respect to the energy market. As for the box model the HBV-Scania model needs to be calibrated and vertified. The model uses the Nash-Sutcliffe Efficiency (NSE) coefficient based on daily, weekly and monthly outflows. NSE is calculated according to Equation 2.5 where Q^{obs} is the observed value, Q^{sim} is the simulated output and Q^{mean} is the average flow. The coefficient can be between -∞ to 1 where 1 equals perfect fit between the observed values and output, and 0 is at which point the average flow will describe the reality equally well as the model. As a perfect model is not achievable it is commonly stated that a model with higher than 0.7 can be seen a good model (Moriasi, et al., 2007).

$$r^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - Q^{mean})^2}$$ *Equation 2.5*

3 Method

This thesis will be performed according to the four steps in Figure 3.1. Firstly, a study over the climate, hydropower system and energy market will be performed to get a good overview to understand things like where important hydropower plants are located and what behaviour can be expected in the target series.

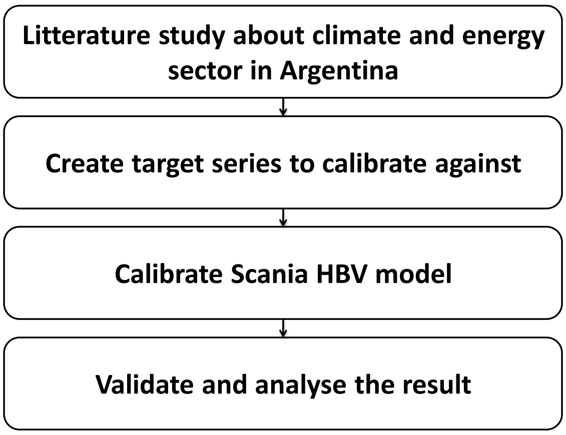


Figure 3.1: Basic overview of the methods main steps.

Secondly, data for the target series needs to be collected. The target series is optimally an inflow series in GWh per day. However, if such a series is not available and depending on what data that can be found, processing the data will be necessary to construct the target series. Two ways to construct a series are either with production data and reservoir change in energy units (MWh or GWh), or production and unregulated upstream flow data. With production data and reservoir change the handling is simply adding the production and reservoir change to get the inflow, according to Equation 3.1. In the case that reservoirs are not used, the storage will be equal to zero making it possible to assume that the inflow is the same as the production.

$$Inflow[GWh/day] = Production[GWh/day] + Storage[GWh/day] \quad \text{Equation 3.1}$$

When using the second method, with production and flow data, the idea is to apply a factor to the inflow series that will match the production during a larger period of time, fulfilling Equation 3.2 and Equation 3.3. The reasoning for extending the time frame is to assume the reservoir levels to be the same at the start and the end of the time frame to neglect the storage in Equation 3.1. An assumption over which periods the inflow will be equal to the production is therefore necessary. This assumption can either be based on an estimation with the help of seasons in the climate and/or locating at what time the minimum value of the accumulated difference between production and inflow in energy occur. For the example in Figure 3.2 an estimated value for the factor has been used. It seems to be a bit low as the accumulated difference is decreasing over time. The minimum value for the accumulated difference can be found in July and an assumption could then be to assume the inflow equal to the production from July to July and would perhaps give a better factor. The assumption will make it possible to calculate the factor as Equation 3.4.

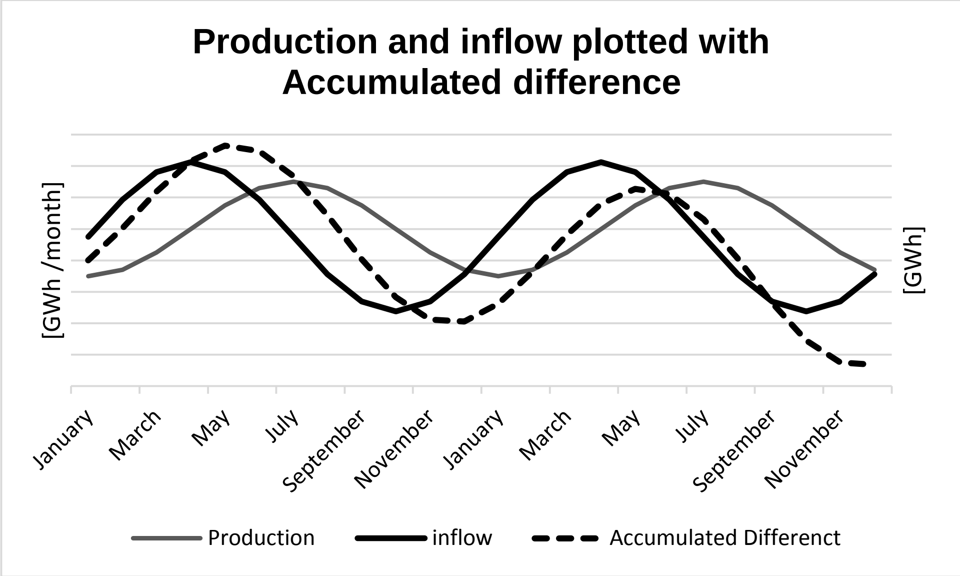


Figure 3.2: Example of production and inflow variation over two years. The accumulative difference has its minimum value in December. Production and Inflow are plotted against the left y-axis and the Acc. Diff. is plotted against the right y-axis.

$$Inflow[GWh/day] = Inflow[m^3/day] * Factor[GWh/m^3] \qquad \text{Equation 3.2}$$

$$Inflow[GWh/time\ period] = Production[GWh/time\ period] \qquad \text{Equation 3.3}$$

$$Factor[GWh/m^3] = \frac{Production[GWh/time\ period]}{Inflow[\mathrm{m}^3/time\ period]} \qquad \text{Equation 3.4}$$

When using this method it is possible that the factor might be too low. To avoid an underestimation, it is necessary to know about the spillage past the turbine. The consequence of spillage would be that the model will underestimate the amount of available energy during low flows with the possibility to make a difficult situation look even harsher. The production would be estimated over a larger inflow than the inflow contributing to the production. The production data should also reflect the production with the current hydropower. This means that if a new power plant is connected or a power plant starts to operate at a higher head during the time period, the production data needs to be modified to reflect the current situation.

The available data will decide whether it is possible to do models for different regions within Argentina. Data could be found for different spatial resolution such as individual power plants, regions or whole countries. When a larger spatial resolution contains more than one river, the method using inflow values in cubic meters requires an estimation of the production of each individual river. To account for this in the construction of the factor the right hand side in Equation 3.4 will be multiplied with percentage of production done by that river.

With one river it is possible to use basic optimization tools to minimize the difference between left hand side and right hand side in Equation 3.3 by changing the Factor in Equation 3.2. If this is done with several rivers the final result might result in an incorrect energy distribution over the rivers. By knowing the percentage of production by the individual rivers an estimate of where the energy comes from can be set up. Having data for plants within a region can therefore be of help, as well as knowing the average production for the plants can give an idea of how much energy each river gives.

Important to note is that the series chosen to construct the target series with must be a non-regulated flow. If there is a dam or other power plants upstream the measuring point they will alter the flow to a pattern which cannot be described by the model. This has to be considered when setting up the series for Paraná and Uruguay River as they originate from Brazil where hydropower constructions exist in the rivers.

With the data that was found the solution used for this case was to apply the production in MWh to inflow series originally in m^3/s for 4 different regions, more on this in chapter 4.4.

When the target series have been constructed, TR's Scania-HBV-model will be calibrated together with temperature and precipitation data. TR has requested that CPCp precipitation data and CSFR temperature data should be used, they are further described in chapter 4.3. The calibration includes parameters in the model as well as weighting and choosing temperature and precipitation stations. For calibration time the 10 most recent years will be used and the 5 years prior to the calibration will be used as validation.

The accuracy of the model will be measured with the NSE coefficient as described in chapter 2.6.1. Further validation of the result will be done by studying the accumulated difference between the model and the target series. The results will be presented with an aggregation of all models as well as for each of the models. The average daily inflow and snow storage over a year will be presented and a comparison between the modelled yearly inflow and the production will be made. To see if there is a clear trend between the spot price and hydropower, a comparison between the deviation from the average storage in snow and soil, and the spot price is made.

The precipitation data consists of two datasets (further described in chapter 4.3) and it could be of interest to analyse if there is any difference between the datasets. If there are issues with the input making it impossible for the model to get the same yearly flow as the target series, a double mass curve analysis will be done. By comparing the precipitation data with an observed stations in the same region it will be possible to locate if the sets are inconsistent. The comparison is done by plotting the accumulated yearly volumes of the precipitation data and the observed station in a scatter plot. If they form a straight line the sets are consistent but if not, one set is wetter than the other and a model will not be able to fit the target series for both sets. Creating a trend line between the observed station and the precipitation data and plotting the deviation from the trend line makes it easier to see the result of the double mass curve analysis. An example of a double mass curve analysis can be seen in Figure 3.3, in this case a difference can be spotted after 2009. During the years before 2009, the precipitation data carries more water than the trend line indicates that it should and after the precipitation data becomes too dry.

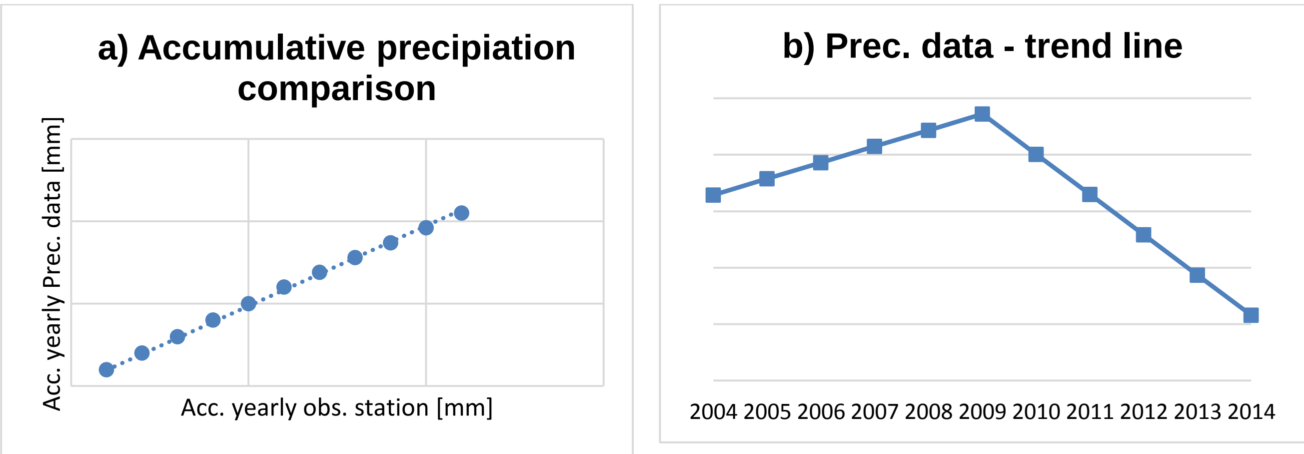


Figure 3.3: a) Example of accumulative comparison of precipitation data and observed station data. b) Difference between precipitation data and trend line from a).

4 Collection of data

4.1 Regions, Hydropower plant selection

Based on the background in Chapter 2.2-2.4 it is possible to derive regions that show similar traits as well as list the relative importance of the regions and power plants for the production. In Figure 4.1 all power plants are marked with a circle sized relatively to their size, green markers are plants with a reservoir and red marker indicates that the plant has a pumping storage. Two regions have been marked with a circle, the red circle shows the plants located in the Comahue region and the orange is the San Juan-Mendoza region. These regions have similar climate and meteorological conditions and could be modelled together. In Table 2.2 they are represented by Limay and Neuquén (red circle in Figure 4.1) and Colorado and Desaguadero (orange circle in Figure 4.1). The other power plants should preferably not be grouped together as they are located in different regions.

The 5 remaining plants are Cabra Corral, Yacyretá, Salto Grande, Rio Grande N°1 and Futaleufú. Cabra Corral is isolated by itself and only accounts for 0.2 TWh per year making it highly likely to be excluded when trying to put up models (Secretaría de Energía, 2003). Rio Grande N°1 has a pumping storage providing almost half of its yearly production making the access of energy for the plant not only dependable on natural rainfall. Due to this non complete dependency it will be harder to model and make use of the model as a lack of natural inflow will not have the same effect for this plant.

Regarding the relative importance for focus when modelling natural inflow, the regions' and hydropower plants' yearly production gives the order Yacyretá, Comahue region, Salto Grande, San Juan-Mendoza region, Futaleufú, Rio Grande N°1 and lastly Cabra Corral.

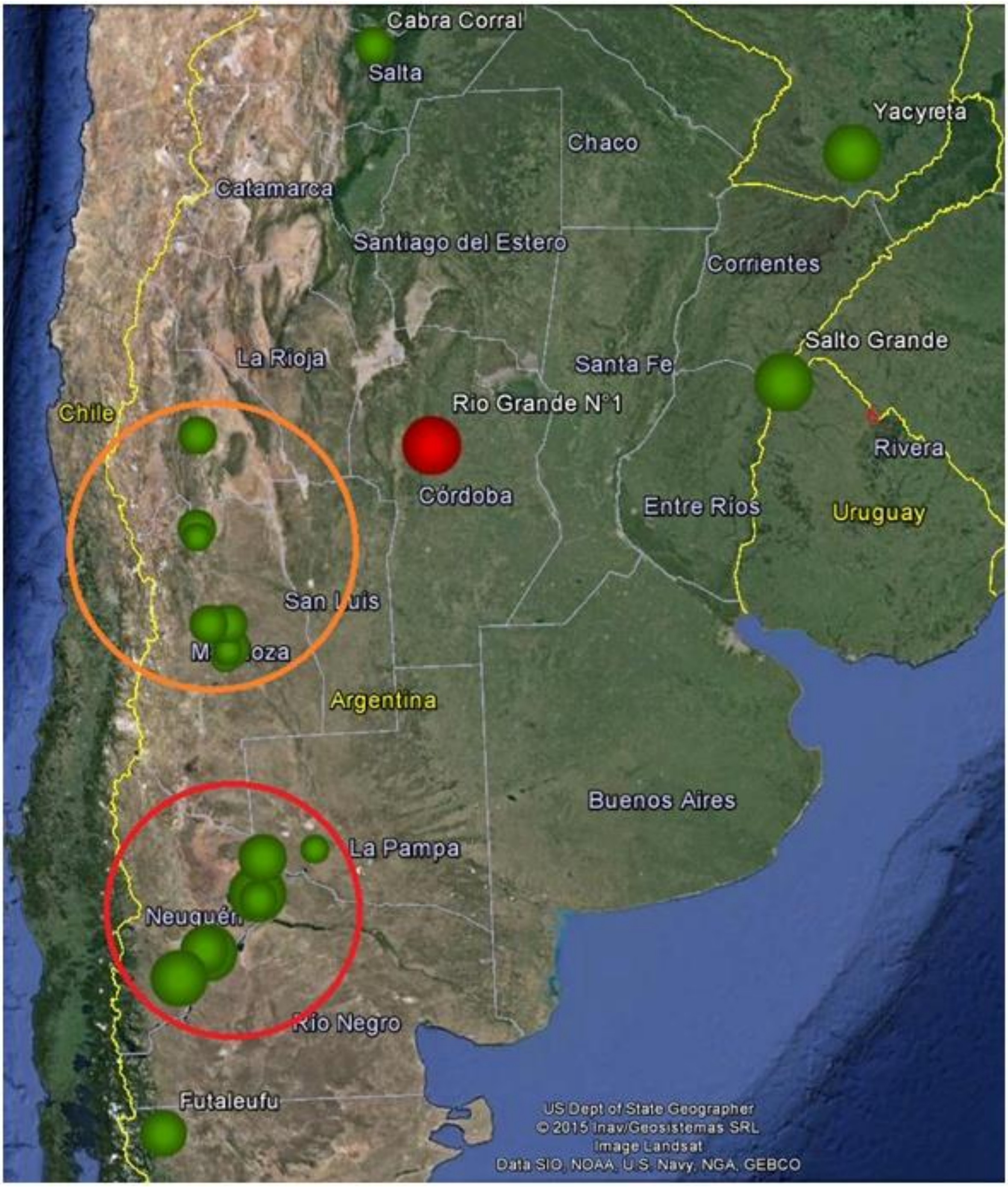


Figure 4.1: Hydropower plants in Argentina, green filled circles are reservoir power plants and red filled circles are pump and reservoir power plants. The red zone is the plants in Comahue region and orange is San Juan and Mendoza region. Picture taken with Google Earth.

4.2 Data for Target series

No series for inflow values in GWh have been found and no information regarding changes in reservoir levels has been found. What can however be found in units of GWh are the monthly production values. The values are divided in monthly production for Yacyretá, Salto Grande, the Comahue region and value for the rest production.

From CAMMESA's website it is possible to access daily information of the inflow, flow through the turbine and spillage in $m^3 s^{-1}$ for the hydropower plants in the major rivers, Futaleufú, Limay, Neuquén, Paraná and Uruguay River. The daily data accessed runs from 2009 to 2014 and have been complemented with weekly upstream flow values until 1943 given by CAMMESA. There are daily values for San Juan River (tributary to Desaguadero), unfortunately they are not of the same quality and have more days without data than with. However, the secretariat of water resources in Argentina manages an open database, called BDHI, where there is possible to get flow data for the rivers located in the San Juan-Mendoza region.

If the inflow values from CAMMESA for Paraná and Uruguay River show signs of being too regulated, then TR has inflow series from their Brazilian model for the rivers Paraná, Uruguay and Iguaçu a tributary to Paraná, which they are willing to give if needed.

4.3 Meteorological data

As for meteorological data, TR has collected precipitation measurements from CPCp and temperature measurement from CFSR. CPCp stands for Climate Prediction Center precipitation and is provided by the name giving center, CFSR stands for Climate Forecast System Reanalysis. Both are part of NOAA, National Oceanic and Atmospheric Administration, and provide global grid data with a grid size of 1 degree longitude and latitude, roughly 100x100 km, which is used in this thesis. The grid data used for this thesis covers areas in Argentina and in Brazil as the rivers Paraná and Uruguay originate in Brazil. The strength with these data is that they provide continuous series with no missing data for any day.

CPCp is a gauge-based analysis covering all the land areas across the globe. It uses observed values to construct grid precipitation data and has the strength of using a lot of stations. The dataset consists of two parts, a retrospective part using 30000 stations providing data for the time period 1979 to 2005 and a real-time part using 17000 stations covering from 2006 to present day. The analysis is quality controlled based on historical records and independent information such as nearby measurement stations, concurrent satellite observations and numerical model forecasts. The real-time dataset is to be reprocessed in the future to better match with the retrospective dataset. The downside of using this data is that the quality varies with the stations density and no information regarding the situation in Argentina has been found. (National Center for Atmospheric Research Staff (Eds)., 2014)

CFSR is a reanalysis product using an atmosphere-ocean-land surface-sea ice system to estimate the state of the domains with a high resolution all over the globe. It includes coupling of the atmosphere and ocean, an interactive sea-ice model and assimilation of satellite radiance. From this complicated system the temperature will be used in the model. The main benefit of CFSR is that it incorporates millions of observations into a steady data assimilation system, though it also gives limitations. The biases in observations and models can create variations and trends that do not exist in reality. The reanalysis reliability is also dependent on location, time period and the variable in question due to limitations in the observations. (Dee, et al., 2014)

The stations used for the double mass curve analysis described in the last paragraph of chapter 3 are from the product Global Summary of the Day (GSOD) produced by National Climatic Data Center (NCDC) and derived from The Integrated Surface Hourly (ISH) dataset. GSOD provides daily summary data of the precipitation from stations all over the world and the stations used from GSOD will be selected based on the missing data percentage, time period and location. (NCDC, 2014)

4.4 Data used

The production data provided by CAMMESA is the common factor for constructing the time series and as they are provided for four “regions” four models will be constructed with these values. Since all regions’ target series have been constructed differently they will be presented separately in the sub-chapters below. The regions are circled on a map in Figure 4.2 and the included rivers and power plants are listed in Table 4.1.

Table 4.1: Overview of the included rivers and power plants in the regions. Multiple rivers in the same region are listed from north to south and several plants within the same river are listed with the most upstream power plant first. The circles refer to Figure 4.2 where the regions are located on a map.

Region	Rivers	Power Plants
Comahue (red circle)	Colorado	Casa de Piedra
	Neuquén	Planicie Banderita
	Collon Cura & Limay	Piedra del Aguila, Pichu Picun Leufu, El Chocon, Arroyito,
	Limay	Alicura
Rest - San Juan Mendoza & Futaleufú (orange circle)	San Juan	Los Caracoles
	Mendoza	Caucheta, Alvarez Condarco,
	Diamante	Aqua del Toro, Los Reyunos,
	Atuel	Nihuil I, Nihuil II, Nihuil III
	Futaleufú	Futaleufú
Yacyretá (blue circle)	Paraná, Iguaçu	Yacyretá
Salto Grande (green circle)	Uruguay	Salto Grande

The meteorological data has been provided until 2014-05-22 and to capture both high and low flows it has been decided to use the 10 most recent years for calibration and the 5 earlier years for validation. The calibration period is then from 2004-05-23 to 2014-05-22 and the validation from 1999-05-23 to 2004-05-22.

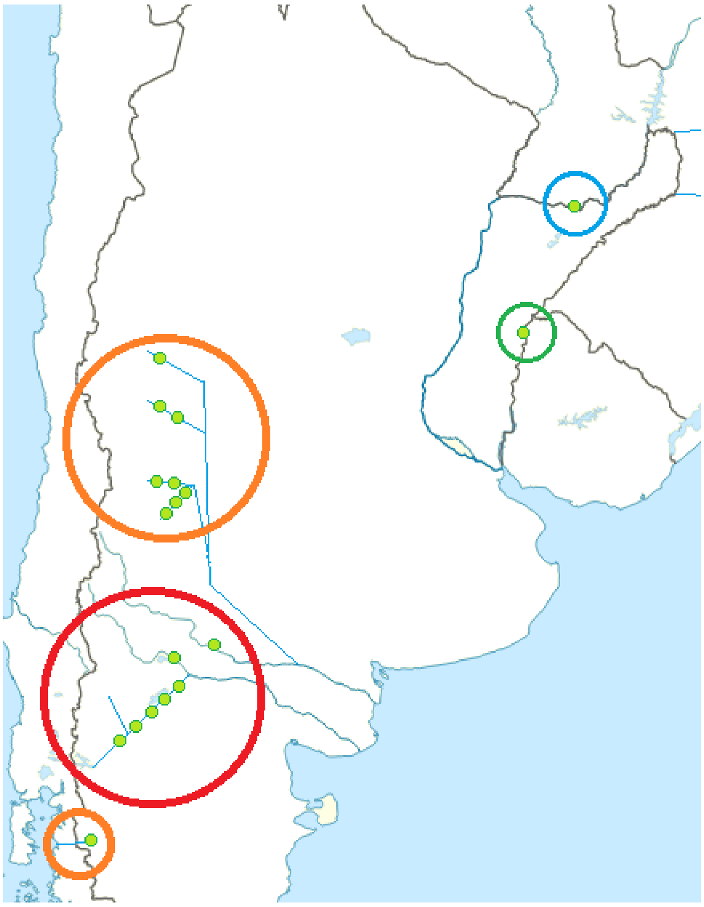


Figure 4.2: Map over the regions and power plants used to estimate the target series. Red circle is the Comahue region, blue is the Yacyretá region, green circle is the Salto Grande region and the two orange circles are the rest region.

4.4.1 Comahue Region

In the Comahue region there are four rivers with hydropower plants (see Figure 4.3). A larger part of the production is from the rivers Limay and Collon Cora giving around 85 % of the production while the other two rivers, Neuquén and Colorado, give around 12 % and 2 % based on the average production (Secretaría de Energía, 2003). As Colorado River represents such small part of the production it has been assumed to have a similar flow pattern as the others, reducing the rivers included in the estimation to three. The three remaining rivers show a similar pattern and based on the inflow data there is a seasonal variation fitting with the expected snow melt and spring floods.

Figure 4.3: Overview over plants in Comahue region. Picture taken with Google Earth

During the period 2009-2014 barely any water was spilled and hence no modification to the production data is done. As the region has more than one river an estimation of how the production is divided between the rivers is needed. Since all plants' average yearly productions are known the division is done based on this. The plants with inflow from both Limay and Collon Cora will have their production divided based on the flow of the rivers. Collon Cora's flow during the studied period is 61% of the flow to the power plants. The estimation leads to the energy distribution found in Table 4.2.

Table 4.2: Energy distribution between the rivers in the Comahue Region

	Limay	Collon Cora	Neuquén
Estimated distribution [%]	44	45	11
Factors $\left[\frac{GWh}{day} / \frac{m^3}{s}\right]$	0.0641	0.0416	0.0141

Multiplied with the factors from Table 4.2 the sum of the inflows will become as shown in Figure 4.4 where it is compared with the production. It is possible to see a yearly trend with a minimum difference between the inflow and the production around June as during this time know and rain will began to refill the reservoirs used during the summer when there is less rain. With MATLAB an effort to minimize the difference between production and inflow was made on a yearly basis from June. However, it was concluded that any change done by MATLAB did not prove a better fit but would instead favour a few years and give bigger errors for other years but all in all smaller total error.

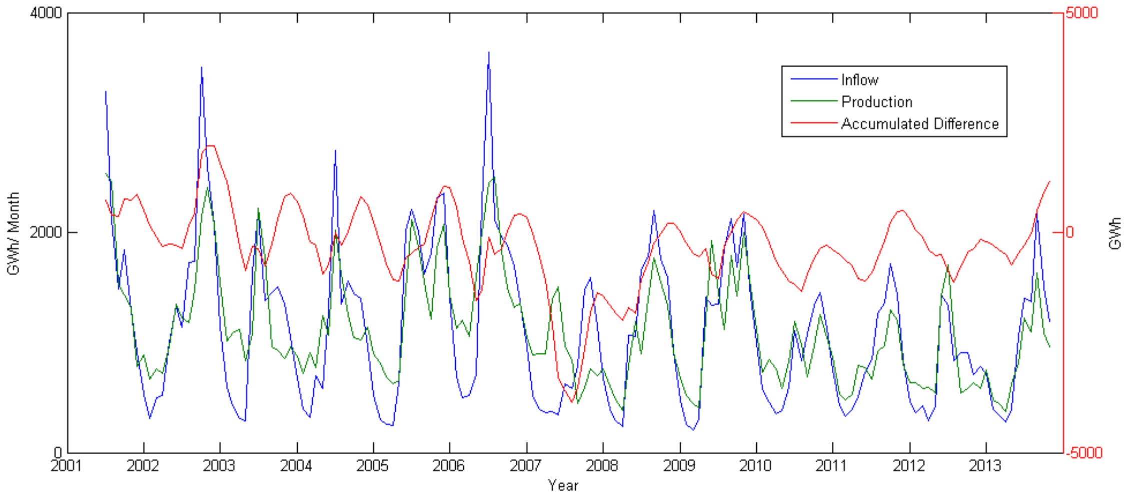


Figure 4.4: Monthly inflow compared to production for Comahue region.

4.4.2 Yacyretá Region

Figure 4.5: Yacyretá and closest part upstream. Picture taken with Google Earth

The region consists of one power plant (see Figure 4.5). CAMMESA presents daily data for the Yacyretá power plant with Paraná's river flow. The inflow data series was tested with the model to check if the flow is too regulated for the model to handle. The model indicated that the flow variation could not be accurately described with natural processes. In Brazil upstream Yacyretá there are plenty of power plants regulating the flow both in the Paraná River and in Iguaçu River, another fairly large river connecting to Paraná. With GRDB's stations averages it has been estimated that around 71% comes from the Paraná main stream and 13% from Iguaçu, concluding that most water to Yacyretá has been regulated. The target series given by TR will therefore be used and scaled according to Yacyretá's production, note that these are expressed in GWh/day hence the factors will not describe GWh/m^3 and instead describe how much Brazil can generate from the rivers compared to Argentina.

CAMMESA's daily data presented in Figure 4.6 provides information which shows that the production needs to account for spillage and that the reservoir is filled over time. However, the data is inconsistent as the inflow will add up to the flow through the turbine and spillage making the increase of reservoir level impossible. Monthly values for inflow, spill and reservoir level can be found on Yacyretá's own webpage as well and they are identical with CAMMESA's values (EBY, 2015). The most probable explanation is that the inflow is not the actual inflow and does not include the water used to fill the storage during this time.

The spillage, turbine flow and the reservoir head are believed to be accurate and can be used to adjust the production data series. The spillage is important to note as the model should describe the natural inflow value without considering how the plants are operating. By adding the turbine flow and spillage, then dividing them with the turbine flow as in Equation 4.1 on a monthly basis, a ratio can be found. Multiplied with the production this ratio will give a value of how much would be produced if all the water passed through the turbine.

$$Ratio = \frac{Turbine\ flow + Spillage}{Turbine\ flow} \qquad \text{Equation 4.1}$$

The reservoir head change is accounted by calculating the mean value for GWh/m^3 of turbine flow from April 2011 when the reservoir level stabilizes. Multiplying this value with the turbine flow of each month will make the production reflect today's conditions and make sure that the scaling of the inflow will be done correctly. With these changes the production series is limited to a shorter period as the turbine and spill flow are not available before June 2009. The scaling of the inflow series can therefore only be verified by looking at this shorter time frame.

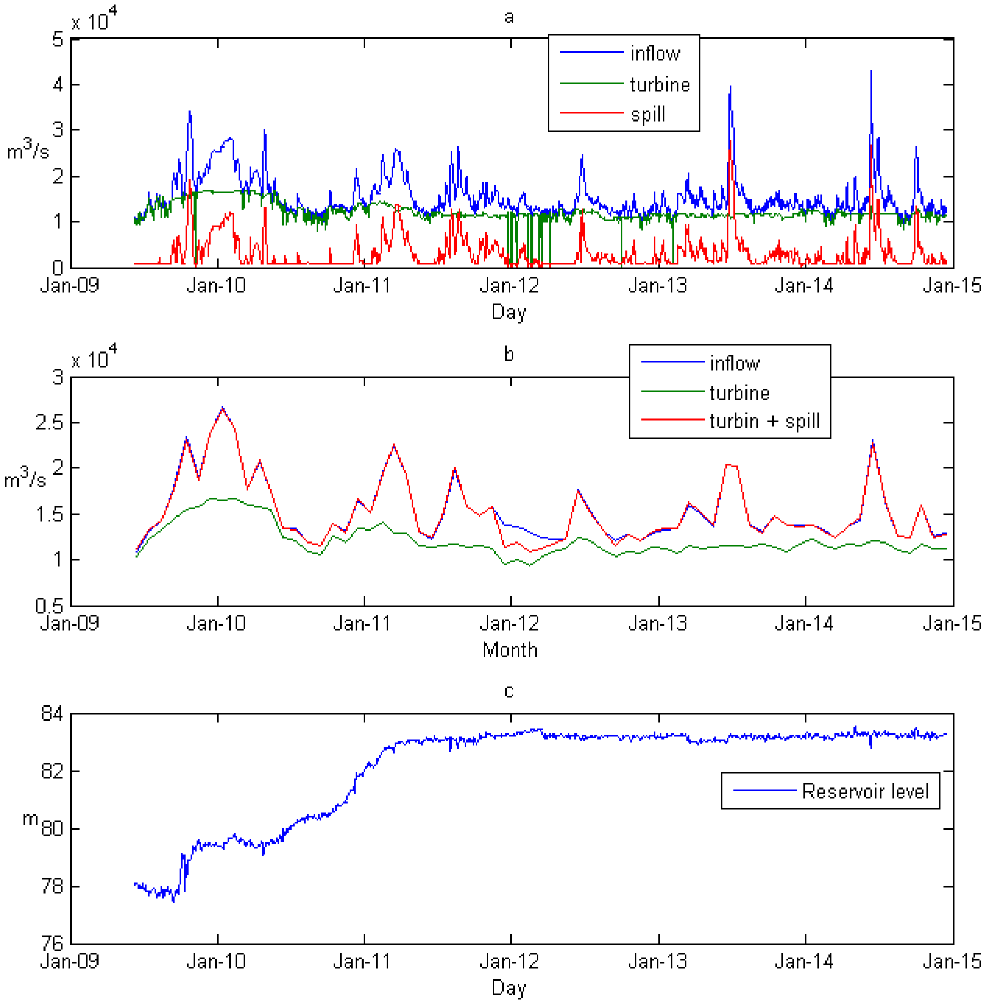


Figure 4.6: a) Daily values for inflow, flow through turbine and spillage flow at the Yacyretá power plant. b) Monthly average daily flows for inflow, flow through turbine and spillage flow at the Yacyretá power plant. c) Reservoir level in Yacyretá's reservoir.

When estimating the energy distribution between the Paraná and Iguaçu series, GRDB station averages were initially used, giving Paraná roughly 71% and Iguaçu 13%. The rest of the percentages are assumed to be equally distributed over the two series which results in the initial estimated distribution as showed in Table 4.3. The target series shows a yearly seasonal trend with the production and the minimum accumulated difference between series can be found around November as displayed in Figure 4.7 where the year on the x-axis starts with November. For this region the optimized factors received with MATLAB was used as they somewhat lowered the deficit of energy occurring during 2010 and the factors with their energy distribution are shown in Table 4.3. Note that the factors here are a relation between the energy Argentina can produce and the energy that Brazil can produce with the same flow, i.e. Argentina produces 0.0743 of what Brazil produces with the same amount of water in Paraná River.

Table 4.3: Energy distribution between the rivers flowing into Yacyretá.

	Paraná	Iguaçu
Initial estimated distribution [%]	79	21
Used distribution[%]	77	23
Factors $\left[\frac{GWh}{day} / \frac{GWh}{day}\right]$	0.0743	0.1174

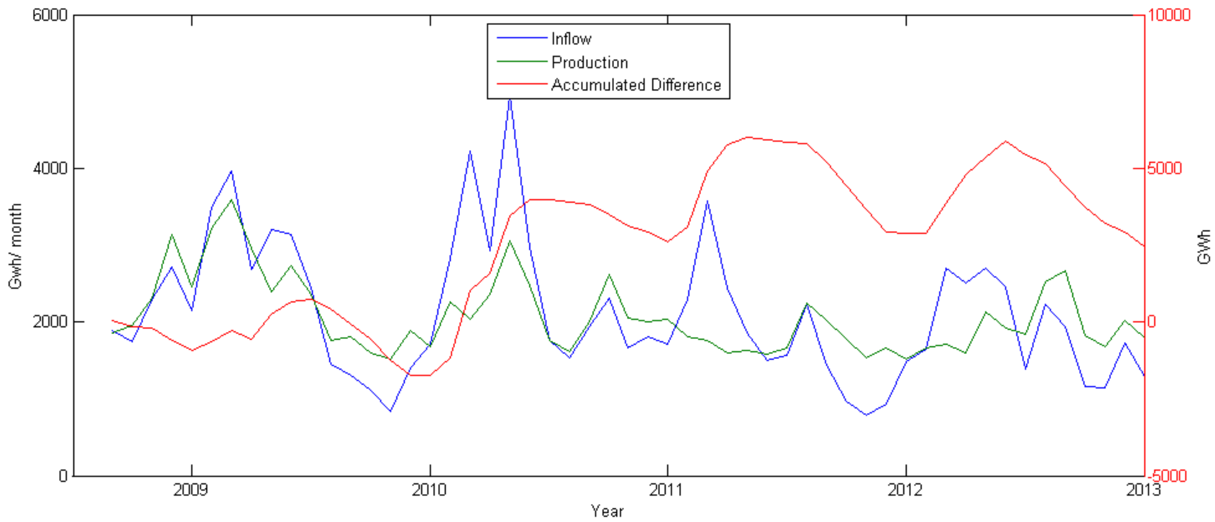


Figure 4.7: Final monthly inflow compared to production for Paraná River. The graph is shifted starting the year with November.

4.4.3 Salto Grande Region

Salto Grande is similar to Yacyretá in the sense that both regions only consist of one power plant in Argentina while upstream in Brazil there are plenty of power plants. A big difference is that the amount of regulated water is a lot less for Salto Grande. With GRDB's stations' averages the amount of water coming from upstream the power plants in Brazil has been estimated to around 20% of the flow to Salto Grande. The daily data provided by CAMMESA was tested with the model and proved to be able to capture the pattern somewhat.

Figure 4.8: Salto Grande and closest part upstream. Picture taken with Google Earth

With one river no assumptions regarding distributions needs to be done. The production series on the other hand needs to account for the spillage as seen in Figure 4.9 and will be done in the same way as for Yacyretá, described in the section above with Equation 4.1.

When multiplying the inflow with the factor to fit with the production, no significant yearly pattern was seen. The reservoir is not used over a longer period of time and for the optimization the hydrological year was simply set from January. The optimization proved to give a slightly smaller accumulated difference between the production and the inflow series and was therefore chosen as the target series for this area. The factor in $(GWh/day)/(m^3/s)$ for this area was estimated to 0.0026.

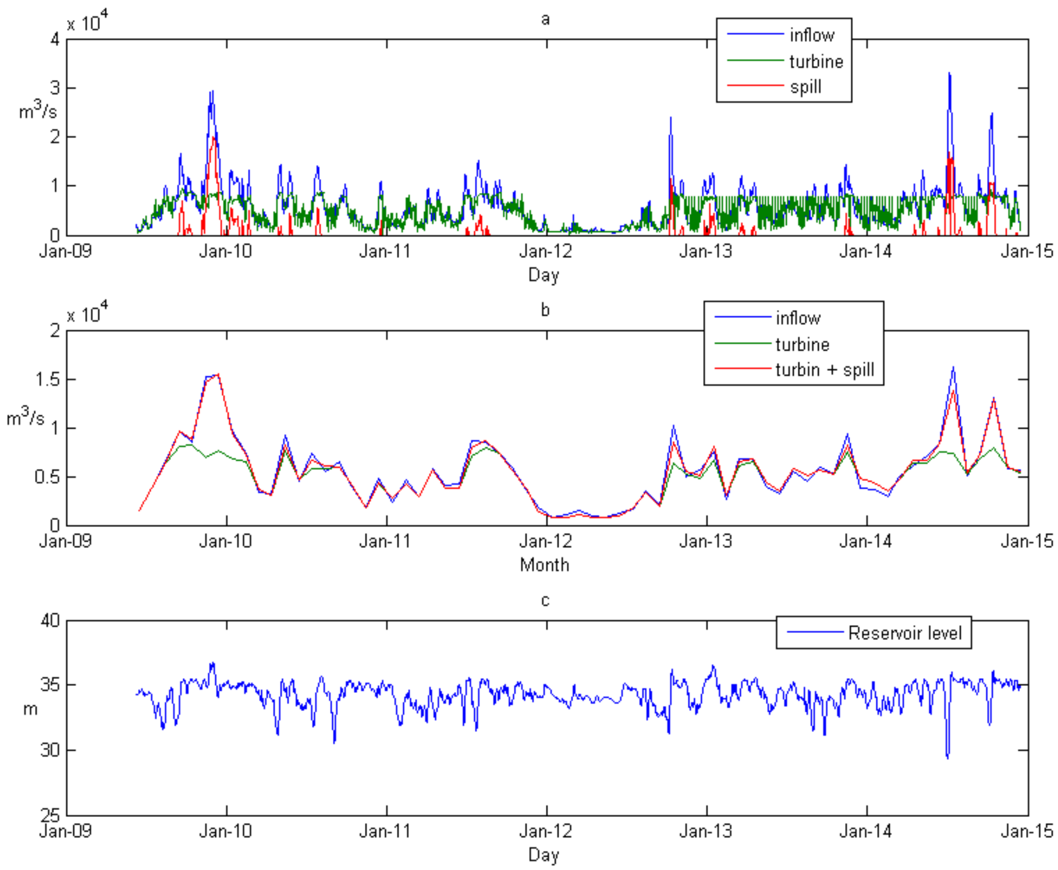


Figure 4.9: a) Daily values for inflow, flow through turbine and spillage flow at the Salto Grande power plant. b) Monthly lumped daily flows for inflow, flow through turbine and spillage flow at the Salto Grande power plant. c) Reservoir level in Salto Grande's reservoir.

4.4.4 Rest Region (San Juan, Mendoza and Futaleufú Region)

The Rest region is based on the production of all the remaining hydro power plants that has not been included in the other regions. To use this value, more assumptions have been made, and the values presented will not be as trustworthy as in the other regions. Five rivers are assumed to produce the rest production and are located in San Juan, Mendoza and Futaleufú region as shown in Figure 4.11 and Figure 4.10. Futaleufú is a single river and San Juan has the river San Juan and in Mendoza the rivers Atuel, Diamante and Mendoza are used for production.

The average yearly production values known for the power plants in the rivers in comparison with the average annual production for the rest region shows that the rivers actual contribution accounts for 88% of the production. As a full view of spillage and turbine flow is not available for all the power plants, even for those assumed to be the producing plants, the production has not been altered to account for spillage.

Figure 4.11: Futaleufú basin. Picture taken with Google Earth

The energy distribution between the rivers were firstly based on average yearly production. The remaining percentages were evenly distributed over all the rivers expect for Futaleufú. As most of the remaining production comes from northwest of Argentina these rivers were assumed to best fit with the remaining percentages. The optimization in MATLAB then moved these remaining percentages to make a better fit. The end distribution can be found in Table 4.4 as well as the resulting factors.

Figure 4.10: Mendoza and San Juan region. Picture taken with Google Earth

Table 4.4: Energy distribution between the rivers for the rest region. First row is the energy contribution based on the average productions known equal to 88% of the energy. Second row is with the assumed distribution together with the last percentages. Third row is the final used distribution estimated with MATLAB.

	Futaleufú	Atuel	Diamante	Mendoza	San Juan
Energy contribution to rest[%]	41	14	9	13	11
Initial estimated distribution [%]	41	17	12	16	14
Used distribution[%]	42	14	16	13	15
Factors $\left[\frac{GWh}{day}/\frac{m^3}{s}\right]$	0.0303	0.1025	0.1282	0.0759	0.0767

5 Results and discussion

The result will first be presented and discussed for the sum of all the models representing all of Argentina. Afterwards in the subchapters 5.1 to 5.4 the results of each of the models will be presented and discussed.

The calibration and validation results for all of Argentina are shown with the NSE coefficients in Table 5.1 and sum of the models results compared with sum of the target series in Figure 5.1. The calibration reached an NSE of 0.77 on a weekly basis and 0.8 on a monthly basis proving good conditions to model the inflow. However, the validation has values around -1 as three models, Comahue, Yacyretá and the rest model, continuously overestimates the flow summing up to around 90 TWh too much compared to the target series during the validation. The worst region is the Rest region described in chapter 5.4 where the validation has values around -3. The calibration was most successful in the Comahue region, chapter 5.1, and the validation proved Salto Grande, chapter 5.3, to be most fitting outside of the calibration period.

Table 5.1: NSE coefficients on a Weekly and Monthly basis for Argentina.

NSE time frame	Calibration	Validation
Weekly	0.7703	-1.028
Monthly	0.8095	-0.929

Figure 5.1 show that the validation still pinpoints the peak flows, though they are greatly overestimated. Figure 5.2 tells us that the overestimation of the available energy simulated reaches above 40 % during 2000 and 2001. As the peaks are well placed it seems likely that the error is induced by the data used and not the model itself. The target series have not drastically changed as the annual energy is at about the same level during both periods and the model should not misinterpret to that extent. The question is then, whether the error is with the precipitation or the target series. The CPCp, precipitation data, changes from its retrospective dataset to the real-time data set with the beginning of year 2006. The accumulated difference starts to stabilize during 2005 meaning that there is no exact correlation though it is close enough to question if there is a possible mismatch between the retrospective dataset and the real-time dataset. The precipitation errors could then be further enhanced as the model multiplies the input with a factor to make it into GWh. A very simple double mass curve analysis have been done to study the precipitation data in every region and they are discussed in the corresponding subchapters. It could also be that the inflow is too low for these years as the amount of water used for irrigation might vary from year to year.

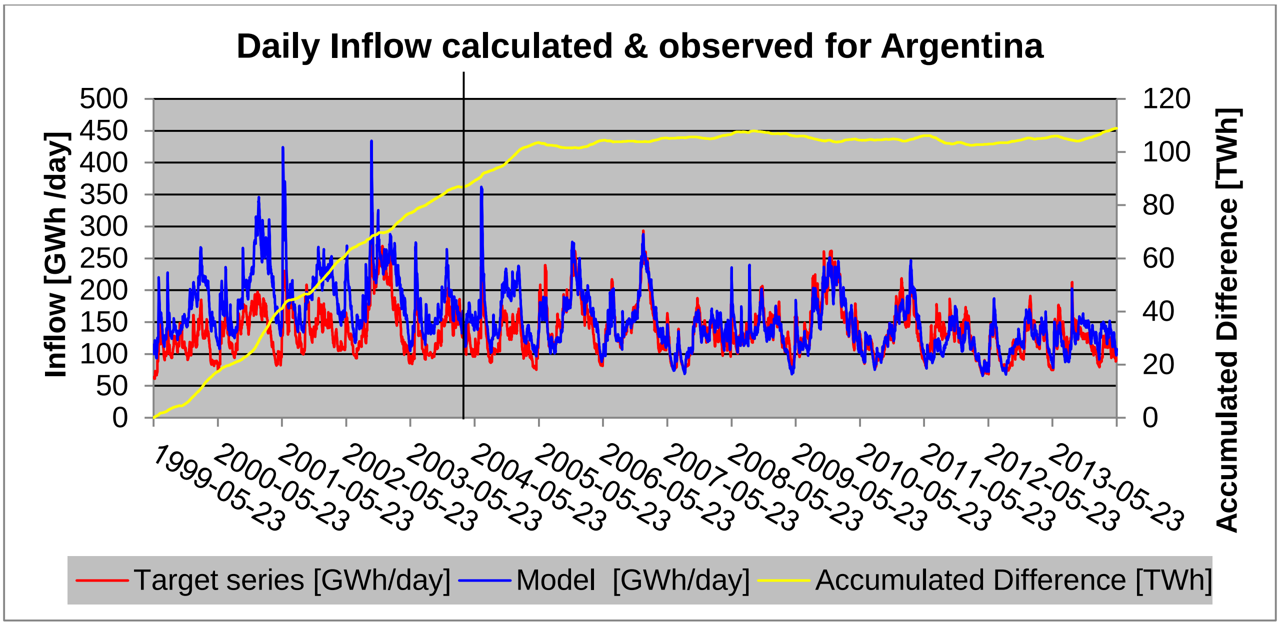


Figure 5.1: Observed and modelled inflow values for calibration, from 2004-05-23, and validation, before 2004-05-23 for all of Argentina.

The annual observed inflow for all hydropower under the studied period gives roughly 50 TWh a year as seen in Figure 5.2. The production hovers around 40 TWh per year, meaning that around 20% of the potential energy production is spilled. Yacyretá and Salto Grande are the known power plants which need to spill when higher flows reaches their reservoirs. As discussed in the end of chapter 2.4 both of these plants will have their capacity increased with 10% which would make the current hydropower system more efficient. The total amount of spill might not be an accurate number as it seems as if the Rest region spills a larger part as well, this is further discussed in the Rest region chapter.

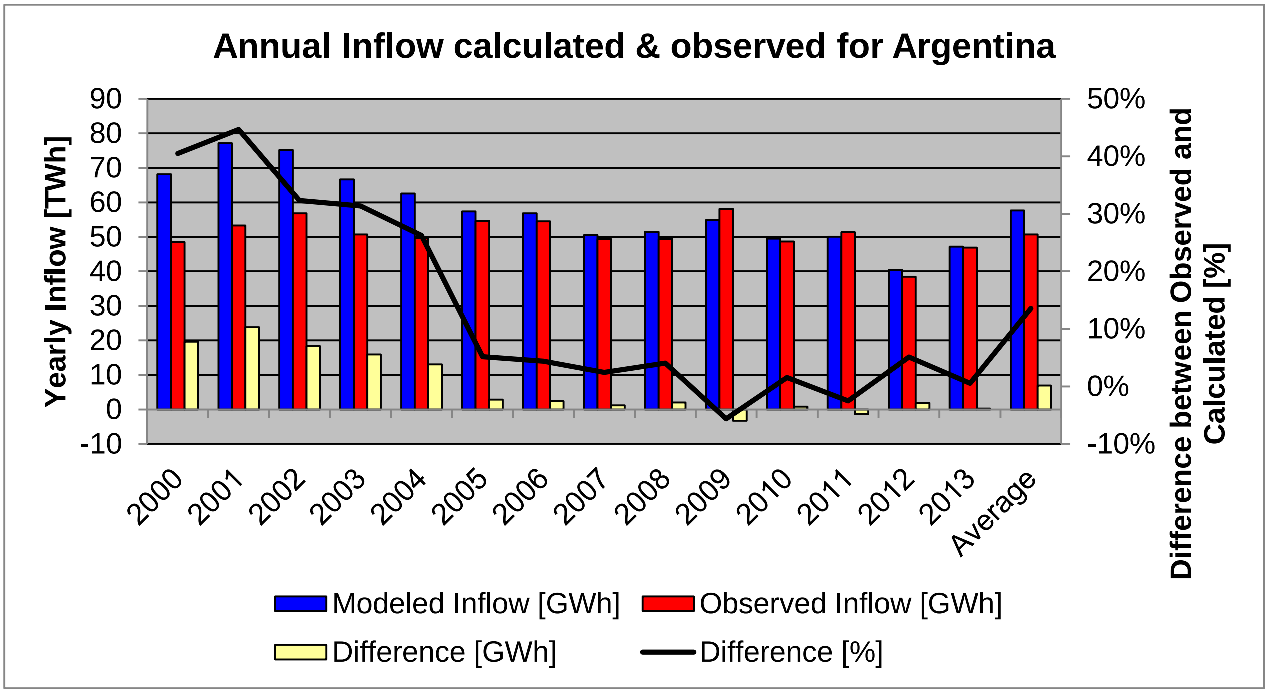


Figure 5.2: Annual inflow in TWh for the model compared with the observed values. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

When looking at the different regions it is clear that even if the yearly sum is around 50 TWh the amount of available energy to the regions changes over the years. It is for example possible to notice in Figure 5.3 that during the early 2000s the Comahue region receives a larger share than in the 2010s. The opposite trend can be seen for Yacyretá disregarding that from 2012 both regions have had dry years giving a noticeable lower inflow during these years.

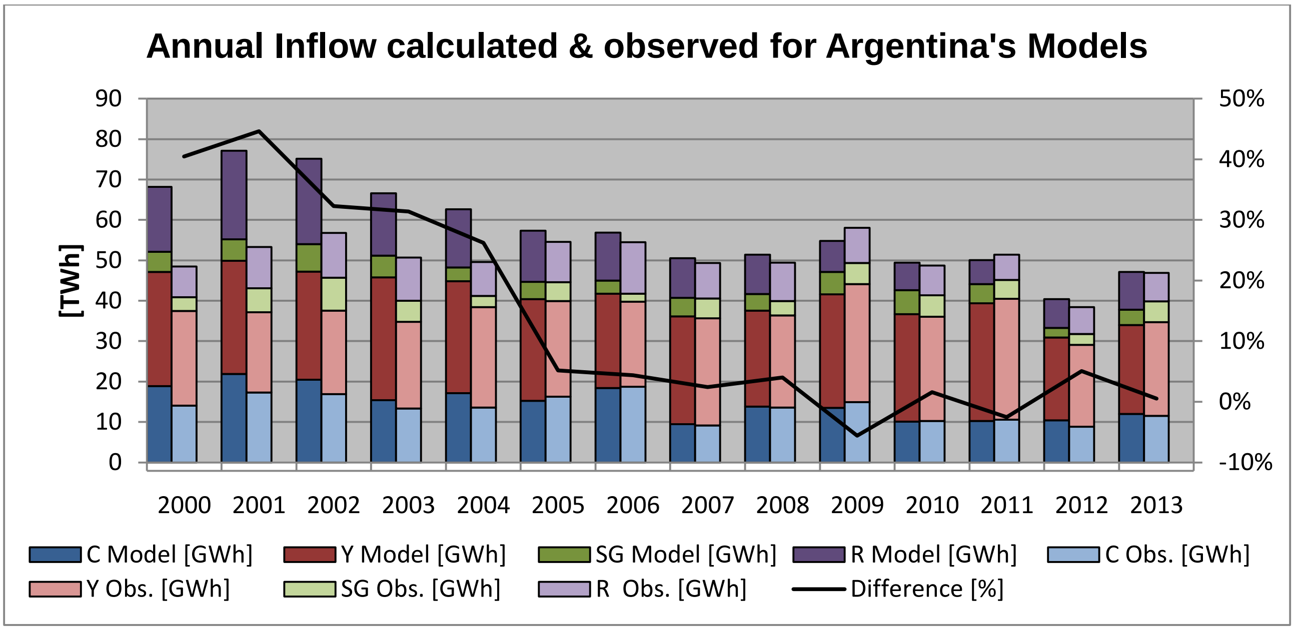


Figure 5.3: Annual inflow in TWh for the model compared with the observed values showing the contribution of the different regions. C stands for Comahue, Y = Yacyretá, SG = Salto Grande and R = Rest region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

To get an image of a normal year, the average daily value for each day during a year were used to construct normal series. Inflow from the target series and the models are plotted in Figure 5.4 and as expected the models overestimate during all seasons. The normal snow pack level computed by the model is also presented in the figure and is generated by the Comahue and Rest region. The difference between observed values and modelled values is likely to be seen in the snow pack as well and should therefore be considered to be higher than the actual, especially since the Rest region is the least fitting model. However, it indicates that the energy stored in the snow pack is less than 15% of the energy seen in a normal year. As the contribution between the regions changes from year to year the percentage will change, for example during 2005 the snow pack reaches 10 TWh which is around 20%.

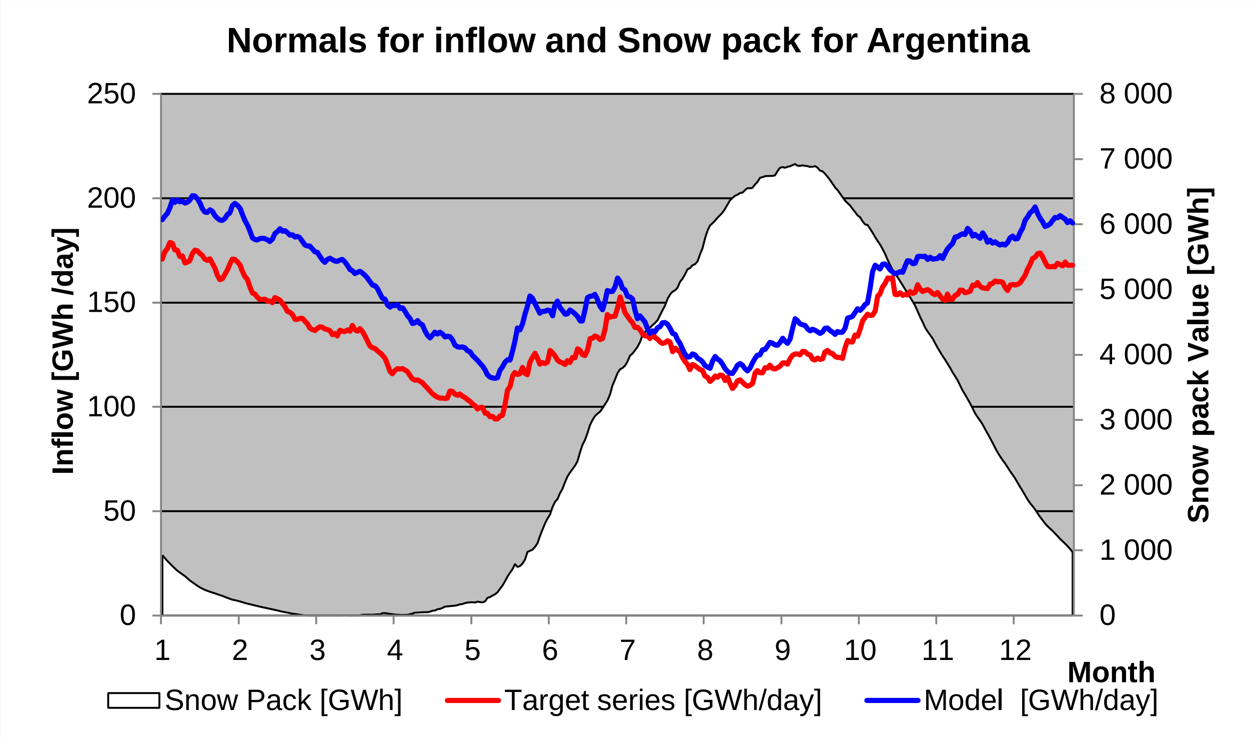


Figure 5.4: For the time period 1999-05-23 to 2014-05-22 average modelled and observed inflow together with the snow pack value for the aggregation of all models throughout the year.

Same as for inflow and snow a normal series for the energy stored in the soil has been calculated. With the combination of the two storages, snow and soil, it is possible to evaluate if there is an abundance or deficit of available energy stored by comparing the current situation with the normal values. This is useful as it will affect how large the inflow will be at a later time and can be used to perform better estimates of the future energy situation. With this it is possible to see if there are any effects on the spot price depending on the availability of hydropower energy. The recent years have had a drastic increase in price during the winter months and both 2012 and 2013 have been dry years with low precipitation. With a scatter plot between the storage deviations from normal against the spot price from 2001 until 2013 as done in Figure 5.5, it can be concluded that no clear trend between the storage and the spot price can be found. It is possible to see a pattern with higher prices when the storages has large deficits but the uncertainty increases when the deficit drops. With a time series of the years 2011 to 2013 as presented in Figure 5.6a, this is further verified as a clear pattern cannot be seen. During the winter of 2011 the price increases with the decrease in storage while it seem to have the opposite trend during the other two years. Argentina has reservoirs not accounted for in these storage numbers which when included might improve the correlation, but since no information about the filling degree of the reservoirs has been found it is impossible to study as of now.

The market has, as stated earlier in the report, a small margin between the demand and using its full capacity to generate. A possible trend between the generation and the spot price might therefore be easy to spot. It seems as if markets are a bit more complex than this since the generation peaks both during summer and winter as shown in Figure 5.6b. The limitation on the spot price set by the government is likely a cause of this since the discharge surplus possibly does not account for the limitation of resources. The spot price found could also include more than just the generation cost and include costs for distributing the electricity. The winter peak's demand could be to sources in another region with a more limiting network than for region causing the summer peak.

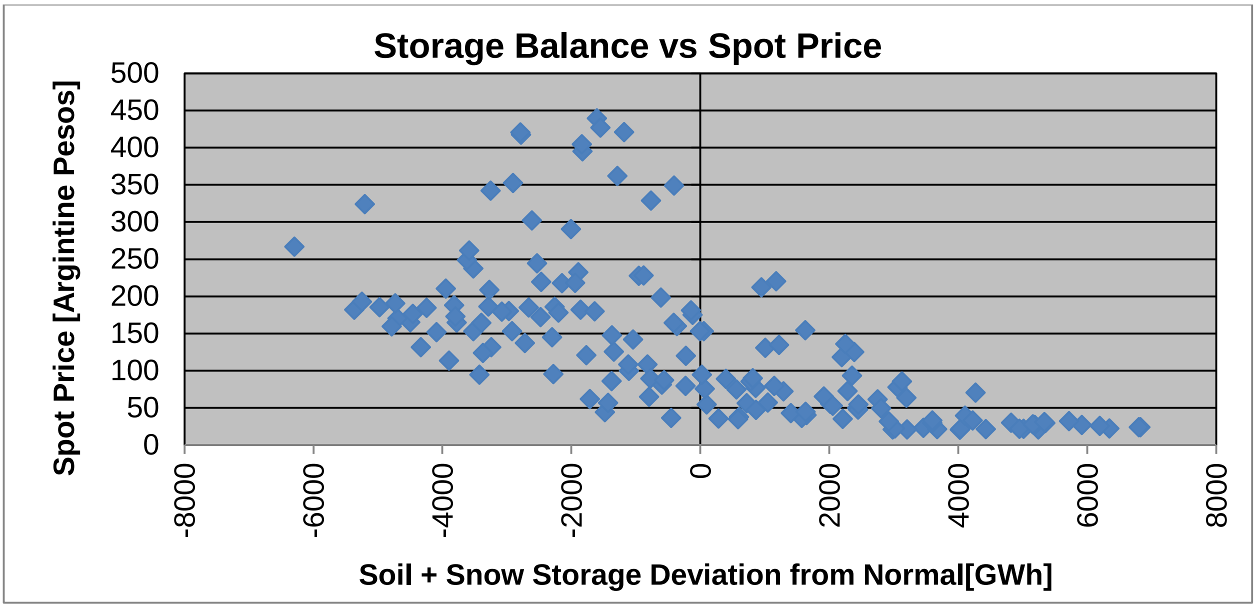


Figure 5.5: Monthly spot price plotted against the deviation from normal conditions in the soil and snow.

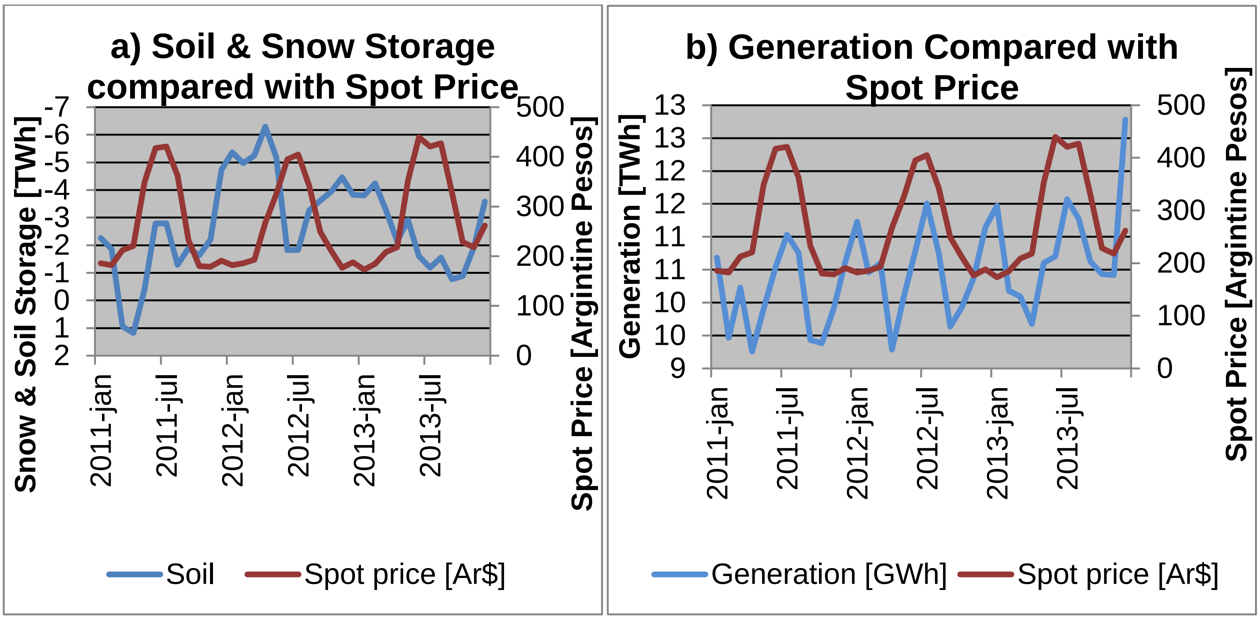


Figure 5.6: a) Month storage deviation and spot price plotted over time. Not that the left y-axis is inverted. b) Generation and spot price plotted over time.

5.1 Comahue Region

The calibration and validation results are shown with the NSE coefficients in Table 5.2 and the model result compared with the target series in Figure 5.7. While the calibration went well achieving NSE values around 0.9, the validation drops with about 0.25. The model maintains an accurate flow pattern but overestimates with almost 4000 GWh for each year during validation. This is about 32% of the observed average available energy during one year. As discussed in chapter 5 this could be due to the fact that the CPCp datasets has an inconsistency between them, either giving too much precipitation in the retrospective dataset until 2006 or too little in the real-time dataset.

Table 5.2: NSE coefficients on a Weekly and Monthly basis for the Comahue Region.

NSE time frame	Calibration	Validation
Weekly	0.8742	0.6113
Monthly	0.9064	0.6611

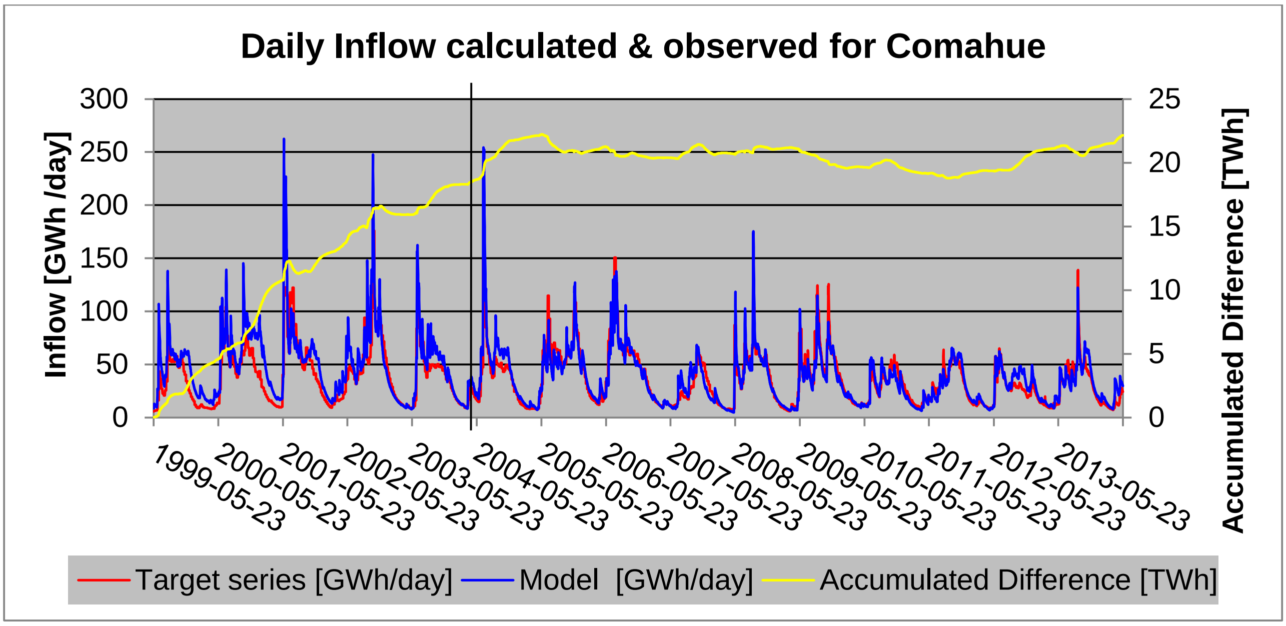
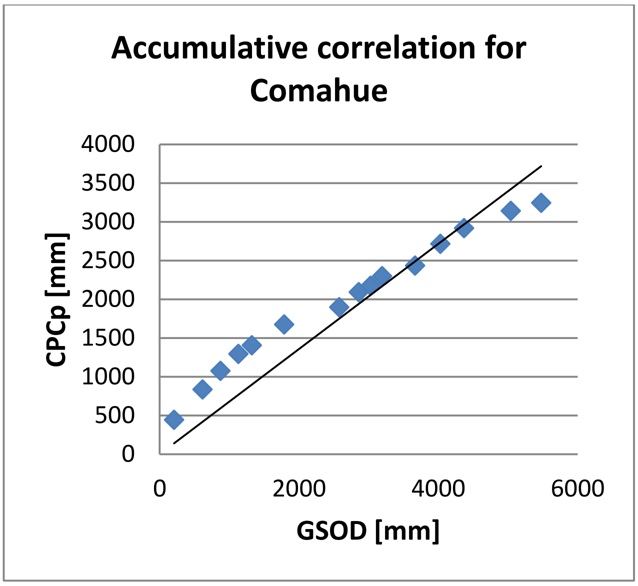


Figure 5.7: Observed and modelled inflow values for calibration of Comahue region, from 2004-05-23, and validation, before 2004-05-23.

The result of a double mass curve analysis with an observed station in the Comahue region and the grid data polygon which the station is located in is viewed in Figure 5.8. The result is not as clear as a textbook example which makes it a possible that there is a problem with the data. The validation years are too wet in the CPCp data in comparison with the measuring station, mostly because of the year 1999. During the calibration an overall decline can be seen in the difference between CPCp and the linear trend. This indicates another correlation with the observed station during this time. The time period does not completely correlate with the datasets time periods. Adjusting the data will therefore be tricky as there is no clear pattern to adjust accordingly, by only multiplying either dataset with a number would not make the trend perfect.



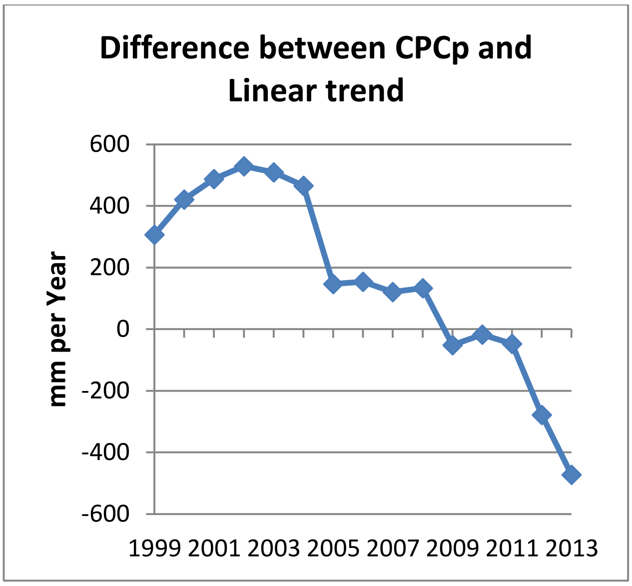


Figure 5.8: Results from double mass analysis comparing a CPCp polygon and an observation station within the polygon in the Comahue region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

The inflow correlates well with the production, if the overestimation occurring before 2005 is neglected. They would not match completely as the production values are not fitted to the hydrological year creating a small overlap between when the energy flows in and when it is used. In 2007 there is a major deficit that cannot be from the inflow of previous year. A reason for this could be that a higher inflow was expected but it never came. Figure 4.4 plots the observed inflow compared with the production and during 2007 the production goes up before the inflow and then drops, probably because the inflow did not meet the expectations.

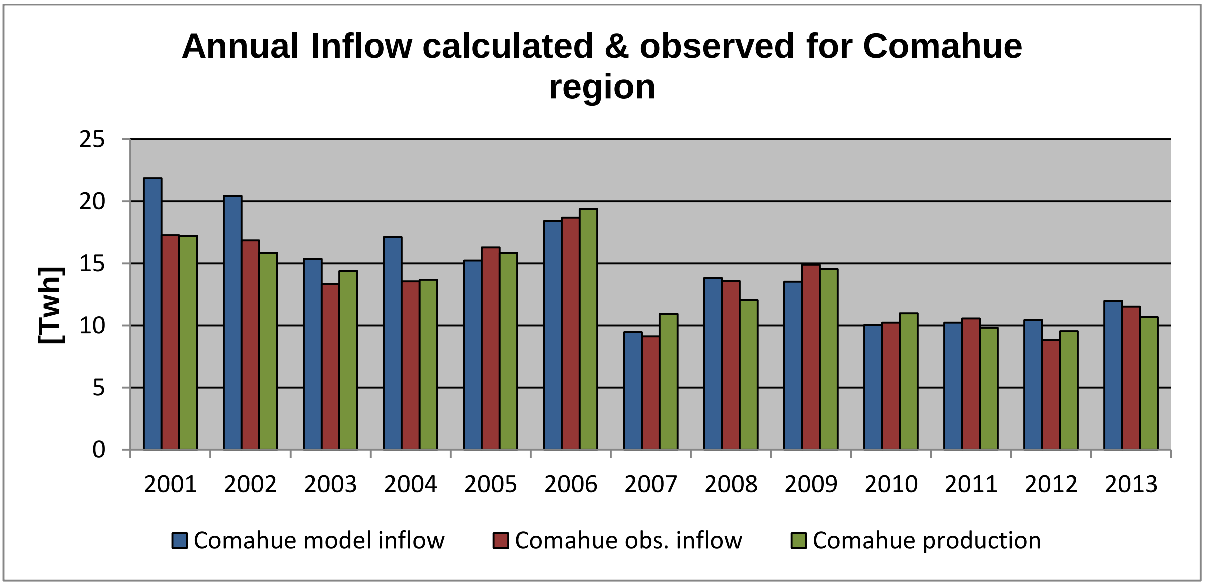


Figure 5.9: Modelled and observed inflow compared with the annual production for Comahue region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

The normal conditions for the Comahue region is heavily dependent on the precipitation during the winter months. One could expect the inflow to become less during the winter as the precipitation would be snow forming a snow pack and then have a larger spring flood during the spring. For the Comahue region almost all precipitation comes during the winter making the flow early in the year heavily dependent on how large the precipitation was last year. The temperature in the region does not drop far below 0 making it possible for both rain and snow to occur during the winter, which is why the inflow increases during this time of the year. All of the precipitation will not end up in the snow pack and will partly melt and build up during the winter creating a higher flow during this period. The snow pack reaches 2.8 TWh, which is around 20% of the modelled annual inflow of 14.7 TWh. The amount of precipitation contributing to the snow pack could potentially shift from year to year based on if it is a strong or mild winter. The dependency with temperature can be seen in Figure 5.7, years with larger early peaks (2001) indicates a mild winter as more of the precipitation will be rain and not stored in the snow pack while years with larger late peaks (2002) indicates a strong winter with less precipitation will be rain.

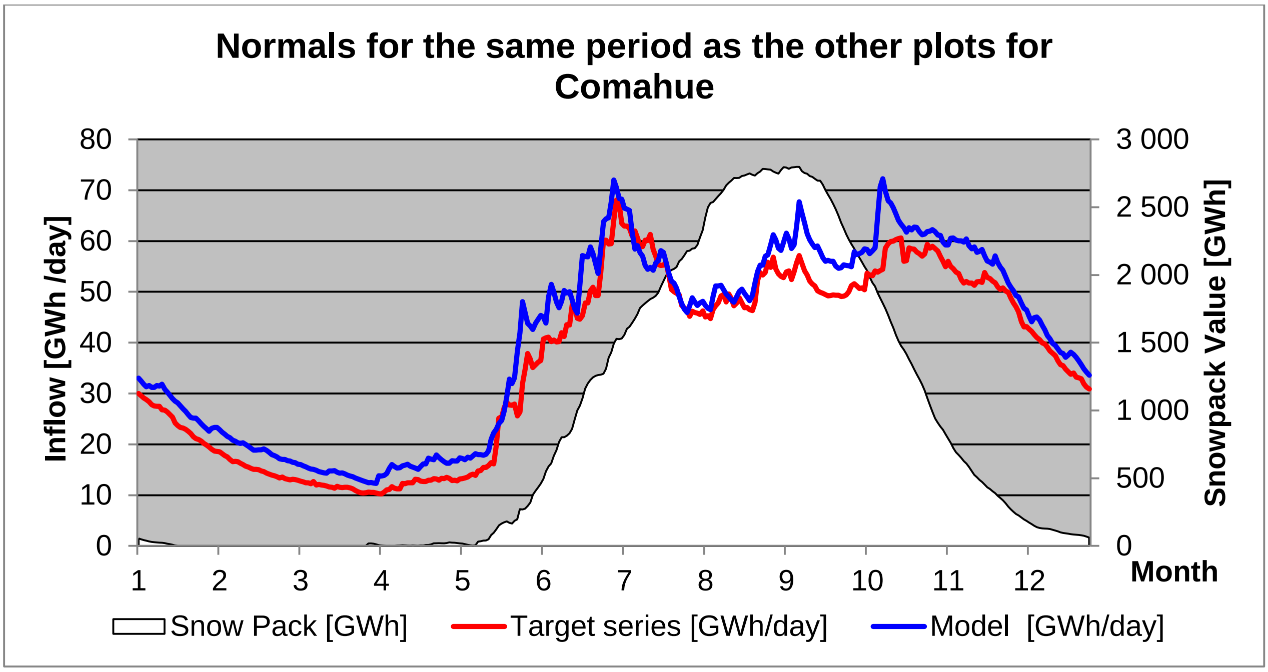


Figure 5.10: For the time period 1999-05-23 to 2014-05-22 average modelled and observed inflow together with the snow pack value for Comahue region throughout the year.

5.2 Yacyretá Region

The calibration and validation results are shown with the NSE coefficients in Table 5.3 and the model result compared with the target series in Figure 5.11. Similar to the Comahue region the calibration went well with NSE coefficients over 0.85 but the validation became way worse for Yacyretá dropping to levels below 0.4. During the validation period the flow becomes too large and models about 6000 GWh too much each year, an overestimate of 27% from the observed average accessible energy. The error could be induced by CPCp and in Figure 5.11 the increase, though smaller for the later years, can be registered until 2006 when the CPCp changes dataset.

Table 5.3: NSE coefficients on a Daily, Weekly and Monthly basis for the Yacyretá Region.

	Calibration	Validation
Daily	0.8568	0.3589
Weekly	0.8639	0.3550
Monthly	0.8844	0.3462

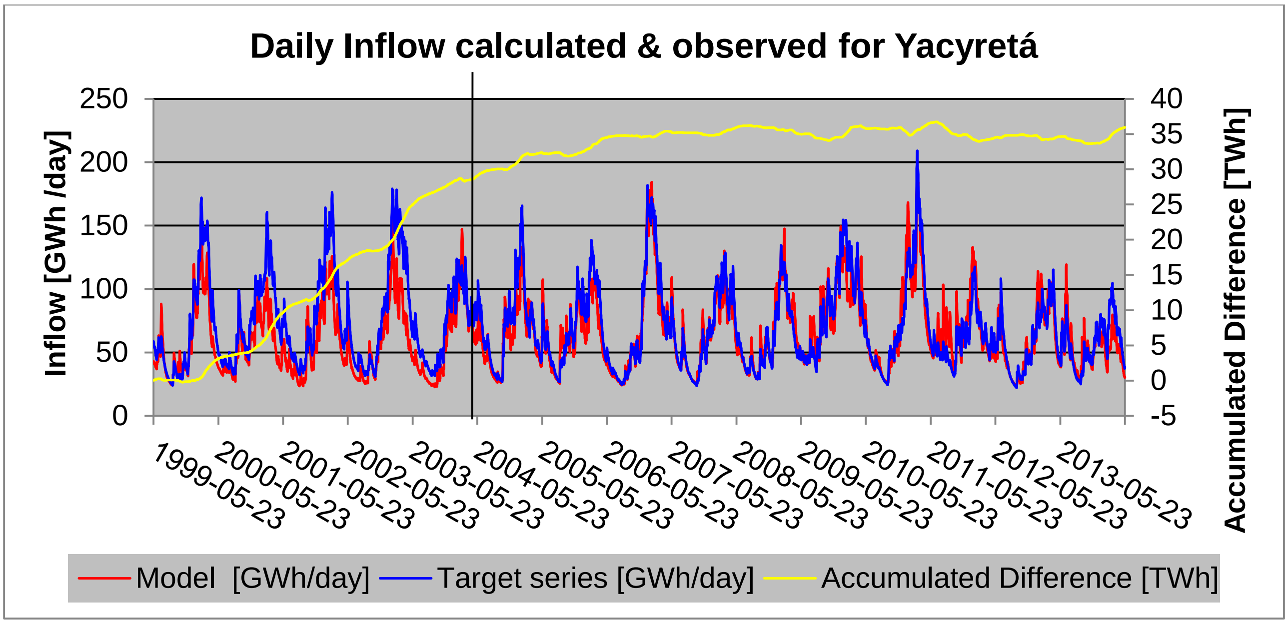
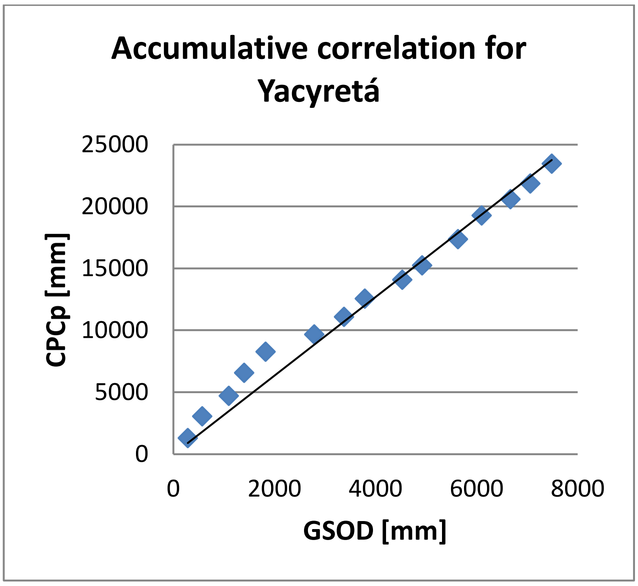


Figure 5.11: Observed and modelled inflow values for calibration of Yacyretá region, from 2004-05-23, and validation, before 2004-05-23.

The result of a double mass curve analysis with an observed station in the Yacyretá region and the grid data polygon in which the station is located is viewed in Figure 5.12. The result show that the data might have errors. The early validation years are too wet as expected. During the calibration the difference between CPCp and the linear trend seems to stabilize after declining. Similar to the Comahue region the change happens earlier than the change between the datasets. Adjusting the data might be tricky as there is no clear pattern to adjust according, by multiplying either dataset with a number would not make the trend perfect.



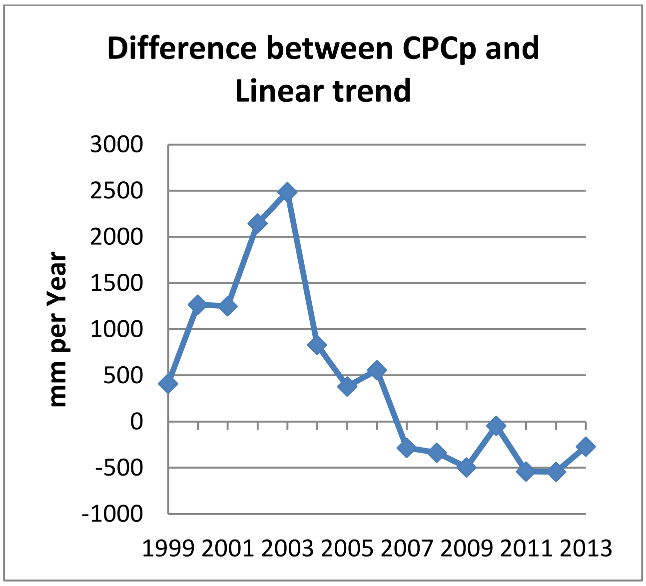


Figure 5.12: Results from double mass analysis comparing a CPCp polygon and an observation station within the polygon in the Yacyretá region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

When comparing the inflow with the production as done in Figure 5.13 one needs to note that the production has not been changed to account for the reservoir head. The years before 2010 produces with a lower potential head as the reservoir was not filled completely and therefore it looks as if they spill a lot more than they did. Yacyretá is forced to spill during the summer peak, to minimize the spillage they plan to put turbines in one of the passages to make the plant more efficient. What is modelled is the natural flow, which will be different from when the water actually reaches the plant because Brazil has many power plants upstream. The amount of spillage in a year can therefore not be accurately pinpointed based only on the model since the regulation might spread the peak in a way that Yacyretá can utilize a larger part of the flow.

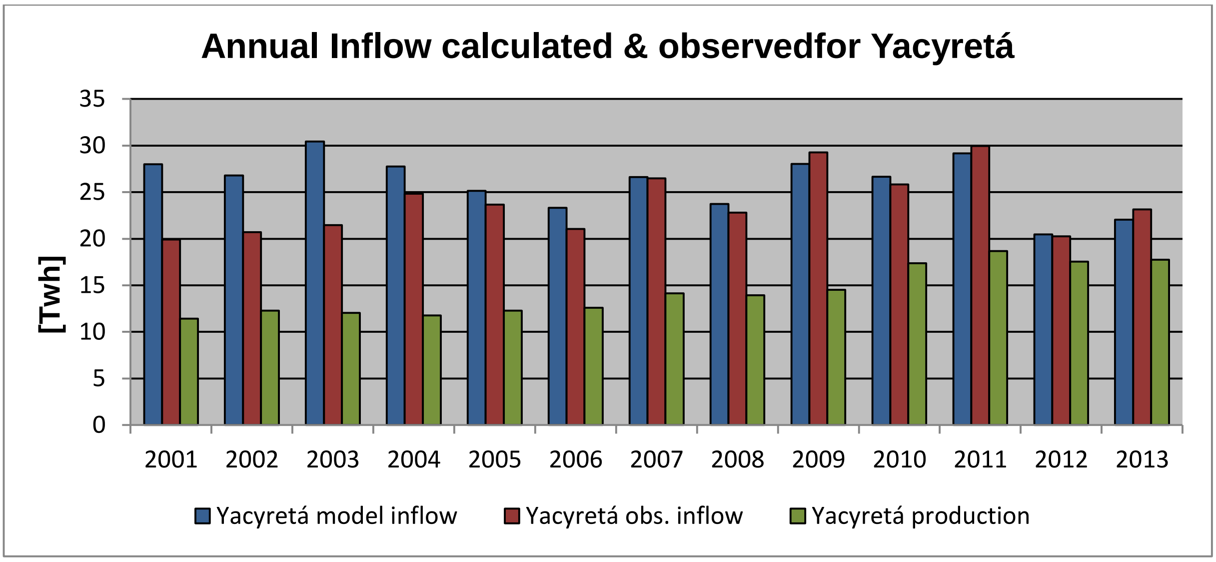


Figure 5.13: Modelled and observed inflow compared with the annual production for Yacyretá region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

The yearly profile for the natural inflow is shown in Figure 5.14 and it correlates well with the precipitation profile for the upper part of Brazil displayed in Figure 2.4. During the summer there is heavy rainfall and with no snow during the winter, the summer rain will be the key feature shaping the annual inflow profile.

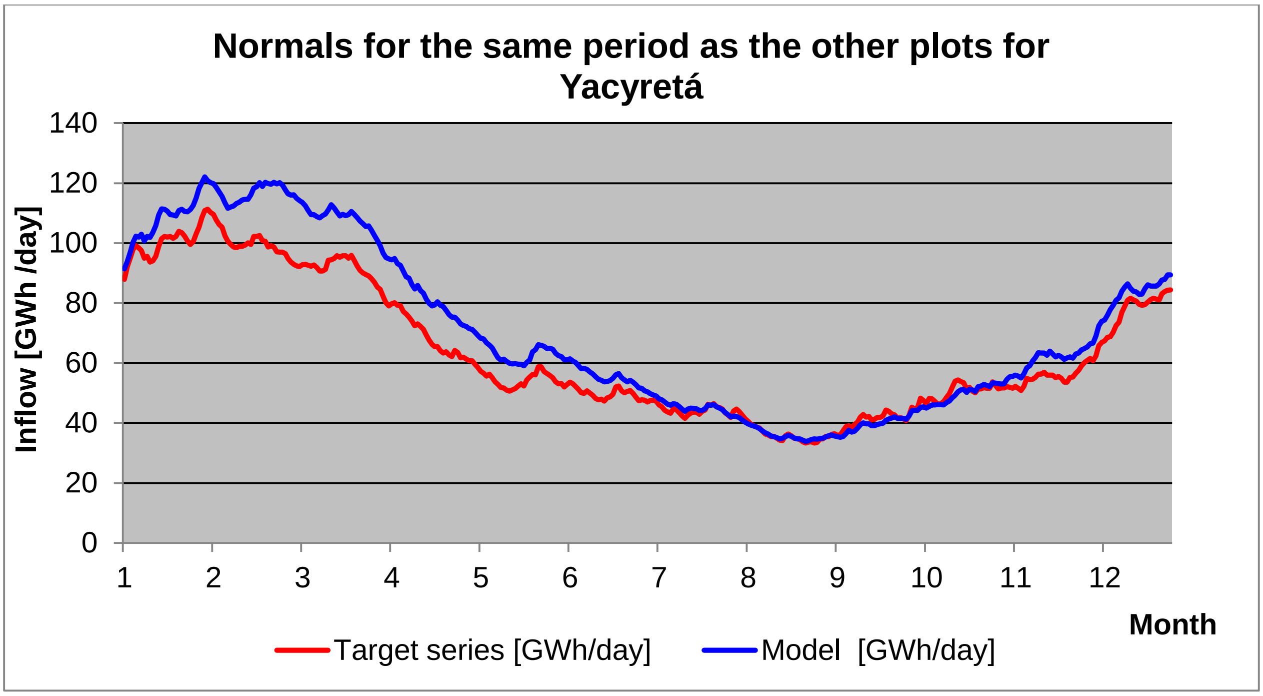


Figure 5.14: For the time period 1999-05-23 to 2014-05-22 average modelled and observed inflow for Yacyretá region throughout the year.

5.3 Salto Grande Region

The calibration and validation results are shown with the NSE coefficients in Table 5.4 and the model result is compared with the target series in Figure 5.15. The calibration for this area is almost reached a weekly NSE of 0.7. The validation only drops with 0.06 for the weekly NSE proving that the model keeps its quality outside of the calibration range. As viewed in Figure 5.3.1 the flow pattern of the target series during the year 2000 gives some worries as the fast smaller peaks doesn't seem to be well matched by the model at all. The target series is constructed with a flow data series containing about 20% of regulated flow, which is possibly the reason why it's so difficult to reach higher NSE values. For this region there is no increasing error in the validation period, instead there seems to be another pattern in the accumulated difference that might be caused by the precipitation data. The accumulated difference during the calibration does not show a healthy trend, as it increases until 2012 when it drastically drops to the level seen in the beginning of the calibration.

Table 5.4: NSE coefficients on a Weekly and Monthly basis for the Salto Grande Region.

NSE time frame	Calibration	Validation
Weekly	0.6947	0.6286
Monthly	0.7744	0.7474

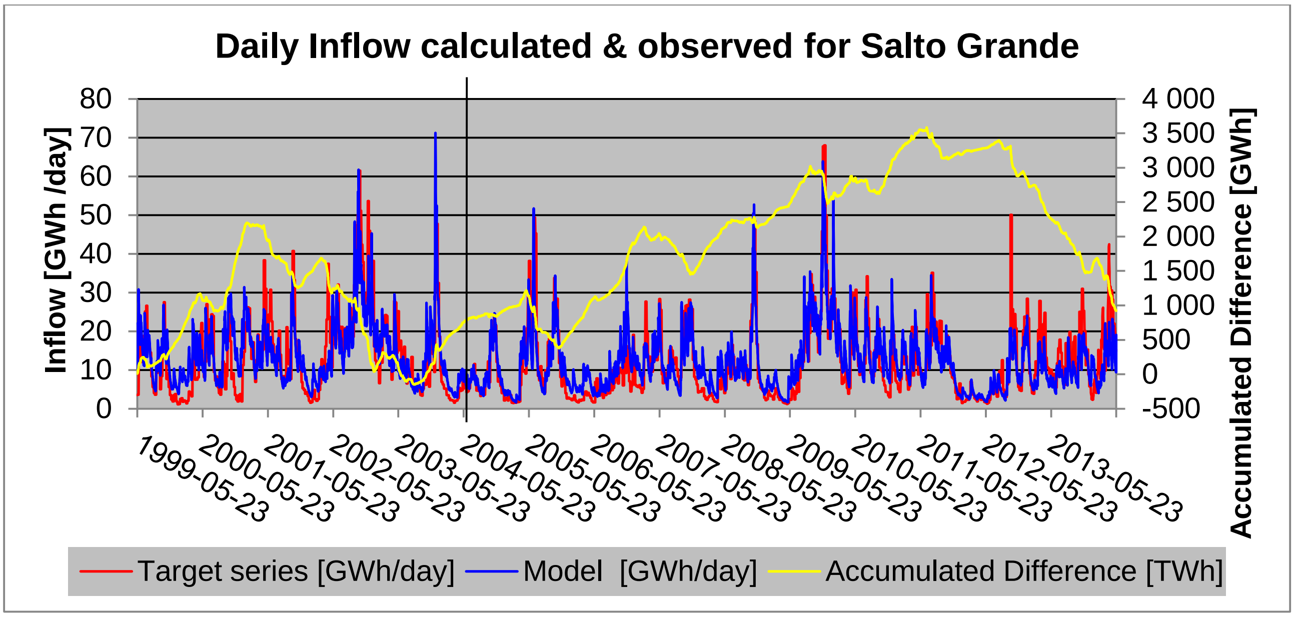


Figure 5.15: Observed and modelled inflow values for calibration of Salto Grande region, from 2004-05-23, and validation, before 2004-05-23.

The accumulated difference in Figure 5.15 seems to correlate really well with the difference between CPCp and the linear trend. During the years when CPCp greatly underestimates the precipitation the model underestimates the inflow as well. The reason for the error seems to be unrelated to the two datasets of CPCp. By correcting these years it would be possible to increase the accuracy of the model.

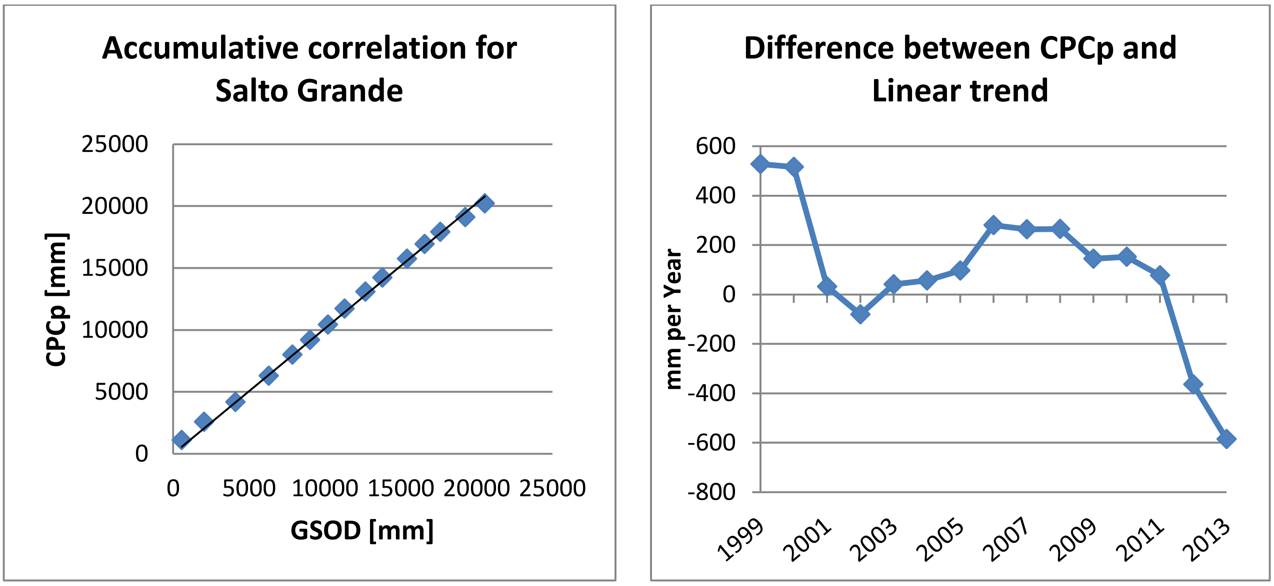


Figure 5.16: Results from double mass analysis comparing a CPCp polygon and an observation station within the polygon in the Salto Grande region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

The target series was constructed based on the production from 2009-2013 and the relation between the inflow and the production seem to follow as expected for earlier year, as seen in Figure 5.17. During years with high flows, Salto Grande is forced to spill water which seems to happen every other year. Salto Grande lacks the capacity to store a larger amount of water and will be forced to spill during years such as 2009 when the flow will not be evenly distributed over the year. To be able to better utilize this model it would therefore be necessary to understand which kind of level of flow that forces the plant to spill water.

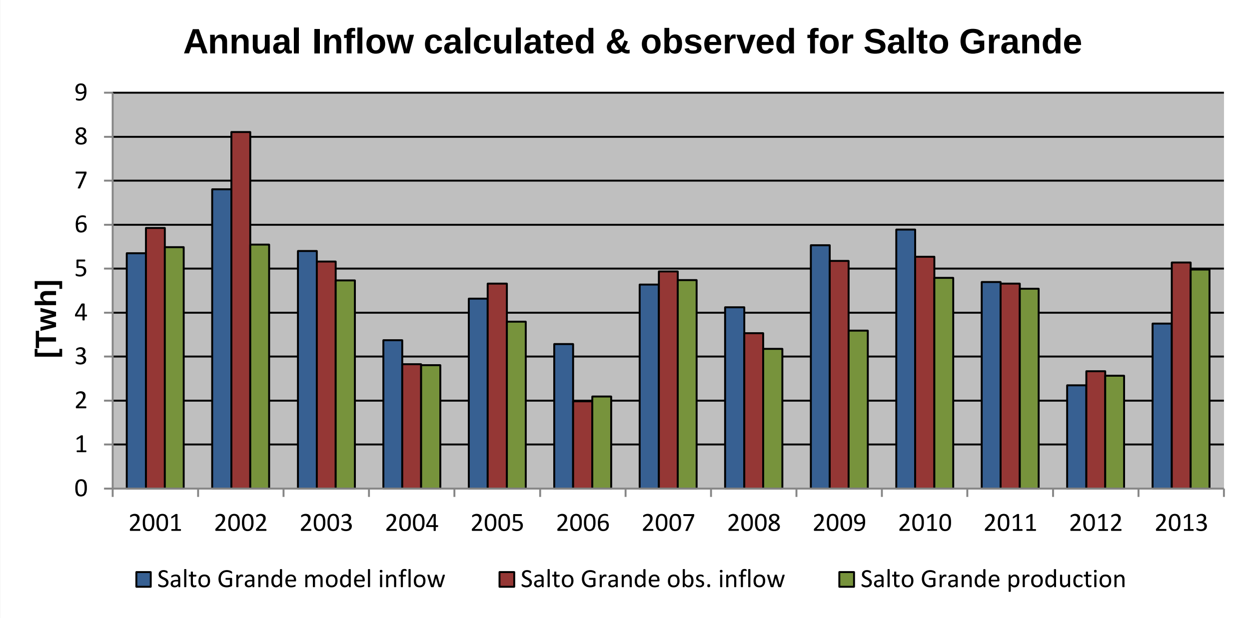


Figure 5.17: Modelled and observed inflow compared with the annual production for Salto Grande region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

The target series contains many fast floods, giving the graph a very spiky appearance. This can also be seen when plotting the daily averages of the year as done in Figure 5.18. The profile seems to be significantly different than Yacyretá's profile, seen in Figure 5.14, the peak is for this region occurs in early summer around October and November. The precipitation profile for the Salto Grande region does not decrease to the same extent as for Yacyreta during the winter months, as seen in Figure 2.4. The soil will be continously wet and will not display the same lagg in this region.

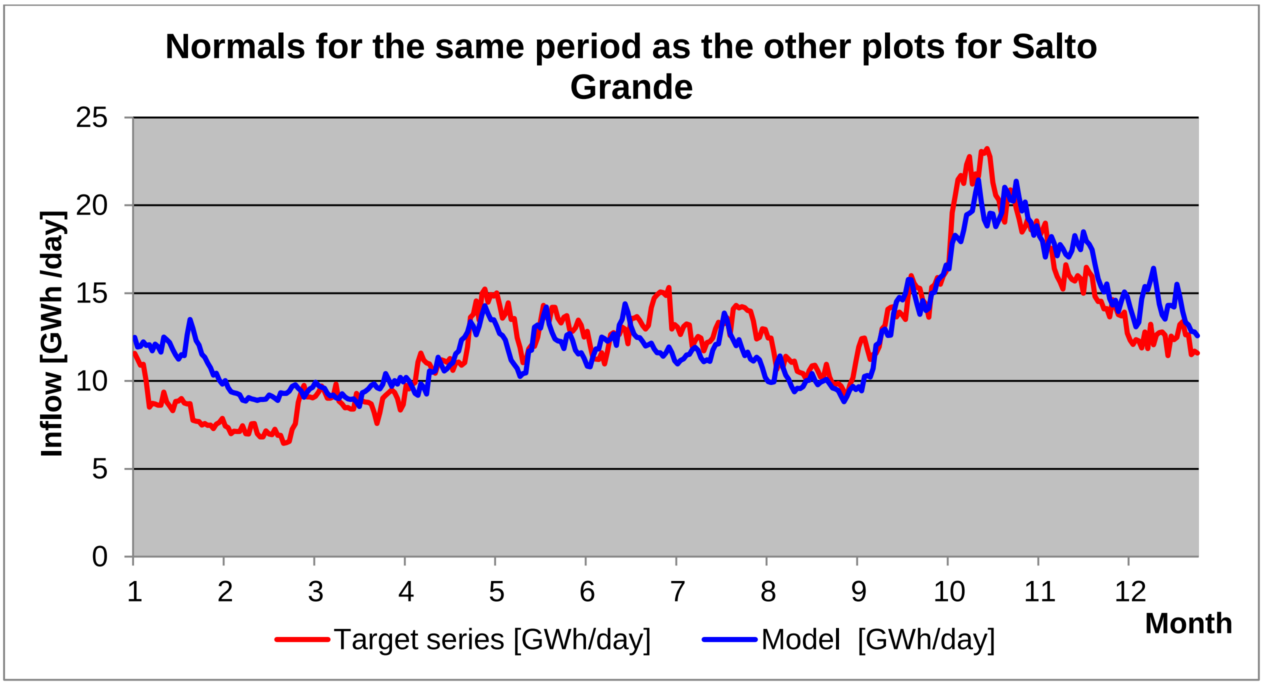


Figure 5.18: For the time period 1999-05-23 to 2014-05-22 average modelled and observed inflow together with the snow pack value for Salto Grande region throughout the year.

5.4 Rest Region (San Juan, Mendoza and Futaleufú Region)

The calibration and validation results are shown with the NSE coefficients in Table 5.5 and the model result compared with the target series in Figure 5.19. Since the rest region models two different regions in Argentina, a good result might be hard to achieve. The calibration managed to get NSE coefficients higher than 0.5. However during the validation the model generates close to twice the amount of water giving values below 0. Unlike for Yacyretá and Comahue the overestimation is present in the first year of the calibration period as well. During calibration is was found that the overestimated peak at the end of year 2004 was induced by the northern area, San Juan and Mendoza, where the precipitation data for all over the region gave more water between April 2004- April 2005 than April 2005 - April 2006. This contradicts the target series and the river flow used as 2006 should give a much higher peak for all 4 rivers.

Table 5.5: NSE coefficients on a Weekly and Monthly basis for the Rest Region.

NSE time frame	Calibration	Validation
Weekly	0.5096	-3.007
Monthly	0.5517	-2.942

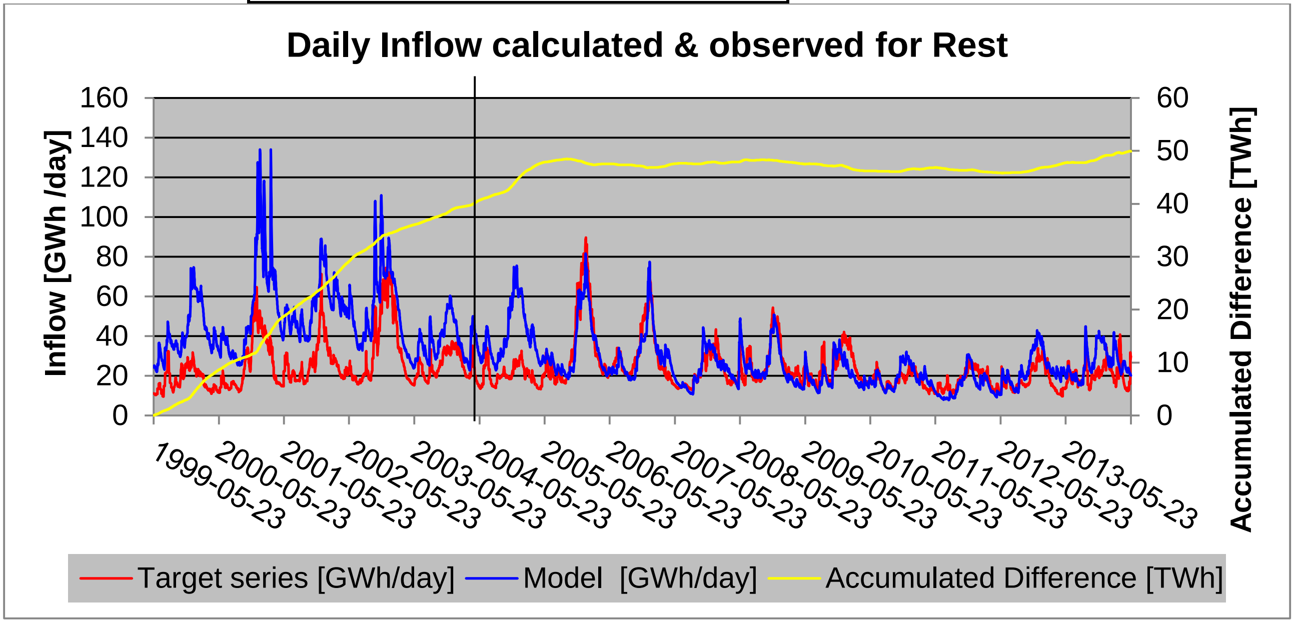


Figure 5.19: Observed and modelled inflow values for calibration of rest region, from 2004-05-23, and validation, before 2004-05-23.

The result of a double mass curve analysis with an observed station in the Futaleufú region and the grid data polygon which the station is located in is viewed in Figure 5.20. For this region the result shows two break points in the difference between CPCp and the linear trend, first between 2003 and 2004 and second between 2007 and 2008. The real time dataset is from 2006 and the change should therefore be seen between 2005 and 2006 if that was the cause. The analysis cannot pinpoint the datasets to be inconsistent with each other, however, there seem to be other factors that makes the datasets change over time.

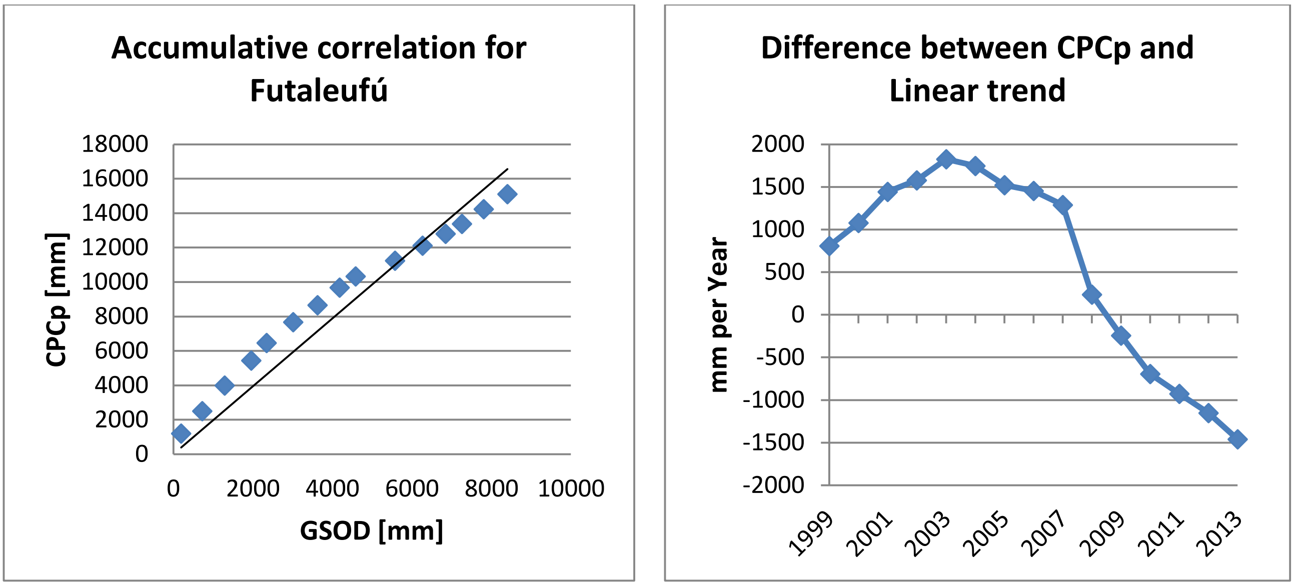


Figure 5.20: Results from double mass analysis comparing a CPCp polygon and an observation station within the polygon in the Comahue region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

Comparing the inflow with the production for this region can indicate if the rivers are good representatives for the overall rest production. By examining Figure 5.21 it possible to note that the observed flow is nowhere close to the amount produced in 2001 and several years has a substantial spillage. As noted, Futaleufú power plant does have to spill some of the years but for the other no knowledge about this is known.

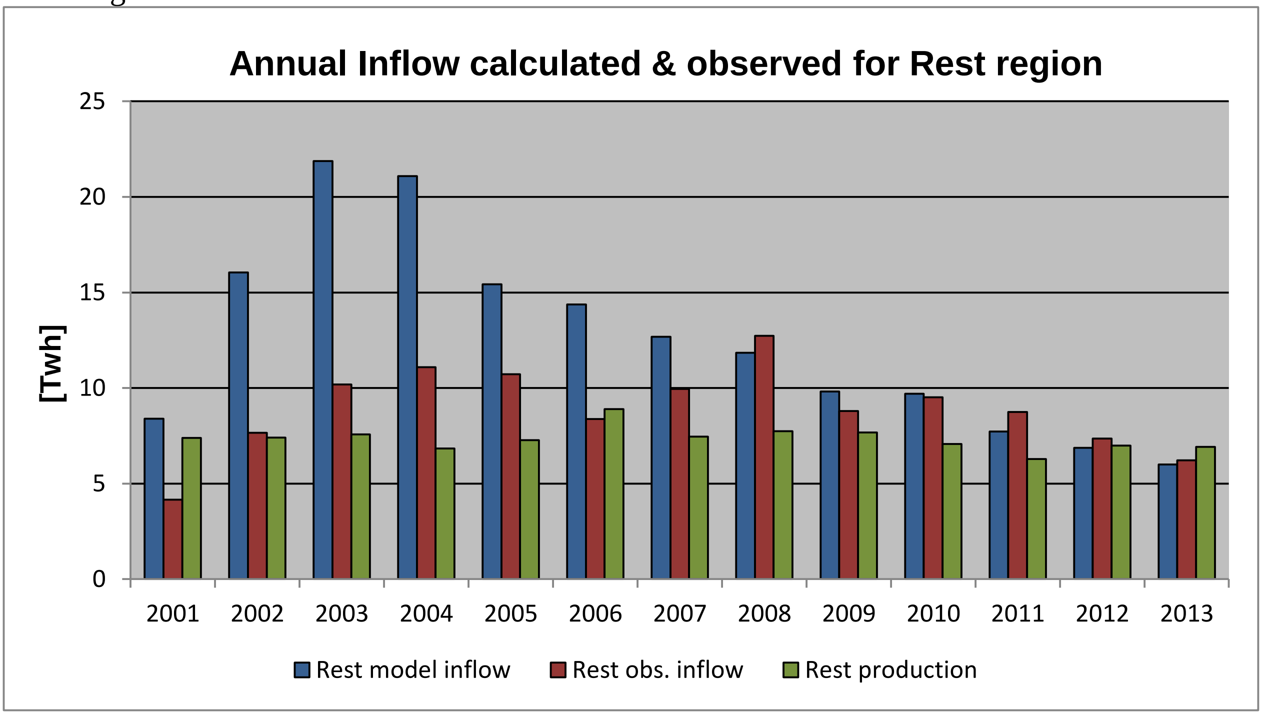


Figure 5.21: Modelled and observed inflow compared with the annual production for rest region. The calibration period is from 2004-05-23 and the validation period before 2004-05-23.

Looking at the average inflow and snow pack it looks as a typical snow induced hydro cycle would, with a low flow as the snow pack build up and then floods as the snow pack melts. Displayed in

Figure 5.22, the snow pack has a peak at the end of the winter and inflow reaches its maximum flow during the summer. The region is located in the mountains which is why the flood occurs during the summer and not the spring.

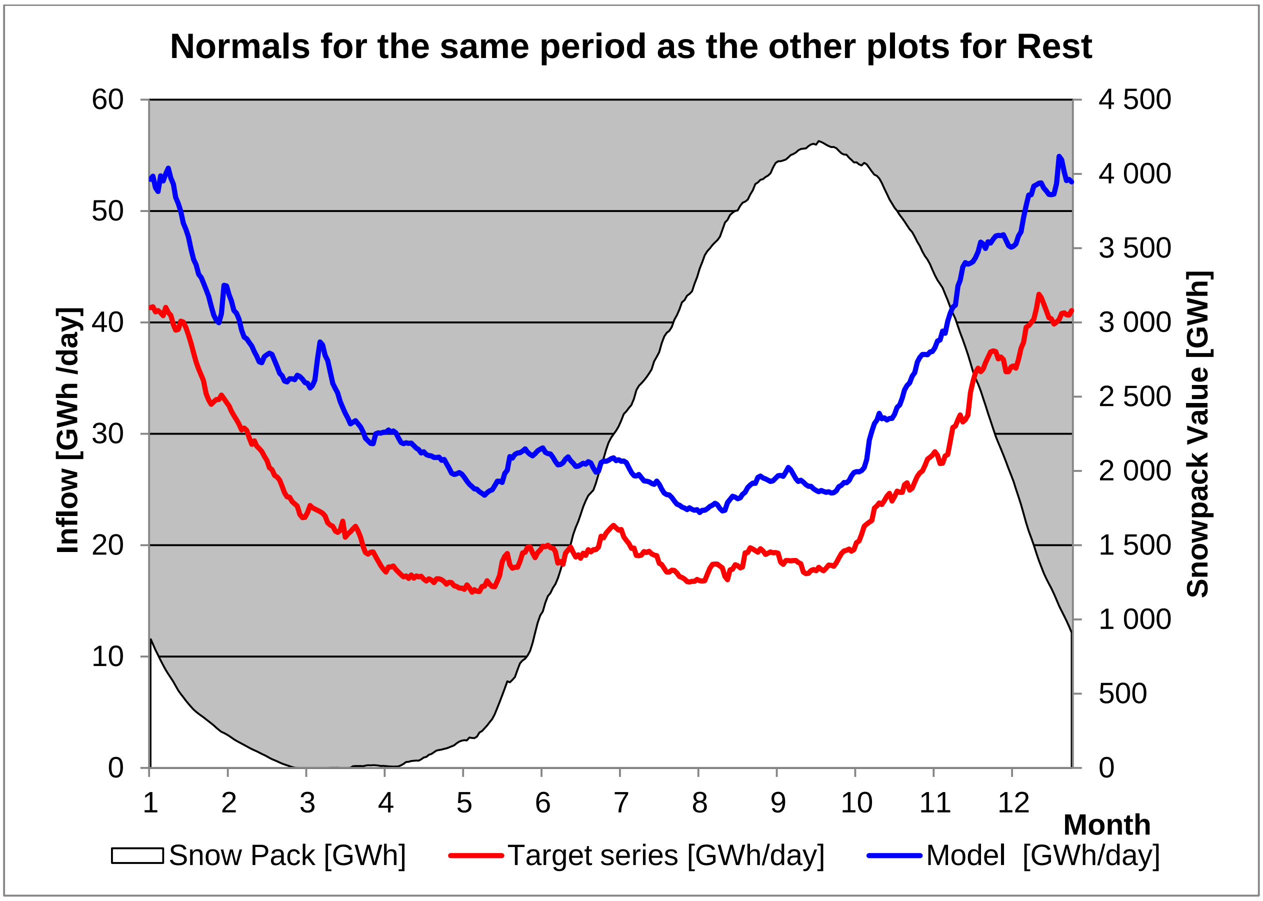


Figure 5.22: For the time period 1999-05-23 to 2014-05-22 average modelled and observed inflow together with the snow pack value for rest region throughout the year.

6 Conclusion

There is a good chance that it would be possible to construct good models for the majority of the hydropower plants in Argentina. The two largest producing regions, Yacyretá and Comahue, have been proven to be very easily calibrated. For the four regions modelled the calibration result varies from 0.9 to 0.5 and the validation gave NSE coefficient values of 0.74 to -3. To be able to use the Argentine models and further validate them one would have to look into the input data. The CPCp data seems to have a varying performance over the years giving the low NSE values for the validation. The current models are accurate with CPCp's real-time dataset but the dataset is not yet large enough to provide an accurate normal series. To be able to make better normal series it would be necessary to look into the precipitation data and, if possible, adjust it to increase the time period.

The natural inflow of energy to the hydropower plants in Argentina varies between close to 100 GWh/day during the winter and 200 GWh/day during the summer. The snow pack stands for about 13% of the yearly inflow. The inflow's dependency of rain periods has an emphasis on the summer season but as a whole the different regions complement each other and creates a more even inflow.

While no clear trend between the price and water stored in the soil and snow has been found it still is possible to see that there is a small correlation between the two of them. With values of the reservoir or normal series based on a larger time period it might be possible to find a clearer pattern.

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