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Cologne University of Applied Sciences - Institute for Technology and Resources Management in the Tropics and Subtropics

HYDROLOGICAL HEADWATER RESPONSES TO LAND USE CHANGES IN THE RIO DOIS RIOS BASIN, RIO DE JANEIRO

Veronica Jazmin Campos Zeballos

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PRESENTS:
Veronica Jazmin
Campos Zeballos
SUPERVISOR OF THESIS ITT
Prof. Dr. Lars Ribbe
ADVISOR
Juan Ramirez M. Sc.

DATE OF SUBMISSION
02.10.2017
presented by

Veronica Jazmin Campos Zeballos Student no.: 11113206 Email: jcamposzeballos@gmail.com

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I personally thank to the person who gave me the last push to be here, family and friends.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Hydrological Headwater Responses to Land Use Changes in the Rio Dois Rios Basin, Rio de Janeiro

Student: Veronica Jazmin Campos Zeballos, Tutor: Prof. Lars Ribbe, Advisor: Msc. Juan Ramirez.

ABSTRACT

The changes on Land Use can have a large impact on the rivers health jeopardising the water quality and quantity. This study focusses on the Land Use changes and its impact on the Rio Dois Rios headwater sub basins located in Rio de Janeiro, Brazil. The basin analysed had two main rivers, the Negro River and the Grande River, the study focused on the Grande River headwater which in turns has two main rivers: the Grande River upper sub basin and the Bengalas River sub basin. The city of Nova Friburgo is settled on the Bengalas River, which is developing along this river and its tributaries. The water source to cover the city demand is located in the Grande River upper basin, which presents an important impact from agriculture. Local data and remote sensing data were used to run three SWAT models for each sub basin (1985 – 1996, 1997 – 2005, 2006 – 2015), which were calibrated using SWAT CUP. The Land Use maps were processed for the years 1996, 2005 and 2015 through eCognition.

1. INTRODUCTION

The natural water balance and the development and surviving of living being depend on the natural ecosystem cover, therefore, to assess the state of the natural conditions is important to consider the landscape perspective. A change on the land cover configuration creates a new ecosystem and a hydrological response (Saavedra Briones and Sepúlveda-Varas, 2016; Haque and Basak, 2017; Robin Abell *et al.*, 2017)

As the headwaters are the beginning of the rivers and help to regulate the natural river flow, nutrients, etc., a change in this area can determine the health of the rest of the basin. The natural land cover on those areas is being lost all around the world, endangering the natural water availability; e.g, around 60% of the water supply in the west US comes from headwaters covered by forest, without those areas the water security is jeopardised (River Keepers, 2005). In that direction, the conservation and restoration of natural cover of the headwaters should be studied as key points for an integral water resource management.

The modelling of hydrologic responses to different land uses changes plays a very important role to assess the water availability. This response helps to understand the relationship between these two natural components helping to predict future scenarios, identify vulnerable areas, create policies to help to the sustainable development in the area and to take decision regarding the water resources management (Dwarakish *et al.*, 2015; Fohrer *et al.*, 2001).

For instance, to address water scarcity usually reforestation and forestation measurements are taken in order to assure the quality and quantity of water on a basin; and reforestation and soil conservation have shown to be a good measure to reduce peak flows and storm flows (Robin Abell *et al.*, 2017).

2. BACKGROUND

In Brazil, the Forest Code from 1965 established that the landowners must conserve between 20 to 80% from their land covered by original forest (Legal Reserves); it also mentions the Areas of Permanent Preservation (APPs) that area areas considered as vulnerable, e.g. the areas along the rivers. However, due the changes on the law in 2012, now some farmers can cultivate land near to the hilltops and riverbanks, areas that are considered sensitive, jeopardising the basins health (BBC News, 2012; World Wide Fund for Nature; Globo, 2011). This can result in the loss of natural cover on headwaters leading to an imbalance on the basin.

The water management in the city of Nova Friburgo is responsiblility of the company Águas de Nova Friburgo which is in charge since 2009 (Águas de Nova Friburgo). They have fourteen points to extract water, the most important is the Grande de Cima point located in the Grande River, from which they take around 48% of the total water extracted and it is located within the studied area.

3. STATEMENT OF THE PROBLEM

In general, the analyses of the land use changes and its impacts on the hydrological dynamics, is an issue studied in different basins with distinctive characteristics, especially regarding water quality. There are different models that were used to study the hydrological responses on the basin but only few that studied the headwater responses and fewer concentrated on water quantity.

The Brazilian institutes have done research regarding flood and drought management in the area. There is concern about the erosion in the basin and the plans are focus on that issue; however, the relation between the land use and the hydrological health are not yet well understood.

Currently they have a strategic action line regarding the sustainability of the land use and its impact in water quantity, but there is still the gap knowledge regarding the real impact of the land use change on the basin.

In the images below, the land uses changes within the last 30 years in the basin can be notice. The headwaters are marked with a light blue line that delineates the area to be analysed to know the impact of the land use, land-use changes and forestry (LULUCF).

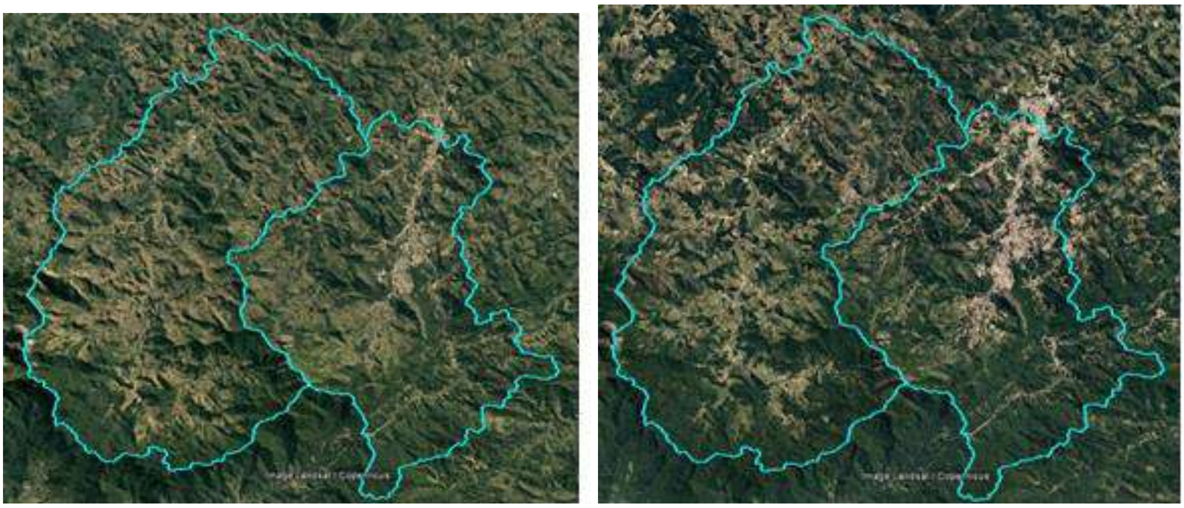

Figure 1: Changes in the land use on the headwaters of Rio Dois Rios. Left: year 1985; right: year 2015 (Source: (Landsat Copernicus, 1985) & (Landsat Copernicus, 2015)).

4. OBJECTIVES OF THE STUDY

The main objective in this work was to analyse if the Land Use, Land-Use Change and Forestry (LULUCF) in the headwaters have been affecting the basin flow and to establish if those changes jeopardise the water security in terms of water availability.

To accomplish the main objective, the following specific objectives were achieved:

- Collect historical meteorological data from station within the basin and complement it with remote sensing data.
- Collect historical rivers flow rates data from stations.
- Model, calibrate and validate the basin behaviour using SWAT.
- Analyse the sub basins with land use changes

- Analysed if the trend on land use changes jeopardise the water availability for the area.

5. STUDY AREA

Hydrologically, Brazil is divided on nine basins, the 5th one located in the south east, contains the Paraíba do Sul basin which in turn contains the Hydrographic Region VII (RH-II) or Rio Dois Rios hydrographic region (RH – R2R) where the Rio Dois Rios basin is located (Figure 2).

The main rivers in the Rio Dois Rios basin are the Negro River and the Grande River creating a drainage area of 3,169km^2. Of the total territory, 22.5% is occupied by forest (713 km^2) which makes it one of the most forest covered areas within the Paraíba do Sul basin, however this extension is still not enough to protect the soil from the erosive processes (Associação Fundação COPPETEC - Laboratório de Hidrologia e Estudos de Meio Ambiente, 2006).

Along its entire course, the Grande River suffers from the agricultural activity, especially in the municipalities of Nova Friburgo, Bom Jardim and Trajano de Moraes (Figure 3). Even do 29% of the area of the Grande River basin is covered by forest, the basin presents a fragile environmental situation with critical erodible conditions, especially due to the urbanization and abandon of land (Associação Fundação COPPETEC - Laboratório de Hidrologia e Estudos de Meio Ambiente, 2006).

The Bengalas River is a main tributary to the Grande River and it flows through the city of Nova Friburgo, collecting wastewater from the city, suffering the impacts of the urban development. It is formed by the San Antônio River and the Cônego River, both rivers born at the Três Picos National Park and then flow through the south area of the city (Carlos Emerson Junior, 2012). Currently, the city continues growing along the Bengalas River and its tributaries.

Figure 2: Study area location (Source: own preparation through ArcGIS. Data sources: (Agência Nacional de Águas; METI & NASA)).

For this study were considered the headwater of the Grande River and the headwater of the Bengalas River that covers the Cônego River and the San Antonio River. The area has geographical coordinates of 22°24’52.88’’ to 22°10’18.78’’ S latitude and 42°27’47.96’’ to 42°39’32.13 W longitude.

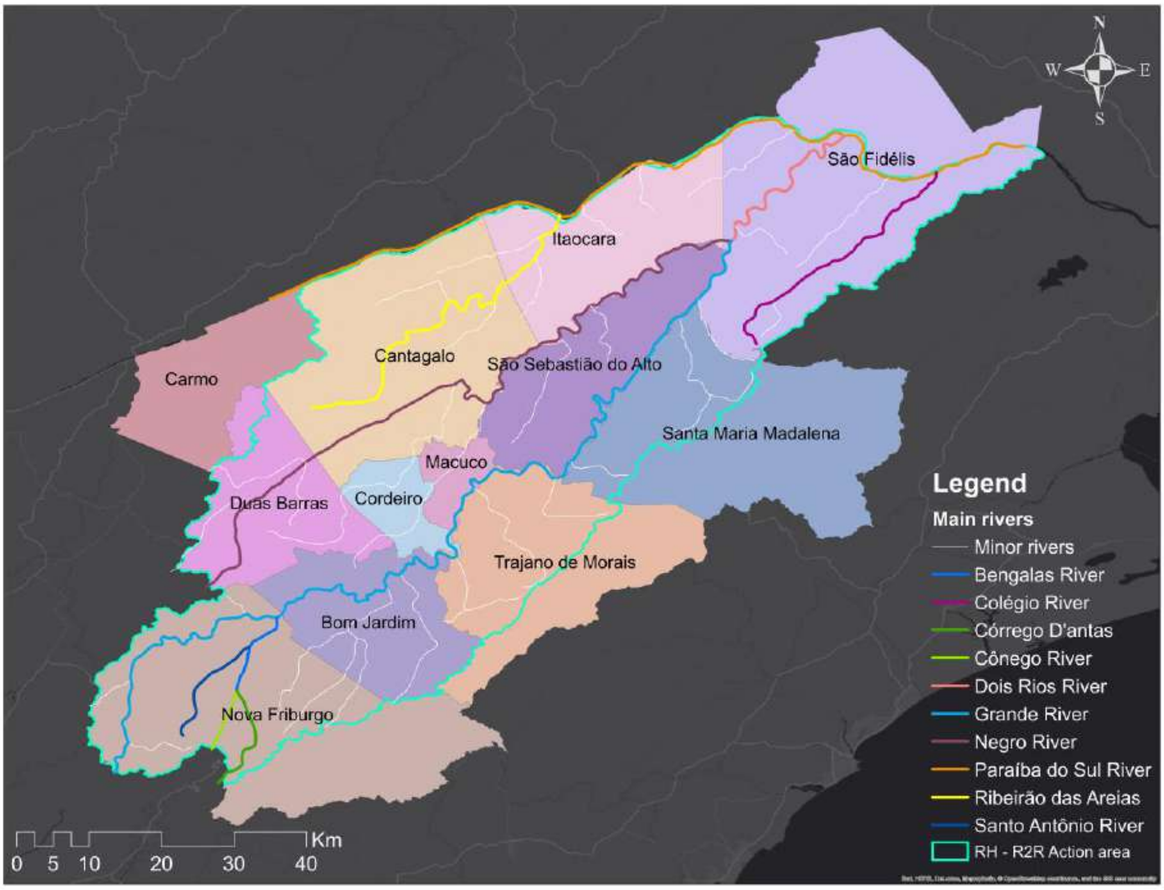

Figure 3: Rivers within Rio Dois Rios River basin (Source: own preparation through ArcGIS. Data sources: (Agência Nacional de Águas; METI & NASA)).

6. MATERIAL AND METHODS

6.1. Data collection

6.1.1. Primary data collection

The main primary data were the weather data. The precipitation data was acquired from the *Hidroweb* the national hydrologic information system managed by the National Water Agency (ANA in portuguese), seven ground stations were located within and close to the boudaries (Figure 4) these stations have data from 1985 to 2015. The temperature data were acquired from two stations managed by the Meteorological Database for Education and Research (BDMEP – INMET in portugues).

The discharge historical data were also acquired from the *Hidroweb*, two stations were considered both managed by the ANA, each one located by the end of each subbasin analysed.

The volumen of the total water treated to cover the water demand of the city was acquiered from the database of the National Sanitation Information System of the Ministry of Cities of Brazil, it covers the time period from 1999 to the present (Ministério das Cidades). The volume of water abtracted per point was given by the water company of Nova Friburgo, Águas de Nova Friburgo, the data cover a line time from 2013 to the present.

6.1.2. Secondary data collection

The soil characteristics, land use, and precipitation complemetary data were acquired from secondary sources.

The soil data map was acquired from the FAO web page and the information for the SWAT model was retrieve using the plugin MWSWAT for MapWindow (MapWindow GIS Project).

Satellite images were acquired to analyse the land use changes for the years 1996, 2005 (Landsat 4-5) and 2015 (Landsat 8). Due to the low quality of the satellite images for the area during the year 1995, it was decided to analyse the year 1996.

The Digital Elevation Map (DEM), was also download and clipped to the sub basin area since it is an input for the model.

Due to the lack of ground stations for the Grande River sub basin, daily products from CHIRPS were aquired to complement the precipitation data.

6.2. Data analysis

The precipitation data from seven precipitation stations (Figure 4) were completed using the R statistical software and the package "gapfill". It predicts the missing value based on the data around the point and the group itself, considering that the values closer to the point to be filled are more similar than the others (Florian Gerber, 2017). The precipitation data from CHIRPS were abstracted to 19 points corresponding to the cells that cover the Grande River sub basin (Figure 5).

On the other hand, the stations to fill the temperature gaps were not enough to use the same method. There was only one station located within the study area (Nova Friburgo station), and did not present complete data for the time period analysed. A second station (Cordeira station) located around 47 Km. further north, which registered data for the time period analysed, was used as a reference to complete the data (Figure 6). On a first step, data from the station Cordeira was completed and afterward a correlation between both stations, Nova Friburgo and Cordeira, was used to estimate the temperatures in Nova Friburgo station.

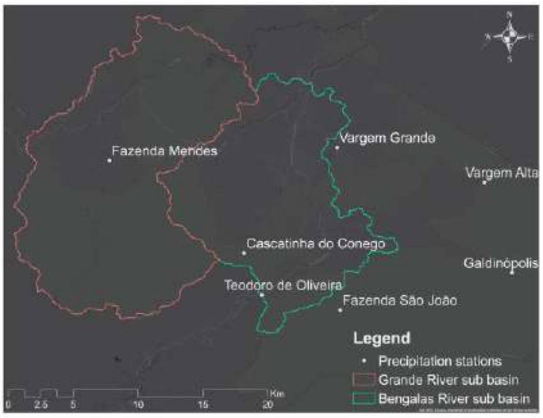

Figure 4: Precipitation stations. (Source: Own preparation through ArcGIS. Data sources: Own sub basins delineation & (Agência Nacional de Águas).

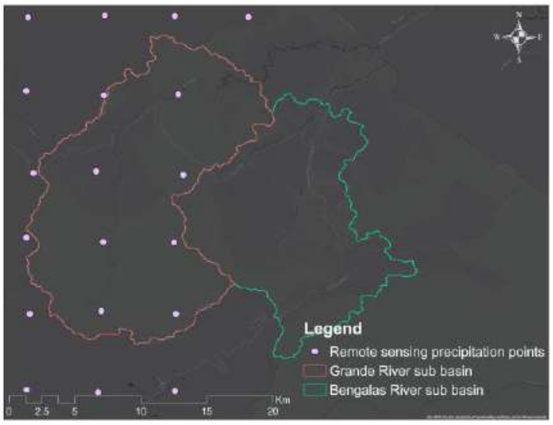

Figure 5: Remote sensing precipitation reference points (Source: Own preparation through ArcGIS. Data sources: Own sub basins delineation & precipitation reference points)

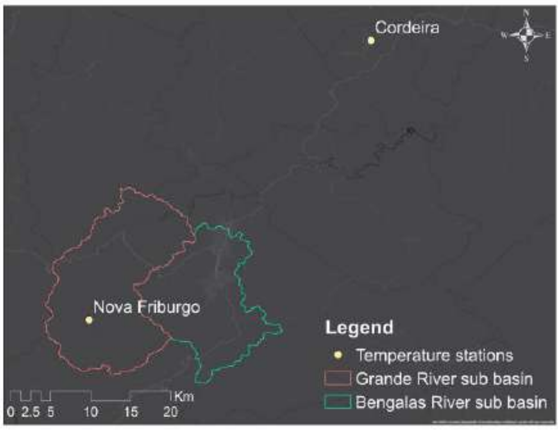

Figure 6: Temperature stations (Source: Own preparation through ArcGIS. Data sources: Own sub basin delineation & temperature stations based on coordinates)

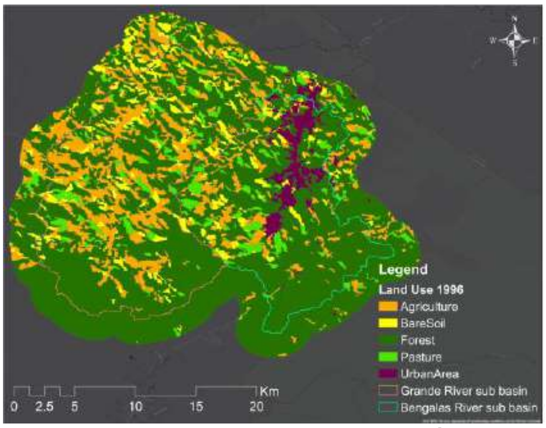

Figure 7: Land use map 1996. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover (Source: Own preparation through eCognition & ArcGIS. Data sources: Own sub basin delineation & (Landsat 4 - 5 TM C1 Level 1, 1996))

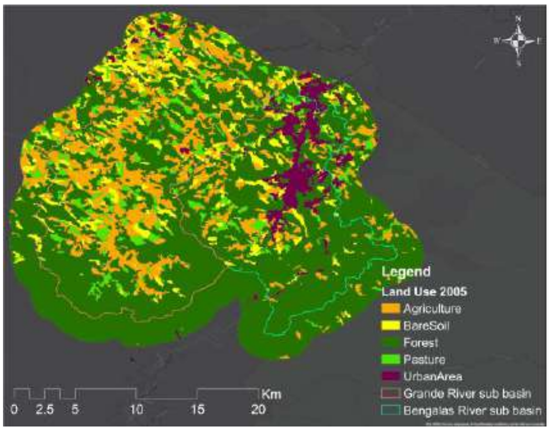

Figure 8: Land use map 2005. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover (Source: Own preparation through eCognition & ArcGIS. Data sources: Own sub basin delination & (L(Landsat 4 - 5 TM C1 Level 1, 2005))

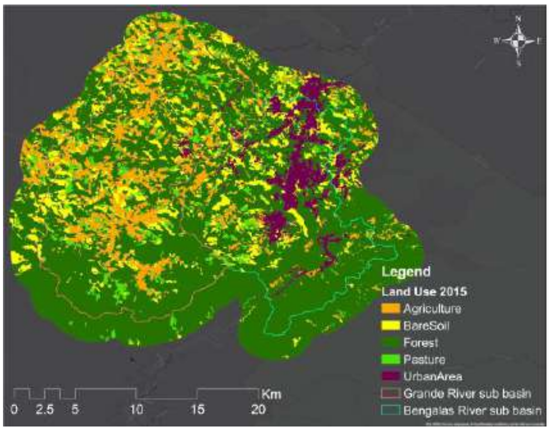

Figure 9: Land use map 2015. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover (Source: Own preparation through eCognition & ArcGIS. Data sources: Own sub basin delineation & (L8 OLI/TIRS, 2015)

Regarding the discharge data, the two stations had enough information for the analysis. It could be noticed some erratic behaviour the last ten years, in which are present higher and lower picks than the previous years. Since the year 2006, there are missing data, especially during the year 2011 in which the studied area suffered the worst flood event.

The satellite images for the land use maps were analysed and processed using eCognition, a software object-based oriented to process images (Trimble Geospatial, 2017). The program analyses the overall accuracy based on four error indexes (producer, user, Hellden and Short) that are complemented by the Kappa Index Agreement (Table 1).

Table 1: Land Use Maps Accuracy

	1996	2005	2015
Overall Accuracy	85%	91%	91%
KIA	65%	73%	78%

Source: eCognition accuracy results

Four maps were prepared but only three were used for the three time periods analysed (Figure 7, Figure 8 and Figure 9). The growth of the city could be clearly noticed, which was supported by the data analysed that showed that the area considered as urban had a growth of 45% between 1996 and 2005 and 24% between 2005 and 2015 (Table 2). The agriculture activity seemed to be reducing, which is a consequence of the urban growth in the Bengalas sub basin where the city of Nova Friburgo is settled. For its geographic position, the city tends to growth along the river where the agriculture activity used to be the major activity, on the other hand, in the case of the Grande River sub basin, the agriculture is more intense every year. Regarding the bare soil, its growth can be due to the flood and landslides event on 2011 and the abandonment of agriculture land.

Table 2: Land use configuration 1985, 1996, 2005 and 2015

Land use	1985		1996		2005		2015	
	Area (km^2)	Change (%)	Area (km^2)	Change (%)	Area (km^2)	Change (%)	Area (km^2)	Change (%)
Agriculture	99	-	97	-2%	101	4%	71	-30%
Bare Soil	31	-	41	32%	47	15%	78	66%
Forest	434	-	421	-3%	403	-4%	401	0%
Pasture	33	-	36	9%	36	0%	30	-17%
Urban Area	19	-	20	5%	29	45%	36	24%

Source: Own preparation based on results from eCognition

Despite the losses of forest area, the forest cover still being the largest on both sub basins (Figure 10).

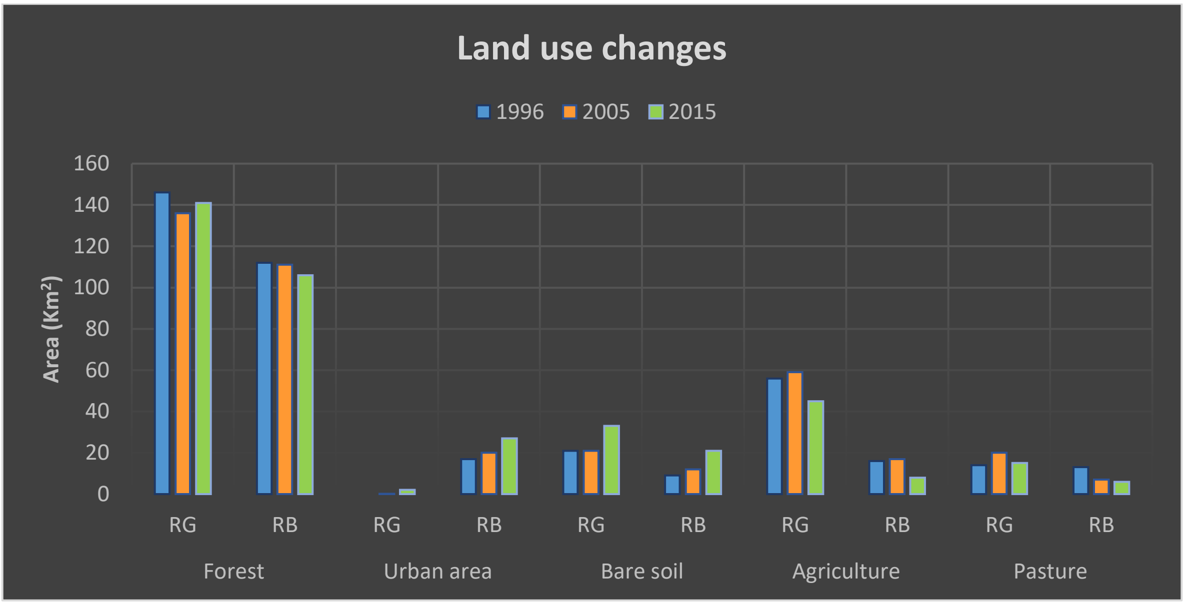

Figure 10: Land use cover 1996, 2005 and 2015. (Source: Own preparation)

6.3. SWAT Model running, calibration and validation

The Soil & Water Assessment Tool (SWAT) for ArcGis 10.4 (ArcSWAT) (SWAT Soil and Water Assessment Tool) was used to analyse the sub basin behaviour. The tool has versions for free tools like MapWindow or QGIS.

SWAT splits the basin into sub basin and then it organises the sub basins into Hydrological Response Units (HRUs). The HRUs are areas within the sub basins that shares distinctive land use, soil and management characteristics. This partition makes the differentiation of the different evapotranspiration values are possible and allows the model to predict the runoff per HRU (Neitsch *et al.*, 2011).

SWATs simulates the hydrological cycle in a daily step using the following equation (Neitsch *et al.*, 2011):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} + E_a - W_{seep} - Q_{gw})$$

Where: "SW_t is the final soil water content in mmH_2O; SW_0 is the initial soil water content on day *i* in mm H_2O, t is the time, R_{day} is the amount of precipitation on day *i* in mm H_2O, Q_{surf} is the amount of surface runoff on day *i* in mm H_2O, E_a is the amount of evapotranspiration on day *i* in mm H_2O, w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* in mm H_2O) and Q_{gw} is the amount of return flow on day *i* in mm H_2O" (Neitsch *et al.*, 2011).

Three periods were evaluated 1985 - 1996, 1997 – 2005, and 2006 - 2015. For each period, the sub basins of the Grande River and Bengalas River were modelled considering the changing on land use covers.

Default methods were used to calculate the water balance except for the channel routing that by default uses a variable storage method instead of the Muskingun method. In the case of the evapotranspiration, due to the lack of data the Penman-Monteith equation could not be used. The model uses Hargreaves equation, that according to the paper "Evaluation of six empirical evapotranspiration equations – case study: Campos dos Goytacazes/RJ", had a very good performance to calculate the evapotranspiration on the area (Fernandes *et al.*, 2012).

To calibrate and validate the model was used the tool SWAT CUP and its algorithm SUFI 2 (Sequential Uncertainty Fitting) that is an algorithm to calibrate and calculate the uncertainty of parameters in a SWAT model and its sensitivity based on Inverse Modelling (IM). It performances several iterations sampling numbers using a Latin Hypercube within a range for the different parameters to be analysed, in every iteration the ranges narrow to find a value that improves the model performance and fits the result better. Finally, the parameters are ordered based on their sensitivities, this final step helps to fix the values of the less sensitive parameters to exclude them from the next calibration and calculate and narrow the most sensitive parameters. For this study, 42 parameters were selected in a first instance but only 14 had impact on the performance of the models. The procedure was performed until the indexes got acceptable values. This analysis routine uses a stochastic calibration approach emphasising the importance of the uncertainties on the model, which are represent as the 95% of the probable distributions regarding the possible parameters values (Abbaspour, 2015; Abbaspour *et al.*, 2004).

The models were calibrated on a monthly step using as a reference the Nash-Sutcliffe (NS) efficiency index and the R^2 indexes that according to Moriasi in his paper *"Model evaluation guidelines for systematic quantification of accuracy in watershed simulations"*, a NS and R^2 values of 0.5 or higher can be judged as satisfactory model simulation on a monthly step model (Moriasi *et al.*, 2007; Arnold *et al.*, 2012; Douglas-Mankin *et al.*, 2010; Gassman *et al.*, 2007). Table 3 shows the results of the coefficients for each model in every period analysed the low value on the validation period for the Bengalas River can be related to the water use data used on the model, which has a declining trend.

Table 3: Efficiency model indexes values

Period time	Parameter	Grande River		Bengalas River	
		Calibration	Validation	Calibration	Validation
1985 - 1996	NS	0.78	0.69	0.81	0.68
	R2	0.83	0.71	0.82	0.69
1996 - 2005	NS	0.83	0.56	0.72	0.43
	R2	0.83	0.62	0.75	0.85
2005 - 2015	NS	0.79	0.51	0.79	-0.21
	R2	0.79	0.68	0.84	0.64

Source: Own preparation based on SWAT CUP results

7. RESULT AND DISCUSSION

Differences between the twenty-nine micro basins of the Grande River and the nineteen micro basin of the Bengalas River were analysed in general, however this study focused on thirteen selected micro basins (eight on the Grande River sub basin and five in the Bengalas River sub basin) which were subjected to the most pronounced land use changes over the time period analysed.

The results from the model for the Grande River sub basin (Figure 11, Figure 12 and Figure 13) showed that the flow on the river tends to increase during the months of January, November and December; which correspond to the months with more rain; and decrease the rest of the year which is most noticeable during the months from February to May.

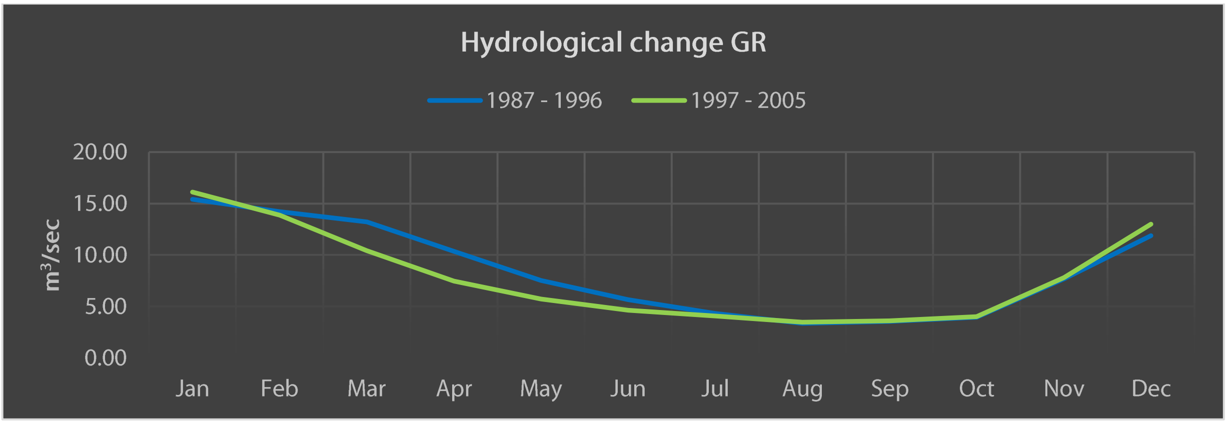

Figure 11: Hydrological change on the Grande River sub basin 1987 – 1996 and 1997 – 2005. (Source: Own preparation).

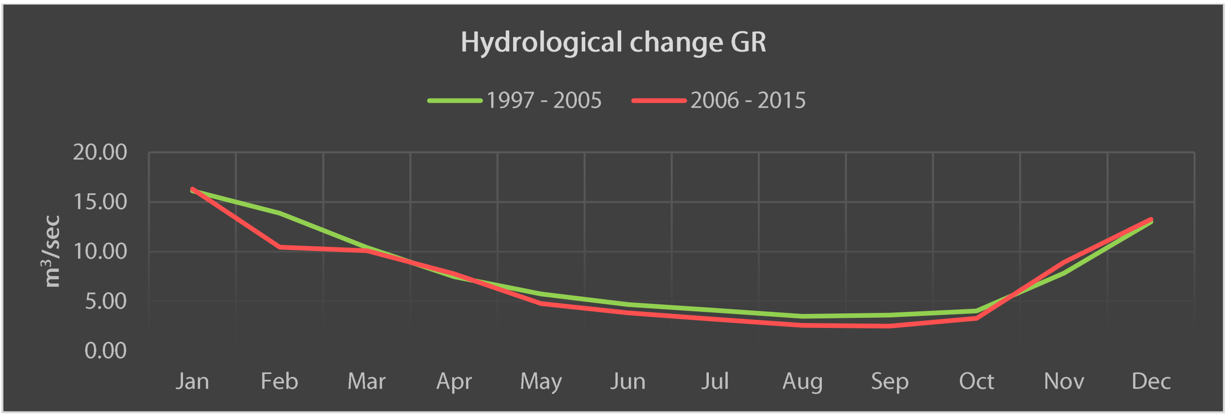

Figure 12: Hydrological change on the Grande River sub basin 1997 – 2005 and 2006 – 2015. (Source: Own preparation).

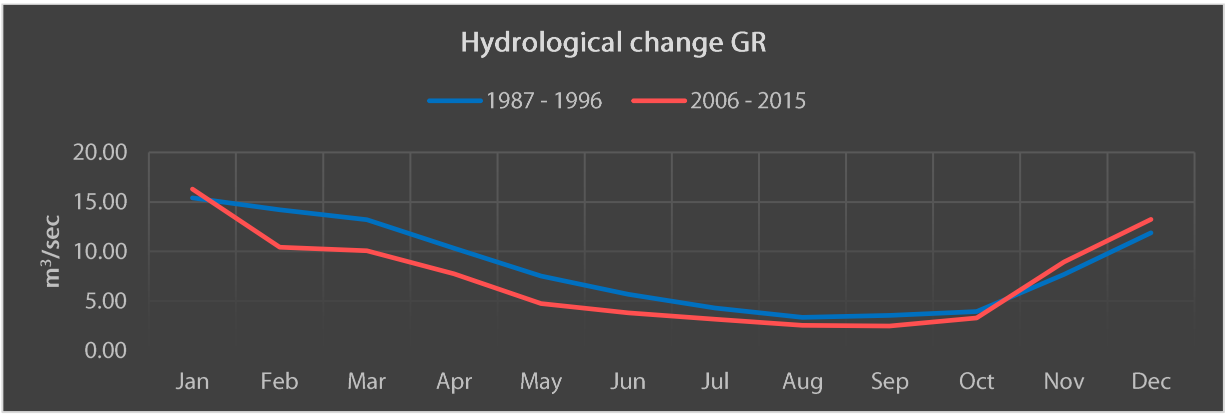

Figure 13: Hydrological change on the Grande River sub basin 1987 – 1996 and 2006 – 2015. (Source: Own preparation).

The average of the monthly discharge of the first and second period of the selected Grande River micro basins were compared and analysed using the percentage change. It was noticed that the main changes on the flow between 1987 and 2005 were located during the months of March to June (Table 1), which are the months when the rainy season ends and the dry season starts. The most affected micro basin was the GR_10 where is located the urban development within the Grande River sub basin analysed, it presents also an increment on the agriculture land us. The micro basin GR_26 also presents relevant changes, as the micro basin GR_10 it presents an increment on the agriculture land use.

Table 4: Changes on the Grande River flow. Comparison between the periods 1985 – 1996 and 1997 - 2005

Micro basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GR_10	8%	-4%	-24%	-33%	-30%	-23%	-7%	1%	-9%	-5%	-1%	11%
GR_26	5%	-2%	-19%	-26%	-22%	-17%	-8%	2%	9%	10%	-1%	10%
GR_28	4%	0%	-17%	-22%	-19%	-12%	-3%	6%	15%	16%	10%	11%
GR_23	5%	-1%	-18%	-22%	-17%	-12%	-3%	5%	6%	4%	5%	10%
GR_21	5%	0%	-17%	-22%	-19%	-13%	-3%	6%	12%	12%	5%	11%
GR_22	5%	0%	-17%	-22%	-19%	-13%	-3%	6%	14%	14%	6%	12%
GR_14	-6%	-5%	-19%	-22%	-18%	-14%	-4%	4%	6%	4%	-4%	1%
GR_29	5%	1%	-15%	-20%	-17%	-11%	-1%	7%	17%	18%	5%	12%

Source: Own preparation

The results for the comparison between the time periods 1997 – 2005 and 2006 – 2015 showed that the main changes were located on the months of May to September, the dry season. The micro basin GR_10 during this period experimented an urban growth and a decrease on agriculture activity that led to a replacement of agriculture cover by pasture and bare soil. The micro basin GR_14 also experimented an increase of bare soil and pasture cover.

Table 5: Changes on the Grande River flow. Comparison between the periods 1997 - 2005 and 2006 - 2015

Micro basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GR_10	-1%	-19%	-7%	4%	-11%	-14%	-17%	-19%	-25%	-17%	8%	-1%
GR_14	1%	-19%	-6%	4%	-13%	-15%	-18%	-21%	-27%	-18%	8%	1%
GR_21	0%	-19%	-7%	4%	-13%	-15%	-18%	-21%	-27%	-18%	8%	1%
GR_22	-5%	-29%	1%	3%	-22%	-20%	-25%	-29%	-27%	-17%	16%	-1%
GR_26	-1%	-19%	-8%	6%	-12%	-15%	-17%	-20%	-26%	-16%	6%	1%
GR_28	5%	-18%	-1%	4%	-12%	-12%	-13%	-16%	-21%	-13%	11%	3%
GR_29	2%	-16%	-7%	7%	-12%	-13%	-16%	-20%	-25%	-13%	9%	5%
GR_23	11%	-20%	-8%	-6%	-18%	-17%	-19%	-23%	-26%	-23%	12%	8%

Source: Own preparation

The sub basin GR_29, which showed an important forest cover recovery on the last period, showed a behaviour more resilient to change experimenting less extreme changes on its flow.

On the other hand, the Begalas River presented an increase on the flow during the entire year especially in the months of January, February, November and December, the rainy season. The last period analysed (1996 – 2005 and 2006 – 2015), showed a decrease from July to October, but compared to the first period analysed (1987 - 1996) it did not present a relevant change (Figure 14, Figure 15 and Figure 16).

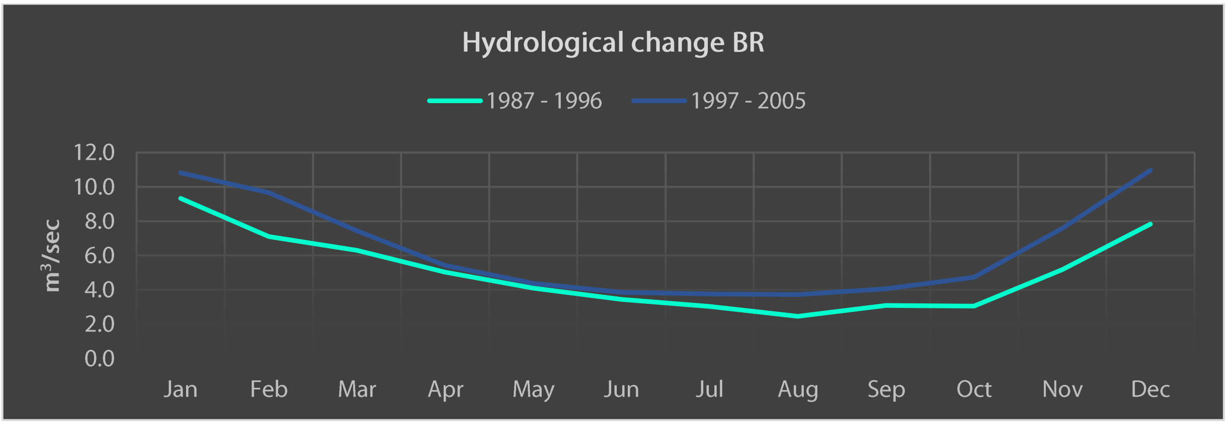

Figure 14: Hydrological change on the Bengalas River sub basin 1987 – 1996 and 1997 – 2005. (Source: Own preparation).

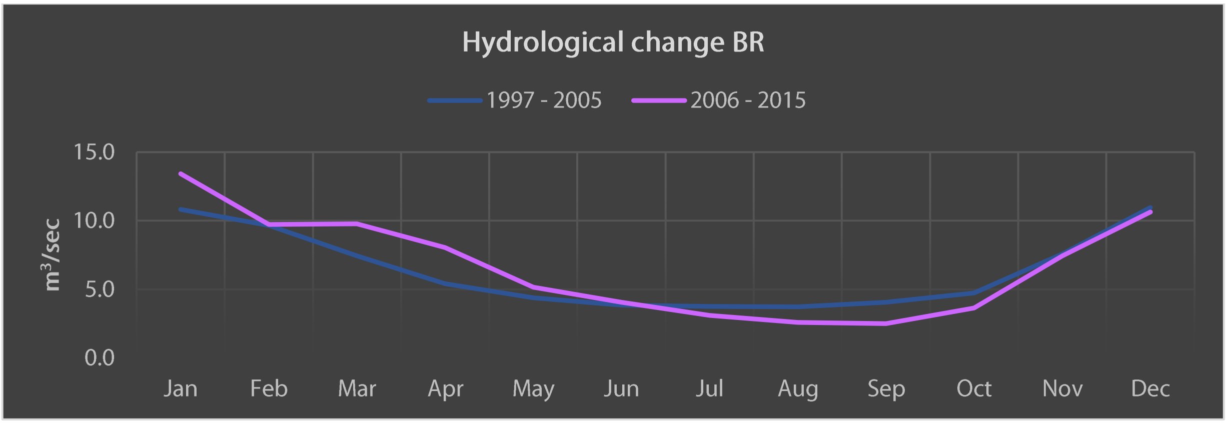

Figure 15: Hydrological change on the Bengalas River sub basin 1997 – 2005 and 2006 – 2015. (Source: Own preparation).

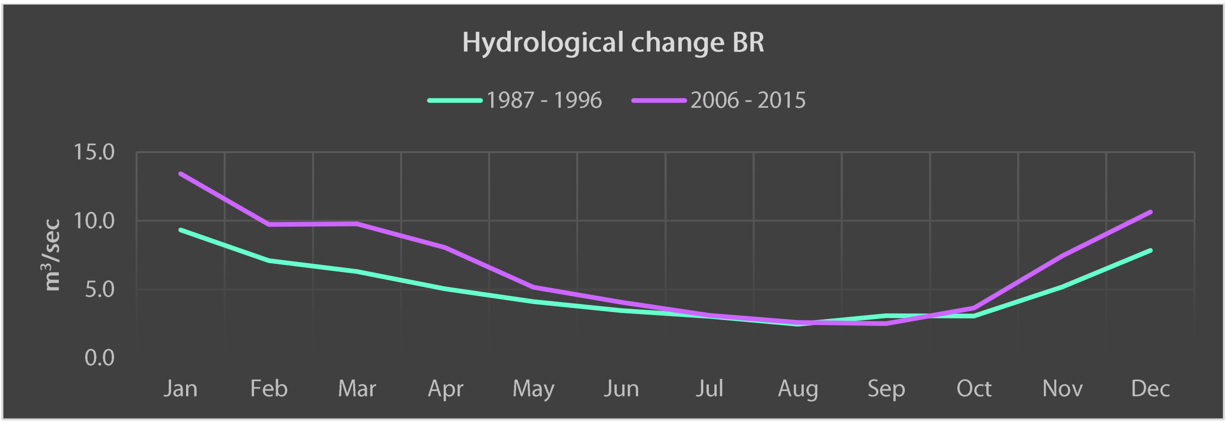

Figure 16: Hydrological change on the Bengalas River sub basin 1987 – 1996 and 2006 – 2015. (Source: Own preparation).

The comparison of the first and second time periods (1987 – 1996 and 1997 - 2005), showed that the micro basin analysed increased their flow during the entire year except for the micro basin BR_13 and BR_16 that presented slightly decreases from March to June (-6% to -1%). The most relevant changes are located on the micro basin BR_18 and BR_14, both presented a growth on the urban area and bare soil and a reduction on forest cover and pasture. The micro basins BR_16 and BR_13 presented an increase on the forest cover and present less changes on their flows.

Table 6: Changes on the Bengalas River flow. Comparison between the periods 1985 – 1996 and 1997 - 2005

Micro basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BR_18	31%	21%	22%	15%	9%	12%	28%	42%	33%	31%	38%	50%
BR_14	24%	19%	19%	9%	7%	12%	26%	48%	38%	46%	39%	43%
BR_17	24%	9%	13%	6%	4%	8%	21%	36%	27%	29%	29%	37%
BR_16	9%	14%	-3%	-6%	-6%	-3%	3%	23%	5%	23%	23%	16%
BR_13	8%	13%	-1%	-5%	-5%	-2%	4%	22%	3%	20%	20%	14%

Source: Own preparation

The comparison between the periods 1997 – 2005 and 2006 – 2015, showed a decrease on the forest cover on all the micro basins analysed. The main flow changes were located on the micro basin BR_16, it presented a rise from an average flow of 0.26 m^3/sec to an average flow of 2.98 m^3/sec and a rise of 0.40 m^3/sec to 5.19 m^3/sec on rainy season. It presented an important increase on urban area and pasture, and a decrease on forest cover. The micro basins BR_13 and BR_14 presented a reduction on their flows the entire year, both presented a growth on urban area and reduction on the pasture cover, both areas are located bordering the sub basin close to the forest area. The micro basins BR_17 and BR_18 presented lower changes compared to the rest and are also the micro basins with less forest cover loss.

Table 7: Changes on the Bengalas River flow. Comparison between the periods 1997 - 2005 and 2006 - 2015

Micro basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BR_16	1487%	1260%	1342%	1553%	1145%	1054%	916%	714%	666%	687%	1143%	1151%
BR_13	-87%	-96%	-98%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-98%	-97%
BR_14	-74%	-78%	-77%	-76%	-79%	-80%	-83%	-85%	-88%	-88%	-81%	-80%
BR_17	16%	28%	28%	54%	27%	16%	-11%	-20%	-29%	-8%	1%	-3%
BR_18	10%	16%	19%	46%	24%	19%	-12%	-19%	-28%	0%	-1%	-8%

Source: Own preparation

To analyse if the changes jeopardise the water availability for the city, the average flow from the years 2006 to 2015 was used. An important component was the Environmental Flow Requirement (EFR), which is the water volume required to maintain the integrity of the ecosystems along the rivers ((Dyson et al., 2003; Acreman, 2016) thus it was subtracted from the flow. There are several methods to measure it, according to the Water Footprint Network (Hoekstra, 2011), the environmental flow of a river should be between 20 to 40% of the total flow if the river presents moderately to significantly modification. The flow for the year 2025, the flow was estimated using the percentage change per month between the last two time periods analysed (1996 - 2005 and 2006 – 2015). It was assumed that the water extracted presented a steady behaviour that will continuo, therefore the average water abstraction from the sub basin was used.

In the case of the Grande River (Table 8), the available flow will be still being enough to cover the water demand. In the months of August and September the available flow is almost the same flow it is needed to abstract, this during the dry years will be a problem (Figure 17)

Table 8: Grande River average flow, environmental flow and estimated flow for 2025, m³/sec

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average flow (2006-2015)	16.30	10.42	10.08	7.76	4.75	3.82	3.17	2.56	2.48	3.29	8.94	13.24
Environmental flow (2006 - 2015)	6.52	4.17	4.03	3.10	1.90	1.53	1.27	1.02	0.99	1.31	3.57	5.29
Available flow (2006 - 2015)	9.78	6.25	6.05	4.65	2.85	2.29	1.90	1.54	1.49	1.97	5.36	7.94
Estimated flow for 2025	9.89	4.70	5.85	4.83	2.37	1.89	1.48	1.13	1.03	1.61	6.13	8.10
Water extraction	0.25	0.26	0.25	0.25	0.25	0.25	0.24	0.23	0.24	0.23	0.24	0.25

Source: Own preparation

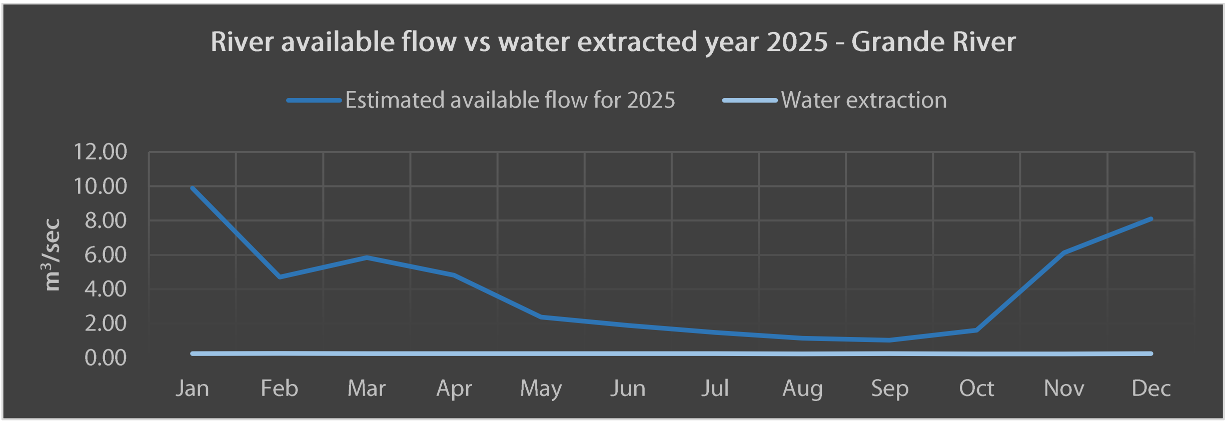

Figure 17: River available flow Vs Water extracted – Grande River. (Source: Own preparation)

Regarding the Bengalas River, the analysis was more complex considering that the river flow measured is the sum of the natural flow and the water discharge from the urban area. In order to analyse the natural flow, the average of the imported water was subtracted from the measured average flow (Table 9).

The results showed that the environmental flow for 2025 will be jeopardise during the months of August and September (Figure 18), as the case on the Grande River.

Table 9: Bengalas River average, environmental and estimated flow for 2025, m^3/sec

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average flow (2006-2015)	13.42	9.74	9.76	8.04	5.16	4.07	3.10	2.58	2.50	3.64	7.45	10.63
Imported water (2006 - 2015)	0.32	0.33	0.32	0.32	0.32	0.32	0.31	0.30	0.31	0.30	0.30	0.32
Natural flow	13.10	9.41	9.45	7.73	4.84	3.75	2.79	2.28	2.20	3.34	7.14	10.31
Environmental flow (2006 - 2015)	5.24	3.76	3.78	3.09	1.93	1.50	1.12	0.91	0.88	1.33	2.86	4.12
Available flow (2006 - 2015)	7.86	5.65	5.67	4.64	2.90	2.25	1.67	1.37	1.32	2.00	4.29	6.19
Estimated flow for 2025	9.8	5.7	7.4	6.9	3.4	2.4	1.4	0.9	0.8	1.5	4.2	6.0
Water extraction	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.17	0.18	0.18	0.18	0.19

Source: Own preparation

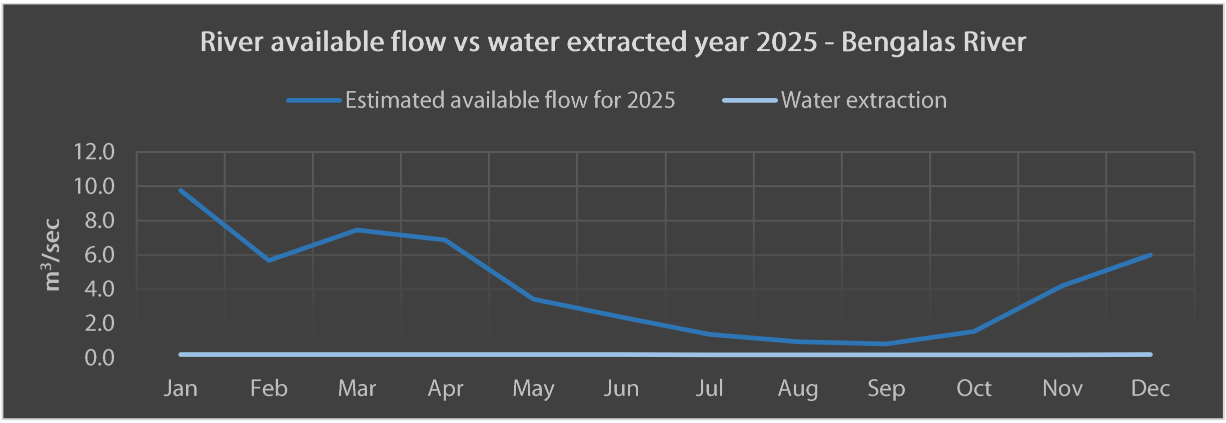

Figure 18: River available flow Vs Water extracted – Bengalas River. (Source: Own preparation)

8. CONCLUSION

The SWAT model is a complex model which in this study performed better on the Grande River sub basin, which does not have a strong urban impact as the Bengalas River does. It needs a lot of data and not all of it could be acquired from a primary source, for instance, the soil information was not completed and data from the FAO was used, which is not as detailed as the data from EMBRAPA could be, this soil information can have a relevant impact on the calibration of the model, as the calibration analyses showed. Further studies to complement the soil data from EMBRAPA should be carried out, the soil characteristics could be simulated and then verified on the field.

The parameters and equation that model the water quantity are complex and at the time to calibrate resulted on long calibration running. In this study where used 38 parameters from which 14 had a real impact on the behaviour of the sub basins, using the half of those parameters is possible to get similar model indexes using less time and having more control on the values changes. It was also relevant to perform the sensitivity analysis for each model that helped to improve the results since the models are sensible to different parameters.

The general results from both sub basins suggested that there is an increase on the flow average during January, November and December that are not strongly related to the land use, but more probably to the climate changes on the area. The precipitation data from the ground stations showed an increment on the precipitation on January and December the las 8 years, except during 2010 that presented a low precipitation on January. Furthermore, the results also showed that the micro basins with less changes on forest cover or with recovery on the forest cover present less changes on the flow patterns. This characteristic makes those micro basins more resilient to the climate changes on the area that makes the dry season dryer and increases the precipitation during the months with high precipitation.

The results on the Land Use Changes imagery processing, showed that the predominant land cover still being the forest despite the losses. Both sub basins presented growth regarding the urban area and bare soil replacing agriculture area, which seems to be related to the lack of resilience on some micro basins. Since all the micro basins analysed presented forest cover, can be concluded that without it the changes on the flow would be more relevant.

The indexes values of the Bengalas River and the simulation results suggested that the data regarding the water extraction and the water use on the sub basin are not complete. A decrease on the water consumption in a basin experimenting urban and population growth is unlike unless large infrastructure improvements were carried on. According to the institutions working on the water management in the city, improvements on the water network were done, however it is needed to have detailed information to verify that the decrease on water consumption by the city is due to these actions.

The results regarding the micro basin BR_16 showing an increment on the flow seams difficult to occur on the reality and should be measured on the field to validate the behaviour. Analyses regarding the land use changes and water used leading to those results on this area should be carried on.

Regarding the precipitation data, the new product from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) could lead to a better model performance and results closer to the reality (Beck et al., 2017a; Beck et al., 2017b). Those two products should be compared on the model to analyse if there is any improvement and also could be used to validate the future model behaviour.

The comparison between the available flow and the water extraction for the year 2025, showed that the basin environmental flow will be jeopardise during the months of August and September. Considering that average were used, the situation can be worst during dry years in which the water abstraction could be higher than the available flow.

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ANNEXES

Annex 1: Precipitation data preparation

The precipitation data were retrieved from the Hydrological Information System developed and administrated by the National Water Agency of Brazil (ANA in Portuguese). Seven meteorological stations located within and close the study area were used (see Figure 1).

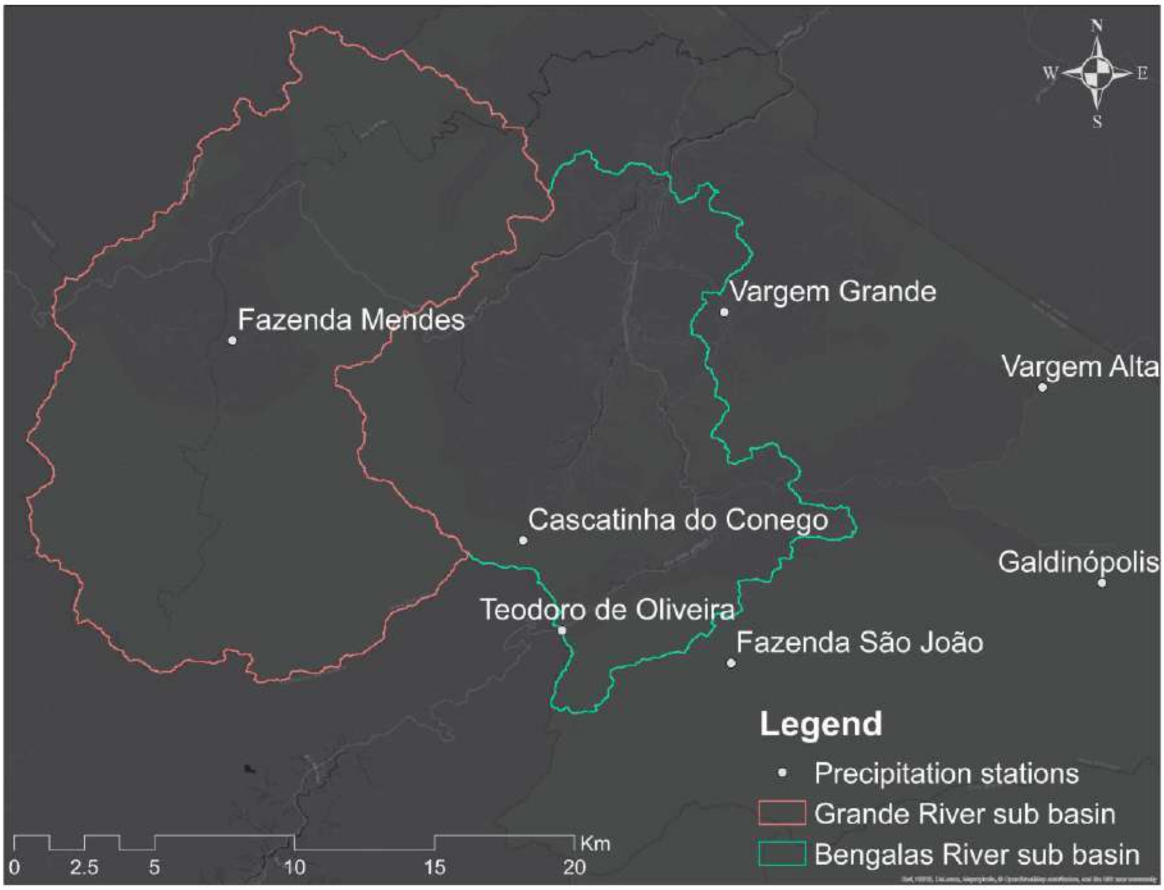

Figure 1: Precipitation stations. (Source: Own preparation through ArcGIS. Data sources: Own sub basins delineation & (Agência Nacional de Águas))

In a first step, the statistical computer software "R" was used to fill the incomplete data from the ground stations. The correlation coefficients results are detailed below.

Table 1: Correlation coefficient

	Galdinópolis	Fazenda_São_João	Teodoro_de_Oliveira	Cascatinha_do_Conego	Fazenda_Mendes	Vargem_Alta	Vargem_Grande
Galdinópolis	1	0.46	0.56	0.62	0.15	0.40	0.30
Fazenda_São_João	0.46	1	0.48	0.28	0.02	0.52	0.10
Teodoro_de_Oliveira	0.56	0.48	1	0.69	0.14	0.32	0.23
Cascatinha_do_Conego	0.62	0.28	0.69	1	0.16	0.17	0.25
Fazenda_Mendes	0.15	0.02	0.14	0.16	1	0.08	0.23
Vargem_Alta	0.40	0.52	0.32	0.17	0.08	1	0.19
Vargem_Grande	0.30	0.10	0.23	0.25	0.23	0.19	1

Source: Results from R statistical analysis

Table 2: Correlation order

	1	2	3	4	5	6
Galdinópolis	Cascatinha_do_Conego	Teodoro_de_Oliveira	Fazenda_São_João	Vargem_Alta	Vargem_Grande	Fazenda_Mendes
Fazenda_São_João	Vargem_Alta	Teodoro_de_Oliveira	Galdinópolis	Cascatinha_do_Conego	Vargem_Grande	Fazenda_Mendes
Teodoro_de_Oliveira	Cascatinha_do_Conego	Galdinópolis	Fazenda_São_João	Vargem_Alta	Vargem_Grande	Fazenda_Mendes
Cascatinha_do_Conego	Teodoro_de_Oliveira	Galdinópolis	Fazenda_São_João	Vargem_Grande	Vargem_Alta	Fazenda_Mendes
Fazenda_Mendes	Vargem_Grande	Cascatinha_do_Conego	Galdinópolis	Teodoro_de_Oliveira	Vargem_Alta	Fazenda_São_João
Vargem_Alta	Fazenda_São_João	Galdinópolis	Teodoro_de_Oliveira	Vargem_Grande	Cascatinha_do_Conego	Fazenda_Mendes
Vargem_Grande	Galdinópolis	Cascatinha_do_Conego	Teodoro_de_Oliveira	Fazenda_Mendes	Vargem_Alta	Fazenda_São_João

Source: Results from R statistical analysis

Table 3: Linear coefficients

	1	2	3	4	5	6
Galdinópolis	0.55	0.35	0.65	0.83	0.73	0.67
Fazenda_São_João	0.75	0.38	0.74	0.56	0.71	0.36
Teodoro_de_Oliveira	0.75	0.85	0.81	0.83	0.83	0.92
Cascatinha_do_Conego	0.36	0.64	0.58	0.66	0.67	0.67
Fazenda_Mendes	0.36	0.14	0.14	0.11	0.19	0.09
Vargem_Alta	0.55	0.69	0.29	0.79	0.48	0.21
Vargem_Grande	0.53	0.42	0.25	0.40	0.69	0.46

Source: Results from R statistical analysis

From the data obtained and filled can be noticed a more extreme behaviour during the past 15 years specially in the month of April, May, June and October (Figure 5, Figure 6, Figure 7 and Figure 11). Hereunder the figures of the monthly precipitation behaviour during the period studied are presented.

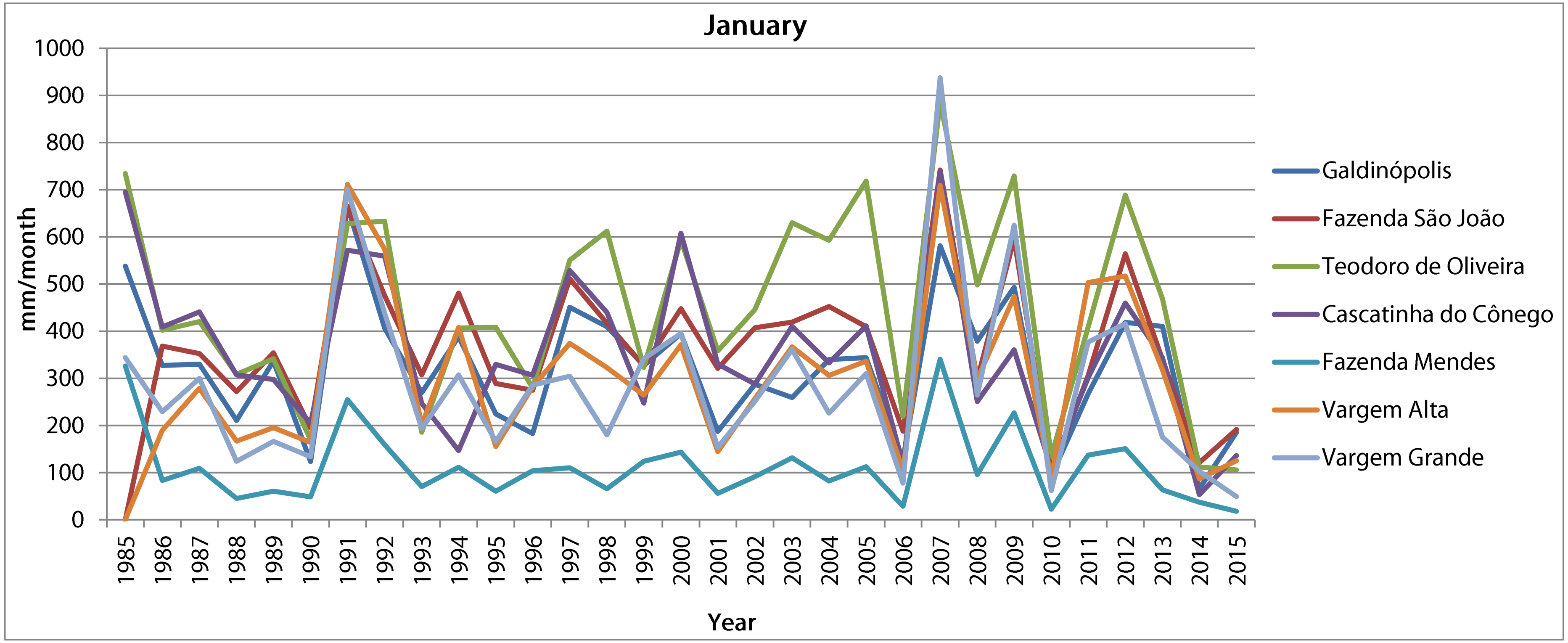

Figure 2: January precipitation behaviour

Source: Own preparation based on the results from R.

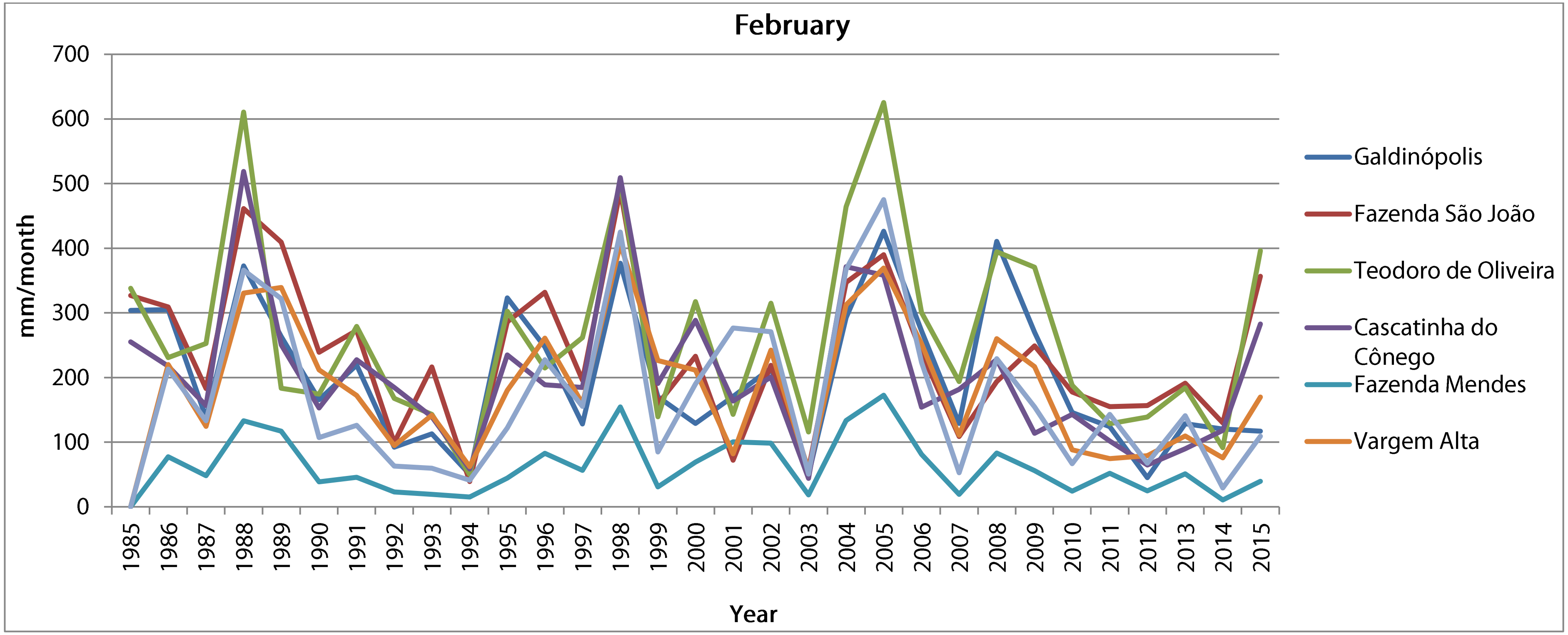

Figure 3: February precipitation behaviour

Source: Own preparation based on the results from R.

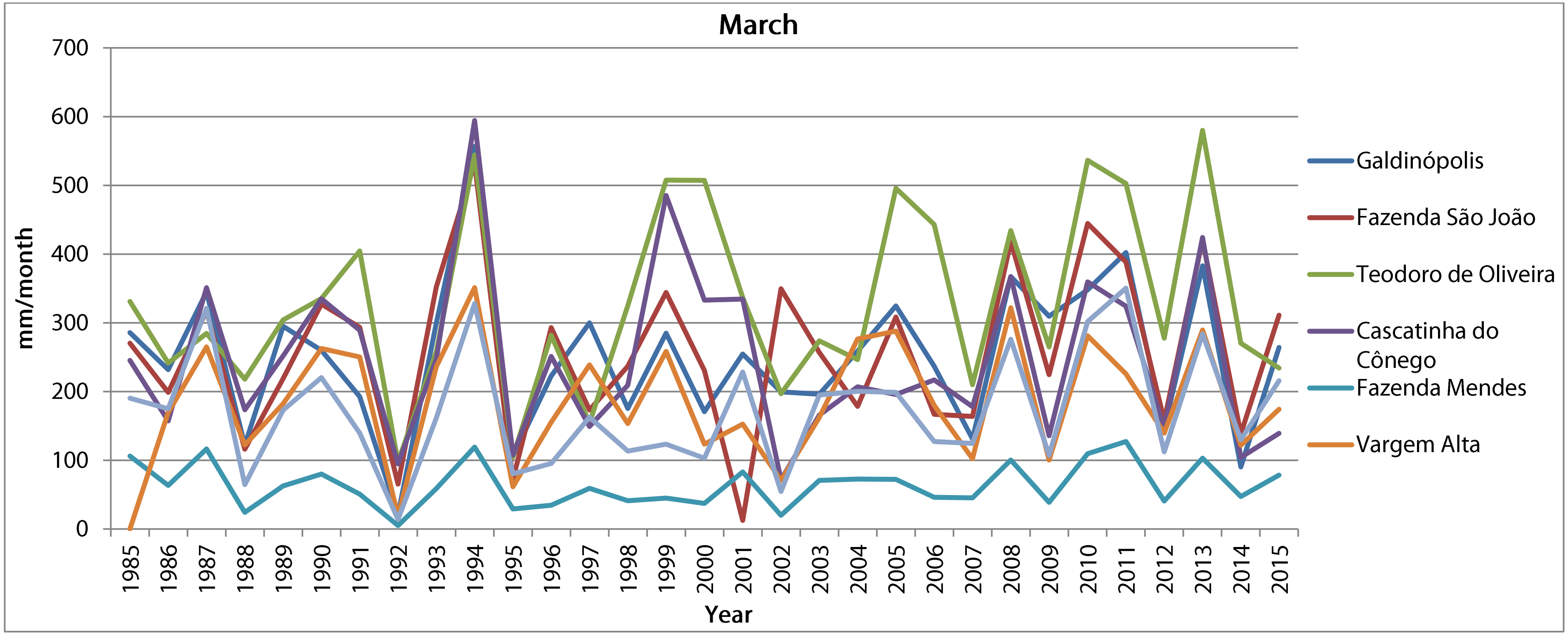

Figure 4: March precipitation behaviour

Source: Own preparation based on the results from R.

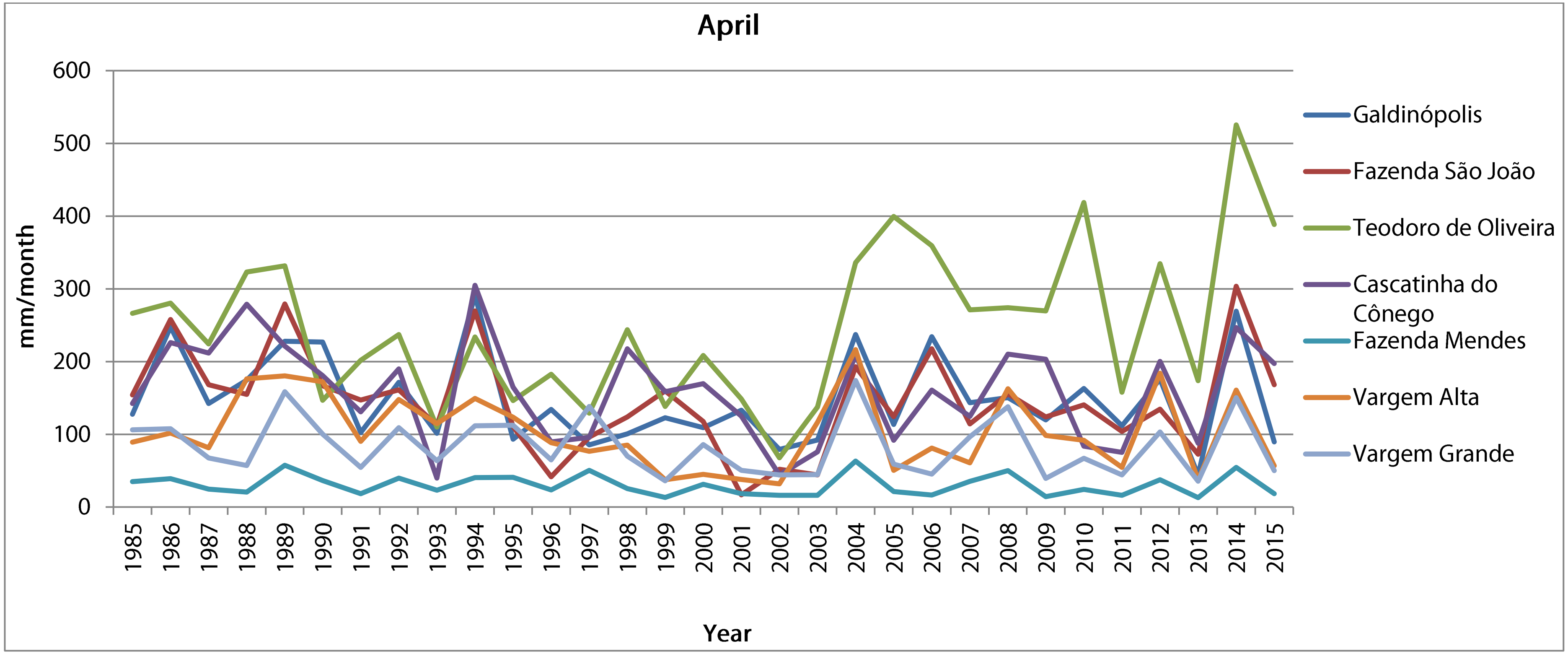

Figure 5: April precipitation behaviour

Source: Own preparation based on the results from R.

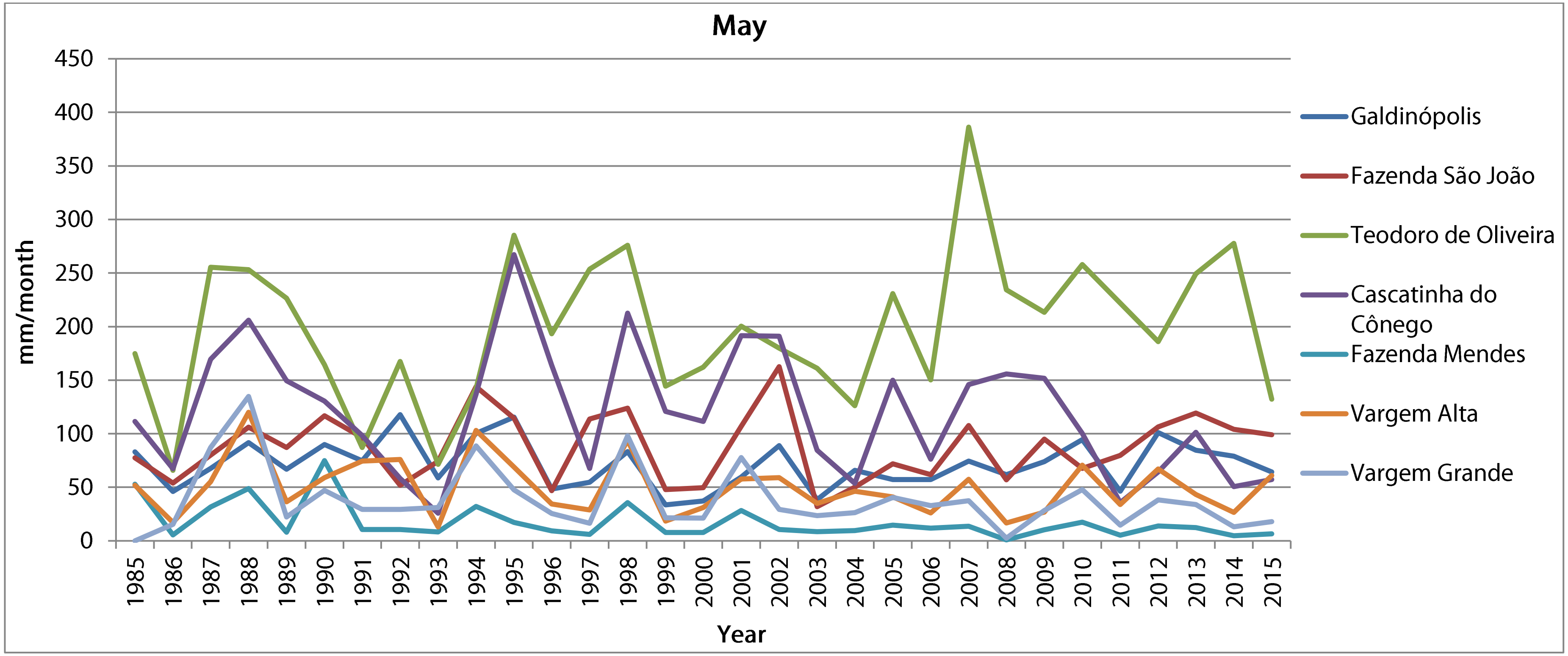

Figure 6: May precipitation behaviour

Source: Own preparation based on the results from R.

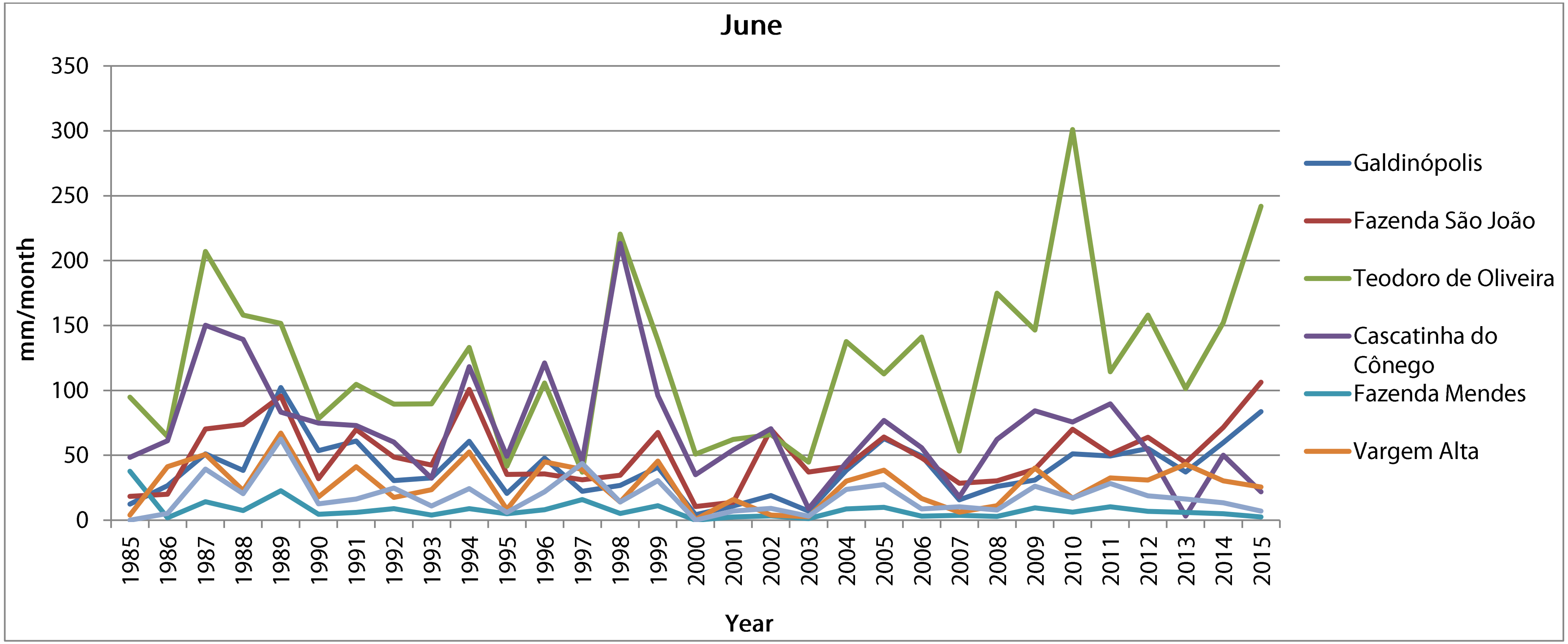

Figure 7: June precipitation behaviour

Source: Own preparation based on the results from R.

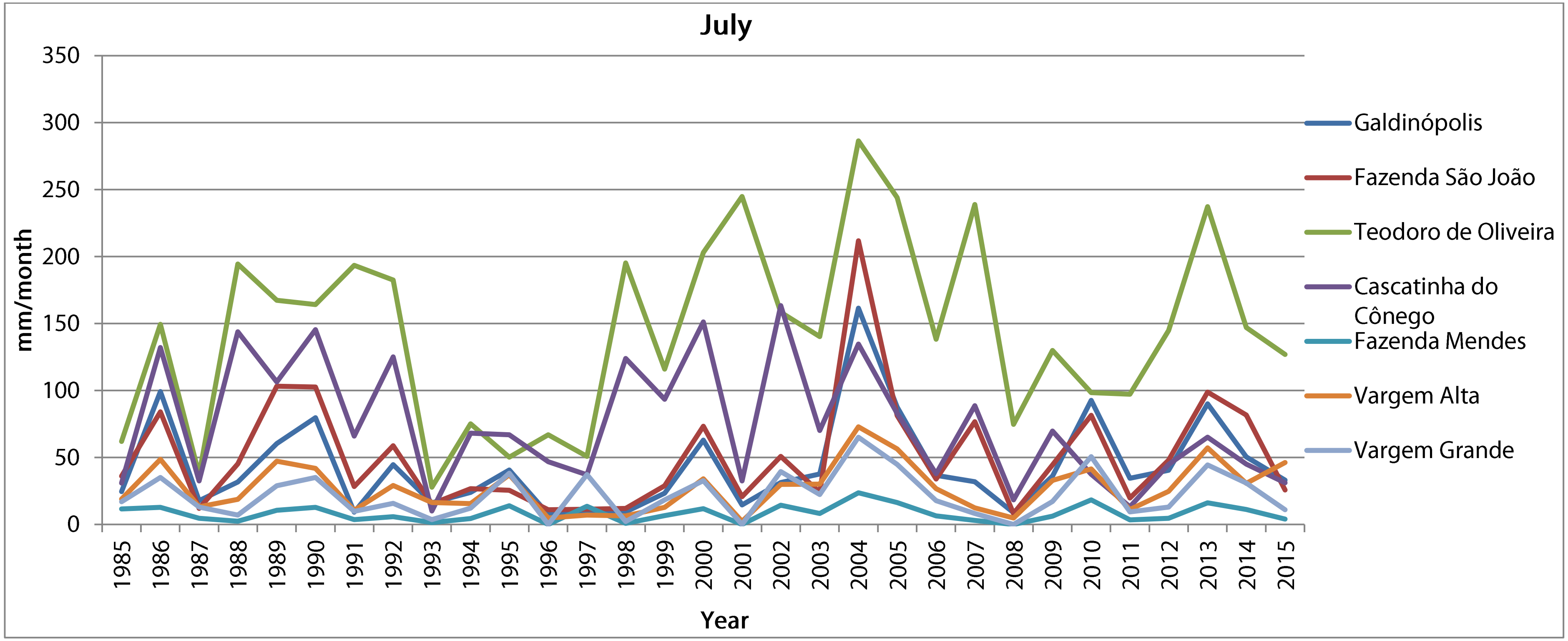

Figure 8: July precipitation behaviour

Source: Own preparation based on the results from R.

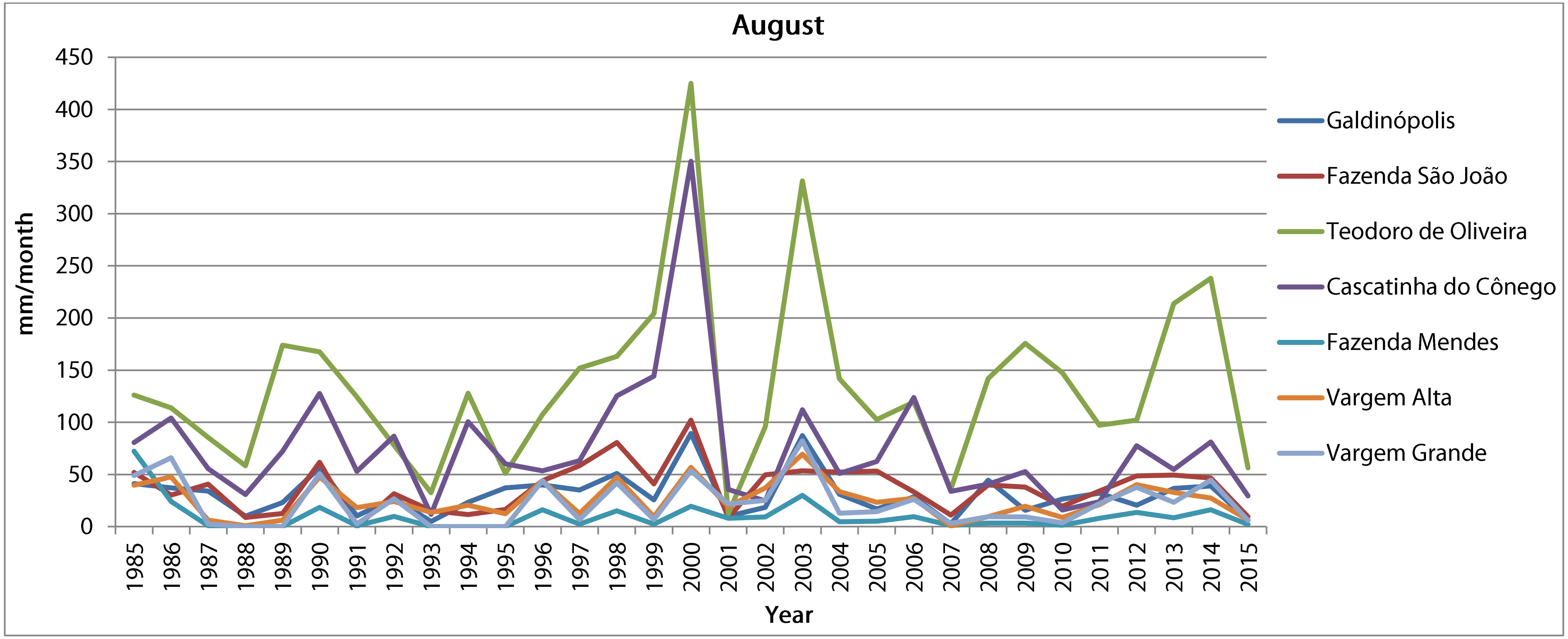

Figure 9: August precipitation behaviour

Source: Own preparation based on the results from R.

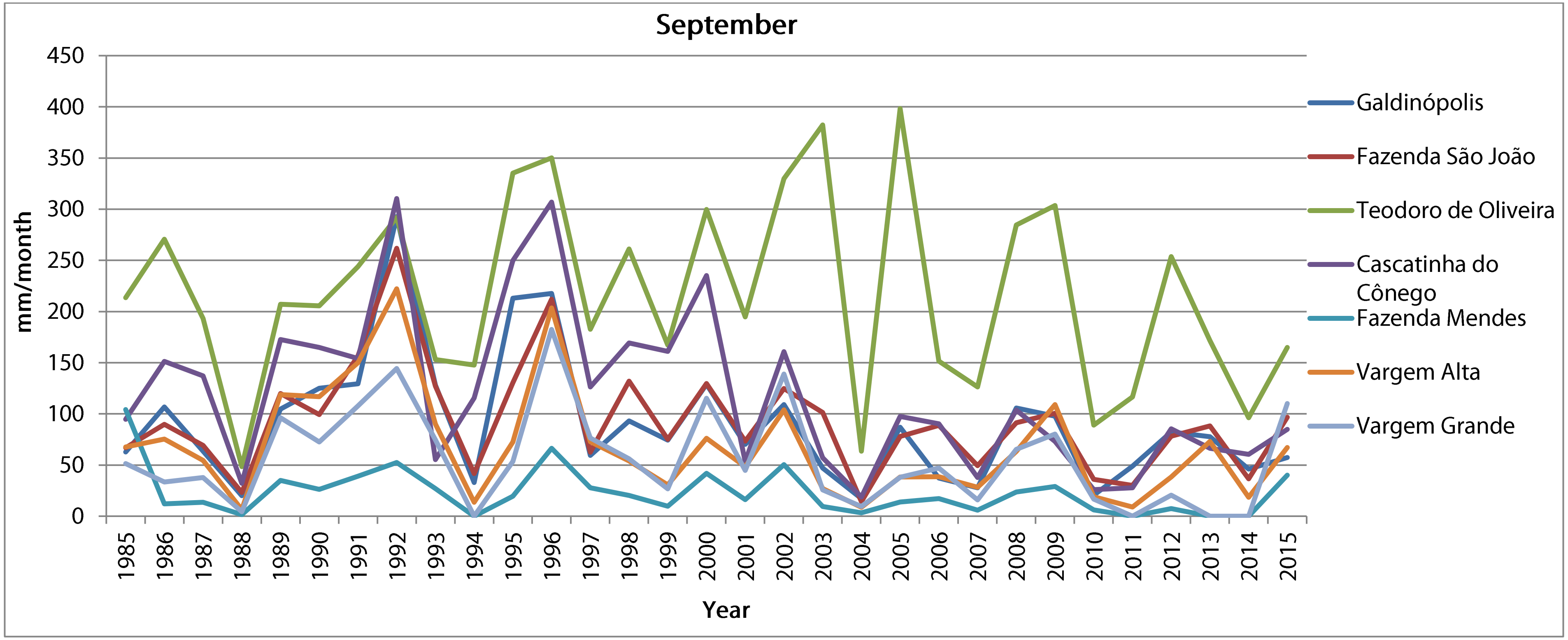

Figure 10: September precipitation behaviour

Source: Own preparation based on the results from R.

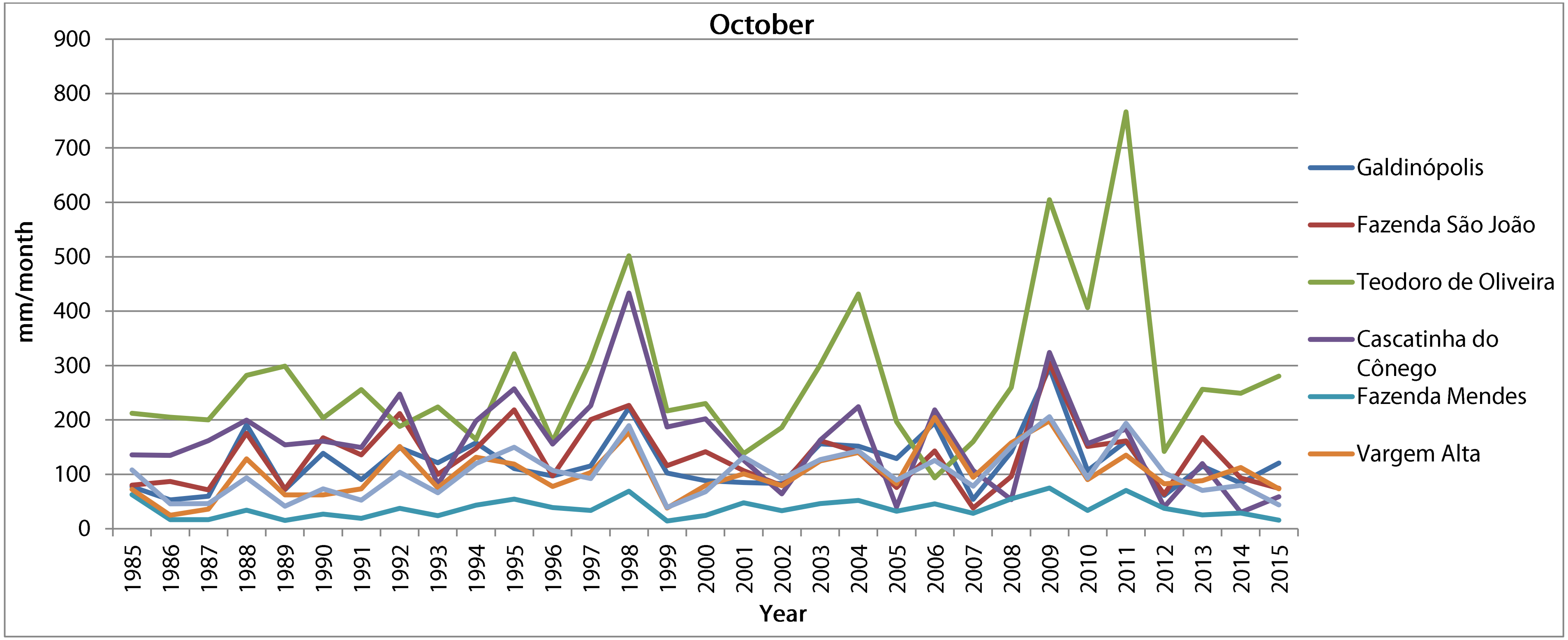

Figure 11: October precipitation behaviour

Source: Own preparation based on the results from R.

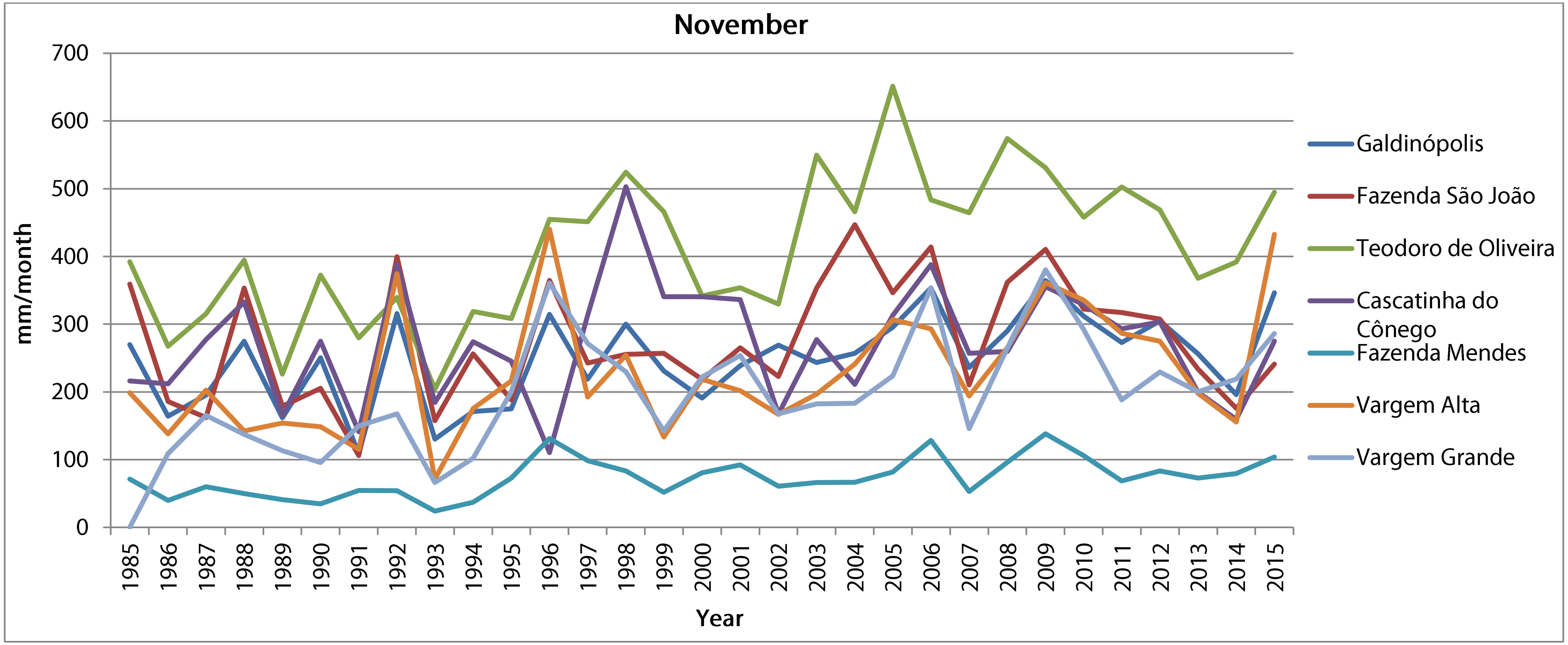

Figure 12: November precipitation behaviour

Source: Own preparation based on the results from R.

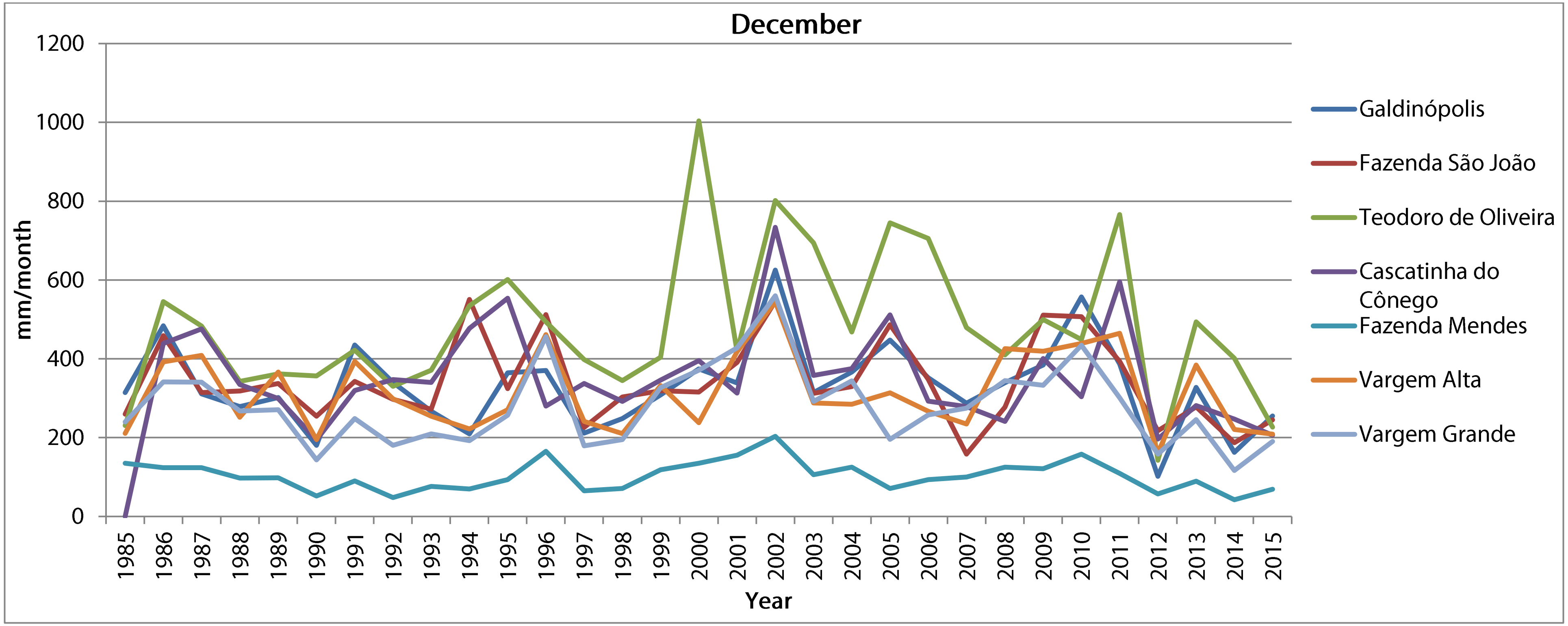

Figure 13: December precipitation behaviour

Source: Own preparation based on the results from R.

Due to the lack of enough precipitation stations within the Grande River sub basin, the data were complemented using the high resolution grid daily product (0.05°) from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Climate Hazards Group InfraRed Precipitation with Station data, 2017). Nineteen points of data were added, one for every cell covering the sub basin (see Figure 14), the values from the cells were extracted to these points to be used afterwards as input for the model.

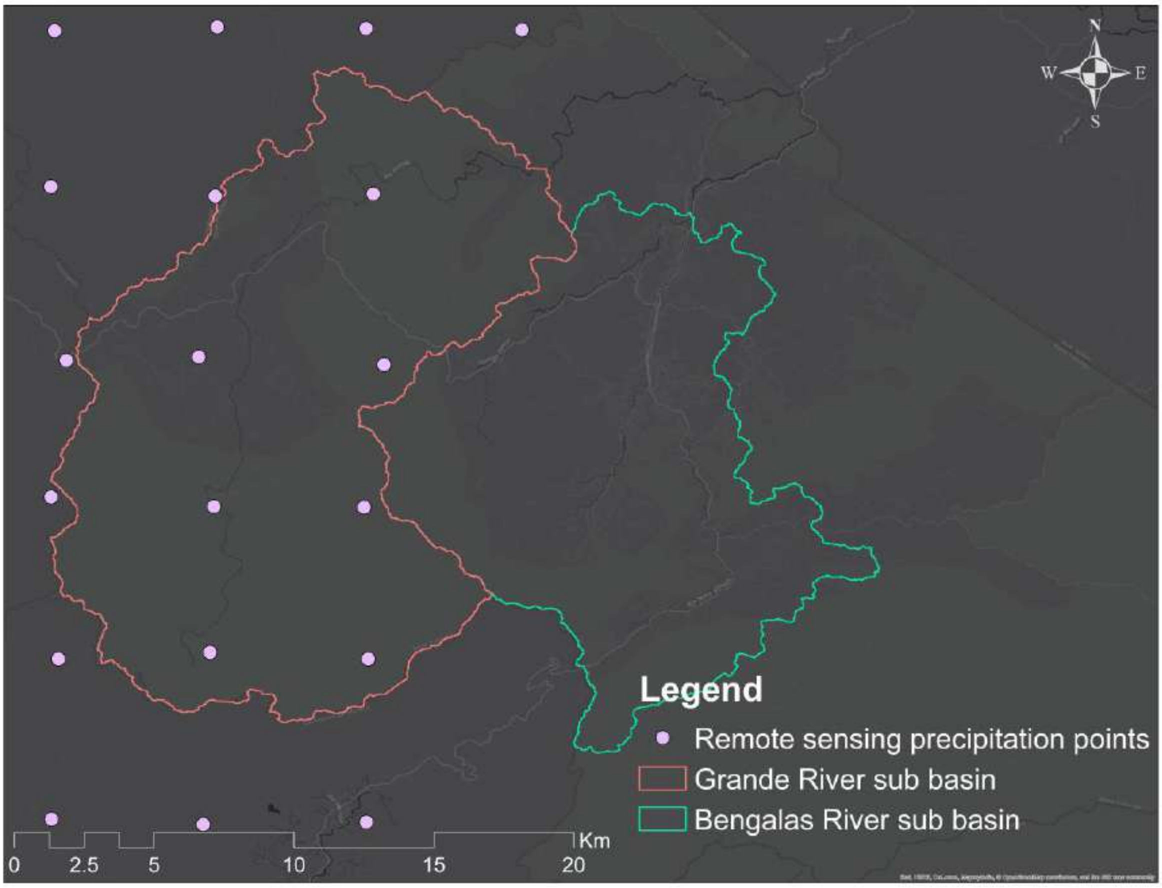

Figure 14: Remote sensing precipitation reference points (Source: Own preparation through ArcGIS. Data sources: Own sub basins delineation & precipitation reference points)

References

Agência Nacional de Águas (ANA), *Hidroweb - Sistema de Informações Hidrológicas*, available at: http://hidroweb.ana.gov.br/default.asp (accessed 1 May 2017).

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (2017), "CHG Data CHIRPS. Index CHIRPS 2.0 global-daily tifs p05", available at: ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/global_daily/tifs/p05/.

Annex 2: Temperature data preparation

The temperature data were acquired from the Meteorological Database for Education and Research (BDMEP – INMET in portugues). The density regarding temperature stations with available data in the area is very low, only one station with available data is located within the study area (Nova Friburgo station) and it registers data only since April,2016. A second station located around 47 Km from the Nova Friburgo Stations, outside the boundaries (Cordeira station) registers data since 1971, covering the time period studied (see Figure 1).

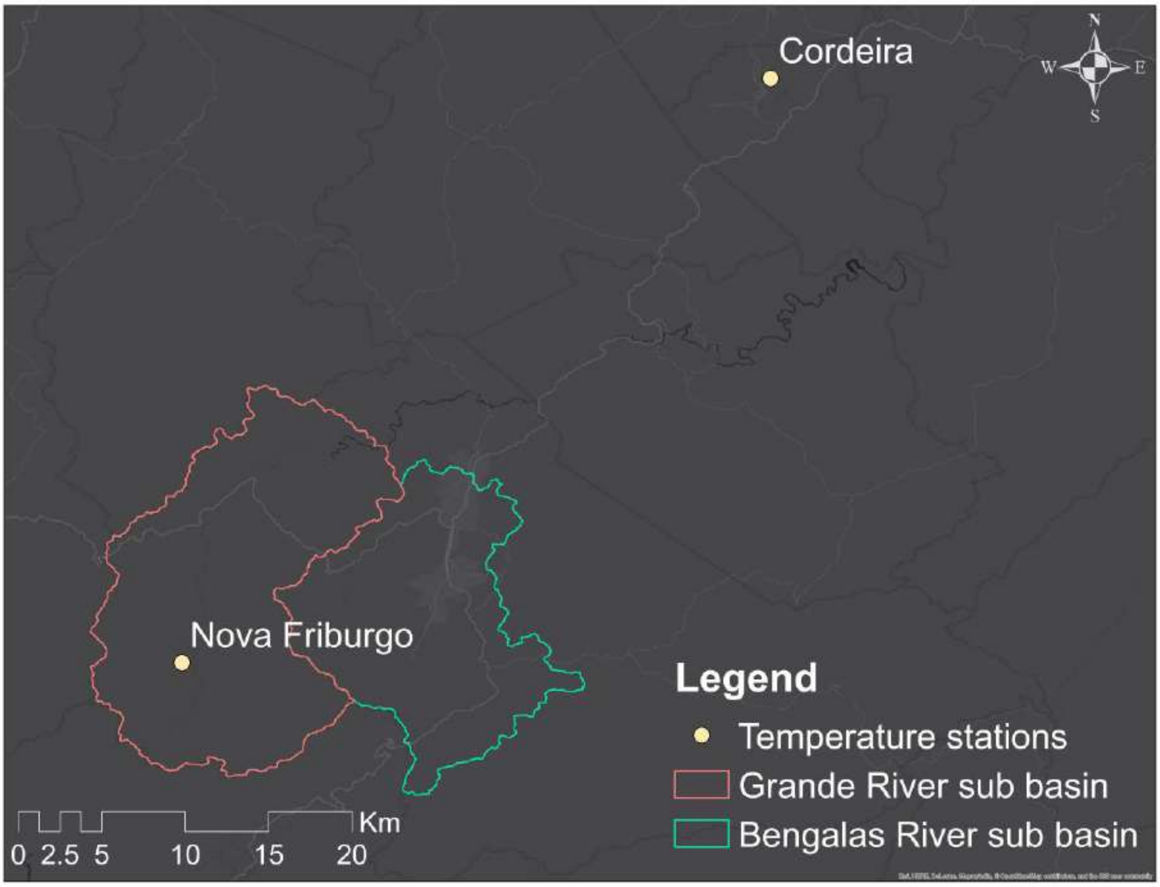

Figure 1: Temperature stations (Source: Own preparation through ArcGIS. Data sources: Own sub basin delineation & temperature stations based on coordinates)

In a first step, the missing data from the Cordeira station were completed using the average of the previous two days and the two following. For long period with missing values was used the average of the temperature of the same day during years with similar temperature behaviour. For instance, to complete the data for January 2004 the average of the days in January in the years 1987, 1992, 1998, 1999, 2000, 2004 and 2013 were used (Figure 2).

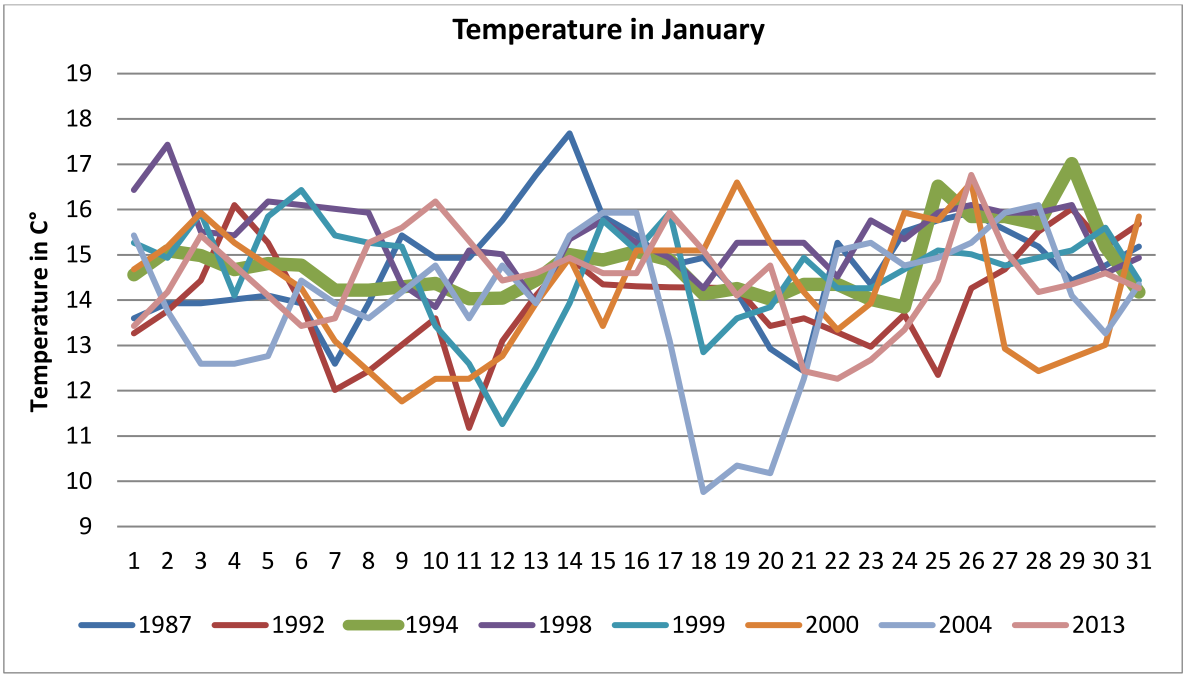

Figure 2: Temperature behaviour in Cordeira station during January in 1987, 1992, 1998, 1999, 2000, 2004, and 2013. (Source: Own preparation based on the data from (Instituto Nacional de Meteorologia))

Hereinafter, the existing data from both stations that coincide during the same period were analysed to extrapolate the data from the Nova Friburgo station (year 2016). The maximum and minimum temperatures were arranged by lowest to highest value and a linear regression was applied (Figure 3 and Figure 4)

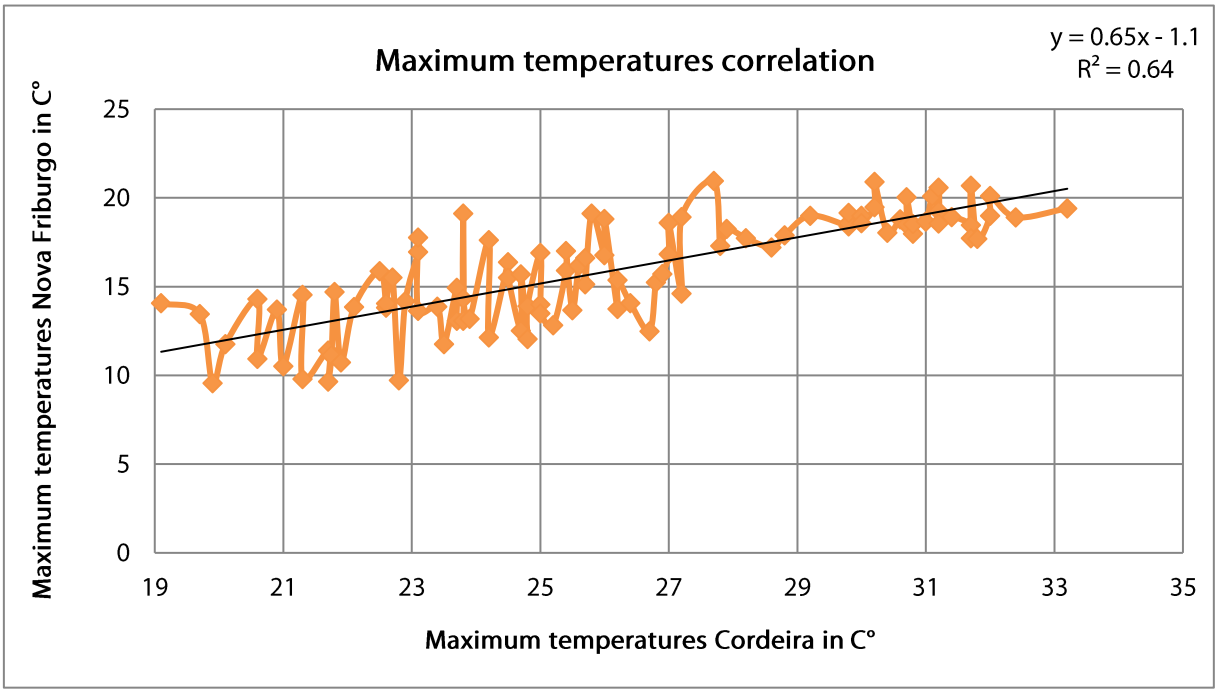

Figure 3: Maximum temperatures correlation (Source: Own preparation)

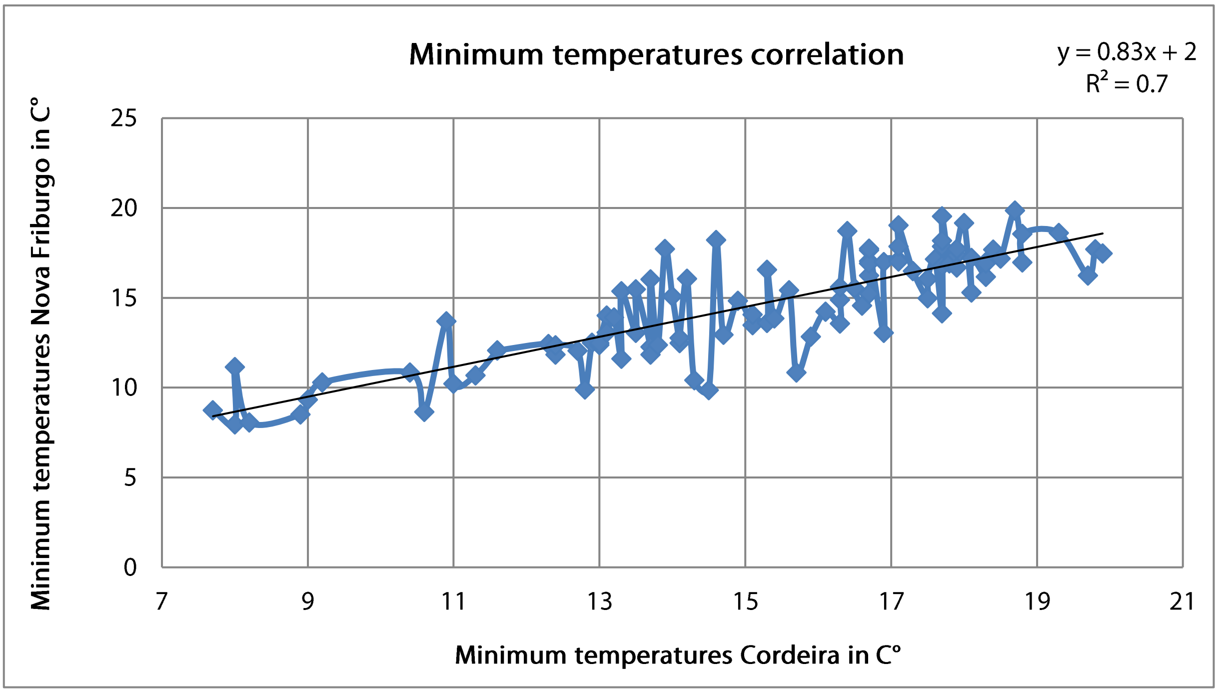

Figure 4: Minimum temperature correlation (Source: Own preparation)

With those results the missing data were completed and used as input for the model.

References

Instituto Nacional de Meteorologia (INMET), "Banco de Dados Meteorológicos para Ensino e Pesquisa (BDMEP)", available at: http://www.inmet.gov.br/projetos/rede/pesquisa/ (accessed 23 June 2017).

Annex 1: Water balance

The discharge data was acquired from two stations, Ponte Estrada Dona Mariana (INEA 58825000) and Conselheiro Paulino (INEA 58826000), which correspond to the discharges of the Grande river and the Bengalas River (see Figure 1). Daily measurements are available from 1985 to 2015 at both stations, though some data blanks exist (Table 1).

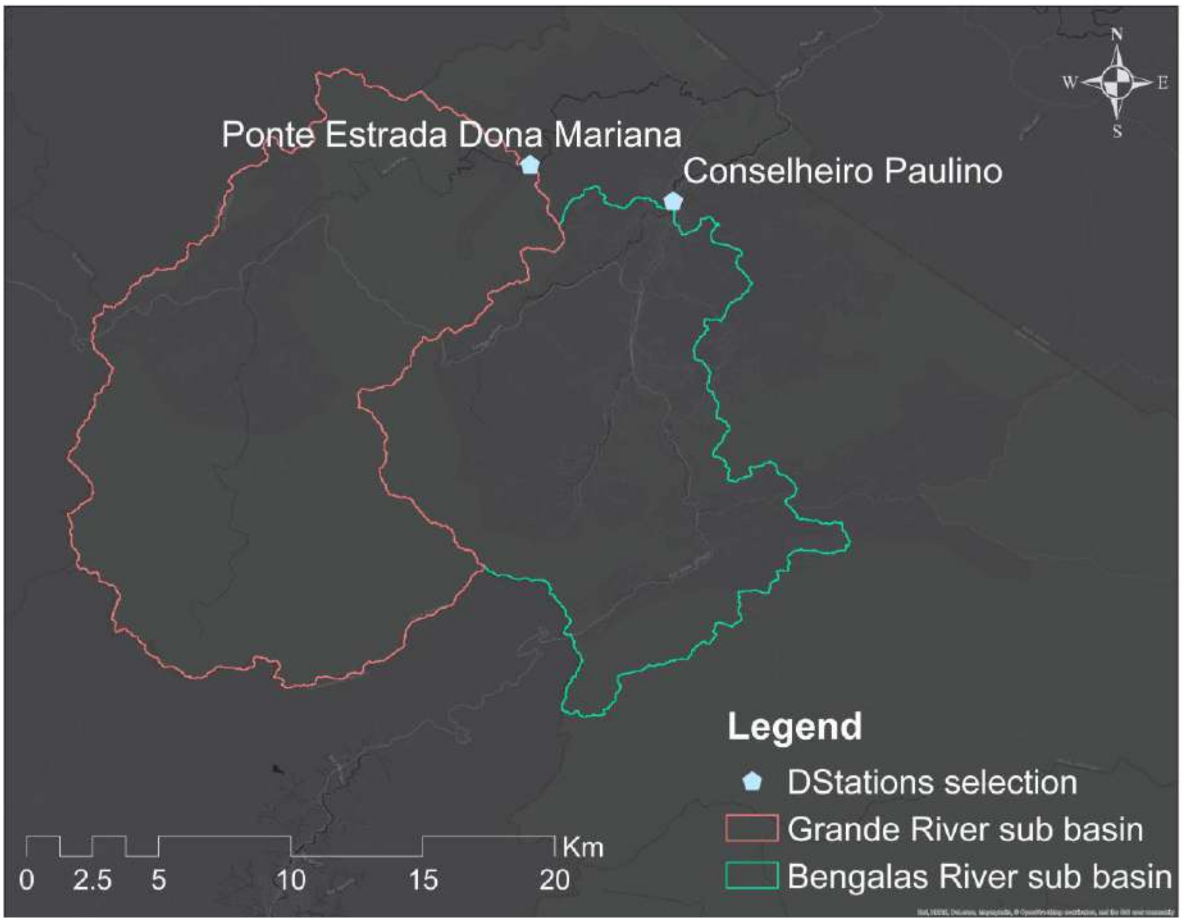

Figure 1: Discharge measurement points (Source: Own preparation through ArcGIS. Data sources: Own sub basins and rivers delineation & (Agência Nacional de Águas))

Table 1: Dates without information

Ponte Estrada Dona Mariana	Conselheiro Paulino
05.01.2007	08.11.2006
28.12.2009 - 14.02.2010	04.01.2007
10.08.2010 -16.08.2010	06.10.2007
22.08.2010 08.09.2010	13.10.2007 - 16.10.2007
12.09.2010 - 30.09.2010	27.11.2009 - 13.10.2010
12.01.2011 - 19.05.2011	
03.08.2014 - 12.09.2015	
29.04.2016 -30.04.2016	

Source: Own preparation based on the information provided by the HidroWeb (Agência Nacional de Águas)

Water treated

The data regarding the treated water for the city of Nova Friburgo was acquired from the National System of Sanitation Information (SNIS in Portuguese) and it is available only from 1999 to 2015 (Table 2). The data demonstrate that the volume of water treated for the city (AG006 - Volume de água produzido, name given by the SNIS in its report) is decreasing every year. That could be due the improvement of the water supply system. To estimate the treated water for the city from 1985 to 1998, a linear regression was used to extrapolate the data (see Table 2 and Figure 2).

Table 2: Total water produced per year

year	Volume of treated water (back projected)	year	Volume of treated water (given)
	(1.000 m^3/year)		(1.000 m^3/year)
1985	27.149	**1999**	20.871
1986	26.722	**2000**	22.118
1987	26.295	**2001**	20.204
1988	25.868	**2002**	20.407
1989	25.441	**2003**	20.452
1990	25.015	**2004**	20.407
1991	24.588	**2005**	17.971
1992	24.161	**2006**	17.314
1993	23.734	**2007**	16.208

1994	23.307	**2008**	15.404
1995	22.880	**2009**	15.604
1996	22.453	**2010**	15.968
1997	22.027	**2011**	15.954
1998	21.600	**2012**	15.612
		2013	15.874
		2014	15.889
		2015	15.540

Source: Data provided by (Ministério das Cidades) and linear regression results

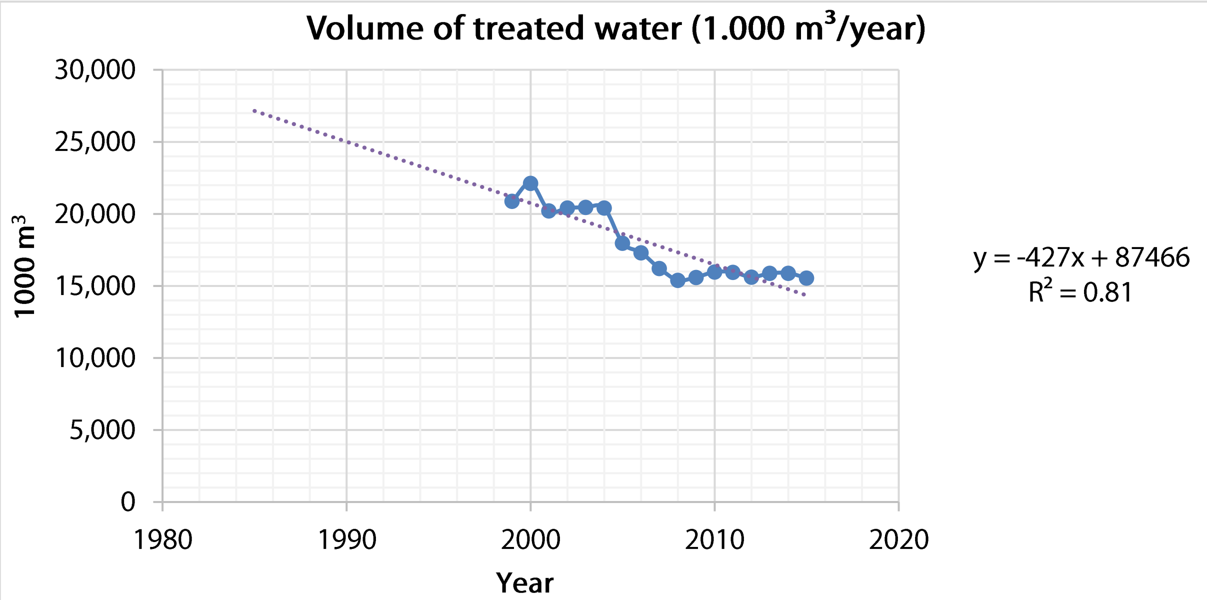

Figure 2: Linear regression of treated water (Source: Own preparation based on the data from (Ministério das Cidades))

Points of water extraction

In order to supply water to the city of Nova Friburgo, the water supply company extracts water from 15 different points. Four of these points are within the Grande river sub basin (Rio Grande de Cima, Santa Cruz, Jason and Santana), being Grande de Cima the most important, it supplies approximately 45% of the water demanded by the city. Three are within the Bengalas river sub basin (Debossan, Caledônia and Cascatinha I) and seven are located outside the boundaries (Curuzu, Bela Vista, Tapera, Amparo, Boa Esperança, Santa Margarida, Bocaina and Riograndina).

Due to a lack of information available regarding the start of the operation of each plant, it was considered they supply and cover the same percentage of water to the city since 1985 to the present.

In order to calibrate the model, the volumes of water abstracted from those points were added to the discharge measurements, so the final data to calibrate the model would be represented by the follow formula:

$$Q_{Grande} = Q_{discharge} + Abs_{Grande\ do\ Cima} + Abs_{Santa\ Cruz} + Abs_{Jason+} Abs_{Santana}$$

Where:

Q_{Grande} is the total river flow considered for the calibration

$Q_{discharge}$ is the flow of the river measured

$Abs_{Grande\ do\ Cima}$ is the volume abstracted by the water treatment plant Grande do Cima

$Abs_{Santa\ Cruz}$ is the volume abstracted by the water treatment plant Santa Cruz

Abs_{Jason} is the volume abstracted by the water treatment plant Jason

$Abs_{Santana}$ is the volume abstracted by the water treatment plant Santana

In the case of the Bengalas River, the measured discharge is the sum of the natural river discharge plus the imported water:

$$Q_{Bengalas} = Q_{natural\ flow} + Imported\ Water$$

$$\begin{aligned} Imported\ water &= (Abs_{Curuzu} + Abs_{Bela\ Vista} + Abs_{Tapera} + Abs_{Amparo} + Abs_{Boa\ Esperança} \\ &+ Abs_{Santa\ Margarida} + Abs_{Bocaina}) \\ &+ (Abstracted\ water\ in\ Grande\ river\ basin) - WF\ Blue\ domestic \end{aligned}$$

Where

$Q_{Bengalas}$ is the measured flow

$Q_{natural\ flow}$ is the river flow without further discharges

Abs is the volume of water abstracted by every Water Treatment Plant

WF Blue domestic, refers to the Water Footprint of the domestic sector

The imported water refers to the volume of water that is abstracted from other basins but it is used, consumed and discharged in the Bengalas river sub basin. It included the abstracted water in the Grande river and the water abstracted by Curuzu, Bela Vista, Tapera, Amparo, Boa Esperança, Santa Margarida, Bocaina water treatment plants , it was not include Riograndina because it supplies water to an small zone in the south area of the city, beyond the discharge measurement point.

From this volume of water abstracted, there is a fraction that is consumed, the rest is discharged to the Bengalas River. The volume consumed is considered as a Blue Water Footprint and was extracted from the imported water because it was consumed.

The water footprint data was acquired from the Water Footprint Network database, where it is reported a Blue Water Footprint (BWF) of 6.86 m^3/year per habitant in Brazil (Mekonnen and Hoekstra, 2011), and multiplying it by the population in Nova Friburgo the BWF of the domestic sector can be calculated. There was no information about the other economic sectors (industrial, commercial, public, etc.), for that reason those were excluded.

In order to calibrate the model, the imported water was considered as a *Point Source Discharge* from the city.

References

Agência Nacional de Águas (ANA), *Hidroweb - Sistema de Informações Hidrológicas*, available at: http://hidroweb.ana.gov.br/default.asp (accessed 1 May 2017).

Mekonnen, M.M. and Hoekstra, A.Y. (2011), *National water footprint accounts: The green, blue and grey water footprint of production and consumption: Value of Water Research Report Series No. 50, UNESCO-IHE.*

Ministério das Cidades, "Sistema Nacional de Informações sobre Saneamento. SNIS - Série Histórica", available at: http://app.cidades.gov.br/serieHistorica/ (accessed 25 June 2017).

Annex 4: Land Use Maps preparation

The land use maps were prepared using eCognition Developer, an object – based image analysis tool (Trimble Geospatial). Three maps were prepared using imagery from Landsat 5-4 TM for the years 1996 and 2005, and Landsat 8 for the year 2015.

A multiresolution segmentation method was used to perform the land use characterisation, which merges spatially connected pixels with similar spectral characteristics into objects. To obtain the segmentation maps were used: a scale parameter of 100, it "determines the maximum standard deviation of homogeneity regarding the weighted image layers", a shape of 0.1 that "define the weight the shape criterion should have when segmenting the image. The higher its value, the lower the influence of colour on the segmentation process", and a compactness of 0.5 that "define the weight of the compactness criterion. The higher the value, the more compact image object may be".

The Figure 1 shows an example of the segmentations results.

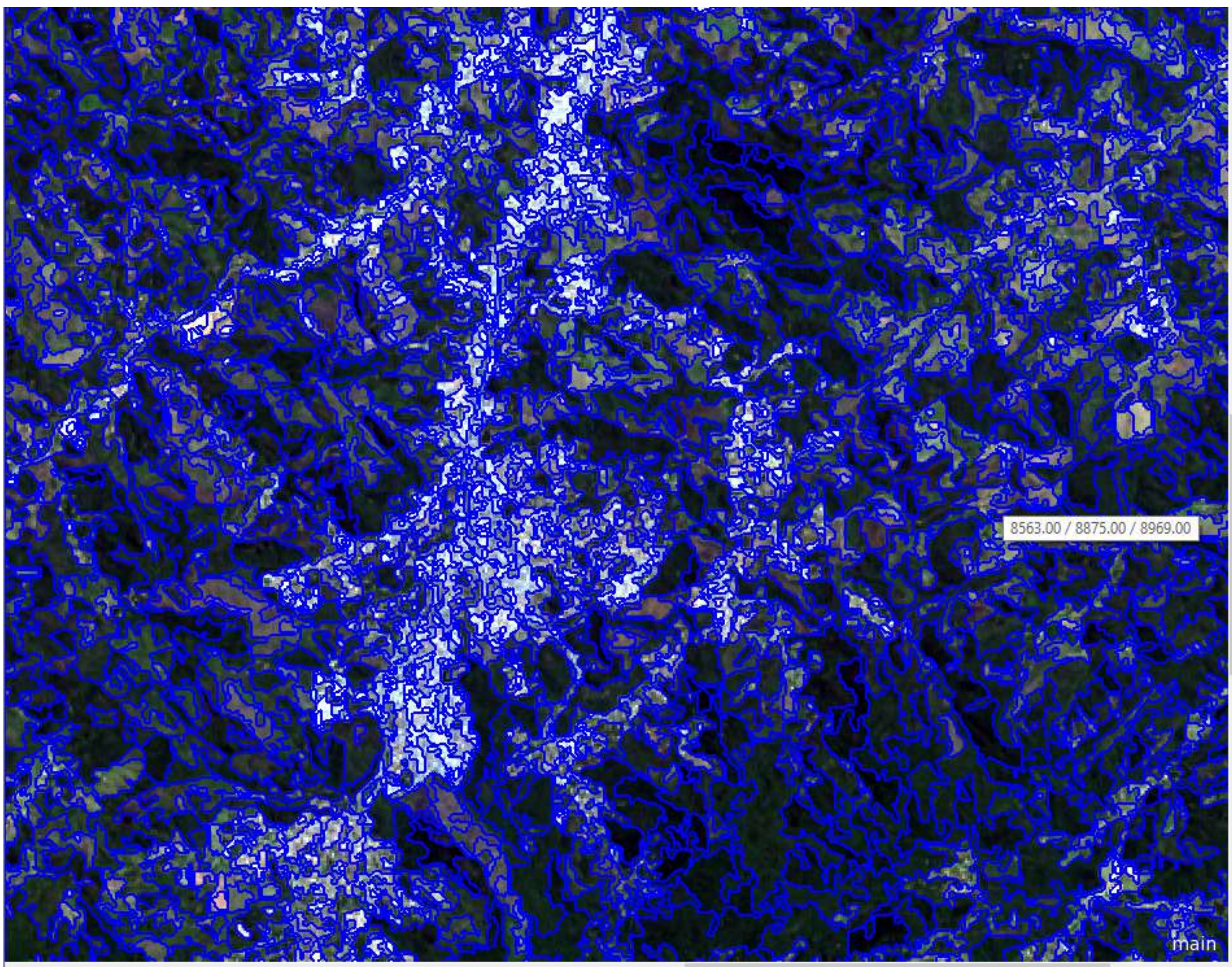

Figure 1: Segmentation results for 2005 (Source: Own preparation through eCognition)

Subsequently, five land uses to take samples were identified: urban settlements, forest area, agriculture activity, pasture area and bare soil (Figure 2).

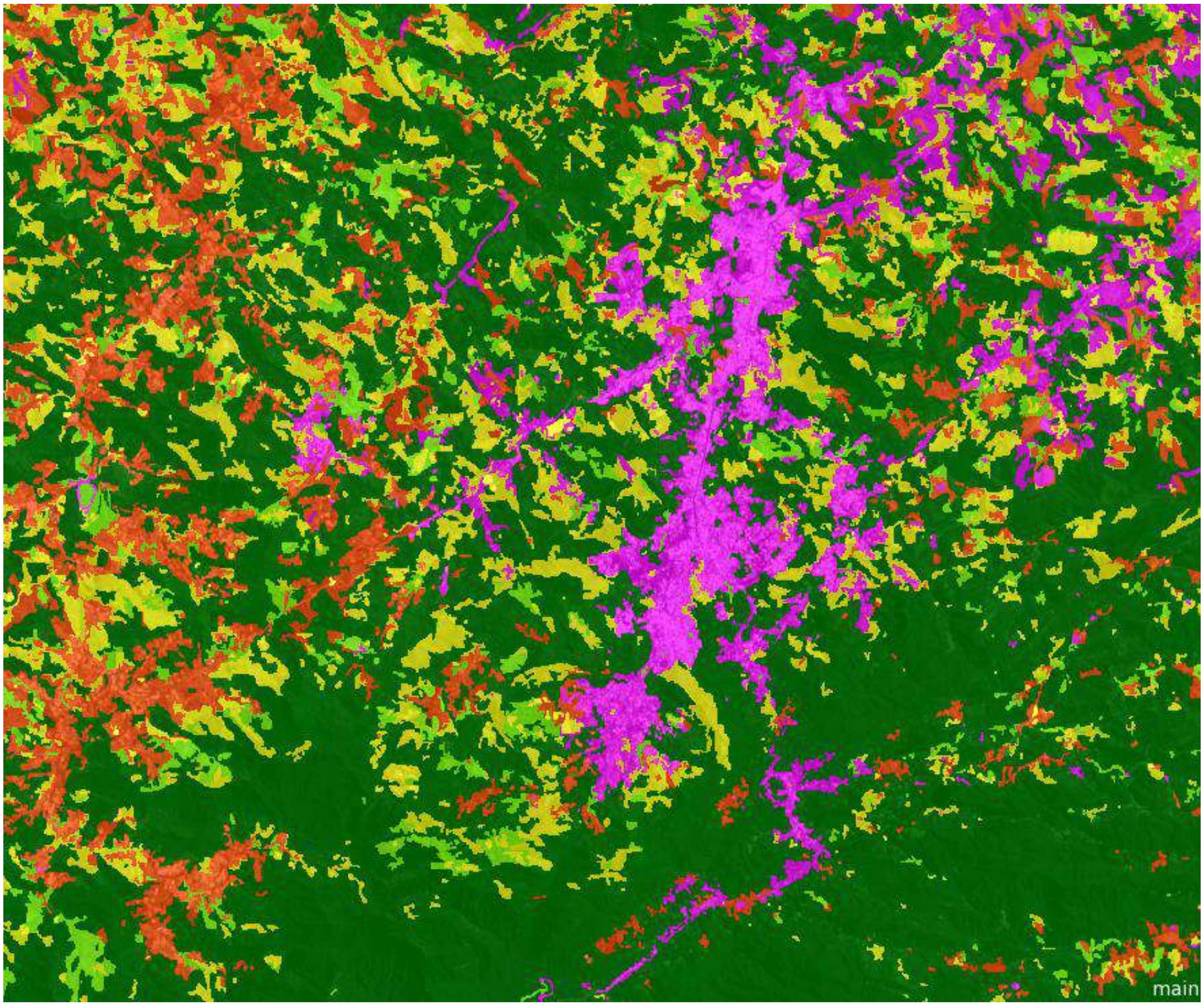

Figure 2: Land Use classification. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover (Source: Own preparation through eCognition).

The Error Matrix based on the Test and Training Area (TTA) was used to analyse the accuracy of the maps, it shows the overall accuracy and the Kappa Index of Agreement (KIA) complemented by five indexes of accuracy. Hereunder are the maps and results for the three years analysed.

Land Use 1996

For the year 1996 the overall accuracy was the 85% and the Kappa Index of Agreement (KIA) 65% (Table 1). The land use with less error was the Forest and the one with more errors was the Agriculture, which was often confused with pasture; the bare soil also had a high error considering that it was confused with pasture and agriculture in several occasions (Table 2).

Table 1: Error Indexes LU 1996

	Urban Area	Forest	Pasture	Agriculture	Bare Soil
Producer	67%	96%	60%	50%	40%
User	65%	96%	45%	51%	67%
Hellden	66%	96%	52%	51%	50%
Short	49%	92%	35%	34%	33%
KIA Per Class	65%	86%	56%	46%	37%
Overall Accuracy	85%				
KIA	65%				

Source: Accuracy analysis eCognition Developer 9

Table 2: Error Matrix LU 1996

	Urban Area	Forest	Pasture	Agriculture	Bare Soil
Urban Area	67%	1%	3%	1%	9%
Forest	18%	96%	14%	13%	5%
Pasture	6%	1%	60%	29%	25%
Agriculture	5%	1%	15%	50%	22%
Bare Soil	4%	0%	7%	6%	40%
unclassified	0%	0%	0%	0%	0%

Source: Accuracy analysis eCognition Developer 9

Figure 3 show the satellite images and the land use map resulted from the imagery processing, which in overall represents the land use of the analysed sub basins. Is evident that the land use varies within the region and is characterised by area with many small section devoted to agriculture and pasture among areas covered by forest, this makes the land use classification more complex regarding the pixels spectral characteristics within the objects.

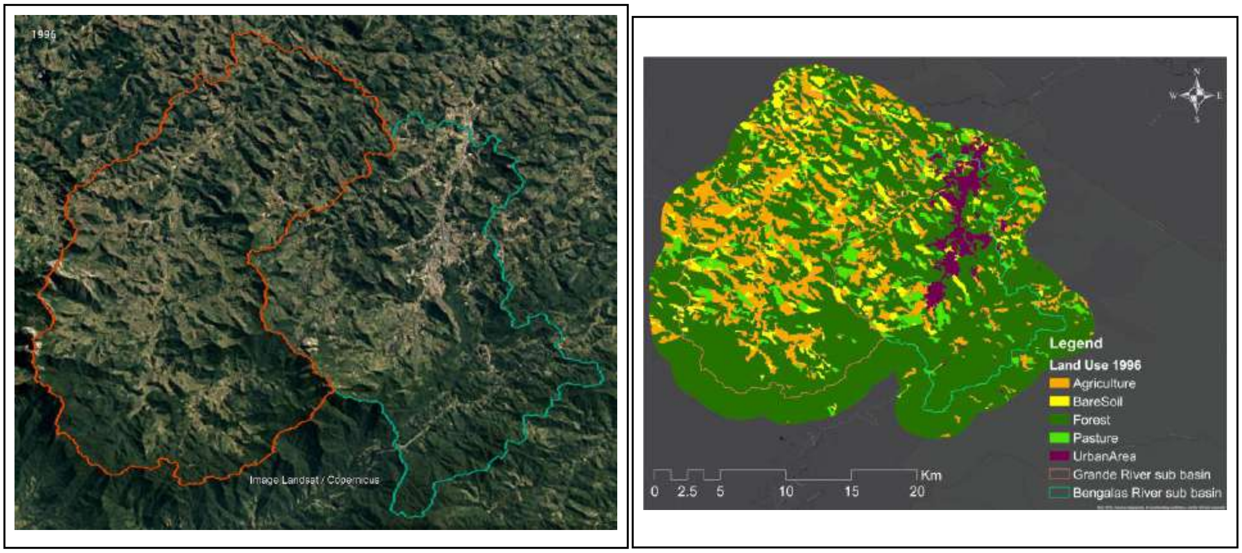

Figure 3: Left: Satellite image. Right: land use map the study area, 1996. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover. Source: Own preparation through Google Earth Pro, eCognition & ArcGIS. Data sources: Own basin delineation, Landsat Copernicus, 1996 & Landsat 4 - 5 TM C1 Level 1, 1996.

Land Use 2005

For the year 2005 the overall accuracy was 91% and the KIA was 73% (Table 3). The land use with less error was the forest and the one with the highest error was the pasture that was often confused with agriculture (Table 4).

Table 3: Error Indexes LU 2005

	Forest	Agriculture	Urban Area	Pasture	Bare Soil
Producer	97%	71%	83%	32%	65%
User	98%	64%	82%	43%	52%
Hellden	98%	67%	83%	37%	58%
Short	95%	50%	70%	23%	41%
KIA Per Class	86%	68%	83%	30%	64%
Overall Accuracy	91%				
KIA	73%				

Source: Accuracy analysis eCognition Developer 9

Table 4: Error Matrix LU 2005

Class	Forest	Agriculture	Urban Area	Pasture	Bare Soil
Forest	97%	7%	1%	15%	10%
Agriculture	2%	71%	4%	42%	15%
Urban Area	0%	1%	83%	5%	4%
Pasture	0%	13%	4%	32%	6%
Bare Soil	0%	9%	9%	7%	66%
unclassified	0%	0%	0%	0%	0%

Source: Accuracy analysis eCognition Developer 9

The map resulted of the imagery processing comparing to the satellite imagery (Figure 4) in overall represented the land use configuration of the area. Similar to the map from 1996, the land use variability increased the complexity of the land use classification.

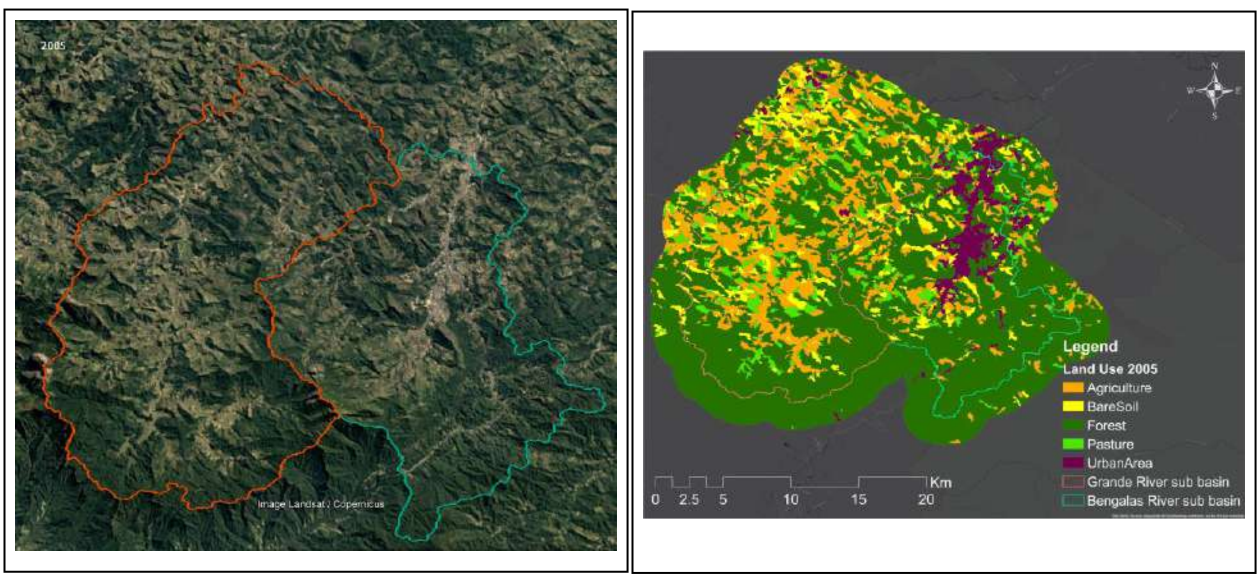

Figure 4: Left: Satellite image. Right: land use map the study area, 2005. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover. Data sources: Own basin delineation, Landsat Copernicus, 2005 & Landsat 4 - 5 TM C1 Level 1, 2005.

Land Use 2015

The overall accuracy for the year 2015 was the 91% and the KIA was 78% (Table 5). The land use with better results was the Forest (97%) and the land use with more error was the pasture that was often confused with agriculture (Table 6).

Table 5: Error Indexes LU 2015

	Forest	Agriculture	Urban Area	Pasture	Bare Soil
Producer	97%	74%	88%	46%	76%
User	99%	78%	86%	54%	50%
Hellden	98%	76%	87%	49%	61%
Short	96%	61%	77%	33%	43%
KIA Per Class	88%	71%	88%	44%	74%
Overall Accuracy	91%				
KIA	78%				

Source: Accuracy analysis eCognition Developer 9

Table 6: Error Matrix LU 2015

Class	Forest	Agriculture	Urban Area	Pasture	Bare Soil
Forest	97%	4%	4%	1%	8%
Agriculture	0%	74%	2%	29%	10%
Urban Area	0%	2%	88%	5%	3%
Pasture	1%	6%	2%	46%	3%
Bare Soil	1%	14%	4%	19%	76%
unclassified	0%	0%	0%	0%	0%

Source: Accuracy analysis eCognition Developer 9

Figure 5 shows the satellite imagery for the year 2015 and the map resulting of the imagery processing. The imagery for this year had a better quality that affects the achievement of a better accuracy.

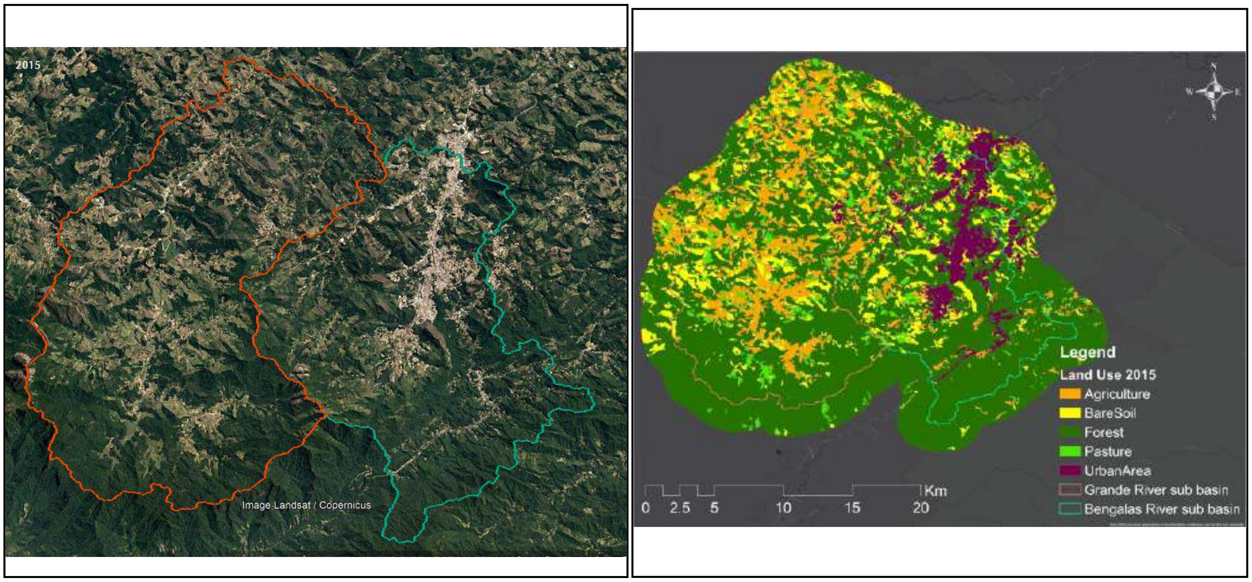

Figure 5: Left: Satellite image. Right: land use map the study area, 2015. Dark green: forest land cover, light green: pasture land cover, yellow: bare soil land cover, orange: agriculture land cover, purple: urban land cover.. Data sources: Own basin delineation, Landsat Copernicus, 2015 & L8 OLI/TIRS, 2015

To analyse the hydrological reaction to land use changes, the land changes were analysed in a sub basin level using as a reference the basin delineation of each sub basin. In the case of the Grande River basin eight sub basins were subjected of significant changes, the Bengalas River basin presented five sub basins with significant changes to analyse (Figure 6, Table 7 and Table 8).

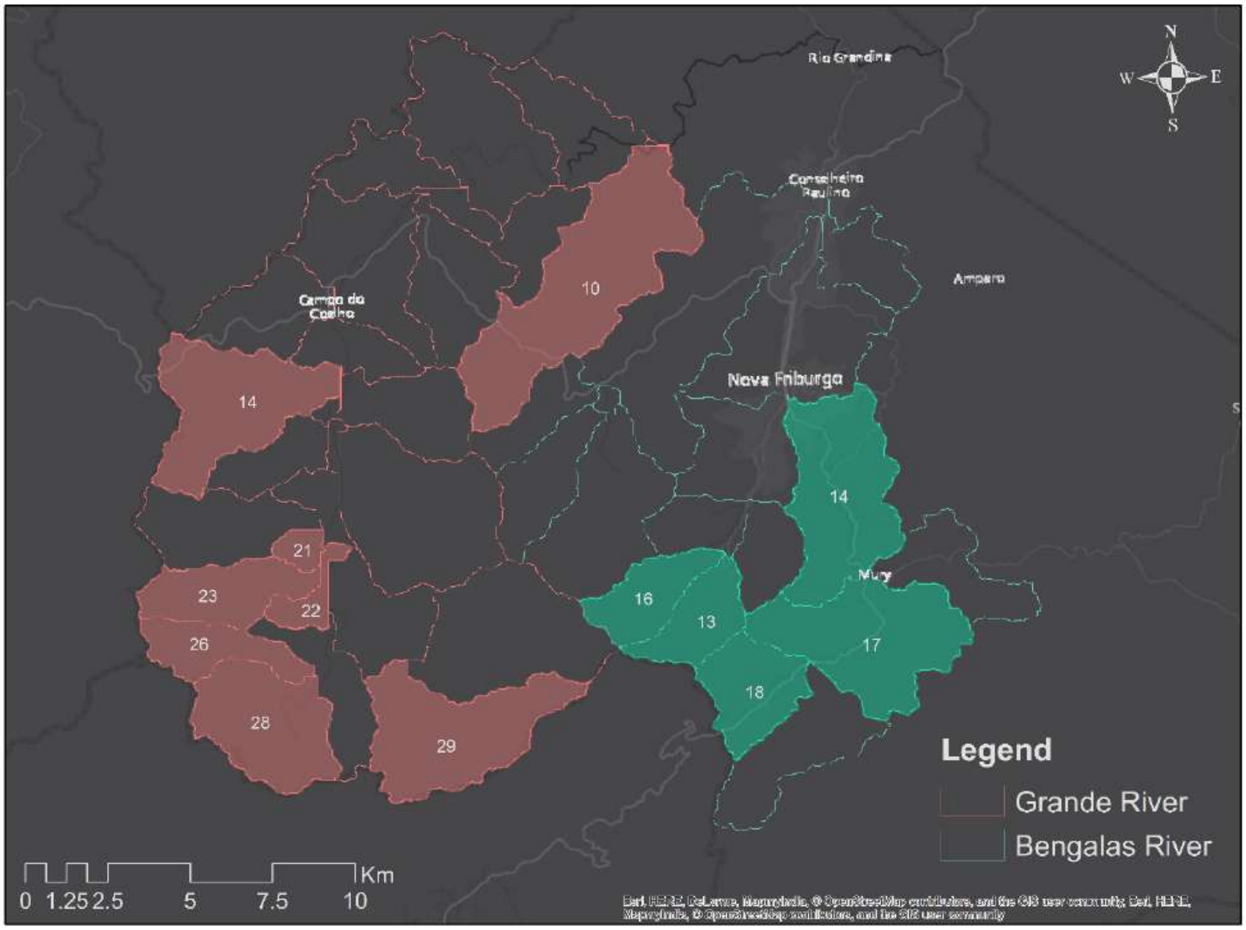

Figure 6: Micro basins analysed. Source: Own preparation through ArcGIS

Table 7: Grande River sub basins analysed

Year	1985 - 1996	1996 - 2005	2006 - 2015
	Area (km²)		
Sub basin 10			
Agricultural Land-Generic --> AGRL	5.09	6.38	3.64
Southwestern US (Arid) Range --> SWRN	2.98	2.85	3.72
Forest-Evergreen --> FRSE	14.10	13.16	13.06
Pasture --> PAST	2.00	1.48	1.89
Residential --> URBN	0.00	0.29	1.85
Sub basin 14			
Agricultural Land-Generic --> AGRL	5.81	5.93	3.34
Southwestern US (Arid) Range --> SWRN	1.43	1.55	4.21

Forest-Evergreen --> FRSE	6.52	5.95	5.56
Pasture --> PAST	1.08	1.41	1.63
Residential --> URBN	0.00	0.00	0.10
Sub basin 21			
Agricultural Land-Generic --> AGRL	0.80	0.41	0.73
Southwestern US (Arid) Range --> SWRN	0.20	0.38	0.16
Forest-Evergreen --> FRSE	0.09	0.05	0.24
Pasture --> PAST	0.40	0.64	0.35
Sub basin 22			
Agricultural Land-Generic --> AGRL	0.85	1.22	0.99
Southwestern US (Arid) Range --> SWRN	0.08	0.00	0.20
Forest-Evergreen --> FRSE	1.32	0.95	1.08
Pasture --> PAST	0.06	0.13	0.03
Sub basin 23			
Agricultural Land-Generic --> AGRL	1.82	2.27	1.33
Southwestern US (Arid) Range --> SWRN	0.78	0.48	0.85
Forest-Evergreen --> FRSE	4.38	4.16	4.93
Pasture --> PAST	0.81	0.88	0.68
Sub basin 26			
Agricultural Land-Generic --> AGRL	0.26	0.32	0.05
Southwestern US (Arid) Range --> SWRN	0.21	0.09	0.39
Forest-Evergreen --> FRSE	5.35	5.40	5.31
Pasture --> PAST	0.00	0.01	0.06
Sub basin 28			
Agricultural Land-Generic --> AGRL	0.27	0.01	0.00
Southwestern US (Arid) Range --> SWRN	0.07	0.06	0.49
Forest-Evergreen --> FRSE	12.03	11.47	11.39
Pasture --> PAST	0.00	0.82	0.49
Sub basin 29			

Agricultural Land-Generic --> AGRL	1.28	1.51	1.23
Southwestern US (Arid) Range --> SWRN	0.43	0.50	0.41
Forest-Evergreen --> FRSE	13.36	13.15	13.56
Pasture --> PAST	0.29	0.19	0.15

Source: Own preparation

Table 8: Bengalas River sub basins analysed

Year	1985 - 1996	1996 - 2005	2006 - 2015
	Area (km^2)		
Sub basin 13			
Agricultural Land-Generic --> AGRL	0.83	0.27	0.33
Southwestern US (Arid) Range --> SWRN	0.28	0.73	1.01
Forest-Evergreen --> FRSE	3.79	4.54	4.07
Pasture --> PAST	0.84	0.30	0.17
Residential --> URBN	0.24	0.14	0.39
Sub basin 14			
Agricultural Land-Generic --> AGRL	1.04	1.01	0.43
Southwestern US (Arid) Range --> SWRN	0.41	0.87	1.55
Forest-Evergreen --> FRSE	12.77	11.31	10.78
Pasture --> PAST	0.44	0.21	0.05
Residential --> URBN	1.83	3.09	3.68
Sub basin 16			
Agricultural Land-Generic --> AGRL	1.49	1.07	0.62
Southwestern US (Arid) Range --> SWRN	0.91	0.56	1.08
Forest-Evergreen --> FRSE	2.36	4.01	3.29
Pasture --> PAST	1.25	0.41	1.00
Residential --> URBN	0.08	0.05	0.10
Sub basin 17			
Agricultural Land-Generic --> AGRL	0.88	0.48	0.46
Southwestern US (Arid) Range --> SWRN	0.01	0.45	0.33

Forest-Evergreen --> FRSE	15.40	15.34	14.57
Pasture --> PAST	0.45	0.14	0.18
Residential --> URBN	0.02	0.35	1.22
Sub basin 18			
Agricultural Land-Generic --> AGRL	0.25	0.53	0.47
Southwestern US (Arid) Range --> SWRN	0.11	0.17	0.17
Forest-Evergreen --> FRSE	6.93	6.73	6.57
Pasture --> PAST	0.32	0.08	0.00
Residential --> URBN	0.13	0.23	0.51

Source: Own preparation

References

L8 OLI/TIRS (2015), "LC82170752015284LGN00", Satellite imagery, in *Earth Explorer USGS*.

Landsat 4 - 5 TM C1 Level 1 (1996), "LT05_L1TP_217075_19960616_20170104_01_T1", Satellite imagery, in *Earth Explorer USGS*.

Landsat 4 - 5 TM C1 Level 1 (2005), "LT05_L1TP_217075_20050828_20161125_01_T1", Satellite imagery, in *Earth Explorer USGS*.

Landsat Copernicus (1985), "Landsat Copernicus imagery archive", Satellite imagery, in *Google Earth Pro*.

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Annex 5: Calibration parameters and process

SWAT CUP is a free license program developed to calibrate and validate SWAT models (SWAT Soil and Water Assessment Tool). In this case, the parameters used to calibrate the model were selected considering that the model was used to study the impact on the quantity of the water rather than the quality of the water. Those were selected based on the parameters usually used to calibrated the water balance in a SWAT models (Arnold et al., 2012) and were complemented by the SWAT literature detailed further on the document.

In general, the parameters identifiers have the following form (Abbaspour, 2015):

X_<parname>.<ext>

Where X_ is the identifier code used to indicate the type of change that will be applied to the parameter that can be 1) v_ , the parameter will be replaced by a resulting value, 2) a_, the value will resulted will be added to the existing parameter value or 3) r_, the value will be multiplied by a given value with the format 1+resulted value. <ext> refers to the file extension code that contain the parameter to be adjusted (e.g., .sol, .hru) (Abbaspour, 2015).

The parameters selected in a first instance can be found in SWAT-CUP "Absolute_SWAT_Values.txt" and were completed by the input data .bsn and .hru (Chapter 4 and 19 SWAT Manual respectively). The table below (Table 1) contains the 42 parameters that can have an impact on the resulting flow; however, they were reduced to 38 and for the calibration half of them were settled after the first sensibility analyse.

It is usually assume that the more complex is the model calibration the better results and closer to the reality are got, nevertheless, "over parameterization can lead to loss control over the model behaviour" (KRYSANOVA & ARNOLD, 2008), hence if a process can be modelled and calibrated with simple mathematics and available information is a better choice than a complex parameterization. Further, "there are several parameters sets leading to a similar simulation results, a equifinality problem, which suggests that there are several representation of a river basin that are equally valid in terms of their ability to reproduce the studied processes" (KRYSANOVA & ARNOLD, 2008).

Table 1: Parameters used to calibrate and validate

Parameter	Values			Description
	Minimum	Maximum	Default	
ALPHA_BF.gw	0	1	0.048	Base flow alpha factor (days).
ALPHA_BNK.rte	0	1	0	Base flow alpha factor for bank storage.
CANMX.hru	0	100	0	Maximum canopy storage.
CH_K2.rte	0.025	127	0	Effective hydraulic conductivity in main channel alluvium (mm/hr)
CH_N1.sub	0.01	30	0.014	Manning's "n" value for the tributary channels.
CH_N2.rte	-0.01	0.3	0.014	Manning's "n" value for the main channel.
CN2.mgt	35	98	Values per HRU	SCS runoff curve number f
CNCOEF.bsn	0.5	2	1	Plant ET curve number coefficient.
DEP_IMP.hru*	0	6000	6000	Depth to impervious layer for modelling perched water tables
DEPIMP_BSN.bsn	0	6000	0	Depth to impervious layer for modelling perched water tables
DIS_STREAM.hru	0	10000	35	Average distance to stream (m)
ESCO.hru	0	1	0	Soil evaporation compensation factor.
FFCB.bsn	0	1	0	Initial soil water storage expressed as a fraction of field capacity water content.
FLD_FR.hru	0	1	0	Fraction of HRU area that drains into floodplain
GDRAIN_BSN.bsn	Not specified		Not defined	Drain tile lag time (hours)
GW_DELAY.gw	0	500	31	Groundwater delay (days).
GW_REVAP.gw	0.02	0.2	0.02	Groundwater "revap" coefficient
GW_SPYLD.gw	0	0.4	0.003	Specific yield of the shallow aquifer (m3/m3).
GWQMN.gw	0	5000	0	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).
MSK_CO1.bsn*	0	2000	0.75	Calibration coefficient used to control impact of the storage time constant (K_m) for normal flow (where normal flow is when river is at bank full depth) upon the Km value calculated for the reach.
MSK_CO2.bsn*	0	2000	0.25	Calibration coefficient used to control impact of the storage time constant (K_m) for low flow (where low flow is when river is at 0.1 bank full depth) upon the K_m value calculated for the reach.

MSK_X.bsn	0	0.3	0.2	Weighting factor controlling relative importance of inflow rate and outflow rate in determining water storage in reach segment.
OV_N.hru	0.01	30	Values per land use	Manning's "n" value for overland flow.
POT_FR.hru	0	1	0	Fraction of HRU area that drains into the pothole.
POT_TILE.hru	0	100	0	Average daily outflow to main channel from tile flow if drainage tiles are installed in the pothole.
POT_VOL.hru	0	100	0	Initial volume of water stored in the pothole.
POT_VOLX.hru	0	100	0	Maximum volume of water stored in the pothole.
RCHRG_DP.gw*	0	1	0.05	Deep aquifer percolation fraction.
REVAPMN.gw	0.02	0.2	750	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H2O)
RIP_FR.hru	0	1	0	Fraction of HRU area that drains into riparian area
SLSOIL.hru	0	150	Values per HRU	Slope length for lateral subsurface flow.
SMXCO.bsn	0	10	1	Adjustment factor for maximum curve number S factor
SOL_ALB().sol	0	0.25	Values per soil type	Moist soil albedo.
SOL_AWC().sol	Not specified		Values per soil type	Available water capacity of the soil layer.
SOL_BD().sol	0.9	2.5	Values per soil type	Moist bulk density.
SOL_CRK.sol	Not specified		Values per soil type	Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume.
SOL_K().sol	0	2000	Values per soil type	Saturated hydraulic conductivity.
SOL_Z().sol	Not specified		Values per soil type	Depth from soil surface to bottom of layer (mm)
SOL_ZMX.sol	Not specified		Values per soil type	Maximum rooting depth of soil profile (mm). If no depth is specified, the model assumes the roots can develop throughout the entire depth of the soil profile.
SURLAG.bsn	0.1	1	4	Surface runoff lag coefficient

TRNSRCH.bsn	0	1	0	Fraction of transmission losses from main channel that enter deep aquifer.
VCRIT.bsn	0	10	5	Critical velocity

*parameters not used during the calibration and validation

The sensibility analysis is performed by the program using a multiple regression (Abbaspour, 2015):

$$g = \propto + \sum_{i=1}^{m} \beta_i b_i$$

Where g is the function goal value and b_i is the parameter analysed.

The program uses the t-Stat and the P-Value as indicator of the sensibility of a parameter. The t-stat is “the coefficient of a parameter divided by its standard error” (Abbaspour, 2015) that measures the precision of the regression coefficient measurement. The p-value assesses the “null hypothesis that the coefficient is equal to zero (no effect)” (Abbaspour, 2015), a value less or equal to 0.05 is frequently accepted as a value to discard the hypothesis, a large value means that the parameter sensitiveness is low (Abbaspour, 2015).

The calibrations of the models were performed separately; each one showed slightly different parameters values and sensibilities. The next table shows the most sensitive parameters and their values for each model.

Table 2: Sensitive parameters

Grande River			Bengalas River		
1985 - 1996	1996 - 2005	2005 – 2015	1985 - 1996	1996 - 2005	2005 – 2015
ALPHA_BF.gw	ALPHA_BNK.rte	ALPHA_BF.gw	ALPHA_BF.gw	CH_K2.rte	CANMX.hru
CH_K2.rte	CANMX.hru	CANMX.hru	CH_K2.rte	CH_N2.rte	CH_K2.rte
CH_N2.rte	CH_K2.rte	CH_K2.rte	CH_N2.rte	DEPIMP_BSN.bsn	CH_N1.sub
CN2.mgt	CNCOEF.bsn	DIS_STREAM.hru	DEPIMP_BSN.bsn	DIS_STREAM.hru	CH_N2.rte
DEPIMP_BSN.bsn	ESCO.hru	GDRAIN_BSN.bsn	ESCO.hru	ESCO.hru	CN2.mgt
ESCO.hru	FFCB.bsn	GW_DELAY.gw	FFCB.bsn	GDRAIN_BSN.bsn	DIS_STREAM.hru
FFCB.bsn	GW_DELAY.gw	GW_REVAP.gw	GDRAIN_BSN.bsn	GW_REVAP.gw	ESCO.hru
GDRAIN_BSN.bsn	OV_N.hru	GWQMN.gw	GW_REVAP.gw	GWQMN.gw	FFCB.bsn
GW_REVAP.gw	REVAPMN.gw	POT_FR.hru	POT_TILE.hru	MSK_X.bsn	FLD_FR.hru
POT_TILE.hru	RIP_FR.hru	RIP_FR.hru	REVAPMN.gw	POT_TILE.hru	GDRAIN_BSN.bsn
REVAPMN.gw	SLSOIL.hru	SOL_BD().sol	SLSOIL.hru	RIP_FR.hru	GWQMN.gw
SLSOIL.hru	SMXCO.bsn	SOL_K().sol	SOL_ALB().sol	SLSOIL.hru	POT_TILE.hru
SOL_K().sol	SOL_K().sol	SOL_Z().sol	SOL_K().sol	SMXCO.bsn	RIP_FR.hru
SOL_Z().sol	VCRIT.bsn	SOL_ZMX.sol	SOL_Z().sol	VCRIT.bsn	SLSOIL.hru

Source: Own preparation based on the results from SWAT-CUP

For the purpose of the study, the models were run on a monthly step. Those were calibrated using the Nash-Sutcliffe (NS) and R^2 efficiency index, which values according to Moriasi in his paper “Model evaluation guidelines for systematic quantification of accuracy in watershed simulations” should be 0.5 or higher to for a monthly step time model to be considered as a satisfactory model simulation (Arnold et al., 2012; Douglas-Mankin, Srinivasan, & Arnold, 2010; Gassman, Reyes, Green, & Arnold, 2007; Moriasi et al., 2007)

The table below shows the values of the index for the calibration and validation of each model and basin.

Table 3: Efficiency indicators values

Time period	Parameter	Grande River		Bengalas River	
		Calibration	Validation	Calibration	Validation
1985 - 1996	NS	0.78	0.69	0.81	0.68
	R2	0.83	0.71	0.82	0.69
1996 - 2005	NS	0.83	0.56	0.72	0.43
	R2	0.83	0.62	0.75	0.85
2005 - 2015	NS	0.79	0.51	0.79	-0.21
	R2	0.79	0.68	0.84	0.64

Source: Own preparation based on the results from SWAT-CUP

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Declaration in lieu of oath

By

Veronica Jazmin Campos
Zeballos

This is to confirm my Master's Thesis was independently composed/authored by myself, using solely the referred sources and support.

I additionally assert that this Thesis has not been part of another examination process.

Cologne, 02.10.2017

Place and Date *Signature*