VIAS Hydro: Impact and vulnerability assessment in the drought impacted basins of the Cantareira System

Bachelor Thesis – Civil Engineering, University of Twente

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PREFACE

This report presents the research to the impact of drought and vulnerability to drought in the water basins of the Cantareira System, the water supply system for millions of inhabitants of the Metropolitan Region of São Paulo. The research has been carried out at the Universidade de São Paulo, campus São Carlos, in close cooperation with the research institute CEMADEN and has been completed in the context of a Bachelor Thesis for the study Civil Engineering at the University of Twente.

I would like to use this preface to thank both my supervisor at the University of Twente, M.S. Krol, and my supervisor at the Universidade de São Paulo (USP), E.M. Mendiondo, for their advice during the project. They have provided me with feedback and new insights throughout the ten weeks of research and have offered their help on many occasions. I would also like to thank the researchers at NIBH, the laboratory at USP at which I performed the research. They could always provide me with first-hand knowledge about the research area, the models and the available data. Due to their ready knowledge, data and information some parts of my research could significantly be speeded up. A special thanks goes to Guilherme Mohor who was always available for a discussion on any topic related to my Bachelor Final Project.

Performing this research meant hard work, newly acquired knowledge and, above all, an enjoyable time with great new experiences.

I hope you enjoy reading this report as much as I did enjoy my time in Brazil,

Jules Hazeleger

São Carlos, 30th of July 2015

SUMMARY

A recent drought in the Cantareira System – a major water supplier of the metropolitan region of São Paulo – has caused reservoirs to run dry and has forced water agencies to pump water from the reservoir's dead volume. Water supply has been decreased drastically, albeit too late according to several experts, and the drought has already resulted in economic losses of billions of euro in the water-energy-and-food sector. There is still a need for more risk-based adaptive measures to prevent consequences of future droughts. An assessment of impacts and evaluation of the vulnerability to droughts is hereby highly desirable. The report's goal is to determine the vulnerability of and impacts on the water supply from the Cantareira system to droughts to allow planners to apply feasible risk-based approaches to future droughts. Research questions focus on the identification of hazards, potential impacts and vulnerability.

To achieve this goal, research first focused on a literature study on the functions and the pros and cons of several low flow indicators and drought indices (chapter 2). After a study on the region (chapter 3) – three parallel watersheds with reservoirs which are interconnected through the usage of tunnels – the most applicable indicators have been chosen for the identification of hazards, impacts and vulnerability (chapter 4): the Standardized Runoff Index (SRI) – both for 1 month and for 6 consecutive months – the Flow Duration Curve (FDC), the Base Flow Index (BFI) and the Deficiency Volumes (DV) of the reservoirs. The study on the hazards and (potential) impacts focused on both single watersheds and the whole system. Vulnerability, contrary to hazards and potential impacts taking into account the adaptive capacity of a system, is evaluated for the system as a whole.

Results show that annual and seasonal variability in flows cause hazards during dry seasons. Furthermore, SRI and exceedance probabilities in the FDCs reached very critical values during the 2013-2015 drought, imposing big hazards on the metropolitan region of São Paulo. Spatial analysis between the SRI-values of the watersheds (Jaguari-Jacarei, Cachoeira and Atibainha) show more extremes for the relatively smaller watersheds Cachoeira and Atibainha, thus imposing more severe hazards, which are accompanied with lower values for annual base flow index.

Assessment of impacts has shown potentially high impacts for low flows due to both annual and seasonal variability; demand exceeds supply for many months throughout a year. The recent drought has, as a result of the severity of the hazard, shown even higher potential impacts with average runoff between May 2013 and May 2015 not even reaching half of the demand for the primary usage of water – the sum of the demand for human and animal consumption and the water necessary to reach 70% of the efficiency of irrigation.

The function of the reservoirs as adaptive capacity – they even out both spatial and temporal variability – has a high positive influence on the vulnerability of the water supply to drought hazards. The region is in essence not vulnerable to low flows occurring due to normal seasonal or annual variability. However, consecutive years of mild drought accompanied by continuous outflow matching the total water demand of 36 m^3/s, might cause problems on the long term, leaving the water supply system of MRSP slightly vulnerable to mild, consecutive droughts. Calculations have furthermore shown that the region is highly vulnerable to the severe drought which was faced during the past few years. Deficiency volumes exceeded the useful volume of the reservoir to great extent. Interesting to note is however that consequences would have been far less if the outflow of water had been restrained to the outflow for the primary demand of water since 2006.

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1. INTRODUCTION

The metropolitan region of São Paulo has faced the consequences of a fierce drought in the Cantareira System, a major water supplier of the city, over the past couple of years. Economic losses have reached as high as 40 billion euro and inhabitants of the metropolis have encountered water shortages throughout the past months. Reservoir levels have dropped to below zero and agencies are pumping water from the dead volume of the reservoir (Escobar, 2015). Water supply from the reservoirs to São Paulo has drastically been decreased over the months through, for example, the reduction of water pressure in the pipes and the usage of other, more contaminated reservoirs (SABESP, 2015). Inhabitants of São Paulo have already felt the consequences of the drought and problems are likely to increase further with researchers expecting the reservoirs to run completely dry in August 2015 (Dezem, 2015). The economic centre of Brazil goes through the most extreme drought in 80 years.

There is a chance that severe or extreme droughts might occur more occasionally in the future either due to climate change or due to deforestation in the Amazon (Maddocks, Shiao, & Mann, 2014). Adaptive measures to prevent severe consequences of future droughts are of the utmost priority. To apply the correct measures, a good understanding of the possible impacts of droughts and the vulnerability to droughts of the water supply system of the Metropolitan Region of São Paulo (MRSP) is highly desired.

ORGANIZATION

This research has been carried out at the Engineering School of São Carlos, part of the Universidade de São Paulo. Work has been established at Núcleo Integrado de Bacias Hidrográficas (NIBH), a part of the laboratory of Hydraulics at EESC/USP. The research was carried out in close cooperation with CEMADEN (Centro Nacional de Monitoramento e Alertas de Desastres Naturais) as part of a running cooperation between the university and the monitoring centre.

DEFINITION OF TERMS

Terms such as 'impacts' and 'vulnerability' have already come across in the first two paragraphs of the introduction. For the correct use of these multi-interpretable terms, a thorough definition is required. Therefore, before the report continues to discuss its goal and research questions, several important terms will be defined.

Especially vulnerability is a term that has been interpreted in many different ways in scientific research. It is often referred to as the level to which a (water) system is susceptible to the effects of changes that influence the system (Jun, Chung, Sung, & Lee, 2011). If interpreted in the aforementioned way, factors that influence the degree to which the system is vulnerable include – in case of droughts – for example the population density, the state of the infrastructure and even the literacy rate. In this research, a broader definition of vulnerability is used. Vulnerability is:

> *"… the degree of fragility of a natural or socio-economic community or a natural or socio-economic system towards hazards." (Walker, Deeming, Margottini, & Menoni, 2011)*

It is:

"… a function of exposure, sensitivity to impacts and the ability or lack of ability to cope or adapt." (Bizikova, Bellali, Habtezion, Diakhite, & Pinter, 2009)

IPCC (2014) states that, in their report, the term 'impacts' is used primarily:

"… to refer to the effects on natural and human systems […] Impacts are also referred to as consequences and outcomes."

The second definition of vulnerability is given in a training manual for vulnerability and impact assessments as part of a VIA (Vulnerability, Impact, Adaptation) Module. It considers a certain hazard, takes a look at whether a person, system or community is exposed to this hazard en defines its sensitivity to the situation. Together, these variables form a potential impact. However, a system has a certain adaptive capacity which influences the vulnerability of the system. Adaptive measures might be undertaken to reduce the vulnerability; those measures could be directed to minimize the hazard, the sensitivity, the exposure or the adaptive capacity (Bizikova, Bellali, Habtezion, Diakhite, & Pinter, 2009). How these terms are used within the specific situation of the Cantareira System is explained in chapter 4.

Goal of the Research

The first two paragraphs present the motivation of the research. The anomalously severe drought gave occasion to a discussion on necessary adaptive measures among researchers and politicians. However, there is a gap to be bridged: assessment of impacts and evaluation of vulnerability for a feasible risk-based methodology in the drought impacted basins of the Cantareira System. This research will focus on the assessment of impacts and evaluation of vulnerability in the Cantareira System. This leads to the following goal:

"Determine the vulnerability of and impacts on the water supply from the Cantareira system caused by drought in its basins to allow planners to apply feasible risk-based approaches to future droughts."

Research Questions and Methodology of Research

The goal leads to two obvious research questions (2 and 3). However, for the determination of impacts and vulnerability, as is shown in the definition of terms, knowledge about hazards is necessary. The following research questions can thus be distinguished:

1. What are the hazards faced by the users of the Cantareira water supply system as a result of drought in its watersheds.
2. Which potential impacts to the water supply from the drought impacted basins of the Cantareira system can be identified through impact assessment?

3. Which vulnerabilities to the water supply from the drought impacted basins of the Cantareira system can be identified through vulnerability evaluation?

Several steps will be undertaken to answer the research questions and achieve the goal of the research study. These will shortly be explained in the following paragraph.

Firstly, a literature research to possible drought and low flow indicators will be held in order to have a good understanding of the possibilities for the identification of hazards, impacts and vulnerabilities. A thorough research of the study area will provide valuable information on the available data and the region itself. As a follow-up to these steps, several indices will be chosen to be calculated for the evaluation and assessment of hazards, impacts and vulnerabilities. These indices will be chosen based on the function of the researched indices, the desired outcomes of the research and the characteristics of the environment. After calculation of these indices – with the use of output-files of a Probability Distributed Model (PDM) and a Soil and Water Assessment Tool (SWAT) – an evaluation/discussion will be held through comparison of the outcomes with pre-defined thresholds. A drought indicator will provide insights in the severity of the hazards. The low flow measurements will, if discussed in comparison with the sensitivity of the system and the accompanying severity of a drought, provide insight in the potential impacts of certain droughts. Adding the adaptive capacity of the reservoirs to the discussion will provide input for the discussion of the vulnerability of the system. The general outline of the methodology is summarized in Figure 1.

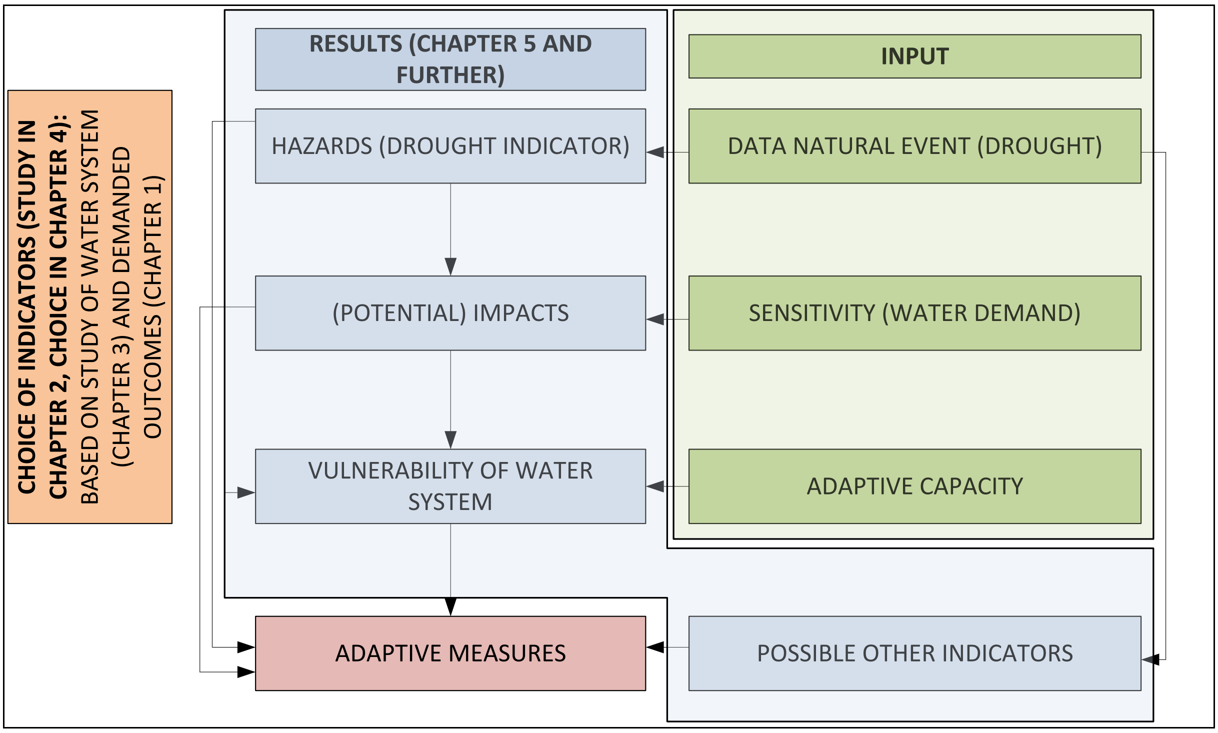


FIGURE 1: GENERAL OUTLINE OF THE METIODOLOGY OF THE RESEARCH

Structure of Reading

As already partly summarized in figure 1, the research will kick off in chapter 2 with a literature study on several drought indices and low flow measurements. The measurements' functions, their input variables and, in case of drought indices, their pros and cons will be described. Chapter 3 will provide the reader with essential information on the characteristics of the study area. Combining the information of the drought indices, low flow measurements, the study area and the desired outcomes, the appropriate indices for the identification of hazards, impacts and vulnerability are chosen in chapter 4. Their role in the determination of impacts and vulnerabilities will be described as well. Chapter 5 will present the most important results of the calculations which are carried out, followed by a thorough discussion of the results in chapter 6 to reflect on the research questions in the context of annual and seasonal variability, spatial variability and the 2013 – 2015 drought. The report is concluded with a conclusion and several recommendations.

2. THEORETICAL FRAMEWORK

In many areas over the world, researchers have tried to map the drought situation in drought impacted regions or have tried to measure the low flow situation, usually also resulting in an indicator for the, sometimes threatening, condition of the water system. In itself, these indices are just an indicator for hazards – a natural phenomenon – and do not yet address the impact or vulnerability. However, if used in comparison with an environment's sensitivity and its adaptive capacity, they can give insight into the (potential) impact of the hazard/natural event on the person, system or community and the person's, system's or community's vulnerability.

This chapter will elaborate about several drought and low flow indices that have been used in prior research to identify the conditions of water system. Herewith, a division will be made between drought indices and low flow indices. Before its elaboration, the definitions of low flows and droughts will be given to define the difference between the indicators of both.

Situations with small amounts of water flows can be subdivided in periods of drought and of low flows. The definitions of these terms are presented in Smakhtin (2001):

"Drought [...] is a natural event resulting from a less than normal precipitation for an extended period of time."

"Low flows is a seasonal phenomenon, and an integral component of a flow regime of any river."

According to Hisdal et. al. (2000), drought usually goes along with low flows, however, low flows just represent the drought magnitude.

a. DROUGHT INDICES

Drought indices have been used in many countries and regions to define the severity of drought compared to historical data. They provide the information to evaluate an ongoing or previous drought. Many researchers have either designed or used different indices. This chapter will provide an insight in these indices, their adaptability, required input variables, strengths and weaknesses.

i. PALMER DROUGHT SEVERITY INDEX (PDSI)

The PDSI is a relatively old, but extensively used index which has shown good results for many states in the United States of America. It estimates the moisture demand and supply with the use of a two-layer soil model. It measures the moisture conditions and standardizes those in order to compare its values with other locations and other times. The index is meteorological by nature and responds to anomalously dry and wet condition. Its values do not immediately return to normal during a month with regular amounts of precipitation after several months with severe drought, however, it does not take into account long-term hydrological factors (National Drought Mitigation Center).

The index is calculated based on values for the precipitation, temperature and the local available water contents of the soil (AWC). With these input variables, it is able to calculate values for the evapotranspiration (PET), soil-recharge, runoff (Q) and moisture loss (Vicente-Serrano, et al., 2012). Since the index' main focus is the soil moisture, it is most suited for agricultural purposes. Over the past few decades, several researchers have endeavored to slightly improve the PDSI by, for example, changing the transition between dry and wet spells (PMDI – modified PDSI) and developing a Palmer Hydrological Drought Index (PHDI); a near-real time hydrological index (National Drought Mitigation Center).

PROS

+ Provides an insight in abnormal weather conditions in both spatial and temporal perspective.
+ Has shown good results for many prior cases.
+ Is sensitive to both precipitation (P) and evapotranspiration (PET).

CONS

- It is complex.
- The index does not respond well to regions that face extremes in their precipitation and mountainous regions.
- Lag between P and Q not considered.
- Values to quantify drought and the signals for begin and end of drought are arbitrarily.
- Thorntwhaite method used to calculate PET (Hisdal, Tallaksen, Stahl, Zaidman, Demuth, & Gustard, 2000).

ii. Standardized Precipitation Index (SPI)

A second, widely used index is the SPI. It determines its drought index by the probability of precipitation for any given timescale. Based on a, preferably long, series of precipitation records, the historic data for precipitation is fitted to a probability distribution. Although there seems to be no probability function that suits all precipitation records, various researchers have used the Pearson III-distribution and gamma-distribution. Afterwards, its values are standardized with the index-value of 0 as its average and a standard deviation of 1 (McKee, Doesken, & Kleist, 1993; National Drought Mitigation Center; Trambauer, Maskey, Werner, Pappenberger, Beek, & Uhlenbrook, 2014; Mishra & Singh, 2011).

The SPI is able to identify different kinds of droughts due to its applicability in different timescales. A SPI-3 for example calculates its index based on the precipitation records of three subsequent months and the values of those same months in previous years. Due to this multi-timescale applicability, it can, compared to PDSI, more closely estimate the hydrological drought which usually responds to long-term precipitation abnormalities. The SPI does only take into account the precipitation for its calculation of the SPI and hereby assumes that the variability of precipitation is much higher than of other variables and that the other variables do not have a temporal trend (Vicente-Serrano, et al., 2012).

PROS

+ Computable for different time scales
+ Can provide an early warning for droughts
+ Less complex than the PDSI

CONS

- Different lengths of precipitation records have influence on the SPI-outcomes
- Unknown which probability distribution suits the precipitation records best
- Time-steps with ‘zero precipitation’-records might cause problems
- Dependent on the use of the indicator (for meteorological/hydrological droughts), not considering the lag between P and Q is a ‘con’.

iii. *STANDARDIZED PRECIPITATION EVAPORATION INDEX (SPEI)*

The SPEI is an index which is directly derived from the SPI and its value is calculated in an almost similar way. In contrast to the SPI, SPEI does take into account the evaporation in an area, a factor that was proven not to be negligible for hydrological droughts by several researchers. Especially with the knowledge of a possible climate change in the upcoming decades, the influence of temperature plays a role in drought assessment. The SPEI thus uses the difference between the precipitation and evaporation as the input value for the index (Vicente-Serrano, et al., 2012).

PROS (COMPARED TO SPI)

+ Does take into account the evapotranspiration

CONS (COMPARED TO SPI)

- Needs more input variables

iv. *STANDARDIZED RUNOFF INDEX (SRI)*

The SRI is another indicator which has great similarity with the SPI. Instead of meteorological data, the SRI uses the hydrological component runoff to estimate the drought in a region. The idea behind this is that, although climate abnormalities do result in droughts, drought's impacts are mostly a result of threatening hydrologic (runoff) conditions. The SRI determines its index including the seasonal lag between climatic anomalies and its influences on the streamflow and thus directly determines the hydrologic conditions (Shukla & Wood, 2008).

PROS (COMPARED TO SPI)

+ Directly determines the hydrologic condition.
+ Predictability does also depend on hydrologic initial conditions and is thus less dependable of unpredictable climatic forecasts.

CONS (COMPARED TO SPI)

- The uncertainties of simulated runoff data are also reflected in the SPI.

v. *EFFECTIVE DROUGHT INDEX (EDI)*

The EDI has been introduced as a response to the SPI. This index is also determined by solely using precipitation values. It, however, has implemented several changes compared to the SPI. It, most importantly, takes into account a time-dependent reduction factor which accounts for the reduction of water resources over time, creating the effective precipitation. Byun and Wilhite (1999) have designed several formulas to determine the effective precipitation, however, the following equation has shown most promising results:

$$EP_i = \sum_{n=1}^{i} \left[\left(\sum_{m=1}^{n} P_m \right) / n \right] \qquad \begin{cases} i = \text{duration of summation (DS)} \\ P_m = \text{precipitation of } m \text{ days before} \end{cases}$$

Byun and Wilhite (1999) have furthermore changed the time steps for their index and use daily time steps. The value of the effective precipitation can be applied in many ways and several characteristics of the water resources in the region can be determined, which conclude the deviation of the EP to the mean value, its standardized value, the dry and drought duration, the accumulated precipitation deficit, the precipitation needed for a return to normal and the effective drought index (EDI). EDI is defined as the deviation of the EP to the value divided by the standard deviation of this variable.

PROS

+ Only uses precipitation records as input variables and is thus not complex.

CONS

- Although it does take into account the diminishment of water through, for example,

+ Takes into account the diminishing water resources over time and the storage term.
+ Uses small time steps.
+ Does not have to be fit to a distribution model.

evapotranspiration. This term is not considered to be a temporal value.

vi. *Standardized Water Supply Index (SWSI)*

The SWSI has been developed as an addition to the PDSI and, while the PDSI does primarily calculate the soil conditions, SWSI determines the state of the surface water. Using the snowpack, streamflow, precipitation and reservoir storage as input variables it can determine its index. The values of the variables are normalized and the probability of non-exceedance is defined. The standardized values can be evaluated and assigned a weight for its specific contribution to the water supply in the reach of the reservoir to determine an SWSI which is unique to that specific basin (Hisdal, Tallaksen, Stahl, Zaidman, Demuth, & Gustard, 2000; National Drought Mitigation Center; Mishra & Singh, 2011).

PROS

+ Uses a combination of hydrological and meteorological factors.
+ Represents surface water supply properly
+ Simple to use
+ Determines an index unique to the specific basin

CONS

- Unique to each basin; comparison between different watersheds thus difficult

vii. *Summarized*

The above mentioned indices are some of the most used for the evaluation and classification of droughts. Many other indices have been designed over the past few years, some of the remaining indices will be summarized are summarized in appendix A. Underneath, a summary of the above mentioned indices is given:

Index	**Abbreviation**	**Input variables**
Palmer Drought Severity Index	PDSI	P, T, AWC
Standardized Precipitation Index	SPI	P
Standardized Precipitation Evaporation Index	SPEI	P, T
Standardized Runoff Index	SRI	Q
Effective Drought Index	EDI	P
Standardized Water Supply Index	SWSI	Q, P, Storage, (snowpack)

b. Low Flow Measurements

This chapter will elaborate several low flow measurements which can be used to evaluate (critical) low flow situations in a region. Since the measurements do only give insight in specific features of flow or low flow ranges and they do not attempt to classify a drought, negative and positive points of the measurements will not be pointed out. The chapter will elaborate about the possibilities there are to picture certain specifics of low flows and their calculations. Appendix A will provide additional information of some of the remaining low flow measurements.

i. *Flow Duration Curve (FDC)*

The most well-known, yet most informative, flow measurement is possibly the flow duration curve. It determines the relation between a certain runoff and the probability the given discharge is equaled or exceeded. The flows can either be clustered in classes or every single measured runoff can be ranked and plotted. The FDC can be set up for every possible time-step and can even be applied to moving averages. Furthermore, it can obviously be used to display the frequency of occurrence of every flow during a year, but also for a season and a specific month. The exceedance probability of a specified flow in a series of flow records is, after all records are ranked from high to low, calculated using the following formula:

$$P = 100 * \frac{m}{n+1} \quad \left\{ \begin{array}{l} P = \text{exceedance probability (\%)} \\ m = \text{ranked position of flow} \\ n = \text{total amount of flow records} \end{array} \right.$$

As mentioned, the FDC can be very useful to determine a broad range of low flow characteristics. The flow can be shown as a percentage of a predefined threshold (e.g. water demand) in a duration curve. Furthermore, the curve of the flow can inform one about the variability of flows and about the contribution of groundwater to the total flow. A steep curve is an indicator of low or variable base flow contribution, whereas a quite linear curve represents relatively high groundwater contribution to the total flow. Ratios between the runoff that has been exceeded 20% of the time and 90% of the time show a curve's variability (Q20/Q90). Q50/Q90 might also be used for this, while Q90/Q50 might be used as an indicator for the groundwater's contribution to streamflow. Other interesting indicators might be the amount of days during a specific period of time at which the discharge was lower than the Q75, Q90 or Q95. The application of two vertical axis – both runoff and the exceedance probability – and the time on the horizontal axis, might give a good insight in the temporal low flow conditions (Smakhtin, 2001).

The flow duration curve itself cannot be used to determine the sequence of certain low flow characteristics although a 'moving average' and the use of two vertical axis might partly solve this issue. The FDC is furthermore quite sensitive to the length of the flow records, especially for very low flows. When one determines the FDC with data from limited amount of years, the extreme values might be affected to large extent by one or two years of extreme drought. Vogel and Fennessey (1994) have opted a different strategy and develop FDC's for every year after which the mean or median for each year is used to determine the eventual FDC for all years. This strategy proves to be less sensitive to extreme drought when using limited time scales.

ii. Low Flow Frequency Analysis (LFFA)

The LFFA is designed to provide an insight in the probability for the runoff to reach values below a defined threshold during a certain period of time (usually a year). The LFFA can be calculated by determining the annual minimum flow for the available flow records. The annual minimum flow might be computed as the daily annual minimum flow, the weekly annual minimum flow (sum of seven consecutive days) or other time intervals. The minimum flows are, after determination of the data's independency of each other, fitted to a distribution function. Since most river basins do not have flow records for a sufficient amount of years, and do thus not have enough data to give sufficient insight in extreme low or high flows, the fit to a certain distribution function is a necessity (Smakhtin, 2001).

If the fit proves to be good enough, one is able to draw several conclusions. Most importantly, one is able to say what the probability is of a certain low flow occurring within a predefined time interval or –

the other way around – which low flow has the recurrence interval of a predefined period of time. Some widely used indices here fore are the 7Q10 and the 7Q2, representing respectively the lowest average flow that can occur for seven consecutive days with a recurrence interval of 10 and 2 years. Other indices which can be derived from the LFFA are the Dry Weather Flow, known as the average of the annual 7-day minimum flows, or the slope of the curve. Steep curves represent low flow characteristics with high variability whereas a break in a curve might mean that one has found the point which is regarded to be the turning point between drought conditions and conditions which are the result of the variety of normal conditions (Smakhtin, 2001).

A disadvantage of the LFFA is its need for long flow records. If one just has limited records at their disposal, plenty of distribution models will fit the data properly, leaving the user with several probability possibilities for the (extreme) low and high flow ranges. Therefore, it is told to be inadvisable to use LFFA-data for areas which don't have records of a length of 25 years or more.

iii. CONTINUOUS LOW FLOW EVENTS AND DEFICIT VOLUMES

The impact of a drought is not only dependent on the frequency of low flows occurring, but also on its consecutiveness. Several researchers have dedicated their research to the identification of the duration of low flows and/or the deficiency volumes during droughts. The available low flow records have to be analyzed with the approach of the so-called 'truncation level' or 'threshold' concept. It analyzes the length – known as the run or spell duration - , start and end date at which the low flow is below a certain predefined threshold (Yevjevich, 1967). The threshold can be defined as the flow using a certain percentage of exceedance in the FDC, a percentage of the mean daily flow, but also derived from the objective of the research study (Hisdal, Tallaksen, Stahl, Zaidman, Demuth, & Gustard, 2000). The severity of drought – the deficit/deficiency volume – can coordinately be defined by summing the negative values during the drought spell. It is hereby important to take into account that one day of flows above the truncation level does not necessarily solve the deficiency problems (Smakhtin, 2001).

The results may be presented in a graph in which either the frequency of a deficiency volume or the amount of deficiency volumes greater than a threshold might be plotted against the values of deficiency volumes for a given threshold. One could also plot the relation between both the frequency of runs for defined durations and the amount of runs greater than the selected duration against the duration of runs. It could furthermore be a possibility to assign a cumulative frequency curve to the derived values for the deficit or duration and their amount of occurrences, representing the occurrence probability of certain deficits or drought spells (Smakhtin, 2001).

These indices are thought to be very useful to determine the storage capacity of reservoirs and thus for the identification of drought or low flow situations in region which rely on water from reservoirs.

iv. BASE FLOW INDEX (BFI)

"The Base Flow Index can be thought of as measuring the proportion of the river's runoff that derives from stored resources" (Institute of Hydrology, 1992). The BFI – sometimes also named as the reliability index since its value gives information about the variability of total runoff – can be calculated through dividing the average discharge of the separated base flow hydrograph and the average total discharge. Such an index is related to long-term base flows of a watershed and can be calculated after continuous base flow separation techniques which account for the long-term separation of quick and base flow. An explanation of a continuous base flow separation technique can be found in Appendix C. Contrary to the continuous base flow separation techniques, it is also possible to divide the total flow into

surface and base flow with the use of event-based separation techniques. Their values are however usually arbitrarily and since these techniques mostly focus on floods, they are of little use in studies to low flows *(Smakhtin, 2001)*.

The BFI can be calculated per year or for the whole series of records. It is furthermore possible to calculate the BFI for the whole series of records by calculating the mean of the annual BFI (Institute of Hydrology, 1992). The BFI-value gives insight in the nature of the watershed. High values indicate areas with high groundwater contribution – and thus usually permeable soils – while low values indicate streams which are fed by surface flow (Smakhtin, 2001).

3. Study Area

For a decent analysis of the drought situation in an area, knowledge of the study area is of great importance. The area subject to the research is the part of the Cantareira System (*Sistema Cantareira*) which drains into the Piracicaba River and thus part is of the Piracicaba basin. This basin is located on the boundary of the state of Minas Gerais and the state of São Paulo and is known as the *Sistema Equivalente*. The water supply system in the Piracicaba basin consists of three main reservoirs which are provided with water from several watersheds, being the Jaguari, Jacarei, Atibainha and Cachoeira watersheds. Their water is directed to three main reservoirs named after their water suppliers: the Jaguari-Jacarei, Cachoeira and Atibainha basins. The Jaguari-Jacarei reservoir consists of two reservoirs which are in direct contact with one another through the usage of a canal. The drainage areas of the reservoirs, presented in Figure 2, are, respectively, 1230 km², 392 km² and 312 km². The Cantareira System consists of two more reservoirs, located closer to the Metropolitan Region of São Paulo: Paiva Castro and the relatively small reservoir called Águas Claras. The Paiva Castro reservoir – with a drainage area of 369 km² - is part of the Alto Tietê basin and receives water from the Rio Juquery. Águas Claras is a reservoir with a drainage area of just 26 km² situated after the *Elevatória Santa Inés* which lifts the water to the height of São Paulo (Agencia Nacional de Águas (ANA); Departamento de Águas e Energia Elétrica (DAEE), 2013).

The water from the reservoirs is of great importance for the water supply of South America's biggest city, São Paulo, and can, according to São Paulo decree No. 8468/1976, with exception of the Jaguari-basin, be used without previous treatment (Mendiondo, 2015). This chapter will elaborate about the details of the reservoirs in the *Sistema Equivalente*, their watersheds, its supply of water to the residents of the state of São Paulo, details about the inflow of water throughout present years and the severity of the recent, still ongoing, drought.

a. The watersheds in the Sistema Equivalente

The three main reservoirs in the Piracicaba basin in the Cantareira Region, assigned to the task to serve a great deal of the Metropolitan Region of São Paulo with water, rely on the water supply from the Jaguari, Jacarei, Cachoeira and Atibainha watersheds. The regions are located in a mountainous area with tops up to 2054 meters above sea level. Its elevated valleys have heights of approximately 950 meters. The highest tops are located in the Mantiqueira Mountains and the total reservoir is located in the Atlantic Rain Forest Biome (Mendiondo, 2015).

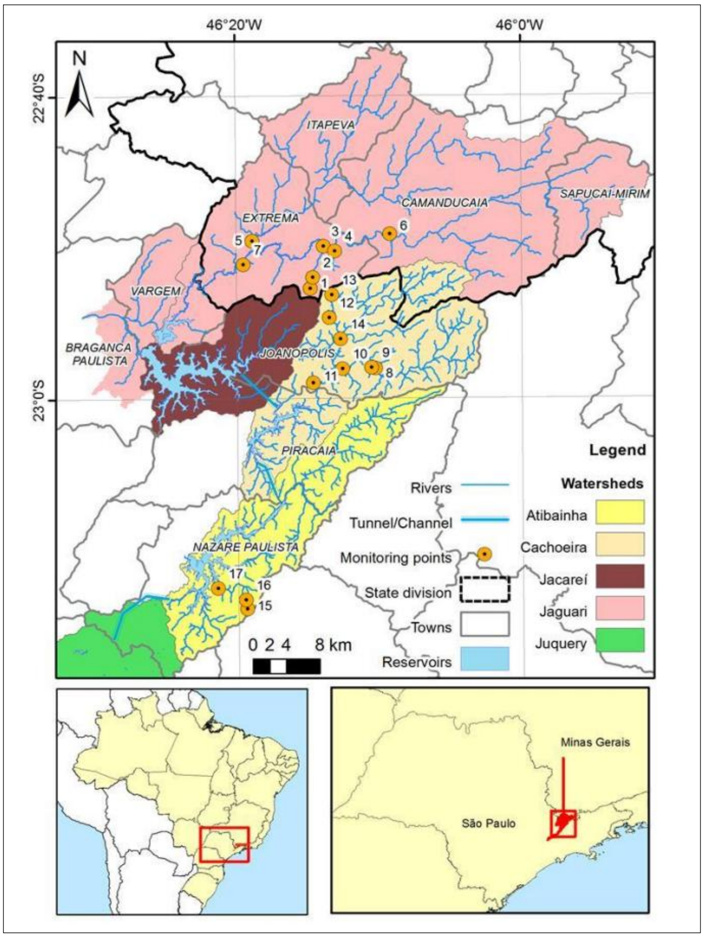


FIGURE 2: THE DRAINAGE AREAS OF THE CANTAREIRA REGION (TAFFARELLO ET. AL. IN (MENDIONDO, 2015))

The several geological domains within the region are sedimentary rocks and effusive rocks on top of a crystalline foundation and covered by sediment. The region has a very compact soil, consisting of orthents, fluvents, inceptisols and red-yellow oxisols, which can cause large floods even during normal rain conditions since the soil is not very permeable (Mendiondo, 2015). Over the past few years, the average impermeability of the soil could have been slightly increased due to changes in soil usage (Table 1).

TABLE 1: PERCENTAGE OF LAND USE IN 1989 AND 2010 (TERCEIRA VIA)

	1989	2010
Anthropogenic usage	72.0%	69.6%
• Reforestation	12.7%	15.0%
Urban usage	4.0%	5.7%
Natural vegetation usage	21.1%	22.5%
• Secondary vegetation in advanced stage	9.4%	9.1%
Water	2.2%	2.2%

b. THE RESERVOIRS IN SISTEMA EQUIVALENTE

The main reservoirs in the *Sistema Equivalente*, which are named earlier in this chapter, have a total storage capacity (useful volume) of 973.13 hm^3 of which the largest portion is contributed by the Jaguari-Jacarei reservoir. All reservoirs do furthermore have a significant dead volume which has for a great part been used during the recent drought. The dead volume is the amount of water which is located underneath the water level from which water can be discharged with the use of gravity and should thus be pumped out of the reservoir if in favour of usage. Additional information about the reservoirs can be found in Table 2.

TABLE 2: CHARACTERISTICS OF RESERVOIRS (AGENCIA NACIONAL DE ÁGUAS (ANA); DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA (DAEE), 2013)

	Jaguari-Jacarei	Cachoeira	Atibainha	Total
Reservoir Capacity				
• Useful volume	808.12 hm^3	69.75 hm^3	95.26 hm^3	973.13 hm^3
• Dead Volume	239.43 hm^3	46.81 hm^3	194.93 hm^3	481.17 hm^3
Max. inundated area	49.91 km^2	8.6 km^2	21.8 km^2	
Min. inundated area	21.15 km^2	5.2 km^2	17.8 km^2	
Max. water level (m.a.s.l.)	844.00 m	821.88 m	786.72 m	
Min. water level (m.a.s.l.)	820.80 m	811.72 m	781.88 m	

c. Cantareira's Water Supply

The Cantareira System as a whole is responsible for the delivery of water to circa half of the Metropolitan Region of São Paulo (MRSP) – 6.2 million people (9 million people until mid-2014) (Osava, 2015). It furthermore is obliged to send a portion of water downstream, into the Piracicaba water basin, to provide a part of the state of São Paulo State with water. The rest of MRSP is served with water by reservoirs of the basins of Alto Tietê, Alto Cotia, Rio Claro, Rio Grande and Guarapiranga (SABESP, 2015).

The several reservoirs within the Cantareira Region are interconnected via the usage of tunnels which can regulate the inflow of water from one reservoir to the other (Figure 3). Tunnel T7 connects the reservoir Jaguari-Jacarei with Cachoeira, T6 connects Cachoeira with Atibainha and so on. The water is eventually transferred to the *Elevatória Santa Inés* (ESI) after which the water passes the Águas Claras reservoir, is treated at *Estação de Tratamento de Agua (ETA)* and afterwards transferred to MRSP. The main outflow component of the several reservoirs in *Sistema Equivalente* is thus the water that is transferred via the tunnels to the water treatment stations. A small amount of water flows downstream into the basin of the Piracicaba River. In case of very high water levels in the reservoirs, water surplus will be discharged into the basin of the Piracicaba River (Agencia Nacional de Águas (ANA); Departamento de Águas e Energia Elétrica (DAEE), 2013).

FIGURE 3: INFOGRAPHIC OF CANTAREIRA SYSTEM (AGÉNCIA NÁCIONAL DE ÁGUAS (ANA))

SABESP (*Companhia de Saneamento Básico do Estado de São Paulo*), the public-private company that operates the water supply of the major part of the cities in São Paulo State, is obliged to follow certain regulations/limits. Table 3 presents the limits that were set for the outflow of the *Sistema Equivalente* to both the Piracicaba basin and the MRSP for certain percentages to which the reservoir is filled and herewith distinguishes the primary usage – shaded in orange - and the sum of primary and secondary usage – shaded in green – of water. It furthermore presents the fractions of the retracted water which will be sent to the Piracicaba region – the downstream flow of the three main reservoirs in *Sistema Equivalente* – and via Tunnel 5 transferred further in the direction of São Paulo (Agencia Nacional de Águas (ANA); Departamento de Águas e Energia Elétrica (DAEE), 2013). The primary usage is defined as the water which is necessary to fulfil the water demand for human and animal consumption plus the water which is needed to maintain 70% of the efficiency of the irrigation. The sum of both the primary and secondary usage is the regulated outflow which has been defined as a reference outflow for which, with long term flows, the water levels of the reservoirs are maintained sustainably – thus without any usage of the dead volume. It is hereby relevant that 40% of the outflow mentioned in Table 3 leakes through the pipes and does not fulfil any demand (Drummond & Netto, 2015). If water infrastructure would thus have been better, long term outflows of values equalling the primary usage could be possible without further consequences, although it should be noticed that one expects the water demand to increase in the future (Agencia Nacional de Águas (ANA); Departamento de Águas e Energia Elétrica (DAEE), 2013). It is important to notice that these limitations are set for the *Sistema Equivalente* – subject to this research – and do possibly not represent the values for the Cantareira Supply Catchments as a whole.

TABLE 3: LIMITATION ON WITHDRAWAL OF WATER (DATA FROM (AGENCIA NACIONAL DE ÁGUAS (ANA); DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA (DAEE), 2013))

			Combined Water Volume in Reservoirs of *Sistema Equivalente* (% of useful volume)											
Limited withdrawal amount (m^3/s)	Portion MRSP (m^3/s)	Portion Piracicaba (m^3/s)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
27.0	24.08	2.92	16.3	15.7	15.8	15.8	16.6	15.3	12.9	9.9	6.6	3.0	0.0	0.0
27.8	24.80	3.00	21.4	20.7	20.5	20.4	20.9	19.4	16.7	13.6	10.0	6.3	3.0	2.0
28.0	24.95	3.05	22.7	21.9	21.7	21.5	22.0	20.4	17.7	14.5	10.9	7.1	3.8	2.5
29.0	25.70	3.30	29.2	28.1	27.6	27.1	27.4	25.5	22.6	19.1	15.2	11.1	7.5	6.0
30.0	26.46	3.54	35.6	34.3	33.5	32.7	32.8	30.6	27.4	23.6	19.4	15.1	11.3	9.5
31.0	27.22	3.78	42.1	40.4	39.4	38.4	38.1	35.7	32.2	28.2	23.7	19.1	15.0	13.0
32.0	27.97	4.03	48.5	46.6	45.3	44.0	43.5	40.8	37.1	32.8	28.0	23.2	18.8	16.5
33.0	28.73	4.27	55.0	52.8	51.2	49.7	48.9	45.9	41.9	37.3	32.3	27.2	22.6	20.0
34.0	29.48	4.52	61.4	59.0	57.1	55.3	54.2	51.0	46.7	41.9	36.6	31.2	26.3	23.5
35.0	30.24	4.76	67.8	65.2	63.0	60.9	59.6	56.1	51.6	46.4	40.9	35.3	30.1	27.0
36.0	31.00	5.00	74.3	71.3	68.9	66.6	65.0	61.2	56.4	51.0	45.2	39.3	33.8	30.5

d. HYDROLOGICAL AND METEOROLOGICAL SITUATION OF THE CANTAREIRA SYSTEM

This sub-chapter will present tables which give insight in the hydrological and meteorological situation of the *Sistema Equivalente* and the Cantareira System as a whole over the past few years (precipitation: 2004 – 2014; water withdrawal: 2008 – 2014) and, regarding the runoff of the main tributaries of the *Sistema Equivalente*, for many decades (1930 – 2014). Data was given by researchers at CEMADEN and is derived from measurements by SABESP and DAEE.

TABLE 4: WATER SUPPLY AND PRECIPITATION CHARACTERISTICS SISTEMA EQUIVALENTE

	Total (Sistema Equivalente)	Jaguari-Jacarei	Cachoeira	Atibainha
Mean Monthly Water Supply (m^3/s)	39.06	24.82	8.32	5.94
Minimum Monthly Water Supply (m^3/s)	3.96	2.61	0.45	0.50
Maximum Monthly Water Supply (m^3/s)	165.70	118.00	33.90	27.50
Mean Monthly Precipitation (mm)	122.21			
Miminum Monthly Precipitation (mm)	0.00			
Maximum Monthly Precipitation (mm)	486.5			

TABLE 5: WATER WITHDRAWAL CHARACTERISTICS SISTEMA EQUIVALENTE

	2008 – 2014 (1-1-2013 – 28-2-2014 misses for MRSP and thus for the sum as well)			2008 - 2014		
	Total (Sistema Equivalente)	**Downstream (Piracicaba)**	**MRSP**	**Total (Cantareira System)**	**Downstream (Piracicaba & Juqueri)**	**MRSP**
Mean Daily Water Withdrawal (m^3/s)	33.97	8.3063	24.92	39.05	9.20	29.85
Minimum Daily Water Withdrawal (m^3/s)	0.81	0.30	0.00	17.07	0.77	16.10
Maximum Daily Water Withdrawal (m^3/s)	150.01	128.00	35.00	158.70	128.20	33.00

e. THE 2014-DROUGHT

2014 has been the driest year in 80 years and also in 2015, the dryness holds the MRSP in a fierce grip. Water levels in the Cantareira Region have dropped to threateningly low levels and while governmental organizations proclaim water levels have reached levels as low as 6.2% on the 15th of January 2015, water levels actually reached negative values since water was being pumped from the dead volume of the reservoir, below the intake point (Osava, 2015).

To illustrate the severity of the drought, Figure 4 and Figure 5 present the monthly runoff in cubic meters per second from January 2004 to January 2015 and the water volume in the reservoirs of *Sistema Equivalante* (January 2013 – January 2015). Note the abrupt increases in reservoir volume twice during the past couple of months. These 'peaks' indicate the moments at which was decided to pump up (more) water from the dead volume of the reservoirs.

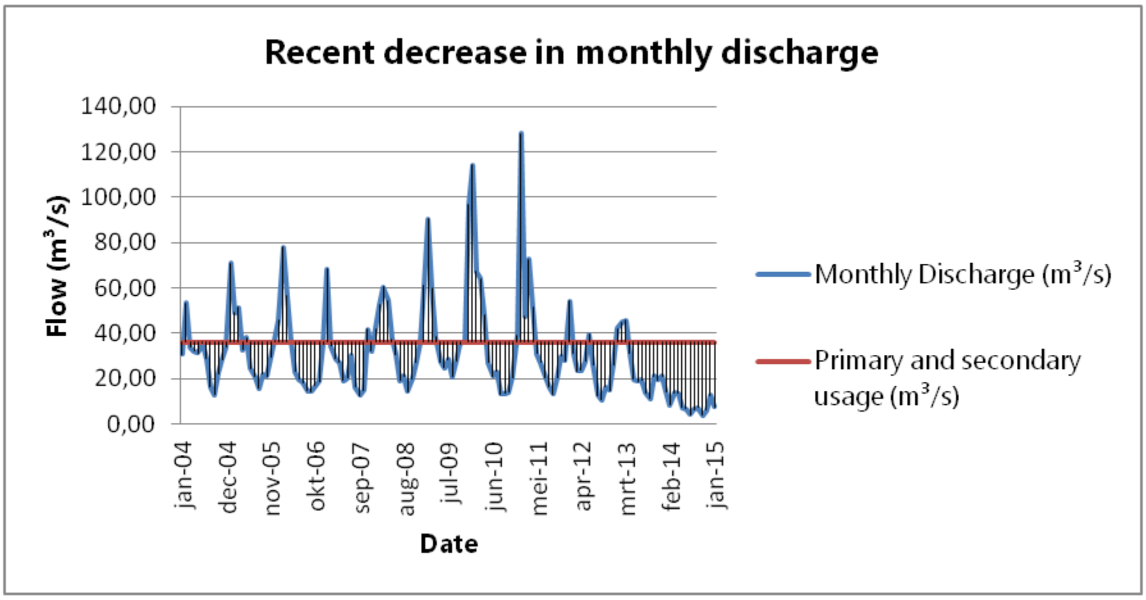


FIGURE 4: MONTHLY DISCHARGE FROM JANUARY 2004 ONWARDS IN COMPARISON WITH THE PRIMARY AND SECONDARY USAGE OF 36 M^3/S

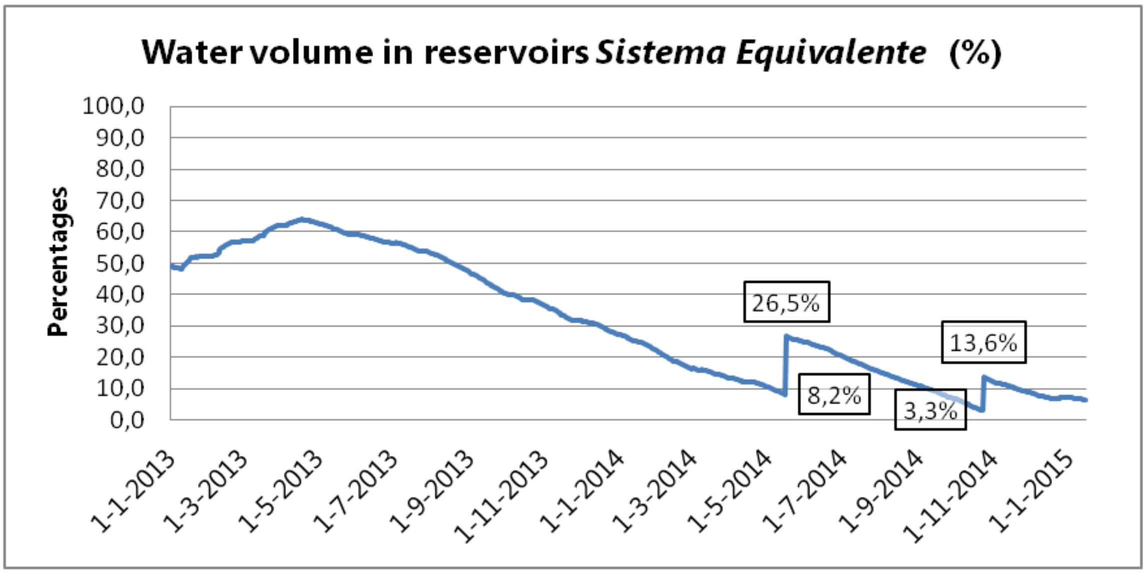


FIGURE 5: WATER VOLUME IN RESERVOIRS SISTEMA EQUIVALENTE FROM 2013 – JANUARY 2015

The figures show a severe drought in 2014 which already had its start early 2013. Even though the withdrawal of water from the Cantareira reservoirs has been reduced over the past couple of months, the water level in the reservoir continued to drop. The reduction of water withdrawal has been achieved through the implementation of several tactics. SABESP holds four different actions accountable for the 56% (17.74 m^3/s) reduction of Cantareira's water use: pressure control/loss accounts for 8.2 m^3/s, the increase of usage of water from other water systems for 5.4 m^3/s, the usage of bonuses for people who use significantly less water than before for 3.5 m^3/s and permissionaires for 0.6 m^3/s (SABESP, 2015).

SABESP has acknowledged that, as mentioned in the previous chapter, around 40% of the water leaked through the pipes – an improvement of water infrastructure could thus drastically decrease the water demand of 36 m^3/s – and mentions that the reduction of pressure has reduced the leakage of water through the pipes (Drummond & Netto, 2015). It furthermore has long stated that there was no rationing of water. From several media however, it can be understood that the loss of pressure in the pipes did not only cause a reduction of water use due to a reduction of leakage, it furthermore caused rationing of water in the, mostly poor, regions on hilltops in São Paulo. During parts of the day, water does not reach the high regions of the metropolitan area. Rumours go that upcoming elections caused politicians to refuse acknowledging the severity of the drought in 2014 and that actions like rationing should have been introduced earlier (Nolen, 2014). Measures that are thought to be necessary to take are for example mentioned by the *Alliance for Water* that calls for participative management, reforestation of drainage basins and, on short term, public campaigns and heavy fines (Osava, 2015).

The above mentioned late intervention is not the only reproach against the state. Researchers have openly questioned undertaken measures like the pumping of the dead volume in the reservoir. It was mentioned that the quality of the stagnant dead water is questionable and that the move was risky, knowing that it would take a lot of time to saturate the soil again afterwards. Furthermore, researchers point out the difficulties of the fragmented management of the water supply and the fact that the public-private conflict within SABESP might have caused mismanagement of water (Meckien, 2014).

f. THE MODELS

The modelled data from two models are at use to perform the evaluation of vulnerability and the assessment of impacts in the Sistema Equivalente. Both models – both their operation and output data – will shortly be described in this chapter. Appendix D provides a table in which all available data, both measured and modelled, is presented.

i. *PROBABILITY DISTRIBUTED MODEL (PDM)*

A probability distributed model is a conceptual model and differs from empirical models in the way that conceptual models intend to describe natural processes and their interactions. Whereas empirical models might predict the runoff purely determined on statistics, the PDM, on contrary, determines the prediction based on the interaction of several sub-processes and will thus not only be able to interpolate values (empirical models) but also to extrapolate. However, compared to physically based models, the PDM is easier to use since it abstracts certain processes. Whereas a physically based model describes the surface runoff process as a function of many variables like the soil texture and the infiltration capacity of the soil, PDM does not try to represent the physical characters of the region but considers the runoff as two sequential basins (Langbein, 2014).

How does it work?

The model considers that every single point in the watershed has a specific storage capacity. The spatial variation of this capacity is represented by a probability distribution (Figure 6). In case of precipitation, a part of the water will recharge the soil moisture and the remaining part of the precipitation will form the direct (surface) runoff. The ratio between these two variables at time step t+1 is defined by the distribution and the soil moisture content at time step t. Water that is being added to the soil moisture volume can either infiltrate to the groundwater reservoir or disappear due to evapotranspiration, whilst the water that forms the direct surface runoff will fill the surface storage reservoir. Both the surface water and groundwater reservoir will produce a runoff which are combined at the outlet forming the total runoff. These 'steps' which the model follows are presented in Figure 7.

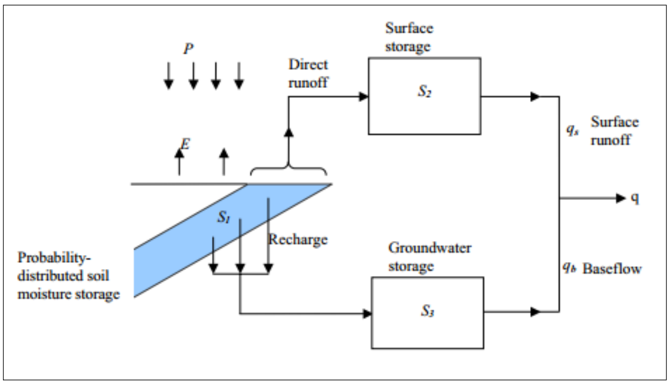


FIGURE 7: RAINFALL-RUNOFF MODEL PDM (MOORE, 2007)

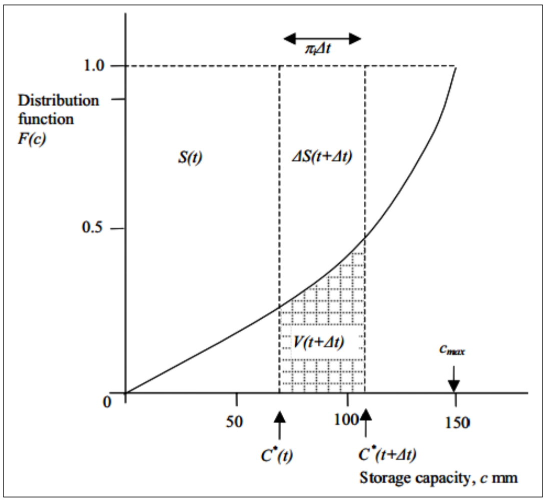


FIGURE 6: PROBABILITY DISTRIBUTION FUNCTION FOR STORAGE CAPACITY OF SOIL (MOORE, 2007)

Which data is being used:

For the Cantareira System the model uses the daily precipitation data from six rain gauging stations in the area, calculates it average and uses this as the daily precipitation (in mm) for the whole system. The evapotranspiration is defined using the historical data of evapotranspiration in the city Campinas, located outside of the Cantareira System. Furthermore, the PDM is calibrated, both per sub-basin and for the whole system, to measured runoff data by SABESP by changing model parameters ranging from the minimum and maximum store capacity in the probability distribution function to the time constants for the cascade of the two reservoirs and the groundwater recharge time constant k_g.

ii. Soil and Water Assessment Tool

Contrary to the conceptual based model PDM, the Soil and Water Assessment Tool (SWAT) is a physically based model that has proven to be successful for the assessment of water resources. It is, just like PDM, able to provide data for daily time steps and for simulation for long time records. It is able to calculate more than just the water resources and could, if provided with the correct input variables, give insight in, for example, crop yields, the amount of sedimentation and the degree of pollution of the water (Gassman, Reyes, Green, & Arnold, 2007). In this research, the focus will however be reclined to the assessment of water resources.

How does it work?

The watershed under revision is subdivided into different sub-basins which are separated into so-called hydrological response units (HRUs). The land use and management as well as the soil characteristics in a single HRU are homogeneous. Per HRU, the water yield is calculated. The water yield is a result of the calculation of the total hydrologic balance of the hydrological response unit, including all physical processes in the sub-basin: precipitation, evaporation (method of Priestly-Taylor), irrigation water, lateral subsurface flow etcetera. The water yields of the several HRUs within a sub-basin are summed resulting in a water yield per sub-basin. The water yields of sequential sub-basins are summed to form the outflow of the reach (Gassman, Reyes, Green, & Arnold, 2007).

Which data is being used:

For the precipitation, data of several gauging stations is used, after which the precipitation per unit area is determined through interpolation of the measured data for the centroids of each sub-basin. Values for relative humidity, temperature, and solar radiation data are necessary for the calculation of the evapotranspiration. Furthermore, characteristics of the region, like dominant land use and soil characteristics, are loaded into the model.

4. CHOICE OF LOW FLOW AND DROUGHT INDICATORS

Based on the information presented in chapter 2 and chapter 3 a choice for appropriate low flow measurements/indicators and drought indices has to be made. It is advised, according to Smakhtin (2001) that:

> *"… wherever an observed flow record of good quality is available, it should be used directly to obtain a variety of different low-flow indices."*

Due to a lack of available time, it is however not possible to calculate every single indicator. Based on required information and available data, a choice has been made for the indicators that are named in this chapter. However, it will first be addressed how the terms hazard, (potential) impact and vulnerability can be defined with regard to *Sistema Equivalente*.

a. HAZARDS, IMPACTS, VULNERABILITY AND ADAPTATION STRATEGIES (VIAS) IN THE CANTAREIRA SYSTEM

This research will focus on the role of drought in the water supply of *Sistema Equivalente* to the Metropolitan Region of São Paulo. Since the definition of a hazard faced by the community and the potential impact of this hazard on the water supply of this community, would not take into account any kind of adaptive capacity, the metropolitan region of São Paulo supplied by the Cantareira System could actually face three different hazards which have their own potential impact. A hazard would in this case be the occurrence of a low flow, being a low runoff, within a watershed (Jaguari-Jacarei, Cachoeira and Atibainha) into the *Sistema Equivalente*. These three parallel basins however, are currently interconnected through the usage of tunnels which has changed their nature; they have become sequential basins instead of parallel basins. This adaptive capacity has changed the nature of the system to great extent and creates the situation in which the whole part of São Paulo supplied by the Cantareira System is exposed to hazards (droughts) in three different watersheds. This research will both focus on the hazards and their potential impacts in single watersheds, but will also determine the potential impact taking into account the sequential connection as if not being an adaptive capacity. The fact that the MRSP is exposed is taken for granted since the part of the MRSP which is usually supplied by the Cantareira System, which would thus be exposed in case of a drought, is subject to the research.

A comparison with the water demand in cubic meters per second – divided by the percentage of total drainage area when calculated for a single watershed – indicates the potential impact of the hazard (the low flow). The water demand does in this sense represent the sensitivity of the supply; when the water demand is lower, the potential impact of a low flow is lower as well.

The next step is to incorporate the adaptive capacity; the water supply by the Cantareira system is not vulnerable to short periods of low flows due to the usage of reservoirs. These sequential reservoirs mediate both spatial – the interconnection of reservoirs – and temporal variability of low flows. In other words: a resident of São Paulo will not feel any consequences of a single day or week of low runoff values – the water supply will not run dry – due to a storage volume in the reservoirs and will furthermore not directly feel any consequences of a severe drought in one of *Sistema Equivalente's* watersheds if the other watersheds are still able to supply enough water to fulfil the total needs. In this research, the reservoirs and their interconnection are considered to be the only adaptive capacity. When one wants to address the vulnerability of the water users in the MRSP who rely on the water supply from the Cantareira system, the adaptive capacity to use water from other reservoirs should, for example, also be taken into account.

The research will not focus on the design of adaptive measures. However, it is interesting to know what kinds of measures are possible in order to know which information about the environment should be visualized. Some measures include: a change in the trade-off of the distribution of available water throughout a year, a change of soil usage in the watershed, change of water demand in the city (e.g. reducing the leakage through pipes) and a change of water usage upstream.

The above described interpretation of the terms hazard, (potential) impacts, adaptive capacity and vulnerability is summarized in Table 6.

TABLE 6: THE VARIABLES THAT REPRESENT THE SEVERAL COMPONENTS OF THE VIAS-ANALYSIS IN THIS RESEARCH

	Vulnerability			
	Hazard	**(Potential) Impact**	**Adaptive Capacity**	**Adaptive measures**
"Demand vs. Supply"-approach: vulnerability of the MRSP to droughts	Low Flows (Q)	Q_{supply} divided by Q_{demand}.	E.g.: the reservoirs, their management etcetera	E.g. more effective water management, planting trees, reduction of leakage.

b. Drought Indices

Chapter 2 presents a summary of several well-used drought indicators. Most of these indicators need long data records to present adequate and reliable results. In case of short records, the indicators might be influenced to great extent by a single year of drought. Furthermore, it would for the *Sistema Equivalente* be of the highest interest to calculate an index which indicates the hydrological drought. The watershed's main task is to deliver water to downstream regions and the consequences of a drought are mainly caused by a change in hydrological conditions during a drought spell – more specifically, a reduction in runoff. Furthermore, it might be interesting to compute the index on different time scales. Due to the usage of reservoirs, downstream areas – or, in case of the Cantareira System, both downstream areas and MRSP – won't feel the consequences of a single month of drought but might be more susceptible to drought periods with longer spells.

i. Standardized Runoff Index

The Standardized Runoff Index matches all the above mentioned criteria and monthly runoff data is available from 1930 onwards. This runoff data does, on first sight, not show any big down- or upwards trends throughout the years which might be caused by long term changes in the watersheds such as changes of river slopes, roughness and even changes of river sections which might have been of influence to the outcomes of the SRI. The long data records can thus well be used and ***SRI-1* and *SRI-6*** will be calculated for these measured monthly values from 1930 onwards. SRI-1 will provide some basic information about the severity of drought in single months, whereas the SRI-6 can be used for the identification of the continuity of drought and thus on reservoir levels. To calculate the indices for the period 2006 to June 2015, measured data will be replaced by outputs from both the PDM and SWAT-model (to June 2014). The SRI will be calculated for *Sistema Equivalente* and for each separate watershed to discuss both the temporal and spatial variability of the runoff.

Due to the usage of runoff values in an area which can rely on a continuous base flow during the whole year, problems with zero-flow values won't occur. Finding the correct fit of runoff data with a distribution model remains a problem. For this report, it is assumed that the runoff records in the Cantareira Region, do (closely) fit a gamma distribution.

The periods with low flows will be identified using low flow measurements and will be compared with the values for the SRI during the same time steps to identify the values of the SRI at which the hydrological runoff condition of *Sistema Equivalente* reaches critical values. Comparing the values of the SRI's of the three separate basins might give, next to insight in the severity of the hazards, valuable information in choosing adaptive measures which are to be adapted within specific watersheds (Table 7).

The used formulas to calculate the Standardized Runoff Index with the gamma distribution, including an explanation, can be found in appendix B.

TABLE 7: WHAT DOES THE SRI DETERMINE IN THE CONTEXT OF THIS ANALYSIS?

		Vulnerability			
		Hazard	**Impact**	**Adaptive Capacity**	**Direct information for which adaptive measures?**
A	"Demand vs. Supply"-approach: vulnerability of the MRSP to droughts	Direct representation of the hazards to which the community is exposed to, both from the different watersheds (comparison possible) and the system as a whole.			Comparison between watersheds gives information for measures within the watersheds : reducing water usage/different distribution over the year, change soil usage etc.

c. Low Flow Indices

A low flow index presents a certain feature of the low flow range. To get insight in the broad range of characteristics of low flows it is, as Smakhtin (2001) highlights, useful to calculate as many low flow indices as possible. Different studies and regions, however, prioritize the knowledge of different characteristics depending on the eventual goals of a project. This research is primarily being held to get to know the vulnerability to drought and impact of drought in downstream regions to eventually give a handheld for adaptive risk-based water management. The presence of reservoirs furthermore characterizes the region and the region of São Paulo and the residents in the Piracicaba basin are thus not susceptible to short periods of low flows.

It is furthermore important to take into account that a comparison between the modelled data and measured data might be relevant. In future planning, forecasted (meteorological) data might be used to model the runoff values. Knowledge of the reliability of the used models, especially during dry periods, is thus of importance. The low flow measurements, with the accompanying indices, chosen for this research are the flow duration curve (FDC), the deficiency volume (DV) and the base flow index (BFI).

i. FLOW DURATION CURVE

The FDC gives an insight in the occurrence probability of flows and is one of the most basic but meanwhile most informative measurements to get an insight in the flow range of a region. It can furthermore be used to compare both modelled and measured data since it is easy to standardize. For this research, several flow duration curves will be drafted. FDCs of ***daily runoff values*** derived from the PDM and SWAT data will be set up to project a detailed rendition of the flow range from 2006 onwards. Since this is just a very short time record, a method of ***Vogel and Fennessey*** (1994) – the mean FDC – will also be applied in order to compensate for the huge impact which one extreme year – which is present in these records – can make. Although both PDM and SWAT have been calibrated to SABESP measured data and both models are said to have good calibration results, a FDC will be set up for daily measured runoff data by SABESP in order to **verify** the modelled data from PDM and SWAT. FDCs will be calculated for both the *Sistema Equivalente* as a whole and the separate watersheds.

For the FDCs of the PDM and SWAT curves, the ***exceedance probability*** of both 27.8 m^3/s (primary usage) and 36 m^3/s (primary and secondary usage) as well as the average runoff during the 2013 – 2015 drought and the minimum average monthly flow will be calculated. Furthermore, to get an insight in the flow range of the *Sistema Equivalente* and to compare the measured and modelled data the long term flow (the average flow), Q95 and Q75 will be calculated for all FDCs.

The FDC of both *Sistema Equivalente* - when assumed that the interconnection of the reservoir is not part of the adaptive capacity – and of the separate basins form an indicator for the potential impact of a hazard since it can be used to compare the demand and the supply within the system (Table 8).

TABLE 8: WHAT DO THE FDCS DETERMINE IN THE CONTEXT OF THIS ANALYSIS?

		Vulnerability			
		Hazard	**Impact**	**Adaptive Capacity**	**Direct information for which adaptive measures?**
A	"Demand vs. Supply"-approach: vulnerability of the MRSP to droughts	The FDC itself presents the hazard (low flows) which can be faced by the community.	Comparing the values of the FDC with the demanded values gives insight in the potential impact of flows with certain probabilities.		Comparison between watersheds gives information for measures within the watersheds: reducing water usage/different distribution over the year, change land use. Comparison of FDC with demanded runoff values gives information on whether it would be necessary, and to which extent, to change the needs in the MRSP.

ii. DEFICIENCY VOLUME

The water supply to MRSP and the Piracicaba basin is influenced to great extent by the presence of reservoirs. It is thus interesting to see the occurrence of consecutive low flows and whether the reservoirs are able to withhold enough water during wet periods to prepare for the abnormally dry seasons. The calculation of the deficiency volume will occur through comparison of the inflow in the reservoirs, calculated by both PDM and SWAT, and the desired outflow of *Sistema Equivalente*. ***Several*** '***truncation levels***' can be defined, being: the primary usage of 27.8 m^3/s, the total usage of 35 m^3/s, the outflow limited by the regulations presented in Table 3 and the actual outflow. Daily reliable modelled runoff data is available from 2006 onwards, the DV will thus be calculated from then onwards. In order to calculate the DV with outflow values which depend on the water volume (Table 3), the water volume will be calculated with the use of a water balance.

It is important to notice that in the calculations, contrary to most prior research, the DV won't be set to zero after a couple of days of relatively high runoff values. The Cantareira region has relatively dry summers which can last for a couple of months and a couple of days of high precipitation in July won't compensate for the multiple relatively arid months before.

In order to visualize the vulnerability of the Cantareira System to drought and its impact on the water resources in the region, a couple of results will be highlighted. The ***amount of days*** at which the deficiency volume ***exceeded*** the useful ***volume*** of the reservoir, the useful volume of the reservoir plus its first raise of dead volume and the useful volume of the reservoir including the first and second raise of dead volume Figure 5. Furthermore, the ***increase/decrease in deficiency volume*** during a dry/wet ***season*** will be presented in a table. A comparison with the accompanying SRI-values for that season might provide useful information on the vulnerability to certain degrees of drought.

The deficiency volume of *Sistema Equivalente* will be calculated for the system as a whole and does take into account the adaptive capacity of the water system. In combination with information from the drought indicator and the region's sensitivity – the water demand – the deficiency volume presents information on the vulnerability of the water supply from the Cantareira system to droughts (Table 9).

TABLE 9: WHAT DOES THE DEFICIENCY VOLUME DETERMINE IN THE CONTEXT OF THIS ANALYSIS?

		Vulnerability			
		Hazard	**Impact**	**Adaptive Capacity**	**Direct information for which adaptive measures?**
A	"Demand vs. Supply"-approach: vulnerability of the MRSP to droughts			With the DV, all aspects of the determination of vulnerability can be taken into account. The hazard (low Q into reservoirs), the potential impact (comparison with demanded values) and adaptive capacity (the reservoirs). The region can make use of the reservoirs and inhabitants of São Paulo will only feel the consequences if the reservoirs reach their end. The reservoirs even out the spatial and temporal aspects of drought.	DV gives information for a successful trade-off of water distribution throughout a year and by calculating the DV for different outflow values, one can see whether the usage of water in MRSP might have to be changed.

iii. *Base Flow Index*

The last low flow measurement to be calculated is the base flow index. Both the flow duration curve and the deficiency volume are measurements that mainly give insights which can help planners in decision-making on which trade-off to make in the distribution of water throughout a year. The Base Flow Index, however, responds to different kind of strategies. A strategy, on the verge of being adapted in the Cantareira Region, is the planting of enormous amounts of trees. A change in the degree of forestation – and thus in soil usage – changes the portion of flow that originates from the base flow and thus changing the quickness of response in runoff to changes in precipitation. It might be interesting to influence the 'travel time' of water from the moment it precipitates to the moment it flows into the reservoir. A spatial comparison between the watersheds might provide useful information on where adaptive measures like aforestation might prove to be most effective. The

annual BFI will be calculated from 2006 onwards for the modelled data from PDM and SWAT. In order to be able to define the BFI, first, the base flow shall be separated from the total flow by the technique further explained in Appendix C.

It has to be said that changes in the BFI throughout the years or differences per watershed can be caused by many reasons. One of which would be the surface area of the watersheds. It is important to take this into account before drawing conclusions.

Contrary to the other indicators, the Base Flow Index does not give direct input for the determination of either hazards, impacts or vulnerability, although it might explain the severity of hazards in the comparison between several watersheds. It does however provide useful information for the implementation of adaptive policies, which is the reason of this research to impacts and vulnerabilities. Also for this indicator, its function is presented in a table (Table 10)

TABLE 10: WHAT DOES THE BASE FLOW INDEX DETERMINE IN THE CONTEXT OF THIS ANALYSIS?

		Vulnerability			
		Hazard	**Impact**	**Adaptive Capacity**	**Direct information for which adaptive measures?**
A	"Demand vs. Supply"-approach: vulnerability of the MRSP to droughts				The Base Flow Index is no indicator for hazards, impacts or vulnerability. It is however able to address differences in watersheds, pointing out the ratio between quick (surface) and slow (base) flow and thus in the variability of runoff. Planners might want to have influence on this and might have so by changing, for example, the land use.

5. RESULTS

In this chapter, the most important results of the calculations of the several indicators will be presented. In the next chapter, these results will be discussed and conclusions on the impacts of drought and the vulnerability to drought, as well as a spatial comparison between the basins and conclusions on the severity of the ongoing drought will be presented. The calculations were carried out on the modelled datasets from both PDM and SWAT. However, before drawing any conclusions, it is important to compare modelled and simulated data in order to know how well modelled data matches the real world.

a. COMPARISON OF MODELLED AND SIMULATED DATA

A comparison of modelled and simulated data has been carried out with the use of Flow Duration Curves. These have been set up for every basin for the data from the 1st of January 2006 onwards. Both the exceedance probability for several important runoff values as well as the runoff values (in mm) for Q75, Q95 and the long term flow are presented to get an insight in the flow regime of the basins and the degree to which the modelled data fits the simulated data. The comparison for *Sistema Equivalente* is presented in Table 11. The comparison for each sub-basin is presented in appendix G.

TABLE 11: COMPARISON OF MEASURED AND SIMULATED RUNOFF DATA FOR *SISTEMA EQUIVALENTE (1934 KM²)*

	PDM (2006 – June 2015)	**SWAT (2006 – June 2014)**	**SABESP (2006 – May 2015)**
Runoff Q95	0.339 mm/day	0.339 mm/day	0.273 mm/day
Runoff Q75	0.693 mm/day	0.557 mm/day	0.607 mm/day
Long Term Flow	1.375 mm/day	1.322 mm/day	1.363 mm/day

The modelled data for *Sistema Equivalente* is very close to the values measured by SABESP, especially for long term flows, and will thus suit to draw conclusions from the calculated indicators. When taking a closer look at the results for the singular basins (appendix G), SWAT-data strongly differs from the measured data for the runoff values from the Atibainha watershed. The close match between modelled and measured data from *Sistema Equivalente* is mostly due to the fact that the Atibainha reservoir just contributes to small extent to the total runoff of the system, but also due to slight 'compensation' from the other reservoirs. A spatial comparison between the sub-basins should thus mainly be carried out with PDM-data.

b. Presentation of Results

This chapter will present the calculated indicators both in graphs as well as in tables. In these tables, the significant values within the long range of data records, as well as information that can be derived from this data will be presented.

i. Standardized Runoff Index

Both the SRI-1 and SRI-6 have been calculated for PDM-data. For SWAT-data, the SRI-1 has been calculated. The mentioned indices have been calculated for every watershed and for *Sistema Equivalente* as a whole. The SRI-1 for the PDM-data is presented in Figure 8 and several important values in Table 12, the other graphs and tables can be found in appendix F. Other information presented in this sub-chapter (Table 13) is the amount of months in which the SRI-1 and SRI-6 remained below -2.0 (usually an indicator for severe droughts) and -3.0 (extreme droughts). Early discussion of these results show more extreme values for the smaller basins (Atibainha for values lower than -3.0 and Cachoeira for values below -2.0) and do furthermore show that not only the existence of extreme low monthly flows has occurred often after 2006 (including the dry period from 2013-2015), but that especially the duration of the low flows has been exceptional. Table ... furthermore shows the average SRI-1 per dry and wet season and the average annual SRI-1 for PDM-data for *Sistema Equivalente*. A comparison with the decrease or increase in deficiency volume during these periods can provide valuable insights for vulnerabilities for several drought severities. Outcomes for other basins and for SWAT-data can be found in appendix F.

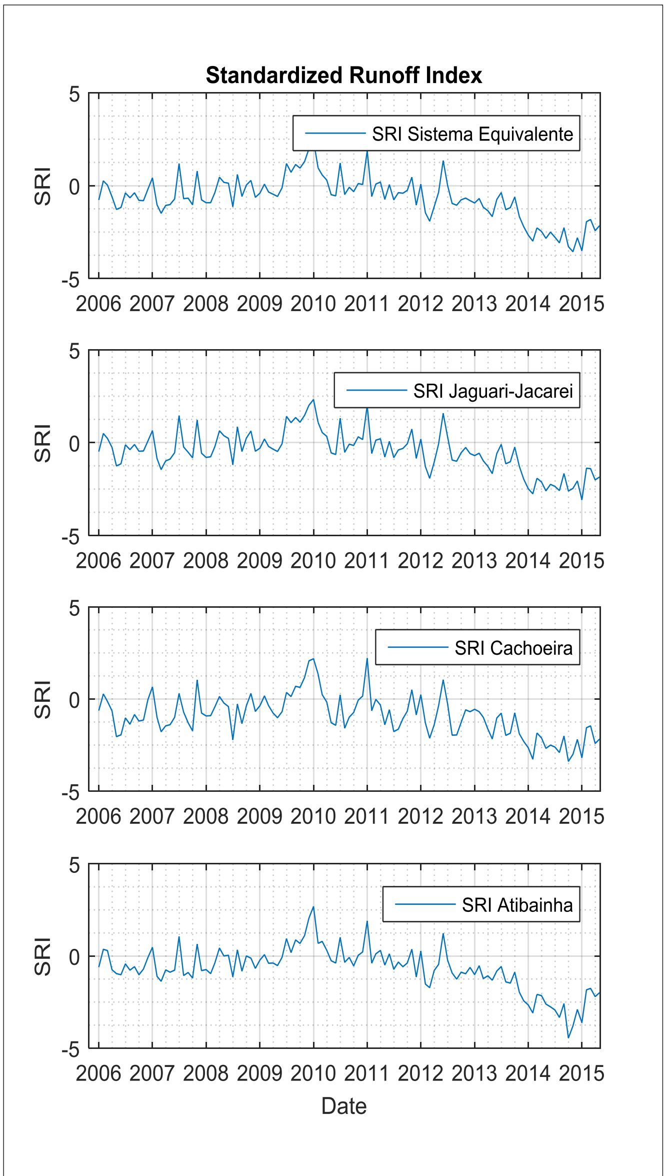


FIGURE 8: SRI-1 PER WATERSHED AND FOR SISTEMA EQUIVALENTE: PDM-DATA

TABLE 12: AVERAGE SRI-1 VALUES PER DRY AND WET SEASON AND ANNUAL VALUES: PDM-DATA

	PDM		
	Sistema Equilvalente		
	May – November	December (t-1) – April	Full year
2006	-0,78	-0,29	-0,56
2007	-0,31	-0,67	-0,51
2008	-0,07	-0,50	-0,24
2009	0,66	-0,35	0,45
2010	-0,09	1,25	0,31
2011	-0,29	0,33	-0,13
2012	-0,35	-1,10	-0,64
2013	-1,08	-0,99	-1,16
2014	-2,90	-2,52	-2,79
2015	-2,15	-2,50	-2,37

TABLE 13: AMOUNT OF TIME SRI-VALUES DID NOT REACH INDICATED VALUE (UNTIL MAY 2015)

	SRI-1 PDM - <-2.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	1	1	19	9
Total	17	13	38	24
	SRI-1 PDM - <-3.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	0	0	1	2
Total	4	1	5	7
	SRI-6 PDM - <-2.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	0	0	16	4
Total	17	17	33	21
	SRI-6 PDM - <-3.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	0	0	0	0
Total	11	8	6	13

ii. Flow Duration Curve

This sub-chapter presents the flow duration curves (flow in mm) for both PDM and SWAT modelled data and for every sub-basin. It furthermore presents for the PDM and SWAT modelled data from *Sistema Equivalente* which exceendance probabilities match important demand and supply values in m^3/s. These results might be used in a follow-up analysis of both the potential impact and the hazards faced during the recent drought. Data for the different sub-basins can be found in appendix G. Early

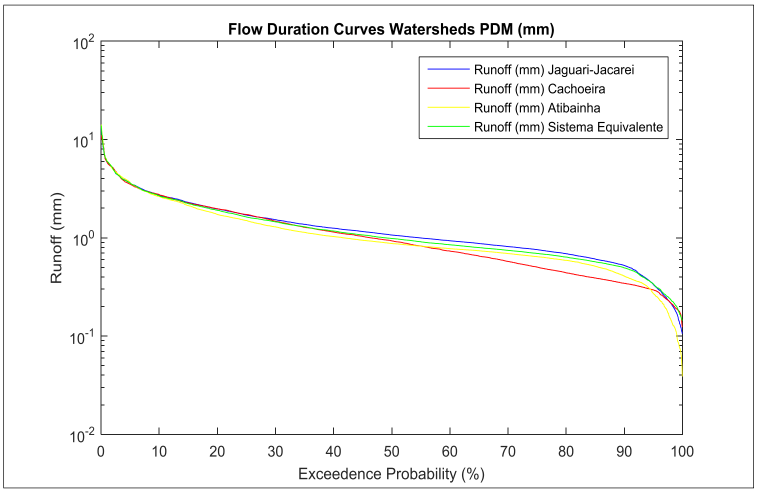


FIGURE 9: FLOW DURATION CURVES PDM RUNOFF FROM 2006-JUNE 2015

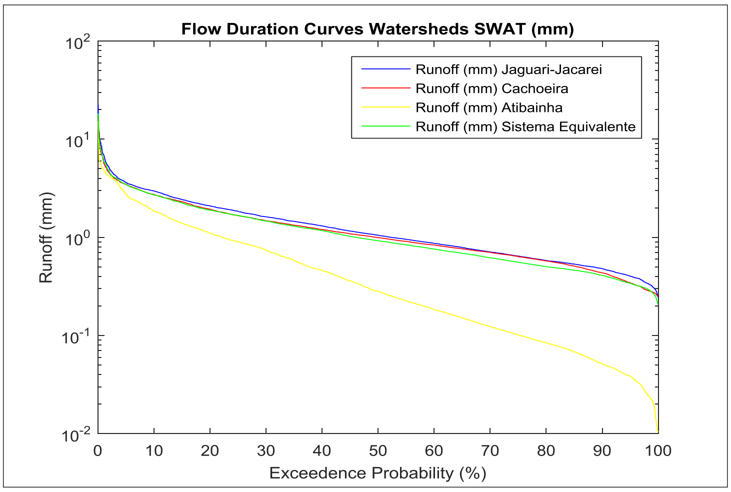


FIGURE 10: FLOW DURATION CURVES SWAT RUNOFF FROM 2006 – JUNE 2014

discussion on the data in table 14 shows relatively low exceedance probabilities of the demanded outflows – indicating harmful situation for downstream areas – and high exceedance probabilities for the average supplies during the recent drought – indicating the severity of the drought. One should notice that the exceedance probabilities for the runoff values during the drought do by no means represent information on the recurrence interval of the drought. The average flow of two years is compared with the flow duration curves of daily flows and the percentages are solely to present that, although the region knows high seasonal variability, even the average runoff is far below the average flow. In comparison, the mildy dry two years of May 2006 – May 2008 (negative values for SRI-1) have had an average flow which matches the exceedance probability of daily flows of circa 39.3%.

TABLE 14: EXCEEDANCE PROBABILITIES AND RUNOFF VALUES FOR SEVERAL INDICATORS: FLOW DURATION CURVES OF DAILY RUNOFF VALUES

	PDM (2006 – June 2015)	SWAT (2006 – June 2014)
Runoff Q95	7.60 m^3/s	7.60 m^3/s
Runoff Q75	15.51 m^3/s	12.47 m^3/s
Long Term Flow	30.77 m^3/s	29.60 m^3/s
Exc. Prob. 36 m^3/s	25.39%	26.51%
Exc. Prob. 27.8 m^3/s	36.59%	37.09%
Exc. Prob. Avg. Runoff During 2013-2015 drought	82.50%	71.20%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	99.30%	100%

iii. Deficiency Volume

Results for deficiency volumes are presented in Figure 11 and Figure 12. The volumes were calculated based on a water balance with modelled runoff values and for several outflow values: the outflow according to regulations presented in table ..., outflows of 36 and 27.8 m^3/s and the actual outflow. Evaporation of the water in the lake has not been taken into account since a comparison between calculated and measured water volumes with actual out- and inflows showed little but no differences when the evaporation from the reservoir was not considered in the model. The different outflow values provide insights in how the storage volume in the reservoir might be affected by different water usages. The deficiency volumes have been calculated with a fixed minimum of 0 m^3 - for which the reservoir is completely full – but without a maximum so that the graphs indicate which storage volumes the reservoirs should have had in order to have been able to cope with the recent dry situation. Only the deficiency volume based on actual outflows does take into account a surplus of outflow once the storage volume in

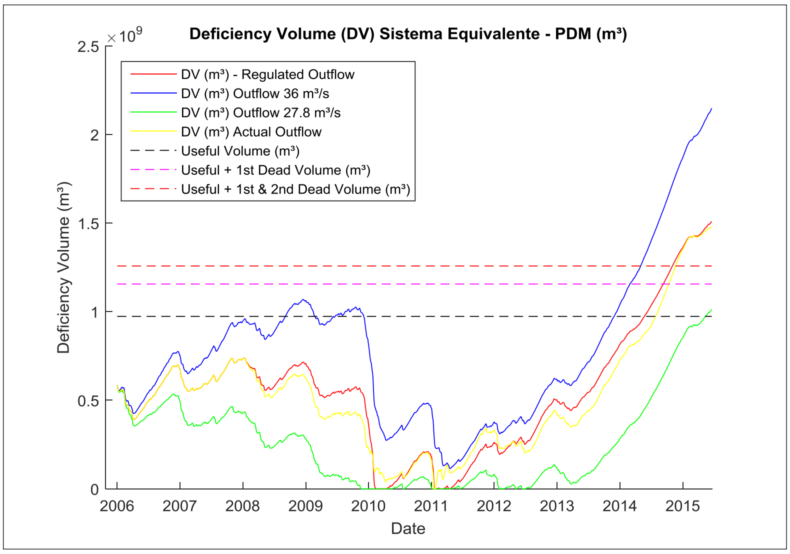


FIGURE 11: DEFICIENCY VOLUMES OVER TIME FOR SEVERAL OUTFLOW SCENARIOS (PDM MODELLED DATA)

the reservoir does almost reach values close to the full volume. Other outflows only take into account the fact that the deficiency volume can't reduce further once the reservoir is filled.

The deficiency volume for actual outflow is slightly higher than the measured deficiency volume, which is due to the fact that for 2006 and 2007, outflow has been set at the outflow values according to the regulations since daily outflow values were not at hand for these two years.

Figuur 13 furthermore represents the amount of days at which the deficiency volume exceeded certain water volumes (PDM-data). It is important to keep in mind in the discussion that the useful volume of the reservoir should not be surpassed and that the dead volumes of the reservoir was something not to be considered before the 2013-2015 drought. Additional information for SWAT-data can be found in appendix H. In this same appendix, useful information is presented for the discussion of deficiency volumes in terms of seasonal and annual variability. The increase in deficiency volumes during dry seasons and decrease in wet seasons can be compared with the accompanying average SRI-1 during the specific period of time to draw conclusions on the vulnerability for different drought severities.

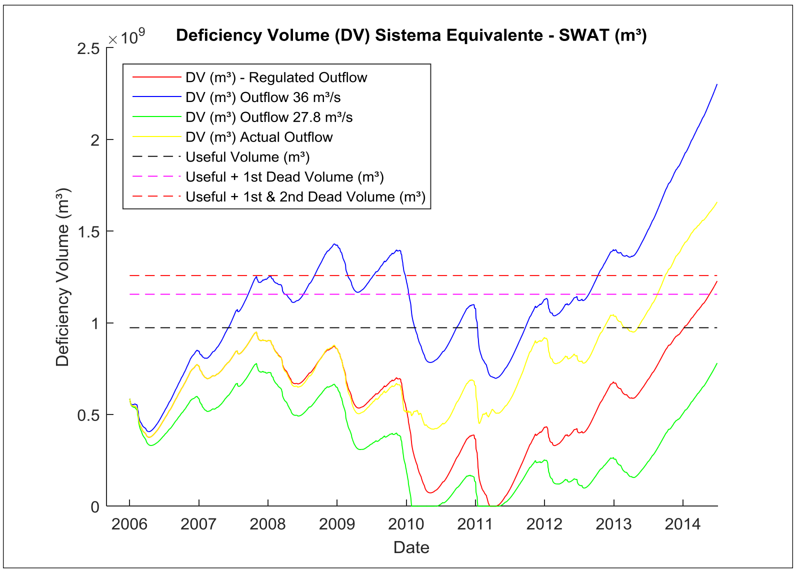
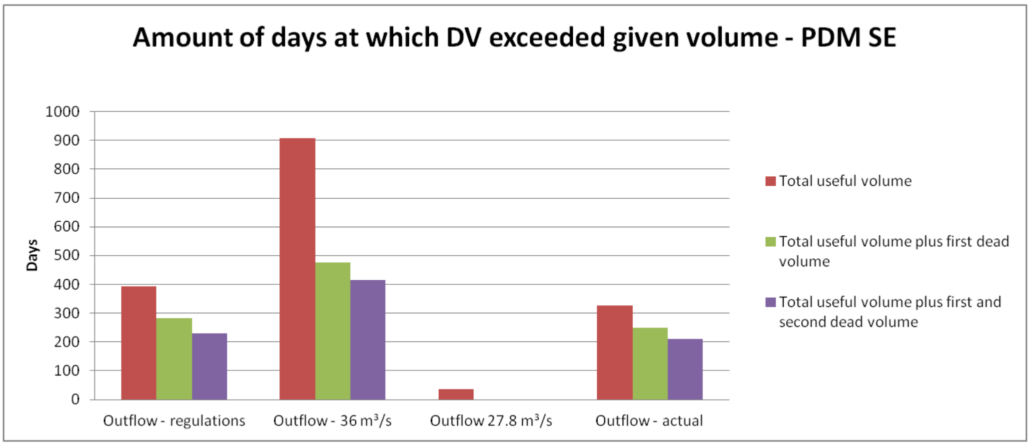


FIGURE 12: DEFICIENCY VOLUMES OVER TIME FOR SEVERAL OUTFLOW SCENARIOS (SWAT MODELLED DATA)

Interesting to notice is the fact that deficiency volumes would have barely exceeded the total useful storage volume of the reservoir by the end of May 2015 if the outflow had not exceeded the primary usage of MRSP and the Piracicaba Region combined (27.8 m^3/s).



FIGUUR 13: AMOUNT OF DAYS AT WHICH DEFICIENCY VOLUME EXCEEDED GIVEN VOLUMES (PDM-DATA) FROM 2006 - NOW

iv. Base Flow Index

An annual Base Flow Index has been calculated for all watersheds and for *Sistema Equivalente* as a whole. The base flow was first to be determined by the base flow separation technique of the Institute of Hydrology (1980) – explanation in appendix I – since modelled base flow from SWAT-data did include lateral flow in the base flow. The annual BFIs for both SWAT and PDM data are shown in Figure 14 and Figure 15, the average BFI over the entire time record is shown in Table 15. A short look on the data teaches us that the Atibainha watershed knows a lower BFI. A lower BFI might be the result of different, less favourable soil usage. A further analysis of these results will however follow in the discussion of the results.

TABLE 15: AVERAGE ANNUAL BASE FLOW INDEX PER WATERSHED

	Base Flow Index (2006 – 2014) – PDM				Base Flow Index (2006 – 2013) – SWAT			
	Jaguari-Jacarei	Cachoeira	Atibainha	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha	Sistema Equivalente
Average	0.759	0.715	0.689	0.724	0.660	0.640	0.558	0.633

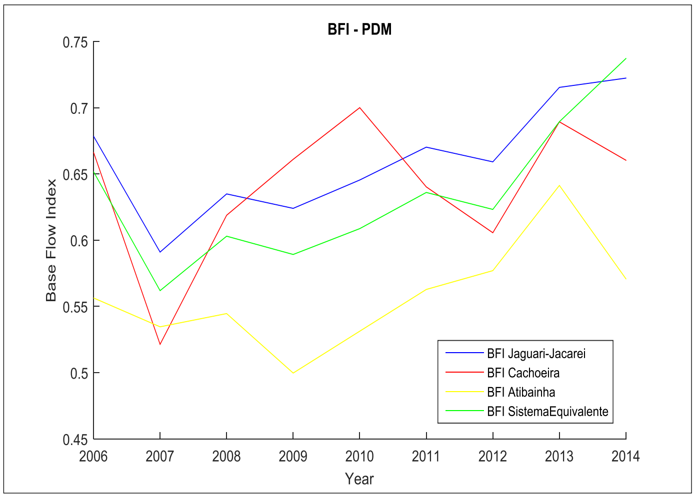


FIGURE 15: ANNUAL BASE FLOW INDEX (PDM-DATA)

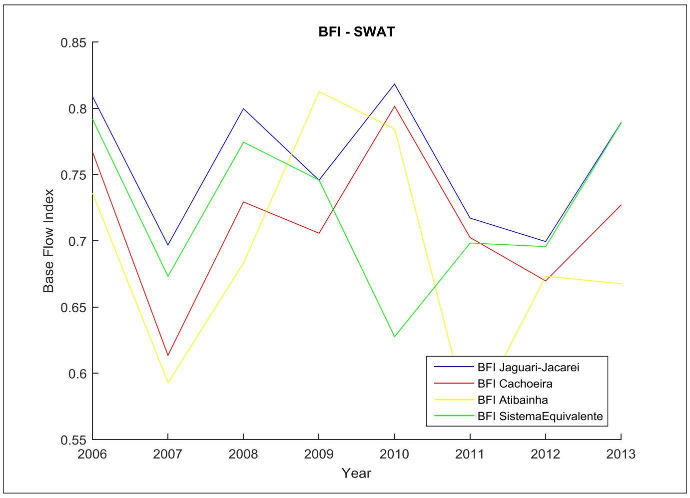


FIGURE 14: ANNUAL BASE FLOW INDEX (SWAT-DATA)

6. Discussion of Results

This chapter will discuss the results presented in chapter 5 and in the several appendices to which is referred in the aforementioned chapter. The discussion will be subdivided into an analysis of the hazards, (potential) impacts and vulnerabilities in the context of drought. In each sub-section a spatial analysis, as well as an analysis of the terms in the context of the recent historical drought and the normal annual and seasonal variability will be held. It is important to note that the discussion is carried out on historical data. Indices are calculated based on runoff data between January 2006 and June 2015 and are discussed in comparison with the current demanded outflows.

a. Hazards

For the analysis of the hazards, a closer look will be thrown upon the Standardized Runoff Index, the Flow Duration Curves and the Base Flow Index. This sub-chapter will be sub-divided in a discussion on the normal seasonal and annual variability, the recent extreme drought and a spatial analysis.

Annual and Seasonal Variability

Throughout a year, the runoff from the watersheds into the reservoirs fluctuates to great extent due to the differences in wet and dry season. The tributary's runoff values for which SRI-1 approaches zero, does not exceed 35 m^3/s from May to November and do remain, except for a slight exceedence in May, below the long term flow (Table 16). Flows do thus reach low values and can form hazards during a significant part of a year. Annual variability is also non-negligible. Maddocks, Shiao and Mann (2014) present a map with the annual variability in water supply and show ratios between 0.25 and 0.50 (standard deviation/mean annual water supply) for the Cantareira Region. This variability is also visible in the SRI-1 for both SWAT and PDM data. Average annual SRI-1 values range from -0.64 to 0.45 between 2006 and 2012 for PDM-data and between -1.11 and 0.14 for SWAT-data (Table 20 and Table 21). This means that the hazard faced during dry seasons might fluctuate slightly per year.

TABLE 16: MONTHLY RUNOFF DATA FOR MONTH IN WHICH SRI-1 (PDM) APPROACHED ZERO

	Runoff Values for SRI-1 ≈ 0
	Sistema Equivalente (m^3/s)
January	58.40
February	61.10
March	55.90
April	40.50
May	32.50
June	29.50
July	26.13
August	21.20
September	21.10
October	25.40
November	29.70
December	44.20

Drought 2013 – 2015

The recent imminent drought has shown high values for the Standardized Runoff Index. SRI-1 values reached negative values as low as -3.55 for the calculation of SRI-1 of *Sistema Equivalente* with PDM-data and Atibainha-values even reached -4.45. The SRI with SWAT-data does not reach further than June 2014 and thus does not show values for the extreme drought of late 2014 and early 2015. The values for early 2014 are even slightly higher due to this same fact. The drought hazard MRSP faced has been extremely high. A comparison of the amount of SRI-1 values below both -2.0 (severe drought) and -3.0 (extreme drought) before and after 2006 has shown a significant increase of low values from 2006 onwards (Table 13). The severity of the drought however becomes more visible with a quick glimpse on the SRI-6. Low SRI-1 values have occurred before 2006 as well, although with lower frequency, however, the duration of the ongoing drought has made the recent drought more severe.

Sistema Equivalente had not seen SRI-6 reach values below -2.0 before 2006 and has had these for 17 months since (Table 13).

The average monthly runoff from May 2013 onwards (13.517 m^3/s: PDM-values) – the first month in the dry season in which the average SRI-1 value was lower than -1.0 – has an exceedance probability of 82.50% (PDM) and 71.20% (SWAT) in the Flow Duration Curves for daily runoff values from 2006 onwards. The lowest modeled monthly runoff (PDM) was as low as 4.03 m^3/s. This runoff matches exceedance probabilities of 99.30% (PDM) and 100% (SWAT) on this same Flow Duration Curve. When looking at the mean FDC, the exceedance probability reaches 100% for both modeled data records (Table 14). The above mentioned data clearly states that the 2013-2015 drought has been very severe.

It should however also be addressed that the average (annual) SRI-1 has been slightly lower than zero from 2006 onwards; SRI-1 for SWAT values did barely surpass zero between 2006 and 2014 (

Table 21) and, although not statistically proven, a trend is visible. These low runoff values throughout the past years might, amongst other causes, be the result of the deforestation in the Amazon, which have the task to lift huge amount of water into 'flying rivers' supplying water to the southern and central areas in Brazil (Maddocks, Shiao, & Mann, 2014). Hazards might thus have increased, and might further increase, over the years.

Spatial Analysis

Analyzing the different watersheds might provide useful information for the consideration of adaptive management within the watersheds to reduce hazards. SRI-1 and SRI-6 values do differ between the watersheds. The SRI-1 for Atibainha and Cachoeira shows more extremes in with significantly more values below -2.0 and -3.0. Cachoeira shows more SRI-values below -2.0, while Atibainha's SRI-1 shows more values below -3.0 (Table 13).

This higher amount of negative extremes matches the average BFI of the reservoirs with a slight distinction between Atibainha (0.689), Cachoeira (0.715) and Jaguari-Jacarei (0.759) for PDM-data (Table 15). Lower BFI's indicate faster runoff, thus a faster response to the ever-changing precipitation values and possibly more fluctuation in the SRI. Differences in BFI and SRI-1 between watersheds might be especially interesting for adaptive measures if these would directly address the need for different soil usages (e.g. different vegetation). However, it is too soon to conclude anything in this context. With the Atibainha and Cachoeira watersheds being significantly smaller than the Jaguari-Jacarei watershed, the influence of the 'travel time' of water should not be underestimated. Furthermore, the steepness of slopes might have an effect, just like the amount of small streams that drain into the main tributary (Alevel Geography; Gan, Sun, & Luo, 2015). Different precipitation, which usually is also a factor, can't have any spatial influence on the calculated results since PDM has used the same precipitation per unit area for the whole *Sistema Equivalente*.

A Brazilian view upon the results:

Brazilian colleagues at NIBH have showed some doubts on the conclusion of several researchers that runoff might decrease due to an increase in evapotranspiration as a result of forestation. An increase in evapotranspiration might on the long term change the micro-climate in the watersheds and with the region being quite mountainous, it is likely that the evapotranspirated water will rain down again in the same watershed. Furthermore, a quick runoff of water will cause the reservoirs to fill more quickly, resulting in higher storage volumes and bigger areas of open water and thus, eventually, in higher evapotranspiration.

A Brazilian view upon the results:

Why would policy makers want to slow down the water in its travel between precipitation and inflow in the reservoir? Higher BFI would mean that the runoff is more evenly spread out over a year, causing less problems due to variability in water supply. However, the reservoirs do already fulfill this task. Researchers at NIBH do still think higher BFI would be desirable in the Cantareira System. High runoffs during the wet season might trigger water suppliers to increase the outflow to MRSP, eventually resulting in slightly higher deficiency volumes at the beginning of the dry season. A higher BFI might create a buffer for mismanagement of the water due to higher outflows in the beginning of the dry season as a result of the precipitation in the end of the wet season.

b. (POTENTIAL) IMPACTS

As described in the definition of the terms 'impacts' and 'vulnerability' and its interpretation in this research, the potential impact does include both the hazard and the sensitivity of the area – in this case the water demand – and does not incorporate the adaptive capacity of the system. This sub-chapter will incorporate the same three topics as the previous sub-chapter in its discussion on impacts.

Annual and Seasonal Variability

The potential impact of low flows as a seasonal phenomenon and the annual variability is rather high. With the long term average just being slightly above the primary usage of 27.8 m^3/s (Table 14) and being lower than the total usage, it is inevitable that average runoff reaches values far below the demand during the dry season. From May to November runoff values for SRI≈0 are lower than the combined demand of MRSP and the Piracicaba Region (36 m^3/s). It is however important to address in this context that the FDC was set up with just ten years of data including two years of severe drought. The mean FDCs do already show slightly higher runoff values for the same exceedance probabilities, however, still being critical for a huge percentage of the flows.

The SRI-1, being calculated with monthly data from 1930 onwards shows an average annual runoff of above 40 m^3/s in a year (2009) in which the SRI-1 slightly surpassed zero. However, during 2008 – with a SRI-1 of -0.55 being a good example of the annual variability that might occur – the average runoff barely reached 32 m^3/s. It should however be pointed out that also during these relatively normal years, daily runoff values often failed to surpass the primary usage of 27.8 m^3/s.

It is clear that the potential impact of drought is high due to the influence of dry seasons and low flows often stay under the thresholds set by the water demand.

2013-2015 drought

The recent drought is accompanied by an even higher potential impact. According to PDM modeled data, the average runoff from May 2013 to June 2015 was with just a mere 13.5 m^3/s not even half of the demand for the primary usage of water. These values – 13.5 m^3/s – did not even surpass the current actual 'demanded' outflow, which has been reduced to great extent by the usage of other reservoirs, the reduce of pressure in the pipes (causing high areas not to receive water) and rationing. During many days and months the water supply was lower than 13.5 m^3/s, causing high potential impacts with demand/supply ratios high above 1.0. Although possibly negliglble, it should be addressed that potential impacts will be slightly higher for the recent drought for modeled data. As Table 11 shows, the modeled extreme low flows are slightly lower than the measured low flows.

Spatial Analysis

Spatial analysis between the watersheds does not show big differences in potential impacts. In this discussion both the demand and supply are standardized to the full drainage area of *Sistema Equivalente*. Values show a slight difference in exceedence probabilities between the different watersheds for 36 m^3/s and 27.8 m^3/s with Jaguari-Jacarei being the most 'reliable', producing the most amount of runoff per square meter, followed by Cachoeira and Atibainha. For all watersheds however, the exceedence probabilities for these runoff values are far below 50%, causing high potential impacts. The same relation between the watersheds is visible for Q95, with runoff values being slightly higher for Jaguari-Jacarei. Q75 breaks the pattern; Cachoeira has lower runoff values than Atibainha for Q75. The difference between the watersheds can be seen for both PDM and SWAT-outcomes and can thus not only be explained by differences in precipitation. The outcomes of the FDCs might mean that the differences in BFI are not caused by different soil usage. According to, amongst others, L.M. Tallaksen and H.A.J. van Lanen (2004), vegetation causing higher BFIs results in higher potential evapotranspiration and thus lower runoff values, an effect which is opposite to what can be seen in the FDCs. One should however be careful with drawing conclusions since the PDM and SWAT models were mainly calibrated to the whole *Sistema Equivalente* and, as addressed in chapter 5, modeled runoff data differs slightly from measured data for single watersheds.

C. VULNERABILITY

The MRSP faced big hazards in the context of drought during the past years and due to a demand which exceeds the supply on many occasions, the potential impact of the hazard is high. The region however has a certain adaptive capacity to drought, mainly being the reservoirs. With the use of the calculation of deficiency volumes over time, the vulnerability to certain drought hazards can be addressed. The chapter will be sub-divided in a discussion on the 2013-2015 drought and annual and seasonal variability. Spatial variability won't be addressed since, due to adaptive capacity of the system – the interconnected reservoirs – the watersheds are now sequential rather than parallel.

2013-2015 drought

Calculations of the deficiency volume show that the water supply to MRSP is highly vulnerable to droughts which occurred between 2013 and (still ongoing) 2015. Deficiency volumes surpass both the useful volume of the reservoir and the useful plus dead volume of the reservoir with outflow values matching the desired outflow of 36 m^3/s. Also for actual outflow values and outflow values according to the regulations, deficiency volumes surpass the dead and useful volume of the reservoirs, meaning that the water supply of the Cantareira system is influenced by the drought hazard. It is hereby important to keep in mind that real deficiency volumes for actual outflow values were slightly lower due to the fact that the outflow according to the regulations has been used in 2006 and 2007. It should however also be addressed that the actual outflow reached values far below the desired outflows in the last couple of months.

Remarkably, if the reservoirs would have had an outflow of 27.8 m^3/s – the primary usage – ever since 2006, deficiency volumes would just in May 2015 have reached as high as the useful volume of the reservoir (PDM-data). Keeping in mind however that the dry season of 2015 has just started, and that deficiency volumes even increased during the wet season for the past year, the deficiency volume is likely to increase further the upcoming months.

Annual and seasonal variability

The water supply to MRSP is not vulnerable to the low flows which usually occur during one dry season. On the longer term however, even mild droughts accompanied with higher outflows might cause problems.

A dry season with a SRI-1 of approximately zero had a difference in deficiency volume between 30th of April and the highest modeled deficiency volume during the following dry season of 1.90E08 m^3 (Table 17) with an outflow of 36 m^3/s (PDM-data). The total useful volume of the reservoirs is approximately 9.73E08 m^3 and the reservoirs are thus well capable of coping with the usual seasonal low flows, even with outflow values as high as 36 m^3/s. It should however be addressed that with an outflow of 36 m^3/s, the reservoirs are just filled with 1.31E08 m^3 (Table 17) during a wet season with average SRI-1 values of -0.35, well within the 'mild drought' range (Table 18). This means that a wet season with average SRI-1 of -0.35 will not be able to compensate for the losses in a dry season with average SRI-1 of -0.07. On the long term, this might – considering the potential trend of lower runoff values and higher demand – cause a slight increase in deficiency volume over the years, eventually causing problems. Three glosses should however be made; firstly, although average SRI-1 were lower than zero from 2006 to 2015, this trend is not statistically proven in this report. Secondly, outflows according to regulations do already show higher increases in deficiency volume in the named wet season than decreases during the 2008-dry season, thus not causing problems. Thirdly, the average SRI-1 per season is being compared with the difference between the DV at the start of the dry/wet season with the highest/lowest recorded DV. It would however be possible that this maximum or minimum has been recorded well before the end of the season and that the last, possible extreme, month(s) of the season has changed the average SRI-1 over the season to certain extent. These differences would however be minimal since the DV's at the end of the seasons do match the highest or lowest DVs during that specific season quite well over the years.

The annual and seasonal variability of one year can be coped with quite well; only on the long term, with outflows of 36 m^3/s, problems might be visible. However, although not as extreme as the 2013-2015 drought, a couple of years with mild drought, accompanied with an already slightly lower deficiency volume at the start, would already have caused problems in 2008 and 2009 with outflow values of 36 m^3/s (PDM-data). The years 2006, 2007 and 2008 were years with mild droughts and, although the average SRI-1 was positive during the dry season of 2009, deficiency volumes would ran higher than the useful volume of the reservoirs in both 2008 and 2009 (Figure 11). These problems did not occur for regulated outflow, actual outflow and outflows of 27.8 m^3/s, furthermore, the deficiency volume was already as high as two-third of the useful volume in the reservoir in the beginning of 2006. It does however show that the MRSP is slightly vulnerable to a couple of consecutive years of mild drought – still considered to be within the range of near-normal values – since it won't be able to use the full amount of desired water.

It is furthermore remarkable that the influence of a slight difference in runoff between PDM and SWAT-data has high consequences for the deficiency volumes for fixed outflows (approximately 3.15E07 m^3 per year with a 1 m^3/s lower runoff). SWAT outcomes thus show even higher deficiency volumes and DVs exceed the useful volume of the reservoirs for 2008, 2009 and 2010 with fixed outflow values of 36 m³/s These differences would most likely not occur between PDM and measured data since the long term flow of both data sets do closely match (Table 11) and the average in-/decrease of DV thus as well.

TABLE 17: AVERAGE SRI-1 AND DIFFERENCES IN DV FOR DRY AND WET SEASONS (PDM-DATA) WITH OUTFLOW VALUES OF 35 M³/S FROM 2006-2015

	Average SRI-1 and differences in DV for dry and wet seasons: PDM-data, outflow of 36 m³/s				
	Deficiency Volume at 30 Apr.	Difference DV dry period May. – Nov.	Difference DV wet period Dec (t-1) – Apr.	Average SRI-1 dry season	Average SRI-1 wet season
2006	4,50E+08	3,17E+08		-0,78	-0,29
2007	7,01E+08	2,37E+08	-1,16E+08	-0,31	-0,67
2008	8,65E+08	1,90E+08	-6,74E+07	-0,07	-0,50
2009	9,34E+08	9,12E+07	-1,31E+08	0,66	-0,35
2010	2,84E+08	1,99E+08	-7,08E+08	-0,09	1,25
2011	1,25E+08	2,42E+08	-3,66E+08	-0,29	0,33
2012	3,82E+08	2,19E+08	-3,97E+07	-0,35	-1,10
2013	6,27E+08	3,54E+08	-1,83E+07	-1,08	-0,99
2014	1,26E+09	5,42E+08	2,06E+06	-2,90	-2,52
2015	2,06E+09	8,84E+07	2,67E+06	-2,15	-2,50

d. An Expert Opinion

As an addition to the discussion in this report, it is interesting to note how Brazilian experts on hydrology and, more specifically, on the drought situation in the Cantareira System look upon the results of the calculation of the indicator. A researcher at NIBH, part of the laboratory of hydrology at the Engineering School of São Carlos, Universidade de São Paulo, is quoted:

> *"The observed and simulated data showed how the drought was imminent and previous action could have been taken. The enlightened simulation showed that sticking to the primary water use could have avoided the use of the dead volumes and give time for more actions. On the long term, reforestation, which is being popularly mentioned as a solution, would from my point of view have the impact of a more even distribution of water during a year and water with better quality. Although the reservoirs should solve the seasonality issue, recently faced demand did not always follow water availability and restrict operation was needed. An even distribution might lead to a more reasonable use and alleviate the system operation."*

6. CONCLUSION

After a literature study on adequate indicators for a proper assessment of impacts and vulnerabilities, a study of the region suspect to this research and a choice on four different indicators, the hazards, (potential) impacts and vulnerabilities could be analyzed. This conclusion will reflect shortly on the found outcomes to the research questions as proposed in the introduction of this report.

Hazards

The system is opposed to significant low flow hazards both due to seasonal and annual variability. Furthermore, the recent 2013-2015 drought has opposed a huge hazard, with runoff values far below normal and Standardized Runoff Indices occasionally indicating severe droughts, on the inhabitants of the Metropolitan Region of São Paulo. Especially the continuity of the severe drought, resulting in high SRI-6 values, was remarkable. Interesting to note are the differences in hazards occurring in the different watersheds. The Atibainha and Cachoeira watersheds have significantly more extreme SRI-1 and SRI-6 values, accompanied with lower values for the base flow index.

(Potential) Impacts

Very high potential impacts could be identified for the demand/supply ratio in the Cantareira System. Current primary and secondary demand exceeds the supply even during years with normal runoff from May to November and annual variability causes even higher potential impacts during mildly dry seasons. The system shows extremely high potential impacts for the recent drought with average monthly runoff values from May 2013 – May 2015 not even exceeding half of the primary usage of the water system. Spatial analysis does not show large differences between the watersheds, although the Jaguari-Jacarei watershed seems to produce slightly more runoff per unit area.

Vulnerability

The vulnerability to severe droughts, as occurred between 2013 and 2015, is very high. Deficiency volumes, calculated with runoff data from 2006 onwards, would have exceeded the sum of the useful and dead volume of the reservoir with actual outflows, outflow according to regulations as well as with outflows matching the total demanded outflow of 36 m^3/s. Although deficiency volumes just surpassed the total useful volume of the reservoir in May 2015 with outflow values of 27.8 m^3/s (primary usage), deficiency volumes are likely to increase further with another dry season just ahead and, without adaptive measures such as an improvement of the water infrastructure, a continuous outflow of 27.8 m^3/s will cause problems on the long term.

The metropolitan region of São Paulo is in essence not vulnerable to the low flows in one dry season occurring due to seasonal or annual variability. However, during years of mild drought, the wet season is not able to fully compensate for the increase in deficiency volume during the dry season for outflow values of 36 m^3/s. In 2008 and 2009 (2010 as well for SWAT-data), this would already have resulted in deficiency volumes exceeding the useful volume of the reservoir. This leaves the region slightly vulnerable to annual and seasonal variability; problems can be prevented through the regulation of the outflow, but the MRSP would not have been able to use the full demand of water.

7. RECOMMENDATIONS

This report will be finished with several recommendations. The chapter will focus on aspects which might improve the outcomes of the calculated indicators as well as, more extensively, on recommendations on future research.

Possible improvements

Because of time constraints, it has not been possible to define which probability distribution function suits the runoff records best for the calculation of the Standardized Runoff Index. It has been assumed that a gamma distribution matches, or at least closely fits the probability distribution of the monthly runoff values. Further research might however show that, for example, the Pearson III-distribution fits the runoff values best, providing the reader with more precise SRI-1 and SRI-6 values.

It might furthermore be possible to compare the outcomes of the BFI for several base flow separation techniques. In this report, the separation technique of the Institute of Hydrology has been used, eventually resulting in rather high values. A comparison with other techniques might prove to be useful to verify the correctness of the base flow data.

Thirdly, an improvement can be made on the calculation of the deficiency volumes. It is possible to take into account the regulations for the increase in outflow to the Piracicaba region in case of (very) high levels in the reservoirs.

At last, interesting insights on the severity of the present drought might be visible if not only (mean) Flow Duration Curves of daily runoff values would be calculated but if the monthly measured runoff data from 1930 onwards would also be used to make FDCs.

Future research

The impact and vulnerability has been calculated with the possibility of the design of adaptive measures in mind (the VIAS-approach). It was beyond the scope of this project to design any adaptive measures, but future research might focus on this with the acquired knowledge from this report as a starting-point. It might furthermore be interesting to calculate the indices for hazards, impacts and vulnerability considering the implementation of adaptive policies to calculate their (positive) influence. The tables in chapter 4 can provide useful information to decide which information might be used as input for the choice of several adaptive policies. The spatial analysis of hazards, through discussion of the Base Flow Index and Standardized Runoff Index, can form the base to decide where measures within a watershed (reduce of demand, change of soil usage etcetera) might be necessary or effective. A further analysis of the results is however necessary to determine which characteristics of the watersheds caused the spatial differences in SRI and BFI. The discussion on the Flow Duration Curves and Deficiency Volumes should be used in the choice for measures which would, geographically, be taken closer to MRSP; reduce the demand in MRSP, reduce leakage, change the 'trade-off' of water throughout a year etcetera.

Other research might be focused on a more detailed spatial analysis of, mainly, the hazards. Spatial analysis is now constrained to the comparison of the three different watersheds, however, for adaptive measures within the watershed itself, an analysis of the SRI, BFI and FDC (in mm) on different points within the watershed might provide useful information for the implementation of the right measures in the right place and will possibly give better insight in the causes of the differences in BFI and SRI between the different watersheds.

Thirdly, it might be useful to apply a statistical analysis on the outcomes presented in this report. Without this analysis, one is constrained to draw reserved conclusions on vulnerability, impacts etcetera. It might, at last, be interesting to look at vulnerability in a broader picture; can the consequences of a shortage of water be reduced in São Paulo by better health care, infrastructure etcetera?

A last, but not negligible recommendation, mentions the possibility to use this methodology on different study areas. Many regions in the world are impacted by drought and an evaluation of the vulnerability and assessment of the impacts can be relevant across the world. The approach as presented in Figure 1 can be used in many other drought-impacted watersheds. The use of these exact same indicators is however restricted to impact and vulnerability assessments of the water supply from systems that rely on the usage of reservoirs. In case of, for example, a vulnerability assessment of drought in the agricultural sector supplied by rain-fed creeks from a single watershed, other drought indicators (e.g. the Palmer Drought Severity Index) are more applicable and several low flow measurements (e.g. the Deficiency Volume and the Base Flow Index) might be less useful or might have to be used in a different way. The Deficiency Volume would for example still be interesting, but mostly for short periods of drought with values returning back to zero after short rainfall which provides the agricultural land with enough water to saturate the soil. Many drought-impacted basins, especially those exposed to big seasonal variability, do however rely on reservoirs and then the same indicators, albeit with different input variables and discussed in comparison with a different sensitivity, could be used.

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APPENDICES

APPENDIX A: OTHER DROUGHT AND LOW FLOW INDICES

Chapter 2 of the report elaborates about some of the most well-known drought indices and low flow measurements. Some others can however be found in literature. This appendix will shortly provide the most important information about these indices and measurements.

Drought Indices

- Reclamation Drought Index (RDI): A recent developed index which can both determine the severity of the drought and the onset and end of a drought. To a certain extent, the RDI is similar to SWSI, it however includes the evaporation through a temperature component and includes the factor duration (National Drought Mitigation Center).
- Crop Moisture Index (CMI): Effective to determine short-term agricultural drought by calculating the moisture balance with the weekly temperature and precipitation as input variables. The CMI is however not good in monitoring long term droughts and furthermore has some flaws in the determination of its index when temperature changes (Mishra & Singh, 2011).
- Vegetation Condition Index: This index is also mainly designed as an agricultural drought index. With highly advanced satellites, which survey land, climate, ecology and weather condition data, researchers can determine the state of vegetation in a region and herewith determine the Vegetation Condition Index (Mishra & Singh, 2011).
- Percentage of normal: A more simple index is known as the 'percentage of normal'. Its name does already reveal the trick. It is however important to notice that the normal or mean has a different value than the median due to the not-normal distribution of the precipitation (National Drought Mitigation Center).
- Groundwater Resource Index: This hydrological drought indicator standardizes monthly groundwater storage by dividing the difference in current storage and the mean with its standard deviation (Trambauer, Maskey, Werner, Pappenberger, Beek, & Uhlenbrook, 2014).

Low Flow Measurements

- Several rather easy low flow measurements can be distinguished: the mean annual runoff (MAR), the mean daily flow (MDF), the Median Flow (the middle value in a ranked series of runoff values) and the absolute minimum flow (the lowest flow ever recorded). The mean annual runoff is the mean value of the annual flow totals whereas the mean daily flow can be derived through dividing the MAR with the total amount of seconds within a year (Smakhtin, 2001).
- Recession Analysis: during periods of low precipitation, soil storages run dry due to base flow runoff and evapotranspiration. This causes total runoff values to decrease. The rate at which the runoff decreases differs per watershed and is dependent on the characteristics of the watershed. The part of the curve in a stream flow hydrograph showing the reduction of runoff is called the recession curve. As part of a recession analysis, a recession constant can be estimated. This can, for example, be achieved with the use of an envelope; a curve with the flow at a certain day plotted against the flow *n* days before for all single recession curves with a duration longer than *n* amount of days. The slope of the envelope represents the recession constant. (Tallaksen, 1995)

APPENDIX B: CALCULATION OF STANDARDIZED RUNOFF INDEX

This appendix will elaborate the calculation of the SRI in detail. The methodology is derived from the calculation of the Standardized Precipitation Index, as proposed by Edwards and McKee (1997). Edwards and McKee (1997) do also use the well-used gamma distribution as the cumulative distribution function to which the runoff records shall be fit.

The first step of the calculation of the Standardized Runoff Index is to fit the runoff values to a – in this case gamma – cumulative distribution function. With the use of a runoff's value on the gamma distribution curve, an accompanying value on a standard normal deviation can be derived which equals the value of the SRI for the chosen runoff value.

The probability density function of a gamma distribution is as follows:

$$g(x) = \frac{x^{\alpha-1}e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)}$$

g(x) = probability density function

x= amount of runoff (m^3/s)

α & β = shape parameters

Γ(α) = gamma function

The appropriate shape of the gamma distribution differs for every flow record series and can be formed by the calculation of shape parameters 'α' and 'β'. Note that these values change when the SRI is computed for different time scales (SRI-1, SRI-3, SRI-6 and SRI-12):

$$\hat{\alpha} = \frac{1}{4*\left(\ln(\bar{x})-\frac{\sum\ln(x)}{n}\right)}\left(1+\sqrt{1+\frac{4*\left(\ln(\bar{x})-\frac{\sum\ln(x)}{n}\right)}{3}}\right.$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}}$$

$\bar{x}$= average amount of runoff (m^3/s)

x= amount of runoff (m^3/s)

$\hat{\alpha}$ & $\hat{\beta}$ = shape parameters with maximum likelihood

n = number of runoff records

The cumulative probability is subsequently calculated with the use of the integral function of the probability density function of the gamma distribution:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})}\int_0^x x^{\hat{\alpha}-1}e^{-x/\hat{\beta}}dx$$

Since monthly runoff values in the *Sistema Equivalente* do not have zero flow values, the next step is to derive the accompanying value of the runoff value in a standard normal distribution. A graphical representation as given in Figure 16 (Edwards, n.d.) shows the method. However, to calculate the SRI for every value using this graphical method would take a lot of time, the following equation can be used instead:

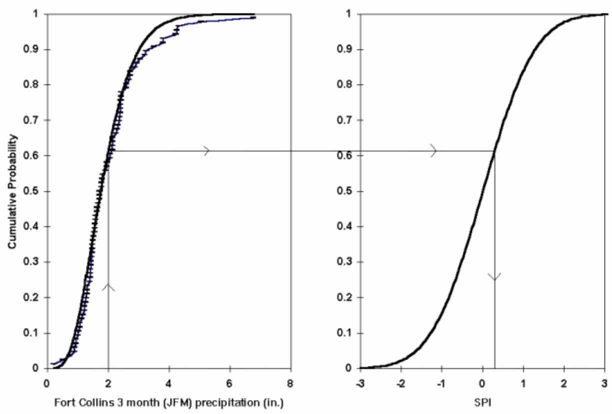


FIGURE 16: GRAPHICAL METHOD FOR TRANSITION FROM GAMMA TO NORMAL DISTRIBUTION (EDWARDS & MCKEE, 1997)

$$SRI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \; for\ 0 < G(x) \leq 0.5$$

$$SRI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \; for\ 0.5 < G(x) < 1.0$$

$$SRI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \; for\ 0.5 < G(x) < 1.0$$

In these formulas, the parameters have the following values:

$$t = \sqrt{\ln\left(\frac{1}{\left(G(x)\right)^2}\right)} \quad for\ 0 < G(x) \leq 0.5 \qquad \& \qquad t = \sqrt{\ln\left(\frac{1}{\left(G(x)\right)^2}\right)} \quad for\ 0.5 < G(x) < 1.0$$

$c_0 = 2.515517$	$c_2 = 0.010328$	$d_2 = 0.189269$
$c_1 = 0.802853$	$d_1 = 1.432788$	$d_3 = 0.001308$

For a correct interpretation of the SRI-results, table 18 presents the severity of drought belonging to the several negative SRI-values (World Meteorological Organization, 2012)

TABLE 18: SEVERITY OF DROUGHT FOR CERTAIN SRI-VALUES

SRI	Category of Drought
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
Smaller than -2.0	Extreme drought

Appendix C: Separating Base Flow

It is difficult, if not impossible, to measure the portion of base flow within a total flow. The following method however is able to separate the base flow from the total flow however to good extent (Institute of Hydrology, 1994).

One should first separate the flow series in blocks of five consecutive runoff values and pick the lowest value (from now on called Q_1, Q_2,... Q_n) of each 'block'. Subsequently, one should, for the whole range of lowest flow values, take three consecutive values (Q_1, Q_2, Q_3; Q_2, Q_3, Q_4; etc.). If both outer values of the range of three Q's exceed the middle value, the middle value is considered to be a value of the base flow. This leaves the user with a range of base flow values (y-value) for a range of scattered time steps (x-value). Using linear interpolation – the expression '*interpl(xvalue,yvalue,desired)*' might be used in Matlab – the base flow values on the other time steps can be found. The last step is to make sure that the base flow values do, after linear interpolation, never exceed the total flow amounts for intermediate time steps.

APPENDIX D: AVAILABLE MODELLED AND MEASURED DATA

To decide on which low flow and drought measurements/indices could be used to identify the vulnerability of the system, this chapter will present the available hydrological and meteorological data for the research.

TABLE 19: AVAILABLE MODELLED AND MEASURED DATA

What?	**Source**	**Explanation**
Runoff (m^3/s)	PDM	Monthly and daily runoff data for the Cantareira System and *Sistema Equivalente* as a whole and the three main reservoirs separately. Reliable data from 2006 onwards.
	SWAT	Monthly and daily runoff data of 20 sub-basins in *Sistema Equivalente* including the three main reservoirs. Reliable data from January 2006 to June 2014.
	DAEE	Monthly data from 1930 onwards for the runoff at the three main reservoirs. Measurements from three inner sites just upstream from the three main reservoirs in *Sistema Equivalente* from the first of April 2014 onwards.
	Measurements on inner sites	Reliable data with significantly long records (from 2008 onwards) from two inner sites: F24 – close to Cachoeira basin – and F25B – close to the Jaguari basin.
	SABESP	Daily runoff values for all four main reservoirs within the Cantareira System from 2004 onwards. The inflow values are calculated with the use of the water balance in which the water level, and thus the water volume in the reservoir, and the outflow at the tunnels and the downstream flow are known.
Baseflow/surface flow (m^3/s)	PDM	PDM separates monthly and daily total flow into base flow and surface flow.
Precipitation (mm)	Gauging sites	PDM uses the measurements of 6 gauging sites to calculate a weighted average for the whole Cantareira region. SWAT uses the measurements in the region to calculate the precipitation per sub-basin by interpolation of the values. Data is available on both daily as monthly scale. Used data is available from 2004 onwards.
Evapotranspiration (mm)	Gauging sites	SWAT uses input variables like the temperature and solar radiation to calculate the evapotranspiration per sub-basin on monthly and daily basis. PDM uses a more easy approach by taking the average historical evapotranspiration in the city Campinas as input variable. Used data is available from 2004 onwards.
Withdrawal of water (m^3/s)	SABESP	Daily and monthly data for the outflow of water to both MRSP and the Piracicaba region is, in usable format, available from 2008 onwards. It also separates the flows per tunnel and the downstream flow per reservoir. If necessary, it is possible to find daily data from 2004 onwards.
Volume in reservoir (%)	SABESP	Daily water volumes in the reservoirs of the Cantareira System are available, in usable formats, from 2008 onwards. If necessary, it is possible to find daily data from 2004 onwards.
Other information	SWAT	SWAT calculates many different other variables, ranging from the amount of sediment in the water to the amount of NH_4 in the water.

APPENDIX E: MATLAB-FILES

Matlab-files have been written to calculate the Standardized Runoff Index, the Duration Curves, the Deficiency Volume and the Base Flow Index. The Matlab-files are presented in this appendix. Comments have been added in green. Separate Matlab-files which were only used for the graphical representation of the indices are not presented.

STANDARDIZED RUNOFF INDEX

The following calculation has been used to calculate all SRI-values. As input variables, the model uses the monthly runoff data (SRI-1), or the summed monthly runoff data for six consecutive months (SRI-6). It should only be addressed that due to the different length of records for the several months (at the time of writing of this report, monthly runoff data is known until May 2015) the model should use different input-files, both for the months January to May and one for the rest of the year. An explanation of the used formulas is presented in Appendix A.

```
function SRI
clear,clc

%Loading data
gegevens = xlsread('RunoffdataSRI1.xlsx');

xjan = gegevens(:,2)';
xfeb = gegevens(:,3)';
xmar = gegevens(:,4)';
xapr = gegevens(:,5)';
xmay = gegevens(:,6)';
xjun = gegevens(:,7)';
xjul = gegevens(:,8)';
xaug = gegevens(:,9)';
xsep = gegevens(:,10)';
xokt = gegevens(:,11)';
xnov = gegevens(:,12)';
xdec = gegevens(:,13)';

Gma = gegevens(:,14)';

%Defining variables
c0 = 2.515517;
c1 = 0.802853;
c2 = 0.010328;
d1 = 1.432788;
d2 = 0.189269;
d3 = 0.001308;

%Decide on for which month the SRI should be calculated:
x = xdec

%Calculating the value on the gamma distribution function and the function's
variables
lnx = zeros(1,length(x));

for k = 1:length(lnx);
    lnx(k) = log(x(k));
end

n = numel(x);

xgem = mean(x);

somlnx = sum(lnx);
```

```
A = log(xgem)-(somlnx./n);

alpha = (1./(4.*A)).*(1+sqrt(1+((4.*A)./3)));

beta = xgem./alpha;

fun = @(x) (x.^(alpha-1)).*exp(-x);

fun2 = @(x) (x.^(alpha-1)).*exp(-x./beta);

Gamma = integral(fun,0,Inf)

GAMMA = zeros(1,length(x));

for k = 1:length(x);
GAMMA(k) = integral(fun2,0,x(k));
end

GAMMAwaarde = GAMMA.*(1./(beta.^alpha.*Gamma))

%Cumulative probability values on the Gamma-curve should be written in the
xlsx.file which is loaded. Note:
%model should be ran twice in order to first calculate the right
%cumulative probability after which the correct values can be used for the rest of
%the calculation
Output = GAMMAwaarde';
filename = 'RunoffdataSRI1juni.xlsx';
sheet = 1;
xlRange = 'N1:N85';
xlswrite(filename,Output,sheet,xlRange)

%Calculation of the SRI-value for the accompanying value on the cumulative
distribution curve.
t = zeros(1,length(Gma));
SRI = zeros(1,length(Gma));

for k = 1:length(Gma);
    if Gma(k) > 0 && Gma(k) <= 0.5;
        t(k) = sqrt(log(1./(Gma(k).^2)));
    elseif Gma(k) > 0.5 && Gma(k) <= 1.0;
        t(k) = sqrt(log(1./(1-Gma(k)).^2));
    end
end
for k = 1:length(Gma);
    if Gma(k) > 0 && Gma(k) <= 0.5;
        SRI(k) = -(t(k)-
((c0+c1.*t(k)+c2.*(t(k).^2))./(1+d1.*t(k)+d2.*(t(k).^2)+d3.*(t(k).^3))));
    elseif Gma(k) > 0.5 && Gma(k) <= 1.0;
        SRI(k) = (t(k)-
((c0+c1.*t(k)+c2.*(t(k).^2))./(1+d1.*t(k)+d2.*(t(k).^2)+d3.*(t(k).^3))));
    end
end

figure(1),clf
plot(SRI)

%SRI-values are presented in an Excel-file. Every month gets its own column
%in the file. Note: for January to May, values are known for 86 years.
Output = SRI';
filename = 'SRI1.xlsx';
sheet = 1;
xlRange = 'L1:L85';
xlswrite(filename,Output,sheet,xlRange)

end
```

DURATION CURVES

The following Matlab code has been used to calculate the FDCs according to the method of Vogel and Fennessey (1994). However, with slight adjustments, presented as comments in the Matlab-script, (parts of) the file could also be used for the calculations of 'normal' FDCs and for determining the duration curves of soil moisture.

```
function FDCVF

clear,clc

%Globalize variables to be able to plot the FDCs of different watersheds in
%one graph
global Qrankedtot

%Load data
gegevens = xlsread('Runoffdata.xlsx');

Q = gegevens(:,1)';
%Dividing the runoff values by the percentage of the watershed's drainage
%area. In the fourth line, one can change the watershed
DAJacJag = 1230./(1230+392+312);
DACachoeira = 392./(1230+392+312);
DAAtibainha = 312./(1230+392+312);
Qda = Q./(1230000000+392000000+312000000).*24*60*60*1000;

%Splitting the runoff values in different years and putting them in
%descending order. For the normal FDC, splitting is not necessary and one
%can just put the whole data record in descending order.
Q2006 = Qda(1:365);
Q2007 = Qda(366:730);
Q2008 = Qda(731:1095);
Q2009 = Qda(1097:1461);
Q2010 = Qda(1462:1826);
Q2011 = Qda(1827:2191);
Q2012 = Qda(2192:2556);
Q2013 = Qda(2558:2922);
Q2014 = Q(2923:3287);

Qranked2006 = sort(Q2006,'descend');
Qranked2007 = sort(Q2007,'descend');
Qranked2008 = sort(Q2008,'descend');
Qranked2009 = sort(Q2009,'descend');
Qranked2010 = sort(Q2010,'descend');
Qranked2011 = sort(Q2011,'descend');
Qranked2012 = sort(Q2012,'descend');
Qranked2013 = sort(Q2013,'descend');
Qranked2014 = sort(Q2014,'descend');

Qrankedtot = zeros(1,length(Qranked2006));

%In the following calculation, take the year 2014 away from the
%calculation for SWAT data.
for k = 1:length(Qrankedtot);
    Qrankedtot(k) =
(Qranked2006(k)+Qranked2007(k)+Qranked2008(k)+Qranked2009(k)+Qranked2010(k)+Qranked
2011(k)+Qranked2012(k)+Qranked2013(k)+Qranked2014(k))./9;
end

%Calculations for determining the Exceedence Probability for each runoff
%value
for k = 1:length(Qrankedtot);
    Rank(k) = k;
end
```

```
n = numel(Qrankedtot);

ExcProb = zeros(1,length(Qrankedtot));

for k = 1:length(Qrankedtot);
    ExcProb(k) = 100.*(Rank(k)./(n+1));
end

Qrankedtot;

%Plotting the FDCs on logarithmic scale
figure(1),clf
semilogy(ExcProb,Qrankedtot)
axis([0 100 0.1 1000])
ylabel('Runoff (mmm)')
xlabel('Exceedence Probability (%)')
title('Flow Duration Curve (mm) Vogel & Fennessey Jaguari - Jagarei - SWAT')
legend('Exceedence Probability Runoff Values JagJac - SWAT','Location','NorthEast')
```

Deficiency Volume

The Matlab-file for the calculation of the deficiency volume over time is presented underneath. Some parts of the script are left out since these parts show close comparison to other parts of the script (e.g. calculation of deficiency volume with outflows of 36 m^3/s and 27.8 m^3/s).

```
function DV
clear,clc

%Globalize for comparison with DV's from other watersheds
global DeficiencyVolume DeficiencyVolumewatergebruik
DeficiencyVolumeprimairwatergebruik DeficiencyVolumeactual

%Loading data
gegevens = xlsread('InputgegevensDV6_2006_2015.xlsx'); %Inladen meetgegevens

%To be used for standardization of watersheds; division of percentage of DA
DAJacJag = 1230./(1230+392+312);
DACachoeira = 392./(1230+392+312);
DAAtibainha = 312./(1230+392+312);
DATotal = 1;

%All the different Volumes are the restricted outflow volumes per month for
%certain water levels in the reservoirs
Datum = gegevens(:,1)';
Qinp = gegevens(:,2)'.*86400;
Qinput = Qinp./DAJacJag;
Qpc = gegevens(:,3)'.*86400;
Qtot = gegevens(:,4)'.*86400;
Volume1 = gegevens(:,5)';
Volume2 = gegevens(:,6)';
Volume3 = gegevens(:,7)';
Volume4 = gegevens(:,8)';
Volume5 = gegevens(:,9)';
Volume6 = gegevens(:,10)';
Volume7 = gegevens(:,11)';
Volume8 = gegevens(:,12)';
Volume9 = gegevens(:,13)';
Volume10 = gegevens(:,14)';
Q5_Qjuseq = gegevens(:,15)';

%Other data

watergebruik = 36.*86400; %m³/s
```

```
primairwatergebruik = 27.8.*86400; %m³/s

capatibainha = 95.26.*1000000;
capcachoeira = 69.75.*1000000;
capjagjac = 808.12.*1000000;
capreseq = capatibainha + capcachoeira + capjagjac

Inhoudreseq = 388042737.*ones(1,length(Datum));
Qdemand = watergebruik.*ones(1,length(Datum));
DV = -(capreseq-388042737).*ones(1,length(Datum));

%Calculation of the Deficiency Volume per time step when using regulated
%outflow (depending on the month and the reservoir level)
for k=2:(length(Datum));
    DV(k) = Qinput(k) - Qdemand(k) + DV(k-1);
    Verschil(k) = Qinput(k) - Qdemand(k);
    if DV(k) > 0;
        DV(k) = 0;
    else DV(k) = DV(k);
    end

    if Inhoudreseq(k) < (Volume2(k).*capreseq./100);
        Qdemand(k+1) = 27.*86400;
        elseif (Volume2(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume3(k).*capreseq./100);
        Qdemand(k+1) = 28.*86400;
        elseif (Volume3(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume4(k).*capreseq./100);
        Qdemand(k+1) = 29.*86400;
        elseif (Volume4(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume5(k).*capreseq./100);
        Qdemand(k+1) = 30.*86400;
        elseif (Volume5(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume6(k).*capreseq./100);
        Qdemand(k+1) = 31.*86400;
        elseif (Volume6(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume7(k).*capreseq./100);
        Qdemand(k+1) = 32.*86400;
        elseif (Volume7(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume8(k).*capreseq./100);
        Qdemand(k+1) = 33.*86400;
        elseif (Volume8(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume9(k).*capreseq./100);
        Qdemand(k+1) = 34.*86400;
        elseif (Volume9(k).*capreseq./100) < Inhoudreseq(k) && Inhoudreseq(k) <
(Volume10(k).*capreseq./100);
        Qdemand(k+1) = 35.*86400;
    else Qdemand(k+1) = 36.*86400;
    end

    Inhoudreseq(k+1) = Qinput(k) - Qdemand(k) + Inhoudreseq(k);
    if Inhoudreseq(k+1) > capreseq;
        Inhoudreseq(k+1) = capreseq;
    elseif Inhoudreseq(k+1) < 0;
        Inhoudreseq(k+1) = 0;
    else Inhoudreseq(k+1) = Inhoudreseq(k+1);
    end

end

%Calculation of the DV for a fixed outflow of 36 m³/s
Inhoudres2 = 388042737.*ones(1,length(Datum));
Qdemand2 = watergebruik.*ones(1,length(Datum));
DVwatergebruik = -(capreseq-388042737).*ones(1,length(Datum));

for k=2:(length(Datum));
    DVwatergebruik(k) = Qinput(k) - Qdemand2(k) + DVwatergebruik(k-1);
    Verschil2(k) = Qinput(k) - Qdemand2(k);
```

```
    if DVwatergebruik(k) > 0;
        DVwatergebruik(k) = 0;
    else DVwatergebruik(k) = DVwatergebruik(k);
    end

    Inhoudres2(k+1) = Qinput(k) - Qdemand2(k) + Inhoudres2(k);
    if Inhoudres2(k+1) > capreseq;
        Inhoudres2(k+1) = capreseq;
    elseif Inhoudres2(k+1) < 0;
        Inhoudres2(k+1) = 0;
    else Inhoudres2(k+1) = Inhoudres2(k+1);
    end

end

%Calculation of the DV for a fixed outflow of 27.8 m³/s and with the actual
outflows are in the real script present here. They are left out in this report
since they show close comparison with the part of the script to calculate the DV
with a fixed outflow of 36 m³/s. In the calculation of the DV with actual outflows,
outflows according to regulations were used in 2006 and 2007.

%Setting up the different variables for determination of the amount of days at
%which certain Deficiency Volumes are exceeded
count1_DV = zeros(1,length(Datum));
count2_DV = zeros(1,length(Datum));
count3_DV = zeros(1,length(Datum));
count4_DV = zeros(1,length(Datum));

%Similar vectors were set up for the deficiency volumes determined with other
outflow values (36 m³/s, 27.8 m³/s and actual)


%Counting the amount of days at which the Deficiency Volumes exceeds the
%reservoirs capacity, the capacity plus the first dead volume, plus the
%first and second dead volume and the amount of water which, on average,
%has been in the reservoir on the first of May - the start of the dry
%period.
for k=2:(length(Datum));
    if DV(k) < -capreseq;
        count1_DV(k) = count1_DV(k-1)+1;
    else count1_DV(k) = count1_DV(k-1);
    end
    if DV(k) < -(capreseq+182470000);
         count2_DV(k) = count2_DV(k-1)+1;
    else count2_DV(k) = count2_DV(k-1);
    end
if DV(k) < -(capreseq+182470000+102000000);
           count3_DV(k) = count3_DV(k-1)+1;
    else count3_DV(k) = count3_DV(k-1);
    end
    if DV(k) < -565870000;
              count4_DV(k) = count4_DV(k-1)+1;
    else count4_DV(k) = count4_DV(k-1);
    end
end

%Similar calculations were carried out for the deficiency volumes determined with
other outflow values (36 m³/s, 27.8 m³/s and actual)

%Giving the appropriate (Dutch) nametags to the calculations so that they
%can easily be derived from the Matlab outputfile. The value of the vector on the
last day of the simulation presents the desired value (for SWAT-modelled data day
3103).
Overschrijdingsaantalreservoirvolumeregulier = count1_DV(3103)
Overschrijdingsaantaldoodreservoirvolume1regulier = count2_DV(3103)
Overschrijdingsaantaldoodreservoirvolume2regulier = count3_DV(3103)
Overschrijdingsaantalvolumedroogseizoenregulier = count4_DV(3103)
```

```
%Once again; the determination of the value of the vector at the end of the time
series has also been done for other outflow values.

%Deficiency Volumes are turned into positive values for a better
%understanding of the graph
DeficiencyVolume = -DV;
DeficiencyVolumewatergebruik = -DVwatergebruik;
DeficiencyVolumeprimairwatergebruik = -DVprimairwatergebruik;
DeficiencyVolumeactual = -DVactual;

Qdemandseconde = Qdemand./86400;
Qtotseconde = Qtot./86400;
Qdemandseconde2 = Qdemand2./86400;
Qdemandseconde3 = Qdemand3./86400;
Qdemandseconde4 = Qdemand4./86400;

%Checking the calculations
Inhoudres4(731)
Inhoudres4(2191)
%Construction of time series to plot on the x-axis
t = datetime(2005,12,31) + caldays(1:3457);
t2 = datetime(2005,12,31) + caldays(1:3456);

%Exporting values of the regulated outflow in 2006 and 2007 so that they
%can be used in the calculations of the Deficiency Volume 4 (of the actual
%outflow). Note: Matlab file should be ran twice.
Qoutput = Qdemand'./86400;
filename = 'InputgegevensDV6_2006_2015.xlsx'
sheet = 1
xlRange = 'O1:O730'
xlswrite(filename,Qoutput,sheet,xlRange)

%Design of the lines which represent 'thresholds' within the graphs
Niveau = capreseq.*ones(1,length(t));
NiveauDV = capreseq.*ones(1,length(t2));
Niveau1 = (capreseq+182470000).*ones(1,length(t2));
Niveau2 = (capreseq+182470000+102000000).*ones(1,length(t2));
Wateruseyear = (27.8*24*60*60*365).*ones(1,length(t));
%Plotting
figure(1),clf
hold on
plot(t,Inhoudreseq,'-red')
plot(t,Inhoudres2,'-blue')
plot(t,Inhoudres3,'-gr')
plot(t,Inhoudres4,'-y')
plot(t,Niveau,'--black')
plot(t,Wateruseyear,'--blue')
%axis([0 3456 0 980740000])
ylabel('Volume (m³)')
xlabel('Date')
title('Combined water volume in reservoirs Sistema Equivalente - PDM (m³)')
legend('Volume (m³)- Regulated Outflow','Volume (m³)- Outflow 36 m³/s','Volume
(m³)- Outflow 27.8 m³/s','Volume (m³)- Actual Outflow','Total Annual Outflow (27.8
m³/s)','Useful Volume Reservoirs (m³)','Location','NorthWest')

figure(2),clf
hold on
plot(t2,DeficiencyVolume,'-red')
plot(t2,DeficiencyVolumewatergebruik,'-blue')
plot(t2,DeficiencyVolumeprimairwatergebruik,'-gr')
plot(t2,DeficiencyVolumeactual,'-y')
plot(t2,NiveauDV,'--black')
plot(t2,Niveau1,'--m')
plot(t2,Niveau2,'--r')
ylabel('Deficiency Volume (m³)')
xlabel('Date')
title('Deficiency Volume (DV) Sistema Equivalente - PDM (m³)')
legend('DV (m³) - Regulated Outflow','DV (m³) Outflow 36 m³/s','DV (m³) Outflow
```

```
27.8 m³/s','DV (m³) Actual Outflow','Useful Volume (m³)','Useful + 1st Dead Volume
(m³)','Useful + 1st & 2nd Dead Volume (m³)','Location','NorthWest')

figure(3),clf
hold on
%plot(Qtotseconde,'-k')
plot(t,Qdemandseconde,'-red')
plot(t2,Qdemandseconde2,'-blue')
plot(t2,Qdemandseconde3,'-gr')
plot(t2,Qdemandseconde4,'-y')
ylabel('Flow (m³/s)')
xlabel('Date')
title('Outflow (m³/s) Sistema Equivalente - PDM')
legend('Outflow according to regulations (m³/s)','Maximum outflow - 36 m³/s
(m³/s)','Maximum outflow - 27.8 m³/s (m³/s)','Actual Outflow
(m³/s)','Location','NorthWest')

end
```

BASE FLOW INDEX

For the calculation of the Base Flow Index, two Matlab-files were used. A first Matlab-file is used to determine which values of the minima of the blocks of five days would actually be a base flow value. The second Matlab-file interpolates the known values of the base flow for other time steps, corrects the data by making sure the base flow value does not exceed the total flow and calculates the surface under both the base flow and the total flow curve which can be used to determine the BFI.

```
function BF
clear,clc

%Load data
Gegevens = xlsread('Baseflow.xlsx');

Baseflow = Gegevens(:,4)';
Baseflowdef = zeros(1,length(Baseflow));

%Determining which low flows would be base flow values
for k = 6:(length(Baseflowdef)-5);
    if (0.9.*Baseflow(k)) < Baseflow(k-5) && (0.9.*Baseflow(k)) < Baseflow(k+5);
        Baseflowdef(k) = Baseflow(k);
    else Baseflowdef(k) = NaN;
    end
end

%Exporting the values to an Excel-file
Baseflowdef
Output = Baseflowdef'
filename = 'Baseflowoutput.xlsx'
sheet = 1
xlRange = 'B1:B3456'
xlswrite(filename,Output,sheet,xlRange)

end
```

```
function Baseflow
clear,clc

%Load data
gegevens = xlsread('Baseflowvalues.xlsx');
gegevens2 = xlsread('Baseflow.xlsx');

xvalue = gegevens(:,1)';
yvalue = gegevens(:,2)';
gewenstex = 0:3456;
simulatedQ = gegevens2(:,5)';
```

```
%Interpolate values
bf = interp1(xvalue,yvalue,gewenstex)
%Extrapolating base flow values for start and end of time series
bf(1:21) = bf(22)
bf(3433:3456) = bf(3432)

%Making sure the base flow does not exceed the total flow
for k=1:length(bf);
    if bf(k) <= simulatedQ(k);
        bf(k) = bf(k);
    else bf(k) = simulatedQ(k);
    end
end

%Calculation of surface areas under graphs
Area1_2006 = trapz(bf(1:365))
Area2_2006 = trapz(simulatedQ(1:365))

Area1_2007 = trapz(bf(366:730))
Area2_2007 = trapz(simulatedQ(366:730))

Area1_2008 = trapz(bf(731:1096))
Area2_2008 = trapz(simulatedQ(731:1096))

Area1_2009 = trapz(bf(1097:1461))
Area2_2009 = trapz(simulatedQ(1097:1461))

Area1_2010 = trapz(bf(1462:1826))
Area2_2010 = trapz(simulatedQ(1462:1826))

Area1_2011 = trapz(bf(1827:2191))
Area2_2011 = trapz(simulatedQ(1827:2191))

Area1_2012 = trapz(bf(2192:2557))
Area2_2012 = trapz(simulatedQ(2192:2557))

Area1_2013 = trapz(bf(2558:2922))
Area2_2013 = trapz(simulatedQ(2558:2922))

Area1_2014 = trapz(bf(2923:3287))
Area2_2014 = trapz(simulatedQ(2923:3287))

BFI2006 = Area1_2006./Area2_2006
BFI2007 = Area1_2007./Area2_2007
BFI2008 = Area1_2008./Area2_2008
BFI2009 = Area1_2009./Area2_2009
BFI2010 = Area1_2010./Area2_2010
BFI2011 = Area1_2011./Area2_2011
BFI2012 = Area1_2012./Area2_2012
BFI2013 = Area1_2013./Area2_2013
BFI2014 = Area1_2014./Area2_2014

%Plot
hold on
plot(bf,'-blue')
plot(simulatedQ,'-red')
axis([0 3456 0 200])
ylabel('Runoff (m³/s)')
xlabel('Days after 1st of January 2006')
title('Baseflow vs. Total flow (m³) Jaguari-Jacarei - PDM')
legend('Baseflow (m³/s)','Total flow (m³/s)','Location','NorthWest')
```

APPENDIX F: RESULTS STANDARDIZED RUNOFF INDEX

Chapter 5 presents some of the most important results from the calculation of the Standardized Runoff Index. In addition to the results in chapter 5, this appendix presents both the SRI-1 curves for SWAT-data as well the SRI-6 curves for PDM-data. Also, the average SRI-1 per dry/wet season and per year for both PDM and SWAT data will be presented, as well as a table which presents the monthly runoff values for which the SRI-1 of PDM-data approached zero. At last, a table will be shown which gives the amount of months for which the SRI-1 for SWAT-data did not surpass either -2.0 or -3.0. Values for SRI-1 and SRI-6 for PDM-data can be found in chapter 5.

STANDARDIZED RUNOFF INDEX CURVES

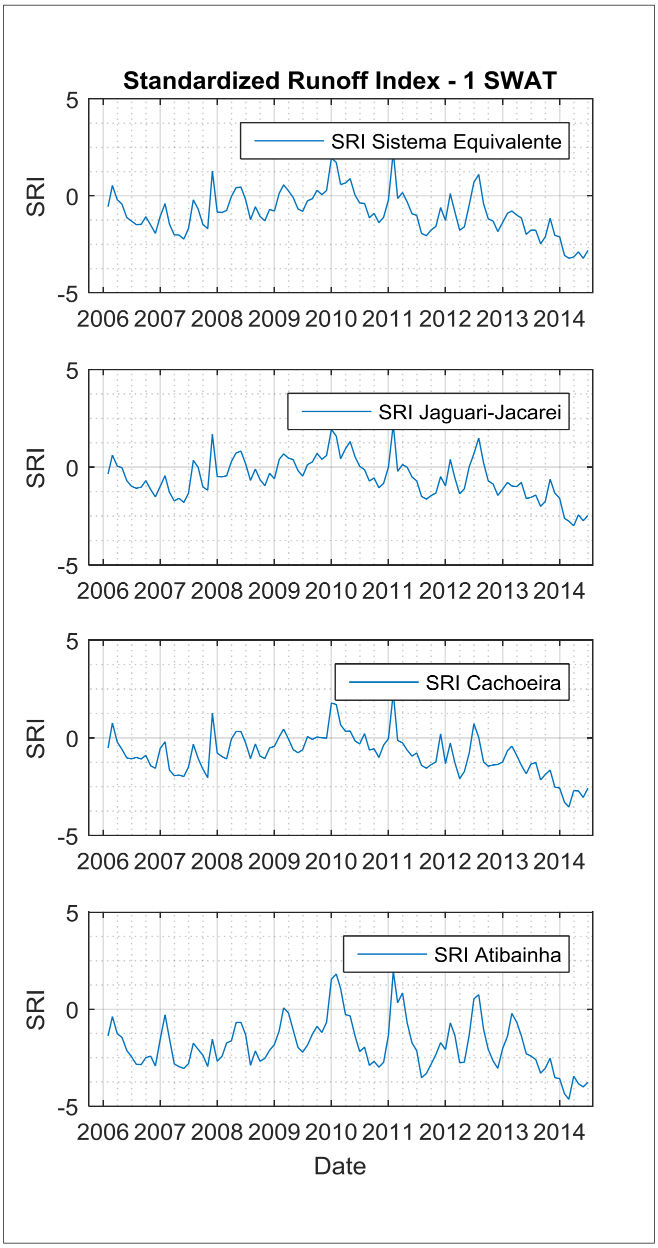
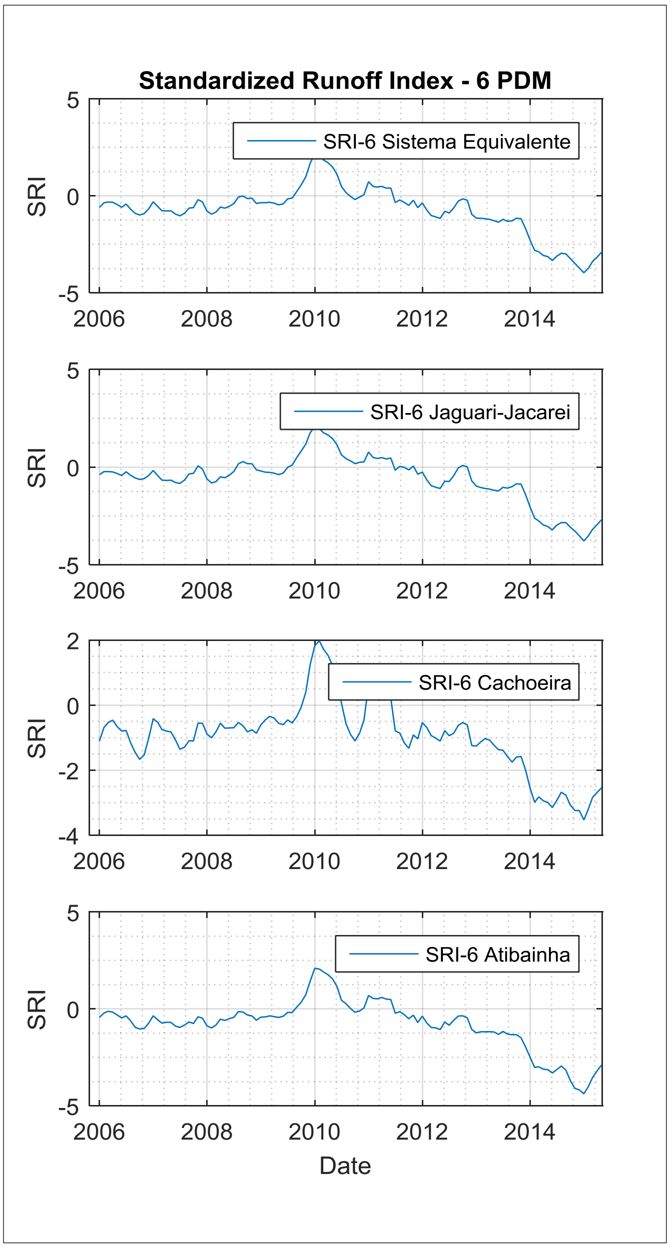


FIGURE 17: SRI-1 (SWAT-DATA) FOR SISTEMA EQUIVALENTE AND ITS SINGLE WATERSHEDS



FIGUUR 18: SRI-6 (PDM-DATA) FOR SISTEMA EQUIVALENTE AND ITS SINGLE WATERSHEDS

AVERAGE SRI-VALUES PER SEASON

TABLE 20: AVERAGE SRI-1 VALUES FOR DRY AND WET SEASON AND FULL YEAR (PDM-DATA)

	PDM					
	Sistema Equilvalente			Jaguari-Jacarei		
	May – November	December (t-1) – April	Full year	May – November	December (t-1) – April	Full year
2006	-0,78	-0,29	-0,56	-0,56	-0,05	-0,32
2007	-0,31	-0,67	-0,51	-0,05	-0,51	-0,29
2008	-0,07	-0,50	-0,24	0,09	-0,34	-0,08
2009	0,66	-0,35	0,45	0,84	-0,23	0,60
2010	-0,09	1,25	0,31	-0,04	1,26	0,35
2011	-0,29	0,33	-0,13	-0,22	0,39	-0,05
2012	-0,35	-1,10	-0,64	-0,13	-0,98	-0,46
2013	-1,08	-0,99	-1,16	-0,86	-0,82	-0,96
2014	-2,90	-2,52	-2,79	-2,36	-2,25	-2,32
2015	-2,15	-2,50	-2,37	-1,85	-1,99	-1,94
	Cachoeira			Atibainha		
	May – November	December (t-1) – April	Full year	May – November	December (t-1) – April	Full year
2006	-1,37	-0,41	-0,90	-0,78	-0,17	-0,52
2007	-0,68	-0,72	-0,76	-0,44	-0,57	-0,55
2008	-0,65	-0,58	-0,61	-0,24	-0,48	-0,33
2009	0,18	-0,40	0,17	0,46	-0,32	0,36
2010	-0,84	1,13	-0,17	-0,08	1,31	0,35
2011	-0,94	0,28	-0,52	-0,29	0,43	-0,10
2012	-0,77	-1,09	-0,89	-0,49	-0,98	-0,65
2013	-1,49	-0,91	-1,38	-1,20	-0,89	-1,22
2014	-2,73	-2,43	-2,60	-3,21	-2,48	-2,94
2015	-2,17	-2,16	-2,16	-1,99	-2,46	-2,28

TABLE 21: AVERAGE SRI-1 VALUES FOR DRY AND WET SEASON AND FULL YEAR (SWAT-DATA)

	SWAT					
	Sistema Equilvalente			Jaguari-Jacarei		
	May – November	December (t-1) – April	Full year	May – November	December (t-1) – April	Full year
2006	-1,41	-0,20	-0,96	-1,02	0,01	-0,65
2007	-0,95	-1,39	-1,11	-0,47	-1,20	-0,73
2008	-0,65	-0,41	-0,55	-0,24	-0,08	-0,18
2009	-0,18	0,02	0,14	0,21	0,27	0,45
2010	-0,75	1,16	-0,13	-0,38	1,24	0,13
2011	-1,41	0,36	-0,76	-1,08	0,43	-0,54
2012	-0,48	-1,07	-0,74	-0,08	-0,71	-0,36
2013	-1,90	-1,03	-1,60	-1,47	-0,93	-1,28
2014	-3,01	-2,89	-3,06	-2,61	-2,48	-2,67

	Cachoeira			Atibainha		
	May – November	December (t-1) – April	Full year	May – November	December (t-1) – April	Full year
2006	-1,15	-0,29	-0,76	-2,59	-0,90	-2,01
2007	-1,03	-1,25	-1,14	-2,37	-1,83	-2,24
2008	-0,55	-0,51	-0,50	-2,06	-1,84	-1,89
2009	-0,19	-0,12	0,02	-1,44	-0,82	-0,90
2010	-0,40	0,97	0,02	-2,41	0,76	-1,33
2011	-1,01	0,25	-0,59	-2,52	0,22	-1,44
2012	-0,78	-1,33	-1,00	-1,27	-1,92	-1,54
2013	-1,81	-0,92	-1,55	-2,82	-1,14	-2,25
2014	-2,81	-2,97	-2,98	-3,89	-3,98	-4,01

MONTHLY RUNOFF VALUES FOR SRI ≈ 0

TABLE 22: MONTHLY RUNOFF VALUES FOR MONTHS IN WHICH SRI-1 = 0

	Runoff values for SRI-1 ≈ 0			
	Sistema Equivalente (m^3/s)	Jaguari-Jacarei (m^3/s)	Cachoeira (m^3/s)	Atibainha (m^3/s)
January	58.40	37.70	11.90	8.30
February	61.10	40.40	12.50	8.60
March	55.90	35.80	11.70	8.00
April	40.50	25.80	8.80	5.90
May	32.50	19.80	7.00	6.28
June	29.50	18.10	6.40	4.60
July	26.13	22.10	5.90	4.06
August	21.20	12.30	4.70	3.40
September	21.10	12.50	4.60	3.70
October	25.40	15.70	5.60	3.49
November	29.70	18.50	6.40	4.90
December	44.20	28.50	9.10	6.50

AMOUNT OF MONTHS WITH SRI < -2.0 AND -3.0

TABEL 23: AMOUNT OF MONTHS UNTIL JUNE 2014 FOR WHICH SRI-1 (SWAT-DATA) WAS NOT HIGHER THAN GIVEN SRI (-2.0 OR -3.0)

	SRI-1 SWAT - <-2.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	1	2	24	2
Total	15	9	35	55
	SRI-1 SWAT - <-3.0			
	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha
Before 2006	0	0	2	0
Total	4	1	5	14

APPENDIX G: RESULTS FLOW DURATION CURVES

In chapter 5, the Flow Duration Curves of both PDM and SWAT data are presented. Furthermore, a table with exceedance probabilities of characteristic values is incorporated in the report. This appendix will present the characteristic values of all flow duration curves, both the mean and normal. It thus presents the characteristic runoff values both in mm and in m³/s for the normal FDCs for SABESP, PDM and SWAT data (table … and table …) and the characteristic values of the mean FDCs of PDM and SWAT data (table …).

TABLE 24: RESULTS FLOW DURATION CURVES - IN MM/DAY: DAIILY RUNOFF VALUES FROM 2006 – JUNE 2014 (SWAT) AND TO JUNE 2015 (SABESP/PDM)

	Sistema Equivalente		
	PDM	**SWAT**	**SABESP**
Runoff Q95	0.339 mm	0.339 mm	0.273 mm
Runoff Q75	0.693 mm	0.557 mm	0.607 mm
Long Term Flow	1.375 mm	1.322 mm	1.363 mm
	Jaguari_Jacarei		
	PDM	**SWAT**	**SABESP**
Runoff Q95	0.334 mm	0.401 mm	0.235 mm
Runoff Q75	0.758 mm	0.645 mm	0.595 mm
Long Term Flow	1.429 mm	1.465 mm	1.427 mm
	Cachoeira		
	PDM	**SWAT**	**SABESP**
Runoff Q95	0.295 mm	0.343 mm	0.128 mm
Runoff Q75	0.503 mm	0.636 mm	0.388 mm
Long Term Flow	1.310 mm	1.362 mm	1.212 mm
	Atibainha		
	PDM	**SWAT**	**SABESP**
Runoff Q95	0.271 mm	0.038 mm	0.146 mm
Runoff Q75	0.642 mm	0.102 mm	0.390 mm
Long Term Flow	1.290 mm	0.711 mm	1.308 mm

TABLE 25: RESULTS FLOW DURATION CURVES – IN M³/S DIVIDED BY PERCENTAGE OF DRAINAGE AREA: DAIILY RUNOFF VALUES FROM 2006 – JUNE 2014 (SWAT) AND TO JUNE 2015 (SABESP/PDM)

	Sistema Equivalente		
	PDM	**SWAT**	**SABESP**
Runoff Q95	7.60 m³/s	7.60 m³/s	6.11 m³/s
Runoff Q75	15.51 m³/s	12.47 m³/s	13.58 m³/s
Long Term Flow	30.77 m³/s	29.60 m³/s	30.53 m³/s
Exc. Prob. 36 m³/s	25.39%	26.51%	27.10%
Exc. Prob. 27.8 m³/s	36.59%	37.09%	37.87%
Exc. Prob. Avg. Runoff During 2013-2015 drought	82.50%	71.20%	75.17%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	99.30%	100%	97.77%
	Jaguari_Jacarei		
	PDM	**SWAT**	**SABESP**
Runoff Q95	7.47 m³/s	8.98 m³/s	5.27 m³/s

Runoff Q75	16.97 m³/s	14.43 m³/s	13.31 m³/s
Long Term Flow	31.99 m³/s	32.79 m³/s	31.95 m³/s
Exc. Prob. 36 m³/s	27.65%	30.36%	29.76%
Exc. Prob. 27.8 m³/s	40.64%	42.27%	41.74%
Exc. Prob. Avg. Runoff During 2013-2015 drought	85.05%	78.04%	74.53%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	98.80%	100%	97.29%
	Cachoeira		
	PDM	**SWAT**	**SABESP**
Runoff Q95	6.61 m³/s	7.68 m³/s	2.85 m³/s
Runoff Q75	11.25 m³/s	14.24 m³/s	8.70 m³/s
Long Term Flow	29.33 m³/s	30.49 m³/s	27.12 m³/s
Exc. Prob. 36 m³/s	27.46%	26.50%	24.29%
Exc. Prob. 27.8 m³/s	36.46%	38.44%	33.05%
Exc. Prob. Avg. Runoff During 2013-2015 drought	68.30%	77.64%	61.70%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	99.40%	100%	93.30%
	Atibainha		
	PDM	**SWAT**	**SABESP**
Runoff Q95	6.07 m³/s	0.86 m³/s	3.28 m³/s
Runoff Q75	14.38 m³/s	2.27 m³/s	8.74 m³/s
Long Term Flow	28.88 m³/s	15.92 m³/s	29.27 m³/s
Exc. Prob. 36 m³/s	27.46%	12.39%	25.49%
Exc. Prob. 27.8 m³/s	31.11%	17.68%	34.73%
Exc. Prob. Avg. Runoff During 2013-2015 drought	78.56%	34.49%	62.88%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	97.37%	60.44%	93.58%

TABLE 26: RESULTS FLOW DURATION CURVES VOGEL & FENNESSEY - IN M³/S DIVIDED BY PERCENTAGE OF DRAINAGE AREA: DAIILY RUNOFF VALUES FROM 2006 – JUNE 2014 (SWAT) AND TO JUNE 2015 (SABESP/PDM)

	Sistema Equivalente	
	PDM	**SWAT**
Runoff Q95	12.82 m³/s	9.80 m³/s
Runoff Q75	16.49 m³/s	13.63 m³/s
Exc. Prob. 36 m³/s	27.71%	30.97%
Exc. Prob. 27.8 m³/s	39.06%	39.73%
Exc. Prob. Avg. Runoff During 2013-2015 drought	91.70%	75.62%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	100%	100%
	Jaguari_Jacarei	
	PDM	**SWAT**
Runoff Q95	13.75 m³/s	11.20 m³/s
Runoff Q75	17.99 m³/s	15.57 m³/s
Exc. Prob. 36 m³/s	29.84%	34.93%

Exc. Prob. 27.8 m^3/s	42.14%	45.02%
Exc. Prob. Avg. Runoff During 2013-2015 drought	95.99%	83.70%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	100%	100%
	Cachoeira	
	PDM	**SWAT**
Runoff Q95	8.11 m^3/s	11.44 m^3/s
Runoff Q75	13.10 m^3/s	15.76 m^3/s
Exc. Prob. 36 m^3/s	28.82%	29.13%
Exc. Prob. 27.8 m^3/s	39.37%	40.43%
Exc. Prob. Avg. Runoff During 2013-2015 drought	73.70%	84.38%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	100%	100%
	Atibainha	
	PDM	**SWAT**
Runoff Q95	11.56 m^3/s	1.30 m^3/s
Runoff Q75	15.15 m^3/s	2.76 m^3/s
Exc. Prob. 36 m^3/s	23.85%	15.16%
Exc. Prob. 27.8 m^3/s	32.93%	22.17%
Exc. Prob. Avg. Runoff During 2013-2015 drought	84.52%	36.16%
Exc. Prob. Lowest Monthly Runoff 2013 – 2015	100%	65.30%

APPENDIX H: RESULTS CALCULATION DEFICIENCY VOLUME

This appendix will present the outcomes of the calculations of the deficiency volume for both PDM and modelled data and for several outflow values, additional to the information presented in chapter 5. The graphs of the deficiency volumes itself are presented in this chapter, this appendix will provide graphs with the storage volume in the reservoirs over time and the outflow of water, both to the Piracicaba region and to MRSP over time. In tables, the amount of days at which the deficiency volumes surpassed certain water volumes and the deficiency volumes at certain dates as well as the increase and decrease of deficiency volumes during respectively dry and wet seasons are presented.

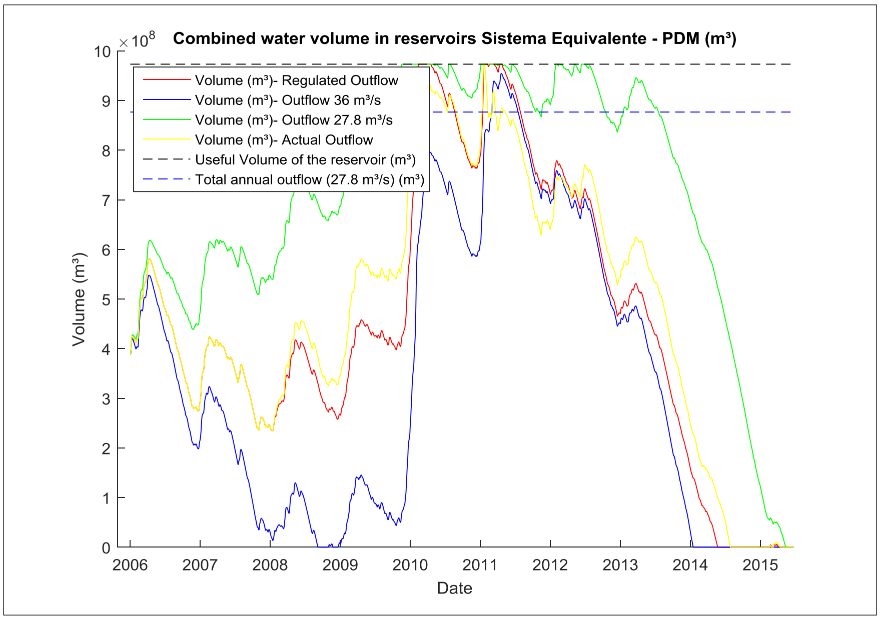
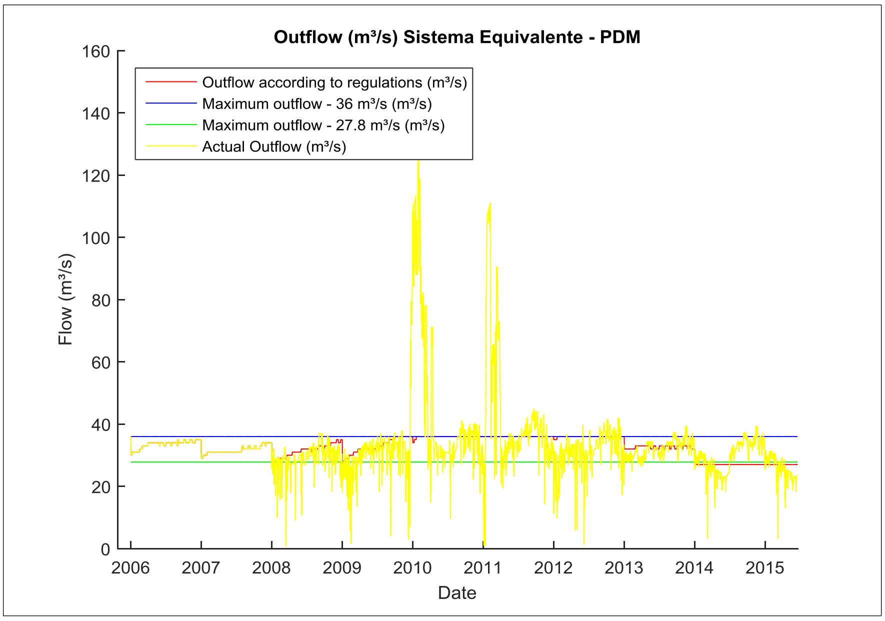
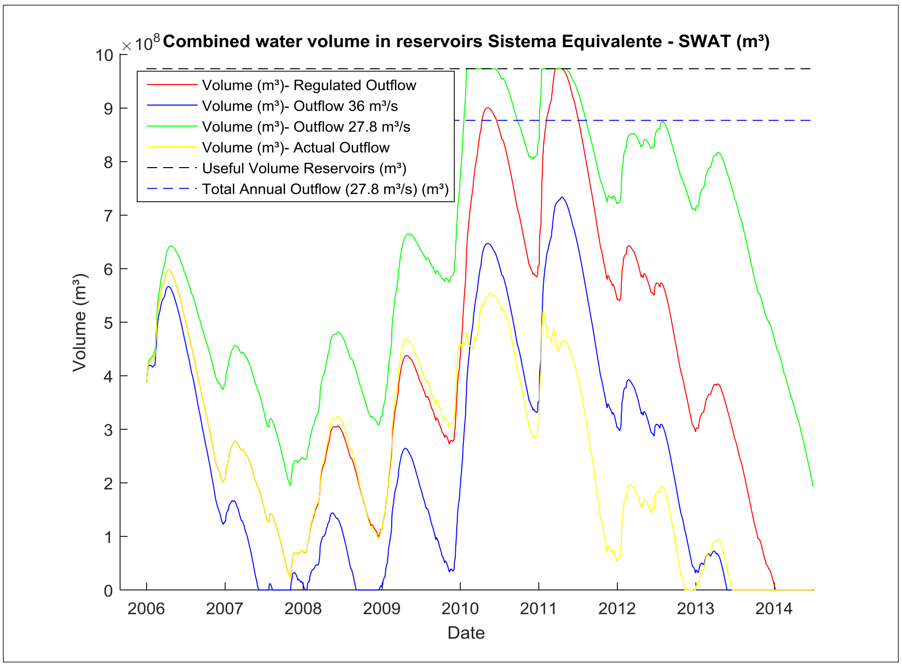


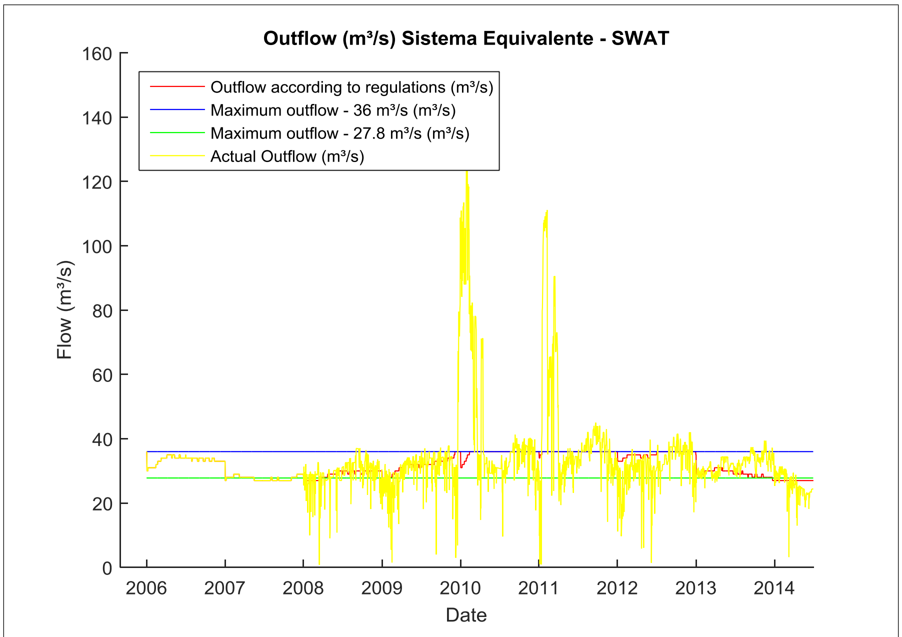
FIGURE 19: STORAGE VOLUME IN RESERVOIR OVER TIME (PDM DATA)



FIGUUR 20: COMBINED OUTFLOW TO MRSP AND PIRACICABA REGION OVER TIME (M^3/S) (PDM DATA)



FIGUUR 21: STORAGE VOLUME IN RESERVOIRS OVER TIME (SWAT DATA)



FIGUUR 22: COMBINED OUTFLOW TO MRSP AND PIRACICABA REGION OVER TIME (M^3/S) (SWAT DATA)

TABEL 27: AMOUNT OF DAYS BETWEEN 2006 AND JUNE 2015 FOR WHICH DEFICIENCY VOLUMES EXCEEDED GIVEN VOLUMES (PDM-DATA)

	Amount of days exceeding given volumes – PDM *Sistema Equivalente*			
	Outflow - regulations	Outflow - 36 m^3/s	Outflow 27.8 m^3/s	Outflow - actual
Total useful volume	393	908	36	327
Total useful volume plus 1st dead volume	282	477	0	250
Total useful volume plus 1st and 2nd dead volume	229	414	0	211

TABEL 28: AMOUNT OF DAYS BETWEEN 2006 AND JUNE 2015 FOR WHICH DEFICIENCY VOLUMES EXCEEDED GIVEN VOLUMES (SWAT-DATA)

	Amount of days exceeding given volumes – SWAT *Sistema Equivalente*			
	Outflow - regulations	Outflow - 36 m^3/s	Outflow 27.8 m^3/s	Outflow - actual
Total useful volume	176	2108	0	539
Total useful volume plus 1st dead volume	41	1429	0	316
Total useful volume plus 1st and 2nd dead volume	0	975	0	274

TABLE 29: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - PDM: REGULATIONS

	Deficiency Volumes PDM - Outflow: Regulations				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	4,13E+08		3,92E+08		
		6,92E+08	6,94E+08	2,81E+08	
2007	5,69E+08		5,49E+08		-1,42E+08
		7,24E+08	7,37E+08	1,68E+08	
2008	5,81E+08		5,83E+08		-1,41E+08
		7,03E+08	7,03E+08	1,22E+08	
2009	5,21E+08		5,15E+08		-1,88E+08
		5,31E+08	5,75E+08	5,42E+07	
2010	1,02E+07		0,00E+00		-5,31E+08
		2,07E+08	2,09E+08	1,99E+08	
2011	1,04E+07		0,00E+00		-2,07E+08
		2,35E+08	2,52E+08	2,42E+08	
2012	2,66E+08		1,94E+08		-4,12E+07
		4,85E+08	4,85E+08	2,19E+08	
2013	4,75E+08		4,42E+08		-4,35E+07
		7,67E+08	7,67E+08	2,92E+08	
2014	9,40E+08		7,69E+08		1,80E+06
		1,31E+09	1,31E+09	3,75E+08	
2015	1,46E+09		1,32E+09		1,89E+06
			1,51E+09	5,11E+07	

TABLE 30: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - PDM: 36 M^3/S

	Deficiency Volumes PDM – Outflow: 36 m^3/s				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	4,50E+08		4,25E+08		
		7,66E+08	7,67E+08	3,17E+08	
2007	7,01E+08		6,49E+08		-1,16E+08
		9,31E+08	9,38E+08	2,37E+08	
2008	8,65E+08		8,64E+08		-6,74E+07
		1,06E+09	1,06E+09	1,90E+08	

2009	9,34E+08		9,24E+08		-1,31E+08
		9,81E+08	1,03E+09	9,12E+07	
2010	2,84E+08		2,73E+08		-7,08E+08
		4,81E+08	4,83E+08	1,99E+08	
2011	1,25E+08		1,15E+08		-3,66E+08
		3,50E+08	3,67E+08	2,42E+08	
2012	3,82E+08		3,10E+08		-3,97E+07
		6,01E+08	6,01E+08	2,19E+08	
2013	6,27E+08		5,83E+08		-1,83E+07
		9,81E+08	9,81E+08	3,54E+08	
2014	1,26E+09		9,84E+08		2,06E+06
		1,80E+09	1,80E+09	5,42E+08	
2015	2,06E+09		1,80E+09		2,67E+06
			2,15E+09	8,84E+07	

TABLE 31: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - PDM: 27.8 M³/S

	Deficiency Volumes PDM – Outflow: 27.8 m³/s				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	3,65E+08		3,55E+08		
		5,29E+08	5,34E+08	1,69E+08	
2007	3,58E+08		3,53E+08		-1,76E+08
		4,35E+08	4,64E+08	1,07E+08	
2008	2,62E+08		2,65E+08		-1,71E+08
		3,00E+08	3,16E+08	5,36E+07	
2009	7,27E+07		7,04E+07		-2,29E+08
		0,00E+00	8,30E+07	1,02E+07	
2010	2,83E+05		0,00E+00		0,00E+00
		5,54E+07	6,86E+07	6,83E+07	
2011	3,09E+06		0,00E+00		-5,54E+07
		7,65E+07	1,06E+08	1,03E+08	
2012	1,35E+07		0,00E+00		-7,65E+07
		1,23E+08	1,23E+08	1,10E+08	
2013	4,29E+07		2,75E+07		-9,55E+07
		2,45E+08	2,45E+08	2,02E+08	
2014	4,15E+08		2,46E+08		1,35E+06
		8,04E+08	8,04E+08	3,89E+08	
2015	9,58E+08		8,06E+08		1,96E+06
			1,01E+09	5,44E+07	

TABLE 32: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - PDM: ACTUAL

	Deficiency Volumes PDM – Outflow: Actual				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	4,13E+08		3,92E+08		
		6,92E+08	6,94E+08	2,81E+08	

2007	5,69E+08		5,49E+08		-1,42E+08
		7,24E+08	7,37E+08	1,68E+08	
2008	5,52E+08		5,54E+08		-1,70E+08
		6,39E+08	6,49E+08	9,67E+07	
2009	3,99E+08		3,92E+08		-2,47E+08
		3,72E+08	4,37E+08	3,79E+07	
2010	5,60E+07		3,97E+07		-3,33E+08
		2,04E+08	2,04E+08	1,48E+08	
2011	9,47E+07		0,00E+00		-2,04E+08
		3,20E+08	3,44E+08	2,50E+08	
2012	2,59E+08		2,27E+08		-9,31E+07
		4,21E+08	4,21E+08	1,62E+08	
2013	3,70E+08		3,48E+08		-7,30E+07
		6,73E+08	6,73E+08	3,03E+08	
2014	8,46E+08		6,75E+08		1,79E+06
		1,29E+09	1,29E+09	4,42E+08	
2015	1,44E+09		1,29E+09		2,40E+06
			1,48E+09	3,45E+07	

TABLE 33: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - SWAT: REGULATIONS

	Deficiency Volumes SWAT – Outflow: Regulations				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	3,84E+08		3,76E+08		
		7,49E+08	7,50E+08	3,66E+08	
2007	7,40E+08		6,95E+08		-5,37E+07
		9,05E+08	9,50E+08	2,10E+08	
2008	6,92E+08		6,97E+08		-2,08E+08
		8,62E+08	8,62E+08	1,70E+08	
2009	5,36E+08		5,35E+08		-3,27E+08
		6,92E+08	7,01E+08	1,64E+08	
2010	7,37E+07		7,40E+07		-6,18E+08
		3,81E+08	3,81E+08	3,07E+08	
2011	5,89E+06		0,00E+00		-3,81E+08
		3,97E+08	3,97E+08	3,91E+08	
2012	3,89E+08		3,30E+08		-6,70E+07
		6,41E+08	6,41E+08	2,51E+08	
2013	6,02E+08		5,88E+08		-5,22E+07
		9,31E+08	9,31E+08	3,29E+08	
2014	1,12E+09		9,32E+08		1,03E+06
		0,00E+00	1,23E+09	1,06E+08	

TABLE 34: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - SWAT: 36 M³/S

	Deficiency Volumes SWAT – Outflow: 36 m³/s				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	4,17E+08		4,06E+08		
		8,22E+08	8,23E+08	4,06E+08	
2007	9,02E+08		8,06E+08		-1,55E+07
		1,23E+09	1,25E+09	3,50E+08	
2008	1,12E+09		1,13E+09		-1,01E+08
		1,41E+09	1,41E+09	2,88E+08	
2009	1,17E+09		1,17E+09		-2,46E+08
		1,39E+09	1,40E+09	2,27E+08	
2010	7,85E+08		7,85E+08		-6,07E+08
		1,09E+09	1,09E+09	3,07E+08	
2011	7,03E+08		6,97E+08		-3,95E+08
		1,09E+09	1,09E+09	3,91E+08	
2012	1,10E+09		1,04E+09		-5,66E+07
		1,36E+09	1,36E+09	2,58E+08	
2013	1,39E+09		1,36E+09		-3,95E+06
		1,84E+09	1,84E+09	4,58E+08	
2014	2,15E+09		1,85E+09		1,72E+06
		0,00E+00	2,30E+09	1,52E+08	

TABLE 35: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - SWAT: 27.8 M³/S

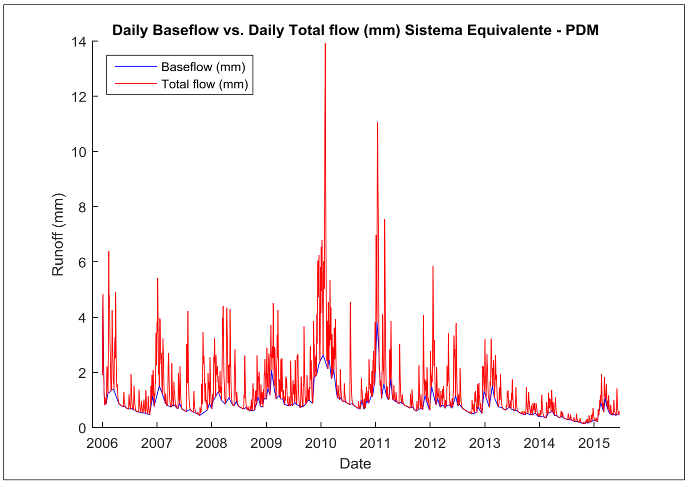
	Deficiency Volumes SWAT – Outflow: 27.8 m³/s				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	3,32E+08		3,31E+08		
		5,85E+08	5,86E+08	2,54E+08	
2007	5,59E+08		5,17E+08		-6,86E+07
		7,33E+08	7,79E+08	2,20E+08	
2008	5,21E+08		5,26E+08		-2,07E+08
		6,57E+08	6,57E+08	1,35E+08	
2009	3,09E+08		3,09E+08		-3,48E+08
		3,78E+08	3,98E+08	8,94E+07	
2010	0,00E+00		0,00E+00		-3,78E+08
		1,68E+08	1,68E+08	1,68E+08	
2011	0,00E+00		0,00E+00		-1,68E+08
		2,40E+08	2,49E+08	2,49E+08	
2012	1,42E+08		1,21E+08		-1,19E+08
		2,47E+08	2,47E+08	1,05E+08	
2013	1,65E+08		1,56E+08		-9,10E+07
		4,71E+08	4,71E+08	3,06E+08	
2014	6,71E+08		4,72E+08		1,01E+06
		0,00E+00	7,80E+08	1,10E+08	

TABLE 36: (DIFFERENCES IN) DEFICIENCY VOLUME THROUGHOUT THE YEAR - SWAT: ACTUAL

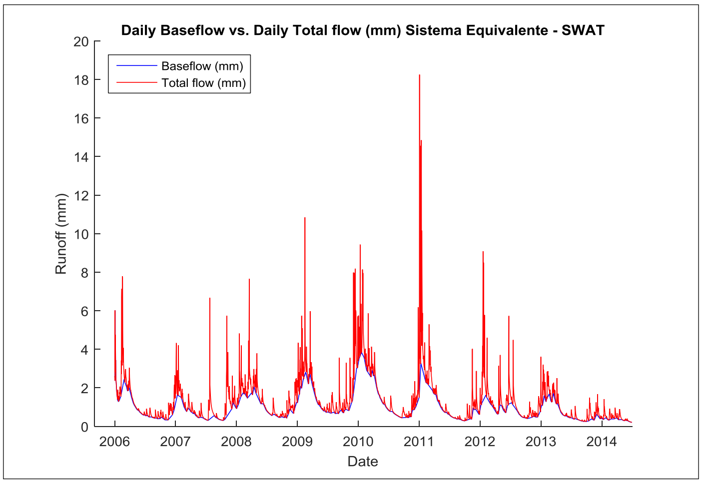
	Deficiency Volumes SWAT – Outflow: Actual				
	Deficiency Volume 30 Apr.	Deficiency Volume 30 Nov.	Min. (wet) & Max. (dry) DV	Difference DV dry period	Difference DV wet period
2006	3,84E+08		3,76E+08		
		7,49E+08	7,50E+08	3,66E+08	
2007	7,40E+08		6,95E+08		-5,37E+07
		9,05E+08	9,50E+08	2,10E+08	
2008	6,82E+08		6,86E+08		-2,18E+08
		8,66E+08	8,66E+08	1,85E+08	
2009	5,06E+08		5,04E+08		-3,62E+08
		6,54E+08	6,69E+08	1,63E+08	
2010	4,28E+08		4,28E+08		-2,26E+08
		6,86E+08	6,86E+08	2,58E+08	
2011	5,08E+08		4,50E+08		-2,36E+08
		8,99E+08	9,02E+08	3,95E+08	
2012	8,15E+08		7,77E+08		-1,23E+08
		1,02E+09	1,02E+09	2,01E+08	
2013	9,63E+08		9,49E+08		-6,69E+07
		1,37E+09	1,37E+09	4,07E+08	
2014	1,57E+09		1,37E+09		1,45E+06
		0,00E+00	1,66E+09	8,59E+07	

Appendix I: Results Calculations Base Flow Index

The base flow index has been calculated in roughly two steps. The first one is the separation of the base flow from the total flow, afterwards the annual base flow index was calculated. In this appendix, the graphs of the base flow and total flows for *Sistema Equivalente* for both PDM and SWAT outcomes will be presented, as well as the table of the annual BFI over time. The graphs of the annual base flow have been presented in chapter 5.



FIGUUR 23: BASE FLOW AND TOTAL FLOW (MM) OVER TIME FOR SISTEMA EQUIVALENTE (PDM DATA)



FIGUUR 24: BASE FLOW AND TOTAL FLOW (MM) OVER TIME FOR SISTEMA EQUIVALENTE (SWAT DATA)

TABLE 37: ANNUAL BASE FLOW INDEX FOR PDM AND SWAT DATA

	Annual Base Flow Index – PDM				Annual Base Flow Index – SWAT			
	Jaguari-Jacarei	Cachoeira	Atibainha	Sistema Equivalente	Jaguari-Jacarei	Cachoeira	Atibainha	Sistema Equivalente
2006	0,809	0,767	0,736	0,792	0,679	0,666	0,556	0,652
2007	0,697	0,614	0,593	0,673	0,591	0,521	0,535	0,562
2008	0,800	0,729	0,683	0,774	0,635	0,619	0,545	0,603
2009	0,746	0,706	0,813	0,746	0,624	0,661	0,500	0,589
2010	0,818	0,802	0,784	0,628	0,645	0,700	0,531	0,609
2011	0,717	0,702	0,562	0,698	0,670	0,640	0,563	0,636
2012	0,699	0,670	0,673	0,696	0,659	0,606	0,577	0,623
2013	0,789	0,727	0,668	0,789	0,715	0,689	0,641	0,689
2014					0,722	0,660	0,571	0,737
Average	0,759	0,715	0,689	0,724	0,660	0,640	0,558	0,633