Depletion of small reservoirs in a semiarid region based on remote sensing

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Summary

This thesis shows a way to model water flows during the dry season of a semiarid region in Brazil. The eventual goal to which this thesis is a start, is to be able to use remote sensing as a way of predicting the water decay of reservoirs which are too small and therefore too costly to monitor using permanent monitoring devices or highly intensive fieldwork. To get an idea of the local population and because there is little information available, interviews have been held in the studied area with the inhabitants. Using this way of gathering information the average household composition has been established for the communities. Also the use of different available water sources are clarified during the interviews.

With the use of open source satellite images areas have been measured of water surfaces and vegetation areas during the year to be used in a model. This model is an earlier developed model which is used in similar semiarid regions and is able to connect reservoir shape, volume, water height and water surface area during a period of time to each other combined with evaporation values and water balance flows. The results of these measurements are then compared to on-site measurements.

Index

1. Introduction

1.1 Background

Brazil has different climate types, including a large semiarid region. Because the dry season lasts from July till January and fresh groundwater is scarce due to the impermeable ground, the affected areas strongly depend on reservoirs to provide water during this season. The state of Ceará consists almost completely of a semiarid environment, as seen in Figure 1. The longest river in this state, the Jaguaribe, has two large dams to prevent the river from drying out and provide water during the dry season. Other main rivers also have large reservoirs for the same purposes. However, the state has a surface of 150 thousand square kilometers and therefore a couple of large retention areas are not enough. The distance between the larger reservoirs is too much for smaller communities to be able to use them. The total network alongside rivers consists of approximately 30 thousand reservoirs with storage capacities ranging from 10^3 to 10^7 m^3. The main function of these reservoirs is for the local population to provide water for their animals and also to use for irrigation of crops. The other main factors on the water balance during the dry seasons consist of evaporation and infiltration.

Figure 1 Semiarid region (Agencia Nacional de Aguas, 2016)

In the past five years there has been a large water deficiency caused by not enough rain during the rain seasons, what caused a lot of reservoirs to be nearly empty. At the end of December 2016, the available water was only 6,7% of the total possible volume in monitored reservoirs (Governo do estada do Ceará, 2016). The government agencies have been able to monitor the reservoirs with a storage capacity of over 10^6 m^3. Those are responsible for approximately 90% of the total stored volume and built to provide water for large irrigation areas and metropolitan areas. Permanently monitoring every reservoir is not feasible because of the sheer number of them. The smaller reservoirs are used to provide water for the local inhabitants and smaller communities. Because there are thousands of those smaller reservoirs, the local influences on hydrological variables such as water availability (Malveira, de Araújo, & Güntner, 2012), floods (Mamede, Araújo, Schneider, de Araújo, & Herrmann, 2012), sediment fluxes (Lima Neto, Wiegand, & de Araújo, 2011), and droughts (de Araújo & Bronstert, A method to assess hydrological drought in semi-arid environments and its application to the Jaguaribe river basin, Brazil, 2016) are significant.

To map these reservoirs, research already has been performed to accurately measure the water capacity of a limited number of reservoirs (Zhang, et al., 2016). Those researches however depend on field monitoring the water level and the use of relations between the water height, flooded area and volume of the water mass based on imagery obtained on the same dates as the field measurements. Because of this, it is not possible to accurately estimate the volumes of un-gauged reservoirs, since it then is assumed that the reservoirs in the studied area are all the same shape and calculations are made based on the measured data of the other reservoir. To improve the estimations of water volumes in the smaller reservoirs, another method could be used. When the shapes, capacity and the way of use are known, the estimation of the water use during the dry season can be more precise. The idea of this method is that it is applicable to a large number of reservoirs, so determining the reservoir shape, capacity and use can happen more efficiently. With the use of remote sensing, meteorological data and local variables such as number of households in the area, agricultural areas and livestock it is possible to model the water level decay during the dry season. With this information available, it could become more easy to manage water on a state level by having the possibility to predict the water availability. The shape parameters of the reservoirs can be calculated with the use of an existing model, called the VYELAS-model (de Araújo, Güntner, & Bronstert, 2006). This model represents a simplified water balance that has been used for similar reservoirs in semi-arid regions. The main variables, like water usage and surface areas can be estimated with the use of remote sensing.

> *Is it possible to use the VYELAS-model to accurately assess the water volume decay in small reservoirs using meteorological data and remote sensing?*

For this, seven reservoirs are measured and modeled. The ones selected are located within the Madalena basin, which consists of a middle-sized reservoir, six small dams and over twenty small reservoirs. The chosen area has been used multiple times for research.

2. Research proposal

In this chapter, the proposal will be elaborated with former performed research on the subject and research questions that are relevant for this thesis.

2.1. Aim and research questions

The main aim of this thesis is **to model the decay rate of small reservoirs during the dry season using remote sensing to estimate water usage and reservoir morphology and evaluate if this is a viable method**. To answer the main research question, other sub questions also need to be answered. Three main characteristics of water usage by local people, described further below, for each reservoir help to determine the withdrawal of water based on the population. Also, the larger the population, the larger the amount of water withdrawn from the reservoirs will be. These factors put together the first question:

1. What is the human influence on water withdrawal from a specific reservoir?

Because there are a lot of reservoirs, people could choose from which one they take the water. For the calculation of water withdrawal from a specific reservoir, it is relevant to know which one people extract water from and e.g. if it is safe to say that people will always go to the nearest reservoir. The type of water use may be relevant. Is the water mostly used for agriculture, or livestock, or just for domestic purposes? When the types are known, the last question that remains is how much water is used. Based on the type and quantity of them, better estimations can be made. The area of grown crops has to be known to calculate the water use based on known water usage per square meter. The same goes for the number of animals, although this has to be calculated based on the average number of animals the people have.

The main purpose of the reservoirs is to provide water for the surrounding communities, but a part of the water also vanishes due to other variables. The main two of these are evaporation and infiltration.

2. What is the influence of evaporation and infiltration on the water decrease of the reservoirs?

Because of the typical ground in the studied area, it is safe to assume no water infiltrates deeply into the ground to run off, but only saturates the top ground layer for a limited area around the reservoir. This means that a stroke of vegetation grows on the side of each water mass that uses the infiltrated water to grow. From satellite imagery, this stroke of green can be measured, and since living trees have a known evaporation rate that is equal to the amount of water they take from the ground it is possible to determine how much water is lost by infiltration. The evaporation of the water depends on the surface area of the reservoir and the evaporation rate of a specified period, based on temperature and sunlight. These rates are measured at measuring stations around the state and give an accurate estimation of the evaporation.

Besides the water loss during the dry period the reservoirs itself also play a role in the water availability during the year. Although some reservoirs look similar, there are still differences visible and measurable. Besides the size of the water surfaces, also the steepness of the slopes can differ. This ratio between horizontal and vertical placement of the reservoir bedding is described as the shape factor. Both shape factor and surface area are relevant to determine the amount of influence the subtraction of water has on the reservoir. The third sub question therefore refers to the shape of the reservoirs.

3. What are the shape factors and dimensions of the reservoirs at different moments?

3. Available data

In this chapter, the research part is explained. This contains all the information necessary to make the execution of this research possible.

3.1. Human influence

Relevant data about the human influence in the research area is not available. What is needed for this research, is the number of houses that make use of a reservoir and how much water is actually taken from the reservoir per household. This includes both human consumption, as well as animal consumption. This means also the number of animals that live in the area need to be known. The average water need per species per day is known (EMBRAPA-CPATSA/SUDENE, 1984). Another form of human influence is irrigation.

For the irrigation of crops, an irrigation system is needed to provide sufficient water for the plants. This usually involves either installing a sprinkler installation or from time to time disperse water over the fields manually or with the use of a machine. There is however another widely used method that is also frequently used in the semiarid regions and is the most used method in this study area. The crops are grown on the dried reservoir beds close to the water surface. Because of this, the still moist and saturated soil of what once was the bottom of the reservoir is providing the water the crops require to grow. When this method is applied, no other forms of irrigation need to be applied as well. The stroke of irrigation fields that form around a reservoir this way is also called a vazante.

3.2. Weather stations

Besides the water withdrawal from humans and animals, water loss due to evaporation and infiltration is also significant. Also, the influence of transpiration by plants surrounding the reservoirs contributes to this, since they consume the water that infiltrates into the surrounding ground of the reservoir. This is often combined with the evaporation rate as evapotranspiration. The value of evaporation is measured at class A pan measuring stations. These are cylinders that hold water and each 24 hours, the evaporation is measured by the depletion of water in that time period. These stations however, are not available in this research area. Other kinds of measurement stations are available. These stations record temperature, humidity, dew point, air pressure, wind speed and direction, solar radiation and precipitation. The data from the measurement stations is collected from the Instituto Nacional de Meteorologia (INMET), which collect data every hour of the day.

3.3. Water heights

Water height of eleven reservoirs were set to be measured multiple times during the years of 2015, 2016 or both. Four of those were unfortunately already empty at the first measurement in 2015 and due to the remaining drought of the last couple of years they have not been filled. The remaining seven have measurements for at least two possible measuring steps each. Those reservoirs are: Marengo, São Nicolau, Paus Branco, Nova Vida 1, Nova Vida 2, Raiz and Mel. The water level is measured relative to the overflow spillways of the dams as reference points, as they are fixed points. Compared to the known total depth of the reservoir, the current water level is calculated. The measurements that can be used require them to take place in the dry season with at least two in the same season. Only when these conditions are met, it is possible to use the data. The tools used for this are optical levels, as seen in Figure 2.

Figure 2: Optical level

3.4. Available satellite images

Satellite images are obtained with the open source Landsat 8 satellite. Approximately once every two weeks every part of the earth is photographed and because of this, it is possible to compare the same area in different points of time. This satellite creates images not only in the visible light spectrum, but also spectral bands outside of that range are captured. This gives more options to work with. In total, the images offered are provided in 11 different band spectrums (NASA, 2016), as seen in the table in Appendix B.

Although every two weeks photos of the studied area are made, most of them turned out to be useless. This is because of the clouds that are present in the photos. Whenever they are covering the areas to be worked with, the photo cannot be used. Even with very few clouds this is causing difficulties, because if the reservoirs are only partially covered by them, the actual boundaries have to be estimated and because of the small size of the reservoirs this causes a large uncertainty. In total of eight images during the dry seasons of 2015 and 2016 are suitable for analyses. Four in 2015, of which one is only suitable for one reservoir because of cloud coverage, and four in 2016.

4. Methodology

The elements needed to answer the sub-questions and the way these are obtained are elaborated in this chapter.

4.1. Water balance

To understand the data that is needed, it is necessary to understand the water balance during the dry season of each reservoir. This water balance is presented in a schematization below.

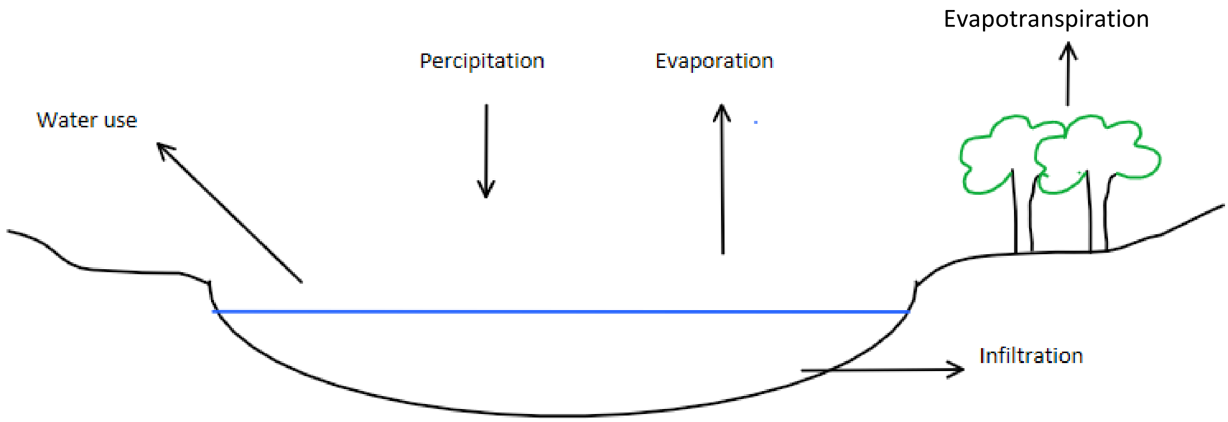

Figure 3 Simplified water balance

4.2. Human influence

4.2.1. Daily water use

To acquire an estimation of the population in the research area, interviews with the locals will be held. Because of the language barrier and the possible fear of strangers, a translator and someone from one of the local communities will support these interviews. Especially in the more remote areas between two reservoirs the main concern will be from which one the water is used, because the information of preferred reservoirs contributes to the accuracy of water use calculation. Therefore, in case of limited time or low interest in participating in the interview from locals, the first two of the questions below will be sufficient.

1. From which reservoir do you take daily water usage?
2. What are the secondary options when the reservoir runs dry?
3. How many persons live in your house?
4. How many animals do you have per species?

Every person interviewed will also get a corresponding GPS tag, so the locational data can be analyzed as well. Based on the answers given at questions (1) and (2), it is then possible to show in ArCGIS if the main reservoir is also the one the most nearby and if this is also true for the second and third choices. When the influence area of each reservoir is known, this knowledge can be used to link houses to reservoir use in other cases. Other than these questions, it is also relevant to ask per community if there are other large water discharges like water trucks that transport water to other villages in the surrounding area.

About 10% of the population of each village will be interviewed and with these answers, it is possible to create an average usage per house. This will then be used to calculate the total water withdrawal

Q_G for each reservoir. This is done by counting the number of houses in satellite images and use the average water discharge per household. For each animal, except donkeys, cats and dogs, average water consumption is known for this region (EMBRAPA-CPATSA/SUDENE, 1984), and given in Table 1.

	Volume (Liters/day)		
Species	Min	Max	Average
Human	14	28	21
Cow	53	83	68
Horse	41	68	54,5
Goat	6	11	8,5
Sheep	6	11	8,5
Pork	6	16	11
Chicken	0,2	0,38	0,29
Donkey	18	35	26,5
Cat	0,2	0,38	0,29
Dog	0,5	2	1,25

Table 1: Water consumption

4.2.2. Number of houses

When the water use per house is known, the total houses that make use of the reservoir need to be counted. Because the LANDSAT 8 has a too low resolution to distinguish separate houses, other satellite images are used. The relatively high resolution opensource basic alternative is Google Earth. These maps are not updated as frequently as the LANDSAT 8, although with the assumption that the fluctuation in number of houses each year is negligible, slightly older images are no problem. Based on the interviews that are held, the houses can be linked to the preferred reservoir in the area.

4.2.3. Irrigation

Due to the growing of crops fields in the vazantes, water is also withdrawn from the vazantes. This happens through the infiltration of the water into the ground and is extracted by the plants, just like other vegetation. It is however very difficult to measure the size of these vazantes through remote sensing, since the resolution is too low to make a distinction between the crops and other vegetation. Based on earlier research in the semi-arid regions of Brazil (de Araújo J. , 2016), a volume of 160 liters per household per day will be used to assume the influence of agriculture on the water balance.

4.3. Evaporation and infiltration

Because Pan A class values of evaporation are not available for this area, these values need to be calculated. The most commonly used and accurate way of calculating this is by using the Penman equation. This equation however, requires some measurements that are not measured by the locally used weather stations. Evaporation is calculated with the simplified version of the Penman equation. Two methods of calculating evaporation are combined and form a value of evaporation. These methods are calculations based on energy balance (Er) and an aerodynamic method (Ea) and are presented in Appendix A. This way saves a lot of calculations and it needs a lot less input parameters than the original Penman equation. The variables needed are measured in the available weather stations. The required measurements are temperature, wind speed, ground distance from the ground to the measurement station, humidity and solar radiation intensity.

Usually, potential evapotranspiration is calculated with the use of the Penman equation and requires the values of daily windspeed, temperature, air pressure and solar radiation. However, evaporation can also be measured and related to evapotranspiration. The correlation between these two is a coefficient of passage named K and is also dependent on relative moisture of air and wind speeds (Doorembos & Pruitt, 1975). Evapotranspiration (ET_0) is calculated by multiplying this factor with the evaporation (EVT).

$$ET_0 = K * EVT \tag{1}$$

The value of (EVT) is measured at class A pan measuring stations. Class A evaporation stations are cylinders that hold water and each 24 hours evaporation is measured by the depletion of water in that time period. The average coefficient K is estimated at a value of 0,69 based on previous research of the semiarid region in Brazil (Molle, 1989).

The evaporation of the measurement tank is different from the actual evaporation values of large water masses. This is due to the fact that it takes a lot less energy to warm the water of the small measurement water tank instead of a larger volume of water. Warm water evaporates faster than cold water and although the difference might be just a couple of degrees, for a large water mass the difference adds up. Because of this, a coefficient is used to concert the measured value of a Pan measurement (EVT) to an estimated actual evaporation value (EVA). This coefficient is called K_a and has an average value in this region of 0,78 (Nouvelot & Pereira, 1977), but can also be created by the formula given by Molle in which the value of K_a is calculated with the use of surface area in ha. This is represented in the following equations.

$$K_a(S) = 0{,}9 - 0{,}165\ Arctan\ (2 * S/30) \tag{2}$$

$$EVA = K_a * EVT \tag{3}$$

Based on the measured evaporation rate (EVT) and the combination of evaporation and infiltration (EVA + INF) that is measured by water heights of reservoirs, the influence of infiltration can be calculated. This ratio is given in the equation below based on research on 128 measurement values in the semiarid region (Molle, 1989).

$$\frac{EVA + INF}{EVT} = 1{,}07 \tag{4}$$

With the equations (3) and (4) the infiltration value can be calculated, and this results in the following:

$$INF = EVT(1{,}07 - K_a) \tag{5}$$

This means that with a value of 0,78 for K_a the infiltration is 0,29*EVT. This represents the amount of water that infiltrates in the ground and is lost from the reservoir. However, the ET value is more than twice as high as the infiltration rate. This means that any water that infiltrates the ground will immediately be diverted into evapotranspiration by the stroke of vegetation surrounding the reservoir.

4.4. Dimensions of reservoirs

Change in water areas can be measured by comparing two different satellite images created on two different dates. The best results in comparing measured values and modeled values will be obtained if the inspected images are made on the same dates as the on-site water level measurements.

4.4.1. Landsat and NDVI

Each band represents a different range of frequencies in the visible and non-visible light spectrum and because of this, different images can be created by combining different bands. For the measurement of water areas, the visible spectrum of bands 2, 3 and 4 can be used to visually determine what is water and what is not, but this form of observation is not very accurate. Another, more accurate solution is to calculate what is called the Normalized Difference Vegetation Index (NDVI). This method is usually used to observe different forms of vegetation and is based on the principle that plants use most of the visible light for photosynthesis and therefore do not reflect the light. On the other hand, near infrared light is reflected by plants. These two factors are used to calculate the NDVI values using the following formula:

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \tag{6}$$

In this, NIR is the near infrared band and VIS the visible band. For the visible band, the red spectrum is used because this gives the most accurate result. The values of the NDVI are always within a range of -1,0 to +1,0 in which vegetation has values ranging from approximately 0,2 to 0,9. Surfaces of water like rivers, lakes and oceans have negative values, and that makes this method suitable for exposing the reservoirs. There are however situations in which the NDVI value can be positive, even though there is a water surface. This can be caused by the forming of floating vegetation on the water surface. These plants have a different reflection value than water so it can look like there is no water. Also shallow water with water plants or algae forming underneath the water surface on the bottom of the reservoir can cause the same differentiation, although it will be to a lesser extent.

4.4.2. ArcGIS

To work with the landsat images, suitable software is required. For this, the geo information system of ArcGIS is used. This is an elaborate program with many functions and could be used for large variety of analyses or data visualization. The desktop program ArcMap offers these functionalities to work with, and it also has a built in NDVI calculator. This shows the results of equation (6) in a visual layer when the landsat bands 4 (red) and 5 (near infrared) are selected. The NDVI range in ArcMap however, is from 0 to 200 where the values above 100 can be seen as ‘positive’ regarding to the output of (6).

The created layer shows every NDVI value. Only the values below 100 are interesting however, because they represent water surfaces. To filter these values, the spatial analysis toolbox in ArcMap is used to set conditional values and a new layer is created with only values below 100. This results in separate identifiable areas that represent water masses which then can be created into polygons to show the surface area of each reservoir.

When applying the NDVI calculator in ArcMap and using the criteria of a value below 100 to show the water surfaces, not the full surface was shown however. Compared to the image in the visible spectrum, in which the water was visible, the NDVI layer showed only up to the half of that area. The reason for this is probably that the water level is too low to show a significant difference in water and vegetation growing beneath the water surface. Because this difference is better visible in the visible light spectrum, the NDVI was adapted to show an area similar to this. This value has been set to a maximum of 108 and is applied to all images for a consistent measurement.

4.4.3. Calculation of reservoir shape

The reservoir shape is important for calculating water depletion. For this the VYELAS-model is used. The main parameters are volume, surface area and depth. To also involve the morphology another variable is introduced: shape factor alpha. It represents the shape of the reservoir slopes so a more accurate estimation of the unknown variables is possible. The parameter alpha is represented below, defined by (de Araújo, Güntner, & Bronstert, 2006). Within the same reservoir this value of alpha can have different sizes, depending on at which point the measurements are taken. When only the empty and full dimensions of the reservoir are known, the alpha value is the average over the whole time period. This is however a misrepresentation of the true values, as they change during the period caused by change in slope steepness within the reservoir. Reservoirs can have different shapes, but in general, they share that the lower part has steeper slopes, and thus a lower value of alpha. The top parts of reservoirs tend to have increasingly less steep slopes, which results in values of alpha to increase the fuller the reservoir gets. When there are multiple measurements, multiple values of alpha can be calculated to come up with a more precise calculation of the slopes of the reservoir and thus a more accurate estimation of the reservoir volume.

$$\alpha = \frac{\sum V_i}{\sum {h_i}^3} \tag{7}$$

The reservoir volume is given by V_i in m^3 at water depth h_i (m). When the shape factor alpha is known, the volume and surface area can be estimated using the equations below:

$$V(h) = \alpha * h^3 \tag{8}$$

$$A(h) = 3 * \alpha * h^2 \tag{9}$$

In which A(h) is the derivative of V(h). The water balance used for the calculations is simplified to the intentions of this research. Inflow from rivers is neglected, just as the downstream outflow, because of the representation of the dry season. The variables that remain are evaporation, rainfall, infiltration and water subtraction. Because the rainfall is so little during the dry season, only the rain that falls directly onto the reservoir will be taken in the equation. When the precipitation is so high that it generates runoff, this model is not sufficient. The mass conservation principle is as follows:

$$A * \frac{dh}{dt} = -A * \frac{d(E-H)}{dt} - (Q_G + Q_i) \tag{10}$$

Where A is the surface area, E the evaporation, H the rainfall, Q_G the water withdrawal and Q_i the infiltration. No other water inflow than rainfall is included, because there are no sources that can provide a large enough amount of water to produce infiltration or runoff towards the reservoirs. Multiplying this formula by dt, integrating over the measured time and substituting the area with the average area during the time between two measurements $A = (3/2) * \alpha * (h_t^2 + h_{t+\Delta t}^2)$ results in the following equation, based on (de Araújo, Güntner, & Bronstert, 2006):

$$h_{t+\Delta t}^3 + \left(\frac{3}{2}\right) * h_{t+\Delta t}^2 * (E - H) = h_t^3 * \left(\frac{3}{2}\right) * h_t^2 * (E - H) - \frac{Q_G + Q_i}{\alpha} * \Delta t \quad (11)$$

The index *t* refers to the beginning of the measurement, while *t+Δt* is the water height at the end of the period. Both heights are unknown, but when α is estimated, h_t can be calculated using equation (8). The only unknown parameter left can be numerically calculated.

This water balance is used only for the dry season, where there is no inflow from rivers and no outflow downstream. This is because all of the rivers quickly dry out when the rain season is over and rainfall during the dry season is not enough to produce any runoff.

4.5. Model

The model will be made with the use of a combination of Matlab and excel. The in- and outflow of the reservoirs is calculated in Matlab and this is used for the calculation of water heights in excel. In Matlab the flow is calculated in three steps with as inputs the start and end dates of the period results are needed, the number of houses that rely on the water of the reservoir and the green area. The raw data from INMET weather stations is used for calculating the evaporation. This is done by selecting a period and in this period the daily evaporation is calculated. For this the simplified Penman equation is used, as described in Appendix A. The sum of evaporation of the days in the given period is then calculated and the total rainfall in that period is subtracted from this value. In the same way using the model, the evapotranspiration is also calculated for the green areas around the reservoirs, based on the maximum value of infiltration that can take place to ensure the water inflow to the vegetation.

Next, the water use is calculated for each reservoir based on the number of houses that lay within the influence area. Water use for small animals and human consumption is left out of this, as the water for these purposes is used from the rain tanks. The total water flow out of the reservoir is then calculated by using this and the evapotranspiration of the green area surrounding the reservoir.

With these values, formula (9) is used to then calculate the water height and alpha variable in an excel sheet.

4.5.1. Comparison of modeled and measured values

The measured water levels are used to compare them with the modeled water levels. From the satellite images, multiple dates with corresponding water areas are available, but the measured water levels are not measured on the same day as these images are made. To make a comparison, it is necessary to have the modeled data on the same date as the measured data. To attain this, the areas of the satellite images are interpolated in excel and a formula for the trendline is used to find the area on the date of measurement. Alpha is calculated for the periods between the satellite images, so for the calculation of the reservoir measurements, the alpha value in the period closest to the satellite image periods is used. With this, and the water flow calculation in the period between measurements, the water height is then calculated and compared to the measured value. By correcting the data of the water usage, the differences in modeled versus measured water height can be reduced. The size of the factor that is used to correct this shows the under- or overcalculation of the amount of water that is used in the model.

5. Results

5.1. Human influences

In total 50 people are interviewed spread out over the different communities from the research area. Besides from the communities, also people from houses that are located outside of those were questioned to better estimate their choices in reservoirs. Approximately ten percent of the total population has been interviewed. For the locations of the interviews compared to the communities, see Figure 4. The communities are named after the reservoirs they lay next to.

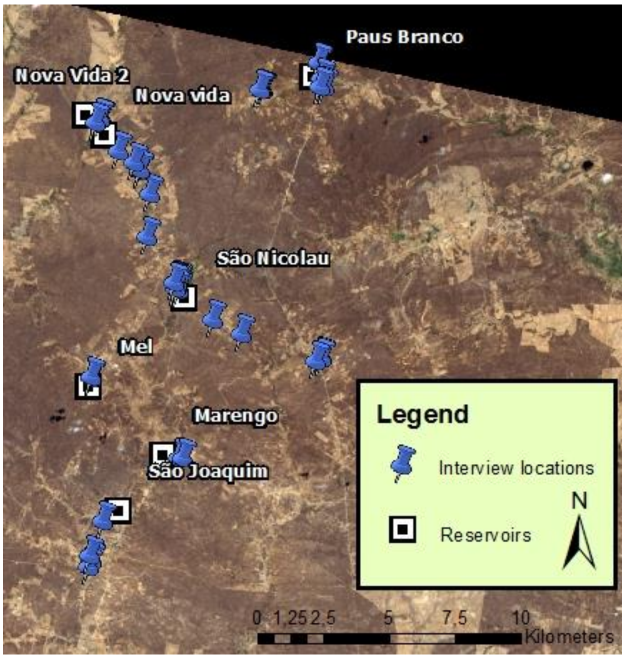

Figure 4 Locations of interviews

5.1.1. Averages per household

The average number of animals per household is more than estimated by previous research. As it is a rural area, having animals is very common and therefore there was not even one household that did not have any animals. The amount and species did differ, as some households have more animals of the same species than others. The individual given answers can be found in Appendix C. Combined with the average water usage per species per day from Table 1, a total average amount of water usage per household is calculated. In the table below these values are represented.

Species	Average amount	Water use (L)
humans	4,2	88,6
cows	7,2	488,2
pigs	1,8	19,9
goats	12,4	105,3
sheep	18,8	160,1
chickens	16,1	4,7
horses	1,4	75,3
donkeys	0,3	8,2
cats	2,3	0,7
dogs	1,8	2,2
	Total average water use per household	**953**

Table 2 Average amount of species and water use per household

From the interviews, another aspect was clarified: almost every household has its own water supply tank for daily drinking water. This water is collected from rain that falls on the roofs of the houses and lasts, depending on how much rain falls in the rainy season, most of the dry season. Besides drinking water, it is also used for cooking and small animals like dogs, cats and chickens. This water is not taken from the reservoir, so for the calculation of water use from the reservoir these species are excluded. When the rain tanks are empty before the dry season has ended, they are either refilled by water trucks that bring the water in from outside of the research area, or community water tanks are used. These community water tanks are also filled from the water trucks. The water use from the reservoir has therefore a different value than the total volume given in the table above. Also, the agricultural water use has to be included in this, since this is also based on a volume per household. The volume of daily water use per household is 850,9 liters for the animal consumption, and 160 liters for agriculture. This gives a total of 1010,0 liter of water per household per day.

5.1.2. Preferred reservoirs

As expected, people use the water reservoir closest to their homes when this is possible. The influence areas are hereby represented for each reservoir and they change depending on depletion of the reservoirs. When each reservoir has water available, people use water from the nearest reservoir. In total 80% of the respondents gave this as an answer, while the other 20% of the answers consists mostly of the use of water trucks or rain tanks to fulfill the need for water.

The second water source for when the closest reservoir runs dry is not always the second closest according to the interviews. Out of the 50 interviews, 29 of them said to use a well nearby for water supply as a backup. These wells however, are mostly located downstream from the reservoirs, so it is a possibility that these wells are fed by water from the same reservoir. Some wells make use of groundwater that is not coming from the reservoirs, but no data about these wells and the exact origin of the water is available. Regardless of this information it is also not relevant for this research, because the wells are seen as backup in case the reservoirs are already empty. As seen in the overview of all of the given answers to where the water is taken in Appendix D, only six people take water from another reservoir as second option. These reservoirs are also not always the closest to their location.

The third option for water supply is almost for half of the respondents a water truck that delivers water from outside of the studied area. The reservoir that is mostly used as a third option is the largest one, Marengo. This is mostly because it is probably the only reservoir that will contain water when all of the others are empty.

5.1.3. Nearest reservoirs

As seen in the results of the nearest reservoirs in Appendix D, the nearest reservoir is indeed the first choice for taking water, but that that is not true for the second and third nearest reservoirs. Only three times the second choice and second nearest reservoir corresponded and this was four times for the third nearest. This is probably partly because when one of the larger reservoirs is located the closest, when that one is empty all of the smaller reservoirs will certainly already be empty. The people that live near a small reservoir tend to prefer water trucks for water supply instead of traveling to the other reservoirs.

5.2. Evaporation and infiltration

The evaporation based on the results from the simplified Penman equation give an evaporation value in meters per day. Each period has a different average daily evaporation, since this is calculated by taking the sum of the daily measured evaporation and dividing that by the number of days in that period. Also the average water area declines each period as a result from all of the water flows combined. This results in the evaporation getting less each period. The results of the dimensions of the reservoirs are found in chapter 5.3 Dimensions.

Since the infiltration value is dependent of the evaporation value and the area of the vegetation, the volume of infiltration Q_i stays pretty much the same during the dry season.

The water use of people and their animals is also shown in the tables below, to show the comparison between these daily volumes of water loss. Since this value is based on the number of houses near a reservoir, this is a constant.

Marengo				
Day 1	Day 2	Q_G/day (m^3)	Q_i/day (m^3)	E/day (m^3)
8-8-2015	24-8-2015	88	59	1117
24-8-2015	27-10-2015	88	64	991
27-10-2015	28-11-2015	88	64	923
25-7-2016	26-8-2016	88	72	184
26-8-2016	29-10-2016	88	50	99
29-10-2016	14-11-2016	88	73	133

Table 3 Daily water flow per period of Marengo

Paus Branco				
Day 1	Day 2	Q_G/day (m^3)	Q_i/day (m^3)	E/day (m^3)
24-8-2015	27-10-2015	116	150	231
27-10-2015	28-11-2015	116	146	217
25-7-2016	26-8-2016	116	162	426
26-8-2016	29-10-2016	116	163	381
29-10-2016	14-11-2016	116	163	377

Table 4 Daily water flow per period of Paus Branco

São Nicolau				
Day 1	Day 2	Q_G/day (m^3)	Q_i/day (m^3)	E/day (m^3)
25-7-2016	26-8-2016	107	59	1345
26-8-2016	29-10-2016	107	60	1081
29-10-2016	14-11-2016	107	60	1006

Table 5 Daily water flow per period of São Nicolau

Nova Vida				
Day 1	Day 2	Q_G/day (m^3)	Q_i/day (m^3)	E/day (m^3)
25-7-2016	26-8-2016	61	55	158
26-8-2016	29-10-2016	61	55	148
29-10-2016	14-11-2016	61	55	130

Table 6 Daily water flow per period of Nova Vida

As seen in the tables, the daily evaporation declines during the year as expected. Only the difference of Paus Branco between the end of 2015 and the beginning of 2016 is not as expected, but this has to do with the sudden increase of water area that was measured for that reservoir.

5.3. Dimensions

In this chapter the results of areas based on the analysis of the available satellite images are presented. Also the on-site measurements of water height are included.

5.3.1. Water areas

The calculated areas for the reservoirs that had water in it are presented in Figure 5 and Figure 6. In 2015 however, Nova Vida had no water inside of the reservoir and São Nicolau only had one measured point, due to the fact that it was empty at the point when the next usable image was analyzed.

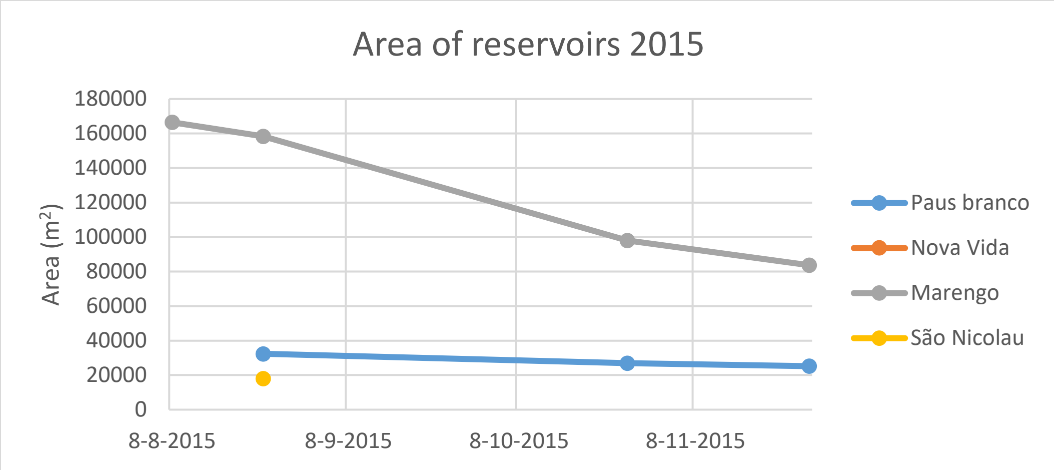

Figure 5 Reservoir areas 2015

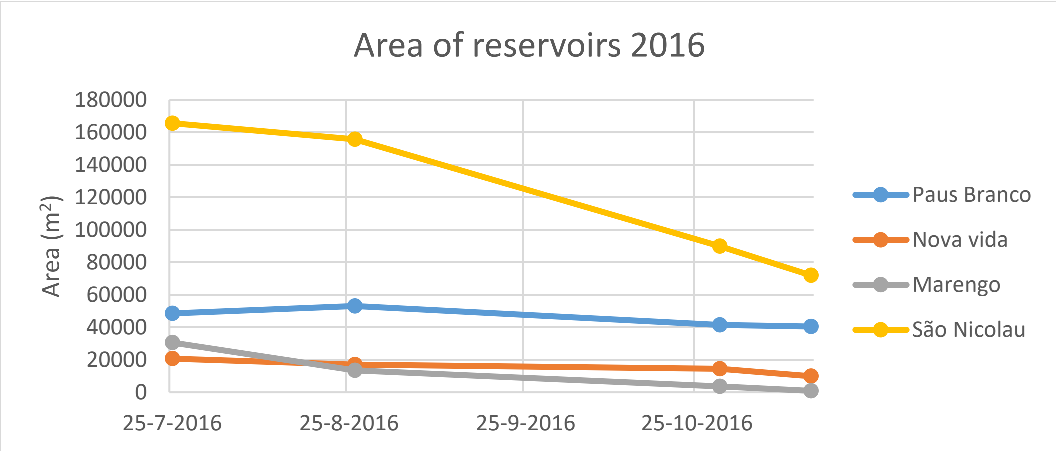

Figure 6 Reservoir areas 2016

Because of the shallow water when the reservoirs are almost empty, they can still contain some water although the satellite measurements show no water. This is also the case with the reservoir Mel, that still contained water when visiting that location for the interviews. With the calculation of the NDVI values however, the last two years no water was shown. This means that there still is water available to be used for drinking water for cattle and for irrigation of crops.

The interpolation of the measured areas is graphically represented in Appendix E. The trendlines show a continuous exponential line with a function to easily calculate the water area at any day in the range of the available images.

5.3.2. Green areas

Difference in types of plants and water use and why they can't be identified

The vegetation that surrounds the reservoirs is more difficult to measure than the water area. These areas are also based on NDVI values, but the difference between green vegetation that consumes water from the reservoir and other vegetation is difficult to differentiate. To measure the vegetation areas, an NDVI value greater than 130 was chosen to select. Although it was expected that downstream close to the reservoirs the vegetation was the densest, it was especially visible that more vegetation is located upstream of the reservoir. The water source of this vegetation is probably not the reservoir, as water flows better downhill than uphill. There is a possibility that some of this vegetation is able to reach the water from the reservoirs due to the increased root system development in the drought combined with only a slight decrease in land height from upstream to the reservoir. This information however was not included in the research, so the choice is made to not include the vegetation upstream. The border that is selected for including vegetation is the distance that vegetation was also visible on the sides of the reservoir.

When comparing multiple images on green areas, it was visible that these areas did not change much during the year. This is why only one value per reservoir is used for calculating the influence of the green area on infiltration, instead of using a different value for each moment. These areas are given in Table 7:

Reservoir	Green area (m^2)
Paus Branco	66600
Nova Vida	22500
Marengo	29700
São Nicolau	24300

Table 7 Areas of vegetation

5.3.3. Measured water heights

Out of all of the on-site measurements in the reservoirs, a total of fifteen measure dates can be actually used. This is because almost half of the measurements took place in the wet season, and some of them were obviously wrong, as the difference with the following measurement was extremely high and out of proportion with the rest of the measurements. Also, some measurements that do meet the requirements are not included, because there are no sufficient satellite images to compare the results to. With these fifteen measurements, it is possible to make ten steps of water height difference which is needed for calibrating the model. These steps are divided across four reservoirs: five steps for Marengo, three steps for Paus Branco and for São Nicolau and Nova Vida each one. In Table 8 the dates these measurements are represented. Instead of measuring the water level, the height from dam overflow inlet and the water level is measured, so this explains why the second measurement is always a greater value than the one before.

Reservoir	Measurement 1	Measurement 2	Difference (days)	Distance 1 (m)	Distance 2 (m)	Difference (m)	Difference per day (mm)
Marengo	14-5-2015	8-7-2015	55	11,80	11,81	0,02	0,3
Marengo	8-7-2015	14-8-2015	37	11,81	12,07	0,25	6,9
Marengo	14-8-2015	11-11-2015	89	12,07	12,86	0,79	8,9
Marengo	13-8-2016	6-11-2016	85	13,66	14,45	0,79	9,3
Marengo	6-11-2016	29-11-2016	23	14,45	14,84	0,39	17,0
São Nicolau	13-8-2016	29-11-2016	108	2,36	3,54	1,18	10,9
Paus Branco	14-5-2015	8-7-2015	55	4,05	5,14	1,09	19,8
Paus Branco	8-7-2015	9-9-2015	63	5,14	5,65	0,51	8,1
Paus Branco	9-9-2015	11-11-2015	63	5,65	6,35	0,70	11,1
Nova Vida 1	13-8-2016	29-11-2016	108	3,54	4,28	0,74	6,9

Table 8 Measurement dates with water level decrease

5.4. Model results

The rest of the results of the model are found in this chapter. In the figure below, a basic illustration of how the model has been built up is shown.

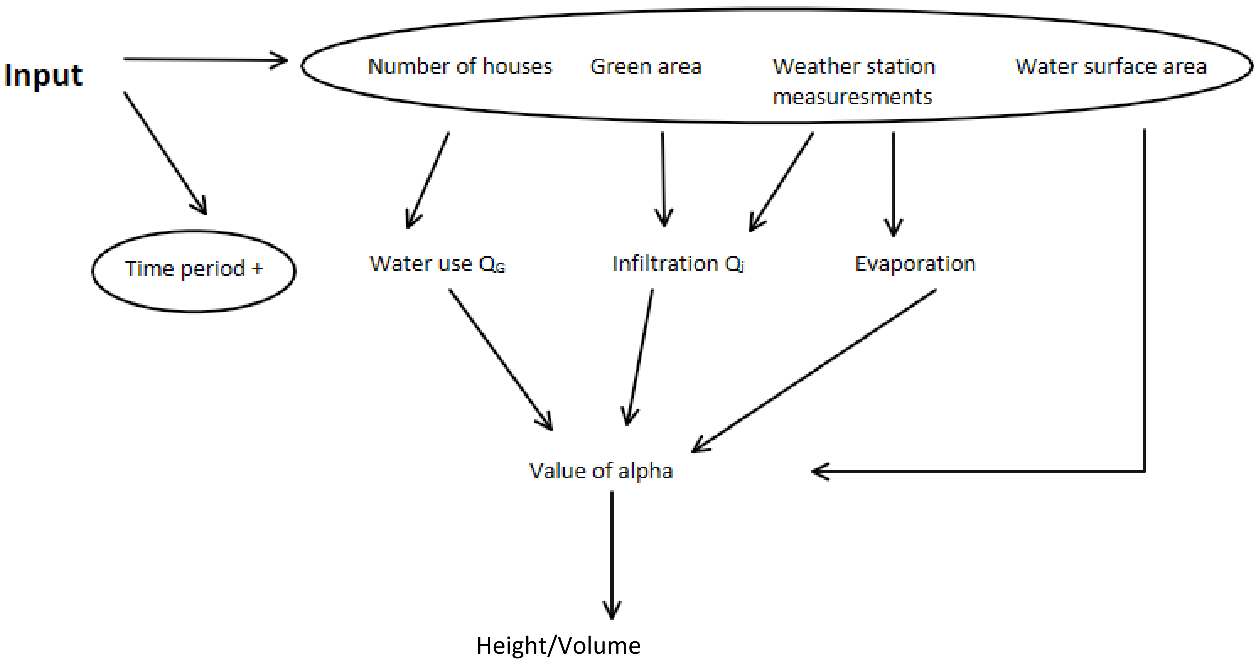

Figure 7 System diagram of the model

5.4.1. Alpha values

For each reservoir, the water flows and evaporation are calculated using the Matlab model in the time frames of the available satellite images. These values are presented in Appendix F. The waterflow includes water use and infiltration together and in the last column the total amount of water loss due to evaporation in the time period is given. The precipitation is already subtracted from this amount. These values are used as input to the VYELAS-model to calculate the unknown alpha value for each period between two dates. Each reservoir has different ranges of alpha, which shows the difference in shape of each reservoir. Larger values of alpha represent less steep slopes while the smaller ones represent steeper slopes of the reservoir banks.

Marengo		
Day 1	Day 2	Alpha
8-8-2015	24-8-2015	2021
24-8-2015	27-10-2015	5661
27-10-2015	28-11-2015	4493
25-7-2016	26-8-2016	3392
26-8-2016	29-10-2016	1870
29-10-2016	14-11-2016	720

Table 9 Alpha values Marengo

The alpha values of the Marengo reservoir show the decrease in size of the variable, which represents the increasing steepness of the slopes, the emptier the reservoir gets. Only the first measurement shows a lower alpha value than the second one, which is not as expected.

Paus Branco		
Day 1	Day 2	Alpha
24-8-2015	27-10-2015	56
27-10-2015	28-11-2015	46
25-7-2016	26-8-2016	-
26-8-2016	29-10-2016	40
29-10-2016	14-11-2016	37

Table 10 Alpha values Paus Branco

One of the values could not be calculated. This happened at the third time period at Paus Branco. This is because the water area of the first measurement in 2016 is larger than the second value. The calculation is based on the second value to be lower, as the water volume is supposed to decline during the year. Because of this it is not possible to calculate the alpha value for that period.

São Nicolau		
Day 1	Day 2	Alpha
25-7-2016	26-8-2016	521
26-8-2016	29-10-2016	3853
29-10-2016	14-11-2016	4517

Table 11 Alpha values São Nicolau

The values of alpha in the São Nicolau reservoir are increasing, instead of declining. This could be caused by the surrounding area of the reservoir being different than with other reservoirs. It seems that the top of the reservoir is surrounded by increasingly steep slopes, while the bottom part almost levels out.

Nova Vida		
Day 1	Day 2	Alpha
25-7-2016	26-8-2016	213
26-8-2016	29-10-2016	71
29-10-2016	14-11-2016	152

Table 12 Alpha values Nova Vida

The smallest reservoir, Nova Vida looks like it has an inconsistent reservoir slope based on the values of alpha.

5.4.2. Simulated heights compared to measured heights

The calculated values of alpha are then used for the simulation of the water heights to compare them with the measured heights. For each period between measurements, the alpha value from the period of satellite images that is closest to the measurements is used. With these known values and the function of the surface area of the reservoirs over time, the difference in height between any two points in time during one dry period can now be calculated by filling in the VYELAS-model. This is done by calculating the water flows for the period between the two height measurements. These values combined with the most appropriate value of alpha and the function of areas over time are filled in into the VYELAS-model to calculate the difference in water heights between the consecutive measurement dates. The output of this is then compared to the actual measured difference in the same period of time. With the alpha values known. The outcomes of water height difference in each period are given in Table 13.

	Date	Measured (m)	Simulation (m)	Difference (m)
Marengo	14-5-2015	0,02	0,24	-0,22
	8-7-2015	0,26	0,25	0,01
	14-8-2015	0,79	0,73	0,06
	13-8-2016	0,76	1,86	-1,10
	6-11-2016	0,39	0,91	-0,52
Paus Branco	8-7-2015	1,09	0,53	0,56
	9-9-2015	0,51	1,05	-0,54
	11-11-2015	0,70	1,42	-0,72
São Nicolau	29-11-2016	1,18	1,15	0,03
Nova Vida	29-11-2016	0,74	2,05	-1,31

Table 13 Measured water height difference compared to simulated

The differences range from a simulated deficiency of 0,56 m to a simulated excess of 1,31 m compared to the measured water height difference. Two of the simulated values in the Marengo reservoir from 2015, as well as the one from São Nicolau in 2016 are very close to the measured values. Other dates and reservoirs however, show a larger difference. These differences can be caused by three things: an inaccurate calculation of the water balances, incorrect water surface areas or an error in the translation to water heights. The last option suggests that the VYELAS-model is not suitable, but since this model has been used in earlier researches with similar circumstances this is probably not the case.

6. Conclusion

Based on the previous chapter, first of all the sub-questions can be answered. A short summarization is given for each answer and with these answers, the main question can then be answered. Other findings that do not belong under one of these questions are given at the end.

6.1. Sub-questions

1. *What is the human influence on water withdrawal from the reservoirs?*

From the interviews held, it was clear that every household in the area has multiple animals to sustain, only with some exceptions. These animals consist for a large number of cattle that all require every day drinking water and are brought to the reservoirs for this. Another influence on the water withdrawal is the agriculture that is mostly located on the banks of the reservoirs. In total of 1010,9 liter per household per day is used from the reservoirs. The water use of animals account for the largest part in this, with 850,9 liter. The rest of this volume is used for agriculture. Water needed for drinking by people and also for small animals and daily household is not taken from the reservoir, but instead from rain tanks that are located near most of the houses. These tanks are used for drinking and every day household water and when empty, they are refilled from water trucks from outside of the area. These numbers are based on averages and assumptions which are very hard to check for accuracy in this research area. Besides this the water trucks are also an uncertainty. Sporadically they take water from the reservoirs for use elsewhere, but there seems to be no fixed schedule for when this happens at which reservoir or how many truckloads are extracted each time.

People use the most nearby reservoir as expected, but only a small part switches to another reservoir when the one of the first choice is empty. For some communities this is because the reservoir they make use of is bigger than the other reservoirs in the area, so when it is empty the other ones will be emptied before. For others, the reservoirs that contain water when the first choice is empty are too far away, in which case it is easier to make use of either the community water tank or call a water truck to deliver water.

2. *What is the influence of evaporation and infiltration on the water decrease of the reservoirs?*

The largest part of the water outflow on a daily basis is in each measured reservoir the evaporation. The quantity changes per reservoir, as each one has a different water surface area for evaporation to take place. Also the amount of people that live near the reservoir compared to the total volume of the reservoir makes contributes to the relative difference in volumes. During the dry period the percentage of water flow from daily evaporation compared to the total water flow can change drastically because of the shrinking of the water volume left. At the Marengo reservoir, for example the evaporation is responsible for 88% of the water withdrawal in the beginning of the dry period in 2015, which is reduced to 45% at the end of the measurements in 2016. This makes the evaporation the most fluctuating variable in the water balance.

Infiltration is in this research a fairly constant factor and is for three out of four reservoirs responsible for the least amount of water flow per day compared to the other factors. Only Paus Branco has a larger green area than the other reservoirs which causes the infiltration volume to be higher than the withdrawal from human factors. Because the infiltration is only dependent on the evaporation value with a constant green area, these values do not differ much during the year. Here in lies probably the largest uncertainty for this sub question, as the real green area is likely to change a bit with the shrinking of the water surface. In this research no of attention is paid to the circumstances in which the vegetation can flourish or not other than the availability of infiltration from the reservoir. This assumption creates a level of unknown uncertainty since further research is necessary to provide a more accurate estimation of the influence of infiltration.

3. What are the shape factors and dimensions of the reservoirs at different moments?

The calculated shape factor and dimensions of the reservoirs are presented in 5.3.1 Water areas and in 5.4.1 Alpha values. The water areas have some measurements in it that are at best doubtful, since they are not in line with the expectations. For example, the area of the Paus Branco reservoir has grown between the first and second measurement of 2016, while the other reservoirs showed only further depletion. In case of a sudden period of rain it can be possible that more water flows into the reservoir, but there was no indication that this happened, and the amount of volume seems like too much to be true. The overall measurements of the areas have not been very precise also. The relatively small resolution of satellite images causes a large uncertainty, especially in the end of the dry seasons when the reservoirs consist of only a small amount of countable pixels. With larger reservoirs the resolution would not be this big of a problem.

This lack of accurate data of water surfaces results also in uncertainty in the calculation of the value of the shape factor alpha. Since this factor is based on the values of measured areas it is directly inflicted by inaccurate measurements which then translates into uncertainties in calculated water heights.

6.2. Main research question

Is it possible to use the VYELAS-model to accurately assess the water level decay in small reservoirs using meteorological data and remote sensing?

With the available data that is used for this research, efforts are made to create an as accurate as possible assessment of the water level decay during the dry periods. Based on the available data there is however a large uncertainty in the results. It is also not clear how big the impact of these uncertainties is on the overall outcomes. Despite this, a part of the results seems to be in accordance with the measured values. That is why it is very well possible that with accurate data this method of assessing the water level decay can be of helpful use. If more accurate data is available, it can also be possible to give more information about the level of uncertainty that comes with this method.

7. Recommendations

First of all and what is also made clear in the conclusion, with more accurate data available this research can have a different outcome and more can be said about the results. Besides that, a couple of variables have been estimated or averaged, where further research was also possible to create more accurate values. This is for example the case with the influence of different types of crops on the water balance. Not every type consumes the same amount of water and also not every type is being grown the whole year around. Another part that could be worked out further is the implementation of the way in which people make use of a different reservoir when the one nearby is empty. Only a limited number of people responded that as a second choice they went to a different reservoir to fulfill their water need. When with more accurate data the time in which a reservoir runs dry can be better estimated, it is possible to incorporate the switch to different reservoirs for water consumption.

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Appendices

Appendix A

The calculation steps for the simplified Penman equation are given below. *Er* is the evaporation based on energy balance method, which uses a constant factor multiplied with the solar radiation to give the evaporation. *Ea* is the evaporation based on the aerodynamic method which also incorporates wind and temperature effects. These two combined give a more precise calculation.

$$Er = 0{,}0353 * Rn$$

In which *Rn* is the average solar radiation per day.

$$Ea = B * (eas - ea)$$

Wherein *B* is based on the wind speed u and distance from the ground of the measurement station *z2*. *Z0* is a constant, based on terrain on which the measurement station is placed.

$$B = (0{,}102 * u)/(\log\left(\frac{z2}{z0}\right)^2)$$

The variable *eas* is based on the temperature and is given by the following formula:

$$eas = 611 * e^{\frac{17{,}27*T}{237{,}3+T}}$$

T is hereby the average temperature in degrees Celsius during 24 hours. The variable *ea* is based on *eas* and multiplies this with the humidity *Rh*:

$$ea = Rh * eas$$

To combine these energy balance and aerodynamic method two more variables are presented. These are Δ and γ, in which Δ is a function based on *eas* and *T*:

$$\Delta = (4098 * \mathrm{eas})/(237{,}3 + T^2)$$

The γ is a constant and has a value of 66,8. The eventual evaporation per day is given in this last step of the formula:

$$E = \frac{\Delta}{\Delta + \gamma} * Er + \frac{\gamma}{\Delta + \gamma} * \mathrm{Ea}$$

Appendix B

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)

Bands	Wavelength (micrometers)	Resolution (meters)
Band 1 - Ultra Blue (coastal/aerosol)	0.43 - 0.45	30
Band 2 - Blue	0.45 - 0.51	30
Band 3 - Green	0.53 - 0.59	30
Band 4 - Red	0.64 - 0.67	30
Band 5 - Near Infrared (NIR)	0.85 - 0.88	30
Band 6 - Shortwave Infrared (SWIR) 1	1.57 - 1.65	30
Band 7 - Shortwave Infrared (SWIR) 2	2.11 - 2.29	30
Band 8 - Panchromatic	0.50 - 0.68	15
Band 9 - Cirrus	1.36 - 1.38	30
Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100 * (30)
Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100 * (30)

Table 14 Landsat 8 bands

Appendix C

Below, the preferred sources of water and number of persons and animals are shown as given in the interviews.

House id/ Waypoint	source 1	source 2	source 3	pers ons	cows	pigs	goats	shee p	chick ens	hors es	Donk eys	Cats	Dogs
1	São Nicolau	well	açude Marengo	3	23	6			15	4			
2	São Nicolau	well	açude Marengo	5	4			15	4				

3	São Nicolau	well	açude Marengo	3	12			30	40	3			
4	São Nicolau	well	açude Marengo	2	4				14	2			
5	São Nicolau	well	açude Marengo	3	3			13		1			
6	São Nicolau	well	açude Marengo	2		3			10	2			
7	São Nicolau	well	açude Marengo	6					28				
8	São Nicolau	well	açude Marengo	3	11	2		45	10	(-)			
MA01	Marengo	well	tank on Marengo	2	19		80		35		1	4	
MA02	são nicolau	paus branco	rain tank	4				13	12	1		1	2
MA03	water truck	são nicolau		8	5			14	5	4			7
MA04	são nicolau	well	rain tank	9	11	2		3	4	2			1
MA05	well at nova vida 2	community water tank	nova vida 2	9	10	3		30	35	4		3	
MA06	army water truck	nova vida 2	são nicolau	2	5	1		25	22				
MA07	own small dam	water truck	well	5	20	3		60	40	4		1	
MA08	nova vida 2	water truck (from nova vida 2)	Water truck (outside area)	6	3			26	15	1			
MA09	nova vida	water truck	desalinator/nova vida	4	17			10	18	1			1
MA10	nova vida	well	water truck	3	6			20		1			1
MA11	rain tank	community well	water truck	2	8	1		18	45	2			1
MA12	nova vida	rain tank	water truck	4	2			7	4	3			1
MA13	nova vida	water truck	well	2	8	1		30		3			1
MA14	rain tank	paus ferro	water truck	6	22			52	10	1			
MA15	rain tank	community dam	well	4		1		100	9	1			1
MA16	rain tank	water truck	community water tank	3					13				1
MA17	Paus Branco	Well		5	2								

MA18	Paus Branco	community water tank	water truck	4		2		40	15	1			1
MA19	Paus Branco	community water tank	water truck	3					15				2
MA20	Paus Branco	Well	Water truck	6					40		3		
MA21	paus branco	well	water truck	7	3			8	50	1			
MA22	paus branco	well	water truck	7	6								
MA23	Paus Branco	well	water truck	2		1			3	2			1
MA24	Paus Branco	well	water truck	3									
MA25	Paus Branco	well	water truck	2	6	2			15	4			
MA26	Paus Branco	well	water tank	4									
MA27	Paus Branco	Well		3	4		30		15				
MA28	well	water truck	paus branco	8	4	1		46	23	1			
MA29	Paus Branco	well	water truck	6		4		3	5	1			3
MA30	Paus Branco	well		3		7	36						
MA31	São Joaquim	community rain tank	water truck	3						1			1
MA32	São Joaquim	Well	water truck	3					20				
MA33	São Joaquim	Well		6	17	10		70	8				
MA34	São Joaquim	Well	desalinator/sao joaquim	4									1
MA35	rain tank	sao joaquim	well	2	10	1		70	20	3			2
MA36	rain tank	well	water truck	4		5		6	17				2
MA37	são joaquim	well	water truck	3	0	0	0	0	0	0	0		
MA38	sao joaquim	raiz	Marengo	3	18	4		50	24	2			2
MA39	Mel	community well	water truck	6	2	4		6	23	1			3
MA40	Mel	Marengo		8	11	0	15	0	30	0	0		
MA41	Marengo	well	water truck	4	3				6				2

MA42	Marengo	Well	Water truck	2	1	1	0	0	6	1	0		

Table 15 Interview answers

Appendix D

In this table the preferred sources from the interviews are shown next to the location of the three closest reservoirs. The nearby reservoirs are ranked from closest to less close.

	Given answers			**Nearby ranking**		
House id/ Waypoint	**source 1**	**source 2**	**source 3**	**Near 1**	**Near 2**	**Near 3**
1	São Nicolau	well	açude Marengo	São Nicolau	Mel	Nova Vida
2	São Nicolau	well	açude Marengo	São Nicolau	Mel	Marengo
3	São Nicolau	well	açude Marengo	São Nicolau	Mel	Marengo
4	São Nicolau	well	açude Marengo	São Nicolau	Mel	Nova Vida
5	São Nicolau	well	açude Marengo	São Nicolau	Mel	Nova Vida
6	São Nicolau	well	açude Marengo	São Nicolau	Mel	Nova Vida
7	São Nicolau	well	açude Marengo	São Nicolau	Mel	Marengo
8	São Nicolau	well	açude Marengo	São Nicolau	Mel	Nova Vida
MA01	Marengo	well	tank on Marengo	Marengo	São Joaquim	Mel
MA02	são nicolau	paus branco	rain tank	São Nicolau	Marengo	Mel
MA03	water truck	são nicolau		São Nicolau	Mel	Marengo
MA04	são nicolau	well	rain tank	São Nicolau	Nova Vida	Nova Vida 2
MA05	well at nova vida 2	community water tank	nova vida 2	Nova Vida	Nova Vida 2	São Nicolau
MA06	army water truck	nova vida 2	são nicolau	Nova Vida	Nova Vida 2	São Nicolau
MA07	own small dam	water truck	well	Nova Vida	Nova Vida 2	São Nicolau
MA08	nova vida 2	water truck (from nova vida 2)	Water truck (outside area)	Nova Vida	Nova Vida 2	São Nicolau
MA09	nova vida	water truck	desalinator/nova vida	Nova Vida	Nova Vida 2	São Nicolau
MA10	nova vida	well	water truck	Nova Vida	Nova Vida 2	São Nicolau
MA11	rain tank	community well	water truck	Nova Vida	Nova Vida 2	São Nicolau
MA12	nova vida	rain tank	water truck	Nova Vida	Nova Vida 2	São Nicolau
MA13	nova vida	water truck	well	Nova Vida 2	Nova Vida	São Nicolau

MA14	rain tank	paus ferro	water truck	São Nicolau	Marengo	Mel
MA15	rain tank	community dam	well	São Nicolau	Marengo	Mel
MA16	rain tank	water truck	community water tank	São Nicolau	Marengo	Mel
MA17	Paus Branco	Well		Paus Branco	Nova Vida	Nova Vida 2
MA18	Paus Branco	community water tank	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA19	Paus Branco	community water tank	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA20	Paus Branco	Well	Water truck	Paus Branco	Nova Vida	Nova Vida 2
MA21	paus branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA22	paus branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA23	Paus Branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA24	Paus Branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA25	Paus Branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA26	Paus Branco	well	water tank	Paus Branco	Nova Vida	Nova Vida 2
MA27	Paus Branco	Well		Paus Branco	Nova Vida	Nova Vida 2
MA28	well	water truck	paus branco	Paus Branco	Nova Vida	Nova Vida 2
MA29	Paus Branco	well	water truck	Paus Branco	Nova Vida	Nova Vida 2
MA30	Paus Branco	well		Paus Branco	Nova Vida	Nova Vida 2
MA31	São Joaquim	community rain tank	water truck	São Joaquim	Marengo	Mel
MA32	São Joaquim	Well	water truck	São Joaquim	Marengo	Mel
MA33	São Joaquim	Well		São Joaquim	Marengo	Mel
MA34	São Joaquim	Well	desalinator/sao joaquim	São Joaquim	Marengo	Mel
MA35	rain tank	sao joaquim	well	São Joaquim	Marengo	Mel
MA36	rain tank	well	water truck	São Joaquim	Marengo	Mel
MA37	são joaquim	well	water truck	São Joaquim	Marengo	Mel
MA38	sao joaquim	raiz	Marengo	São Joaquim	Marengo	Mel
MA39	Mel	community well	water truck	Mel	Marengo	São Nicolau
MA40	Mel	Marengo		Mel	Marengo	São Nicolau

MA41	Marengo	well	water truck	Marengo	São Joaquim	Mel
MA42	Marengo	Well	Water truck	Marengo	São Joaquim	Mel

Table 16 Reservoir preferences compared to location

Appendix E

In this appendix, the trendlines of the water surface area of each reservoir are shown.

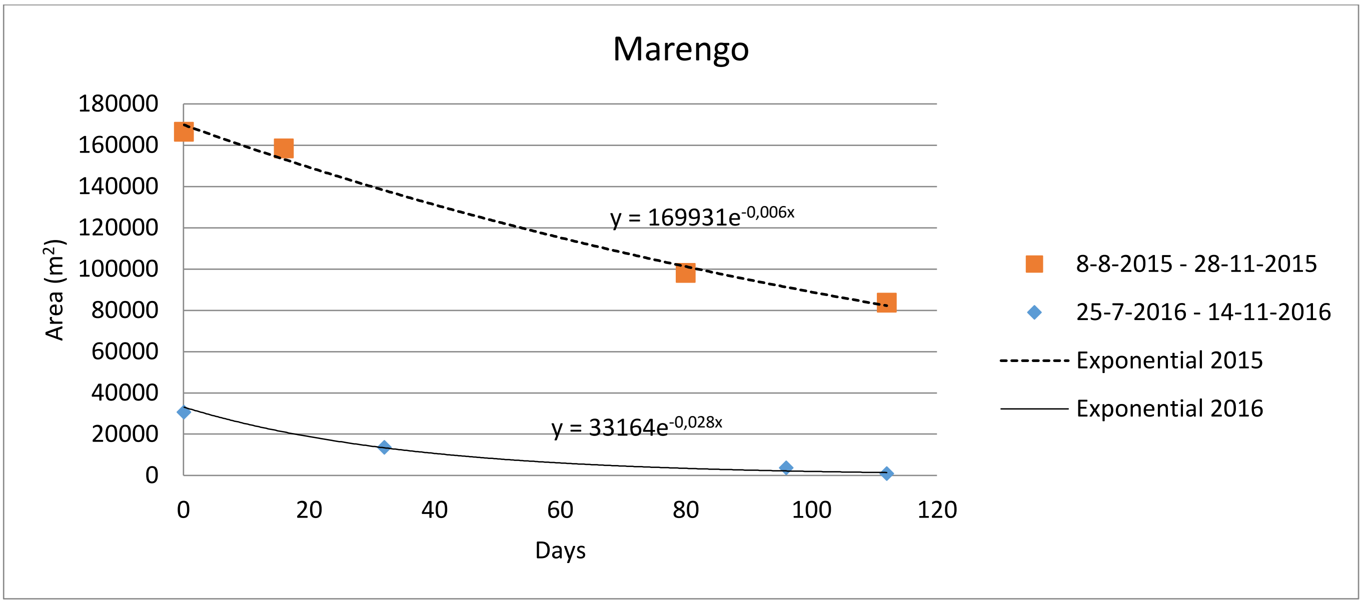

Figure 8 Trendlines Marengo

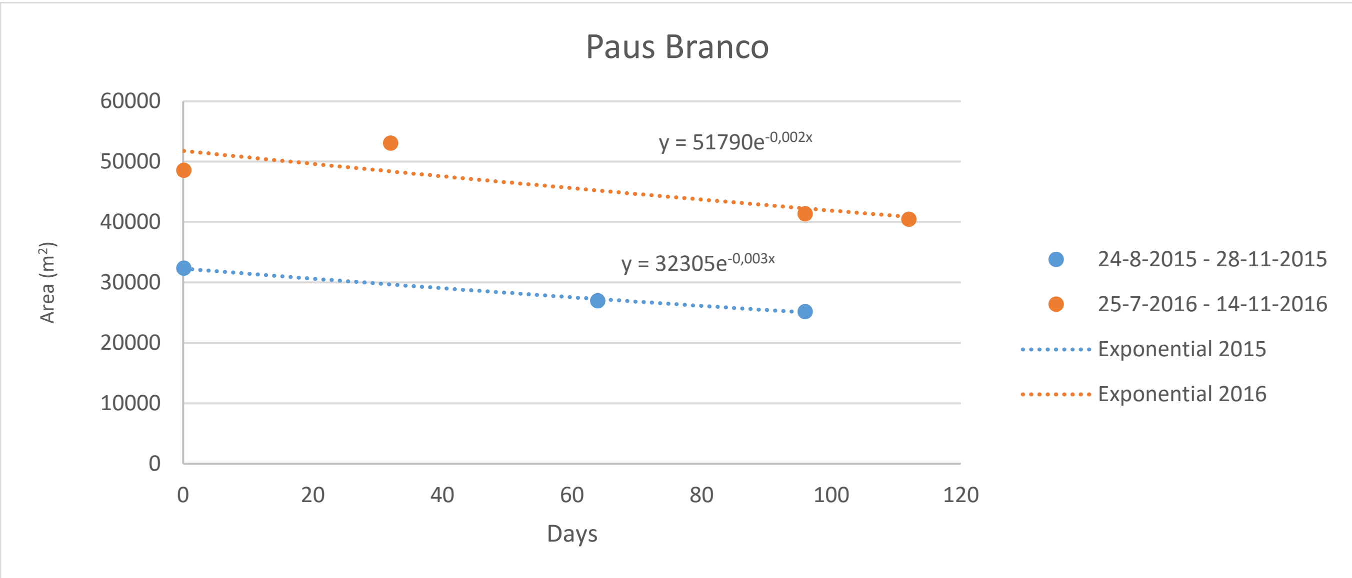

Figure 9 Trendlines Paus Branco

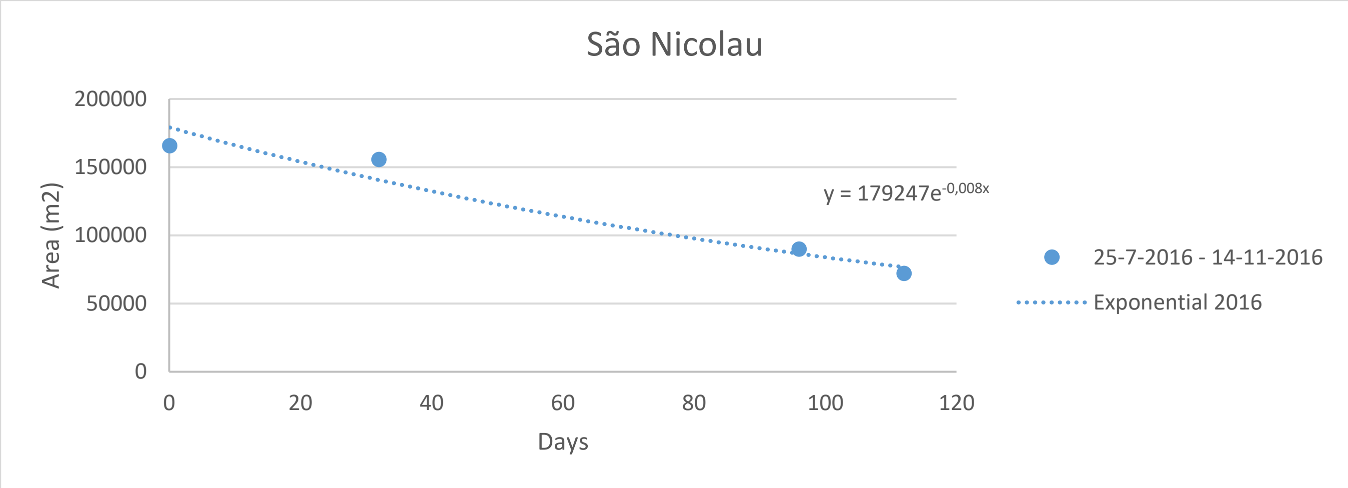

Figure 10 Trendline São Nicolau

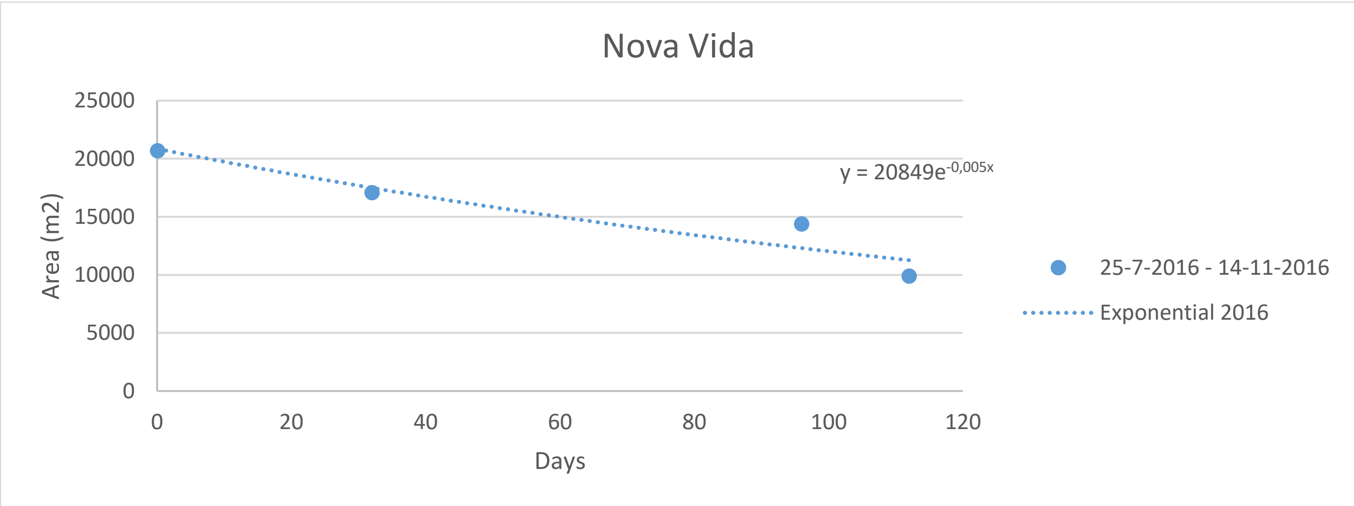

Figure 11 Trendline Nova Vida

Appendix F

The water flow based on remote sensing data and modeled evaporation are represented in the following tables.

Marengo			
Day 1	Day 2	Waterflow Q (m^3)	Evaporation–Precipitation (m)
8-8-2015	24-8-2015	3099	0,11
24-8-2015	27-10-2015	15934	0,60
27-10-2015	28-11-2015	22203	0,83
25-7-2016	26-8-2016	6623	0,27
26-8-2016	29-10-2016	13406	0,55
29-10-2016	14-11-2016	23284	0,95

Table 17 Marengo waterflow and evaporation

Paus Branco			
Day 1	Day 2	Waterflow Q (m^3)	Evaporation–Precipitation (m)
24-8-2015	27-10-2015	21129	0,50
27-10-2015	28-11-2015	31281	0,72
25-7-2016	26-8-2016	10949	0,27
26-8-2016	29-10-2016	33031	0,81
29-10-2016	14-11-2016	38552	0,95

Table 18 Paus Branco waterflow and evaporation

São Nicolau			
Day 1	Day 2	Waterflow Q (m^3)	Evaporation–Precipitation (m)
25-7-2016	26-8-2016	7116	0,27
26-8-2016	29-10-2016	21414	0,81
29-10-2016	14-11-2016	24989	0,95

Table 19 São Nicolau waterflow and evaporation

Nova Vida			
Day 1	Day 2	Waterflow Q (m^3)	Evaporation–Precipitation (m)
25-7-2016	26-8-2016	4730	0,27
26-8-2016	29-10-2016	14251	0,81
29-10-2016	14-11-2016	16632	0,95

Table 20 Nova Vida waterflow and evaporation