GEOMETRY AND WATER HEIGHT-AREA-VOLUME CURVES OF THE RESERVOIRS IN THE SEMIARID MADALENA BASIN IN NORTHEAST BRAZIL

Final Report

Sido Grin

GEOMETRY AND AREA-DEPTH-VOLUME CURVES OF THE RESERVOIRS IN THE SEMIARID MADALENA BASIN IN NORTHEAST BRAZIL

Final Report

Sido Grin *S1232533*

Bachelor Final Project

Civil Engineering

University of Twente

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27 August 2014

PREFACE

During my stay at the UFC and the IFCE in Fortaleza, Brazil, I spend ten weeks working on the bachelor final project. Going there all by myself into a different culture turned out to be a great experience on both social as academic level. It was my introduction to the field of research and my first time on a long field trip. The field trip was the most learning full experience during my stay and maybe even during my whole study. A major contribution therefore was working together with the other students and professors from the UFC, IFCE and the University of Potsdam. I owe my thanks to the persons who gave me this opportunity and supported me during my stay; José Carlos Araújo, Pedro Medeiros and Maarten Krol.

SUMMARY

The water scarcity in the Northeast of Brazil due to high variability of rainfall, evaporation rates that can reach up to 2,500 mm/year, and the occurrence of shallow soils, has led to the construction of thousands of small dams. In this high-density reservoir network no direct monitoring of small reservoirs takes place. Remote sensing has been pointed out as a feasible way of monitoring seasonal changes in order to understand the magnitude of the hydrological processes involved. To support remote sensing development and thereby efficient water management and reservoir planning in the semiarid Northeast of Brazil, it is needed to determine area-depth-volume relations for this region. The study site is the semiarid Madalena Basin, it is an experimental catchment that has been monitored regarding basic hydrological variables since 2008. The objective for the assignment was to determine the geometry and the water height-area-volume curves for the main reservoirs in the semiarid Madalena Basin by performing a bathymetric survey and data-analysis.

The research focused on three of the five main reservoirs. These are the reservoirs Raiz, São Nicolau and Marengo. The reservoir São Nicolau is the youngest reservoir in the Madalena basin, it is constructed in 1995. The reservoirs is very shallow in most areas and there is many vegetation present in the water. When the field surveys took place the reservoir was almost completely filled. The reservoir Raiz, constructed in 1958, was almost dry at time of the field surveys. The reservoir is shaped with two major side branches coming together at the dam. In the reservoir are some minor obstacles located like fences and tall grass. The reservoir Marengo is the biggest reservoir in the Madalena basin. It is built in 1934 and enlarged in 1956. There is no vegetation present in the water and the shores are well accessible. Approximately 22% of the maximum surface area was covered with water in Marengo. The reservoirs only have runoff when they are completely filled and the water passes the spillway, there is no other discharge channel.

The research method is divided into three parts; data collection, reservoir modelling and data analysis. The data is collected by a bathymetric survey consisting of measurement on water and measurement on land. Multiple points with water depths were taken by using an echo-sounder with GPS antenna attached to a boat. To verify that the data from the echo-sounder is correct, multiple points are also measured by a handheld depth meter and handheld GPS. The water surface area was measured by walking around the water and register multiple points with a handheld GPS. To complete the data, the height from the water surface to the spillway is measured by the total station. As the reservoirs of Raiz was almost completely dry, the terrain of this reservoir was mostly measured by the total station.

The collected data for each reservoir is modelled into a 3D-model. The process of creating a model for each reservoir can be divided into four steps; add data, create surface areas, create dataset, and gridding data. After spatial adjustment of the total station data by using GPS control points, all the data contain coordinates. For the reservoirs Raiz and Marengo the water surface area is not equal to the maximum area. Therefore the maximum area was determined by using Landsat 5 images from July 2004, when the reservoirs were completely full. A useful dataset to create the model was formed by removing and adding points. The removal of points was necessary due to errors in the depth values, and the adding of points was needed to make sure a correct surface is created through interpolation. The final dataset and the maximum area was used to create a 1 by 1 meter grid that represents the geometry of the reservoir. An important aspect hereby was choosing the right interpolation method.

Of course each of the above steps slightly differs for each reservoir. For example, for Raiz it was needed to use Landsat 5 images to estimate unmeasured areas and for Marengo there was data used from a previous study to make a complete model. The models extracted from the 1 by 1 meter grids give an overview of the bathymetric shape and the characteristics of each reservoir, which correspond with the observation in the field and approach the reality.

With the developed models, the area and volume for certain depths are calculated for each reservoir, the chosen step value for the water level is 0.1m. The output from the computation allows the creation of logArea-logVolume and logDepth-logVolume curves for each reservoir. As the water in the reservoirs is extracted at every water level, it is necessary to find a curve that is correct for all the water levels. In other words, the dataset used for the log-log curves contains all points. By taking the log-log curves it is possible to make a linear line that represents the relation. The function of the linear line is rewritten to a power function using basic logarithm principles. The derived power function represents the area-volume relation ($V = k * A^a$) or the depth-volume relation ($V = k * D^a$) for the specific reservoir. For both formulas applies that constant a is related with the hillside concavity and the coefficient k represents the openness of the pyramid.

For the a coefficient there seems to be a region specific value for both the area-volume and the depth-volume relation that represents the hillside concavity for the Madalena Basin. But the values of the parameter k do not seem to have direct agreement between each other. Nevertheless, the results give the impression that the reservoirs in the Madalena Basin have a region specific shape that is characterized by being narrow and do not contain an evident open alluvial middle area, and thereby are having linear slopes with a convex tendency. The reliability of the results is affected by the accuracy of the echo sounder, the use of Landsat images, the use of handheld GPS for control points and some reservoir specific issues.

As only three of the five main reservoirs in the Madalena Basin are covered by this research it is not possible to provide complete estimates of the water availability for the area. Nevertheless, the results should be helpful and support the development in remote sensing and efficient water management and reservoir planning in the Madalena Basin and the semiarid Northeast of Brazil.

For further research it would be possible to develop a region specific area-volume relation for the semiarid Northeast of Brazil that can be used by planners to simulate volume in function of surface area. To create such a general power function it is needed to perform bathymetric surveys for much more reservoirs. Another recommendation follows from the field experience and the difficulty in modelling a complete reservoir with various data. It is time consuming to perform measurements on land by total station. Moreover, the inaccuracy increases when Landsat 5 images or output data from previous studies are used for the estimation of the maximum area or to cover unmeasured areas. To avoid these issues it would be better to perform a bathymetric survey by boat when the reservoirs are completely full with calibrated and accurate measurement devices.

CONTENTS

1. INTRODUCTION

To give a complete image of the concerned topic, there first is some background information presented. With the knowledge of the background information the objective for the assignment is made clear. Also a description of the structure is given, to give an overview of the content in this report.

1.1. Background

The background information can be divided into three subjects. First, the function and importance of small reservoirs is addressed. Second, the related development in remote sensing is set forth. And lastly, the importance of bathymetric surveys will be explained.

FUNCTION AND IMPORTANCE OF SMALL RESERVOIRS

Lakes and reservoirs are important as a source for fresh water and sustain activities such as agriculture, fisheries and recreation. In periods of drought, the rural population in most semi-arid environments rely heavily on small reservoirs to sustain their livelihoods (Annor, et al., 2009). Water stored in these reservoirs allows for all year-round irrigated agriculture and ensures that domestic water shortages are reduced during dry periods. The small reservoirs proximity to places of demand is an advantage that makes them an appropriate tool for drought mitigation (Liebe, Van de Giesen, & Andreini, 2005). The reservoirs also have a significant effect on downstream flows, as they can provide a buffer from flooding by delaying and diminishing flash floods by temporarily storing the excess water (Poolman, 2005). Arrays of small reservoirs can potentially have a large impact on the hydrology and the ecology of the surrounding environment (Rodrigues & Liebe, 2013; Rodrigues, Sano, Steenhuis, & Passo, 2012). This impact is simulated to even increase under disadvantageous climate changes (Krol, Vries, Oel, & Araújo, 2011). Therefore, small reservoirs are very important for their environment.

In Brazil thousands of small reservoirs were built in the last few decades to help improve irrigated agriculture and livestock watering in the region (Rodrigues & Liebe, 2013). In order to manage the water effectively for competing uses, the actual storage of these reservoirs need to be accurately estimated (Annor, et al., 2009). However, efficient water management and reservoir planning of small reservoirs are hindered by the lack of knowledge of their number, storage capacity and distribution (Liebe, Van de Giesen, & Andreini, 2005). The absence of adequate knowledge on small reservoir storage capacities has been a constraint in decision-making processes regarding to planning and management of water resources. (Sawunyama, Senzanje, & Mhizha, 2006; Rodrigues, Sano, Steenhuis, & Passo, 2012). The main limitation is formed by the methodologies used to quantify physical parameters, they are costly, time consuming and laborious (Sawunyama, Senzanje, & Mhizha, 2006). This justifies the need to establish the capacities of reservoirs using less expensive methods.

DEVELOPMENT IN REMOTE SENSING

The search to less expensive methods resulted in many developments in the field of remote sensing. Abileah and Vignudelli (2011) showed a promising completely remote sensing approach to monitor reservoir water capacity in lakes and reservoirs worldwide. Their research was based on the fusion of two freely available Earth orbiting satellite data, Landsat optical images and radar altimeters from several satellites. Another completely remote sensing approach was used by Alcantara et al (2010) to develop bathymetric maps of hydroelectric reservoirs in Brazil. This bathymetric method can be used to create maps of the lakebed and to compute water level area and volume tables so that water supply managers can regulate the use of these valuable resources more reliably. Gao, Birkett and Lettenmaier (2012) study of 34 global reservoirs also showed a similar result. All these methods make use of satellite radar altimetry to measure the water depth. Unfortunately, current radar altimeters are not applicable on small reservoirs due to their narrow swaths, large footprints and effect of surrounding topography. So, for the small reservoirs it is not possible to determine the volume of water storage directly by remote sensing techniques.

Nevertheless, several studies showed that remote sensing offers many possibilities for determining the water storage in small reservoirs. In these studies remote sensing is used to detect small reservoirs and accurately measure their surface areas. Liebe, Van de Giesen and Andreini (2005) surveyed 61 small reservoirs in the Upper East Region of Ghana and derived an expression relating reservoir areas to storage volumes. Their method was simple, cost effective and had a high precision (NS=0.975). Using the same technique, Sawunyama, Senzanje and Mhizha (2006) surveyed 12 small reservoirs in the Mzingwane catchment in Limpopo River Basin in Zimbabwe and found a good correlation (R2=0.95) between surface area and storage volume as well. Another survey by Rodrigues, Sano, Steenhuis and Passo (2012) of 147 small reservoirs in the Brazilian Preto River Basin resulted in a correlation of 83% between surface area and storage volumes. These researches show that there exist a power relationship between remotely sensed surface areas and storage capacities of reservoirs. Liebe, Van de Giesen, Andreini, Walter and Steenhuis (2009) recently showed another important application of the technique using small reservoirs as runoff gauges. They estimated runoff volume by change in reservoir areas satellite imagery. These remote sensing techniques are more cost effective for determining small reservoir storage than maintaining level recording devices (Rodrigues, Sano, Steenhuis, & Passo, 2012).

The methods used in the above descripted researches all made use of Landsat images to determine the reservoir water surface. The accuracy of the lateral delineation of these reservoirs with Landsat was very good. However, Landsat images and images obtained from similar optical sensors are affected by cloud cover especially during the rainy season. In contrast radar images, like ENVISAT, ASAR and TerraSAR-X, can penetrate clouds, light rainfall and images taken during night time are usable (Annor, et al., 2009; Kleine, et al., 2013). Therefore radar images can be used to provide similar information all year-round.

It can be concluded that remote sensing, by optical images or radar images, can be used to determine the surface area and subsequent estimate the actual reservoir volume in small reservoirs. Provided that the expression/relation between the surface area and the volume for the reservoir or region is known. This offers many opportunities for efficient water management and reservoir planning for small reservoirs in the inaccessible rural areas, for which detailed information is lacking.

IMPORTANCE OF BATHYMETRY SURVEY

Even though major advances are made in the measurement of lake levels using remote sensing such as satellite altimetry, a bathymetric base line is still required and cannot yet be obtained from remote sensing at low cost and with a high spatial resolution (Dost & Mannaerts, 2008). With a bathymetric survey the surface area-depth-volume curves can be determined. Those curves are the most important physical characteristics of dams’ reservoirs. These curves are used for reservoir flood routing, dam operation, determination of water surface area and capacity corresponding to each elevation, reservoir classification and prediction of sediment distribution in reservoirs (Rodrigues & Liebe, 2013). As a result, obtaining the area-depth-volume equations has great significance from a practical aspect.

The equations derived by indirect satellite imagery methods developed by Liebe, Van de Giesen and Andreini (2005), Annor et al (2007), Sawunyama, Senzanje and Mhizha (2006) and Rodrigues, Sano, Steenhuis and Passo (2012) in respectively the Upper East Region of Ghana, the Limpopo Basin in Zimbabwe and the Preto River Basin in Brazil are not widely usable because they are very region specific. The main reason is that the geology is different, and thereby the valley shapes are different (Rodrigues, Sano, Steenhuis, & Passo, 2012). For example, the cross sections of inland valleys in West Africa are mainly rectilinear types, while in the savannahs area of Brazil they are mainly concave. Besides, the reservoirs in Africa dry up during the dry season, while reservoirs in many parts of Brazil retain water throughout the year (Rodrigues, Sano, Steenhuis, & Passo, 2012). In other words, for efficient water management and reservoir planning of small reservoirs in a region it is needed to perform bathymetric surveys at reservoirs in that specific region.

1.2. Objective

As stated in paragraph 1.1 a lot of small reservoirs were built in Brazil the last few decades. This also applies for the semiarid Northeast of Brazil. Water scarcity in this area due to high variability of rainfall, evaporation rates that can reach up to 2,500 mm/year, and the occurrence of shallow soils, has led to the construction of thousands of small dams in Northeast Brazil (de Araújo & Medeiros, 2013). In this high-density reservoir network no direct monitoring of small reservoirs takes places. Remote sensing has been pointed out as a feasible way of monitoring seasonal changes in order to understand the magnitude of the hydrological processes involved (Kleine, et al., 2013).

Hence, to support remote sensing development and thereby efficient water management and reservoir planning in the semiarid Northeast of Brazil, it is needed to determine the area-depth-volume relations for this region. The study site is the semiarid Madalena Basin (124 km²), it is an experimental catchment that has been monitored regarding basic hydrological variables (rainfall, evaporation, runoff, reservoirs' water level, sediment yield) since 2008.

So, the main objective of the assignment is to determine the geometry and the water height-area-volume curves for the main reservoirs in the semiarid Madalena Basin by performing a bathymetric survey and data-analysis.

1.3. Report structure

The report consists of seven chapters. After the introduction the research design is set forth in chapter 2. The research design first shows the theoretical framework, where the focuses lies on the concepts that are related to the research, and finishes with the research question and its belonging sub questions. In chapter 3 Methodology the research method is divided in three parts; data collection, reservoir modelling and data analysis. But before these aspects will be clarified, the characteristics of the study area are made clear. The results that are achieved by following the steps of the research method are shown in Chapter 4 Results. The results are divided into the geometric models, and the area-volume and depth-volume relationships. The issues that come forward during the research are discussed in Chapter 5. The conclusion and the recommendations can be found in respectively Chapter 6 and Chapter 7.

2. RESEARCH DESIGN

The basis of the research is founded by the theoretical framework, therefore the theoretical framework includes all the aspects related to this research. After the wide description of the theory, the research question and sub questions are given.

2.1. Theoretical Framework

The theoretical framework focusses on the important aspects for the research method, these are the bathymetric survey, reservoir modelling and area-depth-volume relationships.

BATHYMETRIC SURVEY

The bathymetric survey mostly consists of determining the water surface area and the water depth at several points. The bathymetric survey can be conducted in multiple ways.

The shape and size of the reservoir surface area are mostly determined by walking around the reservoir with a GPS tracker and taking large numbers of points along the shoreline. (Liebe, Van de Giesen, & Andreini, 2005; Rodrigues, Sano, Steenhuis, & Passo, 2012)

According to Alcantara et al (2010) the bathymetry inventory is often determined by echo sounders. Echo sounders are based on the time passed between sending pulses and the reception of these pulses after their reflection from the bottom of reservoir. This is confirmed by the research of Annor et al (2009). Another common used method for measuring the depth at several points is the use of a telescopic stadia rod and/or a rope with a plummet (Liebe, Van de Giesen, & Andreini, 2005; Sawunyama, Senzanje, & Mhizha, 2006). Of course, each measurement hereby is accompanied with (GPS) coordinates.

In order to get accurate representations of the reservoirs' shapes, care should be taken to capture the deepest points, as well as the submerged streambed (Rodrigues & Liebe, 2013; Rodrigues, Sano, Steenhuis, & Passo, 2012). This can be done by oversampling those parts of the reservoirs where the deepest points are expected. Because a reservoir is a dammed stream, the deepest point is usually found along its longitudinal axis, in proximity to the dam wall (Liebe, Van de Giesen, & Andreini, 2005). Several studies have shown that the deepest regions are expected to be near the dam, and the shallowest regions are in the small channels (Alcantara, et al., 2010; Rodrigues, Sano, Steenhuis, & Passo, 2012; Rodrigues & Liebe, 2013).

RESERVOIR MODELLING

When the bathymetric surveys are taken the field data needs to be translated into a workable platform. The common platform for this is a 3D-model, which is provided by multiple software programs. These models can be used to obtain area and volume series at varying depths for each reservoir, from full supply to when the reservoir is completely empty (Annor, et al., 2009).

The goal of the model is to approach the reality as best as possible. Hereby it is important to choose the right interpolation method. One of the most used methods is Kriging. The Kriging method produces visually appealing maps for irregularly spaced data. It can compensate for clustered data by giving less weight to the cluster in the overall prediction. Kriging attempts to express trends suggested in the data, high points might be connected along a ridge rather than isolated by bull's-eye type contours. It is possible to exceed the minimum and maximum point values. But this can also be a disadvantage, since the interpolated values will be higher or lower than the real values. The Kriging interpolation method is used by Alcantara et al (2010), Liebe (2002), and Rodrigues, Sano, Steenhuis and Passo (2012).

Another method, the Spline method, also known as Minimum Curvature method, is used by Sawunyama, Senzanje, and Mhizha (2006). The interpolated surface generated by Minimum Curvature is analogous to a thin, linearly elastic plate passing through each of the data values with a minimum amount of bending. Minimum Curvature generates the smoothest possible surface while attempting to honour your data as closely as possible.

It is also possible to use different interpolation techniques and use the method with the lowest error variance (Dost & Mannaerts, 2008). Thereby it is needed to randomly split the data set into two, where both sets contains 50% of the observations. One dataset is interpolated into a bathymetric map and the other one is used to determine the error variance by cross validation.

RELATIONSHIPS

Important aspects of the area-depth-volume relationships are the power function, linear regression and the goodness of fit. Also it is helpful to take a look at the determined relations in the different regions by former researches.

Power function

The theoretical derivation of the surface area-volume relationship and the depth-volume relationship is based on the assumption that the reservoir has the shape of a square pyramid diagonally cut in in half (Liebe, 2002). Resulting in the following power function.

$$y = k * x^a \qquad (1)$$

This makes the standard equations for the area-volume and depth-volume relations as follows:

$$V = k_1 * A^{a_1} \qquad (2)$$

$$V = k_2 * D^{a_2} \qquad (3)$$

$V = volume\ in\ m^3$
$A = surface\ area\ in\ m^2$
$D = depth\ in\ m$
$k_{\mathrm{n}} = constant$
$a_{\mathrm{n}} = exponential\ coefficient$

The constant a is related with the hillside concavity. In the common case of a concave slope in the reservoir, for the area-volume relationship the coefficient a is smaller than 1.5 and for the depth-volume relationship the coefficient a is greater than 3.0. When the slopes are more convex, for respectively the area-volume and the depth-volume relation the coefficient a has a value greater than 1.5 or smaller than 3.0 (Annor, et al., 2009). These statements are shown in Figure 1.

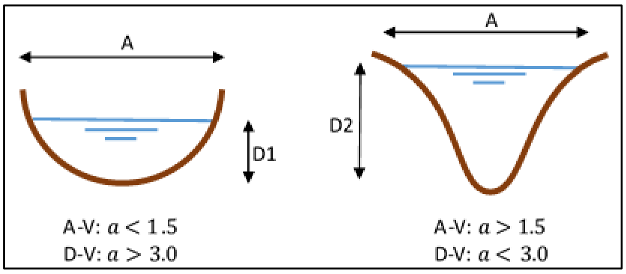

Figure 1 Parameter a for concave and convex slopes

The coefficient k represents the openness of the pyramid. The more open and flatter the valley, the larger is k. It is expected to get high k values in wide and open alluvial reservoirs (Rodrigues & Liebe, 2013). The hillside concavity is not affected by the parameter k, but the steepness is. The corresponding shapes are shown in Figure 2.

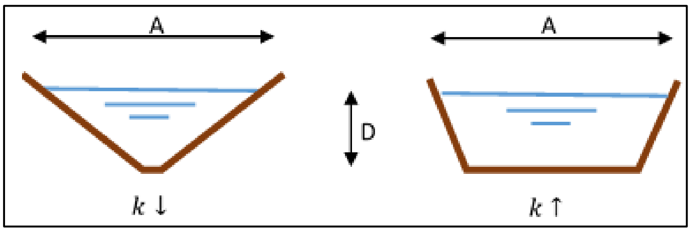

Figure 2 Parameter k for concave and convex slopes

The volume of the reservoir expressed as a function of their surface area allows for storage volume assessment from satellite imagery (Rodrigues & Liebe, 2013). And the volume of the reservoir expressed as a function of the water depth is often used in conjunction with stage data measured at the reservoirs, and this can be important in the derivation of evaporation estimates (Rodrigues & Liebe, 2013; Liebe, 2002).

Linear regression

To derive the area-volume and depth-volume relations to the power equations, it is needed to apply a linear regression analysis. Thereby it is needed to determine the linear regression equations for the logarithms of surface area and volume, and linear regression equations for the logarithms of the depth and volume (Sawunyama, Senzanje, & Mhizha, 2006). When the linear equations for the log-log relations are known, they can be transformed to area-volume and depth-volume relationships using basic logarithmic principles.

The linear equation for the log-log relations will be in the form of:

$$y = m * X + b \tag{4}$$

The different vectors can be outlined by taking the logarithm of the equation:

$$\log_{10}(y) = a * (\log_{10}(x)) + \log_{10}(k) \tag{5}$$

So:

$$m = \text{a} \tag{6}$$
$$X = \log_{10}(x) \tag{7}$$
$$b = \log_{10}(k) \tag{8}$$
$$y = \log_{10}(y) \tag{9}$$

Required for equation 2 and 3 are k and a:

$$b = \log_{10}(k) \tag{10}$$
$$k = 10^b \tag{11}$$

$$m = a \tag{12}$$
$$a = m \tag{13}$$

As stated before, when k and a are known both volume-area and volume-depth relations can be given as in equations 2 and 3.

Goodness of fit

The goodness of fit of a resulting power relationship can be determined with the standard coefficient of determination or the Nash and Sutcliffe efficiency, which is exactly the same as the coefficient of determination when used in linear regression.

The coefficient of determination indicates how well data points fit a statistic model, line or curve. It provides a measure of how well observed outcomes are replicated by the model, as the proportion of total variation of outcomes explained by the model (Steel & Torrie, 1960). In this case it will determine how accurate the area-volume and depth-volume curve approaches the model bases values.

By simple linear regression the coefficient of determination is simply the square of the sample correlation coefficient between outcomes and their predicted value. This is represented by the formula given below.

$$R^2 = 1 - \frac{SE_{residual}}{SE_{total}} \qquad (14)$$

Where,

$$SE_{residual} = \sum_i^i (y_i - f_i)^2 \qquad (15)$$

$$SE_{total} = \sum_i^i (y_i - \bar{y})^2 \qquad (16)$$

Constants in different regions

As mentioned before, some studies determined the area-volume curves for several other regions. The equations derived by indirect satellite imagery methods developed by Liebe, Van de Giesen, Andreini (2005), Annor et al (2009), Sawunyama, Senzanje and Mhizha (2006) and Rodrigues, Sano, Steenhuis and Passo (2012) in respectively the Upper East Region of Ghana, the Limpopo Basin in Zimbabwe and the Preto River Basin in Brazil are given below. These global equations are composed of the equations of multiple reservoirs in the study areas. In order of the equations given below that are respectively 41, 21, 12 and 42 reservoirs.

Upper East Region of Ghana

$V = 0.00857 * Area^{1.44}\ (m^3)$ $\ R^2 = 0{,}98$ (Liebe, Van de Giesen, & Andreini, 2005)

$V = 0.00875 * Area^{1.44}\ (m^3)$ $\ R^2 = 0.98$ (Annor, et al., 2009)

Limpopo Basin in Zimbabwe

$V = 0.023 * Area^{1.33}\ (m^3)$ $\ R^2 = 0{,}95$ (Sawunyama, Senzanje, & Mhizha, 2006)

Preto River Basin in Brazil

$V = 0.45 * Area^{1.11}\ (m^3)$ $\ R^2 = 0{,}83$ (Rodrigues, Sano, Steenhuis, & Passo, 2012)

Comparing the area-volume equations shows that the coefficients a and k, and therefore the shapes, are different. The exponential coefficient in Ghana and Zimbabwe are respectively 1.44 and 1.33, while the exponential coefficient in the Brazilian Preto Basin is 1.11. The relation of the reservoirs in Ghana and Zimbabwe (West Africa) are more curved, while the relation of the reservoir in Brazil is closer to a straight line. These results confirm that the volume-area curves are region specific and vary with the geology of the area.

As for the area-volume relations it is possible to form a general equation for each region, this is not possible for the depth-volume relations. Rodrigues and Liebe (2013) found a great variability in the parameters of the depth-volume relationships, and stated that this indicates that the equations are site specific and as such their use should not be extrapolated.

However, research by Pereira (2014) aimed to characterize the geometry of small reservoirs in the semiarid area of Ceará, by analysing the variability of the geometric coefficients and their correlation with geomorphic units. The values of α varied from 2.16 to 5.21, the average value of α being 3.11. It was observed that 289 reservoirs, 80.7% of the sample, have α values between 2.5 and 3.5. For the K coefficient, the values ranged from 32 to 28,274, which represent a considerable variation, with its average equal to 2,432 and median equal to 1,336. It is possible to conclude that the α coefficient has a low variability, and the k coefficient shows high variability and is very sensitive to the input data. (Pereira, 2014)

2.2. Research Question

To reach the objective of this research it is needed to find an answer on the following main question:

What are the geometric shapes and water height-area-volume curves of the main reservoirs in the Madalena Basin and do the curves provide reliable estimates of water availability?

This question can be broken down into some sub questions:

- *What is the shape and size of the reservoirs water surface area in the end of the rain reason?*
- *What are the belonging water depths in the reservoirs?*
- *If the reservoir is not completely full, what is the height difference between the water level and the spillway?*
- *What is the geometric shape of each reservoir?*
- *What are the relations between the water surface area and volume for each reservoir?*
- *What are the relations between the water depth and volume for each reservoir?*
- *To what extent are the measurements and relationships reliable?*

3. METHODOLOGY

To find the answers on the sub questions, and thereby on the main question, the research method is divided in three parts; data collection, reservoir modelling and data analysis. But before these aspects will be clarified, the characteristics of the study area are made clear.

3.1. Study Area

The study area is the semiarid Madalena Basin, also known as Assentamento 25 de Maio. It is an experimental catchment that has been monitored regarding basic hydrological variables (rainfall, evaporation, runoff, reservoirs' water level, and sediment yield) since 2008.

LOCATION

The Madalena Basin is located approximately 200 km outside of Fortaleza, the capital of the state Ceará in Brazil. The inhabited area is 230 km^2 and is populated by 586 households which are organized in 13 communities (Lopes, 2013; Coelho, 2013). The main economic activities are agriculture by planting dry land maize and beans, beekeeping and overgrazing, dairy cattle, and sheep and goat farming (Pinheiro, 2013).

The area is located in the Banabuiú River sub-basin, which drains 13% of the state Ceará and belongs to the Jaguaribe river basin (Coelho, 2013; Pinheiro, 2013; Feitosa, 2011). It has 11 small dams and 1 medium sized dam. The water infrastructure is good and water storage dams of the region fulfil a social function of livelihood of the settlers; for local demands as household, livestock and human watering, fishing, recreation, and small scale irrigation (Coelho, 2013).

Of the 13 communities, only 5 have water supply by distribution network systems. The other communities draw water directly from the reservoirs or get water from wells. For the direct consumption of water, cisterns are the main source of supply. They serve as a reservoir for rain water in wet periods and can possible store water from reservoirs in periods of drought. The water from reservoirs thereby should be distrusted to the cisterns by tankers/water trucks. (Coelho, 2013)

With regard to the sanitation, the destination of grey water (wastewater from wash hand basins, showers and baths) is in 99% of the cases the backyard. The destination of sewage/black water (wastewater from containing faecal matter and urine) is in 70% of the cases a rudimentary sewage, 28% the backyard, and 2% a septic tank. (Lopes, 2013; Coelho, 2013)

The location of the study area and the reservoirs is shown in Figures 3 and 4 on the next page.

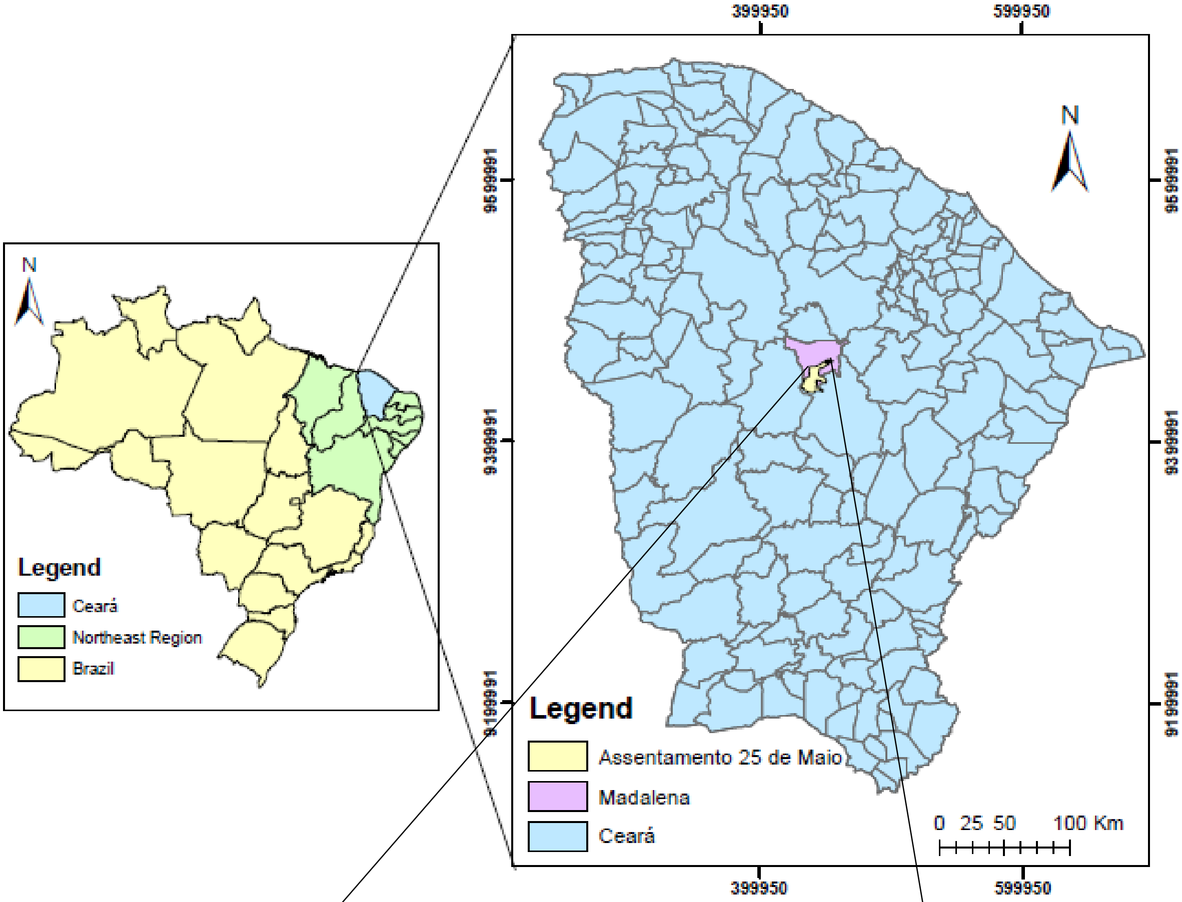

Figure 3 The location of Assentamento 25 de Maio in Madalena in the state Ceará in the Northeast Region of Brazil

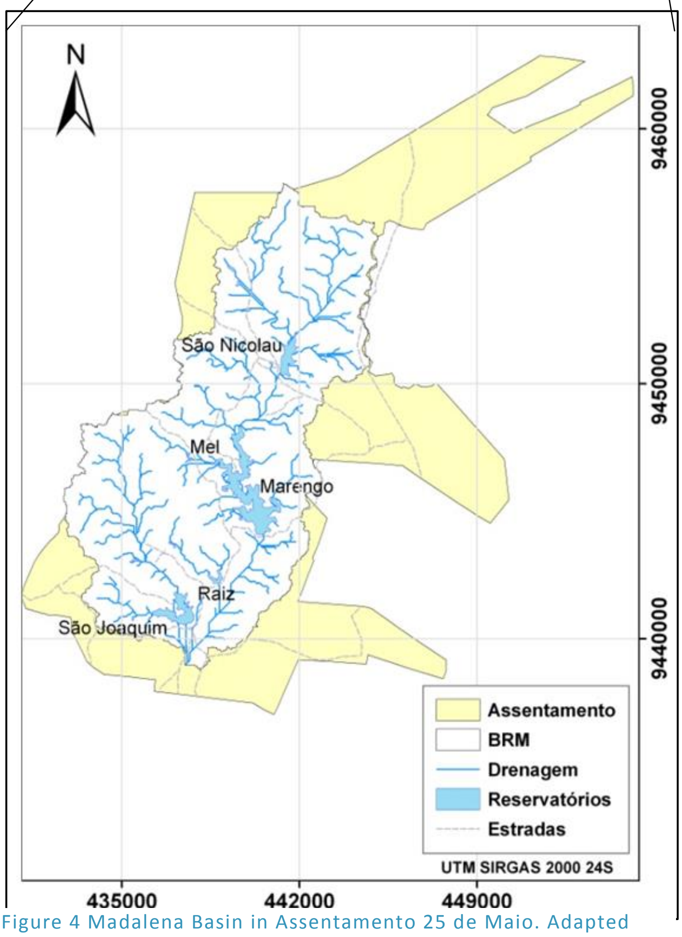

Figure 4 Madalena Basin in Assentamento 25 de Maio. Adapted from "Modelagem Hidrossedimentológica em meso-bacia do semiárido", by J.W.B. Lopes, 2013.

CLIMATE AND RAINFALL CHARACTERISTICS

The climate is tropical hot semiarid and is characterized by temporal variability of rainfall, extended periods of drought, and a steady temperature around 26 to 28 degrees Celsius (Lopes, 2013; Pinheiro, 2013). In addition, the region is subjected to strong dry winds, which contribute to the formation of a dry landscape (Lopes, 2013). The rainfall mainly concentrate in the months of February, March, April, and May, when the state is under the influence of the inter-tropical convergence zone (Pinheiro, 2013).

Due to high temperatures and high evaporation rates, associated with low and irregular rainfall, the region has a deficit of natural water. The time series of rainfall from 1988 till 2009 in Madalena had an annual average of 601 mm (FUNCEME; Fundacão Cearense de Meteorologia e Recur, 2014). The area has an average potential evaporation of 2100 mm/year (Assembleia Legislativa do Ceará, 2009). The last 4 years have been very dry with in 2010, 2011, 2012 and 2013 an annual rainfall of respectively 340, 527, 144, and 373 millimetres (FUNCEME; Fundacão Cearense de Meteorologia e Recur, 2014). In 2014, from January till June there was a total rainfall of 475 millimetres, but it should be mentioned that the measurement in the city of Madalena does not correctly represent the rainfall in the study area, since the rainfall is very local.

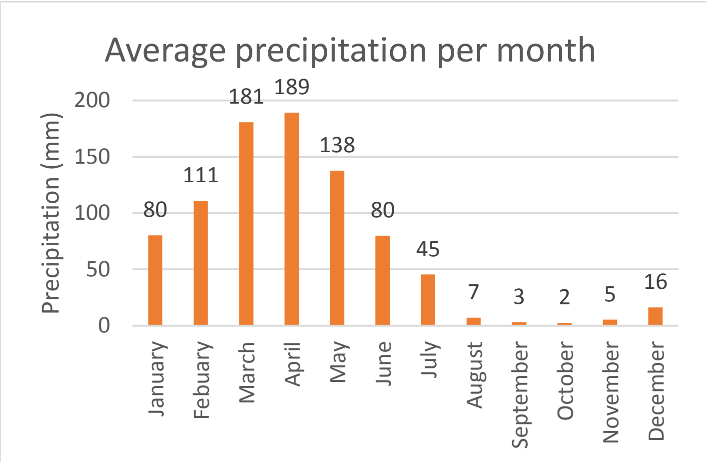

Figure 6 Average precipitation per month. Adapted from "Secretaria dos Recursos Hídricos, Governo do Estado do Ceará", by FUNCEME, 2014. Retrieved May 15, 2014, from http://atlas.srh.ce.gov.br/.

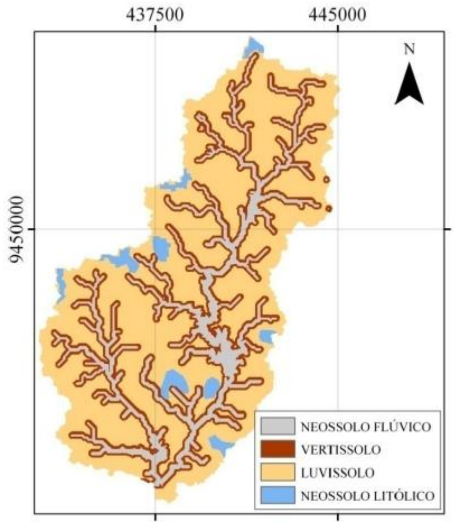

Figure 5 Soil types. Adapted from "Modelagem Hidrossedimentológica em meso-bacia do semiárido", by J.W.B. Lopes, 2013.

GEOLOGY

As the region specific area-depth-volume relationships are expected to have a connection with the geology, the geology information is important for comparison of the results with other researches. The geological formation dates from the Precambrian period. It consists of crystalline basement rocks, formed by various gneisses and migmatites rocks. These are linked to plutonic rocks and a metaplutonic mixture consisting of mainly granitic composition. The geology structure hinders the infiltration of water, resulting in a low potential for groundwater flows through the fracture system (Pinheiro, 2013). The study area consists of the (shallow) soil classes: Luvisols, Litholic Neosols, Vertisols, Fluvic Neosols. The soil distribution over the area is presented in Figure 5.

Further climatological data and information on the relief of the Madalena basin is given in Appendix A: Study Area.

RESERVOIRS

There are five reservoirs that are mainly used for water supply of the rural population (Lopes, 2013). The catchment area of these reservoirs is 124 km^2. The locations of the reservoirs are given in Figure 4 on page 12 and their characteristics are presented below in Table 1. These characteristics are estimated by calculations using literature by two different sources, Lopes (2013) and ACACE (2005). The characteristics for reservoirs Sao Joaquim and Marengo are also determined by data from the construction of the dams and by data from bathymetric survey in 2010 and 2011.

Table 1 General characteristics of the reservoir. Adapted from "Modelagem Hidrossedimentológica em meso-bacia do semiárido", by J.W.B. Lopes, 2013.

Reservoir	Volume (hm^3)	Catchment area (km^2)	Max. surface area (km^2)	Source	Method
Mel	0.06	3.02	0.03	(ACACE, 2005)	Unknown
Raiz	1.50	5.03	0.12	(ACACE, 2005)	Unknown
Raiz	2.50	5.29	0.29	(Lopes, 2013)	Calculated
São Nicolau	0.89	36.10	0.53	(ACACE, 2005)	Unknown
São Joaquim	5.00	31.05	0.82	(ACACE, 2005)	Unknown
São Joaquim	5.15	30.80	1.41	(Lopes, 2013)	Construction
São Joaquim	3.20	…	0.79	(Lopes, 2013)	Bathymetric
Marengo	18.00	75.38	2.84	(ACACE, 2005)	Unknown
Marengo	16.80	120	3.21	(Lopes, 2013)	Construction
Marengo	15.30	…	2.80	(Lopes, 2013)	Bathymetric

There only is run off in the reservoirs when they are completely filled. The water flows over the spillway when the reservoir is full, there are no other discharge channels. The extraction of water from the reservoir goes by the use of pumping station and siphon devices, but also by manually filling buckets and exporting them to their homes.

The research focuses on three of the five main reservoirs. These are the reservoirs Raiz, São Nicolau and Marengo. In preparation of the required measurement of the bathymetry a first field survey was undertaken from 8 May 2014 till 11 May 2014, and the main field trip took place from 28 May 2014 till 8 June 2014. With the gained information from this field surveys, and some additional literature, a description of each of the three reservoirs is made.

São Nicolau

The reservoir São Nicolau is the youngest reservoir in the Madalena basin, and in volume the smallest of the three reservoirs. It is constructed in 1995. The reservoirs is very shallow in most areas and there is many vegetation present in the water. Also the reservoir is surrounded by many different kind of vegetation. When the field surveys took place the reservoir was almost completely filled with a height difference between the spillway and the water of less than 1 meter.

Figure 8 São Nicolau overview

Figure 7 São Nicolau vegetation

Raiz

The reservoir Raiz, constructed in 1958, is potentially not the smallest reservoir in volume, but at time of the field surveys the reservoir was almost dry. The reservoir is shaped with two major side branches coming together at the dam. In the reservoir are some minor obstacles; fences and tall grass. In the water itself are some plants, areas with tall grass and the end of the fences (Figure 10). Unfortunately no further data about technical aspects, like the spillway length, dam height and length, is available.

Figure 9 Raiz

Figure 10 Raiz obstacles reservoir

Marengo

The reservoir Marengo is the biggest reservoir in the Madalena basin. The dam of Marengo was built in 1934 and enlarged in 1956 by the damming cooperative project of the DNOCS, Departamento Nacional de Obras Contra as Secas (Lopes, 2013). It dams the river called either Ipueiras or Marengo, which is one of the stretches of the Banabuiú subsystem, being part of the Rio Jaguaribe system. The homogeneous earth dam is about 415 m long. The weir is of the wall-type spillway and is 65 m wide. During the field surveys the reservoir was far from full. There is no vegetation present in the water and the shores are well accessible.

Figure 11 Marengo overview

Figure 12 Marengo side branch

3.2. Data Collection

In order to determine the relations between water surface area, height and volume it is necessary to have the bathymetric model of the reservoir. For the reservoirs in the Madalena Basin, there is no complete data available on their current physical characteristics. Therefore a bathymetric survey is necessary. Besides some additional data is gained for the further processing.

GENERAL APPROACH

For the reservoirs the field survey consists of two parts, the measurement on water (bathymetric) and the measurement on land (topographic). The topographic measurements were needed when the reservoirs were not completely filled with water, since the last few years have been dry (FUNCEME; Fundacão Cearense de Meteorologia e Recur, 2014).

The goal of the bathymetric measurements was to determine the water depths on multiple points underneath the water level. This is done on a boat by using an echo-sounder of type GPSMAP 188 with a GPS antenna and transducer (Garmin). The single-beamed echo-sounder registers the time passed between sending pulses and the reception of these pulses after their reflection from the bottom of reservoir. By connecting the echo-sounder to the laptop and using the software Fugawi Global Navigation, multiple points with their depth and GPS location are recorded in a file. To verify that the data from the echo-sounder is correct, multiple points are also measured by a handheld depth meter and handheld GPS. The type of GPS used is eTrex Vista HCx (Garmin). The setup on the boat is given below in Figure 13.

Additional it was needed to determine the water surface area in the reservoirs. This is done by walking around the water surface area and register multiple points with the handheld GPS. With the obtained points it is possible to create the outline of the water surface area. To complete the data, the height from the water surface to the spillway is measured by the total station. The type of total station used is Spectra Precision FOCUS 6.

As for the reservoirs of Marengo and Sao Nicolau the lake was respectively partly and completely filled with water, this was not the case for the reservoir Raiz. Therefore the terrain of this reservoir was measured by the total station. More detail on the specific measurement for each reservoir will be given in the next sub-paragraphs.

The specifications of the mentioned equipment are given in Appendix B: Equipment.

Figure 13 Boat setup

Figure 14 Boat on Marengo

PLANNING

The field survey took place from 28 May 2014 till 8 June 2014 , which is in the end of the rain season, so that volume of the reservoirs are at the highest point possible for this year. The table given below shows the dates and activities for each reservoir.

Remarkable are the many topographic measurement for Raiz and the many water depth measurement for Marengo. The first issue is due to the heavy rainfall during the first three days which highly reduced the effectivity of the field work. The second issue was caused by problems with the echo-sounder. The echo-sounder often did not measure any values or the depth values given were unrealistic high. By adjusting some settings, changing the setup and lower the speed, eventually the problem was solved.

Table 2 Planning field survey

Date	Reservoir	Activity
28/05/2014	Raiz	Contour water surface area (GPS)
		Topographic measurements (total station)
29/05/2014	Raiz	Water depth measurements (depth meter & GPS)
		Topographic measurements (total station)
30/05/2014	Post	Data processing
	Marengo	Water depth measurements (echo-sounder)
31/05/2014	Post	Data processing
	Sao Nicolau	Water depth measurements (echo-sounder)
01/06/2014	Marengo	Water depth measurements (echo-sounder)
02/06/2014	Raiz	Topographic measurements (total station)
03/06/2014	Marengo	Contour water surface area (GPS)
	Marengo	Topographic measurements (total station)
04/06/2014	Post	Data processing
05/06/2014	Post	Data processing
06/06/2014	Sao Nicolau	Contour water surface area (GPS)
	Sao Nicolau	Topographic measurements (total station)
07/06/2014	Raiz	Topographic measurements (total station)
08/06/2014	Raiz	Topographic measurements (total station)

SAO NICOLAU

The reservoir of Sao Nicolau was almost completely filled, with a height difference between the water surface and the spillway of 0.88 meter. In this case the water depth and surface area measurements are sufficient to make a model of the reservoir.

A total of 593 points were registered by the echo sounder, and a total of 193 points by the handheld depth meter. In Figure 15, on the next page, the points and thereby the covered route is given. As can be seen, some parts of the reservoir are not covered. The boat was unable to manoeuvre to these areas due to the many vegetation and low water depth. As a result the measured points are mostly taken in the streambed, which is the deepest part of the reservoir. Also shown in Figure 15 are the measured surface area (533,200 m^2) and the place of the spillway, which is presented by the purple points measured with the total station. The maximum water depth measured is 6 meter. The reservoir ends in the north, at a point where two upstream rivers meet.

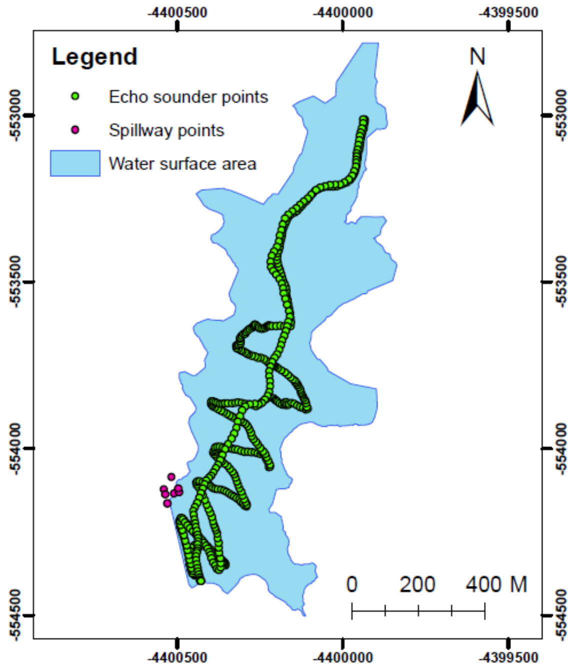

Figure 15 Sao Nicolau measurements

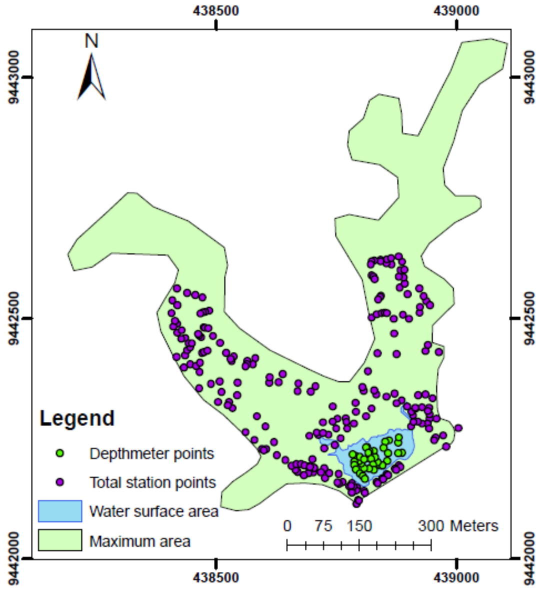

Figure 16 Raiz measurements

RAIZ

The reservoir of Raiz is almost completely measured by the total station, consisting of 223 points. Only in the centre of the reservoir, close to the spillway, was a small area of 11,800 m^2 covered by water. A total of 39 points with water depths and corresponding locations were measured by handheld depthmeter and handheld GPS. The maximum area of the reservoir (283,750 m^2) is extracted from Landsat 5 images of 24 July 2004 (INPE; Instituto Nacional de Pesquisas Espaciais, 2014), when the reservoir was completely filled with water. In Figure 16 an overview of the measurement is given.

As can be seen in Figure 16 there are no points in the most upper parts of the two side branches. This is due to the inaccessibility of those areas with many vegetation and fences and the lack of time in the field. To make an estimation of the topography of those areas, a collection of Landsat 5 images is used. The images used are from 1-8-2001 and 3-7-2008. By projecting the water surface area from the Landsat images on the already collected data, it was possible to make an estimation of the height from the water level in respect to the deepest point or spillway. This information was used to mark points with heights at the contour of the water surface area for these different images. More information on the processing of data can be found in paragraph 3.3.

Figure 17 Total station measurement

Figure 18 Handheld depth meter measurement

MARENGO

The water depths in the reservoir in Marengo are measured twice by echo-sounder, they consist of respectively 1047 and 1054 points, resulting in a total of 2001 points. The second survey with the echo-sounder has an additional of 293 points by handheld depth meter, which are evenly distributed over the track. The total surface area is 638,500 m^2 and the maximal water depth is 6.9 meter. Thereby the height from the spillway to the water surface is 9.5 meter. The collected data is shown below in Figure 19. The most upstream part is not covered by points, because the water level was around 1 meter, which made it unable for the boat to manoeuvre.

As can be seen in Figure 20 the survey data only covers a small part of the reservoir. To be exact there is 22% covered by the survey, 638,500m^2 out of 2,849,000m^2. The maximum area of the reservoir is extracted from Landsat 5 images of 24 July 2004 (INPE; Instituto Nacional de Pesquisas Espaciais, 2014), when the reservoir was completely filled with water. To be able to make a complete model of the reservoir, data from a previous research by Lopes (2013) will be used. This data is obtained through a bathymetric survey in 2011. The equipment used to measure points in the reservoir, were a handheld depth meter and a handheld GPS.

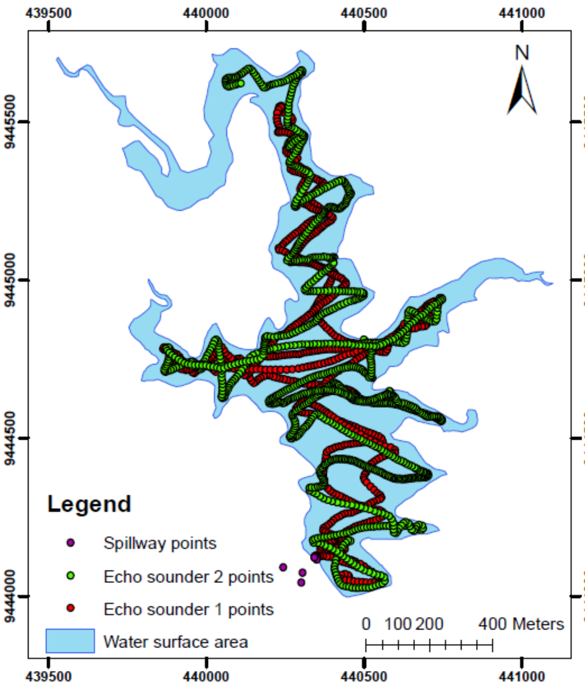

Figure 19 Marengo measurements

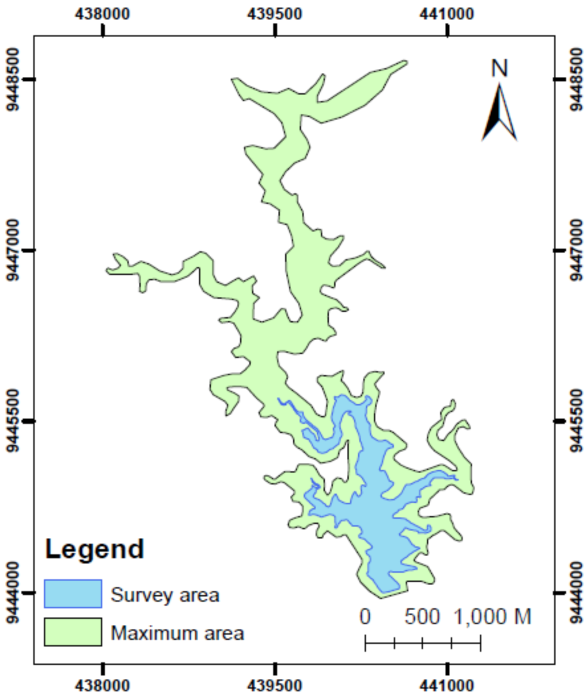

Figure 20 Survey area vs maximum area

3.3. Reservoir Modelling

With the collected data each reservoir can be modelled into a 3D-model. The programs used for this process are ArcMap and Surfer. Thereby ArcMap is used for showing and adjusting the collected data, and Surfer is used for the interpolation to a grid and allows the calculation of volume, area and depth. Each reservoir goes through the same process, which is described in the general approach. The reservoir specific aspects will be explained in the sub-paragraphs after the general approach.

GENERAL APPROACH

The process of creating a model for each reservoir can be divided into four steps; add data, create surface areas, create data set, and gridding data.

First, the collected data from the field survey will be added to the ArcMap file. This data is derived from the echo-sounder, handheld depth meter, total station and the contour of the water surface area. The data from the total station needs spatial adjustment, because the total station measures the XYZ distances in relation to the station points. The adjustment is done by using control points measured by the handheld GPS. The other data already contains coordinates, and therefore are in the right position. Also belonging to this step is the matching of z-values of the different equipment. Hereby the spillway height of the reservoirs is set as zero.

Add data
Data from: echo sounder, depth meter, total station, GPS contour points
Geo-reference total station data
Matching the z-values of equipment

↓

Create areas
Contour points → water surface area
Water surface area ≠ maximum area, then: *Landsat 5 image* → *max. area*

↓

Create data set
Remove points with incorrect z-values
Add points

↓

Gridding data
Resulting points to XYZ file
Interpolation method
Blank grid

Figure 21 General approach

The next step is to create a contour of the water surface, or in other words, the water surface area. The data points from the contour of the water surface are connected and shaped into a polygon. For the reservoirs Raiz and Marengo the water surface area is not equal to the maximum area. Therefore the maximum area was determined by using Landsat 5 images of 24-7-2004, when the reservoir were completely full. The Landsat 5 images consists of 7 bands with different wavelengths. The used band combination is 432. This combination gives a clear view of the land-water boundaries. An example of Raiz maximum area is given in Figure 22.

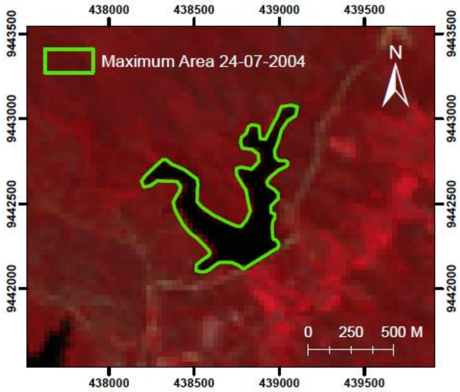

Figure 22 Raiz Landsat 5 image 24-7-2004 with maximum area

The third step is to create a useful data set where the model can be created from. This step consists of the removal of points and adding points. The z-values of the echo-sounder sometimes are unrealistic high and/or have a big difference (2-3 meters) with surrounding points. Also, there were areas were the echo-sounder did not received signals, and because the software still registered points this resulted in a series of points with the same z-values. Therefore all these points were removed. The manual adding of points is needed to make sure a correct surface is created through interpolation. The depths of these points are estimated by using the known points, Landsat 5 images and the experience in the field. More about the adding of points will be described for each reservoir in the next sub-paragraphs.

The resulting points in ArcMap are transferred to a XYZ file, this file is used in Surfer to create a 1x1 grid by using a certain interpolation method. Hereby the maximum area, extracted from the field measurements, is used as breakline. This means that a polygon is added with the Z-values of 0. When the gridding algorithm sees a breakline, it calculates the Z-value of the nearest point along the breakline, and uses that value in combination with nearby data points to calculate the grid node value. To eliminate the irrelevant values outside the maximum area, a blank grid is created using Surfer's blank function. The resulting models out of the grids are given in the next chapter.

SAO NICOLAU

For the reservoir there are three aspects that need some more explanation; the chosen maximum area, the dataset creation and the gridding method.

As the outline of the maximum area of the reservoir is not known and cannot be derived from satellite data, since these are not available, the field measured water surface area is used as the maximum area for the model of Sao Nicolau. The created outline of the water surface area is compared with a Landsat image of 3-7-2008 (INPE - Instituto Nacional de Pesquisas Espaciais, 2014) and with an Ikonos satellite image of 31-10-2010 (GeoEye, 2010). The Ikonos satellite image was available through ArcMap. The images were used to do some minor adjustment in the side branches and to determine the end of the reservoir. This was needed because the reservoir of Sao Nicolau ends at a point where two rivers meet, and field data did not satisfy since this part was very inaccessible and could not be crossed by walking.

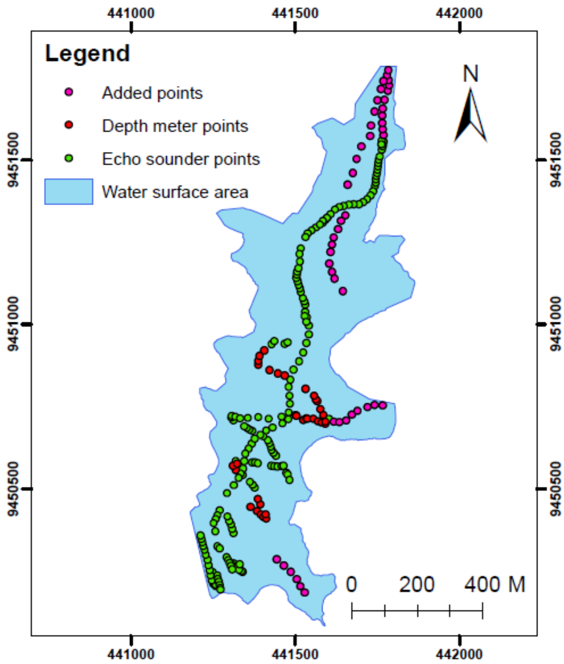

Figure 23 Sao Nicolau data set

As mentioned in the general approach, echo-sounder points needed to be removed because of their incorrect z-values. For Sao Nicolau this meant the removal of 404 points out of 593. As there were registered many points and the density of the points was very high the track still is mostly intact. The areas that were without points are filled up using the data from the handheld depthmeter. But there often was a significant difference in the z-values of the echo-sounder and z-values of the handheld depthmeter. As the echo-sounder has a higher accuracy, the depth meter z-values were adjusted to correspondent with the echo-sounder's z-values by using a bias of 0.9. More info about this adjustment can be found in Appendix C: Depthmeter versus Echosounder.

With these data a first interpolation was done. The resulting grid showed a rather strange trend in the upstream part of the reservoir, which caused a cliff through the centre. This trend is corrected by manually adding some points so that a smooth slope from the streambed till the shore is formed. The total amount of points for gridding the data is 252 points, as shown in Figure 23.

As also can be seen in Figure 23, some parts are missing data while other parts contain many data points. The best interpolation method therefore is Kriging. The Kriging method can compensate for clustered data by giving less weight to the cluster in the overall prediction.

RAIZ

The biggest challenge for Raiz was adding points. The maximum area of Raiz was extracted from Landsat 5 images. As can be seen in the overview in Figure 24, some areas are missing points. This is due to the inaccessibility of those areas with many vegetation and fences and the lack of time in the field. The (automatic) interpolation by Surfer does not create a correct surface for these areas. So, to create a realistic model these empty spaces need to be filled up with some points. The two empty spaces shown in the red circles are simply corrected by adding points manually. The location and Z-values of these points are estimated using the surrounding points, but also by using token pictures and the field experience itself.

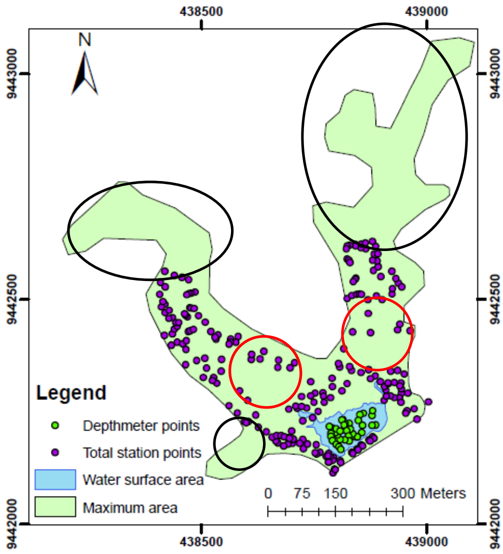

Figure 24 Raiz overview

The points for the other three areas, represented by the black circles, are estimated by using the water surface area of two Landsat 5 images from 1-8-2001 and 3-7-2008 (INPE; Instituto Nacional de Pesquisas Espaciais, 2014). On these dates the water surface area partly covered the areas where points are missing. By determining the outline of the water surface areas and estimating the water levels by using the model of the part that is known, it was possible to create points with z-values for the missing areas. In the two figures given below, the images and the outlines are shown. There are points added in the side branches on these outlines.

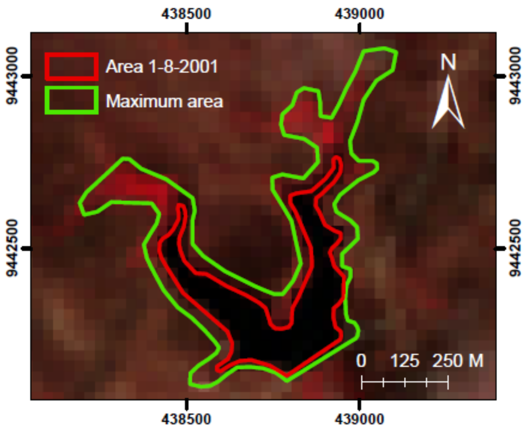

Figure 25 Landsat 5 image 1-8-2001

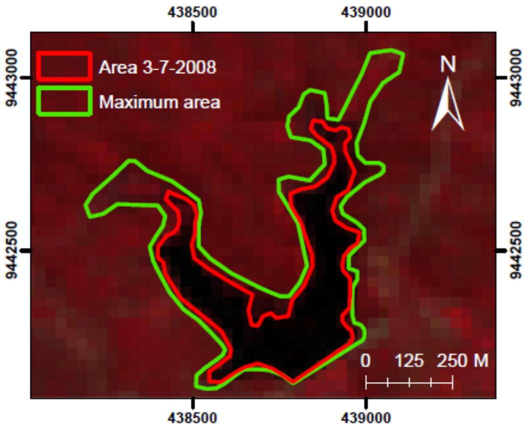

Figure 26 Landsat 5 image 3-7-2008

Furthermore there are points added in the middle of the even more upstream parts in the north. The z-values of these points are estimated by taken a linear relation from the z-value of the last known point till the maximum surface area, which has the same z-value as the spillway (8.9m). Lastly, there are points added on the water surface area. These points all contain a Z-value of -7,5m.

As the result of adding points there is a total of 482 points. In comparison to the 262 points measured in the field, this is a big increase but it must be mentioned that 111 of the added points are extracted from the accurately measured water surface area. An overview is given in Figure 27.

The used interpolation method, or gridding method, is Minimum Curvature. Minimum Curvature generates the smoothest possible surface while attempting to honour your data as closely as possible. While Kriging looks for trends in the data and can extrapolate grid values beyond the range of the data's Z values. Since the data is collected with relative high precision by the total station and points are chosen at the locations were the slope changes, the most realistic model will be formed by the Minimum Curvature interpolation. Comparison of the contour maps of models created by Minimum Curvature and Kriging confirmed this assumption.

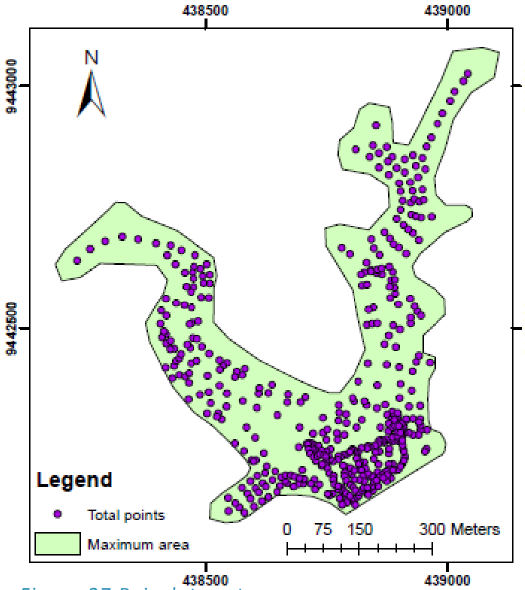

Figure 27 Raiz data set

MARENGO

The modelling of Marengo contains one more extra step than the other two reservoirs. This is because to make a complete model of the reservoir, data from previous research by Lopes (2013) is used.

First, the general steps are taken to create a grid from the field data for the area covered by the survey (22%). Whereby a total of 1013 out of 2001 points were deleted and 17 points were added because of a small island in the reservoir. As can be seen in Figure 28, the remaining data set of 1005 points have some parts that are missing data while other parts contain many data points. The best interpolation method therefore is Kriging.

To create a complete model, the grid created with the field data is combined with the grid from the Lopes (2013) research.

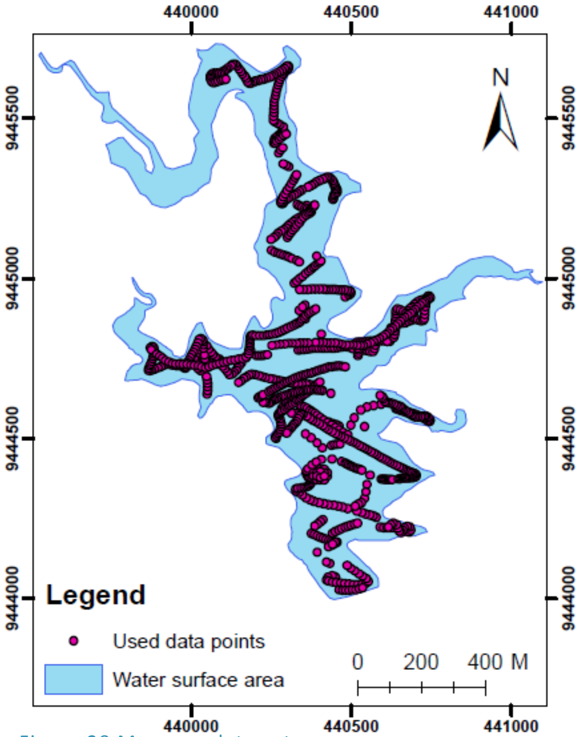

Figure 28 Marengo data set

As the maximum surface area of the Lopes grid is questionable, the maximum surface area is determined with a Landsat 5 image from 24-7-2004, as presented in Figure 29 on the next page.

The Z-values of both grids are adjusted in relation to the spillway. The spillway has a Z-value of zero, therefore the other values are below zero. In some areas the z-values of the survey grid and the Lopes grid are apart. In those areas some points are deleted so that a smoother surface is formed. The same occurs for the points of Lopes grid in relation to the maximum surface area. In the side branches and the upper part of the reservoirs some points are added, because neither of the grids covered those areas. The Z-values of points are made with a linear relationship from the last measured point to next point or to the maximum value of zero. In Figure 30 all the described adjustments can be seen in one of the side branches.

The grids are combined into a 1 by 1 meter grid with Surfer using the Minimum Curvature method. This method makes a smooth surface that goes through all the data points

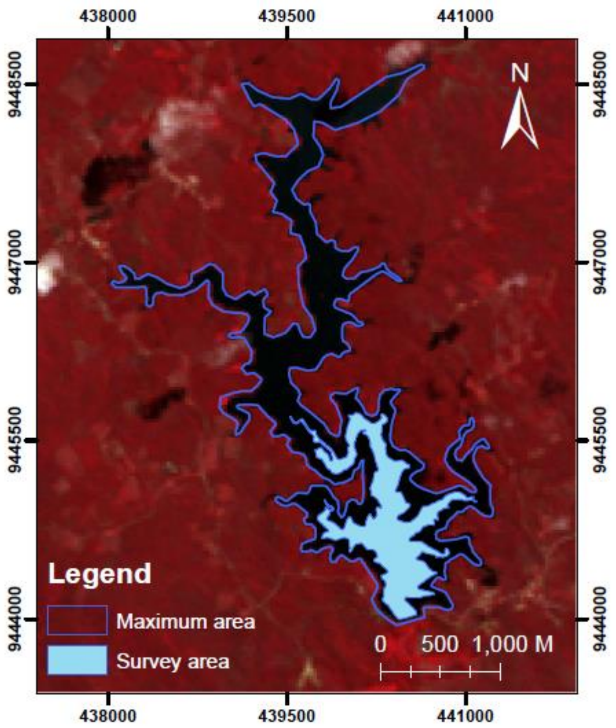

Figure 29 Landsat 5 image 24-7-2004

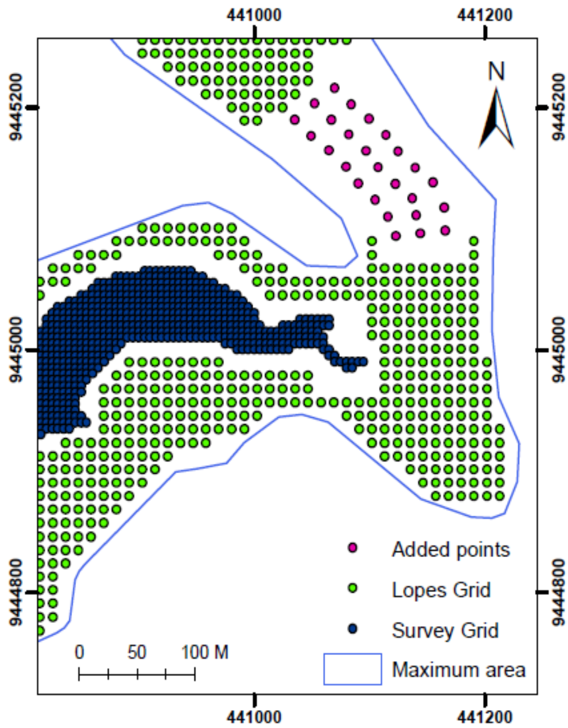

Figure 30 Adjustment of points

3.4. Data analysis

With the developed models the area and volume for certain depths are calculated for each reservoir using the program Surfer. The chosen step value for the water level is 0.1m. For example, for the reservoir of Raiz with a maximum water depth of 8,9m this resulted, including the zero value, in a total of 90 points with depth, area and volume values.

The output from the computation allows the creation of logArea-logVolume and logDepth-logVolume curves for each reservoir. By taking the log-log curves it is possible to make a linear line that represents the relation. The function of the linear line is rewritten to a power function using the basic logarithm principles given in paragraph 2.1 under *Linear Regression*, an example is given in Appendix D: Derivation of power function. The derived power function represents the area-volume relation or the depth-volume relation for the specific reservoir.

The reservoirs in the Madalena Basin do not have a dead volume, the water is extracted from the reservoirs at every water level by pump or manually by buckets. As the water in the reservoirs is extracted at every water level, it is necessary to find a curve that is correct for all the water levels. In other words, the dataset used for the log-log curves contains all points.

The results are given in the next chapter.

4. RESULTS

The results are divided in the geometric models, and the area-volume and depth-volume relations.

4.1. Geometry

The geometric, or bathymetric, shapes are the results from the reservoir modelling explained in the previous chapter. These shapes are required to calculate the area and volume at certain water depths, which are needed to determine the area-depth-volume relations. The bathymetric shapes give an overview of the reservoirs and there characteristics.

SAO NICOLAU

The model of Sao Nicolau is presented in two figures, the contour map and the surface map. The figures show a clear streambed that continues to the most upstream part in the north, where two rivers come together. Furthermore it shows that the reservoir is very shallow, mainly in the side branches. As it was difficult to take measurement, certain areas where not covered with data points and the poor distribution of points results in some 'cracks' in the reservoirs shape. Despite of the bad distribution the model corresponds with the observation in the field and can be used for further processing.

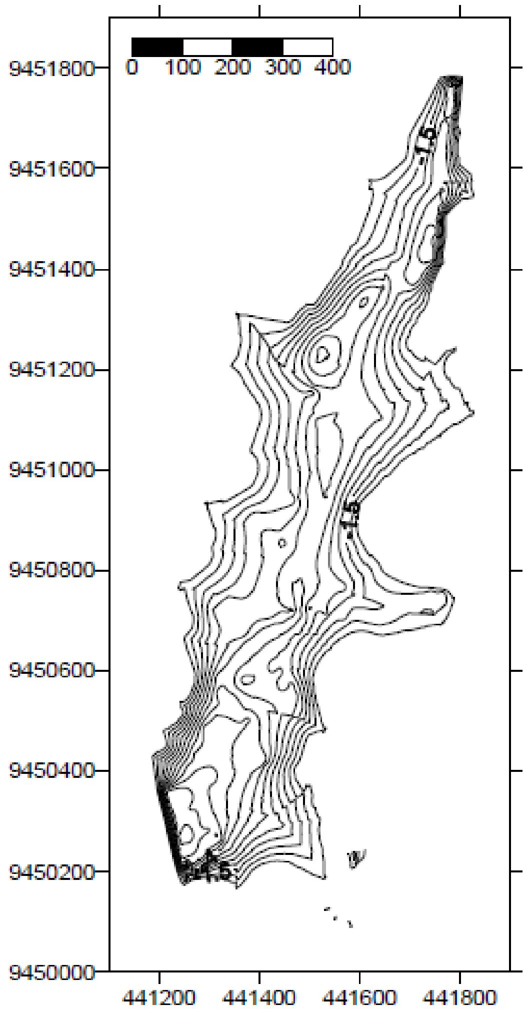

Figure 31 Sao Nicolau contour map

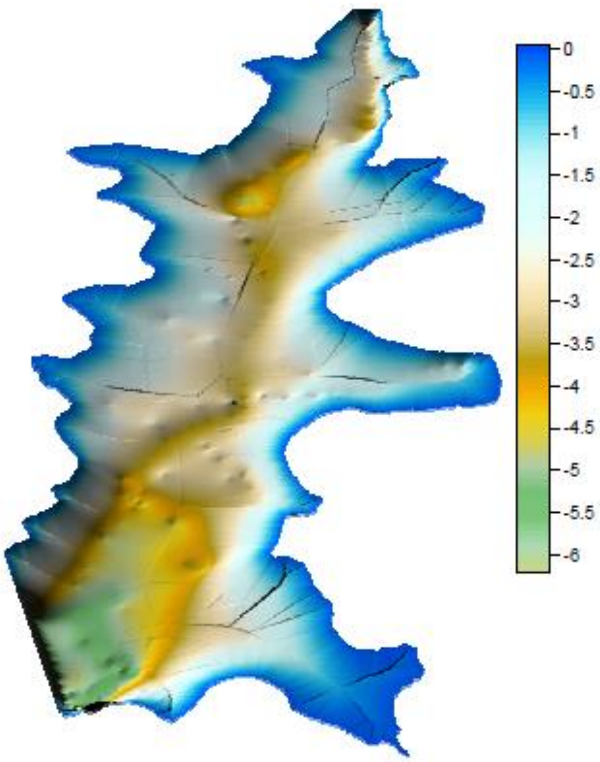

Figure 32 Sao Nicolau surface map

RAIZ

Just as for Sao Nicolau, the resulting model is given by the contour map and the surface map. The reservoir consist of two branches from rivers. Both of these branches have a very smooth surface with a steady slope on the sides and a relative flat middle area. The maximal depth increases as the rivers are followed to the downstream part. Close to the dam, where the rivers meet, the deepest area can be found.

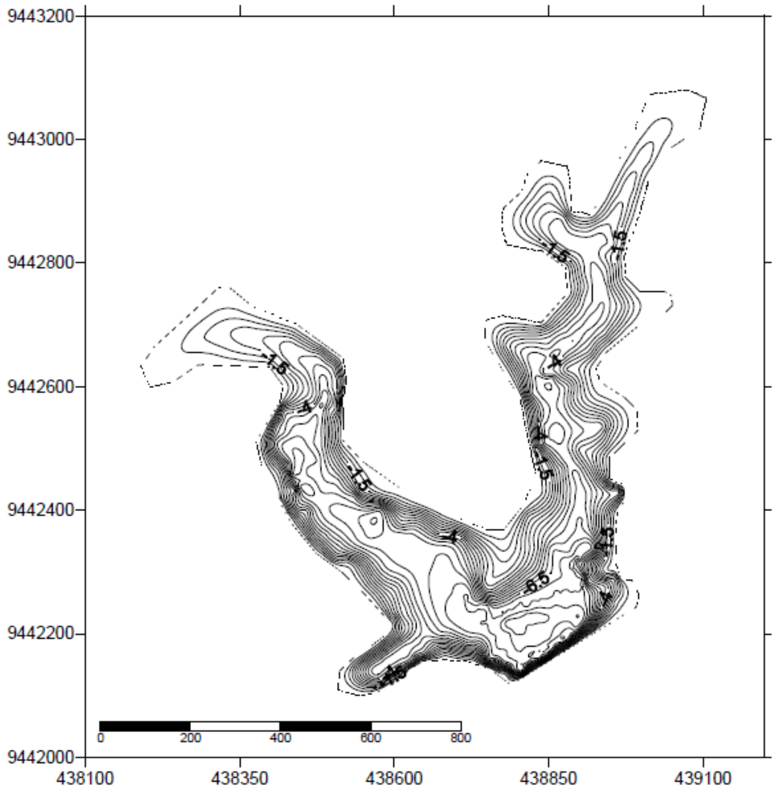

Figure 33 Raiz contour map

Figure 34 Raiz surface map

MARENGO

The model of Marengo is shaped by combining two grids, one formed from the survey data and one from previous research. This can be seen in some areas where the slope is very steep. In these areas the z-values of the survey grid and the Lopes grid have a relative big difference. Nevertheless the shape of the reservoir looks realistic. On the sides of the reservoir the slope is steeper, and in the middle of the reservoir the area is relative flat, just as can be seen in the reservoir of Raiz. Further, it can be seen that some side branches and the most upstream part of the reservoir are very shallow, because there was no data available for these parts. Therefore it is possible that these parts are underestimated.

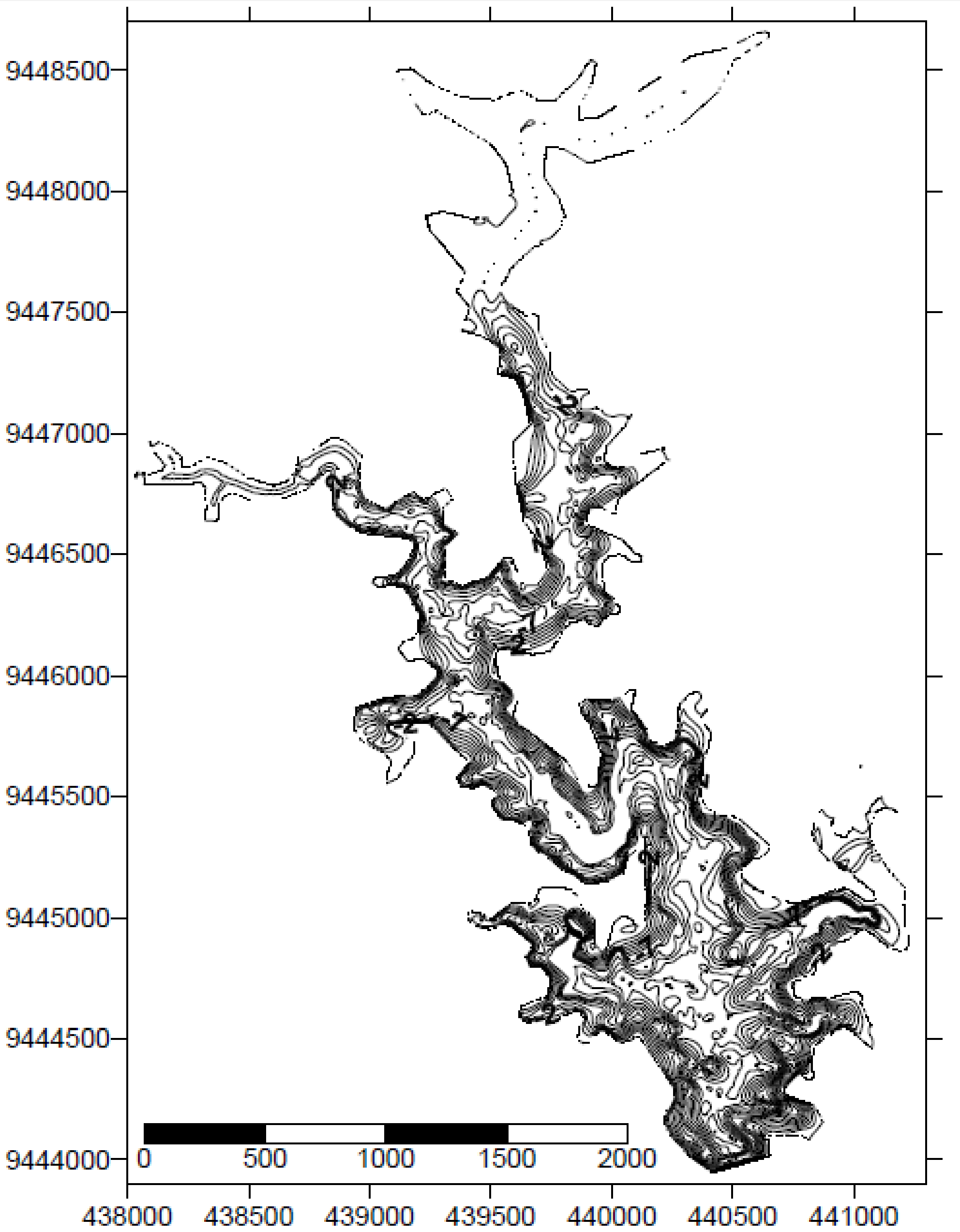

Figure 35 Marengo contour map

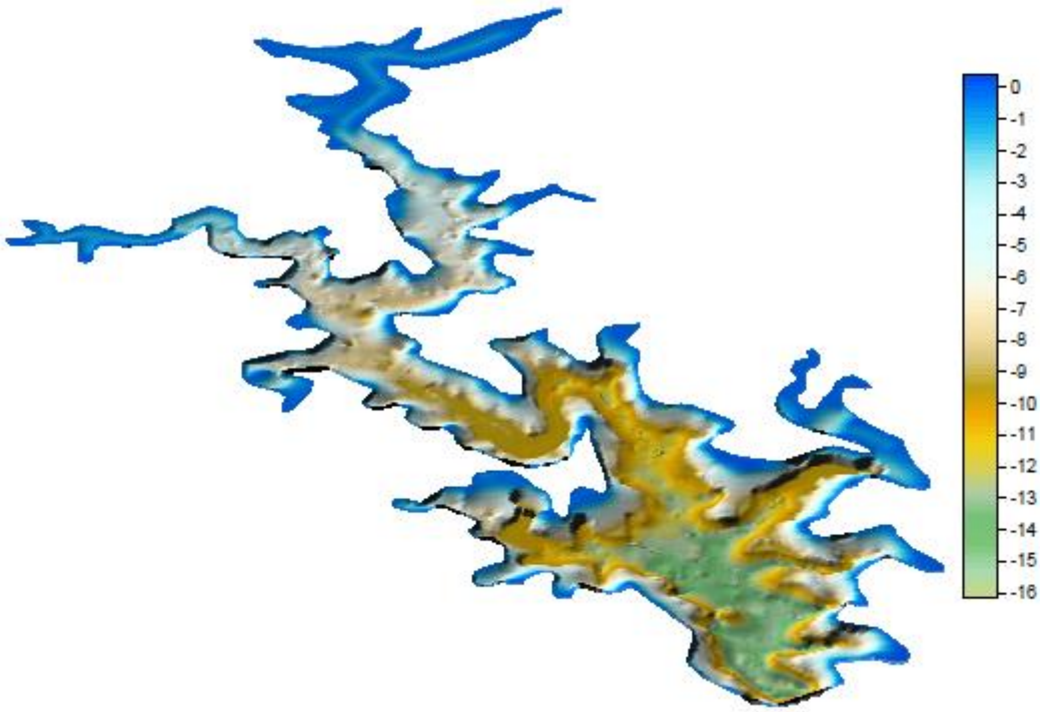

Figure 36 Marengo surface map

4.2. Area-Volume and Depth-Volume relations

The area-volume and depth-volume relations are the result of the steps described in the research method. The complete results are given in Appendix E: Area-depth-volume relations. In this paragraph the characteristics and the meanings of the end results are described for each reservoir and the total area.

SAO NICOLAU

The area-volume regression curve in Figure 37 shows that the maximum volume is 1,082,180m^3, while for the depth-volume curve in Figure 38 the maximum volume is 862,426m^3. The maximum area is 530,191m^2 and the maximum depth is 6.2m. According to the created model the maximum volume corresponding with the maximum area is 1,081,250m^3. The area-volume curve correspond very well, but the depth-volume curve underestimates the maximum area.

The parameter k in the area-volume relationship with the small value of 0.0034 shows that the reservoir is narrow and without an evident flat middle area. The values of the parameter a in the area-volume and depth-volume relation are respectively 1.49 and 2.82. Where the value of the area-volume relations is very close to 1.5 and presents an almost linear slope, the depth-volume relationship presents a more convex slope with a value lower than 3.0. Although, it can be seen that the maximum volumes in depth-volume curves are somewhat off, the goodness of fit (R^2) for the log-log curves in both curves has a value above 0.99, which means the curves fit the model well

Previous calculations by ACACE (2005) estimated a volume of 890,000m^3 and a maximum area of 530,000. While the estimated volume and the volume calculated by ACACE (2005) differ from each other, the maximum areas agree with each other. It is hard to say which data is correct, because the calculation method of ACACE (2005) is not known, and therefore the precision/accuracy is not known.

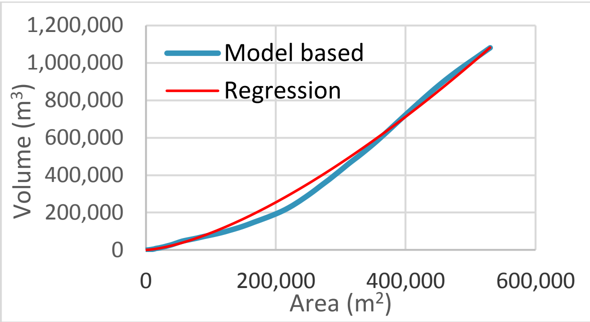

Figure 37 Area-volume curve Sao Nicolau

$$V = 0.00336 * A^{1.49}$$
$$R^2 = 0.994$$

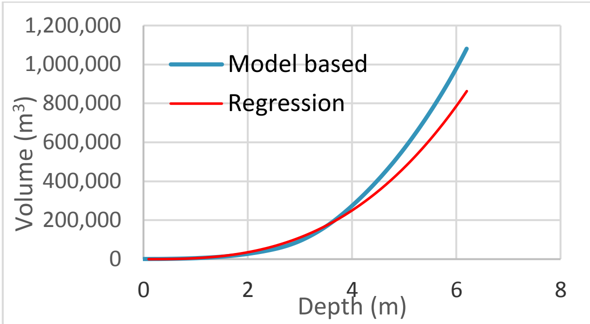

Figure 38 Depth-volume curve Sao Nicolau

$$V = 4980 * D^{2.83}$$
$$R^2 = 0.992$$

RAIZ

The maximum volume of Raiz presented by area-volume curve and the depth-volume curve are respectively 957,425 m^3 and 864,438 m^3. The maximum area is 273,659m^2 and the maximum depth is 8.9m. According to the created model the maximum volume corresponding with the maximum area is 862,271m^3, the volumes related to the depth-volume curve correspond very well, but the maximum volume of the area-volume curve is overestimated.

The small value of parameter k in the area-volume curve, 0.0047, shows that Raiz can be seen as a narrow reservoir. This agrees with the fact that Raiz consist of two narrow branches. Further, the values of parameter a, 1.61 and 2.62, show that the hillside is convex. The curves for Raiz approach the model well, with R^2 greater than 0.99.

There are two estimations available from other researches. ACACE (2005) states that the capacity is 1,500,000m^3 and the maximum area is 120,000m^2. Lopes (2013) states that the capacity is 2,500,000m^3 and the maximum area is 290,000m^2. Comparing the calculated capacity with these studies it seems that the capacity is underestimated. This can be due to the measurement points. It was hard to measure in the middle of the branches, as they were inaccessible because of the high vegetation. And there were no measurements taking in upper parts of the reservoir, these were estimated by satellite images. So it could be that in the middle of the side branches and the upper parts the reservoir actually is deeper than in the model.

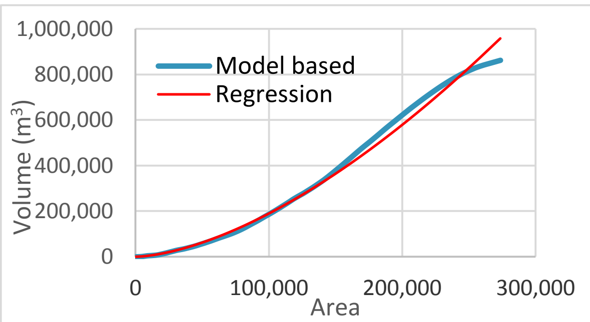

Figure 39 Area-volume curve Raiz

$$V = 0.00172 * A^{1.61}$$
$$R^2 = 0.999$$

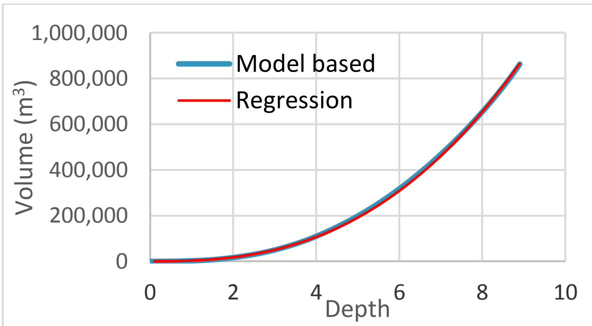

Figure 40 Depth-volume curve Raiz

$$V = 2820 * D^{2.62}$$
$$R^2 = 0.999$$

MARENGO

The maximum volume of Marengo, the largest of the three reservoirs, presented by area-volume curve and the depth-volume curve are respectively 18,479,888m^3 and 17,217,481m^3. The maximum area is 3,098,734m^2 and the maximum depth is 16.1m. According to the created model the maximum volume corresponding with the maximum area is 16,150,112m^3, the maximum volumes related to the area-depth-volume curves have a significant difference of more than 1,000,000m^3.

Marengo is also seen as a narrow reservoir, represented by the parameter k with a small value of 0.0018 in the area-volume curve. The hillside concavity is convex; parameter a for the area-volume and depth-volume curve are respectively 1.54 and 2.82. Although the curves approaches the model just as well as with the other reservoirs, $R^2 > 0.99$, there is some noticeable departure from the A-V curve in relation to the model based curve.

The capacity and maximum area of Marengo are estimated by three other sources. According to ACACE (2005) the capacity is 18,000,000m^3 and the maximum area is 2,840,000m^2. While Lopes (2013) retrieved from construction information that the capacity is 16,800,000m^3 and the maximum area is 3,210,000m^2. Lopes (2013) also estimated it by using a bathymetric survey, this gave a capacity of 15,300,000m^3 and a maximum area of 2,800,000m^3. The calculated capacity and surface area, respectively 16,150,112m^3 and 3,098,734m^2, seem to agree with these researches. Although, the capacity may be on the high side.

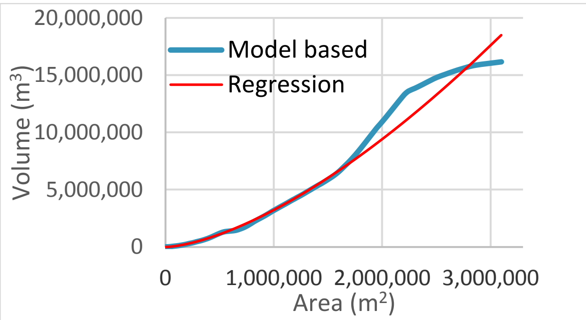

Figure 41 Area-volume curve Marengo

$$V = 0.00181 * A^{1.54}$$
$$R^2 = 0.998$$

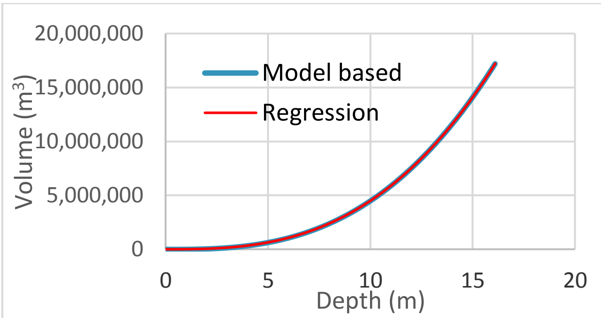

Figure 42 Depth-volume curve Marengo

$$V = 6800 * D^{2.82}$$
$$R^2 = 0.999$$

TOTAL AREA

The effects of results from the three reservoirs in relation to the total study area are set forth in two aspects, the area-volume relation and depth-volume relation.

Area-volume relation

The area-volume relations for the three reservoirs in the Madalena basin and the area-volume relations of other areas determined by previous studies are on the next page. The area-volume relations from the Madalena basin show that the values of the parameter a for the reservoirs of Sao Nicolau, Raiz and Marengo are very close to each other, varying from 1.49 to 1.61. This means that the hillside concavity, in other words the slope, is similar to each other. The values of parameter k from all the reservoirs are low, which means that the reservoirs are narrow and without an evident flat middle area. They differ from each other by a factor of two.

Compared to other studies, also shown below, the three reservoirs in the Madalena basin have a higher a-value. Where in the other studies the value of parameter a is not greater than 1.44 and the slopes are therefore concave, the value of parameter a in all the three reservoirs are above 1.48 and the slopes therefore are more linear with a convex tendency. For parameter k the values of the three reservoirs are much lower than in the other studies. This means that the reservoirs in the Madalena basin are narrower and less open and alluvial than the reservoirs in the other regions.

Area-volume curves

Madalena Basin in Brazil

Sao Nicolau: $V = 0.00336 * A^{1.49}$

Raiz: $V = 0.00172 * A^{1.61}$

Marengo: $V = 0.00181 * A^{1.54}$

Upper East Region of Ghana

$V = 0.0088 * A^{1.44}\ (m^3)$ $R^2 = 0{,}98$ (Liebe, Van de Giesen, & Andreini, 2005)

$V = 0.0088 * A^{1.44}\ (m^3)$ $R^2 = 0.98$ (Annor, et al., 2009)

Limpopo Basin in Zimbabwe

$V = 0.0230 * A^{1.33}\ (m^3)$ $R^2 = 0{,}95$ (Sawunyama, Senzanje, & Mhizha, 2006)

Preto River Basin in Brazil

$V = 0.4500 * A^{1.11}\ (m^3)$ $R^2 = 0{,}83$ (Rodrigues, Sano, Steenhuis, & Passo, 2012)

Figure 43 Area-volume curves of the Madalena basin and published by other researches

Depth-volume relation

The depth volume relations have k values seem to have a higher difference, but just as for the area-volume relation the maximum difference is a factor of about two. The values of parameter a are closer to each other, there vary between 2.62 and 2.83. Whereby the values for Sao Nicolau and Marengo differ by only 0.01. The a-values all present convex slopes.

Depth-volume curves

Madalena Basin in Brazil

Sao Nicolau: $V = 4980 * D^{2.83}$

Raiz: $V = 2820 * D^{2.62}$

Marengo: $V = 6800 * D^{2.82}$

Figure 44 Depth-volume curves of the Madalena basin

Overall

For the a coefficient there seems to be a region specific value for both the area-volume and the depth-volume relation that represents the hillside concavity for the Madalena Basin. But the values of the parameter k do not seem to have direct agreement between each other. This observation correspondents with previous research by Pereira (2014), who states that the k coefficient shows high variability and is very sensitive to the input data.

Nevertheless, the results give the impression that the reservoirs in the Madalena Basin have a region specific shape that is characterized by being narrow and do not contain an evident open alluvial middle area, and thereby are having linear slopes with a convex tendency.

5. DISCUSSION

The discussion is divided into the general topics and the reservoir specific topics.

5.1. General

There are three issues that have an impact on the end result but are discussible; the echo-sounder versus the handheld depthmeter, the use of Landsat images, and the measurement of control points by GPS.

ECHO-SOUNDER VERSUS HANDHELD DEPTHMETER

The difference between the z-values from the echo-sounder and the z-values from the handheld depthmeter is remarkable. During the measurements by boat for the reservoirs Sao Nicolau and Marengo there were points measured by both devices. As there was no experience with the use of the echo-sounder and the expected depth of the reservoirs, the handheld depthmeter functioned as a control device.

The comparison between both devices shows that there were many areas in the reservoirs were the z-values do not match. The echo-sounder measured a higher z-value in those areas than the handheld depthmeter. The difference for respectively Sao Nicolau and Marengo are around -.90m and -1.01m, as calculated in Appendix C: Depthmeter versus echosounder.

There can be multiple reasons for the difference in z-values. The difference can be due to the different frequencies the devices use, in this case it suggests that the echo-sounder penetrates the soft/wet soil and the handheld depth meter does not. Another reason can be that the handheld depth meter needed to be calibrated, this was done for the echo-sounder but not for the handheld depth meter. And of course the accuracy of the devices affect the z-values. Unfortunately, no information about the accuracy of the devices was found.

As the data from the echo-sounder is used for the reservoirs Sao Nicolau and Marengo, there is a possibility that the volumes of these reservoirs are overestimated. Or that previous research by Lopes (2013), where the handheld depthmeter was used, underestimated the volume of Marengo. This issue is noticeable in the results, where the developed model for Marengo estimated a maximum volume of 16,150,000m^3 and the estimation of Lopes (2013) was 15,300,000m^3. Although the difference between the volumes is affected by the difference in maximum surface area, the choice of measurement device has his influence on the resulting model and its volumes. This also effects the area-volume and depth-volume relations.

USE OF LANDSAT IMAGES

For this study there were Landsat 5 images used to estimate the maximum surface area for the reservoirs Raiz and Marengo. Besides there were Landsat 5 images used for Raiz to estimate the z-values of some unmeasured areas. The Landsat 5 images exist of out 30-meter pixels, which directly represents the accuracy of the determined maximum surface area for Raiz and Marengo. While measuring the maximum area with a handheld GPS, what is possible when the reservoir is full, has a much higher accuracy of 5-15m. Although, it should be mentioned that it was possible to improve the accuracy of the determined maximum surface area by Landsat 5 image with the help of the collected field data.

CONTROL POINTS BY GPS

As the total station only measures the XYZ distances in relation to the first point of the total station, it was needed to measure the GPS coordinates at some points. These control points were used to adjust the total station data into the right location. The control points are collected by handheld GPS, which has an accuracy of approximately 5m. It is possible to improve to accuracy by using a DGPS device. The measurement takes more time, but it increases the accuracy to below a meter.

5.2. Reservoir specific

For each reservoir there are some specific remarks to mention.

SAO NICOLAU

The problem for Sao Nicolau were the measurements by boat. Some parts of the reservoir are not covered by measurements, because the boat was unable to manoeuvre to these areas due to the many vegetation and low water depth. As a result the measured points are mostly taken in the streambed, especially in the upper part of the reservoir.

Because there only is a single track through the middle, the interpolation thereby just creates an almost linear slope to the maximum surface area. It is quite possible that the reservoirs shape differs from the model. For example, the upper part of the reservoir could have a much wider streambed. In short, the poor coverage influences the shape, and thereby the relations for the reservoir.

RAIZ

The measurement for Raiz are mostly done by total station, which means walking through an empty reservoir. The middle in both branches, the streambed, was very hard to enter due to high vegetation. For this reason there a not many points collected in the middle of the branches, which mostly is the deepest part of the cross section. Another issue for Raiz is that the upper parts of the reservoir were not measured at all due to the inaccessibility of the area. The depth of those parts are estimated by the use of Landsat 5 images. This brings unreliability.

Comparing the resulting maximum volume with estimations from previous studies, both issues probably resulted in an underestimation of the reservoirs capacity.

MARENGO

The bottleneck for Marengo was the low volume during the measurements, only 22% of the maximal surface area was covered with water. The gap between the collected data and the maximum area was filled with data from a previous study by Lopes (2013). The data for this study was collected by handheld depth meter, and thus the z-values of the data were much lower. Another remarkable problem was that the maximum surface area of this study does not seem to correspond with Landsat 5 images of 2004, when the reservoir was completely full.

So the make a complete model for the reservoir the two grids with different measurement devices and a newly estimated maximum surface area are combined. It would be much more accurate/reliable to use data from one measurement device for the whole maximum area. For example, when the reservoir is completely filled.

6. CONCLUSION

By performing a bathymetric survey at the end of the rain season in the Madalena basin it was possible to determine the geometry for the three reservoirs Sao Nicolau, Raiz and Marengo. From the data of the created geometric model the area-volume relation and the depth-volume relation are derived for each reservoir.

The area-volume and depth-volume relations give the impression that the reservoirs in the Madalena basin have a region specific shape that is characterized by being narrow and without an evident open alluvial middle area, and thereby are having linear slopes with a convex tendency. Whereby for both the area-volume as the depth-volume relations, the parameter a seems to have a certain region specific value, but for the parameter k there is no direct agreement between the relations.

The reliability of the results is affected by the accuracy of the echo sounder, the use of Landsat images, the use of handheld GPS for control points and some reservoir specific issues.

As only three of the five main reservoirs in the Madalena Basin are covered by this research it is not possible to provide complete estimates of the water availability for the area. Nevertheless, the results should be helpful and support the development in remote sensing and efficient water management and reservoir planning in the Madalena Basin and the semiarid Northeast of Brazil.

7. RECOMMENDATIONS

Previous studies by Liebe, Van de Giesen & Andreini (2005), Annor et al (2009), Sawunyama, Senzanje, & Mhizha, (2006) and Rodrigues, Sano, Steenhuis, & Passo (2012) have proven that region specific area-volume relation exists. While there are thousands of small dams in the semiarid Northeast of Brazil, this research only covers three reservoirs in this area and it is not possible to create a region specific area-volume relation. To create a general power function that can be used by planners to simulate volume in function of surface area for the whole semiarid Northeast of Brazil, it is needed to perform bathymetric surveys for much more reservoirs.

Another more logical recommendation follows from the field experience and the difficulty in modelling a complete reservoir with various data. As experienced during the field work it is time consuming to perform measurements on land by total station. The other problem is that inaccuracy increases when Landsat 5 images or output data from previous studies is used for the estimation of the maximum area or to cover unmeasured areas. To avoid these issues it would be better to perform a bathymetric survey by boat when the reservoirs are completely full with calibrated and accurate measurement devices.

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APPENDIX A: STUDY AREA – ADDITIONAL INFORMATION

1. STUDY AREA – ADDITIONAL INFORMATION

1.1. Climatological data

Besides the rainfall statistics there is no further climatological data available of the Madalena basin itself, but there is data available of ten other places in the state of Ceará from 1961 till 1990 (INMET; Instituto Nacional de Meteorologia, 2014). The closest of those places to the research area is Quixaramobim, it is located 30 km from the Madalena Basin, and therefore the climatological data of Quixaramobim can be used as representative for the Madalena basin. But as illustrated in Figure 45, the precipitation data from Quixeramobim, with an annual average of 858 mm, shows some distance from that of Madalena.

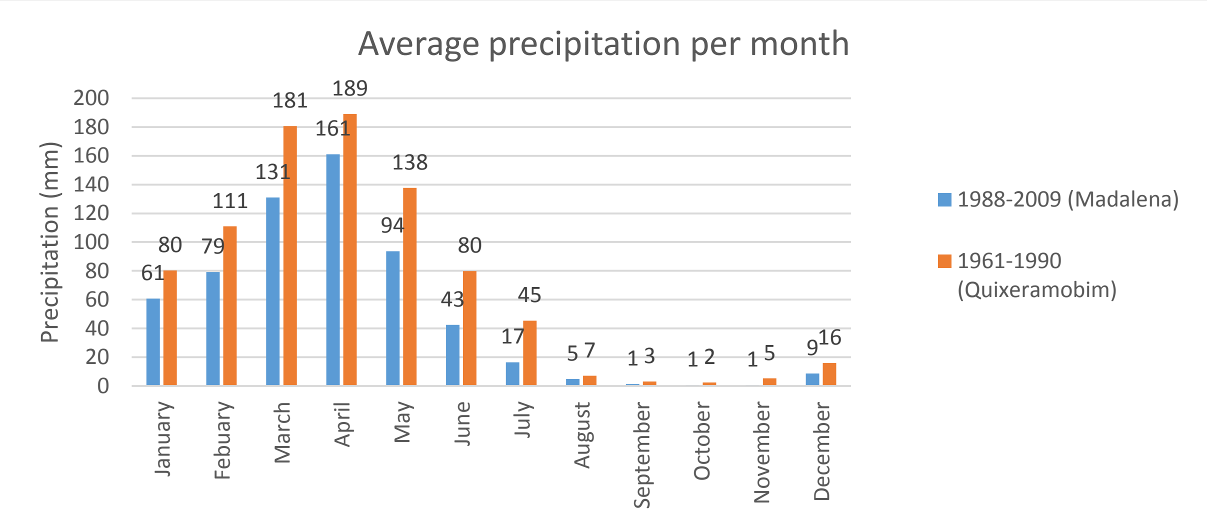
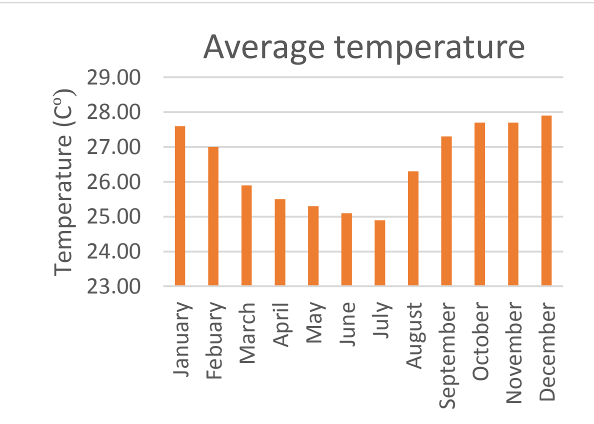


Figure 45 Average precipitation per month. Adapted from "Secretaria dos Recursos Hídricos, Governo do Estado do Ceará", by FUNCEME, 2014. Retrieved May 15, 2014, from http://atlas.srh.ce.gov.br/. And adapted from "NORMAIS CLIMATOLÓGICAS DO BRASIL 1961-1990", by INMET, 2014. Retrieved May 4, 2014, from http://www.inmet.gov.br/portal/index.php?r=clima/normaisclimatologicas.



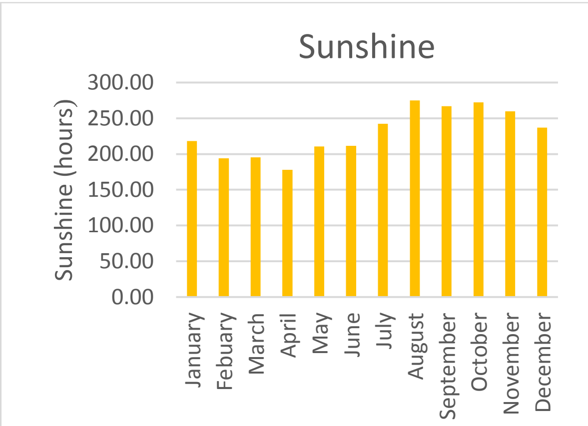


Figure 46 Average sunshine per month 1961-1990.

Figure 47 Average temperature per month 1961-1990

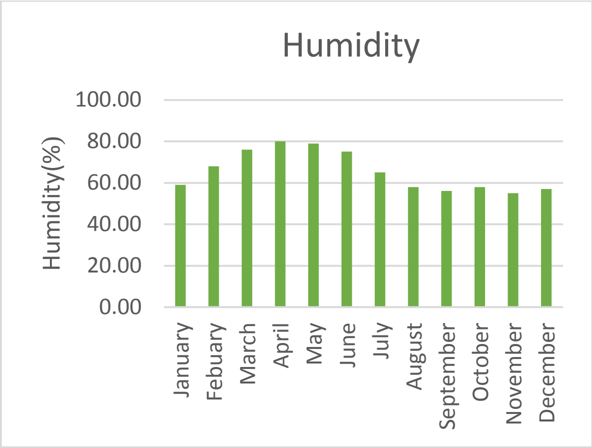


Figure 48 Average humidity per month 1961-1990

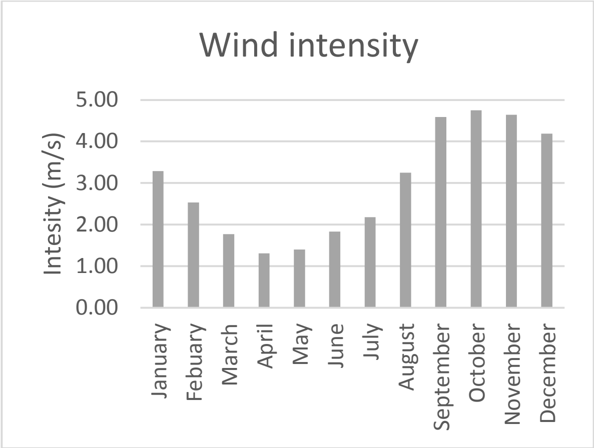


Figure 49 Average wind intensity per month 1961-1990

Figure 45, 46, 47 and 48 are adapted from “NORMAIS CLIMATOLÓGICAS DO BRASIL 1961-1990”, by INMET, 2014. Retrieved May 4, 2014, from http://www.inmet.gov.br/portal/index.php?r=clima/normaisclimatologicas.

1.2. Relief

The heights of the area are between 250 and 470 meter in relation to the sea level, see Figure 50. In 53% of the area there are mainly gentle slopes, where runoff tends to be slow to medium, and erosion does not pose any problems. The location of the slopes is presented in Figure 51 and the total distribution of slopes is given in Table 3.

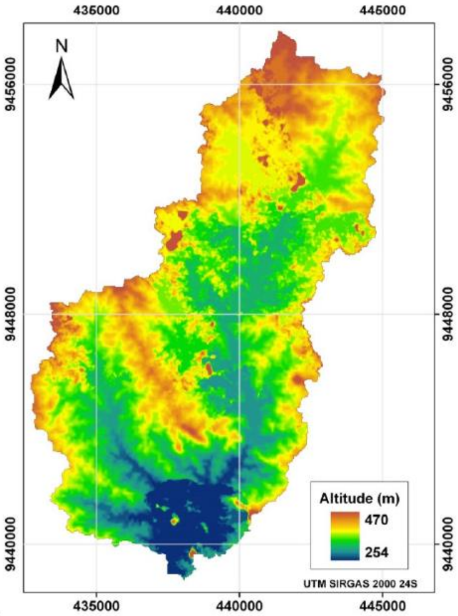


Figure 51 Heights, Adapted from “Modelagem Hidrossedimentológica em meso-bacia do semiárido”, by J.W.B. Lopes, 2013.

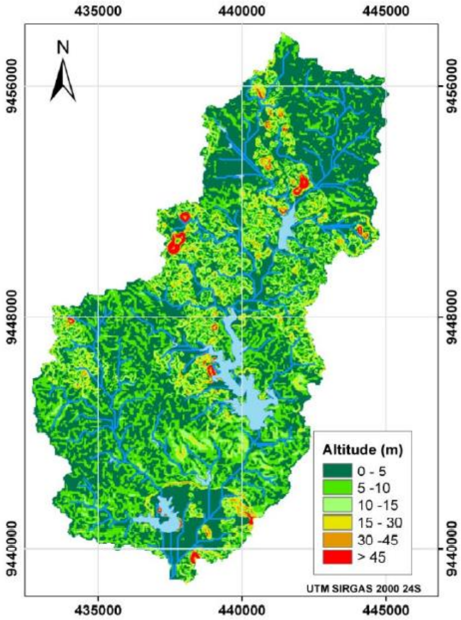


Figure 50 Slopes. Adapted from “Modelagem Hidrossedimentológica em meso-bacia do semiárido”, by J.W.B. Lopes, 2013.

Area (%)	Slope (%)
53	< 5
31	5 – 10
9	10 – 15
5	15 – 30
2	30 – 45

Table 3 Slope distribution. Adapted from “Modelagem Hidrossedimentológica em meso-bacia do semiárido”, by J.W.B. Lopes, 2013.

APPENDIX B: EQUIPMENT

1. EQUIPMENT

1.1. eTrex Vista HCx (Garmin GPS)

APPENDIX

Specifications

Physical

Size: 4.2" H x 2.2" W x 1.2" D

Weight: 5.6 ounces (159 g) with batteries installed.

Display: 1.3" W x 1.7" H, 256-color, high resolution, transreflective TFT(176 x 220 pixels) backlit.

Case: Rugged, fully gasketed, water resistant, IEC-529, IPX7

Temp: 5 to 158°F (-15 to 70° C)*

*The temperature rating of the eTrex may exceed the usable range of some batteries. Some batteries can rupture at high temperatures.

Performance

Receiver: WAAS/EGNOS enabled, high-sensitivity

Acquisition Times: (approx.)
Hot start- 3 seconds
Warm start- 33 seconds
Cold start- 39 seconds

Update Rate: 1/second, continuous
Antenna: Built-in patch

Compass: (Vista HCx/Summit HC only) Accuracy; +/- 5 degrees, resolution; 1 degree, user calibrated

Altimeter: (Vista HCx/Summit HC only) Accuracy; +/- 10 feet, resolution; 1 ft., user calibrated

Power

Source: Two 1.5 volt AA batteries, 12 V DC Adapter Cable, or PC/USB Adapter

Battery Life: Up to 25 hours HCx units
Up to 14 hours HC units

Accuracy

GPS: <10 meters (33 feet) 95% typical*

*Subject to accuracy degradation to 100m 2DRMS under the U.S. DoD imposed Selective Availability (SA) Program when activated.

DGPS: 3 meters (10 feet) 95% typical*

*Wide Area Augmentation System (WAAS) accuracy in North America.

Velocity: 0.1 meter/sec steady state

Interfaces: Garmin Proprietary (USB)

Data Storage Life: Indefinite; no memory battery required

Map Storage: HCx units -Dependant on the formatted capacity of the microSD card.
HC units - 24 MB

Figure 52 Specification eTrex Vista HCX. Adapted from "eTrexHCx Owners Manual," by Garmin, 2007.

1.2. GPSMAP 188 Sounder with GPS Antenna & Plastic Transom Mount Transducer

GPSMAP 188 SOUNDER WITH GPS ANTENNA

specifications

WAAS enabled

Fishing Hot Spots

BlueChart compatible

Navigation features

Waypoints/icons:	3000 with name, symbol and comments; support for proximity waypoints
Routes:	50 reversible routes up to 50 (254 for 182C) points each, plus MOB and TracBack® modes
Tracks:	3000 point automatic track log, 15 saved tracks; 500 points per saved track, lets you retrace your path in both directions
Alarms:	Anchor drag, arrival, off course, proximity waypoint and clock
Tables:	Built-in celestial tables with sun and moon rise, set and location. Tide tables for the U.S.
Map datums:	More than 100, plus user datum
Position format:	Lat/Lon, UTM/UPS, Loran TDs and other grids, including user grid
Languages:	10

GPS performance

Receiver:	WAAS enabled, 12 parallel channel GPS receiver continuously tracks and uses up to 12 satellites to compute and update your position
Acquisition times:	
Warm:	Approximately 15 seconds
Cold:	Approximately 45 seconds
AutoLocate®:	Approximately 5 minutes
Update rate:	1/second, continuous
GPS accuracy:	
Position:	< 15 meters, 95% typical*
Velocity:	0.05 meter/sec steady state
DGPS (USCG) accuracy:	
Position:	3-5 meters, 95% typical
Velocity:	0.05 meter/sec steady state
DGPS (WAAS) accuracy:	
Position:	3 meters, 95% typical
Velocity:	0.05 meter/sec steady state
Dynamics:	6g's
Interfaces:	2-RS232 with NMEA 0183, RTCM 104 DGPS data format and proprietary GARMIN
Antenna:	GPSMAP 188 = GA 29 remote marine mount with 30' cable or bail mount antenna GPSMAP 238 = GA 29 remote marine mount with 30' cable

Plotter/moving map features

Basemap:	Built-in worldwide basemap to 32 nm with coastlines, rivers, lakes, political boundaries, tide data for the U.S., cities and interstates
Data cartridges:	Preprogrammed micro cartridges contain detailed BlueChart® marine cartography

Depth sounder features

Frequency:	50/200 kHz (40°/10°)
Sonar power output:	500 watts (RMS), 4000 watts (peak to peak)
Depth:	1500 foot max depth**
See-Thru® technology:	Shows weak/strong returns simultaneously
Depth control gain (DCG®):	Automatically adjusts fishfinder sensitivity according to depth

Power

Source:	8-35v DC
Usage:	4 watts max. at 13.8v DC

Physical

Size:	GPSMAP 188/188C = 6.3" W x 6.2" H x 2.6" D GPSMAP 238 = 7.7" W x 7.5" H x 2.6" D
Weight:	GPSMAP 188/188C = 1.7 lbs. (.77 kg) GPSMAP 238 = 2 lbs. (.91 kg)
Display:	GPSMAP 188 = 5.5" diagonal (14.0 cm) high-resolution, 10-level grayscale LCD with backlighting (240 x 360 pixels) GPSMAP 188C = 5.0" diagonal (12.7 cm) 16-color TFT display with backlighting (234 x 320 pixels) GPSMAP 238 = 7.1" diagonal (18.0 cm) high-resolution, 10-level grayscale LCD with backlighting (240 x 360 pixels)
Case:	Fully gasketed, high impact plastic alloy, waterproof to IEC 529 IPX7 standards
Temp. range:	5°F to 158°F (-15°C to 70°C)

Accessories

Standard:	Power/data cable bail mount protective front cover remote antenna with 30' cable owner's manual quick reference guide
Optional:	Preprogrammed data cards with BlueChart® marine cartography AC/PC adapter 12-volt adapter cable USB data card programmer Second mounting station GBR 23 beacon receiver MapSource® CDs: Fishing Hot Spots® U.S. Waterways & Lights Roads & Recreation WorldMap

Figure 53 Specifications Echosounder. Adapted from "GPSMAP 188/188C and 238 Sounder," by Garmin, 2001

PLASTIC TRANSOM MOUNT TRANSDUCER WITH DEPTH & TEMPERATURE (DUAL FREQUENCY, 6-PIN)

The 500 W 6-pin transducer has a maximum depth of 1,500 feet (circa 457 meters); an operating frequency of 50 to 200 kHz; a beam width of 40 to 10 degrees; and mounts on a 0 to 70 degree transom. (GARMIN, 2014)

1.3. Spectra Precision FOCUS 6 Total Station

TELESCOPE

Magnification
30x (18x/36x with optional eyepieces)

Effective diameter of objective
2" 40 mm (1.6 in)
2" EDM diameter. 45 mm (1.8 in)
5" 45 mm (1.8 in)
5" EDM diameter. 50 mm (2.0 in)

Minimum focusing distance
1.5 m (4.9 ft)

DISTANCE MEASUREMENT

Reflectorless mode 2"

	Good	Normal	Difficult
KGC (18%)	350 m (1,148 ft	250 m 820 ft	200 m 656 ft)
KGC (90%)	500 m (1,640 ft	400 m 1,312 ft	250 m 820 ft)

Reflectorless mode 5"

	Good	Normal	Difficult
KGC (18%)	280 m (920 ft	250 m 820 ft	200 m 656 ft)
KGC (90%)	500 m (1,640 ft	500 m 1,640 ft	300 m 984 ft)

With single prism 6.25 cm (2.5 in)
2" 1.5m to 3,000 m (4.9 ft to 9,843 ft)
5" 1.5 m to 5,000 m (4.9 ft to 16,404 ft)

Accuracy[2] (Precise mode) ISO 17123-4
Prism ±(2+2 ppm × D) mm
Prism ±(3+2 ppm × D) mm

Measuring interval[3]
Prism mode

2" Precise mode	1.6 sec.
5" Precise mode	1.5 sec.
Normal mode	0.8 sec.

Reflectorless mode

2" Precise mode	2.1 sec.
5" Precise mode	1.8 sec.
2" Normal mode	1.2 sec.
5" Normal mode	1.0 sec.

Least count

Precise mode	1 mm (0.002 ft)
Normal mode	10 mm (0.02 ft)

Figure 54 Specifications Total station. Adapted from "Survey, Construction & GIS Product Catalog," by Spectra Precision Division, 2014.

GENERAL SPECIFICATIONS

Operating temperature range
–20 °C to +50 °C (–4 °F to +122 °F)

5" Winterized
–30 °C to +50 °C (–22 °F to +122 °F)

Atmospheric correction
–40 °C to +60 °C (–40 °F to +140 °F)

Barometric pressure
400 mmHg to 999 mmHg
533 hPa to 1,332 hPa
15.8 inHg to 39.3 inHg

Minimum increment (Degree, Gon, MIL6400)
Degree: 1/5/10"
Gon: 0.2/1/2 mgon
MIL6400: 0.005/0.02/0.05 mil

DIN 18723 accuracy (horizontal and vertical)
2" 0.6 mgon
5" 1.5 mgon

Dust & Water protection
IP66

Tilt sensor
Type
Dual axis

Level vial
Sensitivity of Circular level vial
10'/2 mm

Optical plummet
Magnification
3x

Display face 1
Graphic LCD (128 x 64 dot); Single side

Display face 2 (2" only)
backlit, graphic LCD(128x64 pixel)

Point memory
10,000 records

Dimensions (W × D × H)
14.9 cm x 14.5 cm x 30.6 cm
(5.8 in x 5.7 in x 12.0 in)

Weight (approx.)
Main unit (without battery)
2" 3.8 kg (8.4 lb)
5" 3.6 kg (8.0 lb)

Battery
0.1 kg (0.2 lb)

Carrying case
2.3 kg (5.1 lb)

Internal Li-ion battery (x2)
Operation time[4]

2"
approx. 19 hours (continuous distance/angle measurement)
approx. 57 hours (distance/angle measurement every 30 seconds)
approx. 62 hours (continuous angle measurement)

5"
approx. 10 hours (continuous distance/angle measurement)
approx. 26 hours (distance/angle measurement every 30 seconds)
approx. 31 hours (continuous angle measurement)

Charging time (Full charge)
4 hours

Figure 55 General specifications Total station. Adapted from "Survey, Construction & GIS Product Catalog," by Spectra Precision Division, 2014.

APPENDIX C: DEPTHMETER VERSUS ECHOSOUNDER

DEPTHMETER VERSUS ECHOSOUNDER

The z-values measured by the handheld depthmeter and the echosounder have a remarkable difference. The difference between these z-values is determined by taking, when possible, points measured by the handheld depthmeter and the most nearby points from the echo-sounder. Thereby the unrealistic z-values of the echo-sounder due to malfunction are not taking into account. For each of these points the difference is calculated. The results of this comparison are given below.

Sao Nicolau	
Number of points	69
Average difference*	-0.901449275
Median	-0.8
Marengo	
Number of points	148
Average difference	-1.0067568
Median	-0.9

Figure 56 Results depthmeter vs echosounder

**For the reservoir of Sao Nicolau the average difference of these point is used as a bias to adjust the z-values of the handheld depthmeter for the points used to make the grid for the model.*

APPENDIX D: DERIVATION OF POWER FUNCTION

DERIVATION OF POWER FUNCTION

The derivation of the power function for the area-volume relation of the reservoir Raiz is given below as an example for the derivation of the power function out of the linear line from the log-log curves.

Wanted power function:

$$y = k * x^a \quad (1)$$

Linear function of log Area – log Volume:

$$y = 1.6084 * x - 2.7640 \quad (2)$$

Logarithmic principle:

$$y = m * X + b \quad (3)$$

$$\log_{10}(y) = a * (\log_{10}(x)) + \log_{10}(k) \quad (4)$$

$$m = a \quad (5)$$

$$X = \log_{10}(x) \quad (6)$$

$$b = \log_{10}(k) \quad (7)$$

$$y = \log_{10}(y) \quad (8)$$

Calculation:

$$b = \log_{10}(k) = -2.7640 \quad (9)$$

$$k = 10^b = 10^{-2.7640} = 0.0017 \quad (10)$$

$$m = a \quad (11)$$

$$a = m = 1.6084 \quad (12)$$

Resulting power function:

$$y = 0.0017 * x^{1.6084} \quad (13)$$

Figure 57 Derivation of the power function for area-volume relation of reservoir Raiz

APPENDIX E: AREA-DEPTH-VOLUME RELATIONSHIPS

AREA-DEPTH-VOLUME RELATIONS

For each reservoir the derivation of the area-volume and depth-volume curve with their belonging power function and coefficient of determination value are shown below. Each derivation has three figures; the dataset, the log-log curve and the actual curve in relation to the model based curve. The derivation for the area-volume curves is shown on the left and the derivation of the depth-volume curve is shown on the right.

1. Sao Nicolau

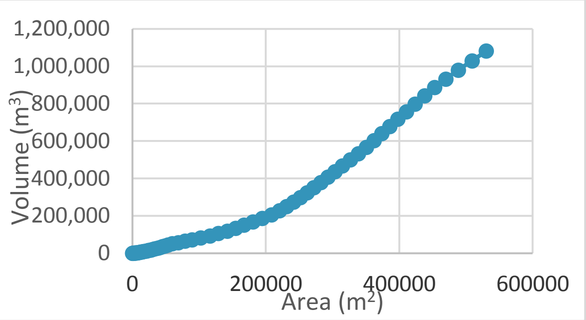


Figure 58 Dataset depth-volume points

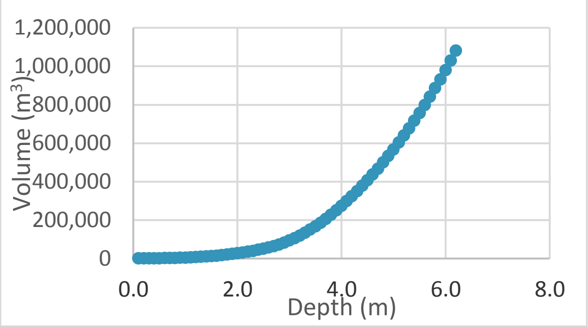


Figure 59 Dataset area-volume points

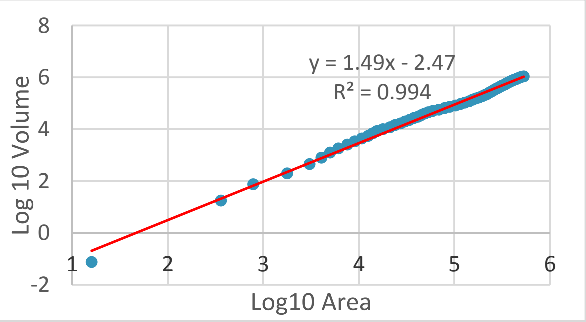


Figure 60 logArea-logVolume

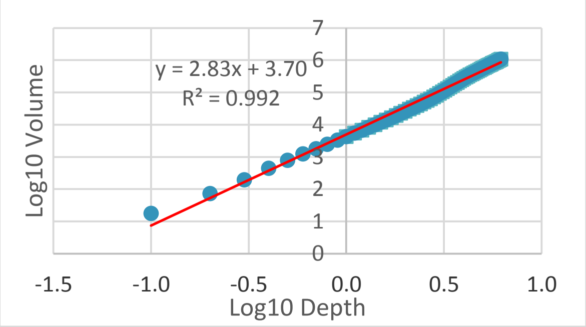


Figure 61 logDepth-logVolume

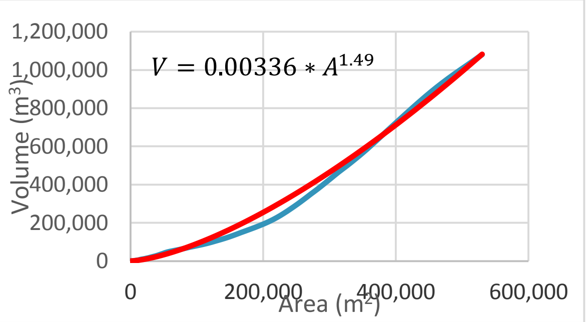


Figure 63 Area-volume curve with model based curve in blue and regression curve in red

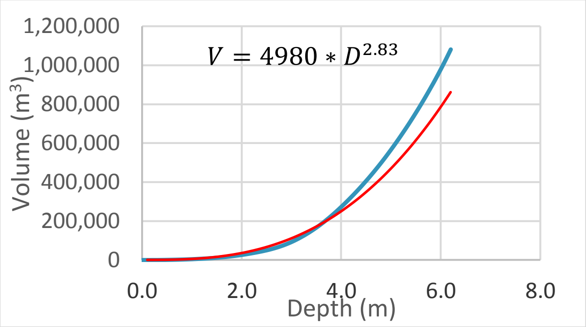


Figure 62 Depth-volume curve with model based curve in blue and regression curve in red

2. Raiz

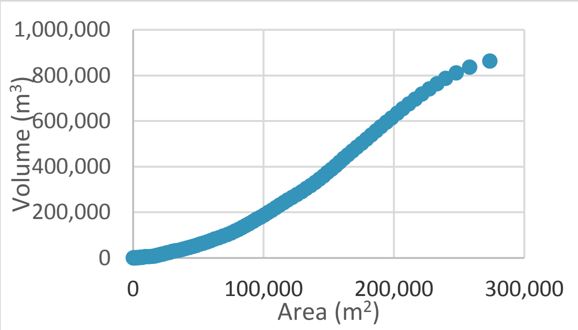


Figure 64 Dataset area-volume points

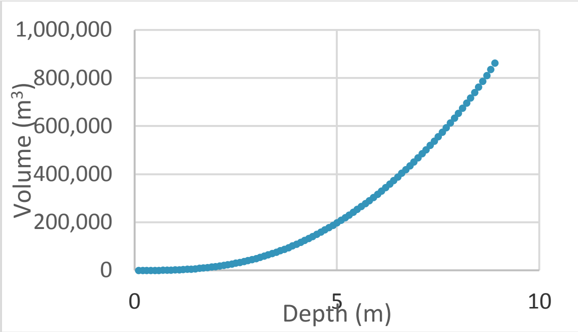


Figure 65 Dataset depth-volume points

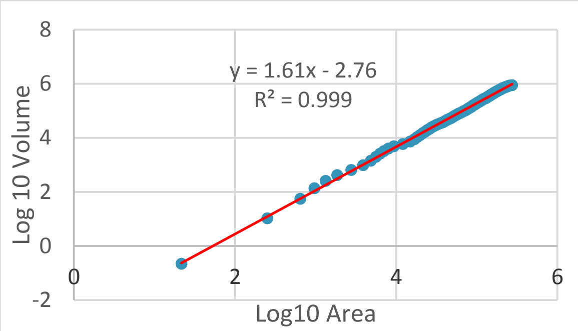


Figure 66 logArea-logVolume

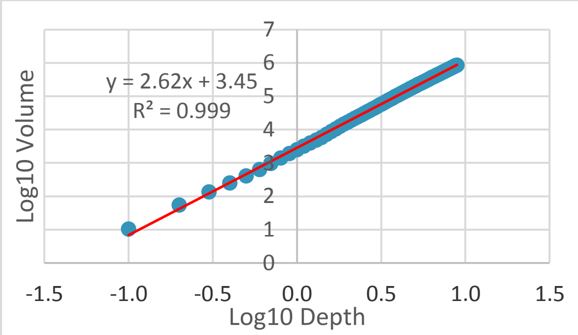


Figure 67 logDepth-logVolume

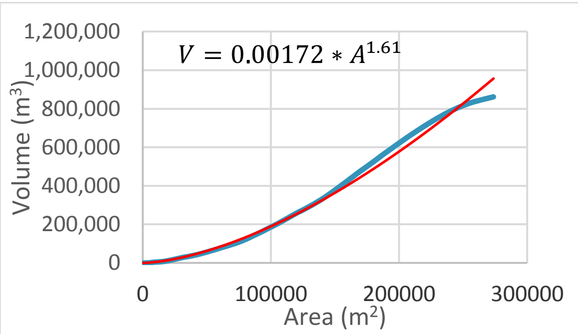


Figure 68 Area-volume curve with model based curve in blue and regression curve in red

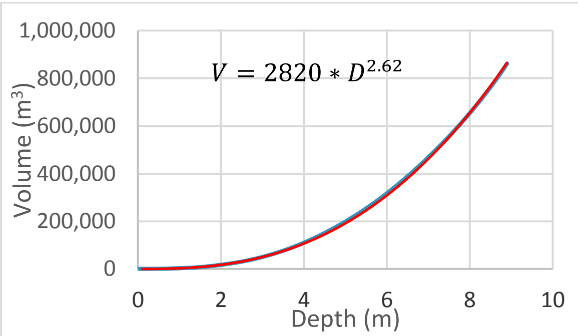


Figure 69 Depth-volume curve with model based curve in blue and regression curve in red

3. Marengo

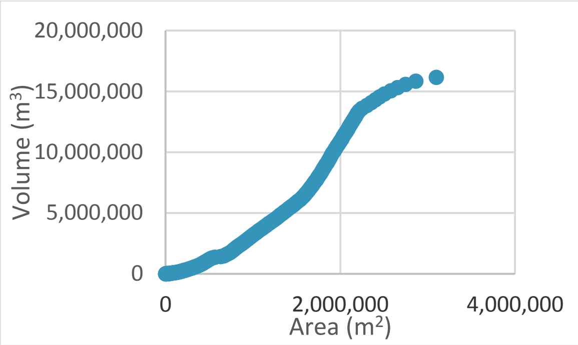


Figure 70 Dataset area-volume points

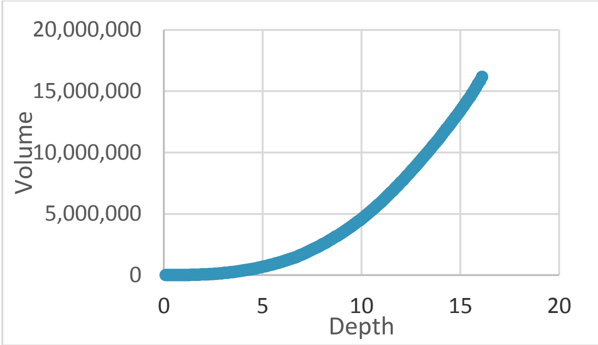


Figure 71 Dataset depth-volume points

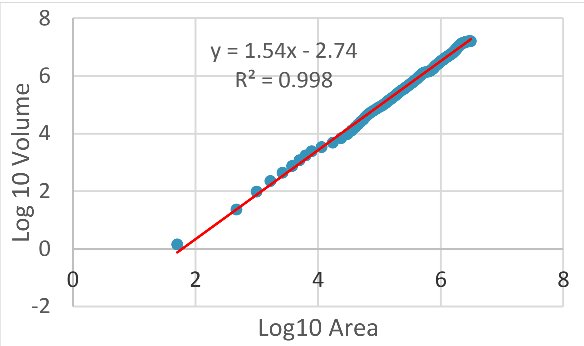


Figure 72 logArea-logVolume

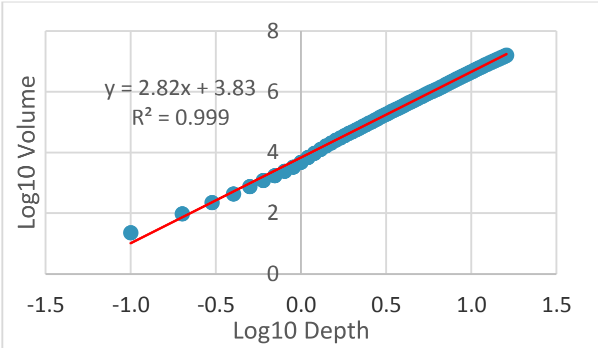


Figure 73 logDepth-logVolume

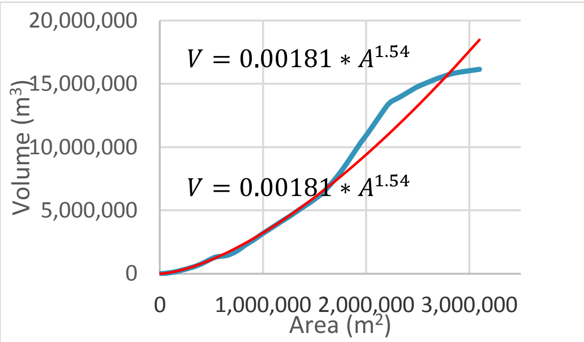


Figure 74 Area-volume curve with model based curve in blue and regression curve in red

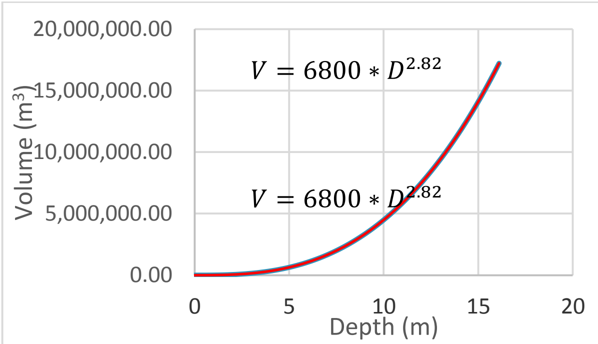


Figure 77 Depth-volume curve with model based curve in blue and regression curve in red