Sedimentation of reservoirs

A method to estimate reservoir sedimentation: a case study of the 'Nga Moe Yeik' reservoir, Myanmar

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Preface

First I would like to thank all the people who supported me in my bachelor thesis and gave me the opportunity to perform this research at the Irrigation Technology Centre, Bago. The place where I stayed, the people I spoke to and the friends that I made, gave me a unique experience that I will never forget. During my stay I learned a lot about performing research, and foreign people and culture as well.

What interested me the most are the cultural differences between Myanmar and The Netherlands. The way people interact which each other, and the low speed of life. People life according to a relax and frequent rhythm. Things come and go in a natural pace and if something is not finished today then maybe tomorrow. During my stay in Myanmar I really learnt to appreciate that very well.

I owe many thanks to Martine Rutten and Alwin Commandeur. Who not only came up with the subject of research, but also supported me with feedback before and during my thesis, and also got me in contact with some of the people of the ITC. I would also like to give many thanks to Sai Wunna, who assisted me during my entire stay at the ITC, always offered me assistance during my field surveys and outside of that. I could ask every question about the ITC, Bago, or about Myanmar to him and he showed me some of nicest places of Bago. Furthermore I need to say thanks to Zaw Min Htut, for giving me a place to live at the ITC. Finally, I need to say thanks to Juliette Cortes, she always provided me with feedback and her critical opinion.

Summary

Myanmar's irrigation and domestic water supply is very dependent on the storage capacity of their fresh water reservoirs. Due to forest fires, deforestation and bad governmental policies, erosion is posing a big treat to the life time of their reservoirs. Erosional processes cause reservoirs to silt up, resulting in major capacity losses. Myanmar does possess more than 200 reservoirs, but there is still very little know about the sedimentation rates affecting them. To improve the reservoir and irrigation management it is important to make estimations about the reservoir life expectancy.

A good method to estimate the sedimentation of a reservoir is by performing a bathymetric survey. But, these surveys can be expensive and time consuming. Therefore it will not always be possible to perform them on a regular basis. A supplementary method is demanded to predict sedimentation in an easy and cheap way and to help interpreting the bathymetric survey's results. This may be possible by modelling the catchment area of a reservoir. By using the InVEST model, based on the Universal Soil Loss Equation (USLE) and a method to predict the trap efficiency of the reservoir, it is possible to make predictions about the accumulated sediment in the reservoir. This prediction can be compared to the results of a bathymetric survey to see if they show agreement. The goal of this research is too see if the combination of InVEST and trap efficiency has potential to be used in Myanmar as a reliable method to estimate the capacity loss of reservoirs.

The area of study in this research is the 'Nga Moe Yeik' reservoir and its catchment area. 'Nga Moe Yeik' is situated 100 kilometres to the north of Yangon City. The reservoir also fulfils an important function within the water supply of Yangon City. The catchment area is 414 square kilometres, it has a capacity of 222 million cubic meters and the dam was finished in 1995. The dam has two supplementary dams: 'Paung Lin' and 'Ma Hu Yar'. Those dams lie upstream of the 'Nga Moe Yeik' dam and are constructed in 2003. The research is conducted at the Irrigation Technology Centre (ITC), Bago. There has been an intensive cooperation with the staff of the ITC to make this research into a success. Several field survey trips from ITC, Bago, have been performed to execute a bathymetric survey and to study the reservoirs and their catchment area.

Three research questions were stated to achieve the research goal. Every research question has its own section within the research methodology and results. Firstly, the spatially explicit InVEST model is used to make average annual predictions for the watersheds sediment yield. Sediment yield is the total amount of sediment that will flow into the reservoir after erosion and deposition within the watershed. Rainfall, land cover and soil characteristics are very important parameters influencing the sediment yield and is therefore demanded input for this InVEST model. The total sediment yield accumulation for the 'Nga Moe Yeik' catchment during the past 21 years is estimated to be between 44,5 $*10^6$ m^3 and 64,4 $*10^6$ m^3. Annual erosion rates are estimated to be between 14,5 $*10^3$ ton/km^2 and 42,3 ton/km^2, which are very high compared to results within the literature.

Secondly, when the eroded material enters the reservoir, some of it will deposit and some of it will flow out. The ratio of sediment inflow and outflow is called the trap efficiency and is determined by multiple factors. The trap efficiency of a reservoir can be estimated by using empirical equations. By using data about daily inflow and stored volume, it is possible to estimate the trap efficiency on basis of the residence time of water within the reservoir. The longer water stays in the reservoir, the more sediment will deposit and that will increase the trap efficiency. The average trap efficiency for the 'Nga Moe Yeik' reservoir is 97,65%.

Thirdly, a bathymetric survey has been performed to assess the capacity loss of the reservoir. The measurements of the bathymetric survey were used to build a digital elevation model (DEM) of the reservoir bed using ArcGIS. An old map of the 'Nga Moe Yeik' area from 1995 was present to model

the before dam situation, also with the use of ArcGIS. The differences between the two DEM's resulted in a capacity loss that represent the real capacity loss during the last 21 years. An error assessment has been performed to estimate the error propagation of the used measurement and model techniques, namely the georeferencing, the interpolation, the gab filling with Landsat and the measuring setup. The sediment accumulation is between 14,74 * 10^6 m^3 and 27,66 *10^6 m^3. Resulting in a capacity loss between 11,94 and 6,36%.

Comparing the InVEST predictions and the trap efficiency with the results of the bathymetric survey, show that there is some agreement between them. However, they differ with a ratio between 2 and 3. This difference is too vast for making proper predictions about reservoir sedimentation. As explained in the conclusion, improvements on the parameterization of the InVEST model will have to be made to develop this model into a proper tool to estimate reservoir sedimentation. In the future, this method may have the potential to develop into an easy and low costing tool to better understand the erosion processes and the impact of individual parameters on the sediment yield.

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1. Introduction

Reservoirs are often considered to be the largest constructions that mankind ever built. Reservoirs can offer many benefits at the expense of economic and environmental assets (Sloff, 1997). The building of large dams tends to be very expensive and the impact on river dynamics and ecosystems can be very substantial. Often one of the main functions of reservoirs is to provide storage capacity and to regulate the discharge of a river system. This can solve the surplus and the shortages of water that might occur at different times in the river basin. Ultimately whole communities and even cities can depend on the function of those reservoirs. Therefore it is very important to maintain the storage capacity of those reservoirs during their life cycle. One phenomenon that is capable of weakening buffer capacities is sedimentation.

When a river enters a reservoir or pond its flow velocity will be reduced, with sedimentation of transported particles as result. Over time this phenomenon will cause sediment accumulation that has a negative impact on the storage capacity. This is a worldwide problem. The Selfidrud reservoir in Iran for example was designed for a lifespan that would exceed 100 years, but after some years measurements demonstrated that the sedimentation rates were so high that the actual useful lifespan of the reservoir would be about 30 years (Sloff, 1997).

At the basis of those transported particles underlie erosional processes. Rainfall and runoff is able to cause erosion of soil and material from the land surface (Smith & Wischmeier, 1962). Runoff through rills and gullies can mobilise soil from the watersheds to end up in rivers. This soil has the potential to be deposited at the bed of the reservoir, causing sedimentation (see Figure 1).

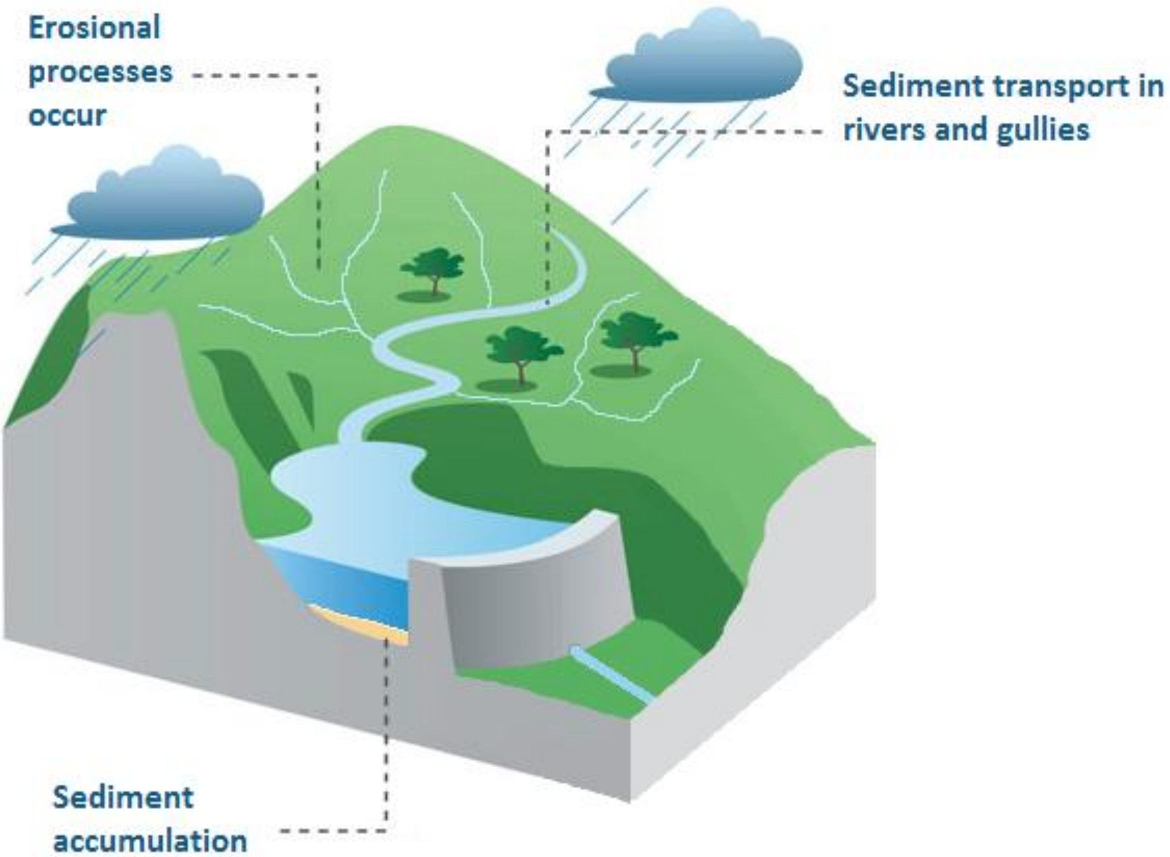

Figure 1: the processes from erosion to sediment ending up in the reservoir

1.1 Problem context

To make clear what systems and variables lay at the basis of the erosional and sedimentation processes, the problem context will describe the inner workings of those processes and address some literature.

This thesis is focused on a watershed system that discharges into a reservoir (Figure 1). Rainfall will infiltrate and replenish the soil moisture content and will runoff at the surface (Basin et al., 2009). The energy impact of rain droplets and surface runoff cause soil erosion at the lands surface (Roose, 1976 and Morgan et al., 1998). If runoff occurs the water and eroded material will be transported to lower sections within the watershed by routing. The routing is mainly determined by terrain height characteristics, like hill slopes (Morgan et al., 1998). During the process of runoff and routing new material will be eroded and some material will be deposited (Renard et al., 1997). Four main types of erosion processes can be distinguished: sheet, rill, gully and in-stream erosion. According to Merritt et al. (2003) it is important to make the distinction between different kinds of erosion processes, because it is very hard to model them all in the same case. Most models tend to predict erosion for one type. It is also hard to judge which type of erosion is the most influential for a certain case or catchment area.

Parameters that have impact on the quantity of eroded material are the following: rainfall intensity, soil erodibility, land use, agricultural practices, hill slopes and runoff rates (de Vente & Poesen, 2005). At the outlet of the watershed the water and sediment particles will flow into a reservoir and all those sediment particles are defined as the sediment yield (m^3/year) of the catchment area (Renard et al., 1997). The different processes and sources impacting the sediment yield is called the sediment budget, see Figure 2 for a general example. In this case study the sediment yield will be defined as all the sediments flowing into the reservoir.

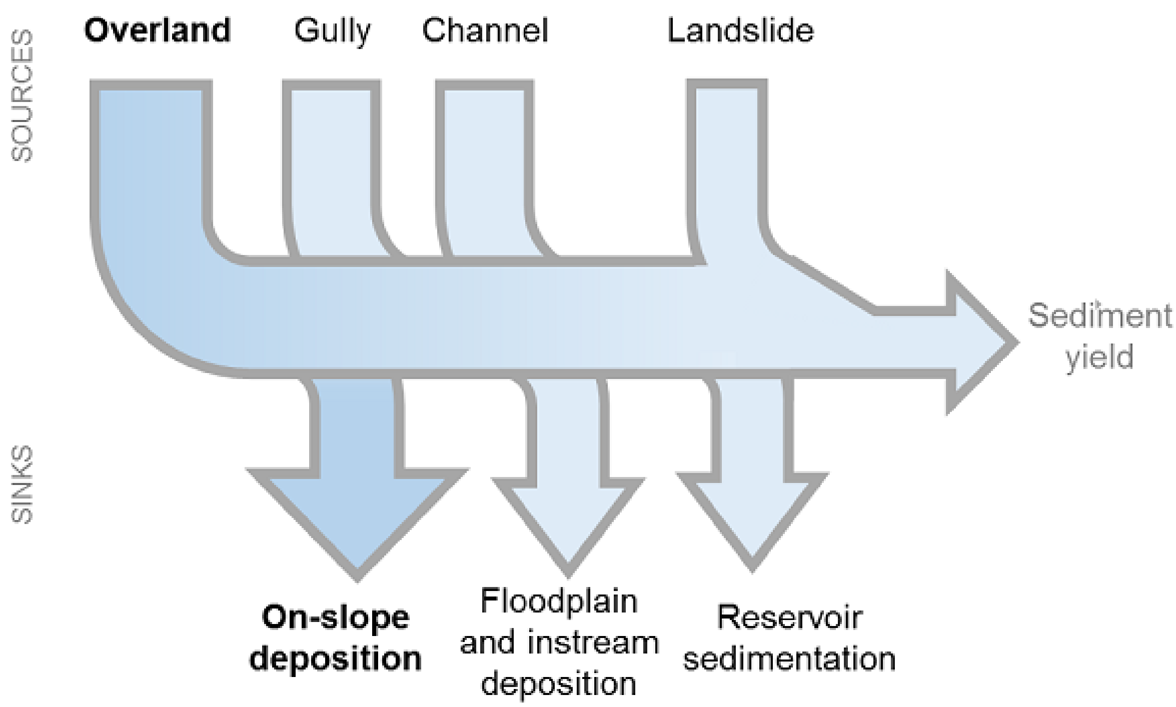

Figure 2: General catchment sediment budget. The Natural Capital Project (2015), http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/sdr.html (20-04-2016)

But not all of those sediments will deposit at the reservoirs bed, some of them will flow out. Plenty of research about the sedimentation of reservoirs has been performed during the past decennia e.g. Sloff (1997), to investigate the impact of sedimentation on the capacity and useful lifespan of reservoirs. It is possible to perform bathymetric surveys on reservoir beds to measure the sedimentation rates of reservoirs, but those surveys are often expensive and time consuming according to Issa et al. (2015). The percentage of sediment that will be trapped in the reservoir is called the trap efficiency (Sloff, 1997). The trap efficiency depends on multiple variables. To estimate sediment accumulation, theory about trap efficiency has been developed by multiple authors e.g. Brune (1953)(based on data in the USA). According to Verstraeten & Poesen (2000), the trap efficiency is dependent on variables like: particles size of sediment, shape of reservoir, volume of reservoir and variation of the inflow. They also state that it can be important to distinguish the effects of single events in the trap efficiency. The sediment yield and the trap efficiency together determine the sedimentation rate (m^3/year) of the reservoir. The sedimentation rate describes how quick the sediment accumulation will take place.

Despite all the research that has been executed during past decades, the knowledge about erosion, sediment transport, and sedimentation rates is particularly complex when data is limited. To make predictions about the sediment yield of a catchment area often data is not consistent or precise enough to state clear conclusions (de Vente & Poesen, 2005). In Myanmar that could be particularly the case. Clearly all interactions and systems described above do happen at watershed scale in Myanmar. To make predictions with scarce data, simple mathematical and empirical formulas and models have to be used that simplify some parts of the complex system. Field work activities will provide some insight about the current sedimentation rates. Outcomes of the erosion and sedimentation simulations will be compared with the current sedimentation rates.

1.2 Research context

As shortly has been noted above in section 1.1 'Problem context', this research will be about a case study in Myanmar. In Myanmar the impact of erosion and sedimentation on reservoirs is not very clear at all; this is also being affected by the lack of proper data. Myanmar does possess almost 200 large dams (Wikipedia, 2016), so the potential impact of sedimentation on the country is obvious. Also the effect of deforestation practices and forest fires might increase the soil erosion conditions and consequently the sediment yield. Therefore the Irrigation Technology Centre (ITC) wants to know the extent of this problem in the reservoirs. They would like to get insight in the present soil erosion quantities and sediment accumulation in the reservoirs. Doing research about this will help the government of Myanmar to better monitor the impact of those systems on the benefits of their land and reservoirs.

This case study was executed in cooperation with the TU Delft, and the ITC, situated in Bago. The case study has been dedicated to one watershed within Myanmar, ultimately discharging at the 'Nga Moe Yeik' reservoir. Above stream of 'Nga Moe Yeik' there are two small supplementary dams: 'Paung Lin' and 'Ma Hu Yar'. The studied catchment area is located near Bago. See Figure 3 for the exact location of the catchment area and the reservoirs. This study area is chosen because of the available data and the important function it fulfils as water supply for the city of Yangon.

All three reservoirs have an earthen dam with concrete conduit and spillway constructions. The catchment areas draining into the 'Paung Lin' and 'Ma Hu Yar' reservoirs are respectively 87 and 53 km^2. The total catchment area discharging at the 'Nga Moe Yeik' reservoir is 414,4 km^2. The average inflow of the 'Nga Moe Yeik' reservoir is 20 m^3/s and its capacity is $222 * 10^6$ m^3. Building of the dam started in 1992 and the construction completed in 1995. The construction of the 'Paung Lin' and 'Ma Hu Yar' dams started and finished in 2003. It is important to make the distinction between these separate periods, because it affects the sediment yield analysis, see section 4.1.4 'Sediment yield – catchment area'. See appendix A, for more technical data about the dams and their catchment area.

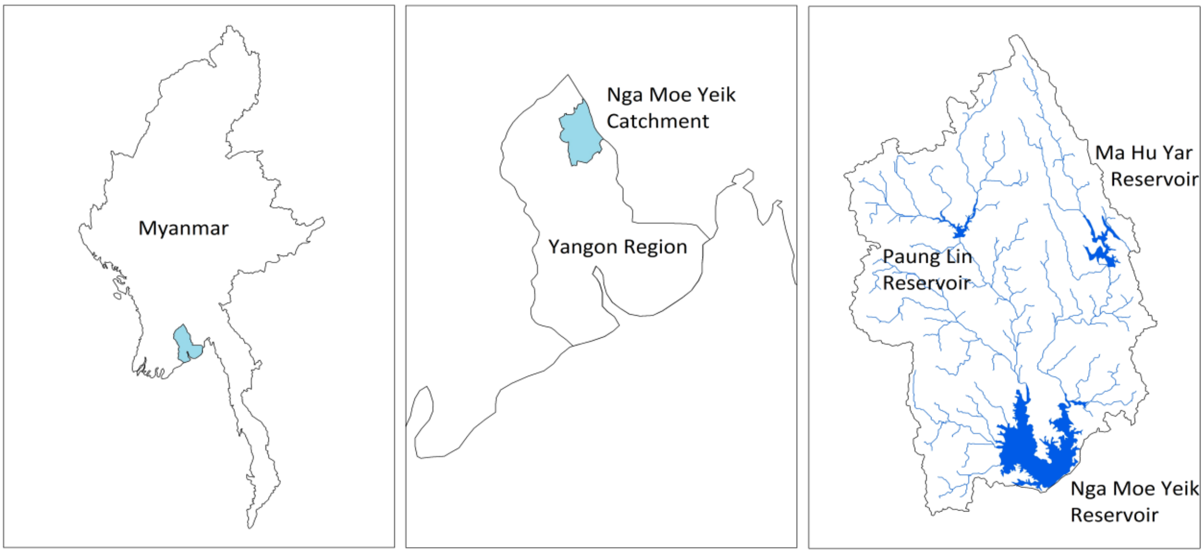

Figure 3: Situation of the 'Nga Moe Yeik' reservoir and catchment and supplementary reservoirs

2. Research design

This chapter of the proposal will make clear what the aim of the research is and which research questions will be answered to achieve this aim.

2.1 Research aim

The purpose of this research is to determine if the capacity loss of the 'Nga Moe Yeik' reservoir in Myanmar can be estimated by modelling the erosion and sedimentation processes within the catchment area.

2.2 Research questions

To structure the research aim, the problem will be divided into three parts: the upstream area contributing to the sedimentation, the trap efficiency of the reservoir and the sedimentation of the reservoir itself.

First the sediment yield (ton) of the catchment will be assessed. To determine the sediment yield, it is necessary to define the upstream areas draining into the 'Nga Moe Yeik' reservoir. Moreover, it is necessary to look into the rainfall characteristics, soil properties and land cover of the catchment area. But criteria like hill slopes and height characteristics will also have an impact on the sediment yield. Furthermore, the specific gravity of the reservoirs sediment has to be determined, to make the transition between the weight and volume of the sediment yield. The research question and sub-questions regarding the sediment yield are the following:

What is the sediment yield of the 'Nga Moe Yeik' catchment area and what is the impact of different geological and hydrological characteristics on the sediment yield?

1. *What are the catchment areas of the rivers flowing into the reservoir?*
2. *What are the soil properties, land uses and rain characteristics in the catchment areas?*
3. *What is the specific gravity of the sediment*

Second, the trap efficiency (%) of the reservoir will be assessed. If the sediment yield (m^3/year) of the upstream catchment areas has been determined, it is possible to predict the sedimentation rate in combination with the trap efficiency. The trap efficiency can be predicted with empirical formulas, in combination with information about variation in stored volume and reservoir inflow and information about particle size distribution. The research question and sub-questions regarding the trap efficiency are the following:

What is the trap efficiency for the 'Nga Moe Yeik' reservoir?

1. *What is the variation of the stored volume and the reservoir inflow?*
2. *What is the particle size distribution of the sediment flowing into the reservoir?*

Third, the sediment accumulation (m^3) of the 'Nga Moe Yeik' reservoir will be investigated to check the accuracy of the sediment yield predictions. At the moment it is unknown how big the impact of sediment accumulation is on the storage capacity of the reservoir. To execute this investigation the original and current capacity of the reservoir will have to be compared. The research question and sub-questions regarding the sediment accumulation is the following:

What is the impact of the sediment accumulation on the reservoirs storage capacity?

1. *What is the original storage capacity of the reservoir?*
2. *What is the current storage capacity of the reservoir?*

To get insight in the structure of the research and to see how the parameters and systems described at 1.1 'Problem context' align with the research questions and different methodologies, a workflow scheme of the research has been added, see Figure 4. Question 1 is represented in green, question 2 is represented in blue and question 3 is represented in yellow. The outcome of research questions 1 and 2 will be compared to research question 3 to look if the sediment yield prediction does match with the sediment accumulation; this is represented by the red chart.

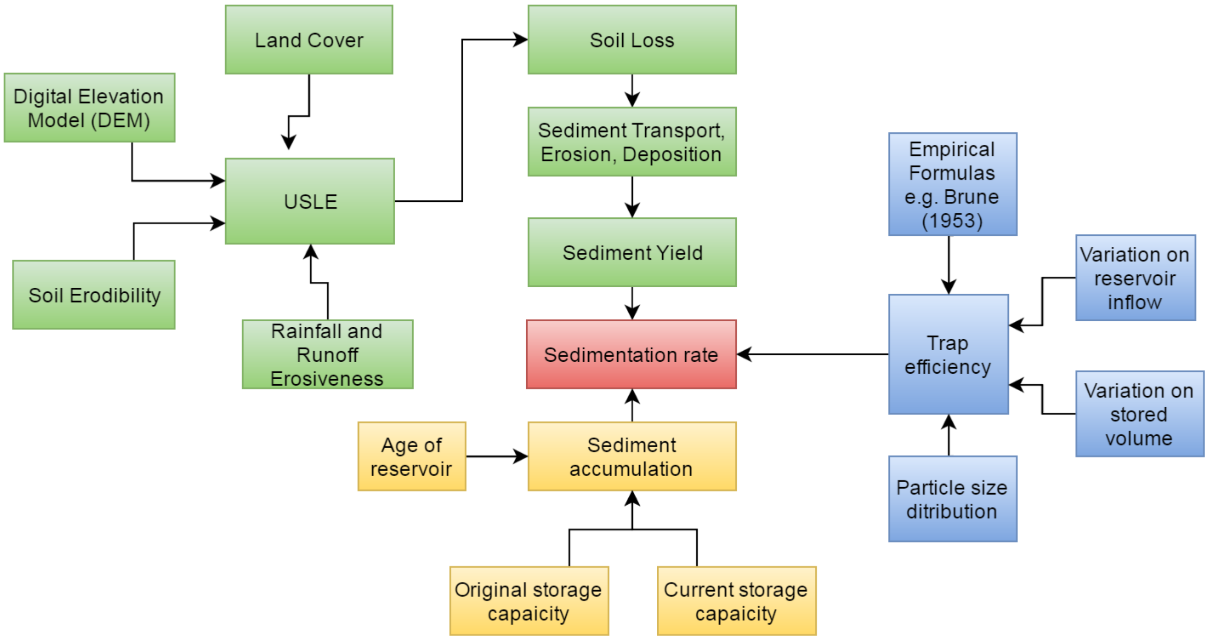

Figure 4: Workflow scheme of the research, green represents 'sediment yield', blue represents 'trap efficiency' and yellow represents 'sediment accumulation'. The red chart represents the convergence of the three methods.

3. Theoretical frame

This chapter will describe and explain the established knowledge within the literature on behalf of the stated research questions. Section 3.1 will explain the erosional processes and sediment yield. And section 3.2 is devoted to trap efficiency predictions for reservoirs.

3.1 Erosional processes

To get insight in the sediment yield of the watershed, it will be useful to examine the processes that lay at the basis of the erosional phenomenon.

3.1.1 Soil loss

One of the first results from a literature search about erosional processes is the Universal Soil Loss Equation (USLE). According to Kinnell, (2010), USLE is the most widely used soil loss estimation model in the world. The basis of the USLE model was found in the 1960s by Smith & Wischmeier (1962). USLE is designed to provide a relatively simple technique for predicting average annual soil loss in specific situations (Renard et al., 1997). The equation had three goals, according to Renard et al. (1997); (1) each factor could be represented by a single number, (2) could be predicted from meteorological, soil, or erosion research data for each location and (3) could be used in every geographically oriented reference. The USLE is quantified by the product of six factors, often given by this equation (Kinnell, 2010):

$$A = RKLSCP \qquad (1)$$

Where,

A	is the average annual soil loss (ton/year)
R	is the rainfall and runoff erosiveness (MJ*mm/(ha*hr))
K	is the soil erodibility (ton*ha*hr/(ha·MJ·mm)
L	is the slope length (m)
S	is the slope steepness
C	is the cover management practice
P	is the conservation practice.

The value of all of those factors can in many cases be determined by different empirical equations. According to Kinnell (2010) many of those equations are based on datasets from the USA and later on have been adopted in other countries. Sometimes local experimental data has been used to adapt the equations to some specific areas.

Investigating the soil loss of a watershed is only one half of the erosional processes. The deposition of eroded soil during runoff is an important factor affecting sediment yield. The difference between sediment yield and erosion is, according to the definition of Renard et al. (1997) the following; ‘In a watershed, sediment yield includes the erosion from slopes, channels, and mass wasting, minus the sediment that is deposited after it is eroded but before it reaches the point of interest’. USLE only takes sheet and rill erosion into account and does not examine erosional processes during runoff and sediment transport (Renard et al., 1997). Besides, USLE does not estimate the sediment sheet and rill deposition. So to make proper predictions about sediment yield at watershed level, sheet and rill deposition between hill slopes and water bodies should also be taken into account (Morgan et al. (1998).

3.1.2 Parameterization of USLE parameters

R-factor

Soil loss is closely related to rainfall by the detaching power of rain droplets striking the surface and by rain running of (Morgan, 2013). The energy impact of rain droplets cause the soil particles to detach (Roose, 1976 and Morgan et al., 1998). The kinetic energy of rainfall depends on the size and velocities of the rain droplets, both are related to the rainfall intensity (Renard & Freimund, 1994). Renard and Freimund state that the R-factor is determined by taking the sum of every individual storm EI-value for a year averaged over a period exceeding 20 years. They also state that EI is a term to abbreviate the rainfall energy multiplied by the maximum intensity during a period of 30 min. So the total energy of a storm depends on the intensity at which rainfall occurs and the amount of precipitation at every intensity.

Unfortunately pluviograph data is not always available. Since, annual, monthly or daily precipitation data are often available for most regions of the world, this problem can be overcome. Various empirical equations have been developed that rely on precipitation data to estimate the R-factor (Lee & Lin, 2014, Mikhailova et al., 1997 and others). Since those empirical equations predict the R-factor only with the input of precipitation data, it is important for this method to use empirical equations that match the climatic conditions and circumstances of the case study as best as possible. Different empirical equations have been developed and applied on tropical conditions; see Table 1 for an overview.

Method	**Location**	**Equation**	**Reference**
Mikhailova et al.	Honduras	$R_{Mi} = -3172 + 7{,}662 * P$ (2)	Mikhailova, E. A., Bryant, R. B., Schwager, S. J., Smith, S. D., (1997)
Yu et al.	Australia	$R_{Yu} = 0{,}0438 * P^{1{,}61}$ (3)	Yu, B., Rosewell, C.J., (1996)
Yin et al.	China	$R_{Yi} = 0{,}5115 * P^{1{,}3163}$ (4)	Yin, S., Xie, Y., Liu, B., Nearing, M. A. (2015)
Morgan	Malaysia	$R_{Mo} = 9{,}28 * P - 8838$ (5)	Morgan, R.P.C. 1994

Table 1: Different equations to estimate the R-factor

Where,

R is the rainfall and runoff erosiveness (MJ*mm/(ha*hr))
P is yearly precipitation (mm)

K-factor

The influence of the soil properties on the soil loss within the USLE is represented by the K-factor (soil erodibility). According to To et al. (1997) the K-factor is defined as the rate of soil loss per rainfall erosion index unit. Erodibility determines the resistance of soil to detachment and transport (Morgan, 2013). Practically speaking the K-factor represents an average annual value of soil reaction to erosion and hydrologic processes. These processes consist of soil detachment and transport by the kinetic energy of rainfall and surface flow, local deposition and rainwater infiltration.

Originally the K-factor was derived from six variables and combined into a K-factor nomograph by Wischmeier and Smith (1978). The six variables are: the silt plus the very fine sand content, the clay content, the organic matter content, an aggregation index, a permeability index, and the rock fragment cover (Auerswald, Fiener, Martin, & Elhaus, 2014). Later Wischmeier and Smith (1978) provided an equation to calculate the K-factor, instead of reading the nomograph to determine it. Because this method requires intensive input data, Williams (1995) developed an alternative method to estimate K-factor values. This method is based on four input variables, namely the sand content, the silt content, the clay content and the organic carbon content. The equations to estimate the K-factor are the following:

$$K = f_{csand} * f_{cl-si} * f_{orgc} * f_{hisand} \tag{6}$$

$$f_{csand} = \left(0{,}2 + 0{,}3 * e^{\left(-0{,}256 * m_{sand}\left(1 - \frac{m_{silt}}{100}\right)\right)}\right) \tag{7}$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_{clay} + m_{silt}}\right)^{0{,}3} \tag{8}$$

$$f_{orgc} = \left(1 - \frac{0{,}25 * orgC}{orgC + e^{(3{,}72 - 2{,}95 * orgC)}}\right) \tag{9}$$

$$f_{hisand} = \left(1 - \frac{0{,}7 * \left(1 - \frac{m_{sand}}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + e^{\left(-5{,}51 + 22{,}9 * \left(1 - \frac{m_{sand}}{100}\right)\right)}}\right) \tag{10}$$

Where,

m_{sand}	is the sand fraction content (%)
m_{silt}	is the silt fraction content (%)
m_{clay}	is the clay fraction content (%)
$orgC$	is the organic carbon content (%)

L-factor and S-factor

The L-factor and S-factor represent the slope length and slope steepness respectively. According to Kouli et al. (2009) these factors reflect the effect of the topography of the catchment area on the erosional processes. Increased slope length and slope steepness contribute to increased runoff velocities and correspondingly higher erosional rates. The L-factor and S-factor can be derived from a digital elevation model (DEM) within geographic information system (GIS) software. The slope length can be calculated by conducting a flow accumulation assessment on the DEM (Bizuwerk et al., 2003). The slope steepness can be calculated by analysing the height differences between adjacent raster cells within the DEM.

C-factor

Vegetation often acts as a protective buffer when rainfall strikes the soil. According to Morgan (2013) the protective properties of vegetation can be divided into two groups, namely the above ground components and the below ground components. Above ground components like leaves and stems do have the ability to partially absorb the kinetic energy from rain droplets and the erosive power of runoff. Below ground components comprising of the root system contribute to the mechanical strength of the soil. The C-factor represents the effect of ground, crop, tree and grass covers on reducing the soil loss (Kouli et al., 2009).

A method to calculate C values for different land cover types has been used by Kouli et al. (2009) and Zaw & Intralawan (2014), but is rather complicated. The method is based on remote sensing of Landsat-ETM imagery and does demand band 3 (0.63–0.69 mm) and band 4 (0.76–0.90 mm).

Within the literature a lot of research has been conducted to estimate the value of the C-factor for different land cover types e.g. Roose (1976), Kuok et al. (2013), Ghosh et al. (2013), Zaw et al. (2014) and You et al. (2013). A summary for four main land cover types from those five references has been given in Table 2. Not for all land cover types the C-factor values show agreement. Therefore, the C-factor has been given in a range if necessary.

Land cover	**C-factor**	**Average C-factor**
Forest	0,001 – 0,02	0,0105
Grass	0,007 – 0,05	0,0285
Bare soil	1	1
Water	0	0

Table 2: given C-factor values for different land cover types

P-factor

The support practice factor (P) is often defined as the ration of soil loss with the use of a specific support practise to the corresponding loss without the use of any support practice (Renard et al., 1997 & Kuok et al., 2013). The support practice factor is capable of reducing erosion by modifying the flow pattern, grade and/or direction of surface runoff and the amount of runoff. The values for the P-factor range from 0 – 1, depending on the employed conservation practice. To assign values for P to different land cover types it is important to make a distinction between agricultural land and other land (Bizuwerk et al., 2003). The agricultural land can be further sub-divided into multiple classes according to the different conservation practices. A table of P-factor values for different conservation practices has been given by (Kuok et al., 2013), see Table 3.

Conservation practice	**P-factor**
None	1
Contouring	0,6
Contour strip-cropping	0,35
Terracing	0,15

Table 3: given P-factor values for different conservation practices

According to Bizuwerk et al. (2003) and Ghosh et al. (2013) the non-agricultural land cover types have a P-factor of 1, because no conservation techniques are being used.

3.3.3 Sediment yield - InVEST model

As section 3.1.1 'Soil loss' discusses, modelling of sheet and rill deposition has to be taken into account to make predictions about sediment yield at a watershed outlet. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is capable of making such predictions, because InVEST does take sheet and rill deposition into account. InVEST has been designed to inform decision-makers about natural resources (Nelson et al. 2011) and comprises of different models. The 'Sediment-retention model' is capable of making sediment yield predictions without the use of complicated and intense input data needs. That makes the model an interesting tool to use in data scarce regions, like Myanmar.

The 'Sediment retention model' comprises of two parts, the USLE model, as described in chapter 3.1.1 'Soil loss', completed by the modelling of sediment deposition along sheets and rills. InVEST is 'spatially-explicit', what means that all the input and output is geographically referenced. Most of the input data have to be configured as raster datasets; this makes it possible to define the resolution on behalf of the needed scale in a certain case study. The model demands the following input:

1. Digital elevation model (DEM) (Raster)
2. Rainfall erosiveness (R) (Raster)
3. Soil erodibility (K) (Raster)
4. Land cover (Raster)
5. Watershed (a shapefile of polygons)
6. Biophysical table (CSV table containing USLE C-factor and P-factor corresponding to each of the land cover classes)

The model uses the DEM to calculate the L-factor and S-factor of USLE, and to derive a hydraulic connectivity model which is used to predict the flow direction of runoff. The InVEST model runs within a standalone application, based on a python script. The input data and output data however, have to be prepared and evaluated within the ArcGIS software.

The 'Sediment retention model' estimates the sediment deposition according to the sediment delivery ratio (SDR). The SDR, is the ratio of soil from the soil loss that will deposit before reaching a gully or stream (The Natural Capital Project, 2015). The total sediment yield is given by the following formula:

$$\sum_i USLE_i * SDR_i \qquad (11)$$

For every raster cell the soil loss is multiplied by the SDR of that cell, to calculate the soil that will be exported to a gully or stream. Summation of all the raster cells yields the total sediment yield at the watershed outlet. The SDR is calculated on basis of the conductivity index by the following formula (Vigiak et al., 2012):

$$SDR_i = \frac{SDR_{max}}{1+e^{\left(\frac{IC_0-IC}{k}\right)}} \qquad (12)$$

Where,

SDR_{max}	is a constant that represents the maximum value of SDR
IC	is the connectivity index
IC_o	is a calibration parameter that defines the shape of the SDR-IC relationship
k	is another calibration parameter that defines the shape of the SDR-IC

According to Borselli et al (2008) the connectivity index is determined by upstream and downstream factors and is calculated by the following formulas:

$$IC = log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \qquad (13)$$

$$D_{up} = \bar{C}\bar{S}\sqrt{A} \qquad (14)$$

$$D_{dn} = \sum_i \frac{d_i}{C_i S_i} \qquad (15)$$

Where,

D_{up}	is the upstream factor
D_{dn}	is the downstream factor
A	is the upstream contributing area
C	is the USLE C-factor
$\bar{C}$	is the average USLE C-factor
S	is the USLE S-factor
$\bar{S}$	is the average USLE S-factor
d_i	is the length of the downstream flow path of the ith cell according to the steepest downslope direction

The upstream contributing area and the downstream flow path are being determined by the D-infinity flow algorithm (Tarboton, 1997). The average values of SDR_{max}, IC_o and k parameters are 0,8; 0,5 and 2 according to (Vigiak et al., 2012). The IC_o and k parameters can be used to calibrate the 'Sediment retention model'.

3.2 Empirical prediction Trap efficiency

Different empirical methods to predict the trap efficiency of reservoirs have been examined by Sloff (1997). These methods have to give a quick approximation of the loss of storage capacity. Three methods are being discussed; the Browns curve (1958), the Churchills curve (1948) and the Brunes curve (1953). According to Issa et al., (2015), each method is based on a different principles. See Table 4.

Method	Principle	Equation	Characteristics
Brown (1958)	Relationship between reservoir storage capacity and catchment area	$TE_{Brown} = 100\left[1 - \left(\frac{1}{1+KCA^{-1}}\right)\right]$ (16)	Big errors can occur, depending of the catchment area (Verstraeten & Poesen, 2000)
Churchill (1948)	Ratio of water retention time to the mean velocity in the reservoir	$TE_{Churchill} = 112 - 800\left(\frac{CI^{-1}}{V}\right)$ (17)	Good at estimating trap efficiency of desilting ponds and partially dry reservoirs (Borland, 1971)
Brune (1953)	Ratio of water inflow to the reservoir stored volume	$TE_{Brune} = 100\left[1 - \left(\frac{1}{1+50CI^{-1}}\right)\right]$ (18)	Widely adopted, easy to use and requires little data (Issa et al., 2015)

Table 4: A comparison between the Brown, Churchill and Brune methods

Where,

TE is the trap efficiency (%)
C is the reservoirs capacity (m^3)
A is the catchment area upstream of the dam (m^2)
I is the reservoirs inflow (m^3/s)
V is the mean annual velocity of the inflow (m/s)
K is a factor that depends on retention time and particle size of sediment

The Brown and Brune curves as presented in Table 4 are described by Issa et al. (2015). The Churchill curve as presented here is described by Lewis et al. (2013).

The Brown curve may produce big errors in the trap efficiency due to hydrological properties of the catchment area that are not incorporated into the equation. The Churchill curve is especially good at estimating the trap efficiency of desilting ponds and partially dry reservoirs (Borland, 1971). The Brune curve is the most interesting method according to Sloff (1997) and Issa et al. (2015), because the Brune curve is widely adopted, easy to apply and it requires a small amount of data. Is has been derived from records of 44 normally ponded reservoirs in the USA and it has widely been used for other parts of the world according to (Kummu & Varis, 2007).

In the survey of Issa et al. (2015), five different empirical methods based on the hydraulic residence time principle (the principle used within the Brune curve) are reviewed to determine the monthly and annual trap efficiency of the Mosul dam reservoir. All those five methods are ultimately based on the Brune's curve, see Table 5. Dendy suggested an algebraic equation by adding more data of 17 small reservoirs. Gill derived three equations for fine, medium and coarse sediment. Ward changed the Brune's curve based on data of very large reservoirs. Heinemann made changes depending on 20 ponded reservoirs in the USA. And at last Jothiprakash and Garg did develop two empirical formulas to make estimations about the trap efficiency for medium and coarse sediments.

Method	**Equation**	
Dendy	$TE_{Dendy} = 100\left[0.97^{0.19^{\log(CI^{-1})}}\right]$	(19)
Gill, fine	$TE_{Gill} = \frac{(C/I)^3}{\left[1.02655(C/I)^3+0.02621(C/I)^2-133\left(\frac{C}{I}\right)+0.1*10^{-5}\right]}$	(20)
Gill, medium	$TE_{Gill} = \frac{(C/I)}{\left[0.012+1.02\left(\frac{C}{I}\right)\right]}$	(21)
Gill, coarse	$TE_{Gill} = \frac{(C/I)^2}{[0.994701(C/I)^2+0.006297(C/I)+0.3*10^{-5}]}$	(22)
Ward	$TE_{Ward} = 100\left[1-\frac{0.05}{\sqrt{C/I}}\right]$	(23)
Heinemann	$TE_{Heinemann} = \left[-22+\frac{119.6\left(\frac{C}{I}\right)}{0.012+1.02\left(\frac{C}{I}\right)}\right]$	(24)
Jothiprakash & Garg, medium	$TE_{J\&G} = \left[\frac{\left(\frac{C}{I}\right)}{0.00013+0.01\left(\frac{C}{I}\right)+0.0000166*\sqrt{C/I}}\right]$	(25)
Jothiprakash & Garg, coarse	$TE_{J\&G} = \frac{8000-36\left(\frac{C}{I}\right)^{-0.78}}{\left[78.85+\left(\frac{C}{I}\right)^{-0.78}\right]}$	(26)

Table 5: Formulas from Dendy, Gill, Ward, Heinemann and Jothiprakash & Garg

Where,

C	is the reservoirs capacity (m^3)
I	is the reservoirs inflow (m^3/s)

At first hand it is hard to determine which of the methods described above will fit the real trap efficiency of the researched reservoir best. Furthermore, the different methods are based on data from different reservoirs and thus the outcomes of them have to be interpreted in respect to the kind of reservoirs they are based on. The outcome of the study about the Mosul dam reservoir performed by Issa et al. (2015) shows that the results of all methods have good agreements with bathymetric surveys. The trap efficiencies predicted on a monthly bases all showed errors between 1,7 and 3,2%.

4. Data and methodological approach

This chapter will address all the data and methodologies that have been used to perform the research.

4.1 Data

All the input data that was used within the methodology is listed here, along with their metadata, see Table 6.

Data set	Period	Resolution/scale	Source	Type
Technical data	1995	-	ITC	E
Landsat-7 images	2016	30 m	USGS	E
Digital Elevation Model	2012	30 m	NASA	E
Precipitation	2006 - 2014	Daily	ITC	E
Reservoir inflow	2006 - 2014	Daily	ITC	E
Reservoir stored volume	2006 - 2014	Daily	ITC	E
Map of Yango – Bago region	2004	4 m	ITC	E
‘Nga Moe Yeik’ bed elevation map	1995	1 inch = 1000 ft.	ITC	E
Watershed boundary	2012	30 m	Digital Elevation Model	G
Land cover	2016	30 m	Landsat images	G
‘Nga Moe Yeik’ bed elevation measurements	6/7-5-2016	8774 measurements	Bathymetric Survey	C
Sediment samples ‘Nga Moe Yeik’	6/7-5-2016	17 samples	Bathymetric Survey	C
Soil samples ‘Nga Moe Yeik’ catchment	26-5-2016	4 samples	Field Survey	C

Table 6: Datasets used within ‘Nga Moe Yeik’ case study; existent (E), generated (G) and collected (C)

4.2 Methodological approach

This section does explain the different methods that have been applied and steps that have been taken to produce the results. The methodology has been split into three separate sub-sections. ‘Sediment yield’, ‘Trap efficiency’ and ‘Sediment accumulation’.

4.2.1 Research question 1 – ‘Sediment yield’

This methodology section will consist of four parts conform the main research question and the three sub-questions.

4.2.1.1 Catchment area

Within ArcGIS there is a method available to calculate the area draining into a spatial explicit location. This method was used to calculate the total area draining into the ‘Nga Moe Yeik’ reservoir and the two supplementary reservoirs ‘Paung Lin’ and ‘Ma Hu Yar’. This method does involve multiple ArcGIS tools. The result of this procedure will be visually and numerically compared to the catchment area that is already available within the map of the Yangon – Bago region. To calculate the catchment area, only a digital elevation model (DEM) of the region is needed as input data, see Figure 5 for the different steps that were performed. The output of each step was used as the input for the next step. The outputs of all the separate steps can be seen in Appendix B.

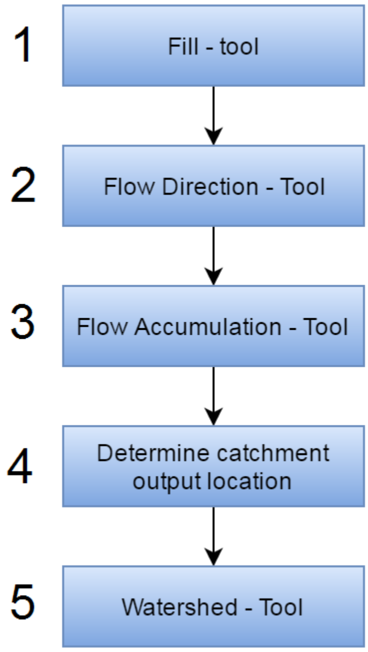

Figure 5: steps to delineate ‘Nga Moe Yeik’ catchment area

(1) At first the DEM dataset had to be hydrologically corrected. All DEM’s contain errors and sinks, because they are the results of measurements and interpolation techniques. Sometimes this cause sinks in the DEM, while there are no sinks. To correct those errors and fill the sinks, the *Fill* – tool is used.

(2) The second step was to calculate the flow direction of each raster cell of the DEM. This was done using the *Flow Direction* – tool. The output of this tool simulates the direction that water will flow according to hydrologic characteristics.

(3) The third step was to calculate the flow accumulation, using the *Flow Accumulation* – tool. This tool calculates for every raster cell of the DEM, the number of raster cells that drain into it.

(4) The fourth step was to determine the spatial output locations of the catchment and sub-catchment areas. The output of the *Flow Accumulation* – tool was used to make this assessment.

(5) The fifth and last step was to use the *Watershed* – tool to actually calculate the total area that is draining into the output locations of the catchment and sub-catchment areas. Two input datasets were needed for this step: the flow direction raster and the determined output points of the catchment and sub-catchment areas.

4.2.1.2 Characteristics - catchment area

This section focuses on the rainfall and precipitation data, soil properties and the land cover classification of the catchment area that was collected during the study. Besides, this section will also cover the parameterisation of those characteristics into suitable InVEST input data.

Rainfall

Unfortunately there is not much rainfall or precipitation data available about the ‘Nga Moe Yeik’ catchment area. There is one rain gauge located at the dam site of the ‘Nga moe Yeik’ reservoir. Although spatial differences and variations of rainfall occur within the catchment area, the assumption has been made that the precipitation data from this rain gauge represent the whole catchment area. Daily precipitation data is available for the 2006 – 2014 period, see Table 7 for the yearly precipitation data. The assumption has been made that the average precipitation over this period represents the total temporal frame of 1995 – 2016.

Year	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Precipitation (mm)	2650	2719	2667	2176	2158	2563	4747	2566	2400

Table 7: yearly precipitation data between 2006 – 2014 for the 'Nga Moe Yeik' catchment

To make estimations for the R-factor, the equations from Table 1 have been used. The calculations were made for each year in the 2006 – 2014 period. Afterwards, the R-factor for each year has been averaged to come to an average yearly R-factor.

Soil properties

There is no data available about soil properties for the 'Nga Moe Yeik' catchment area. Therefore some soil samples were taken during a field survey performed at 26-05-2016, see Appendix D for further details. Four soil samples were taken at different locations and have been tested in the soil lab of the ITC, Bago, to determine the grain size distribution and make a soil type classification, see appendix C. Equations (6), (7), (8), (9) and (10) from section 3.1.2 'Parameterization of USLE parameters' were used to calculate the K-factor. The following input parameters are demanded for this method:

m_{sand} is the sand fraction content (%)
m_{silt} is the silt fraction content (%)
m_{clay} is the clay fraction content (%)
$orgC$ is the organic carbon content (%)

The sand, silt and clay fractions can be derived from the soil type classification; unfortunately it was not possible to examine the organic carbon content from the soil samples, because the proper equipment to perform such a test was not available at the ITC. Therefore organic carbon content values from the literature were used, and their sensitivity on the K-factor has been assessed. According to Wawer et al. (2005) the $orgC$values of their soil samples varied between 0,23 and 1,33%, with an average of 0,86%. Manyiwa & Dikinya, (2013) reported $orgC$values between 0,29 and 0,86%, with an average of 0,56%. The $orgC$values from Wawer et al. (2005) yield a K-factor between 0.1641 and 0.1616. Only a change of 1,5%, so the impact of the $orgC$value on the K-factor output is minor. The assumption was made that the $orgC$values of the four soil samples is equal to 0,86%, resulting in a K-factor of 0.1633.

Land cover

To classify the different types of land cover of the 'Nga Moe Yeik' catchment area, a remote sensing classification has been performed. This classification was based on a Landsat-7 image from 03-05-2016. The used classification method is a supervised image classification. This method does consist of three steps (GISgeography, 2016), see Figure 6.

(1) First, sample locations were selected for each land cover type within the Landsat image that was used for the classification. Four land cover types have been chosen, namely forest, grass, bare land and water. The sample locations have been visited during a field survey to determine their exact land cover. The sample locations were located along roadsides as much as possible. This guarantees a proper accessibility and therefore an efficient field

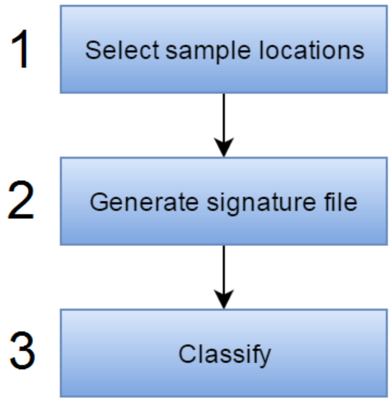

Figure 6: steps to classify land cover

survey. In total, nine sample locations were selected, see appendix D for more details. At 26-05-2016 a field survey was conducted to check the land cover types of the selected sample locations.

(2) Subsequently, a signature file has been created. The purpose of this signature file is to use the data from the sample locations to define for every land cover class a range of pixel values. In this way, the classification algorithm knows which land cover type to assign to which pixel value. The signature file has been created using the *Create-Signature-File* tool in ArcGIS.

(3) The ultimate classification has been performed using the *Maximum-Likelihood-Classification* tool in ArcGIS.

4.2.1.3 Specific gravity – reservoir sediment

Figure 7: Spatial distribution of taken sediment samples

It was necessary to quantify the specific gravity of the sediment, to make the translation from the sediment's weight to the volume. In that way, the sediment yield output from the InVEST model could be compared to the results from the capacity loss analysis. To make the specific gravity analysis, sediment samples from different parts of the reservoir have been taken. During the Bathymetric survey (06-05-2016 until 07-05-2016) a total of 17 sediment samples were taken using a grabber. To make a proper representation of the sediment in the reservoir, the samples have been taken from three locations; the left upper arm of the reservoir, the right upper arm of the reservoir and near the dam. See Figure 7 for the spatial distribution of the taken sediment samples.

The specific gravity of the samples has been tested in the soil laboratory of the ITC, Bago, according to the method from The University of Toledo (1984), see appendix C.

4.2.1.4 Sediment yield – catchment area

The average annual sediment yield of the 'Nga Moe Yeik' catchment area has been estimated using the InVEST model. The InVEST model produces numerical output, namely soil loss and sediment export and raster output, namely soil loss, sediment export and sediment retention index. The following data inputs were used to make the first assessment.

1. Digital elevation model (DEM) (see 3.1 data)
2. Rainfall erosiveness (R) = 16738 (average of the four calculated values, see 4.1.2)
3. Soil erodibility (K) = 0,1633 (see 4.1.2)
4. Land cover (see 4.1.2 for the land cover map)
5. Watershed (see 4.1.1 for the catchment area)
6. Biophysical table (see table 2)

First, two runs with the model have been made, one with the minimal C-factor values (Min sediment yield) and one with the maximum C-factor values (Max sediment yield).

Secondly a sensitivity analysis of some of the InVEST parameters has been performed, to see which input parameters have the greatest impact on the sediment yield output. This analysis was performed for the R, K and C parameters, because the determination of those parameters was most difficult. Seven runs were performed, one with the values as stated above using average C-factor values. Three runs with a 10% decrease in each of the input parameters and three runs with a 10% increase.

4.2.2 Research question 2 – 'Trap Efficiency'

This methodology section will consist of two parts conform the two sub-questions.

4.2.2.1 Variation of stored volume and reservoir inflow

Since the empirical formulas that are chosen to predict the trap efficiency, are all based on the hydraulic residence time principle, hence the variation in stored volume and reservoir inflow are the two input variables. See the 'Theoretical Frame' for the theory about the hydraulic residence time principle. Time series of daily inflow and stored volume are available for 'Nga Moe Yeik' from 2006 – 2014 to assess the variation in these variables. The data was plotted on a monthly scale; for that, the daily inflow data was summed over the month and the daily stored volume data was averaged per month. The stored volume and reservoir inflow data were used as input variables for the different empirical trap efficiency equations as stated in the 'Theoretical Frame'.

4.2.2.2 Particle size distribution - sediment

To determine which empirical trap efficiency formula will yield the best predictions; information about particle size distribution from sediment inflow is needed. This particle size distribution can be approximated by analysing sediment from the reservoirs bed. To make this analysis, the sediment samples from the 6/7-05-2016 bathymetric survey were used.

Those samples have been tested in the soil laboratory of the ITC, to analyse the different grain size fractions, see appendix F for further explanation.

4.2.3 Research question 3 – 'Sediment accumulation'

This methodology section will consist out of two parts conform the two sub-questions.

4.2.3.1 Original storage capacity

A design drawing of the 'Nga Moe Yeik' reservoir is available to make a digital elevation model (DEM). This is a terrain height map of the bed of the reservoir as it was present in 1995, see Figure 9. This map was transferred into a DEM using the ArcGIS application, in that way it was possible to calculate volumes and surface areas of the original reservoir. Those outcomes have been compared to technical data from 1995 that is available for the 'Nga Moe Yeik' reservoir, see Appendix A. To answer the first research question all the steps within the flowchart were executed, see Figure 8.

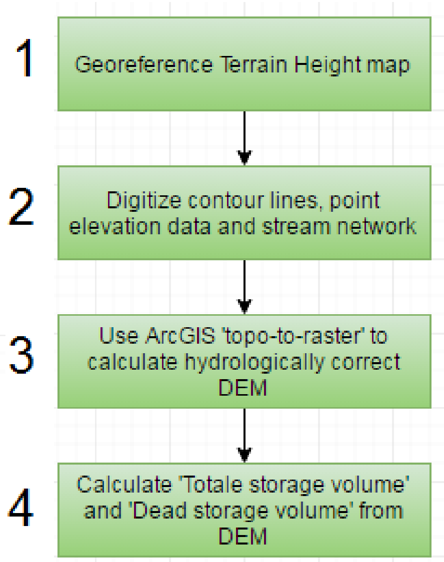

Figure 8: Steps to model Map into DEM

(1) At first the map was geographically referenced to construct a realistic reproduction of the 1995 reservoir bed. Unfortunately the metadata of the map were lost. There is no knowledge about the projection method and coordinate system used for the production of the map. The only option to make a geographically reference, is to manually reference it to a map that has been properly geographically referenced. This has been performed using the Yangon – Bago map, based on a WGS 84 UTM 47N reference system. Using 12 visual recognizable locations it was possible to reference the map in an acceptable way, see appendix E for the 12 georeference locations.

(2) The second step was to translate the information of the map into a digital environment, using ArcGIS. The original map in A0 format was at my disposal to make a more precise translation to the digital format. The map consists of elevation contours between 65 and 125 ft, with intervals of 5 ft. Besides the contour lines, the map also contains point elevation data and stream data. Point elevation data is single height data of multiple locations scattered across the whole bed of the 'Nga Moe Yeik' reservoir. In case of the 'Nga Moe Yeik' reservoir, stream data is information about historic stream and river lines. All of the digitized data will serve as input for the third step, see Figure 10.

Figure 9: terrain height map of the bed of the 'Nga Moe Yeik' reservoir

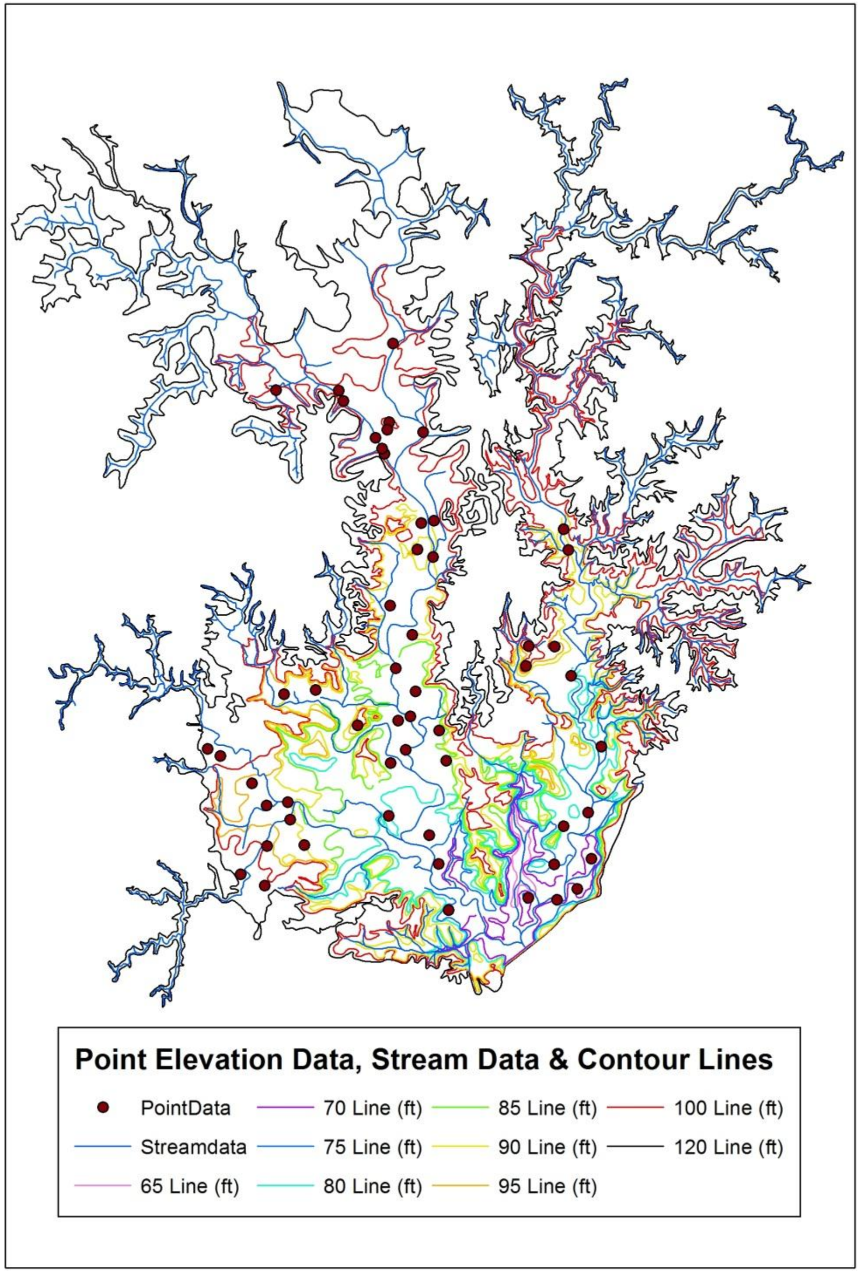

Figure 10: Digitized Point Elevation Data, Stream Data & Contour Lines

(3) The third step was to use all of the map data as input in the *'Topo to Raster'* – tool in ArcGIS. This tool uses an interpolation technique to calculate the height for every raster cell and produce this elevation data to build a DEM. The tool can handle multiple data formats; point elevation, contour lines and stream lines. Stream lines are a powerful way of adding topographic information to the interpolation, further ensuring the quality of the output DEM (ESRI, 2012). The interpolation technique is based on the ANUDEM[1] program developed by Hutchinson (2008). This program is specifically developed for interpolating hydrologically correct surfaces.

(4) The fourth and last step was to calculate the total storage capacity (TSC) and the dead storage capacity (DSC) of the DEM, see figure 11. These volumes have been calculated according to two different water levels:

- Level of TSC (32,6 meter) (107 ft)
- Level of DSC (24,7 meter) (81 ft)

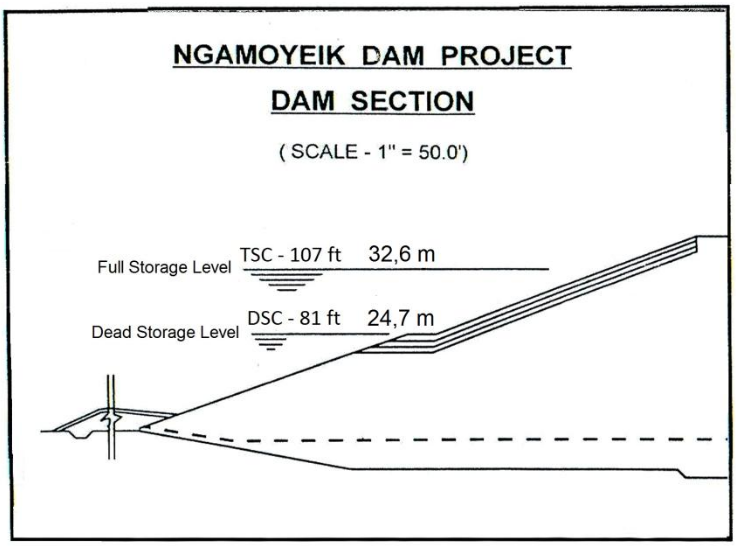

Figure 11 Cross section of the 'Nga Moe Yeik' dam

The volume and surface area have been calculated using the *'Surface Volume'* – tool. This tool can perform an assessment of the volume and surface area of a DEM above or below a given reference plain. When the TSC and the DSC are known, the useful storage capacity (USC) can be calculated using the following formula:

$$USC = TSC - DSC \tag{27}$$

It is important to make a distinction between those different capacities to fully understand the impact of sedimentation on the storage capability of the reservoir

4.2.3.2 Current storage capacity

To produce a DEM of the current reservoir bed, multiple steps had to be taken, see Figure 12.

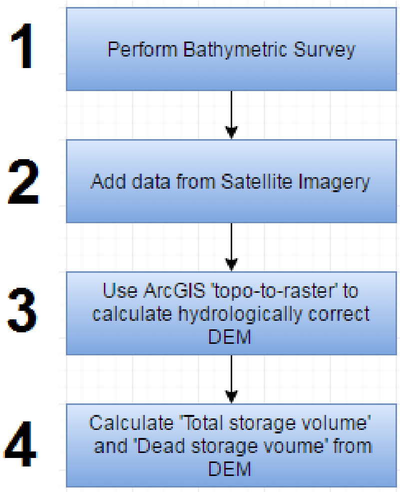

Figure 12: Steps to model current reservoir bed into DEM

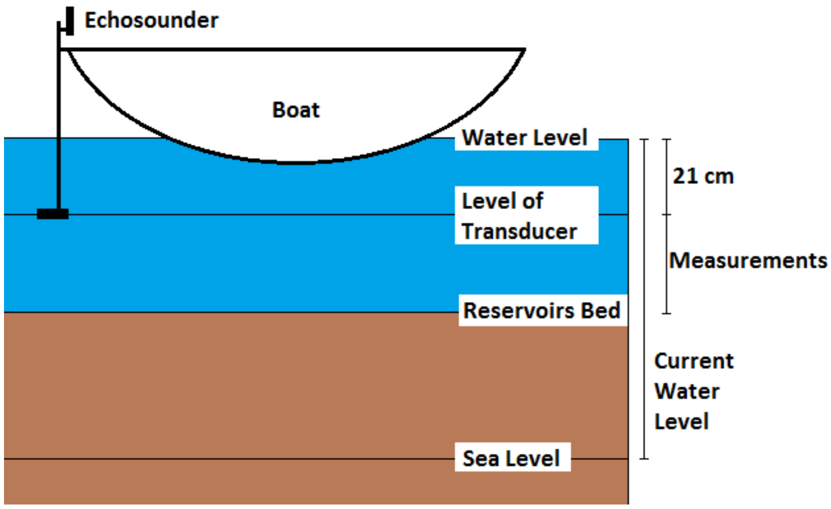

Figure 13: Test alignment of Bathymetric Survey

[1] http://fennerschool.anu.edu.au/research/products/anudem-vrsn-53

To prepare for the bathymetric survey, an observation trip to the 'Nga Moe Yeik' reservoir and catchment area was performed on 04-05-2016. During this trip a questionnaire to some people working and living there was performed to get some more insight from their perception about the sedimentation rates in the reservoir, see Appendix G. The bathymetric survey was performed from 06-05-2016 until 07-05-2016 with a single point echo-sounder. This device consists of 2 main parts; the echo sounder itself with a GPS-module and the transducer. The GPS-module tracks the coordinates of all the measured points and the transducer measures the water depth. The bathymetric survey has been executed according to the following test alignment; see Figure 13. The distance between the transducer and the water level has been measured and resulted to be 21 cm. The distance between the level of the transducer and the reservoir bed was measured with the transducer. Also the 'current water level' during the survey was known. With this data the elevation in meters of the reservoir bed could easily be calculated for all the measurements with the following formula:

$$Elevation = Current\ Water\ Level - Measurement - 0{,}21 \quad (28)$$

Unfortunately it was not possible to mount the echo sounder to the back of the boat. Because of this reason, the measurements of the echo sounder were more prone to errors caused by waves. The bathymetric survey was conducted in calm water, to avoid vast errors in the depth measurements.

In total, 10711 depth measurements have been taken. Not all of the output of the echo sounder was correct and usable for making the DEM. Some measurements resulted in a depth of 0 meter; see Appendix F for the correct and faulty measurements. After removing incorrect data, 8774 depth measurements remained. The faulty measurements could be caused by multiple reasons:

- Turbid water
- Water plants sticking to the transducer
- An air bubble forming around the transducer (this could be due to a too high boat speed)
- Some places were too shallow (below 0,4 meter the transducer cannot perform measurements)

Furthermore, sometimes the echo sounder did not perform measurements at all. This could be caused by one of the following reasons:

- The power supply failed to deliver power to the echo sounder
- The echo sounder is prone to intense sunlight, causing it to overheat

Because the bathymetric survey was performed during the end of the hot-dry season, the current water level of the reservoir was very low. According to the measuring station at 'Nga Moe Yeik', the water level was 26,97 meters, which is approximately 2 meters below the reference level (24,7). This resulted in a situation where a lot of areas of the reservoir were not navigable. Besides, when the reservoir was constructed, the trees were not removed. This resulted in areas that are not navigable, because there are a lot of trees reaching out of the water.

Because of those reasons, the bed elevation was only acquired for the deeper parts of the reservoir. To come to an acceptable result for the 2016 DEM of the reservoir bed, data of the shallow parts of the reservoir have been added. Therefore Landsat imagery has been used to extract contour lines of shallow parts of the reservoir. Images from the Landsat 7 Satellite – which was launched in 1999 – were used. These images were used to determine the water surface area on various moments in time. During the bathymetric survey the water level was 26,97 meter and the full storage level is 32,6 meter. Three Landsat-7 images have been used to determine the water surface at different dates.

The water levels of those specific dates are known. The three images are spread between 26,97 and 29,75 meter. Unfortunately Landsat images of the 'Nga Moe Yeik' reservoir are not taken daily and images with clouds are sometimes not usable. See Table 8 for the date of the used Landsat images and their corresponding water level.

Date	Water level (meters above sea level)
03-05-2016	26,97
01-04-2016	28,04
29-02-2016	29,75

Table 8: Used Landsat-7 images

The Landsat images were used to determine the shoreline of the reservoir at the different dates. The coordinates system of the images is WGS 84 UTM 47N, the same system has been used for the bathymetric survey. The '*Maximum Likelihood Classification'* – tool within ArcGIS was used to classify the colours into two classes of interest; 'water' and 'other'. This is being done by creating different groups of colours of the same land cover, so the '*Maximum Likelihood Classification'* – tool knows which colours to assign to which classification. The '*Raster to Polygon'* – tool can be used to create polygons out of the raster image. After deleting the incorrect polygons, the polygons can be converted into polylines with the use of the '*Polygon to Line'* – tool. See Figure 14 for the results. The polylines can be used as contour input for the '*Topo to Raster'* – tool.

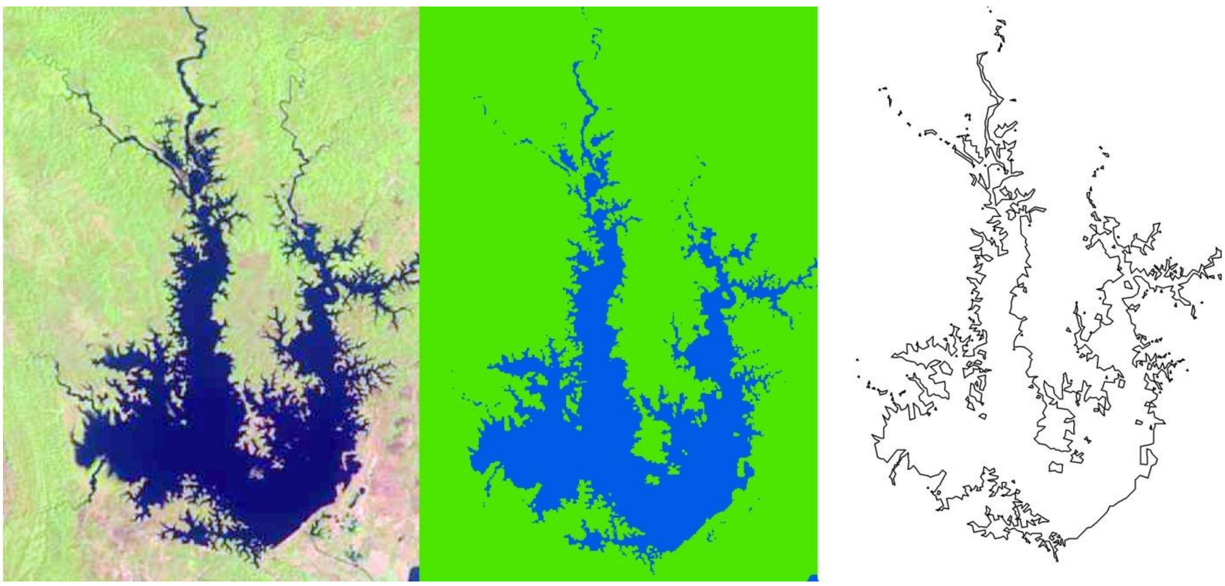

Figure 14: Left, Landsat 7 image from 29-02-2016, middle, output raster from 'Maximum Likelihood Classification' – tool, right, Polylines of water surface

The third and fourth steps are identical in comparison with methodology section 1 'Original storage capacity' and will therefore not be further explained.

5. Results

This chapter will present all the results from the applied methodologies and does consist of three subsections. First a section concerns the sediment yield, second a section concerning trap efficiency and the third section concerning the sediment accumulation.

5.1 Sediment Yield

As described in the section 2. 'Research design' , this section will consist of four parts, the catchment area, the R, K and C factor of USLE, the specific gravity of the sediment and the sediment yield.

5.1.1 Catchment area

The result of the calculated catchment areas of the 'Nga moe Yeik' reservoir and the two supplementary reservoirs 'Paung Lin' and 'Ma Hu Yar' are shown in Figure 15. The 'Nga Moe Yeik' catchment area was compared to the catchment area from the Yangon –Bago region map to show their agreement. See Table 9, for the numerical comparison. It was not possible to compare the catchment areas of the 'Paung Lin' and 'Ma Hu Yar' reservoirs, because their borders were not present in the Yangon – Bago map. I represent the 'Paung Lin' catchment area, II represent the 'Ma Hu Yar' catchment area and I+II+III represents the 'Nga Moe Yeik' catchment area.

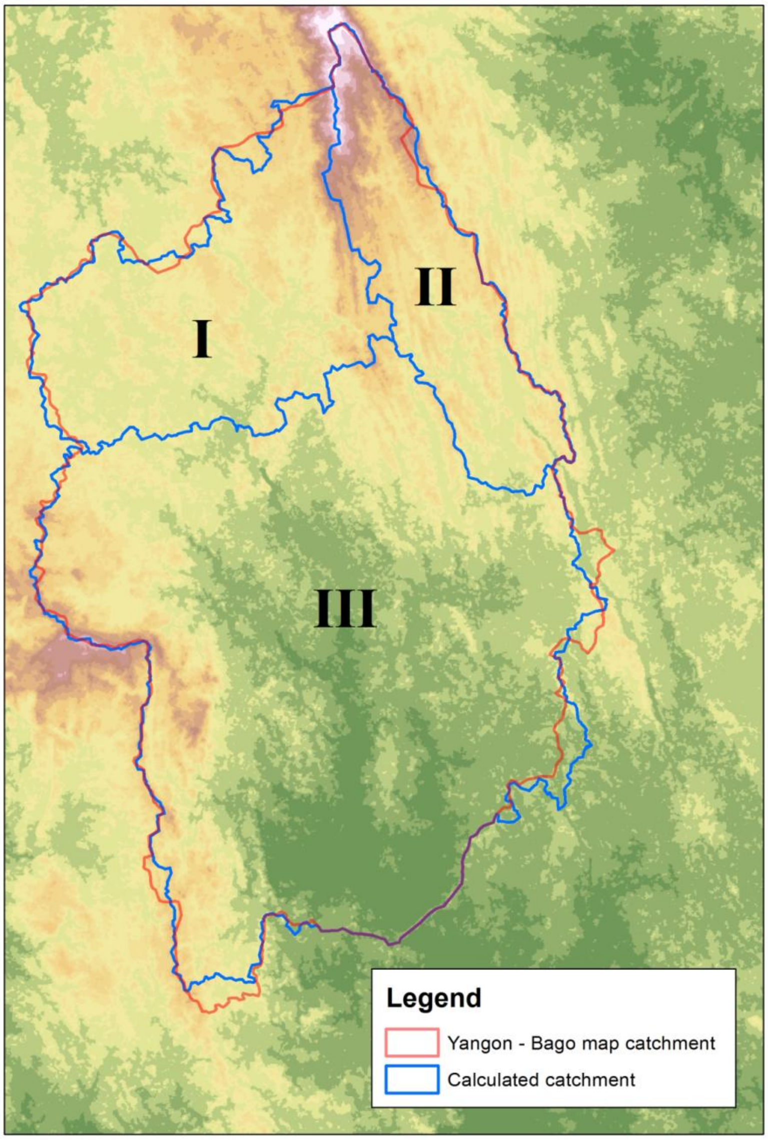

Figure 15: 'Nga Moe Yeik', 'Paung Lin' and 'Ma Hu Yar' catchment area boundaries

Catchment	Calculated Area (km^2)	Area from Yangon – Bago map (km^2)
I + II + II	413	415
I	87	-
II	53	-
III	274	-

Table 9: Areas of 'Nga Moe Yeik' catchment area – numerical comparison

Both visually and numerically, the calculated catchment area does show very good agreement with the catchment area from the Yangon – Bago region map. The difference between them is only:

$$\frac{415-413}{415} * 100 = 0{,}48\ \% \qquad (29)$$

This difference is minor and therefore it will be neglected. Because the DEM was used during the methodology as input for the InVEST model, the calculated catchment area was also used, see section 4.1.4 of the methodology. The catchment area from the Yangon-Bago region map may cause errors when used within InVEST.

5.1.2 Characteristics catchment area

R-factor

The results for the calculated R-factor are the following according to the different empirical formulas used:

$R_{Mi} = 17535\ (\mathrm{MJ} * \mathrm{mm}/(\mathrm{ha} * \mathrm{hr}))$

$R_{Yu} = 15490\ (\mathrm{MJ} * \mathrm{mm}/(\mathrm{ha} * \mathrm{hr}))$

$R_{Yi} = 17355\ (\mathrm{MJ} * \mathrm{mm}/(\mathrm{ha} * \mathrm{hr}))$

$R_{Mo} = 16573\ (\mathrm{MJ} * \mathrm{mm}/(\mathrm{ha} * \mathrm{hr}))$

The results for the different empirical formulas are numerically close and show good agreement with each other. For comparison, calculated R-factor values from different studies within the literature are given in Table 10.

	Zaw et al. (2014)	Calvo-Alvarado et al. (2014)	Bizuwerk et al. (2003)	This case study
Study area	Myanmar	Costa Rica	Ethiopia	Myanmar
Annual precipitation rates (mm)	-	2725 - 3537	136 - 1372	2158 - 4747
R-factor result	3603 - 12077	2384 - 16163	117 - 1187	15490 - 17535

Table 10: Comparison of R-factor results

Zaw et al. (2014) made R-factor calculations for the 'Inle Lake' area within Myanmar, their results ranged between 3603 and 12077 (MJ*mm/(ha*hr)). Calvo-Alvarado et al. (2014) performed an analysis of the R-factor for a case study in Costa Rica, based on yearly precipitation rates between 2725 and 3537 mm. They obtained results between 2384 and 16163 (MJ*mm/(ha*hr)). Bizuwerk et al. (2003) calculated values for the R-factor for a case study in Ethiopia between 117 and 1187

(MJ*mm/(ha*hr)), based on yearly precipitation rates between 136 and 1372 mm. Despite the relative high precipitation values in Ethiopia, the resulting R-factor is low compared to the case studies in Myanmar and Costa Rica. This is probably due to the difference in climatic conditions, because rainfall intensities can have a vast impact on the R-factor.

The results from those studies show that the variation between different climatic conditions can be major. They also show that precipitation differences within the study area can cause great variations in the R-factor values. The resulting R-factors as shown above will be used as input for the InVEST model.

K-factor

The resulting K-factor value is 0.1633. Compared to results within the literature, this is a moderate result. A study conducted by Wawer et al., (2005) on Polish soils with comparable grain size distribution, resulted in K-factor values between 0,071 and 0,249. Manyiwa & Dikinya (2013) calculated values for the K-factor between 0.099 and 0.13 for soils in Botswana. Their values are significantly lower than the values from Wawer et al., (2005) or the value found within this study. That is probably due to the fact of the very low silt contents (between 4 and 9%) within the Botswana study. According to Morgan (2013) coarse soils like sands are resistant to detachment, because of the weight of the larger particles and fine soils like clays are resistant, because the particles bear adhesive and chemical bonding forces. This results in a high erodibility for soils containing big silt contents (above 40%). So a low silt fraction will result in a low K-factor. The silt fractions from the four samples used within this study are between 13 and 46%.

C-factor & P-factor

The remote sensing classification method resulted in the following land cover classification, see Figure 16 and Table 11.

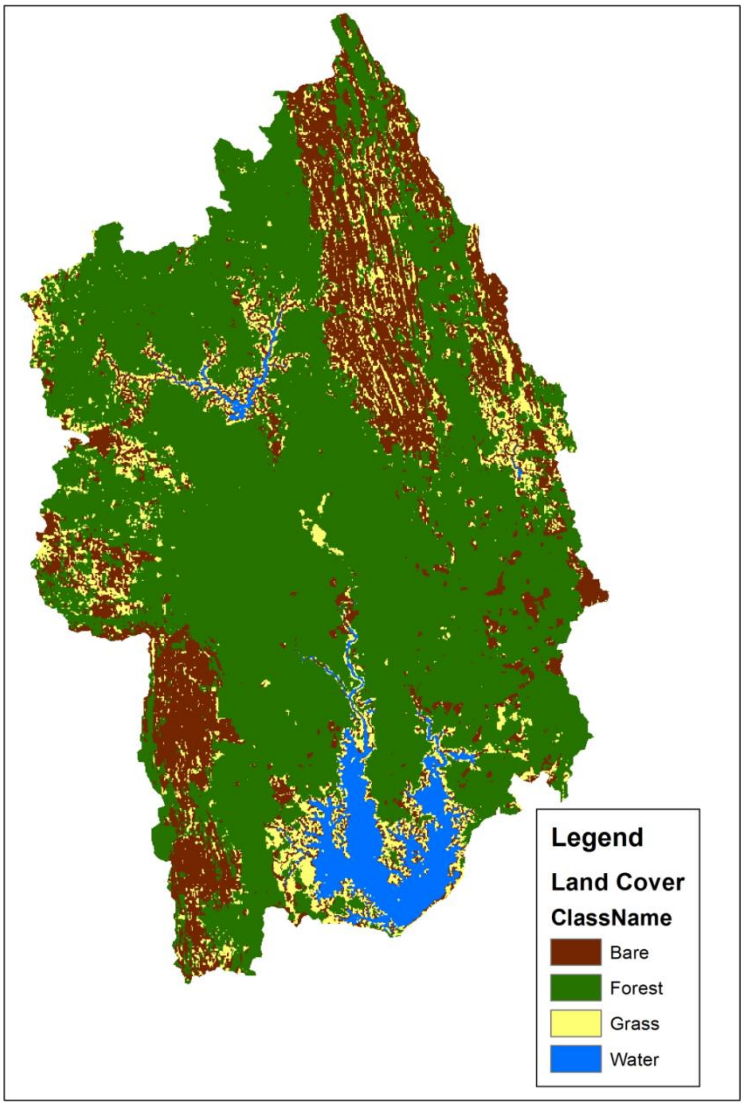

Figure 16: land cover classification for the 'Nga Moe Yeik' catchment area

The classified land cover types will be assigned to C-factor values and P-factor values according to the values given in section 3.1.2 'Parameterization of USLE parameters'.

Land cover type	Area (km^2)	Area (%)
bare	83,6	20.2
forest	273,5	66.2
grass	37,9	9.2
water	18,1	4.4

Table 11: area's of land cover types

5.1.3 Specific gravity – reservoir deposits

The average specific gravity of the sediment samples taken on the bathymetric survey of 6/7-05-2016 is 2,68 according to the 17 samples, see Appendix F for more detailed results.

5.1.4 Sediment yield – catchment area

The annual sediment yield according to the varying C-factor values has been given in Table 12. To make a proper estimation about the total sediment yield during the 21 year lifetime of 'Nga Moe Yeik', it is better to split the catchment area into the three sub-watersheds as pictured in Figure15.

Watershed	Area	Min (ton)	Max (ton)	Min (ton/km^2)	Max (ton/km^2)
I	88	$2,3 * 10^6$	$3,3 * 10^6$	$26,1 *10^3$	$37,5 *10^3$
II	52	$2,2 * 10^6$	$3,3 * 10^6$	$42,3 *10^3$	$37,5 *10^3$
III	275	$4,0 * 10^6$	$5,7 * 10^6$	$14,5 *10^3$	$20,7 *10^3$
Total	415	$8,4 * 10^6$	$12,3 * 10^6$	$20,2 *10^3$	$29,6 *10^3$

Table 12: annual sediment yield

As explained in section 1.2 'Research context', the construction of the 'Nga Moe Yeik' dam finished in 1995 and the construction of the 'Paung Lin' and 'Ma Hu Yar' dams finished in 2003. So the sediment yield of the 'Nga Moe Yeik' catchment area can be split in two timeframes; one before construction of the two supplementary dams finished and one after. The first period did last 8 year and the second does last 13 years until now. If the assumption is made that during the second period the entire sediment yield of the 'Paung Lin' and 'Ma Hu Yar' watersheds does deposit into their respective reservoirs, the total sediment yield during the two periods (lasting 21 years) can be calculated:

$$SY_{total} = t_1 * SY_1 + t_2 * SY_2 \qquad (30)$$

Where,

SY_{total}	is the total sediment yield from the 'Nga Moe Yeik' catchment area during 21 years
t_1	is the first timeframe
t_2	is the second timeframe
SY_1	is the annual sediment yield from watersheds I + II + III
SY_2	is the annual sediment yield from watershed III

The total sediment yield during the 21 years lies between $119,2 *10^6$ and $172,5*10^6$ ton. Using the average specific gravity that yields a sediment yield between $44,5 *10^6$ m^3 and $64,4 *10^6$ m^3.

The results of the sensitivity analysis were plotted in Figure 17. It is remarkable to see that the sensitivity of the R, K and C parameters are very close and R and K are identical. A change of 10% in the R and K value, also yield a change in sediment yield of 10%. This can be explained by the linear character of the USLE. USLE is constructed by six parameters that calculate the soil loss by multiplying all those six parameters. So, obviously a 10% change in one of the parameters will lead to a change in soil loss of 10%. The different sensitivity in the C-factor can be explained by looking at the theory about the sediment delivery ratio (SDR) (see section 3.3.3 'Sediment yield - InVEST model'). An increase in the C-factor value does not only yield more soil loss, but at the same time also yields a higher SDR. And as explained earlier, the sediment yield is the product of the soil loss and the SDR. The SDR will increase because the land cover will retain less sediment particles, resulting in more sediment reaching a gully or stream.

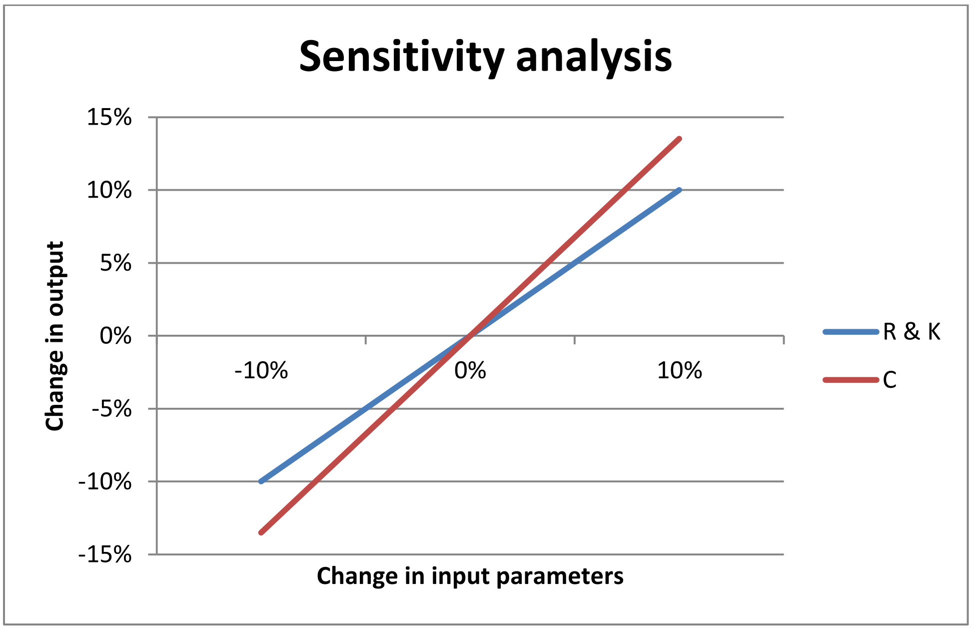

Figure 17: sensitivity of the USLE parameters R, K and C on sediment yield output

5.2 Trap Efficiency

In this section the results of the trap efficiency methodology will be given, with regard to the sub-questions and the main research question.

5.2.1 Variation of stored volume and reservoir inflow

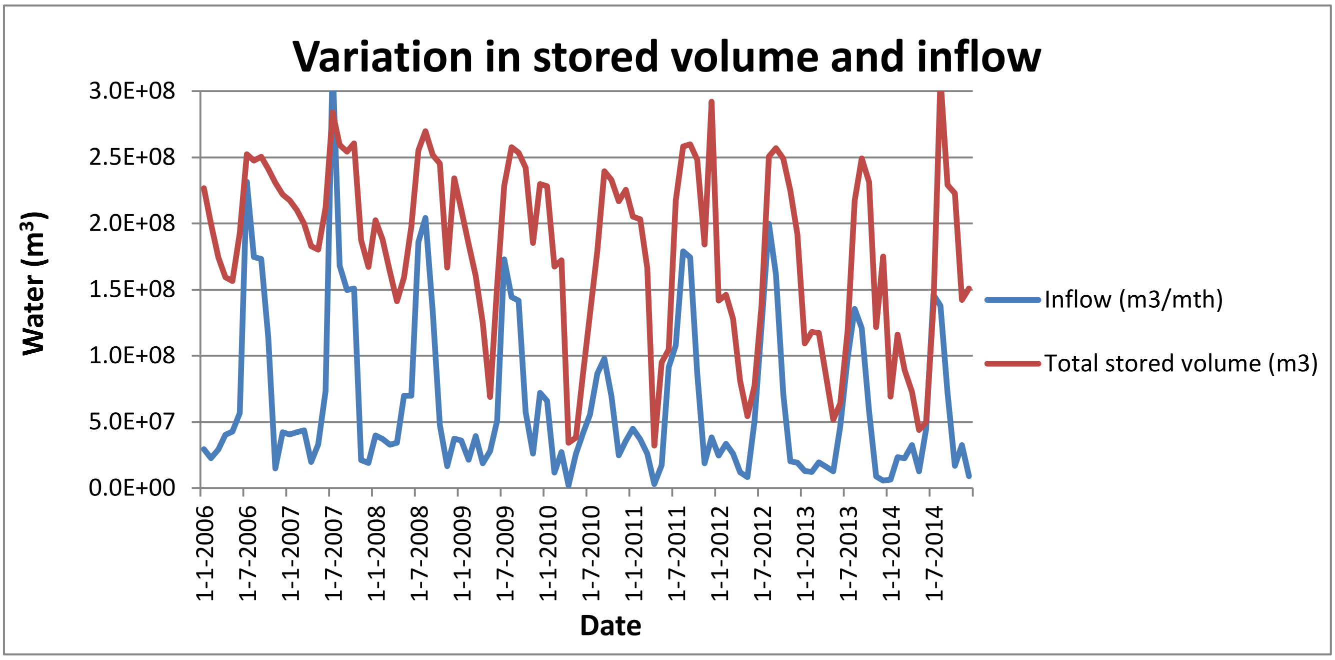

Figure 18: Variation in reservoir inflow and stored volume from 2006 until 2014

The stored volume and reservoir inflow data have been plotted on a monthly base to show the variation see Figure 18.

5.2.2 Particle size distribution

The average results from the 17 sediment samples indicate that the sediment trapped by the reservoir consists of 34,6 % Clay, 49,5 % Silt and 15,9 % Sand, see appendix F for more details. The purpose of this grain size distribution is to choose the best equation to predict the trap efficiency, according to the distribution of the clay, silt and sand fractions. Therefore the average is used as a representation of the soil type classification of the reservoirs sediment. The taken sediment samples represent the sediment that has settled within the 'Nga Moe Yeik' reservoir, instead of the suspended sediment as it flows into the reservoir. This discrepancy may results in an unrealistic representation of the soil type classification of the sediment flowing into the reservoir.

5.2.3 Trap efficiency prediction for 'Nga Moe Yeik' reservoir

The different empirical equations for predicting the trap efficiency are plotted in Figure 19, using the monthly stored volume and reservoir inflow.

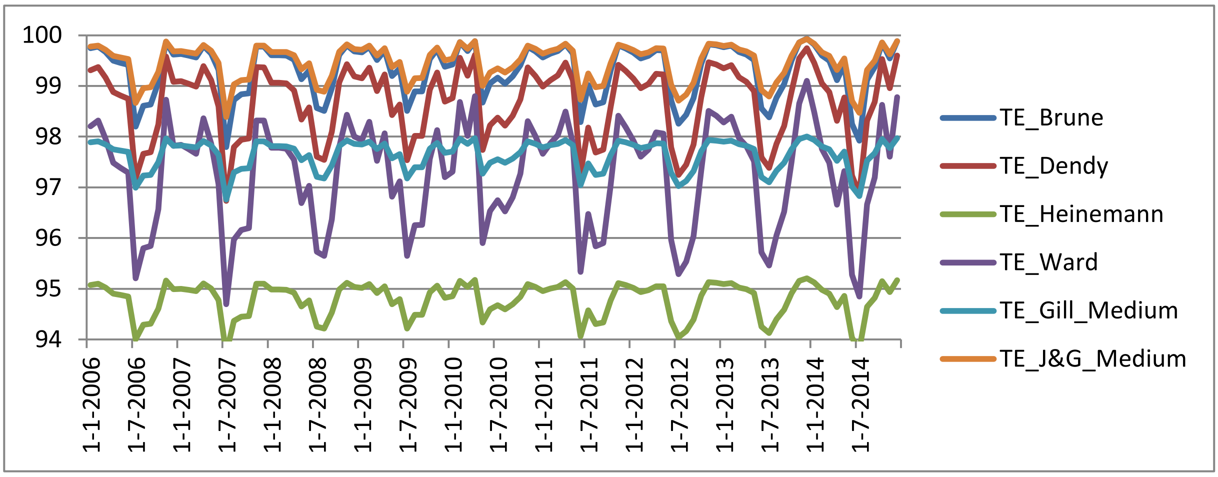

Figure 19: Trap efficiencies resulting from different empirical equations

According to Ketelsen et al. (2013) the method from Gill is good to make trap efficiency predictions, because it has a very close fit to the three curves from Brune (Brune, 1953). Furthermore Gill differentiated three equations with different applications: for course sediment (sand), for medium sediment (silt) and for fine sediment (clay) (Ketelsen et al., 2013). This distinction makes it possible to select an equation that fits the grain size distribution of the sediment inflow best. Since the silt is averagely the biggest fraction, the Gill medium equation will be used from now on. The Gill medium equations predicts an average trap efficiency of 97,65%, based on the 2006 – 2014 data.

5.3 Sediment accumulation

The bathymetric survey conducted between 06-05-2016 and 07-05-2016 has resulted in two navigation routes, see Figure 22. The contour line of the water surface area from 03-05-2016 has been added to give an idea of which areas were navigable and which were not. See Appendix F for more information about the bathymetric survey and the used equipment.

The DEMs of both 1995 and 2016 have been created successfully, see Figure 20 and 21. The different volumes and surface areas have been calculated see Table 13. Figure 23 show the elevation differences between the 1995 DEM and 2016 DEM.

Volume	**Technical Data**	**1995**	**2016**	**Total sediment accumulation**
Total Storage Capacity (* 10^3 m^3)	222.027	231.503	211.313	20.190
Dead Storage Capacity (* 10^3 m^3)	14.802	20.429	15.202	5.227
Usefull Storage Capacity (* 10^3 m^3)	207.225	211.074	196.111	14.963
Area	**Technical Data**	**1995**	**2016**	
Full Storage Area (* 10^3 m^2)	44.515	45.437	45.670	
Dead Storage Area (* 10^3 m^2)	26.709	9.434	$7.17*10^3$	

Tabel 13: Results from the 'Surface Volume' tool for the 1995 DEM and 2016 DEM, compared to technical data

Capacity change 1995 – 2016	**Max**	**Mean**	**Min**
Total Storage Capacity (%)	-11,94	-8.72	-6,36
Dead Storage Capacity (%)	-35,06	-25.59	-18,68
Usefull Storage Capacity (%)	-9,71	-7.09	-5,18

Table 14: capacity change combined with the error

Firstly, it can be observed that there are some major differences between the technical data and the results from the 1995 map. The technical data is a result of a survey performed in 1995, before the dam construction was finished. Unfortunately there is little known about this survey; how it is executed and how the calculations are performed, because there is no official document available. Therefore it is unknown how accurate the technical data is.

It is quite notable that the difference in the dead storage area between the technical data and the 1995 DEM is disproportionately big in comparison to the full storage area. The dead storage area has majorly decreased, while the dead storage capacity has been increased. This seems to be contradictory, but is probably due to the effect of making interpolations with too little input data. It is feasible that because of the lack of enough data on the old 1995 map, the stream beds of the old rivers and creeks are not interpolated accurately. If there is no elevation data close to the stream line data, the stream line data could have a substantial impact on the interpolation of a big area. While the impact of creeks and rivers on the elevation of an area, is in reality probably more locally. This phenomenon could be the cause of the difference within the dead storage capacity. The differences in calculation techniques between the technical data and the 1995 DEM are probably the cause of the total storage capacity difference. This difference could cause the average bed level of the reservoir to be lower, resulting in the dead storage area difference.

To quantify the error of the capacity loss assessment, the uncertainties introduced by different techniques, namely georeferencing, interpolation, gab filling with Landsat and the measuring setup, will be estimated. The total error propagation will be estimated from those individual uncertainties, see Appendix E for further information. The overall error in the capacity change resulted to be 37%

Table 14 does show the capacity change between the 1995 and 2016 DEM's. The mean values are a result from the change in capacity as stated in Table 12, while the max and min are derived from the mean, using the 37% error. So the total sediment accumulation lies between 14,74 * 10^6 m^3 and 27,66 *10^6 m^3.

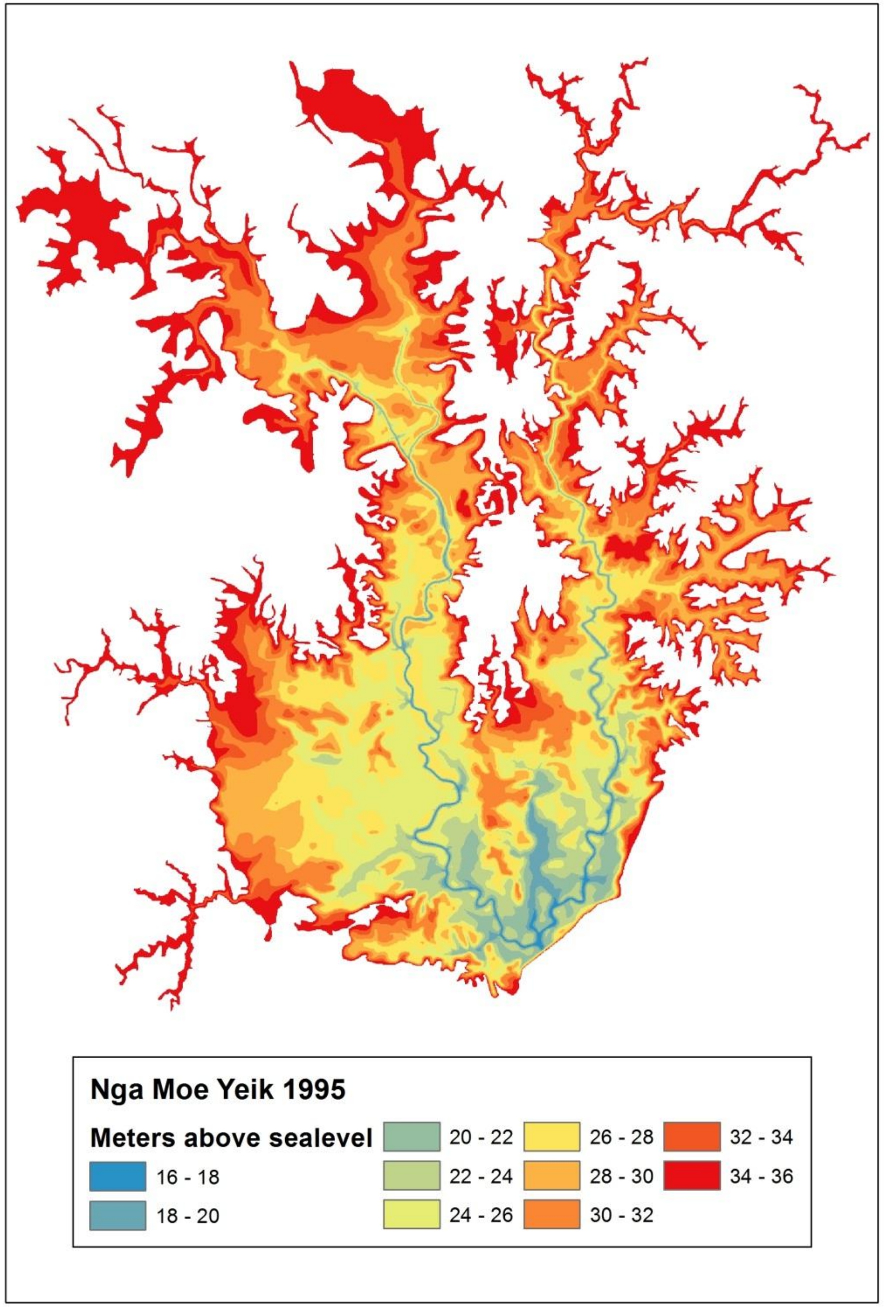

Figure 20: the elevation of the reservoirs bed as is was present in 1995

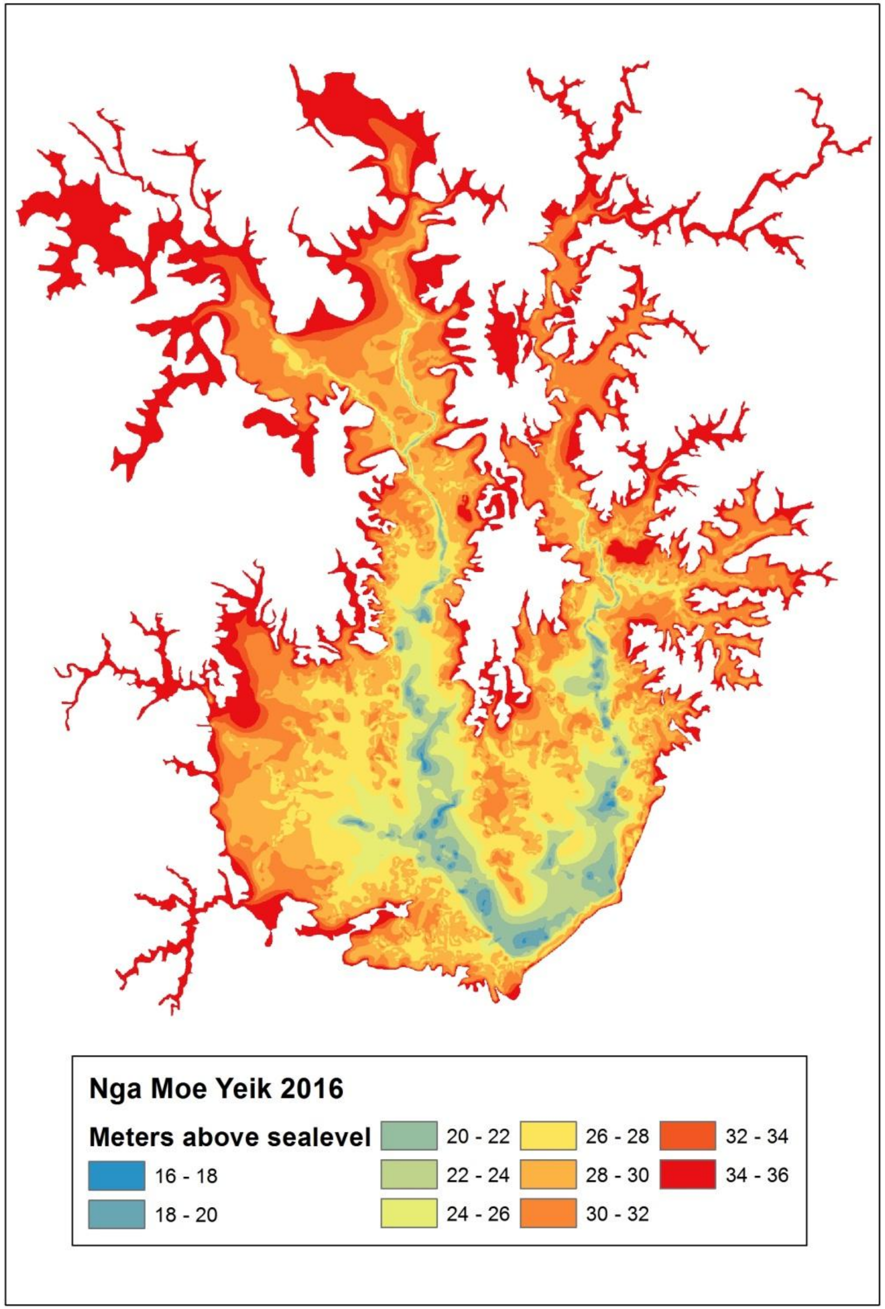

Figure 21: the elevation of the reservoirs bed as it is present in 2016

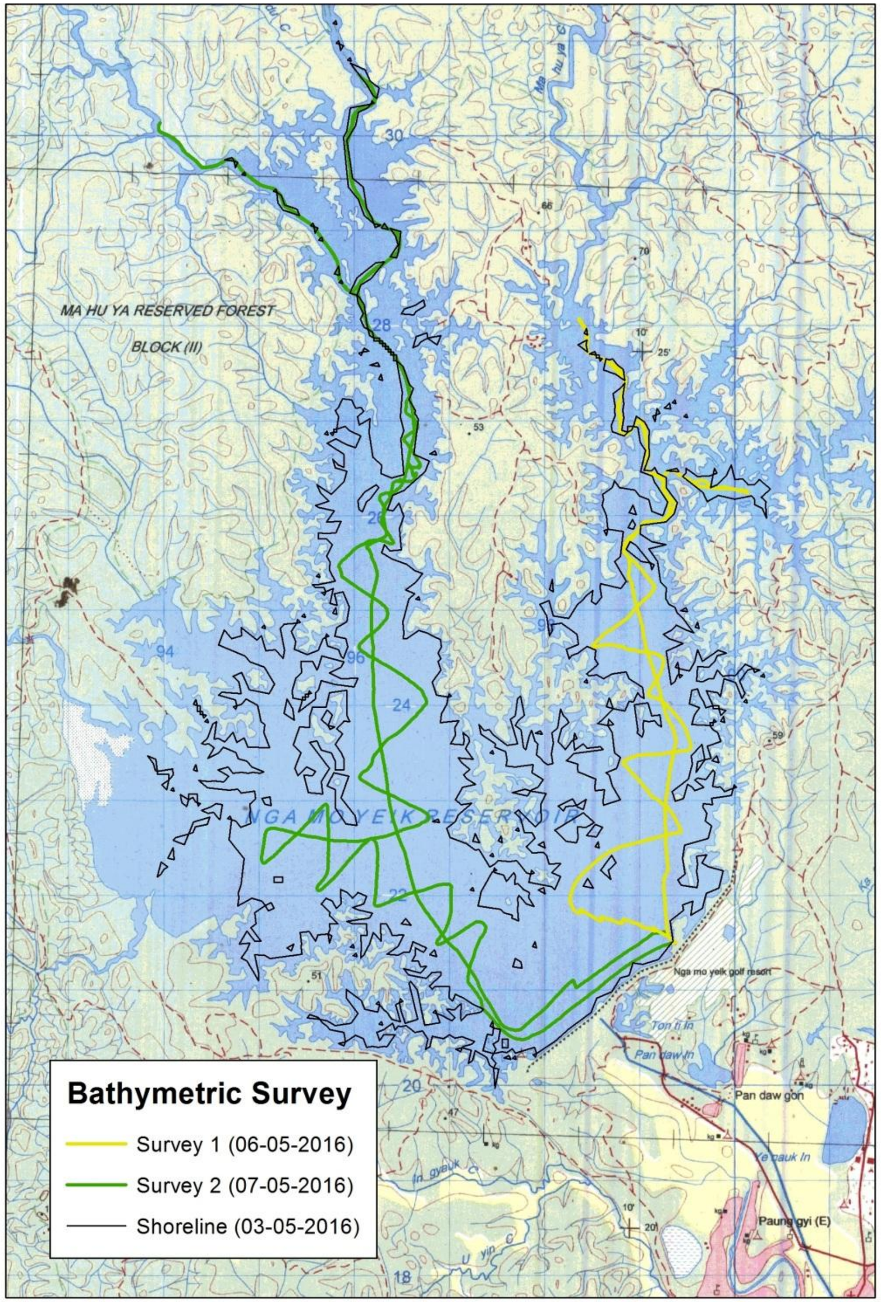

Figure 22: map of the performed bathymetric survey

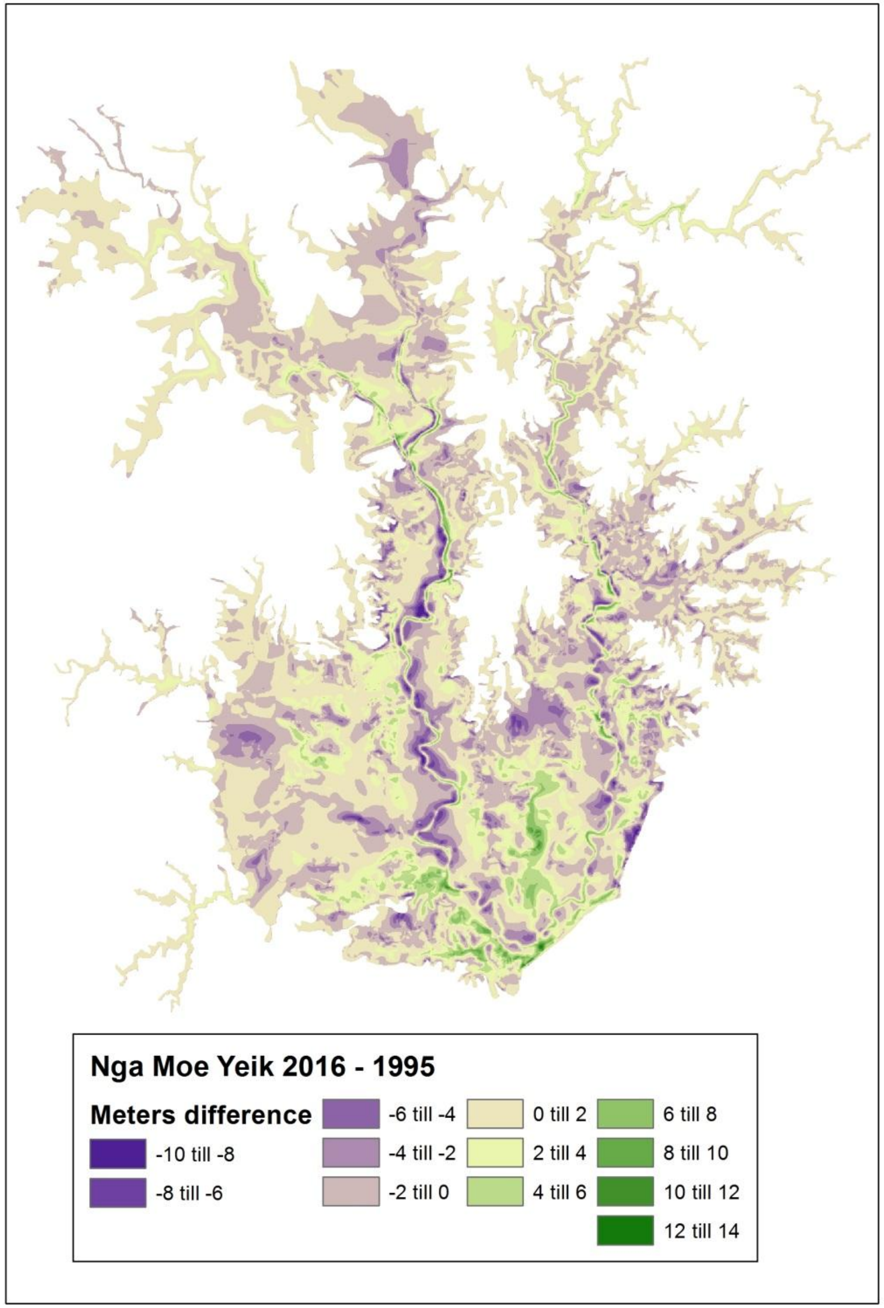

Figure 23: comparison of bed elevation levels, 2016 minus 1995

6. Discussion

Every research use assumptions within their methodologies, techniques and used data, to come to results. For this research that is not any different and within this chapter of the report, the remarks about all the used assumptions will be made. Every chapter of this report will be reflected upon within this discussion. Each section within the discussion represents a chapter of this report. In that way every step within the research will be reflected.

Chapter one introduced the problem context together with the research context. This chapter introduced the erosional processes, sediment yield and trap efficiency. It has been stated that the erosional processes comprise of four main types: sheet, rill, gully and in-stream erosion. This research only modelled sheet and rill erosion to calculate the sediment yield. That does result in a sediment budget where some sources and sinks are being neglected. The assumption has been made that during the complete scope of this research the total erosion and deposition within gullies and streams will averagely be equal to zero. It is unknown how this assumption affects the sediment yield results.

Chapter two introduced the goal of the research and did state the research questions to achieve that goal. The goal of the research introduced the use of the InVEST model. Other models and methods to model catchments areas and predict their sediment yield have been neglected. Other models were not part of the scope of this research, to focus on the InVEST model. InVEST has been chosen because of its low input demand and simple model structure. Also the parameterization of the USLE parameters is easy, especially for a data scarce region like Myanmar.

The third chapter did set the theoretical frame for the research and consisted of two parts: the sediment yield and the trap efficiency. Since the InVEST model makes average annual predictions, the impact of single events on the sediment yield has been neglected. The temporal scope of the case study is 21 years. By making average annual predictions based on parameters that represent the 21 years well, this should not cause errors of any importance. But unfortunately, the parameterization was not this accurate. The annual rainfall input was only based on data from one rain gage between 2006 and 2014. This does not represent the timeframe of 21 years accurately. The same counts for the soil type and land cover. Those parameters have been calculated on the basis of the result from one field survey conducted in 2016. Also the spatial resolution of those parameters does not always represent the catchment area well. Those simplifications can affect the models predictions greatly and according to the comparison with the bathymetric surveys results, that led to an overestimation.

The second point of discussion within the theoretical frame is about the trap efficiency. The assumption has been made that the trap efficiency could best be predicted using the hydraulic residence time principle. For this research, this was certainly the easiest method because of the low input data demand. But this method does not necessarily yield the best trap efficiency prediction. The results of this method did not have been compared to other methods to check its validity. However, according to other studies this method does show good agreement compared to bathymetric surveys.

Chapter four, data and methodological approach also make use of some idealizations and simplifications. InVEST has never been calibrated or validated during the use within the methodology. A lack of proper datasets from other catchment areas made this impossible. This does affect the sediment yield results. The second remark within the methodology is the use of the sediment samples to represent the sediment inflow. The sediment inflow does differ from the deposited sediment, because the smallest particles have already been flushed out. This does affect the grain size distribution of the sediment inflow. The impact of this idealization on choosing the trap efficiency equation is very minor, because the particle type classification is of most importance.

The fifth and last chapter that will be discussed within this chapter of the report are the results. The assumption has been made that the translation between the sediments weight and volume is straightforward and can be made by assessing the specific gravity of sediment samples. In reality the specific gravity of deposited sediments is affected by compaction processes. Those processes usually happen very slowly, but over a long period of time they might have an impact on the specific gravity of the deposited sediment. Ultimately this might yield higher specific gravity ratios. This could implicate that the resulting values for the predicted sediment yield volumes are too high.

The last assumption has been made with regard to the trap efficiency. The trap efficiency of the two supplementary dams was assumed to be 100%. This is assumption has been made because of a lack of data from those two dams. In reality this trap efficiency will be lower; in comparison with the trap efficiency of the 'Nga Moe Yeik' reservoir this will introduce an error of a few percent in the sediment yield of their upstream catchment areas. This error will be even smaller within the sediment yield of the total catchment area, because some of those sediments will probably be trapped by the 'Nga Moe Yeik' reservoir.

7. Conclusion

This report started with the introduction of the three main research questions and their sub-questions. All the sub-questions introduced in 2.2 ‘Research question have been answered in the chapter 5. ‘Results’. This chapter will summarize these results to answer the three main research questions. When these research questions have been answered, the overall conclusion will be drawn.

7.1 Sediment yield

What is the sediment yield of the ‘Nga Moe Yeik’ catchment area and what is the impact of different geological and hydrological characteristics on the sediment yield?

The InVEST model has been used to make predictions about the sediment yield during a 21 year period, resulting in a sediment yield output between 44,5 $*10^6$ m^3 and 64,4 $*10^6$ m^3. Which correspond to an annual sediment yield between 14,5 $*10^3/km^2$/year and 42,3 $*10^3/km^2$/year following local differences, as shown in Table 12. These values are extremely high in comparison with studies from the literature. Zarris et al. (2002) found sediment yields between 0,49 $*10^3/km^2$/year and 2,03 $*10^3/km^2$/year for the Kremasta reservoir basin in Greece. While Rupasingha (2002) found values between 0,0395 $*10^3/km^2$/year and 0,048 $*10^3/km^2$/year for the Naivasha reservoir in Kenya. These extreme differences can probably be explained by the high amount of bare soil within the catchment area. To justify the amount of these values it is recommended to study the land cover into more detail. Furthermore, the land cover classification should be used to improve the land cover practise management.

During the methodology it is found that the InVEST model is capable of assessing erosion prone areas very well. InVEST might be a great tool to help during reforestation programmes to counter high erosion rates. By combining multiple geologic and hydrologic characteristics, like rainfall, soil type and land cover, InVEST can assess which areas are most prone to soil loss. This could help to determine how to prioritize reforestation programmes.

7.2 Trap Efficiency

What is the trap efficiency for the ‘Nga Moe Yeik’ reservoir?

The trap efficiency for the ‘Nga Moe Yeik’ reservoir using the Gill medium equation, resulted in an average 97,65%. Compared to results from the literature, this is a realistic result. Issa et al. (2015) found a sedimentation rate of 95,33% for the Mosul dam in Iraq by comparison of the sedimentation rate from a bathymetric survey with sediment inflow rates of the reservoir. The difference with the Mosul dam can be explained by comparing its capacity and monthly inflow to that of the ‘Nga Moe Yeik’ dam. The ration between the capacity and the inflow is higher for the Mosul dam than for the ‘Nga Moe Yeik’ dam. According to the hydraulic residence time principle (section 3.2 ‘Empirical prediction Trap efficiency’) this will cause higher trap efficiency rates within the reservoir. According to the trap efficiency, between 43,5 $*10^6$ m^3 and 62,9 $*10^6$ m^3 of sediment will deposit within the reservoir.

7.3 Sediment accumulation

What is the impact of the sediment accumulation on the reservoir storage capacity?

During the past 21 years there has accumulated between 14,74 $* 10^6$ m^3 and 27,66 $*10^6$ m^3 of sediment. That is a loss of capacity between 11,94 and 6,36%. Unfortunately there are no estimations about capacity losses from design studies to compare those results with. However, these results are comparable with that of other studies and their bathymetric surveys. Issa et al. (2015)

performed a bathymetric survey on the Mosul reservoir in Iraq. The reservoir lost 10,29% of its storage capacity during a period of 25 years. Rupasingha, (2002) performed a bathymetric survey for the Naivasha reservoir in Kenya. The Naivasha reservoir lost 7% of its storage capacity during a period of 44 years.

7.4 Overall conclusion

Overall, the sediment yield predictions made with the InVEST model differ with a ratio between 2 and 3 with the sediment accumulation outcomes of the bathymetric survey. For making predictions about reservoir sedimentation, this difference is too vast. Although the methodology in this research makes use of very little input data, and the input data is easily and cheaply acquirable, the input data cause multiple errors in the output of the InVEST model. This will be described in the discussion moreover. In the future the InVEST model may have the potential to develop into a proper tool to estimate reservoir sedimentation in data scarce regions like Myanmar. But, therefore the parameterization has to become more accurately and more case studies will have to be conducted. In that way, the results of different case studies can be compared and the InVEST model can be calibrated and validated.

8. Recommendations

Various remarks and conclusions that have been given in this report during the discussion and conclusions lead to recommendations. Recommendations to improve the results make the use of the model more easily, or improve the data collection. All of those recommendations have been listed in this chapter of the report, in that way it is clear for other researchers which ways are the best to proceed.

In this research the sediment yield calculations did only comprise sheet and rill erosion and deposition. To get a better understanding of the total sediment budget, it would be good to assess the long term impact of gully and in-stream erosion and deposition. In this way it is possible to check if the gully and in-stream erosion and deposition really is zero on a long term or not.

To apply the InVEST model on catchments all over Myanmar in an effective way, it would be efficient to map some of the model's parameters on a country wide scale. It may be possible to use data of multiple rain gages spread across the country, to produce a rainfall dataset that represents the average rainfall over a long period of time and also with a proper spatial resolution. The same applies to the soil type. By building these parameters into country wide datasets, that would make InVEST analysis much more time-efficient. For land cover it may be harder to map on a country wise scale, because land cover is very time dependent. For the land over it would be better to study into more details for catchment areas individually with respect to the time frame.

Another aspect that deserves some further investigation is the parameterization of the R, K and C parameters. R has only been calculated using empirical formulas. It would be good to validate the results from the empirical formulas with the results from rainfall intensity measurements. In that way it is possible to check whether the empirical formulas fit the climatic conditions and circumstances of Myanmar well. Secondly, it would be good to validate the used empirical method for calculating K by using an alternative, like the nomograph method proposed by Wischmeier and Smith (1978). Concerning the C-factor, it would be an improvement to compare the values found within the literature with calculated values for Myanmar. There are methods available using Landsat imagery to assess the C-factor values for different crops and land cover types.

If future assessments of sediment yield from catchments will be made, it is important to choose a study area that is easily accessible. For this case study it was sometimes hard to access the catchment area. In that way it is much harder and more time-consuming to collect input data from the catchment area. The recommendation is to choose a catchment area that is easily accessible for a next case study.

In case of the bathymetric survey, the recommendation is to more thoroughly assess the error propagation of the capacity loss assessment. Alternative interpolation techniques should be used to determine their impact on the capacity loss results. Besides it would be good to examine the accuracy of the echo sounder on depths greater than one or two meters, because the accuracy is only known for shallow depths. Furthermore it is worth to repeat the bathymetric survey in a period between 10 and 20 years to see if the reservoir sedimentation is linear or not. A new bathymetric survey can also be used to better understand the error propagation within the results.

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Appendices

Appendix A – Technical Data

This appendix will show the technical data that is available about the 'Nga Moe Yeik' dam, its supplementary dams 'Paung Lin' and 'Ma Hu Yar' and their catchments. This data was supplied by the ITC.

	Technical data of NGAMOEYEIK DAM		
1	Name	Ngamoeyeik Dam	
2	River / Creek	Ngamoeyeik Creek	
3	Location	Hlegu Township, Yangon Region	
	Lat, Lon	96.161141	17.354927
	Altitude (m.s.l)	36.57 m	120 ft
	1" map index	94 C/3 - 542056	
4	Height	22.86 m	75 ft
5	Length	1859.2 m	15500 ft
6	Capacity	222027×10^3 m^3	180000 acre-ft
7	Surface Area	44515×10^3 m^2	11000 acre
8	Catchment Area	414.4 km^2	160 sq-mile
9	Annual Inflow	20.026	512000 acre-ft
10	Spillway Capacity	312 m^3/s	
11	Type of Dam	Earthen	
12	Irrigated Area	283.3 km^2	35360 acre
13	Started Year	1992-93	
14	Completed Year	1994-95	
15	Opening Date	26.3.1995	
16	Project Cost	1050 million kyats	

Table 14: technical data about the 'Nga Moe Yeik' dam

	Technical data of PAUNGLIN DAM (Supplementary Dam of NGAMOEYEIK DAM)		
1	Name	PaungLin Dam	
2	River / Creek	PaungLin Creek	
3	Location	Hlegu Township, Yangon Region	
	Lat, Lon	96.095111	17.508741
	Altitude (m.s.l)	60.96 m	200 ft
	1" map index	94 C/2 - F - 477245	
4	Height	30.48 m	100 ft
5	Length	681.2 m	2235 ft
6	Capacity	147031 x 10^3 m^3	119200 acre-ft
7	Surface Area	18211 x 10^3 m^2	4500 acre
8	Catchment Area	86.2 km^2	33.3 sq-mile
9	Annual Inflow		106560 acre-ft
10	Spillway Capacity		18 ft^3/s
11	Type of Dam	Earthen	
12	Irrigated Area	-	-
13	Started Year	2002-2003	
14	Completed Year	2003-2004	
15	Opening Date	22.3.2004	
16	Project Cost	466.97 million kyats	

Table 4: technical data about the 'Paung Lin' dam

	Technical data of MAHUYAR DAM (Supplementary Dam of NGAMOEYEIK DAM)		
1	Name	Mahuyar Dam	
2	River / Creek	Mahuyar Creek	
3	Location	Hlegu Township, Yangon Region	
	Lat, Lon	96.189713	17.491644
	Altitude (m.s.l)	30.48 m	100 ft
	1" map index	94 C/2 - F - 580238	
4	Height	30.48 m	100 ft
5	Length	205.73 m	2335 ft
6	Capacity	66608 x 10^3 m^3	54000 acre-ft
7	Surface Area	7891 x 10^3 m^2	1950 acre
8	Catchment Area	43.4 km^2	16.77 sq-mile
9	Annual Inflow		49920 acre-ft
10	Spillway Capacity		12 cft/s
11	Type of Dam	Earthen	
12	Irrigated Area	-	-
13	Started Year	2002-2003	
14	Completed Year	2003-2004	
15	Opening Date	26.11.2006	
16	Project Cost	375.92 million kyats	

Table 5: technical data about the 'Ma Hu Yar' dam

Appendix B – Delineating 'Nga Moe Yeik' catchment area

During the process of delineating the catchment area of the 'Nga Moe Yeik' reservoir with ArcGIS, multiple output raster's have been generated. To understand some of the steps and processes within the methodology, these output raster's will be shown in this appendix.

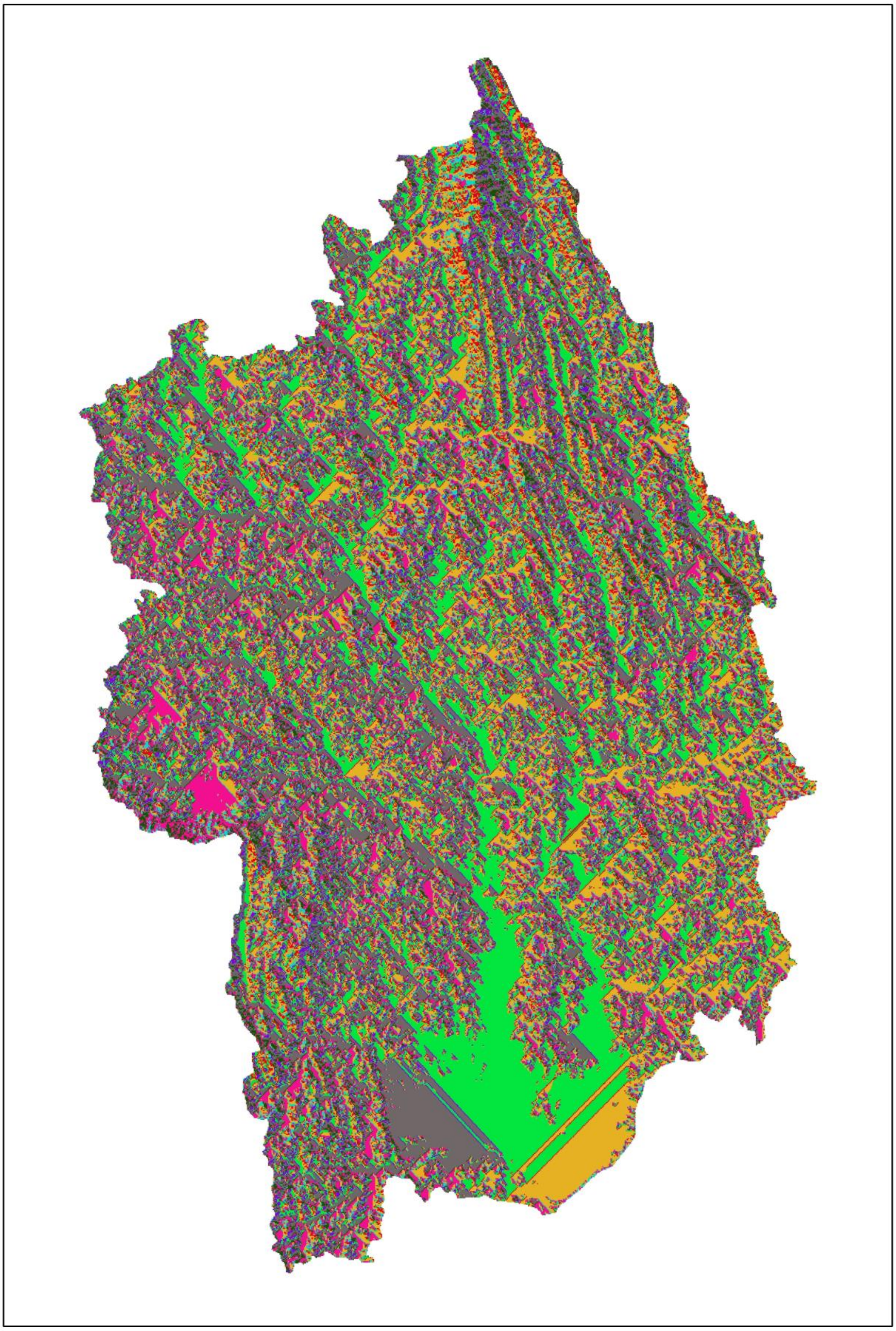

Figure 24: flow direction raster of the 'Nga Moe Yeik' catchment

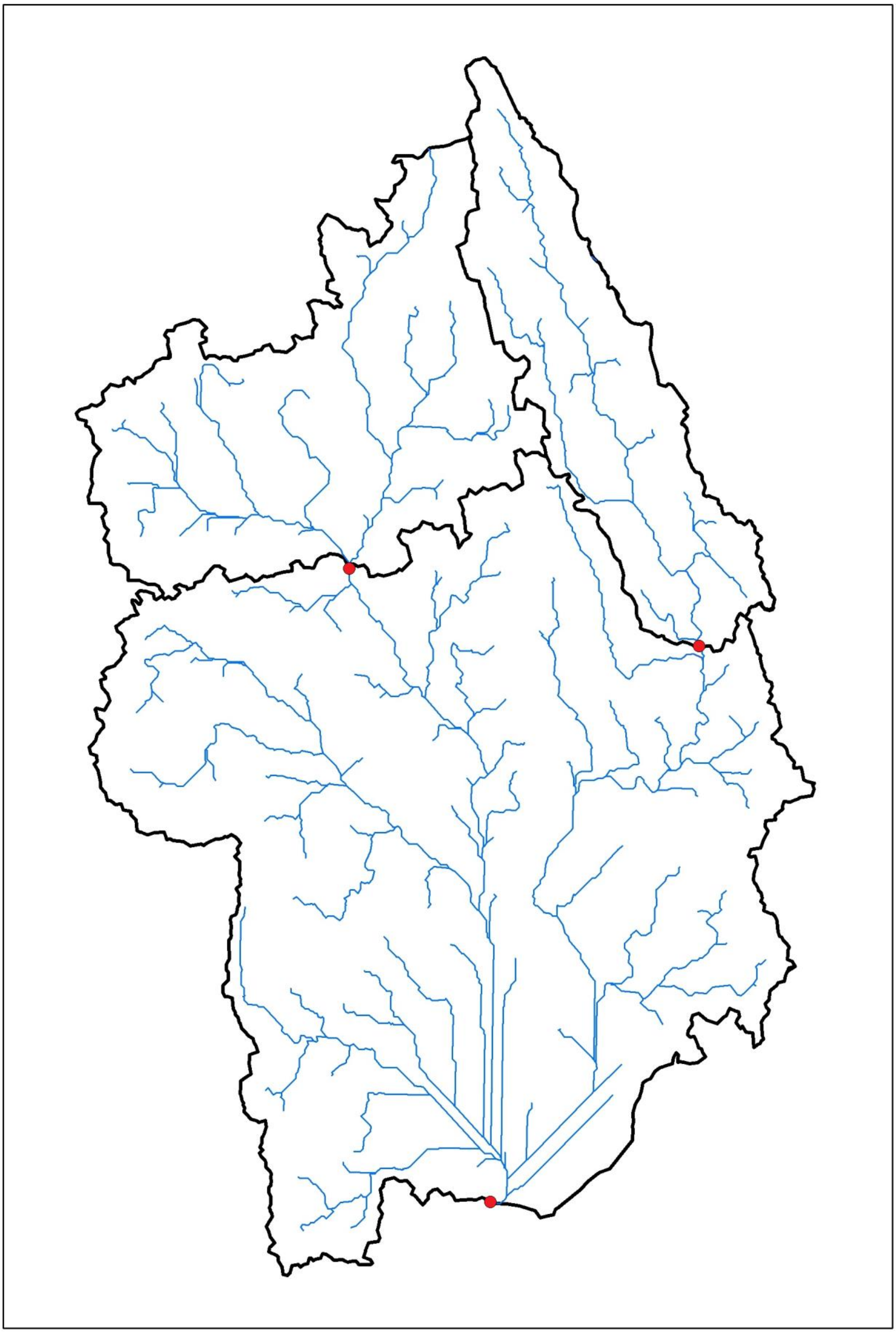

Figure 25: flow accumulation raster of the 'Nga Moe Yeik' catchment, the red dots represent the output points of the catchment and its sub-catchments

Appendix C – Grain size distribution and Specific gavity

This appendix shows the equations that have been used to make the soil assessment.

Grain size distribution

The test to determine the particle size distribution consists of two parts: the distribution of particle sizes larger than 2 mm is determined by sieving, while the distribution of particle sizes smaller than 2 mm is determined by a hydrometer test (The University of Toledo, 1998) based on the sedimentation process. Since all the sediment particles passed through the 2 mm sieve, only the hydrometer test had to be performed. See The University of Toledo (1998) for the full procedure of the hydrometer test. The following equations have been used to make the calculations:

$$D = K\sqrt{L/T} \tag{31}$$

$$P = \left(R_c * \frac{a}{M_s}\right) * 100\% \tag{32}$$

Where,

D	is the soil grain diameter (mm)
K	is a constant depending on the specific gravity of the solids and the temperature of the fluid
L	is the effective depth (cm)
T	is the elapsed time (min)
P	is the percentage soil remaining in the suspension
R_c	is actual hydrometer reading
a	is a correction factor required when the specific gravity of the soil grains is not equal to 2.65
M_s	is the oven dry mass of the soil sample (gram)

Specific gravity

The following equations are used to calculate the specific gravity (The university of Toledo, 1984).

$$M_{dw} = M_{fw} - M_{fws} + M_s \tag{33}$$

$$G_s = M_s/\left(M_{fw} - M_{fws} + M_s\right) \tag{34}$$

Where,

M_{dw}	is the mass of displaced water
M_{fw}	is the mass of the flask and the water
M_{fws}	is the mass of the flask, the water and the soil
M_s	is the mass of the dry soil
G_s	is the specific

Appendix D – Field Survey 26-05-2016

A field survey was performed at 26-05-2016 to take soil samples and land cover samples. A total of, nine locations have been visited to classify the land cover, recognizable on the orange dots in Figure 26. The numbered dots represent the four soil samples.

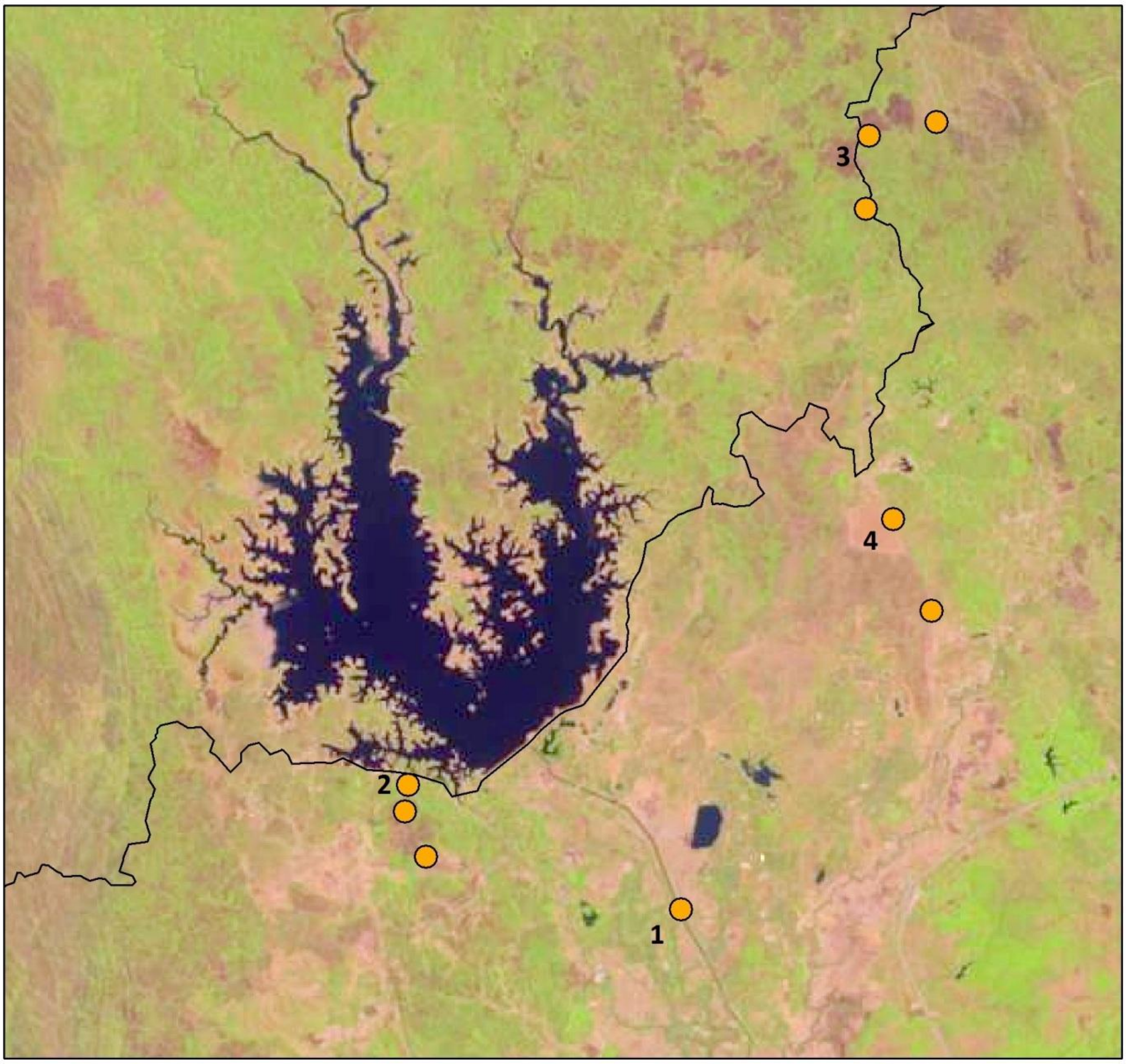

Figure 23: soil samples and land cover samples

Table 17, shows the results from the laboratory on the soil classification of the four soil samples.

Soil classification			
Sample	**Clay**	**Silt**	**Sand**
1	24	46	30
2	22.5	29	48.5
3	19	13	68
4	32	17	51
Average	24.375	26.25	49.375

Tabel 17: soil classification of four soil samples

Appendix E – Error propagation capacity loss

To determine the reliability of the results of the third research question, it is important to assess the errors that have been inflicted by the different methods that have been used. To calculate the total error propagation, the error has been split up into four uncertainties:

7. Uncertainty introduced by manually georeferencing the 1995 Map (ΔG)
8. Uncertainty introduced by the Topo-to-Raster interpolation technique (ΔI)
9. Uncertainty introduced by gab filling with Landsat data of 2016 DEM (ΔL)
10. Uncertainty introduced by the measuring setup of the bathymetric survey (ΔM)

These uncertainties will be assessed independently of each other. Uncertainties ΔG and ΔI are being calculated on the basis of the translation of the 1995 map into the 1995 DEM. Uncertainties ΔL and ΔM are being calculated on the basis of the input data for the 2016 DEM. In all situations the most pessimistic situation has been considered as guiding principle. The total error propagation inflicted by these four uncertainties will be calculated using standard deviations. The following formula we be applied to calculate the total error propagation:

$$\Delta C = \sqrt{(\Delta G)^2 + (\Delta I)^2 + (\Delta L)^2 + (\Delta M)^2} \quad (35)$$

Where,

ΔC is the total error propagation in the total storage capacity. And the other parameters are used as defined above.

1) Uncertainty introduced by manually georeferencing the 1995 Map (ΔG)

To assess the changes in the 1995 Map of the 'Nga Moe Yeik' reservoir bed, caused by manually georeferencing, it is important to understand how the map was manually georeferenced and what the impact of that might be.

The 1995 map was georeferenced along 12 clearly recognizable locations (see figure 27), spread along the map as best as possible to improve the result. These 12 locations have been referenced to a WGS 84 UTM 47N georeferenced map. The transformation made according to the 12 locations is based on the Spline tool. The Spline tool uses an interpolation technique that minimizes overall curvature by using a mathematical function, resulting in smooth surface that passes exactly through the input locations (ESRI, 2016). The result of the Spline tool is a map that is georeferenced well, but shows some distortion. This distortion does cause the uncertainty introduced by the manual georeference procedure. This distortion has been estimated by comparing the surface area of the 1995 DEM with the technical information that is available about the 'Nga Moe Yeik' reservoir. The Full Storage Area has been used to make this calculation.

Full Storage Area, technical data: 44.515 $*10^3$ m^2
Full storage Area 1995 DEM: 45.437 $* 10^3$ m^2

$$Percentage\ Difference = 100 * \left(\frac{45.437-44.515}{44.515}\right) = 2.07\ \% \quad (36)$$

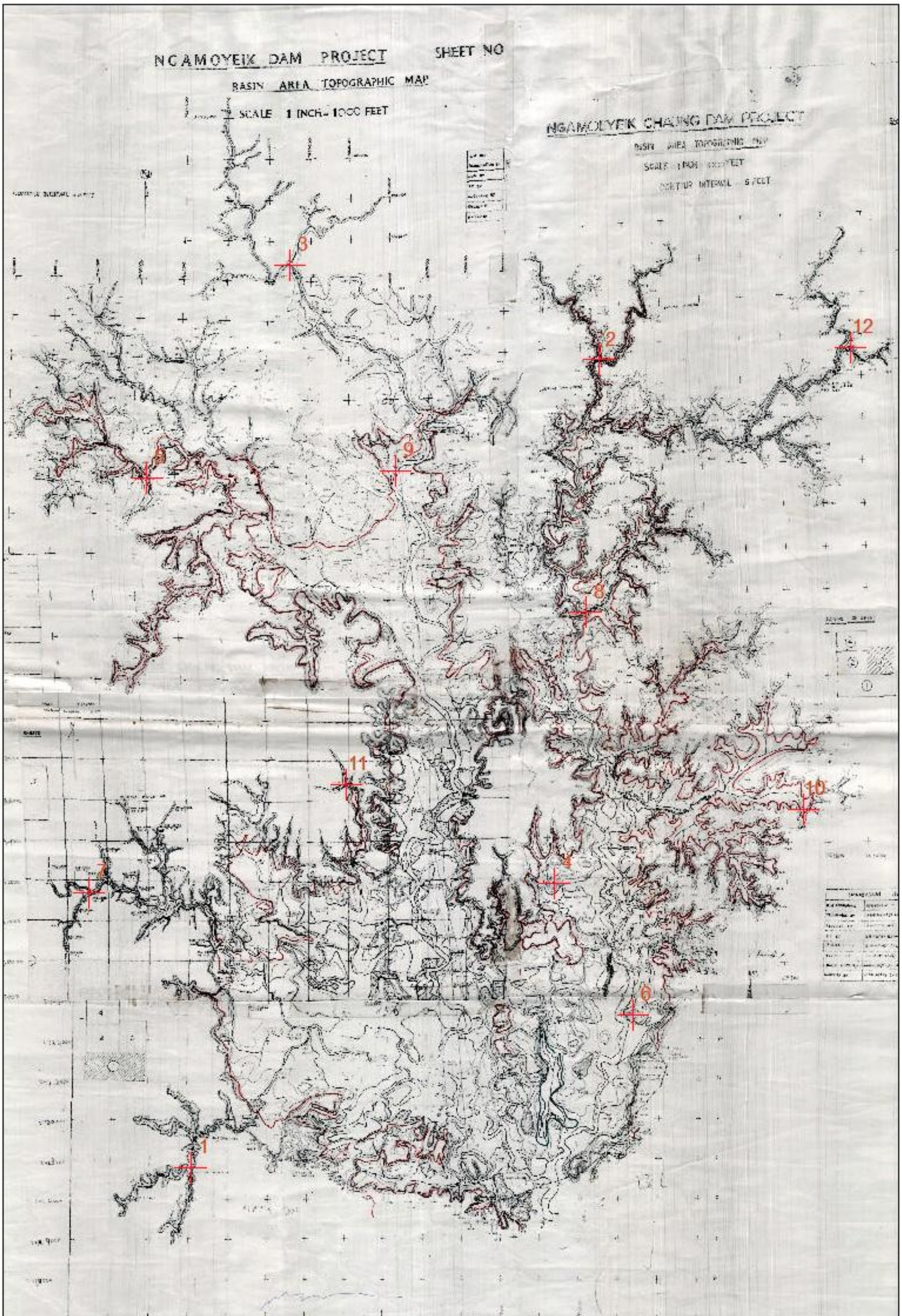

Figure 27: 1995 Map of 'Nga Moe Yeik' reservoir bed with 12 georeference locations

To express the percentage difference into a usable uncertainty, the percentage difference will be expressed as uncertainty of the total storage capacity from the 1995 DEM:

$$\Delta G = 0{,}0207 * 231.503 * 10^3 = 4.792 * 10^3 m^3 \tag{37}$$

2) Uncertainty introduced by the Topo-to-Raster interpolation technique (ΔI)

To estimate the uncertainty introduced by the Topo-to-Raster technique, the interpolation of the contour lines from the 1995 map will be assessed. Figure 28 shows how the uncertainty in interpolated bed elevation will be estimated for two contour lines. The real elevation between the contour lines is unknown. By interpolating the area in between two contour lines an error will be made. The blue surface represents the maximum error that could be made.

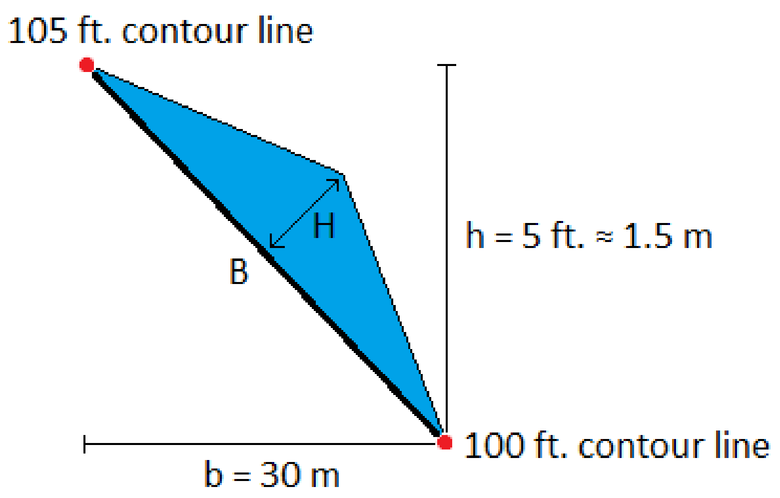

Figure 28: Uncertainty estimation between two contour lines

The total uncertainty inflicted by the interpolation of the contour lines is being calculated according to the following formula:

$$\Delta I = a * L * \frac{1}{2} * H * B \tag{38}$$

Where,

a is the total amount of intervals of contour lines
L is the average length of a contour line (m)
H is the height of the triangle (m)
B is the base of the triangle (m)

There are a total of 8 contour lines used for the interpolation. The total of intervals between the contour lines is therefore 7. The average length of the contour lines was estimated using ArcGIS and resulted to be about 30 km. To make the calculations simple, the assumptions have been made that:

$$B = b \tag{39}$$

$$H = \frac{1}{2} * h \tag{40}$$

Now the uncertainty introduced by the interpolation can be calculated:

$$\Delta I = a * L * \frac{1}{2} * \frac{1}{2} * h * b = 7 * 30.000 * \frac{1}{4} * 1.5 * 30 = 2.363 * 10^3\ m^3 \qquad (41)$$

3) Uncertainty introduced by gab filling with Landsat data of 2016 DEM (ΔL)

The method to estimate the uncertainty introduced by the gab filling with Landsat data is comparable with the calculations of the interpolation error. Translating the shoreline of the Landsat image into a contour line does introduce some uncertainty, because the resolution of the Landsat image is low when zoomed in to the extent of the 'Nga moe Yeik' reservoir. Figure 29 shows how the introduced uncertainty for each Landsat image will be estimated.

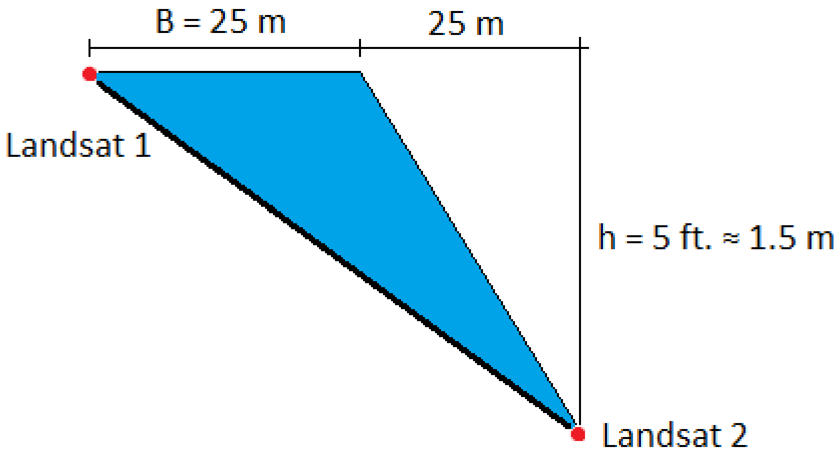

Figure 29: Uncertainty estimation of a Landsat image

The assumption has been made that the spatial uncertainty in the contour line, derived from the Landsat image, can take up to a maximum of 25 meters displacement. In potential the contour line could be shifted 25 meters from the real location. The blue surface represents the uncertainty inflicted by this displacement. The total uncertainty inflicted by the gab filling with the Landsat images is being calculated according to the following formula:

$$\Delta L = a * L * \frac{1}{2} * h * B \qquad (42)$$

Where,

a	is the total amount of Landsat images
L	is the average length of a contour line extracted from the Landsat images (m)
h	is the height of the triangle (m)
B	is the base of the triangle (m)

There are 3 Landsat images used in total. The average length of the contour lines was estimated using ArcGIS and resulted to be about 50 km. The average height difference between the Landsat images is 5 ft. The total uncertainty will be calculated:

$$\Delta L = 3 * 50.000 * \frac{1}{2} * 1.5 * 25 = 2.813 * 10^3\ m^3 \qquad (43)$$

4) Uncertainty introduced by the measuring setup of the bathymetric survey (ΔM)

Finally the uncertainty introduced by the measuring setup of the bathymetric survey will be predicted. This uncertainty can be split up in two sections. The uncertainty caused by the measurements of the echo sounder itself (u_1) and the uncertainty caused by the setup of the boat (u_2). Both are being shown in Figure 30.

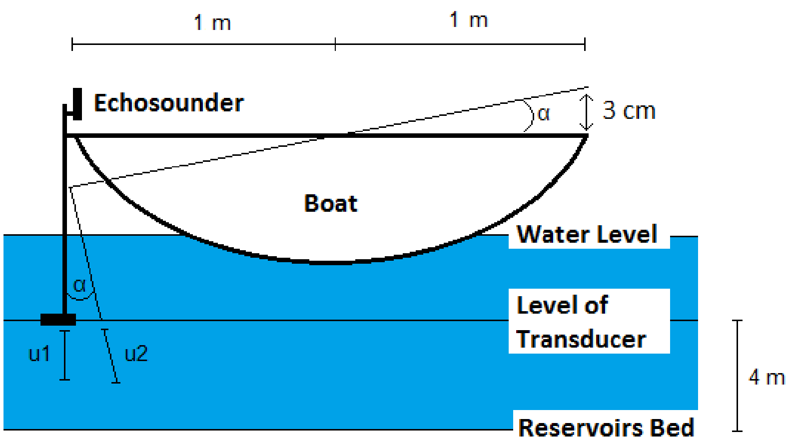

Figure 30: Uncertainty estimation of measuring setup

u_1 represents the uncertainty introduced by the echo sounder itself and u_2 represents the error introduced by the effect of waves on the boat. According to an assessment – previously performed by a TU Delft student about the measurement error of the echo sounder – the introduced error is between 3 and 5 cm. But this is only tested for depths between 0.5 and 2 meter. It would be sensible to measure the error of the echo sounder at greater depths as well. The average depth of all the measurements performed with the echo sounder at 'Nga Moe Yeik' is about 4 meter. The assumption has been made that u_1 is 5 cm at all times.

As a result of the waves at the lakes surface the boat has a tendency to oscillate. Those oscillating movements are causing the echo sounder to be displaced with an angel (α). The angle (α) is inflicting an uncertainty in the depth measurements. The assumption has been made that the maximum oscillation is 3 cm. The uncertainty u_2 is being estimated using simple uniformity calculations:

$$\frac{0{,}03}{1} * 4 = 0{,}12\ m \qquad (44)$$

The motion of the waves is also resulting in another uncertainty. Because when the boat is oscillating, the echo sounder will move up and downwards. The assumption has been made that the left side of the boat is moving up, the same amount of time as the right side. The same assumption has been applies to moving downwards. Because both sides of the boat are equal, this error can be neglected. The total uncertainty is being calculated according to the following formula:

$$\Delta M = A * (u_1 + u_2) \qquad (45)$$

Where,

A is the area of the dead storage level from the technical data (m^2)
u_1 is the uncertainty inflicted by the echo sounder (m)
u_2 is the uncertainty inflicted by the motion of the waves (m)

The area of the dead storage level has been chosen, because that area shows good agreement with the area covered by the bathymetric survey.

$$\Delta M = 26.709 * 10^3 * (0{,}05 + 0{,}12) = 4.541 * 10^3 \qquad (46)$$

Total error propagation

The total error propagation will be calculated using standard deviations:

$$\Delta C = \sqrt{(\Delta G)^2 + (\Delta I)^2 + (\Delta L)^2 + (\Delta M)^2} \tag{47}$$

$$\Delta C = \sqrt{(4.792 * 10^3)^2 + (2.363 * 10^3)^2 + (2.813 * 10^3)^2 + (4.541 * 10^3)^2} \tag{48}$$

$$\Delta C = 7555 * 10^3\ m^3 (\ 1\ )$$

The percentage of error on the capacity change will be accordingly:

$$100 * \frac{7555 * 10^3}{231.503 * 10^3 - 211.313 * 10^3} = 37\% \tag{49}$$

Appendix F – Bathymetric survey 06-05-2016 – 07-05-2016

This appendix shows the equipment that has been used during the bathymetric, the correct and faulty depth measurements that were taken and the results from the grain size distribution and specific weight analysis.

Equipment

The setup of the echo sounder as it was used during the bathymetric survey is shown below, in Figure 31. The echo sounder device is located at the top, the battery in the middle and the transducer at the bottom.

Figure 31: the echo sounder setup

Figure 32, shows the echo sounder itself.

Figure 32: The Garmin EchoMAP 42dv

The grabber to take the sediment samples is shown in Figure 33.

Figure 33: The grabber

Correct and faulty depth measurements

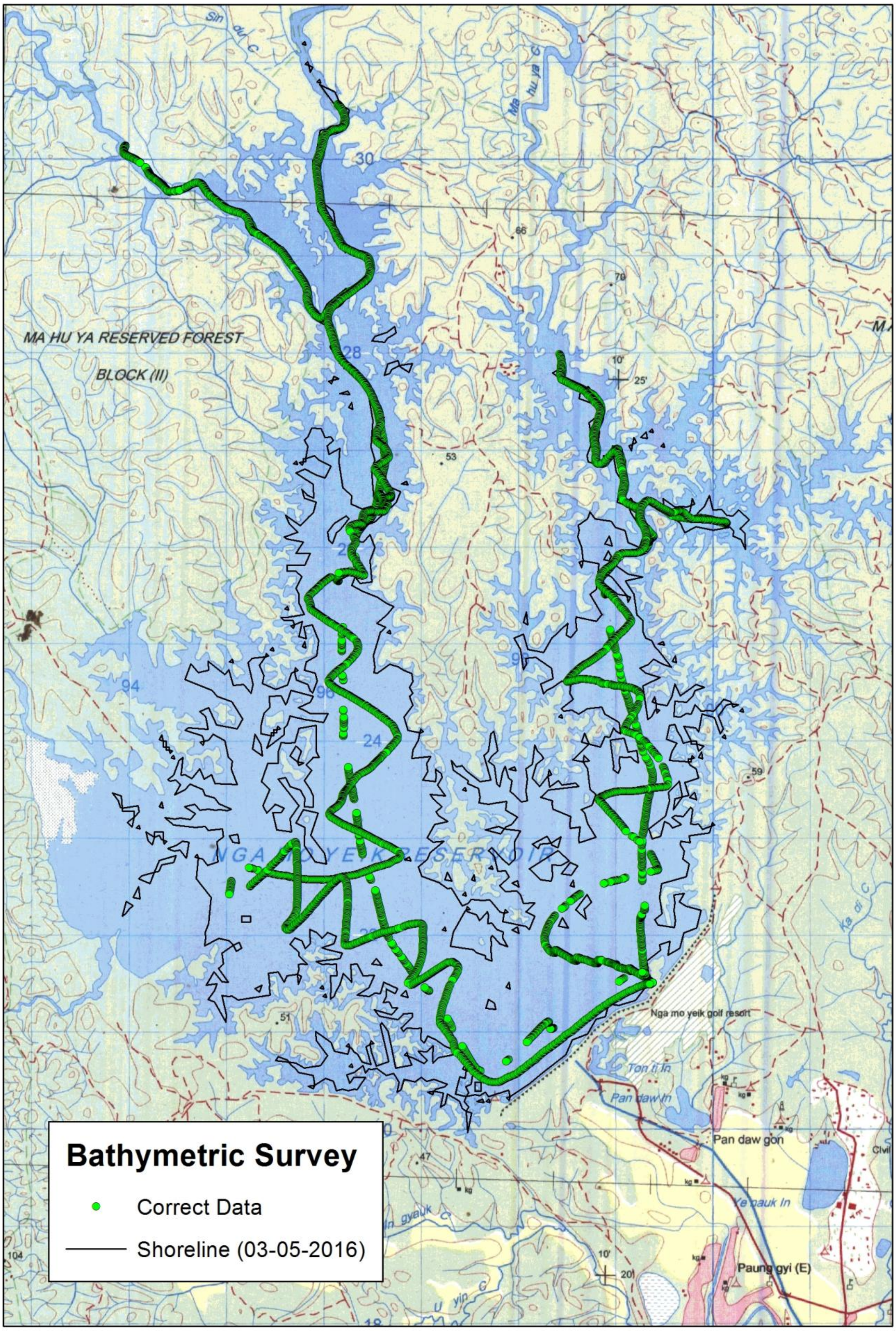

Figure 34: correct depth measurements

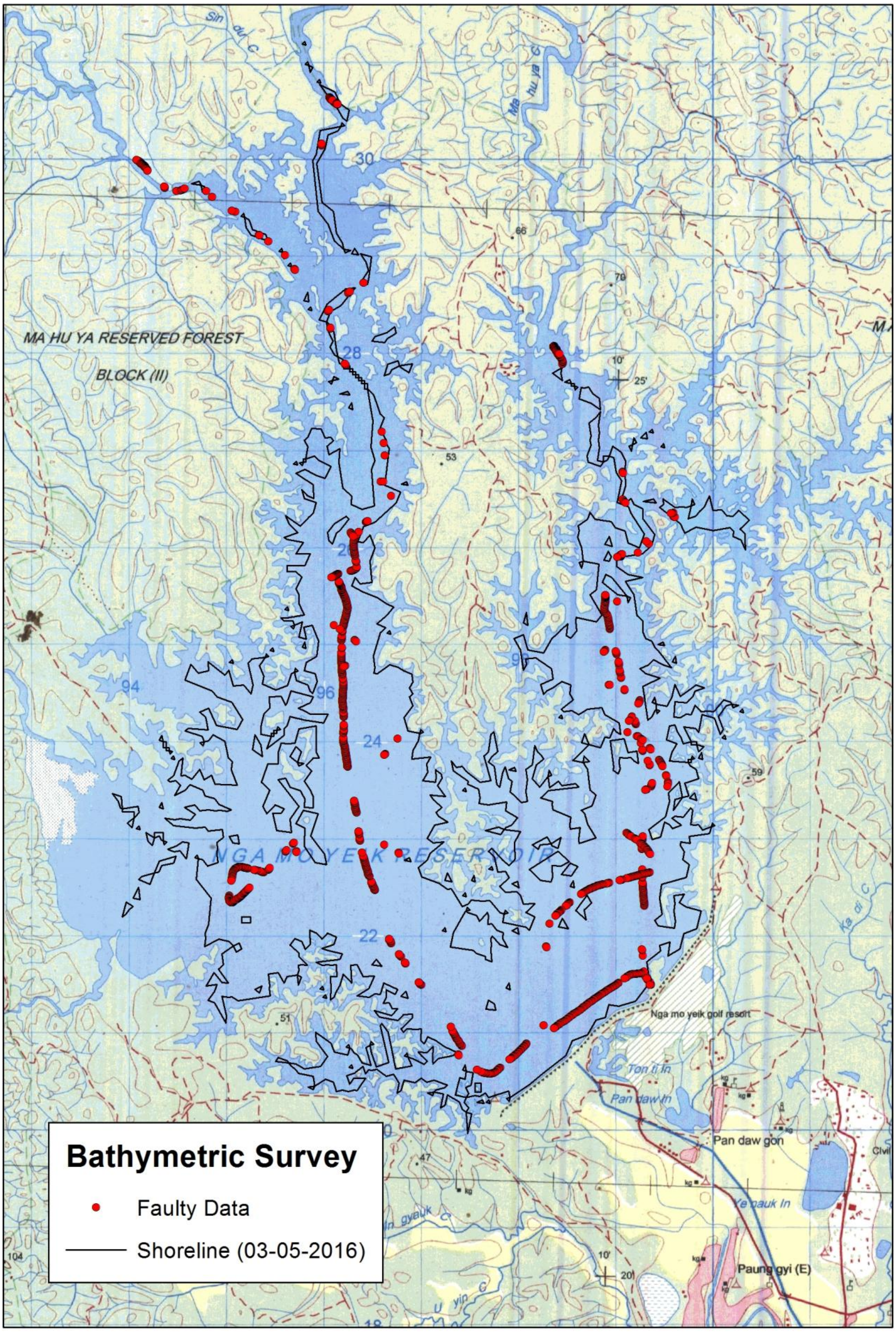

Figure 35: faulty depth measurements

Results of grain size distribution and specific weight

The results of the grain size distribution and specific gravity of the 17 sediment samples taken during the bathymetric survey have been analysed in the soil laboratory on the ITC, Bago, see Table 18.

	Grain Size Distribution			Specific gravity
Samples no.	**Clay (%)**	**Silt (%)**	**Sand (%)**	**m_s/m_w**
1	48,0	45,5	6,5	2,68
2	41,5	54,5	4,0	2,69
3	46,0	53,0	1,0	2,70
4	51,0	44,0	5,0	2,69
5	48,0	51,0	1,0	2,70
6	34,0	63,5	2,5	2,70
7	27,0	64,0	9,0	2,68
8	16,0	2,5	81,5	2,65
9	21,0	41,0	38,0	2,66
10	28,0	64,0	8,0	2,69
11	26,5	46,0	27,5	2,67
12	29,0	69,0	2,0	2,70
13	27,0	52,5	20,5	2,67
14	40,0	59,5	0,5	2,70
15	43,0	43,5	13,5	2,68
16	34,0	60,0	6,0	2,70
17	29,0	28,0	43,0	2,66
Average	34,6	49,5	15,9	2,68

Tabel 18: Results of grain size distribution and specific gravity

Appendix G – Questionnaire about the 'Nga Moe Yeik' reservoir and catchment

This questionnaire has been taken in preparation of the bathymetric survey, to become familiar with the reservoir, its catchment and some of their characteristics.

Location: 'Nga Moe Yeik' dam

Date: 04-05-2016

Participants:

U Khin Maung Hlay (Staf Officer 'Nga Moe Yeik' dam, Hydraulic engineer)
U Aung Myint (Boat driver, was born at 'Nga Moe Yeik' and lived there for his whole life)
U Swe Sein (Operator of 'Ma Hu Yar' dam)
Translator: Sai Wunna (Supervisor from ITC)

1. What are the sedimentation characteristics of the 'Nga Moe Yeik' reservoir?

U Aung Myint*: Right in front of the dam, there has not been deposited a lot of sediment. I think since the construction of the dam a layer of around 1 ft of sediment has accumulated.*

But at the upper parts of the reservoir and at the inlets the sedimentation is a lot worse. I think it is about 3 ft there.

But probably the most sediment particles have been deposited at the rivers and creeks between 'Nga Moe Yeik' and the two upstream reservoirs; 'Ma Hu Yar' and 'Paung Lin'. In the early days, before the 'Nga Moe Yeik' dam was constructed, the creeks used to be about 10 ft deep. Nowadays they are nearly completely filled up with sediments.

2. What are the sediment characteristics of the *'Ma Hu Yar' and 'Paung Lin' reservoirs*?

U Swe Sein*: The sedimentation of the 'Ma Hu Yar' reservoir can sometimes be pretty severe. I think at the base of the dam the annual sediment deposition is about 6 inch. At the inlets of the reservoir it will probably be something more like, 1 ft every year. But still the water flowing into the reservoir is not very turbid, so that does indicate that there are no extreme amounts of sediment particles in the water.*

U Khin Maung Hlay*: For the 'Paung Lin' reservoir we don't know very much, because the dam is only accessible by boat when the creek to the reservoir has been filled by water. There is no road leading to it. We are only present at 'Paung Lin' a few times a year.*

3. How do the reservoirs work together and how is the water divided between them?

U Khin Maung Hlay*: During the rainy season (May until September) the first priority is to completely fill 'Nga Moe Yeik'. To do so, the gates of the 'Ma Hu Yar' and 'Paung Lin' are completely open. When 'Nga Moe Yeik' is full, the gates will be closed and 'Ma Hu Yar' and 'Paung Lin' will be filled.*

During the dry season (October until April) the water of 'Nga Moe Yeik' will firstly be used, when this reservoir is getting pretty empty (usually around February) the gates of 'Ma Hu Yar' and 'Paung Lin' are being opened, so that this water can flow into 'Nga Moe Yeik' .This causes a lot of erosion of the deposited material at the bed of the rivers and creeks between 'Nga Moe Yeik' and the two upstream reservoirs.

4. What do you know about the land-use and land-cover of the catchment area of 'Nga Moe Yeik'?

U Khin Maung Hlay*: Most of the land-cover is just forest. But more and more pieces of land are getting bare, because of the deforestation. The government started a big project in cooperation with timber producers to make money. They build roads and use big machinery to exploit the forests. During the dry period the top soil can be very dusty and because of the activities a layer of up to 1.5 ft of dust particles can emerge at the roads. During the rainy season all this material will end up in the rivers, creeks and reservoirs.*

U Swe Sein*: Also a lot of people living in this area do live from the trees as well. So that also increases the deforestation. The deforestation is causing extra erosion of the soils in our catchment. And I think that the deforestation will increase in the future.*

5. Do you know what kinds of trees are present in the catchment area?

U Swe Sein*: There is a lot of bamboo growing in this area. But the 'Forest Ministry' did sell about 1000 acres to a company to make a plantation.*

6. Do you know anything about the soil type of the top soil being present at the catchment area?

U Khin Maung Hlay*: We do not know a lot about the soil types of this region. There are some soil maps available for the whole extent of Myanmar.*

7. Is there precipitation data available about the catchment area and do you know anything about the rainfall intensity of single events?

U Khin Maung Hlay*: We collect rainfall data of the three dams every day, so that will be available to you. But we don't know anything about the intensity of single events, because our measuring equipment is not precise enough.*

8. Is there any data available from the three reservoirs about the water inflow and outflow and the total stored volume?

U Khin Maung Hlay*: Yes, data about water inflow and outflow and total stored volume is available for the three reservoirs.*