NTNU – Trondheim
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Mulungushi Cascade Hydropower Project

A Technical Economic Assessment Of
Hydrology, Design And Power Production

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Mulungushi cascade

A new hydro power project is being developed in Zambia. The HPP project plan is to utilize the discharge from the Zambian river Mulungushi and the two tributaries Mboshi and Lombwa, in a cascade of two hydro power plants, the Mboshi and Mulungushi 2. The project is located in an area with a scarce data basis regarding hydrology, and this need to be revised. A sketch project has outlined the main components in the project such as dams, waterways and power plants and this will form the background for the thesis. The thesis will address the following topics.

- *An assessment of research regarding methods of improving hydrological basis in catchments with scarce or missing observations.*
- *Evaluation and upgrade of the hydrological data basis for the project area.*
- *Optimization of the main components with related cost estimate.*
- *If relevant specify an alternative design.*
- *Calculation of the estimated power production from the two hydro power plants.*

Preface

This master thesis finalizes the work at the Department of Hydraulic and Environmental Engineering and my two-year master at the Norwegian University of Science and Technology.

The work with this thesis has been challenging and there have been both ups and downs during the semester I have worked with it. The available data has been scarce and therefor I have been forced to make own decisions regarding methods and the data that was available. I have experienced that it is challenging to work on projects in developing countries. The data basis is not close to what we are used to here in Norway, and much time goes to find solutions that are good enough to be utilized. But it has been inspiring for me to work with a project abroad and with skilled professionals.

I would like to thank Professor Knut Alfredsen for his support with the hydrological model. Without his expertise this thesis would not be conducted in the necessary scale. I would also like to thank my supervisor Siri Stokseth for help, consultation, guiding and for connecting me to Lars Ødegård at SN Power. Lars Ødegård has been of great importance to finalizing this thesis. His experience in working in developing countries and his willingness to share both experience and tips have been of great value for me. I would also like to thank Professor Ånund Killingtveit for giving me an introduction to the hydro power simulation tool nMAG and Netra Prasad Timalsinato for helping out with scripts for the Thorntwaite model.

I would also like to thank SN Power for making this thesis possible, by letting me work on their project in Zambia. It has been a pleasure for me to work with such skilled people and an interesting topic.

Trondheim, June 10 2013

Simon Mulelid

Abstract

Steadily increasing economic growth and population growth in Zambia implies that the need for electrical power will increase in the coming years. There are currently developed around 1788 MW of a potential of about 6000 MW. It is therefore expected a major development in the coming years. This will contribute to improved living standard for the natives.

This thesis addresses the hydropower project "Mulungushi cascade", which is to be built about 70 km. southeast of the town Kabwe in Zambia. An Italian consultant has outlined the major components in a sketch project, and this is the basis for this report. It is planned to construct two new hydropower plants in a cascade with respectively 300 and 143 meters of head.

Data on local conditions are mainly obtained from a database with reports from the planning of a larger power plant 60 km. further east. This applies to both hydrology and costs for development, and has been supplemented by more traditional Norwegian costs basis and tools like TunSim.

Hydrological models have been used to simulate the inflow to the ungauged catchments. This has laid the foundation for the technical- economic optimization of the various components, and for the power production simulation.

The report argues for some changes in the conceptual plans. This includes replacing a large dam ($h \approx 70m$) with a small threshold ($h < 3m$) and a transfer tunnel (1100m), at a cost saving of approximately 22.8 M USD. In addition it is argued for replacing the penstock and surface power house for the Mboshi power plant with a solution consisting of a shaft and power station underground. This represents a saving of approximately 5 M USD.

It has been focused on optimizing the major cost drivers in the project such as dams, waterways and power plants and therefore smaller parts of the project has been omitted. This is to get an overview of the main components before optimizing the smaller parts. The total cost of construction is estimated to 165.11 M USD. Simulation of power production based on the overall technical specifications and the hydrological time series gave an average production of 370 GWh.

Sammendrag

Stadig økende økonomisk vekst og befolkningsøkning i Zambia betyr at behovet for elektrisk kraft vil øke de kommende årene. Det er per i dag bygd ut omlag 1788 MW av et potensiale på cirka 6000 MW. Det er derfor forventet stor utbygging i landet de kommende årene. Noe som vil bidra til økt levestandard for de innfødte.

Denne rapporten tar for seg vannkraftprosjektet «Mulungushi kaskade», som er planlagt bygget omlag 70 km. sørøst for byen Kabwe i Zambia. Et Italiensk konsulentselskap har laget et skisseprosjekt, med de viktigste komponentene i prosjektet og dette er grunnlaget for det arbeidet som blir utført. Det er planlagt å bygge ut to nye kraftverk i en kaskade, med fall på henholdsvis 300 og 143 meter.

Data om stedlige forhold er i hovedsak hentet fra planlegging av et større kraftverk 60 km lenger øst, dette gjelder både hydrologi og kostnader for utbygging. Dette har blitt utfylt med mer tradisjonelle norske kostnadsgrunnlag og verktøy som TunSim.

Hydrologiske modeller har blitt brukt for å simulere tilsiget til nedslagsfeltene. Dette har igjen lagt grunnlaget for den teknisk økonomiske optimaliseringen som er gjort av de ulike komponentene og produksjonssimulering av de to kraftverkene.

Rapporten argumenterer for noen endringer i det konseptuelle grunnlaget, blant annet å bytte ut en stor dam (h≈70m), med en overføringstunnel (1100 m) og en liten sperredam (h <3m) til en kostnadsbesparelse på 22.8 millioner USD og i tillegg bytte ut en planlagt rørgate og kraftverk i dagen med en løsning med sjakt og kraftverk under grunnen. Dette innebærer en innsparing på cirka 5 millioner USD.

Det har blitt fokusert på å optimalisere de store kostnadsdriverne i prosjektet slik som dammer, vannvei og kraftverk og derfor er mindre deler av prosjektet utelatt. Dette for å få plass det store bildet. Totale kostnader for utbygging er stipulert til 165.11 Millioner USD. Kraftproduksjonen ble simulert basert av hydrologiske serier og gav en gjennomsnittlig produksjon på om lag 370 GWh.

Contents

Abbreviations

GIS	Geographic Information System
GSMaP	Global Satellite Mapping of Precipitation
GWh	Gigawatt Hours
HBV	Hydrologiska Byråns Vattenbalansavdelning model
HPP	Hydro Power Plant
Km	Kilometer
Km^2	Square kilometer
LHPC	Lunsemfwa Hydro Power Company
l/s/km2	liters/second/square kilometer
M	Million
m.a.s.l	Meters above sea level
MCM	Million cubic meters
MMD	Mott McDonald? (consultant)
MW	Mega Watt
NOK	Norwegian Kroner
PMF	Probable maximum flood
PUB	Predictions in ungauged basins
RCC	Roller Compacted Concrete
SP	Studio Pietrangelli (Italian consultant)
TRMM	NASA's Tropical Rainfall Measurement Mission
TWh	Terawatt hour
USD	United States Dollar

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Chapter 1 Introduction

The majority of the Zambian power supply is provided through hydropower operations along the two rivers Kafue and Zambezi, and additional power generation is required for further economic development. Extensive mining operations are dependent on reliable and increased supply of energy, and an increase in economic growth combined with population growth implies that the power production have to be increased. Approximately two-thirds of Zambians are living in poverty with less than a dollar a day. (Vladimir Stenek, 2011) By developing the country's hydro power potential, the economic growth may continue and the standard of living will improve consequently. As a result of this the life expectancy will increase, from todays 51 to around 60 in 2040 and 76 in 2095. (FN-sambandet, 2014) This shows that an increased supply of electricity will have major consequences for Zambia.

The hydropower potential in Zambia is approximately 6 000 MW, and the installed capacity is approximately 1788 MW. (Energy Regulation Board, 2005) This implies that the country is facing both a challenge and a huge opportunity. Of the Zambian population there are only about 25 % of them who has access to electricity and in the rural areas the access is below 5 %. (Energy Regulation Board, 2005) The power demand in southern parts of Africa is increasing and it is expected that Zambia will be an important exporter of electricity for this region in the years to come. This indicates that there will be a great development in Zambia the coming years.

The purpose of this master thesis is to look into different solutions for the Mulungushi cascade project, developed by Studio Pietrangelli (SP). This involves establishing a hydrologic basis for the ungauged catchments, optimize the technical solutions and perform a power production simulation based on the chosen components.

1.1 Background

SN Power is involved in the plans of developing the Muchinga hydropower project in Central Zambia. In cooperation with SN Power there have been conducted two theses on this project. It was carried out by Marius Jentoftsen and Kristoffer Hansen. They have studied the Lunsemfwa basins, and in their thesis' they have done an economic evaluation of different parts of the project. In relation to the Muchinga project, it was desirable to explore the possibilities in the adjoining areas. In that regard the potential for the Mulungushi cascade project was identified, and this is the project that this thesis will cover.

The Mulungushi cascade is not directly connected with the catchments for the Muchinga project but it is a project within geographical proximity, so it is expected that much of the data basis may also be valid for this project. This project is also initiated by the same project group and involves the same consultants, project management team and owners. This may have positive influence on this project, because increased knowledge about the area before starting on this project.

The project is as stated, located in central Zambia approximately 70 kilometers from Kabwe. In the sketch project there is proposed a cascade of hydropower with three dams, one transfer tunnel, one surface power house and one underground power house. This forms the basis for the thesis, and based on the hydrological modelling the economic viability for the project will be assessed.

Figure 1 shows that there is a huge undeveloped hydropower potential in Africa. But there is a nuanced picture, and it is important that the stake holders manages both energy and water resource in tandem. Both the energy and water demand is increasing and a holistic approach is vital for a safe and secure future. Over 2.7 billion people lives in basins where they experience severe water scarcity at least one month of the year. (Arjen Y. Hoekstra, 2012) This is important to have in mind when designing new projects.

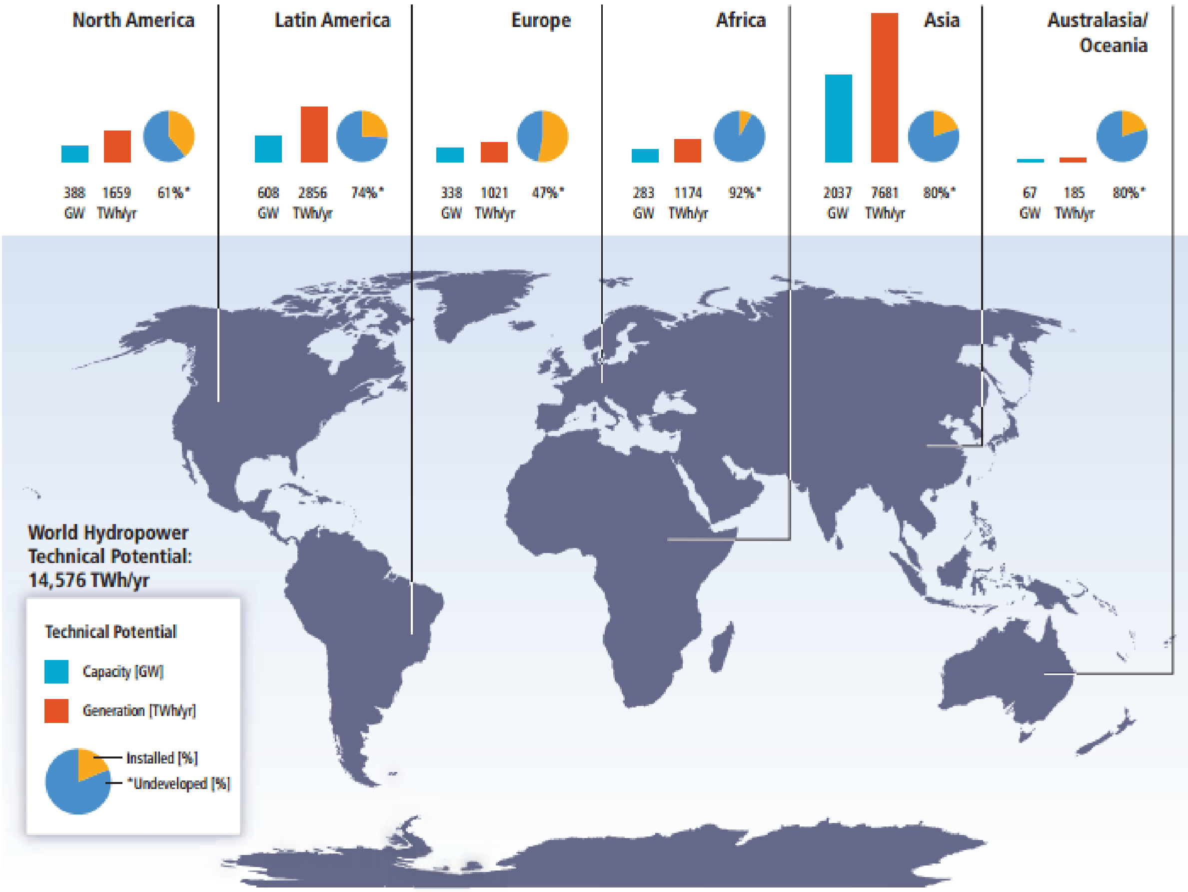

Figure 1 World hydropower technical potential (Intergovernmental panel on climate change, 2011)

1.2 SN Power

This thesis is conducted in cooperation with the renewable energy company SN power. It is a leading hydro power company in emerging markets, contributing to economic growth and a sustainable development. The company was established in 2002 and its owners are the Norwegian state entities Statkraft (60%) and Norfund (40%) (SN Power, 2014) SN Power has a share of 1 192 MW installed capacity in operating plants and construction projects, and an annual mean generation of almost five TWh. SN Power and its subsidiaries were employing 494 people in 2011. And additional 715 people were employed through non-consolidated joint venture companies. SN Power is a part of the Statkraft group, the largest producer of renewable energy in Europe and the leading power company in Norway. Statkraft has over 100 years of experience in developing hydro power. Norfund is the Norwegian Investment Fund for Developing Countries. It is investing risk capital in profitable private enterprises in emerging markets. Through this owner, SN Power has access to experts with knowledge of conducting investments in emerging markets. This ownership helps to form a strong foundation for the work conducted on the different projects around the world.

1.3 Geographical location of the project

The project is located in Zambia, a landlocked country in the southern Africa. The country consists mainly of slightly rolling terrain and plateau landscape, and rages from 2329 - 329 m.a.s.l. but the majority of Zambia is located between 1500-900 m.a.s.l. The cascade project is located in central Zambia and the location is approximately 70 kilometers south east of Kabwe, and about 100km north east of the capital Lusaka. On figure 2 the location of the project has been marked with a red dot.

Figure 2 Zambia geographic location

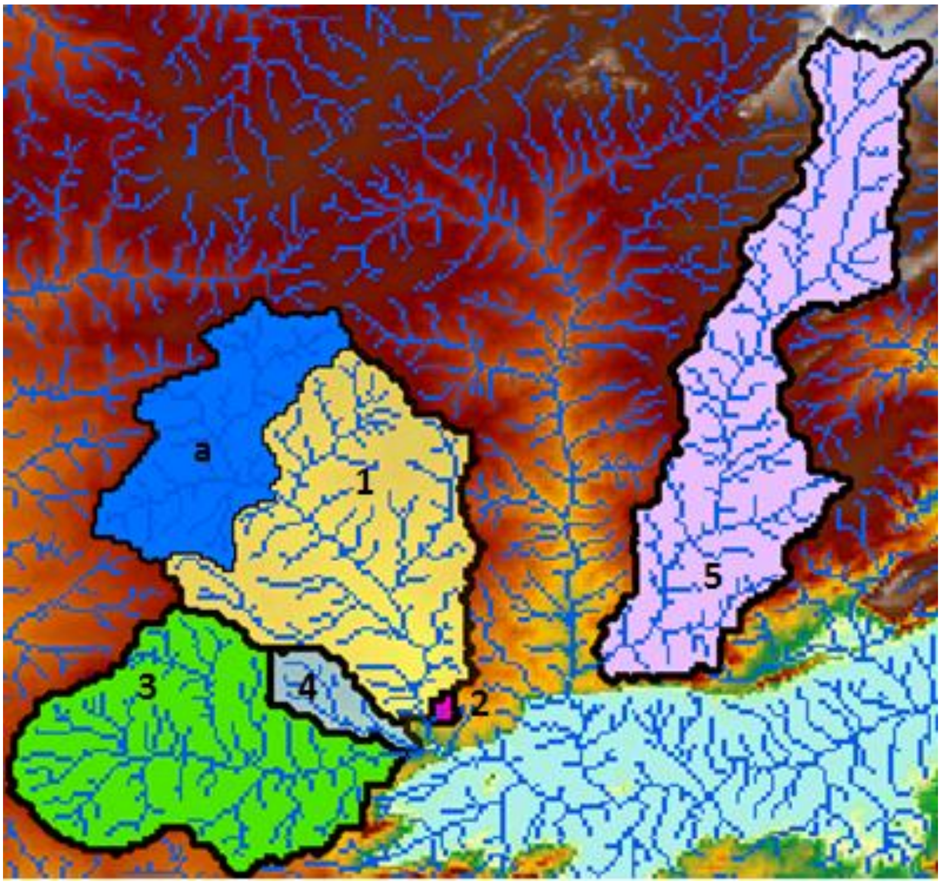

Figure 3 Project area with the catchments and sub catchments.

The project area consists of four different catchments that are showed in figure 3.

1. Mulungushi. In this catchment there is an existing dam and a hydro power plant. It is 4369 km^2. The water from this catchment drains into the planned Mulungushi 2 reservoir planned downstream the Mulungushi 1 power plant.
    a. Great North Road Catchment. The catchment is marked with a thinner black line. This catchment is a sub catchment within the Mulungushi catchment and this is where the daily discharge series for hydrologic modelling has been taken from. The catchment is 1448 km^2.
2. East. The eastern most catchment in the project area is the smallest of the ungauged catchments with its 66 km^2. It drains directly into the planned Mulungushi 2 reservoir.
3. Mboshi. This catchment is the largest of the ungauged catchments and is approximately 2724 km^2.
4. Lombwa is a small catchment, with its 322 km^2. It is a tributary to the Mboshi River.
5. Mkushi catchment is a part of the Muchinga project. It is 3562 km^2. And time series from this catchment has been used to calibrate a Thorntwaite model for hydrological simulation.

1.4 Mulungushi cascade sketch project

A sketch project has been developed for the cascade by an Italian consultant Studio Pietrangeli. During that work, three catchments draining into the project area have been located. In addition there is a catchment where an existing power plant already is installed; this is the Mulungushi catchment. The outlined design is illustrated in figure 4. The preliminary hydrological assessment for the sketch project is based on a specific runoff of 3.8 l/s/km2. (Studio Ing. G. Pietrangeli S.r.l., 2012)

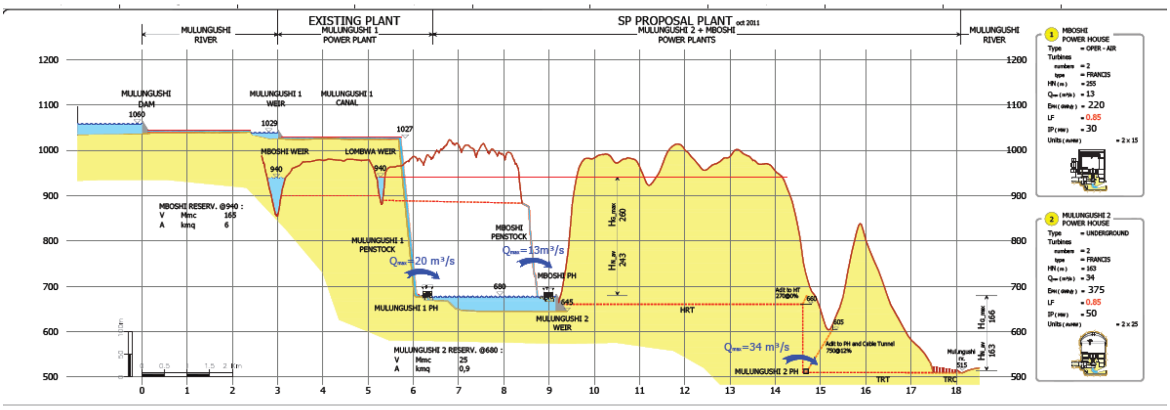

Figure 4 Cascade sketch proposal (Studio Ing. G. Pietrangeli S.r.l., 2012, s. 34)

The project will consist of two reservoirs with storage capacity, it is the Mboshi reservoir (165MCM) and the existing Mulungushi reservoir (233MCM). The other reservoirs have so little reservoir capacity that they will only be useful for limited regulations (days). The Mboshi and Lombwa rivers will form the basis for the Mboshi power plant, and all the catchments will provide water into the Mulungushi 2 reservoir and form the basis for the Mulungushi 2 power plant.

The sketch project is displayed in figure 5. The two basins forming the basis for the Mboshi power plant is in the bottom of the picture, they are planned with two dams and a total storage of 170 MCM, and will be connected with a transfer tunnel. In the left part of the illustration the existing Mulungushi power plant with the Mulungushi dam, the channel and the penstocks is plotted. This is not in the scope of this thesis, but it must be seen in context with the new development. In the upper right corner the tailrace tunnel for the Mulungushi 2 plant is viewed and the power plant is planned underground.

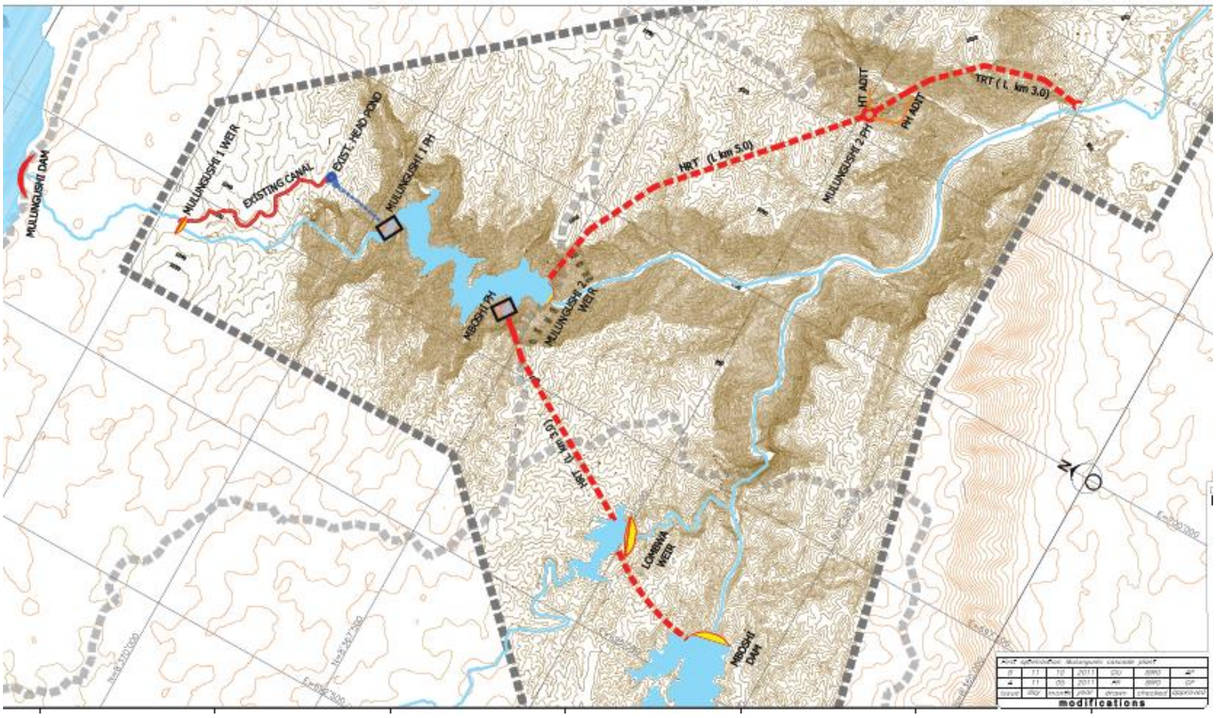

Figure 5 Basic master plan Mulungushi (Studio Ing. G. Pietrangeli S.r.l., 2012, s. 34)

1.5 Hydrological basis

The cascade project is located in an area where there is a scarce data basis regarding hydrology. There are no weather stations or runoff measurements available within the new catchments. This means that data from surrounding stations have to be utilized to establish the basis. There is currently an ongoing work with the Muchinga project, and there have been developed a few reports regarding the hydrology in that area. These will be used as basis for further work.

These reports are based on the surrounding catchments' weather stations and flow measurements. The data quality is variable, and for longer periods there are missing data. There is also varying quality on the measurements that have been conducted and registered. There have been carried out a few hydrological reports from different companies: Scott Wilson Piésold, Sweco, Studio Pietrangeli, Mott MacDonald, and Terrence Muir. These reports have been carried out to establish a hydrological basis for the large Muchinga project (>250 MW), approximately 35 km east of the cascade project. The reports have focused on the scarce data that is available and have utilized different methods, such as rainfall-runoff models, to extend the time series.

For the cascade project there have been conducted a feasibility study by an Italian consultant Studio Pietrangeli, they did not go deep into the hydrology, but based their assumptions on the specific discharge. Parallel to this thesis an experienced hydrologist named Terrence Muir is working on the hydrologic basis for the project. In an email he writes: "Good to see that someone else is struggling to get a good rainfall-runoff correlation as I have." This shows that the data basis could have been better. This is a part of the challenge when working in developing countries. One cannot expect the good data basis that is available in Norway. You have to take what you have and make the best out of it.

The isohyet map in figure 6 has been established for the Muchinga hydropower project, by the hydrological consultant Mott MacDonald. These maps have been made from interpolating between the available precipitation stations in the area. Based on the scarce data basis it is likely that the uncertainty of the isohyet map can be quite large +-20% or even more. But the isohyet map is a good indication on how the precipitation distribution in the area is.

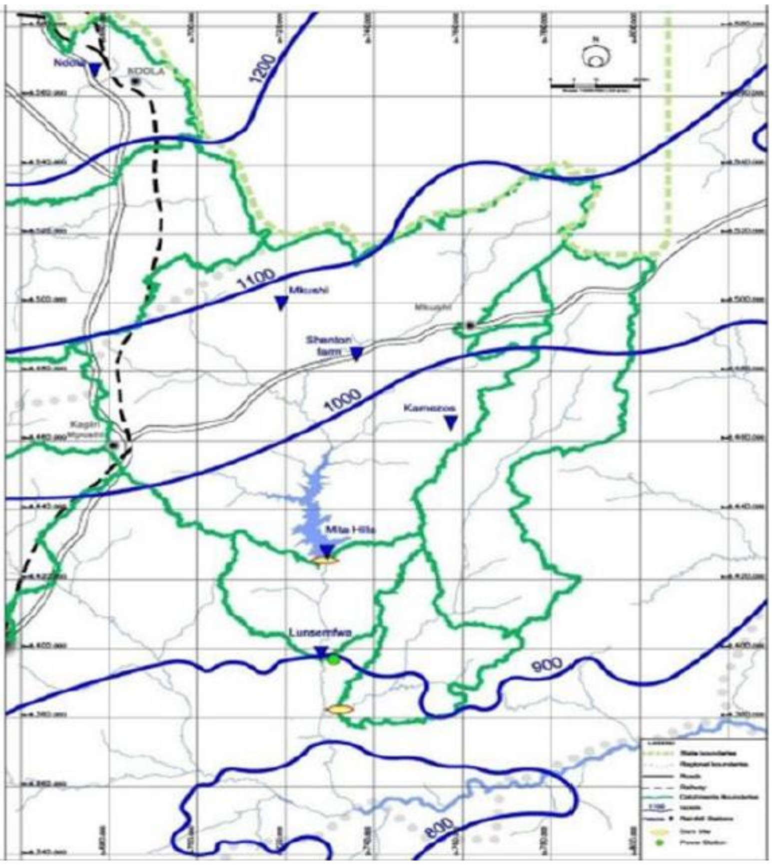

Figure 6 Isohyet map of average rainfall, Muchinga (Mott MacDonald, 2013)

To get the best possible data for the hydrological simulation it was necessary to evaluate the runoff and precipitation stations surrounding the project area to find the best possible match for the catchments. Unfortunately the data basis was, as expected, quite scarce and the most of the runoff stations contained only monthly accumulated values. This is not the most convenient to work with when planning hydropower. But some of the monthly series had been updated and evaluated, this was series from the Mkushi and Mulungushi catchment. They consisted both of more than 50 years of available data, and this was regarded as the best option for the hydrological simulation, although daily measurements had been preferable. The series had been made available from Dr. Terrence Muir, he had quality assured them and unreal values had been corrected or omitted from the study. A more thorough description of the hydrology is described in chapter 3.

1.6 Production Potential

The Mulungushi cascade is planned as a series of power plants. There is as mentioned earlier in the thesis, already an existing power plant, the Mulungushi 1 and there are currently some ongoing plans for upgrading and rehabilitation of this power plant, to utilize more head, but this will not be addressed in this thesis. The existing power plant still creates some restrictions for the new power plants, which have to be considered when choosing dam site for the Mulungushi 2, and outlet for the Mboshi power plant.

The cascade project aims to connect the two river basins Lombwa and Mboshi, for utilization in the Mboshi power station. The feasibility study concludes with a specific discharge of 3.8 l/s/km2. Based on this an estimate on mean runoff has been calculated to be 11.5 m^3/s for the Mboshi power plant, and approximately 28 m3/s for the Mulungushi 2 power plant.

The dry season from April to October is critical in this project and a main objective is to analyze the inflow to the reservoirs, and consider whether it is possible to store water from the wet to the dry season, and produce firm power over the year. The existing Mulungushi reservoir has as mentioned a capacity of 233.6 MCM and the Mboshi reservoir will increase the storage capacity in the area with approximately 165 MCM. The Mulungushi 2 reservoir, which is a small reservoir with only 7 MCM, will be used on a daily basis to optimize the power production.

Studio Pietrangeli have in their feasibility study, identified the theoretical production from the two new plants. They have been quite optimistic and suggest 220 GWh for the Mboshi power plant and 375 GWh for the Mulungushi 2 power plant. It is important to emphasize that this is only theoretical values presented. The production cannot be expected to reach these values, due to different efficiencies, head, evaporation and spill from the reservoirs. Given the current conditions in Zambia where there is a power deficiency it is assumed that distribution of firm power is most important. This imposes restrictions on how the power plants should be operated through the year, and thus also the power production, this has not been taken into account when the potential was calculated. A more thorough investigation of production will be conducted in chapter 5.

1.7 Constraints

When planning and building large projects internationally there will often be several problems occurring and this will have to be considered in the early phases of the project. Especially in developing countries you may encounter problems that are not relevant for development in the Norwegian mountains. Not all countries have as good guidelines and laws for development as Norway, and the governmental institutions is often not of the same magnitude as in Norway. This and a lack of capacity and resources may lead to difficulties when cooperating with the government. There is often different political opinions regarding development and therefore it is important with communication to bring out all the aspects of the development. The locals know the area better than a hired consultant but they often don't possess the technical expertise, so a good dialogue may lead to a better solution for all parts. There is also often a lack of funding for the bigger projects. Therefore it is more common for major foreign companies to contribute with funding and planning. This usually creates a lot of jobs in the construction period for the local people and good tax revenue for the governments in the operational period.

In many developing countries, corruption affects people's everyday life and is a part of the culture. On Globalis' corruption scale, Zambia is in 2012 placed on 37 and Norway is placed on 85 on the corruption scale. The corruption scale ranges from 0-100 where 0 is very corrupt and 100 is completely clean. The scale includes corruption in the public sector and in politics. (Globalis, 2014) Even though corruption may be a part of every people's life it should not be used as an excuse and corruption committed abroad by Norwegian enterprises and citizens is punishable both in Norway and most other countries.

The conditions for the workers are often not the best and it is important to have contracts that ensure safe and good working conditions for them. Health, Safety and Environment must be discussed in advance with the contractor to ensure that they share the same goals as the construction client. This will lead to a safer workplace for everyone involved.

1.8 Objective

This thesis is threefold and consists of three main parts: a hydrological assessment of the project area, a technical economic assessment of the planned project and a power production simulation based on the established terms. The main objective of the thesis is to consider whether the project is economically viable, but to do this one must have some calculations to rely on. The thesis will highlight these points:

- Establish a hydrological basis for the ungauged catchments in the project area.

- Evaluate the proposed technical solution and optimize it.
- Establish a cost estimate for the key components of the project.
- Based on the established hydrology and the optimized technical solution, perform a production simulation.

1.9 Report Composition

The theme of this thesis is based on different fields of study, and the different parts rely on each other. The composition is therefore done in different parts:

1. Hydrology

   The basis hydrology in the catchments is essential and In this chapter the hydrology for the ungauged catchments will be evaluated and a simulation of the hydrology will be presented. The available water, lays the foundation for the technical solutions.
2. Technical specifications and optimization

   The key parts of the hydropower project will be assessed and optimized and a cost estimate for these components will be conducted. Some refinements still have to be made, and smaller parts of the project will be omitted. The main features that will be prioritized are the dams, waterways and power stations. These components are expected to be decisive for total costs.
3. Simulation of production

   When the major components are determined, a power production simulation will be conducted by using nMAG. The hydrological data prepared in chapter 3, and the technical specifications prepared in chapter 4 forms the basis for this simulation.
4. *Conclusion*

   A presentation of the optimized solution.

Chapter 2 Theory

2.1 Collecting data

In order to create a good foundation for the thesis, reliable sources are essential. This applies both to how the conditions are in the area and updated literature regarding theory and methods. The information have been collected from different sources

- Internal database with reports from the Muchinga project and feasibility study regarding the cascade project.
- Articles and books found by searching in public databases, such as: BIBSYS, Google scholar etc.
- Literature suggested by Professors and supervisors.
- Updated maps for the project area created from LIDAR data, distributed from SN Power.

The information gathered makes the basis for this thesis, and is of great importance for the quality of the results. The project manager has made the reports regarding the Muchinga project available, and these have been important to gain insight into the project area. A sketch project outlining the main components for the Mulungushi cascade, performed by SP, lays the foundation for this work and the methods and procedures chosen for this thesis.

Articles which are included are found by searching different databases and relevant articles have also been suggested by supervisors and staff at the department of hydraulic and environmental engineering. The local library has been used to access relevant books. Conversations with the supervisor and skilled professionals at the Faculty of Construction and Department of Hydraulic & Environmental Engineering have been vital for the progress of the thesis.

2.2 Methods

Different methods have been used to establish a basis for the thesis.

- Study of relevant literature
- Communication with experienced professionals
- Different models and databases
- Reports from projects in the same area
- Guidelines and cost basis for hydropower

- (Field trip)

2.2.1 Field trip to Zambia

A field trip, together with the project manager in SN Power, to check the assumptions made in the thesis was planned in April 2014. The plan was to see the project area and evaluate the solutions that are presented in this thesis. The field trip to Zambia was important for this thesis in many ways. To be able to see the places you are working with is extremely valuable, because it will complement the information you get from a map or reports. And talking to the locals may lead to better solutions for all the involved parts. As Professor Leif Lia once said, if you are not visiting the area where you are planning your project and see it with your own eyes, you are not doing your job properly. Unfortunately due to illness in the project group the field trip was canceled and therefore many of the assumptions stated for the thesis could not be verified. But the project manager Lars Ødegård has shared willingly from his experiences and the reports regarding the Muchinga hydropower project.

2.3 Predictions in ungauged basins

The project is planned as a cascade of hydropower plants in an area with lack of good hydrological data. The identified catchments are ungauged so measures have to be taken to obtain data from surrounding measurements stations.

Catchments with no available measurements of runoff or precipitation are often a problematic area in terms of hydropower planning. When working with hydropower it is important to know how the hydrological conditions have developed through the years and how they are now, this gives an indication of what to expect in the future. This is often hard to obtain developing countries and usually some assumptions have to be made. New projects are often established in areas with minimal data available. In catchments where there are no available measurements, this must be obtained from surrounding catchments with precipitation / runoff measurements and adapted to the particular catchment. This is a field within hydrology that has received a lot of attention the last ten years. This is based on that there has been a considerable uncertainty connected to the existing models and methods for predictions in ungauged basins.

Predictions in ungauged basins (PUB) is a field of study where it has been performed substantial research over the last decade. It all started with The Prediction in Ungauged Basins initiative of the International Association of Hydrological Sciences in 2003, and it was concluded by the PUB symposium held in Delft, October 2012. In the early 2000's it was a common understanding among hydrologists, that the hydrological models available at that time was inadequate for predictions in ungauged basins, and a research project was initiated to improve this. The main objective for the research was, as seen on figure 7, to both improve the existing models and to create new innovative models. This approach involves a shift from models strongly based on calibration to new models with a greater emphasis on increased levels of understanding. And eventually by doing this, minimizing the uncertainty and improve the confidence of the results. But there were many challenges and especially the connection between small scale physics and the large scare catchments was a struggle. (M. Hrachowitz et. al, 2013)

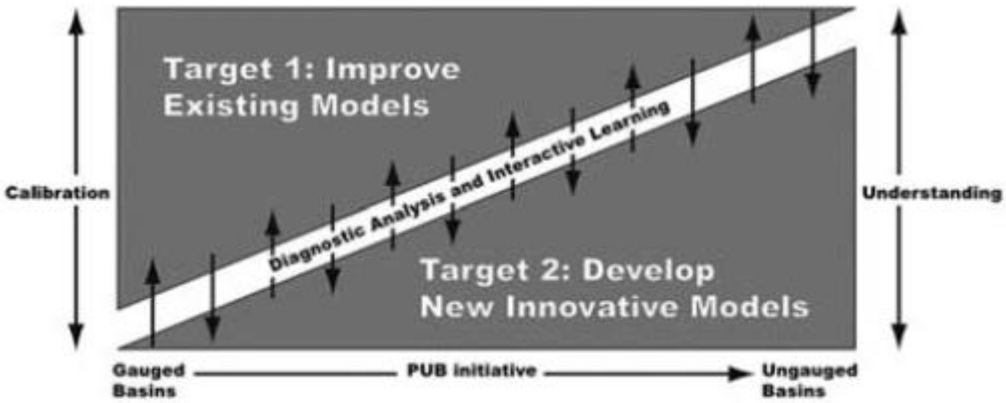

Figure 7 Improvement of hydrological models (M. Hrachowitz et. al, 2013)

The main problem with ungauged catchments is the scarcity and quality of available data. This is a widespread problem, and many ground based measuring stations are being closed due to cut backs of financial support. However this problem will probably diminish in time because of increased access to and quality of remote sensing. The increased accuracy and resolution will lead to increased use in ungauged basin.

Remote sensing technology is an area that has developed much in these years. Extended use of existing and new technologies such as radar and satellite for estimation of precipitation will improve the results further considering the PUB problems. The development has been great and higher resolution, increased areal coverage and minimizing of uncertainty will contribute to make the models more reliable in the future. There are currently several different remote sensing techniques available such as microwave scanning, gravity observations, radar, thermal imagery technology, and snow cover estimations and they are constantly evolving. These techniques will be important tools in hydrological modelling in the years to come.

When it comes to remote sensing, satellite observations has become more available and often for free. Especially the NASA's Tropical Rainfall Measurement Mission (TRMM) has a large potential, it delivers 3- hourly precipitation totals, with a resolution of 0.25° x 0.25°. This is particularly useful for extracting data in areas with poor data availability. These data can be a good source of information, but they still need to be calibrated to the catchment, which means that there must be some data available.

Remote sensing was utilized by Knut Alfredsen and Sunil Ghaju in their work on evaluating satellite based precipitation and their applicability for rainfall runoff modelling in Naranyani basin of Nepal. They were examining the satellite precipitation from TRMM and the GSMaP and comparing them. Their conclusion was that the TRMM data could be used with linear scaling for runoff simulation in hydrological models. They concluded that the work was promising, but that it would require more studies in different catchments to strengthen their conclusion. (Sunil Ghaju, 2012) However based on the extent of the work needed to establish a reliable model based on satellite images, it was concluded that this was not an approach that should be utilized for this thesis.

The research period, of 10 years, have also provided several new and better solutions for ground based observation technology. This involves new technology for stream flow measurements, microwave links for evaporation and precipitation estimation and distributed temperature sensing to mention some of the developments. Extensive use of wireless technology for transmission of data has been implemented, making it more convenient to collect data from the measurement stations. This is technologies that will make hydrological data more available in the future, however for this thesis it has minimal influence, this is because there will not be conducted any field work and the thesis is solely based on the data already available.

When it comes to models there were different opinions on what type of models were best suited for general use in the start of the decade. There are many different models such as: physically-based, index-and conceptual models. Through the research, more openness between the different groups was achieved, but still no one has been able to create a model that emphasizes the complete hydrology. There is still disagreement on how the structure of the model should be and an agreement that many hydrological models are over parameterized. One of the main goals for the PUB initiative was to lead to a more united and coordinated modelling strategy, this has however not been achieved and there are still different opinions on how these model simulations should be performed. In regard to calibration of the model, there are different approaches for each model. But some models can be calibrated with down to 2-3 years of available stream flow data (M. Hrachowitz et. al, 2013), it should be noted that this applies to specific areas but it shows that the work goes in the right direction. Even though there are several different hydrological models available there are still new model developed. This is because there has not been any model managing to describe the hydrological cycle completely.

The prediction in ungauged basins initiative has been a success, and much effort has gone into developing new methods, models and equipment to simplify estimation of runoff in ungauged basins in the future. It has led to a more united hydrological professional group, which can be positive for development in the future. A description of the development is illustrated in figure 8.

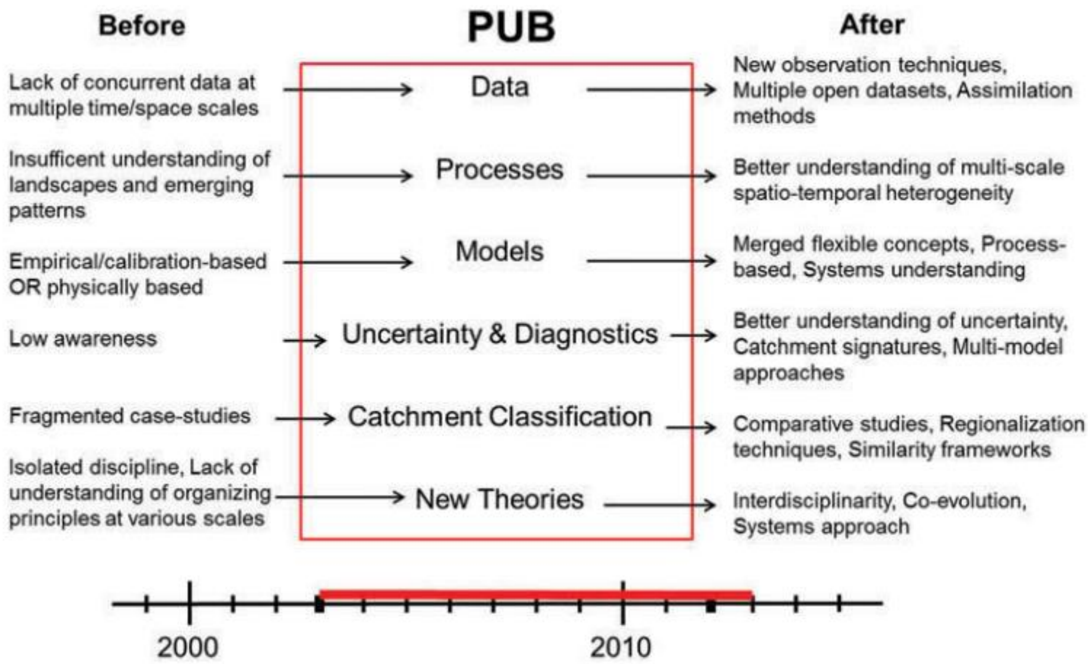

Figure 8 Outline of how scientific understanding evolved during the PUB decade (M. Hrachowitz et. al, 2013)

But even though there are new methods and an increase in advanced equipment it is important to emphasizes that there is not much that beats placing a gauge in the river. That small investment can provide important information about the hydrology in the river, even if it is not for a long period. This also gives the possibility to validate the results from simulations.

2.4 Tools

To create a reliable foundation for this thesis there have been used several different tools. These have been important in different phases of the work. Hydrological models have been used to establish runoff time series. Geographic information system has been used to create basis for hydrological models and technical specifications. Cost database have been used to obtain unit prices for construction and the power production simulation gives the final output. All of the tools have been vital for this thesis and a short description of each tool is presented below.

Thorntwaite model

This is a monthly distributed rainfall runoff model. This means that it uses accumulated values of precipitation and runoff as well as mean monthly temperatures for simulating the response from the river. It is a distributed model because it utilizes spatial distribution of input in combination with algorithms that calculate spatially distributed hydrologic response.

HBV model

This is a daily lumped conceptual rainfall runoff model. It uses daily values of precipitation, temperature and evaporation to simulate the runoff. That it is a lumped model means that it handles the catchment as a whole and there is no accounting for spatial variations in input parameters. Conceptual models have the main components from the hydrological cycle implemented in the model, and the process is described as catchment averages by simplified equations.

TunSim

Is an Excel based cost estimation database, for tunneling. It contains cost data for different machines, and tunneling methods. The database is established based on Norwegian expenses, but it is possible to replace the given parameter with new input and can thus adapt to other markets. The tool is developed at the department of Civil and Transport Engineering at NTNU. This tool is utilized to obtain tunneling cost for the different tunnels. An adaption of the parameters and costs to better fit the Zambian conditions was conducted:

- Drill hole diameter: 48 mm
- Electricity price 0.09 USD / kWh
- Skill level: Low
- Drill hole length: 5 meters
- Blastability / Drillability: Medium (No valid information available)
- Explosive type: ANFO
- Interest rate: 15%
- Hourly wage: Based on table 6, in chapter 4.
- Working hours: 12 hours a day / 6 days a week for underground workers.

These main parameters are locked for all the tunnels, while the tunnel specific parameters were changed for each tunnel. This applies to everything from tunnel length, cross section, distance to dump and so on. The cost per meter tunnel is then established based on the input.

nMAG

Is a power production simulation tool. By implementing the technical aspects of the project and the hydrology it simulates the production through the available years. The model uses the time series established from the hydrological modelling and the final technical specification as input. A guide curve is then specified for each reservoir, determining how they should be operated. The software then calculates production for each time step.

Geographic Information System (GIS)

Gis is a system that allows people to collect, organize, manage, analyze communicate and distribute geographic information. (Esri, 2014) The use of geographic information systems in hydrologic modelling is based on the fact that there is a relationship between the shape and slope of the catchment and the precipitation/ discharge. There has been a development when it comes to this type of modelling, with the increased availability to accurate digital terrain models. New tools have been developed, making it possible to evaluate the hydrological effects on different topographies and terrains. The water is always in motion and the digital terrain models make it easier to take this into account.

For this master thesis the software utilized has been ArcMap 10.1.
The software was used to optimize the location of the dams and the power houses. It was also utilized to create the map data for the Thorntwaite model, and to extract the hypsographic curves for the catchments for the HBV model. It was also used to create the surface-elevation-volume relationship for the planned reservoirs.

All the maps are based on data established by LIDAR (light detection and ranging). "This is an optical remote- sensing technique that uses laser light to densely sample the surface of the earth, producing highly accurate x,y,z measurements. It is primarily used in airborne laser mapping applications." (ArcGis Resources, 2014) The project area has been mapped with increments of 1 meter. This was established before SP started the feasibility study. The good map data has simplified the work and made it easier to make accurate assessments and increased the quality. Figure 9 is a simplified illustration of how the LIDAR data is made.

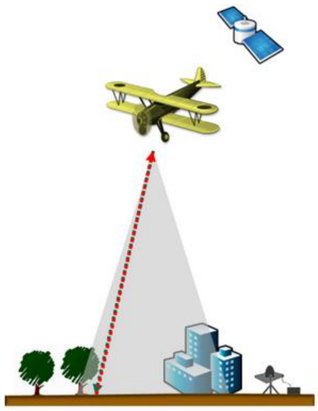

Figure 9 Lidar survey (ArcGis Resources, 2014)

2.5 Uncertainty

Because the project still is in the sketch phase, it is natural that there is a great uncertainty related to the development with regard to hydrology, local conditions, geology, costs etc. This uncertainty should be minimized to make good decisions.

When working with hydrology there is always a great uncertainty, this may be based on the instruments used to perform the measurement or errors connected to technically problems to obtain the data. This may be exemplified by major floods where it is difficult to access the measuring point, or the measuring station. This applies especially to the monthly hydrological model used in this thesis, where it has been used averaged values on a monthly basis, because the deviations in the discharge through the month can vary a lot.

The hydrological basis for the simulation was scarce, and not all of the measurements have been properly conducted.[1] This is some of the challenges that may be encountered when working in developing countries. It is not reasonable to expect the same data basis as when working in Norway, especially not in the early stages of the project planning.

There have not been conducted any mapping of the geological conditions in the project area. This means that all the assumptions regarding rock quality and the dam sites are based on maps, aerial photos and communication with Mr. Ødegård. It has however been conducted extensive mapping of the geology and topography for the Muchinga project 35 km further east, and it consisted mainly of rock with good quality. Since these two projects are in the same area it is assumed similar conditions but this assumption comes with a high degree of uncertainty. An extensive mapping should be carried out for the cascade project area to survey the conditions.

[1] Communicated by Terrence Muir.

Some of the tools that are used to identify the costs for the project are based on Norwegian techniques and costs. For goods sold on the international market, this approach is not considered to be so far from the truth. But for costs connected to tunneling the approach is more uncertain. To minimize the uncertainty there have been taken two measures. The tool was adapted with Zambian prices, and the final costs were compared to the cost base provided by MMD for the Muchinga project. The costs for rock support have been solely obtained from the MMD cost base, but the extent of it is more uncertain due to the lack of geological conditions. A conservative approach is chosen.

Chapter 3 Hydrology

The hydrology in the project area is the factor that provides the foundation for the entire development. The optimization of the individual components is based on this foundation, and therefore the hydrology is processed first. In this part a hydrological model will be calibrated with data from measured precipitation and runoff stations and applied to the ungauged catchments.

3.1 Data basis

The feasibility study is based on hydrological data from the Muchinga report, and calculation of the available yearly flow in the report is presented in table 1. These data, underlies the technical solutions presented in the feasibility study.

Table 1 Average inflow feasibility study (Million m^3 / year) (Studio Pietrangeli consulting engineers, 2011)

Mulungushi	548.7
Mboshi + Lombwa	346.9
East	6.3

The availability of hydrological data in Zambia is not comparable to the Norwegian standard. The hydrometric network of Zambia is not in a good state and the total number of registered stations is 284, but only 127 of them (44.7%) are still operational. The quality of the measurements is not always the best either, and for long periods there may be missing data. (Mwelwa, 2004) This is something that is not only applicable to Zambia, but applies to most developing countries. It is often difficult to obtain good data. This makes it hard to draw reliable conclusions regarding the hydrology. This indicates that the data available must be fully utilized.

3.2 Mboshi hydrometrical station

One of the key elements when working in Africa is that things take time to accomplish. Since the start of the concept project, a hydrometric station has been planned upstream the planned Mboshi dam. The intention was to get a better understanding of the inflow to the planned reservoir. But even though the placement of the station was well planned two years ago in 2012, it has still not been carried out. (Studio Ing. G. Pietrangeli S.r.l., 2012) The deployment of this station (figure 10) should have been carried out as early as possible, even in the sketch phase. This could have provided a good basis for further evaluations of the catchments hydrology.

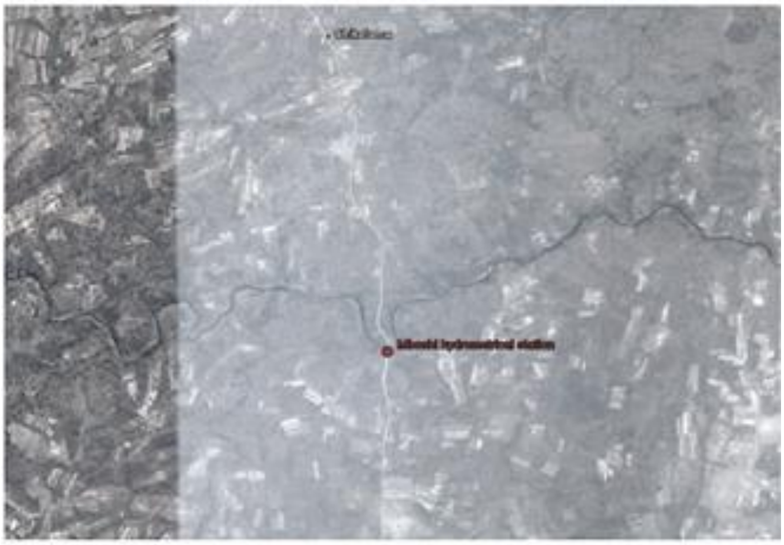

Figure 10 Mboshi hydrometrical station

3.3 Run off data

Even though there is a scarce data basis a few good time series was identified in the Mkushi and Mulungushi catchments, and they will form the basis for the hydrologic model. These two series was considered to be the best available, even though they only contained monthly accumulated values.

3.3.1 Muchinga dam site at Mkushi

This is identified as the longest time series. The series consists of monthly runoff data from 1920 until 2013. This series is generated by application of a Pitman model and the missing data have been transposed from Old Mkushi Road Bridge, by using a factor based on ratio of drainage basin area and monthly precipitations, this has been carried out by Dr. Terrence Muir. The series have been plotted in figure 11 to evaluate the trends in the runoff pattern. Based on the available data, there is no reason to believe that there are major changes in runoff pattern going on. The variations from year to year is simply natural fluctuations, this is based on that the cumulative values show a steady increase throughout the time series.

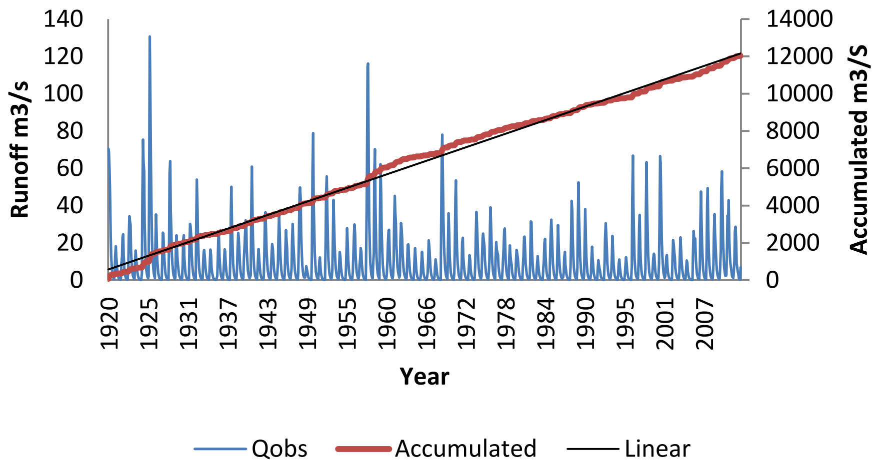

Figure 11 Mkushi runoff (Muir D. T., Note on Derivation of Extended Monthly Precipitation Series for the Mkushi Basin, 2014)

3.3.2 Diversion dam Mulungushi

This time series holds data from naturalized flows computed from operational records. The missing values where reconstituted by calendar monthly regression with other monthly stream flow and precipitation records in the catchment and surrounding. The time series holds data from 1961-2010 and the missing values have been filled by Terrence Muir, so there is a complete series, as illustrated in figure 12.

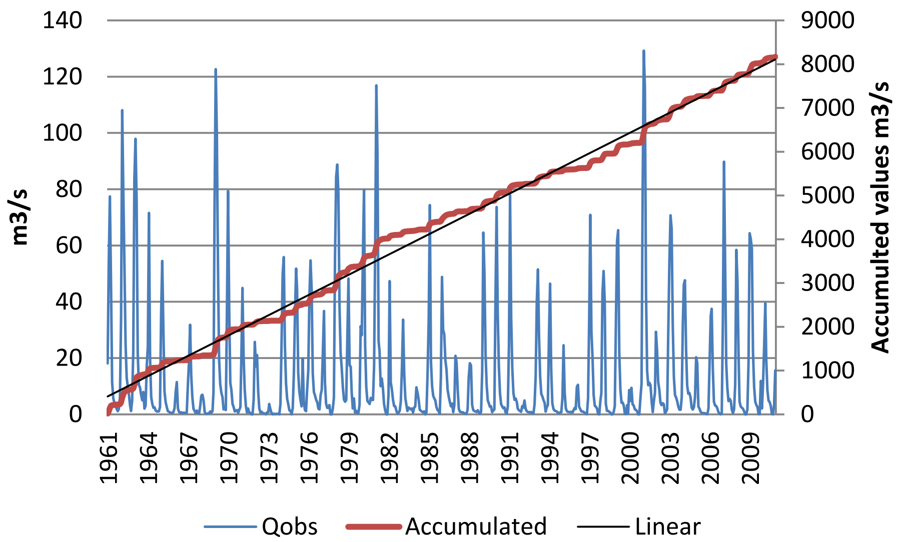

Figure 12 Mulungushi weir runoff

3.4 Precipitation pattern in Zambia

Zambia is a country with a precipitation pattern that is mainly dominated by two seasons; the rainy season between November to April and the dry period from May to October. (Iexplore, 2013) During the wet season the rain falls with great intensity and in the dry period there is hardly any precipitation at all. This entails that there is an abundance of water in the wet period of the year and a shortage of water in the dry period. One of the main objectives with this thesis is to examine whether it is possible to store water from the wet to the dry season, and hence be able to produce firm power through the year.

3.5 Precipitation data

The precipitation series utilized in the simulation is obtained from Dr. Terrence Muir's report "Mulungushi/ Lunsemfwa /Muchinga hydropower projects, Zambia". The series is derived from monthly precipitation series at meteorological stations, using the Thissen polygon. The data is derived for the Muchinga dam site. The data series is continuous from 1920-2013, and is considered to be the best alternative for the simulation. The time series is plotted in figure 13, and there is nothing that indicates changes in the precipitation pattern.

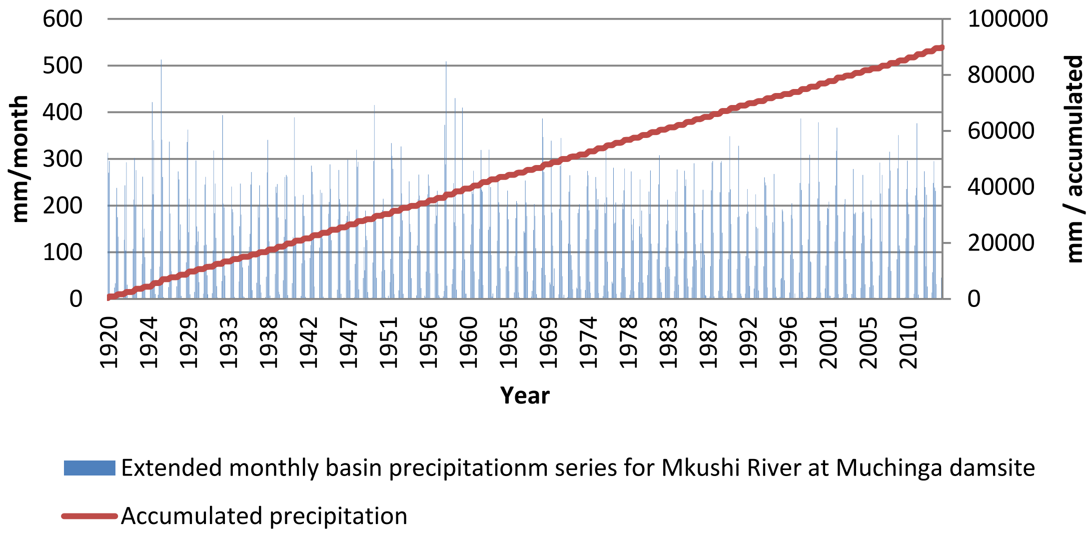

Figure 13 Extended monthly basin precipitation series for Mkushi River (Muir D. T., Note on Derivation of Extended Monthly Precipitation Series for the Mkushi Basin, 2014)

3.6 Temperature

The project area is situated about 1000 m.a.s.l. and the temperature can best be described as pleasant, with temperatures around 20-30 degrees Celsius most of the year. The temperature seldom goes below 10 degrees Celsius and it is with great certainty one could say that the project area is frost free.

For the hydrological simulation the temperature for the project area is needed, and a temperature station has been located in Kabwe. The elevation in Kabwe is about the same elevation as in the catchment about 1100m.a.m.s.l. This means that both the metrological station and the catchment lies on the same plateau and therefor have approximately the same temperature variations. The temperature station in Kabwe holds monthly temperature data back to 1932. However there are some missing values in the period March 1979-May 1980, and December 2005-February 2009. To fill the gaps and complement the series, some additional temperature stations were identified. These were ranked according to their correlation with the Kabwe station, table 2, with Livingstone as the best alternative.

Table 2 Correlation and average temperature in metrological stations

Weather station	Kabwe	Kasama	Livingstone	Mongu
Average temperature	20.44	20.04	22.01	22.19
Correlation	-	0.8897	0.9293	0.9289

Missing values were scaled according to formula 1. Since there is a large section of missing temperature values, all of the mentioned stations had to be used to fill the gaps. The result is shown in figure 14. For months where there were no available measurements the mean temperature from Kabwe was used, and this is particularly evident in the last years.

$$T_1 = T_2 + (avg.T_1 - avg\ T_{2)}$$ Formula 1

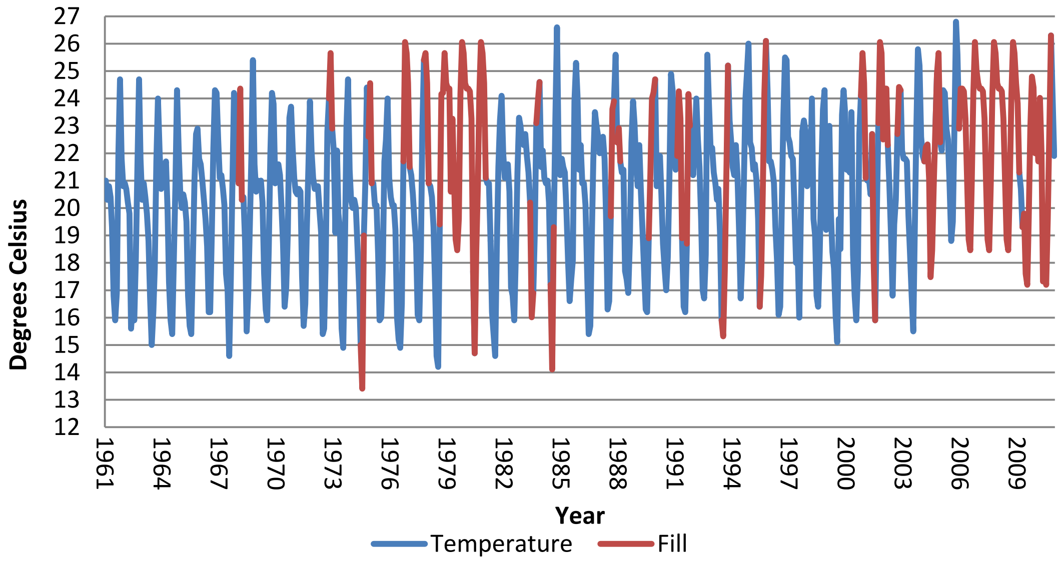

Figure 14 Average monthly temperature data for Kabwe, with filled gaps (DataMarket, 2014)

3.7 Simulation of runoff

Three different approaches were carried out to find the runoff from the unmeasured catchments. This involved simple area scaling and monthly / daily hydrological models.

A rainfall runoff model is used to simulate the hydrological behavior of a catchment. Based on mathematical equations, the measured precipitation and temperature is converted to the catchments discharge. The first rainfall runoff models were established in the 1950's, and since that there has been developed several different models. And even though there has been a development the last 60 years, there has not yet been developed a solution that describes the transformation of precipitation to discharge fully. This means that there will be variations in the results depending on the assumptions that were made and the approach that is chosen. The chosen approach has to be based on the available data and the catchments geographical location. (C.-Y.XU, 1998)

Different approaches were evaluated for the hydrologic modelling, and a few models were evaluated before the model was chosen. The HBV model was at first excluded because it is a daily water balance model, and the scarce data basis did not meet the requirements to run this model. But some additional data was made available later in the project and made it possible to run this model after all. The Pitman rainfall runoff model has been widely used in Africa as a water resource estimation tool. (Kapangaziwiri, 2010) This is also the model utilized by the hydrologist Terrence Muir in the preliminary study for the associated project Muchinga. This favored the model for the hydrologic evaluation of the ungauged basins. Unfortunately the model was difficult to obtain, and to prevent the work from stopping, the Thorntwaite model was launched as an alternative by Professor Knut Alfredsen. This is a model that runs on monthly averaged discharge and temperature.

3.8 Thornthwaite model

This is a distributed rainfall-runoff model. It uses averaged monthly temperature and accumulated precipitation to calculate the monthly runoff from the catchment. (Dingman, 2008) The model was run in RStudio, an open source software for statistical and computing and graphics. The code is originally based on a code written by Qingyn Duan from 16. May 2005, but was translated from Matlab to R and revised by Felix Andrews in 2009. It has also been edited by Emmanuel Jjunju at NTNU.

Model input

- Digital Elevation Model, covering the project area.
- Shapefile containing the boundaries for the catchment area.
- Average monthly temperature (Celsius) for the catchment area.
- Accumulated precipitation through the month. (mm/month)
- The temperature and precipitation in raster format, covering the catchment zone.
- Average runoff per month

Because the Thornthwaite model runs on rasterized temperature and precipitation data, this had to be arranged because it was not available. The solution was to rasterize the point precipitation and temperature data. A script was developed by Netra Prasad Timalsinato to create gridded precipitation and temperature, from the point measurements that were available. Figure 15 shows the rasterized version of the Mkushi and Mulungushi catchment. The measured point precipitation and temperature was distributed over the entire catchment as a grid and put into the model. This method implies that the precipitation and temperature is the same in the whole catchment, this adds uncertainty but is considered as a good approximation.

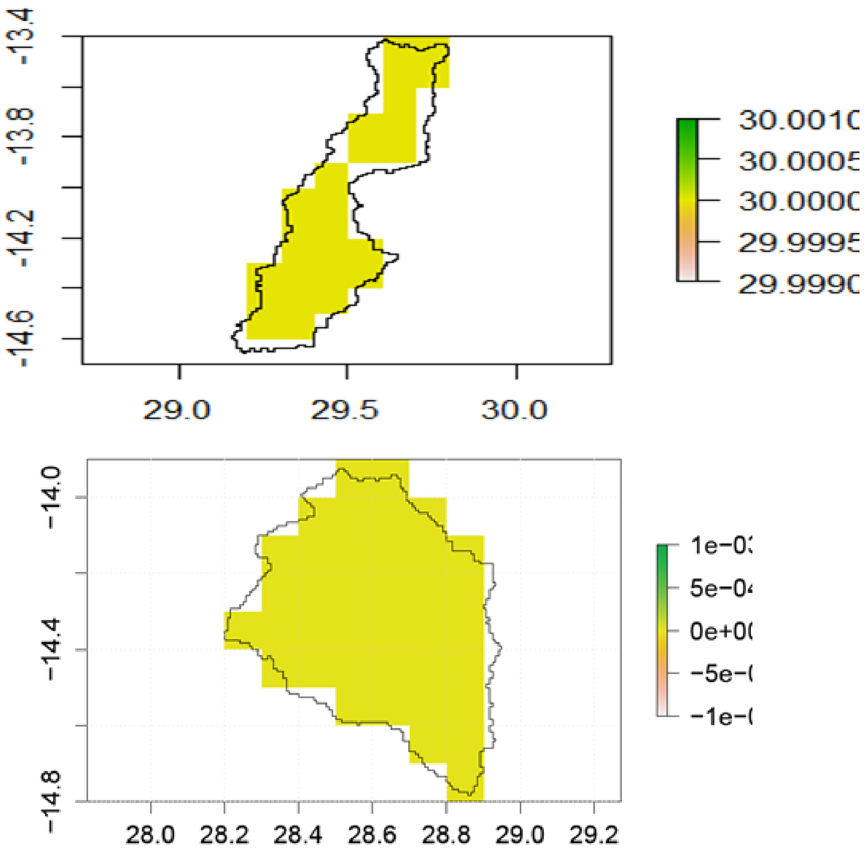

Figure 15 Distributed Precipitation and Temperature in the Mkushi and Mulungushi catchments

Calibration of the Thornthwaite model is based on seven parameters drofrac, rfactor, meltmax, STC, sn1, st1 and s1, where the last three parameters only are the initial start values for the simulation. There is often a perception that there is used too many different parameters in the hydrological models, but this model is manageable with four field-specific discharge parameters and three initial start values. A short description of the different parameters:

Drofrac is the fraction of the precipitation that becomes direct runoff.

Rfactor: Factor for generating runoff, it determines the fraction of surplus that becomes runoff.

Meltmax: Maximum melt rate

STC: Soil moisture storage capacity

sn1: Initial snow storage.

st1: Initial soil moisture storage (as percentage of STC)

s1: Initial surplus storage

(Markstrom, 2007)

3.8.1 Calibration

The model was calibrated for two different catchments, the Mkushi and the Mulungushi basin. The calibration was conducted with the runoff series from the Muchinga dam site, and Mulungushi diversion dam. The precipitation series was the derived series for the Muchinga Dam site.

The series was split to have one calibration and one verification series. The calibration period was from 1920-1969 and the verification period was from 1970-2012. The best results were obtained with the Mkushi catchment. The optimal parameters for this calibration are described in table 3.

Table 3 Thorntwaite optimal parameters

drofrac	0.01
rfactor	0.2
meltmax	0.01
STC	150
Sn1	0
St1	0
S1	0.5

The Nash Sutcliffe efficiency was calculated to evaluate the goodness of fit for the model. It ranges from - ∞ to 1, where 1 indicates a 100% match between observed and modelled discharge, 0 indicates that the model predictions is as accurate as the mean of the observed data and values <0 indicates that the observed mean is a better prediction than the model.

It is calculated by using formula 2, where:

Q_0^t = Observed discharge at time t

Q_o = Mean observed discharge

Q_m = Modelled discharge (Rforge, 2014)

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2} \qquad \text{Formula 2}$$

There are some controversy regarding the use of this criterion of fit, because it is oversensitive to peak flow, due to the use of squared residuals. (M. Hrachowitz et. al, 2013) However it will still be used for this thesis.

Performance Rating	Nash-Sutcliffe (Monthly)	ES Uncertainty Rating
Very good	0.75 < NSE < 1.00	Very Low
Good	0.65 < NSE < 0.75	Low
Satisfactory	0.50 < NSE < 0.65	Moderate
Unsatisfactory	< 0.50	High / Very High

Figure 16 NSE performance rating. (Edgar F. Lowe, 2012)

3.8.2 Results

The Nash Sutcliffe efficiency was calculated to 0.43, for the calibration series and 0.27 for the validation series. This is considered as a calibration with a high degree of uncertainty, based on the NSE uncertainty rating in figure 16. It is also worth noting that even with a NSE of 0.43 the runoff is overestimated with approximately 55%. This overestimation of runoff applied generally for all simulations conducted with this model. This is not a good foundation to make use of with regard to assess the unmeasured catchments. A simulation with the best parameters was conducted for the validation series, and the results are presented in table 4.

Table 4 Results from Thorntwaite simulation

	m^3/s	NSE
Qobs 1920-1969	10.78	0.43
Qsim 1920-1969	16.84	
Qobs 1970-2012	9.48	0.27
Qsim 1970-2012	14.75	

The observed and simulated runoff is presented in figure 17 and 18.

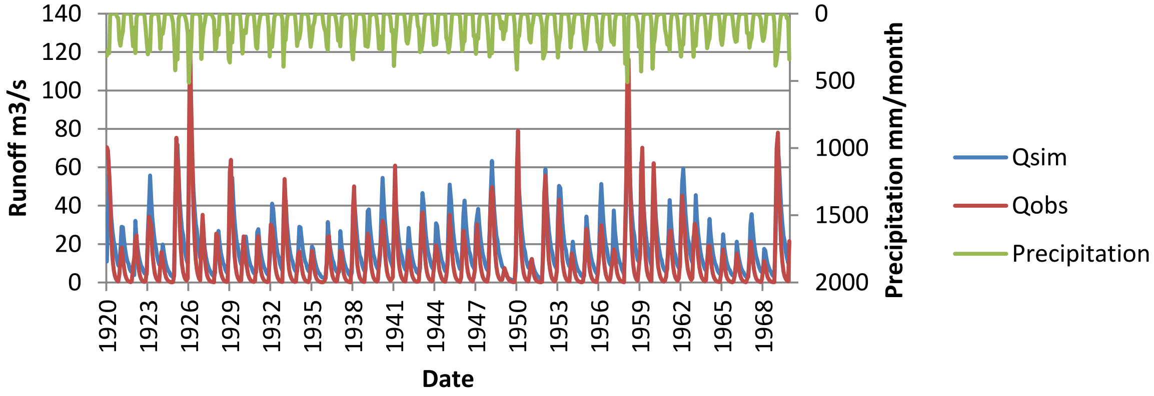

Figure 17 Calibration series 1920-1969

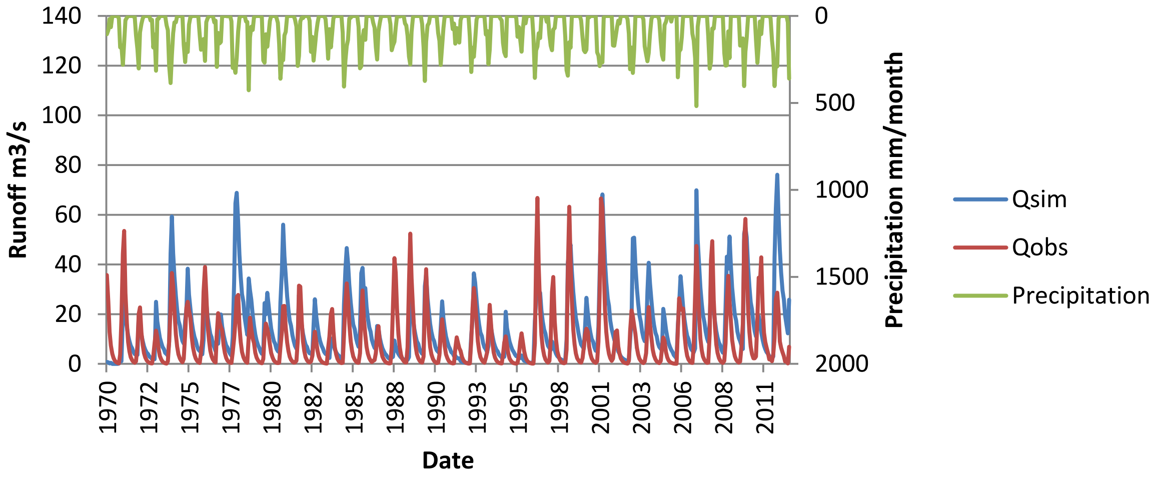

Figure 18 Validation series 1970-2012

The graph in figure 19 shows the accumulated runoff over the simulation period, the simulated values are marked with a green line and compared to the observed values marked with red, a large overestimation is evident, but the trend is quite similar. This overestimation applies both to peak runoff and minimum flow. A simple control was conducted; where simulated values were reduced according to the overestimation to a total of 64% and plotted against the observed values. In figure 19, these values are plotted with blue in the graph, and it is hard to see it, because it is overlapped by the observed values. It is evident that these graphs follow each other closely without major deviations. This indicates that the results obtained from the simulation could be used with an adjustment of the values.

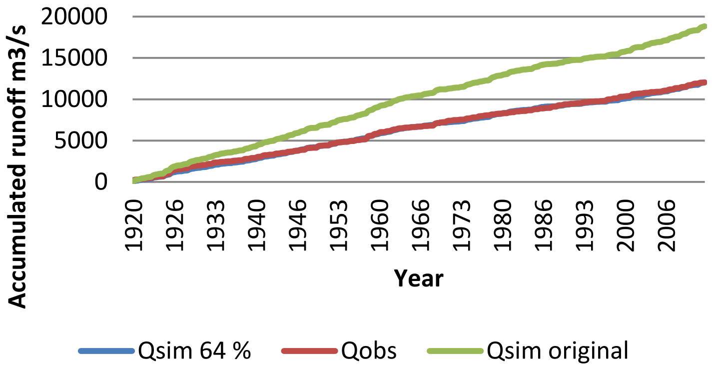

Figure 19 Accumulated runoff from simulation

3.8.3 Conclusion

Unfortunately the Thornthwaite model did not calibrate as well as intended, and it tended to overestimate the runoff significantly. The model was tested on two different catchments, the Mulungushi and the Mkushi catchment with monthly accumulated precipitation and averaged runoff. Several calibrations were performed, and the precipitation was scaled to better fit the model, but the results did not improve enough. And the criteria for goodness of fit were not fulfilled. The average overestimation in the Mkushi catchment was calculated to approximately   55 percent. This was considered to poor foundation for further evaluations.

Because of the insufficient data compiled by the Thorntwaite model, a new approach had to be considered. A new data series of daily runoff measurements from the Great North Road, a sub catchment within the Mulungushi basin was made available. This made it possible to use the HBV model. The daily measurements will also increase the quality of the power production simulations.

3.9 Hydrologiska Byråns Vattenbalansavdeling Model

The HBV model is a lumped conceptual rainfall-runoff model that was developed by Sten Bergström and was first run successfully in 1972. He wanted to create a model that was based on good scientific foundation and where the parameters were available in most areas. He wanted the model to be understandable for the users. (Bergstrøm, 2000) Even though there are many different variants of the HBV model today, it is safe to say that the model was a success, when it is still being used over 40 years after it was developed.

3.9.1 Model structure

The model is made up from three main components.

The snow routine: takes accumulation or melting of snow into account. It is important to get this right to predict the size of the floods. This only applies for areas where the temperatures are so low that you get snow, this is not the case for the project area in Zambia and hence is this module not relevant for the assessment.

The soil moisture routine: Here the moist primarily is utilized by vegetation. This zone is often dehydrated during periods of low precipitation, due to evaporation and plant water uptake, and it is replenished in the first part of the rainfall periods. The variation is important to decide how the field will react on rainfall in the different seasons. When the soil water capacity is filled, the catchment reacts quickly and strongly to precipitation. Conversely, rainfall intensity that might lead to floods when the field capacity is full, might just give a slight increase in inflow when the catchment is dry.

Runoff section: This section addresses the water that is moving within the field, and that is not bound in snow reservoirs or ground water zone. Before it comes as inflow to the reservoir it is delayed by rivers, streams, lakes, ground water. This delay is modelled by a linear tank, where there is difference runoff rate for the different sections. (Norwegian Water Resources and Energy Directorate , 2014)

The model composition is presented in figure 20. .

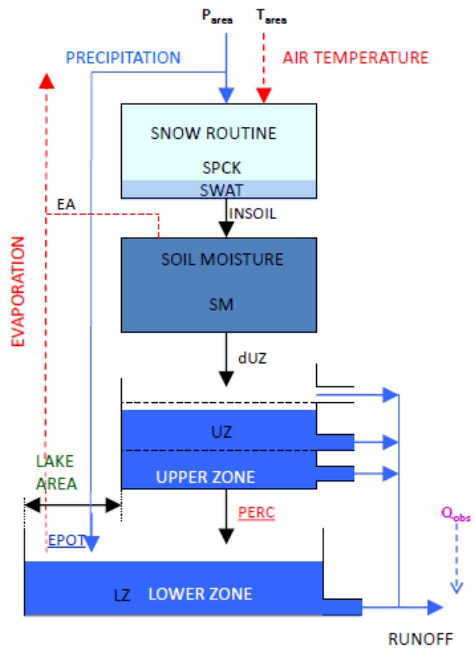

Figure 20 HBV Model Structure

3.9.2 Parameters

The parameters in the HBV model are partly based on physical factors that may be measured in the catchment area, and parameters that require calibration. The physical values are the area, lake percentage and the hypsographic curve, as well as values for terrain vegetation (forest/mountain). The free parameters are the ones that will be optimized in order to reproduce the natural runoff. These parameters consists of fifteen different parameters each describing different aspects of the hydrology. A brief description of the different parameters is given below.

Pkorr: Rain correction

Skorr: Snow correction

HPkorr: Elevation correction

Cx: Degree day factor (snowmelt)

Ts: Threshold temperature snowmelt

Tx: Threshold temperature rain/snow

Cpro: Maximum free water in snow

Fc: Field capacity (soil moisture / water content)

Beta: Soil moisture parameter

LP: Threshold evaporation

k11: Fast drainage coefficient

k12: Slow drainage coefficient

Uz1: Threshold for quick runoff

Perc: Percolation

k0 : Drainage coefficient

The hypsographic curve of the different catchment area is presented in figure 21. As presented in the figure it is possible to see that the area is relatively flat, except from the upper parts of the Mboshi and Mulungushi catchment.

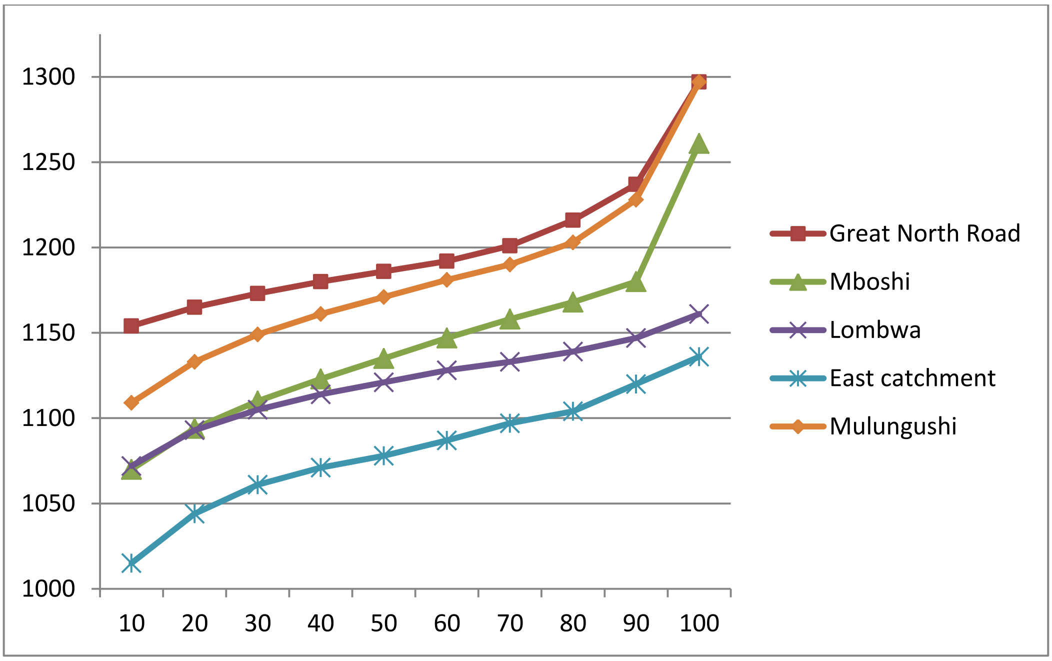

Figure 21 Hypsographic curves of the catchments

3.9.3 Data

With the newly acquired daily runoff data, it was possible to establish a daily model to simulate the hydrological conditions. The new data was a collection of daily discharge measurements from the Great North Road, a sub catchment within the Mulungushi river basin. The data stretched from 1963-2007, but from 1988-2007 there were an extensive lack of data. All of the nineties were excluded and from 2000-2007 there were only random measurements where the most of the year was excluded as well. Based on the available data, the simulation was performed from 1963 to 1987, a total of 25 years, which is not much. The observed runoff values are displayed in figure 22. Even though there are fluctuations in the data series there is a general trend in the runoff pattern. The graph indicates that the catchment is not emptied every year and that it for several years is continuously runoff through the dry period. It is worth noting that there are several years with low inflow. With a limited reservoir capacity this may lead to a problem regarding the firm power production. This is especially critical for several consecutive years with low inflow.

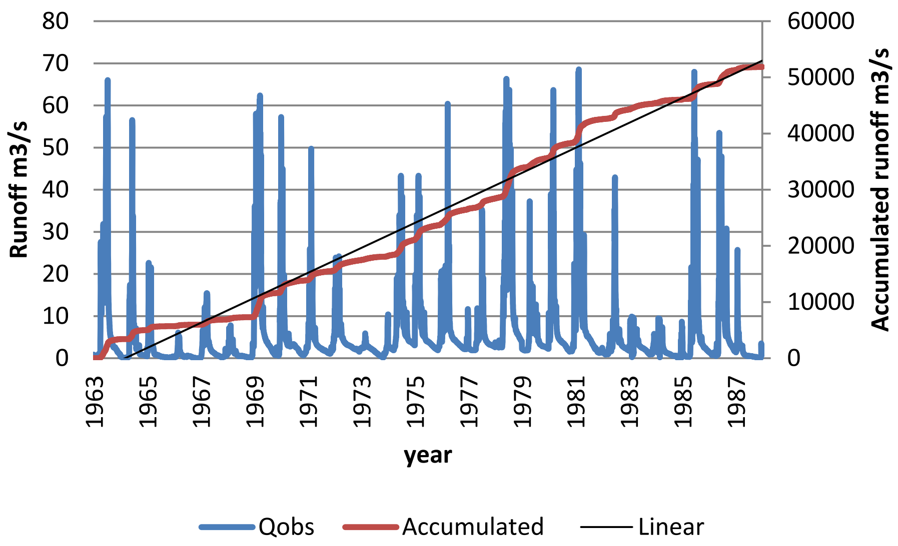

Figure 22 Runoff Great North Road

The sub catchment is marked with blue in figure 23, and the entire Mulungushi catchment is marked with a thick black line. This is used as the basis for the further hydrological evaluations. The catchment specific parameters for the model are obtained by utilizing ArcMap.

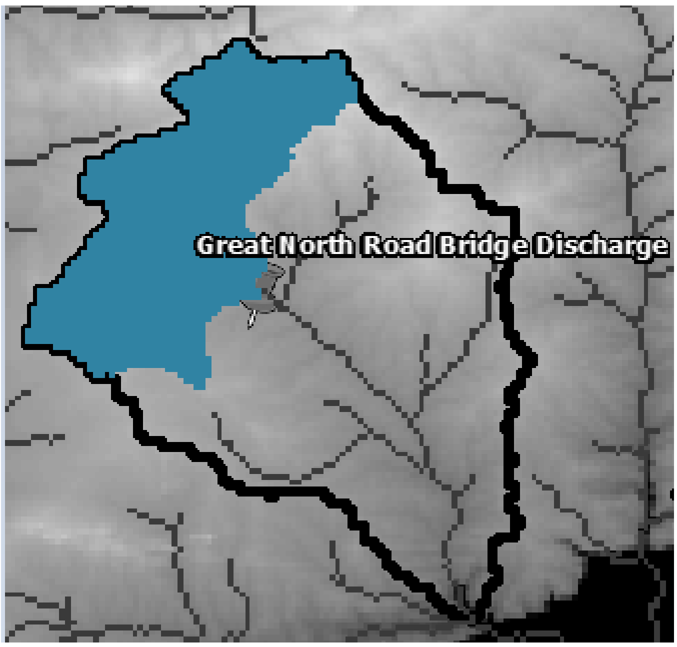

Figure 23 Great North Road catchment.

The precipitation station that provided the data for the simulation is located at Mita hills Dam (14° 13' 50" S, 29° 07' 33" E) approximately 60 km east of the Great North Road Discharge station. This data series contained daily observed precipitation from 1960-2010, but with some years missing in the 1990s.

The temperature is the criterion for the snow accumulation and this is not relevant for a model in Zambia, since the temperatures always are >0. But the derived temperatures will be utilized to meet the requirements of the model.

3.9.4 Calibration

The calibration of the model was conducted by using an excel version of the HBV model, with an implemented Shuffled Complex Evolution optimization algorithm in C++, this algorithm was originally developed by Dr. Qingyum Duan as a part of his doctoral dissertation work at the Department of Hydrology and Water Resources, at the University of Arizona. (Q. Duan, 1994) The implementation of the calibration algorithm into the HBV model was conducted by Emmanuel Jjunju. The optimization process is based on optimization of both the NSE and the water balance. The model has a function for calibration where the free parameters are optimized, and a function for simulation where the catchments response is simulated based on the optimized free parameters. This way the “free” parameters can be locked, and the catchment specific parameters can be adapted to the different catchments and simulations can be conducted.

The optimized model parameters are presented in appendix A.

3.9.5 Results

The calibration of the HBV model was as mentioned earlier in the chapter conducted on the Great North Road catchment. The calibration was not particularly good, with this model either, and the simulated and observed runoff deviates especially in a few years with high peaks. As a criterion for goodness of fit, the NSE was used and this was calculated to be 0.23, this is below the value that was calculated for the calibration of the Thornthwaite model. Even though there are deviations in the peak runoff, the most of the years as displayed in figure 24 is simulated quite well. A comparison of average runoff shows that this is the same for the simulated and the observed runoff, calculated to be 5.66m^3/s. This indicates that the simulated and observed values are equal over the year, but with a slight difference in distribution. It is also evident that the runoff in the dry season is underestimated for a number of years. This implies that the uncertainty connected to the output is high, this is also confirmed by the low NSE value. Even though there is a high uncertainty connected to the simulation, the results will be used further for simulations in the ungauged catchments because the average inflow was calculated quite well.

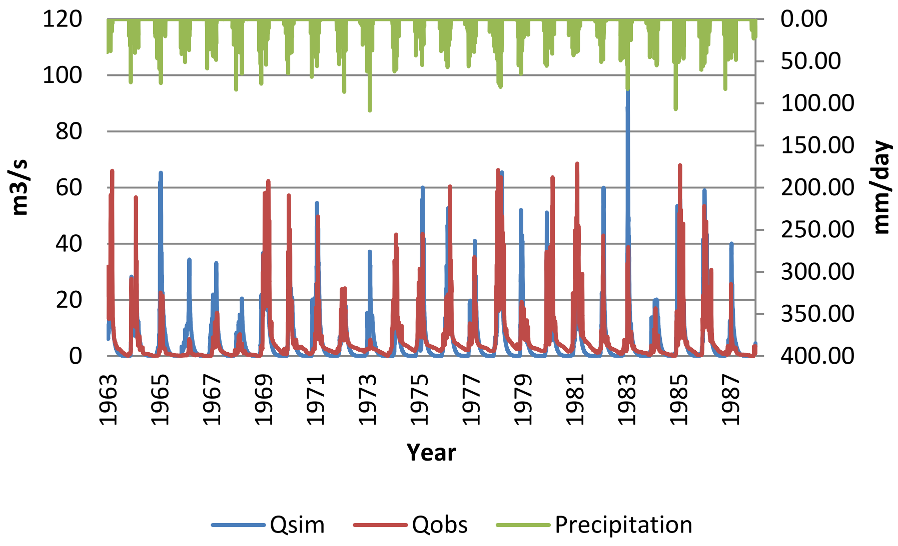

Figure 24 Simulated and observed runoff from HBV model

The optimized parameters, obtained from calibrating the Great North Road Bridge catchment was used to simulate the response of the ungauged catchments. These parameters were set as constants and locked, while the catchment specific parameters were adapted for each catchment. This entails area, hypsographical curve, lake percentage and terrain description. The response from each ungauged catchment was simulated separately, and the results are displayed in table 5.

Table 5 Simulation results from the HBV model

Catchment	Area	Average run off [m^3/s]	Annual inflow[Mm^3]
Great North Road	1448	5.65	178.2
Mboshi	2724	10.65	335.9
Lombwa	322	1.26	39.7
Mulungushi	4369	16.23	511.8
East	66	0.18	5.7

3.9.6 Conclusion

Even though the calibration of the model should have been better, the obtained results will be used further in this thesis. There are discrepancies related to the simulated and measured flow, the model seems to underestimate the inflow during the dry season, and overestimate it during the wet season, for a number of years. But the average discharge for the calibration catchment is reproduced. The results obtained with the HBV model is better than the ones obtained by using the Thorntwaite model, even though the Nash Sutcliffe efficiency in the Thorntwaite model was better with a maximum value of 0.43 in comparison with 0.23 for the HBV model. However the time series simulated by the Thorntwaite model was constantly overestimated with approximately 56 percent. Even though the HBV model covers a smaller time span and has a lower Nash Sutcliffe efficiency than the Thorntwaite model, it was defined as the best base material for further evaluations. This is based on that it managed to simulate the average runoff from the Great North Road catchment, which is essential to establish a basis for the unmeasured catchments. There is also less uncertainty connected to simulating the mean flow, relative to simulating the extreme values. On this basis there will not be conducted any flood calculations based on the simulated data. The fact that the HBV model is based on daily measurements also minimizes the uncertainty that is related to a monthly model.

The simulation gives a good indication of how much water is available, but there are more uncertainty connected to extreme weather such as flood and droughts. Regardless of this, the results will lay the foundation for the technical specifications chosen and presented in chapter 4. It is also the basis for the production simulation performed by using the Nmag tool and presented in chapter 5. But based on the uncertainty connected to the distribution of the water through the year a power production simulation will also be conducted with data based on area scaling for comparison.

3.10 Area scaling

The most basic way to establish the hydrology of a catchment is a simple area scaling. These are basic scaling laws that indicate what to expect in a catchment. In this thesis this was carried out along with the establishment of the Thorntwaite model, to ensure progression in the work, if problems should occur with the model. Based on the poor results from the Thorntwaite model, the hydrological scaled values were used to develop a setup for the Nmag model. This was later updated with the daily values from the HBV model. The basic area scaling assumes that the specific runoffs in two neighboring catchments are the same. There will be approximately the same amount of precipitation and hence is it only the size of the catchment area that is different. The calculations are performed based on formula 3.

$$Q1 = \frac{A1}{A2} * Q2 \qquad \text{formula 3}$$

This method of scaling can provide a good estimate for the initial assessment of the catchment, but it does not take into account the differences in vegetation, slope, lakes, shape etc. This should be in the consideration and therefore a hydrological model is preferable.

To see the differences in the area scaled values and the simulated values they are plotted against each other in figure 25. This is for the ungauged catchment Mboshi. As the figure shows there is a big difference in peaks and minimum flow. But the average discharge is approximately the same with 10.65m^3/s

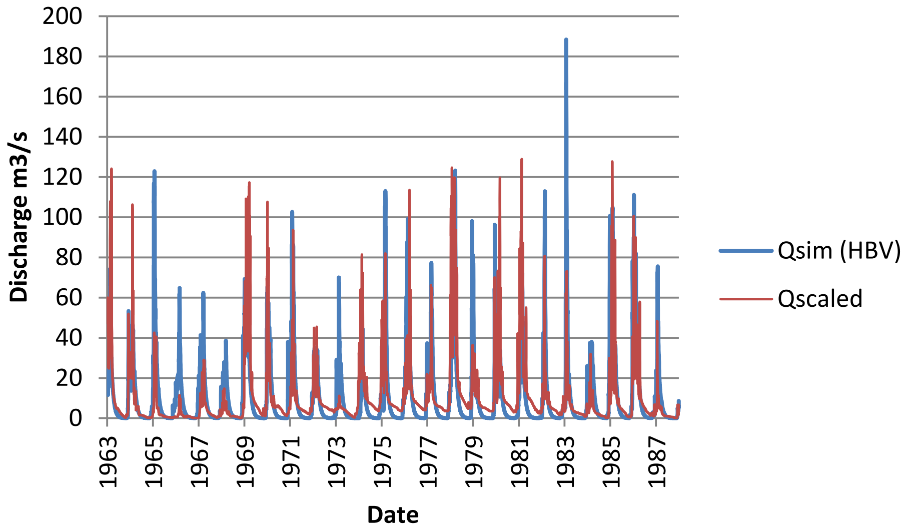

Figure 25 Simulated- and scaled- runoff

3.11 Future scenarios

Global warming of the planet is a great challenge when it comes to planning hydropower. What will the conditions be in 10- 20 or 30 years from now? This is a topic that has been heavily researched. Several different scenarios have been investigated and the only thing that is certain is that there is a lot of uncertainty connected to the future scenarios. But still it is of great importance to be aware of the changes that are happening. Otherwise there is a chance that one overestimates the inflow and hence the future income. This could be significant when power companies invest billions of dollars in large hydro power plants.

Figure 26 represents the large scale changes in annual runoff median from 12 different climatic models. Zambia is marked with a red circle, and as seen from the figure it is not expected the most severe changes in the hydrological pattern and precipitation in Zambia, but still some reduction in potential is expected. Based on this summary there is going to be a reduction in the water availability throughout the whole southern Africa, but Zambia is not the country that will be most affected. The study states that there will be a reduction in in hydropower resource potential in Africa, except from the eastern parts. Even though several research groups conclude with this scenario, there is still some uncertainty connected to it, it is hard to predict what the future brings. Changes in the hydrology may lead to change in river flow, changes in extreme events (floods and droughts) and changes in sediment load. (Kumar et al, 2011) One must be aware of these factors, so that one is prepared when the changes occur. This research is important but will not be included further in the hydrological basis for the project area, in this thesis. The available time series will be utilized to the extent possible, with no further speculations into the future.

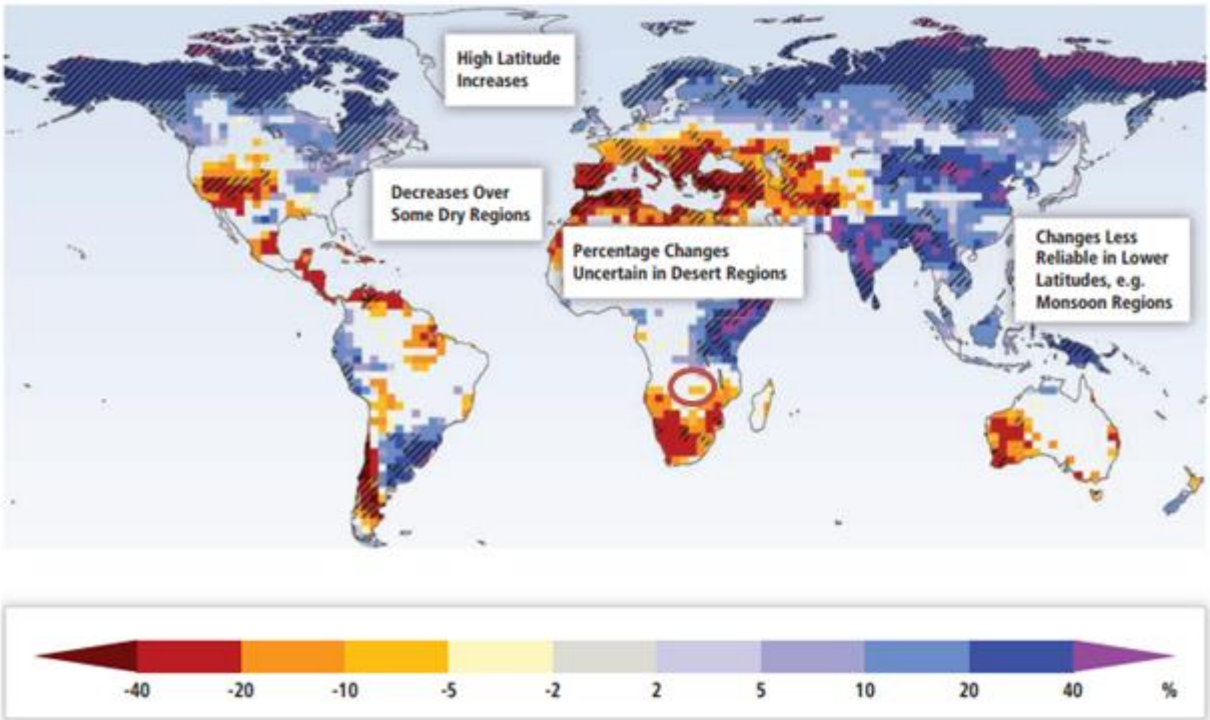

Figure 26 Future climate research (Intergovernmental panel on climate change, 2011)

3.12 nMAG

NMAG is a program developed from an earlier design called ENMAG. It was invented by Professor Ånund Killingtveit at the Norwegian Hydrotechnical Laboratory, which is affiliated to SINTEF and the Norwegian Institute of Technology in Trondheim. It was designed to establish regulation curves, but developed into computing the complete production system. (Killingtveit, 2004)

The program is easily adapted to any power plant, and the input varies based on the simulation that is conducted. The models are constructed based on different modules, as presented in figure 27:

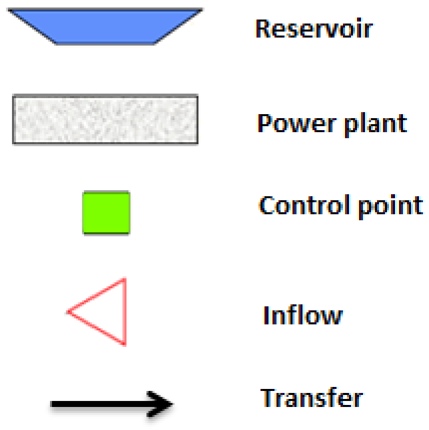

Figure 27 nMAG modules

Each modules specification is described in the model and forms the basis for the simulation. The modules are then numbered and linked to each other by an address defining how the water flows in the model. (Killingtveit, 2004) This way the water is routed through the system. For one module the water can be released in three different ways production release, bypass release or flood spill.

Nmag automatically calculates the head for each time step, based on reservoir level, and the details from each component can be written to an output file. This makes it easy to analyze each part of the system with respect to production (used water), spill water or bypass. The power simulation takes into account the evaporation from the basins, flood spill and head loss, this means that the power production simulation provides real results. The model output can be specified and is based on the chosen time step, and it gives the total production, spill, reservoir level, inflow for each day.

It is possible to utilize different time steps with daily, weekly or monthly values. The smaller the time step is, the less uncertainty there is associated with the flood spill and production. The simulation will be conducted with daily time step, for both the scaled and the simulated time series.

Chapter 4 Optimization of technical specifications

When dealing with hydropower there may be several solutions that meet the given requirements, and there is not always one solution that stands out from the rest. It is a complex task and solutions are often a result of the consultants experience and personal opinions. Because there are several different possible solutions it is important to create a cost estimate to help choosing the best and most cost efficient solution. A cost estimate for the main components of the project will be presented in this chapter. This involves dam, tunnel, shaft, penstock and power house. This will make it easier to compare the solutions when choosing the final design.

4.1 Conceptual design

In 2012 the Italian consultant SP outlined the main elements of the project in a report. Their proposed solutions will be evaluated further and reassessed in this chapter.

The design as proposed from SP for the Mulungushi cascade:

- **Mboshi**
    - A 2 km reservoir connection tunnel between the Lombwa and Mboshi rivers. (D=3m)
    - Two dams about 70m. (in the river valleys Mboshi and Lombwa)
    - One headrace tunnel, about 3 km.
    - 480 meters of penstock
    - Surface power house
    - Water level 940 m.a.s.l.
    - Installation of 30 MW
- **Mulungushi 2**
    - Dam 50 meters
    - Headrace tunnel : 5 kilometers
    - Penstock shaft: 160 meters
    - Tailrace tunnel: 3 kilometers
    - Adits: 1.2 kilometers
    - Highest regulated water level at 680 m.a.s.l.
    - Intake at 660 m.a.s.l.
    - Installation of 50 MW. (Studio Pietrangeli consulting engineers, 2011)

4.2 Optimization

To minimize the cost and optimize the revenue it is necessary to evaluate all the different parts of the project and it is common practice when developing hydro power to reiterate the optimization as a whole based on the different components to find best overall solution. However based on the scope of this thesis it is not possible to evaluate all the parts of the project and therefore the key elements have been prioritized, these are the components with the main costs connected to them.

The focus will be on these components:

1) Dams
   - Location
   - Dam type
   - Construction
   - Cost estimate
2) Waterways
   - Head race tunnel
   - Penstock/ Shaft
   - Tail race tunnel
3) Power stations
   - Underground / Surface
   - Cost estimate

As a result of this priority, some elements of the final solution will not be taken into account when optimizing and creating the cost estimate, such as intakes, trash racks, roads, gates, etc. This is a weakness, but some tradeoffs have to be made and it is important to choose the right parts to evaluate. This means that smaller parts of the plant have to be optimized in a later stage, when the big picture is selected.

The optimization is based on an estimated life expectancy of 30 years and a discount rate of 15 %, which gives a discount factor of 6.57. This is a conservative estimate. The overall efficiency rate of the project is set to 0.85, based on an overall assessment of the technical components. This lays the foundation for the optimizing conducted in the next chapters.

The optimization is also based on the head loss' operating time. This is calculated based on the expected running of the power plant and formula 4, and for the two power stations it is:

- Mboshi: 5800 hours
- Mulungushi 2: 5000 hours

$$\int (\frac{Q}{Qmax})^3 \, dt \quad \text{formula 4}$$

(Guttormsen, Vassdragsteknikk 2 (TVM4165 Vannkraftverk og vassdragsteknikk), 2006)

4.3 Costs

The data basis in Zambia is not even close to what we have in Norway when it comes to updated cost tables. The *Cost base for hydropower plants* published by Norwegian Water Resources and Energy Directorate (NVE) is a useful tool, but it is made for the Norwegian market. To provide a satisfactory cost estimate for this project, all the available cost basis have been assessed. Estimates are based on cost reports from the Muchinga project. Furthermore is it supplemented with data from other sources, such as the cost basis developed by Kristoffer S. Hansen during his field trip to Zambia. Where other data have been inadequate or not available the Norwegian *cost base for hydropower plants* has been used.

To calculate the marginal costs related to tunneling, a computer program called Tunsim was used. This is a program developed at the Department of Civil and Transport Engineering to calculate cost and progress during tunnel construction. The software is based on collected empirical data and has been developed through a PhD thesis. The program is developed in Excel and the user interface is simple. It is based on a number of parameters that must be adjusted by the user, and it is possible to enter your own prices, and estimates on tunnel progression, and regulate everything from labor costs to electricity price. This makes it a useful tool when applying the Zambian costs. The negative side of the program in this context is that it is based on the Norwegian method of drill and blast, which is known to be very effective.

It is hard to compare the Norwegian and the Zambian efficiency but it is evident that the skill level in Norwegian tunneling is high compared to the Zambian skill level. The extensive mining operation in the area suggests that there is adequate knowledge of tunneling and shaft operations. But one cannot expect that local contractors have the capacity and knowledge to take on such a large project. However it is common that international contractors with experience take on the project and make use of local labour.

"Atlas Copco a global Swedish industrial company with construction as one of its main business areas explains that when they sell machines for tunneling, it is relatively easy to train the workers in developing countries on their medium machines. The contractors in these countries tend to avoid the advanced computerized tunnel rigs, in favor for simpler rigs with increased manual operation. This is not primarily based on the machine costs, but on the progress of the project as a whole. Technological advanced rigs may often cause progress problems because there are often very few people with the skills of troubleshooting these rigs." (Jentoftsen, 2013)

Labour cost in Zambia

A cost estimate for the basic labour cost in Zambia has been prepared during the design of the Muchinga project. The estimate has been developed by Mott MacDonald. The cost estimate is made on a general basis, and can therefore be used in the cost estimates for the cascade project as well. The cost basis is divided into two main categories: above ground work and underground work. A small excerpt from the report is presented in table 6.

Table 6 Labor cost Zambia (Mott MacDonald, 2013)

	USD/hour	USD / hour (*All in labour rate, with provision for bonus, tool money, food, allowance, employers' liability insurance, social charges, medical costs, protective clothing, leave travel, recruitment and redundancy
ABOVE GROUND WORKERS		
Laborer unskilled	0,52	1.32
Semi-skilled laborer /Assistant /Helper	0,57	1.42
Electrician	0.75	1.70
Shotcrete Nozzleman	0.85	
Blaster / Shotfirer	0.75	1.70
UNDER GROUND WORKERS		
Shift boss	0.96	2.45
Blaster/ Shotfirer	0.85	2.26
Shotcrete Nozzleman	0.9	
Drill Jumbo Operator	0.9	
Tunnel miner	0.8	2.17
Heavy vehicle driver	0.9	

As shown in the section above, the hourly wage of a worker in Zambia is very low, and is not comparable to Norwegian conditions, where the cost of labour is expensive. The high wages in

Norway has led to a very efficient tunnel industry, and this is something one cannot expect in Zambia. The hourly wages are used as input in TunSim for preparation of costs. The normal shift for above ground workers are 10 hours, and the shift for underground workers are 12 hours.

- *The conversion from NOK-USD is based on the conversion rate from the beginning of March 2014, where 1 USD=5.94 NOK.*

4.4 Dams

The project is planned with three dams and in this subchapter the various dams will be evaluated. The dams are planned on the tributaries Mboshi and Lombwa and on the main river Mulungushi. The different dams are created to make reservoirs for storage of water and to maintain the head for the power production. The proposed solution from SP will be the basis, but will be updated where other solutions seems more promising.

4.4.1 Dam location

The project is planned as cascade of power plants, with different reservoirs. The Mboshi reservoir is intended to store water from the wet to the dry season to maintain power production over the year. The Mulungushi 2 reservoir will be a reservoir with daily regulation. This means that there are different requirements for the different dam sites. In the dam site evaluation several different dam sites have been evaluated for the Mboshi River, because of the requirements of a large storage. But for the Mulungushi 2 reservoir, the dam site has been optimized with respect to dam size, and that the outlet from the Mboshi power plant should be located upstream the dam. When it comes to the dam planned at the Lombwa River, no optimization has been conducted, but a comparison with a transfer tunnel has been carried out. The different dam sites are presented in figure 28.

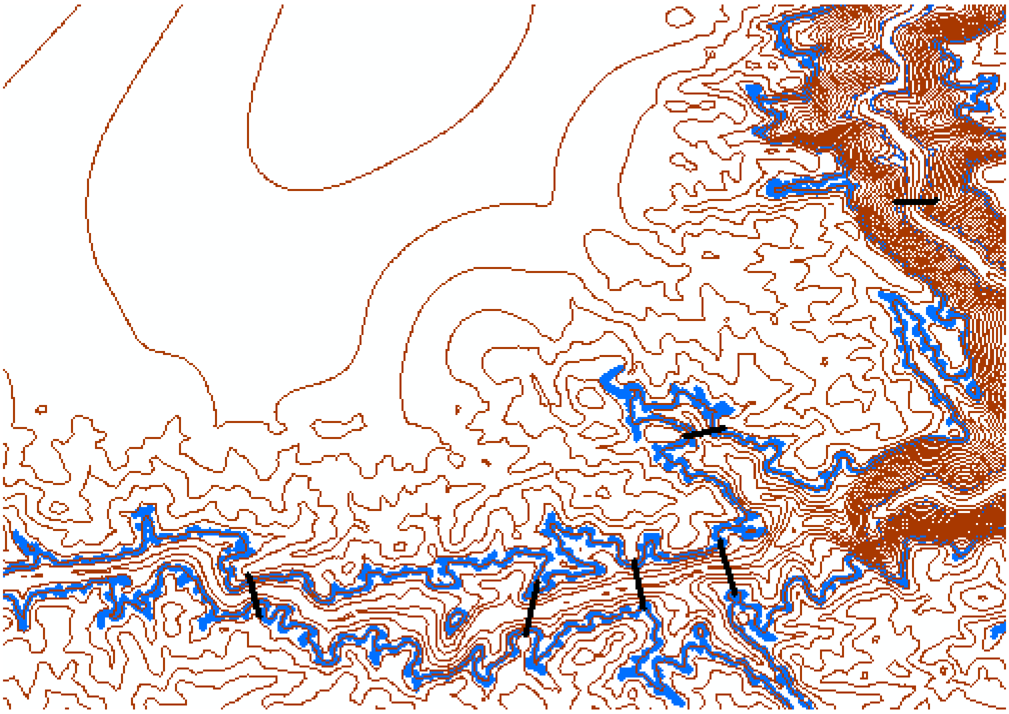

Figure 28 Overview of the project area, water runs from left to right, and from top to bottom

Unfortunately there have not been conducted any geological investigations in the project area, and therefore it is assumed good geological conditions at the dam site. This must be carefully considered before selecting the final dam location, but because of lack of data this is out of the scope for this thesis.

4.4.1.1 Mboshi

Four different dam sites have been considered for the Mboshi dam, and they are presented in figure 29. This is the largest dam in the project and it could create a reservoir of more than 150 MCM, depending on the final location. The dam sites are noted from 1-4 where 1 is furthest upstream. There are significant differences in the size of the dam and the reservoir based on the placement. To minimize the flood spill and increase firm power production, it is beneficial to have as large reservoir as possible. The Mulungushi area is associated with very uneven inflow, and a limited reservoir capacity can cause extensive flood spill.

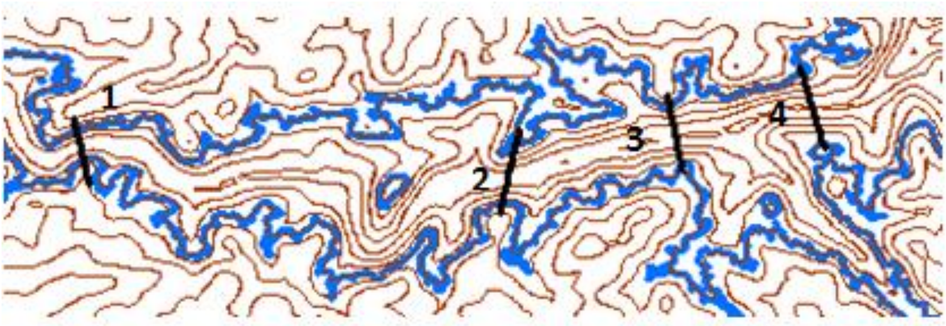

Figure 29 Evaluated dam sites, water runs from left to right

Dam site 1: Dam site located furthest upstream. This is the dam site with the lowest total dam height with only 50 meters, and the narrowest valley (approximately 250 meters). It is also the dam site with the decidedly smallest reservoir capacity, only 50.5 MCM, resulting in much flood loss during the wet season, because of the limited storage capacity. This dam site also requires the longest head race tunnel (approximately 8 km), which implies a disproportionally expensive and bad solution.

Dam site 2: Is located next furthest upstream. It has a live storage of 112.6 MCM. The topography indicates that the dam height will be approximately 74 meters, and the dam crest is calculated to be 440 meters. The head race tunnel connecting the reservoir to the Mboshi power plant is considerably shorter compared to dam site 1 (≈5.5 km).

Dam site 3: This is the dam site proposed by SP in the sketch project. It will create a live reservoir of 133 MCM. The dam site requires a dam height of 79 meters and the dam crest is approximately 468 meters wide.

Dam site 4: This dam site is located downstream of the SP proposed solution. It includes a small tributary, which gives increased storage capacity and creates a live storage of 165 MCM. This is the dam site with the largest capacity but also the dam site that needs the largest dam. The dam height will be approximately the same as dam site 3, but the length is estimated to be 525 meters at the dam crest.

The dam sites were evaluated based on the total reservoir capacity and the dam cross sections, as presented in table 7. The calculations are based on the proposed solution with highest regulated water level at elevation 940. Furthermore a regulation height of 40 meters is assumed, giving lowest regulation height at 900m.a.s.l.

Table 7 Reservoir / dam size Mboshi

Dam site Mboshi	Total Reservoir capacity (MCM)	Dead storage Below 900 m.a.s.l	Dam crest (m)	Live storage (MCM)	Dam cross section (m^2)	Reservoir / Dam size m^3/m^2
1	51.2	0.7	241	50.5	6151.5	8209
2	126.0	13.4	429	112.6	15795	7090
3	153.0	20	468	133	18689	7116
4	194.7	28.9	525	165.8	20867	7945

Dam site 1 is the location where is possible to get most reservoir per volume dam, but it is still not regarded as a good solution. Based on the small reservoir and the length of the head race tunnel this solution is disregarded.

Dam site 4 is the one that seems most promising. Given the large reservoir capacity compared to the other locations. This is the dam site that will be assessed further with regard to dam type and costs.

4.4.1.2 Lombwa

The Lombwa River is a small tributary to the Mboshi River and the concept project suggested a 70 meter high dam. A thorough assessment of the dam site, shown in figure 30, shows that the dam only have to be about 40 meters high and with a dam crest about 320 meters long. The coordinates for the dam site is; 28°49'27.552"E, 14°46'56.057"S.

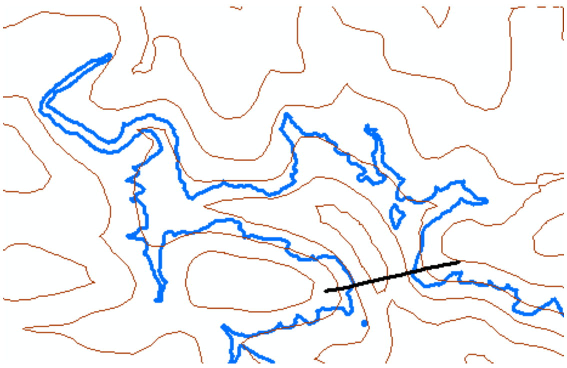

Figure 30 Lombwa dam site

This would create a reservoir of approximately 4.2 MCM, but this is considered to be an expensive and unnecessary investment. For an assumed RCC dam an estimate shows that the dam volume would be approximately 160 000 m3. Based on the cost estimate for concrete, this would be approximately 25 Million USD, just for the construction material alone. This is considered to be disproportionately expensive and the small reservoir capacity of 4 MCM cannot defend a development. Therefore a new solution will be examined. This is to construct a transfer tunnel (≈1 km) from the Lombwa River to the Mboshi reservoir, with a small threshold (H<3 meters). This is conservatively assumed to cost 3M USD, which is much more cost efficient than the proposed solution. A more thorough assessment of the tunnel will be conducted when addressing the waterways.

4.4.1.3 Mulungushi 2

This is the dam site furthest downstream in the cascade. It is creating the head for the planned Mulungushi 2 power plant. From the feasibility study performed by Studio Pietrangeli, the water level is planned at elevation 680. This is not an option because it would flood the existing Mulungushi power plant, which is placed on contour line 663, it is marked with a black pentagon on figure 31.

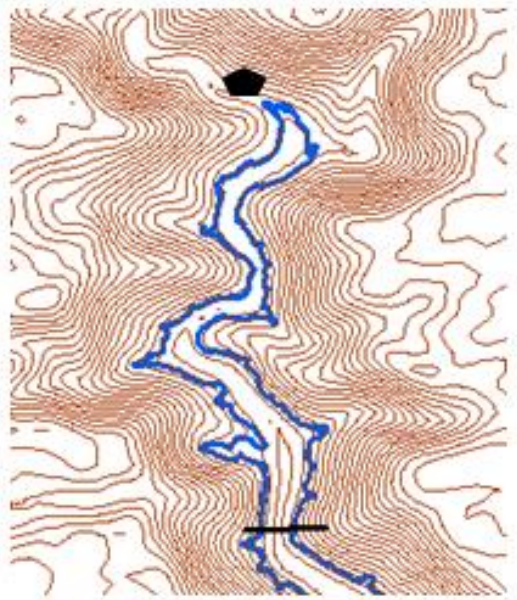

Figure 31 Mulungushi2 dam and planned reservoir

The dam site is locked at coordinates 28°50'39.732"E, 14°45'31.363"S and the top of the dam will be lowered from 680 to 660 meters above sea level, to not interfere with the existing power house. This leads to less head for the Mulungushi power plant, but increased head for the Mboshi power plant which can be moved correspondingly. This will also decrease the planned reservoir capacity from approximately 20 MCM to only 6 MCM. Thus will the reservoir only serve as a daily regulation reservoir, and will run on the inflow from the Mboshi and the Mulungushi reservoir and local inflow. Based on the low reservoir capacity, a large flood spill can be expected from this reservoir.

The dam height is estimated to be 47 meters and the dam crest is estimated to be approximately 215 meters. On the top of the dam there is planned a five meter wide road making the access to the Mboshi power station easier. The volume of the dam is calculated with height increments of 1 meter and this gives a volume of approximately 100 000 cubic meters.

4.4.2 Dam type

Selection of dam type based on the location and ground conditions is a task that should be evaluated thoroughly and it requires both experience and good judgment. Several different dam types may be built and in most cases it is not such that there is only one dam type that is possible to build. There are many factors influencing the choice of dam type, such as topography, geological and geotechnical structure of the dam site, availability of construction material and economy (EMIROGLU, 2008) *this have to be taken into account when selecting dam type*.

Mboshi

With a cross section of approximately 20 000 m^2, this will be a large dam and this indicates that the costs are going to be equivalent. Based on communication with Mr. Ødegård, a concrete dam has come up as a good solution, even though this will be a large dam. With such large volumes, it is essential to minimize the volume where possible. Based on this statement an arch dam is a possibility, however with a height / width relationship larger than 6, this could potentially be a dangerous solution and therefor it is disregarded. A buttress dam could potentially minimize the use of concrete, but the saved concrete is largely offset by the extra reinforcement and formwork needed for construction. This also implies that a higher skill level on the workers is needed.

A roller compacted concrete dam is a solution that has proven to be both effective and cost saving for many projects, especially compared to conventional concrete in gravity dams. This is mainly based on a few characteristics of this dam type:

- It is faster and simpler, compared to other dam types
- Lower formwork costs
- Can be constructed on relatively weaker rock foundations
- Spillway can be constructed into the dam, and non-overflow section can be allowed to overtop during emergency situations.
- Energy dissipator can be implemented into the dam body.
- Often cheaper concrete mixes compared to conventional concrete.

- Low heat generation.
- Diversion schemes can be reduced because the dam can be overtopped during flood without significant damage to the main structure. (Warren, 2012)

There have been built many large RCC dams and there are good opportunities also in Zambia. The effective production and the expected cost savings makes this a good choice for the Mboshi dam and the preferred solution that will be assessed further. The RCC dams are normally built with a nearly vertical water side, while the downstream side has an inclination of 1:0.7-0.9 (Sweco, 2012) A calculation of the volume has been carried out for with height increments for two different inclinations on the downstream side of the dam, the waterside is assumed vertical.

- 1:0.75 Gives a total volume of 468 500 m3
- 1:0.70 Gives a total volume of 437 200 m3.

Based on the size of the dam it is important to minimize the structure where it is possible. There has not been conducted any stability calculations of the dam, just a volume calculation based on the design criteria in the cost base. This means that there is some uncertainty connected to this alternative but still the smallest dam volume is used for further calculations. Based on the lowest volume, this gives a total cost of 68.2 M USD for the concrete alone, based on the cost estimate in table 8. In addition there will be preparation of the foundation, labor, construction equipment and based on the sealing there may be expenses connected to membrane on the waterside of the dam.

A tipper truck handles approximately 10 m3 per load. With an approximate load of 1000 m3 a day, the construction of a RCC dam at the Mboshi dam site would take approximately one and a half year to complete, this is given that no situations occur that stops the construction for a longer period. Construction of RCC dams are easily affected by stops in the construction, because of the continuous construction procedure.

Lombwa

A small threshold is planned on the Lombwa River with a total volume of 250 m3. The intention is to lead the water from the Lombwa River into the transfer tunnel and down to the Mboshi reservoir. It is planned as a small threshold with maximum height of 3 meters. An evaluation of the dam site gives a height of 3 meters and an approximate width of 40 meters. This gives a dam volume of 250 m^3. A small dam like this does not have any influence over the total time consumption for the project, but still it has to be taken into consideration. With this solution the water from the Lombwa river may still be utilized, but without the expensive dam.

Mulungushi 2

The Mulungushi dam site is planned with a height of 47 meters and an approximately 215 meters long dam crest. This indicates that a concrete dam is favorable. Also here it is possible to choose between buttress-, arch- and gravity dam. But based on the fact that the large Mboshi dam will be constructed as a RCC dam, it would be beneficial to choose the same approach. This will lead to less cost for each dam and the trained personnel would know the routines. A conservative approach has been used and a downstream inclination of 0.9 has been selected. The dam volume has been calculated with height increments of 1 meters, this gives a volume of 100 000 m^3, included a road on top of the dam. This gives a total cost of 15.6 M USD for the concrete. The road is intended to permanently ease the access to the Mboshi power plant. A RCC dam on the Mulungushi dam site is estimated to be constructed in under half a year, this is after preparation of fundament and rigging With an average rate of 30 000 m3 per month and no major delays, this dam could be constructed in five months, based on a lift of 0.3 meters. By constructing it in the dry period, it will be possible to avoid constructing the diversion tunnel, and in addition the consequence of rainfall is considered to be low, because it has no great significance for the dam to be over topped during construction.

4.4.3 Construction

The RCC method of constructing dams was first demonstrated in 1974 and have since then proven to be a competitive construction method. The concrete is compacted by roller compaction and this sets some requirements for the consistency of the concrete. To ensure adequate consolidation, the concrete mix must be dry enough to prevent sinking of the vibratory roller equipment but wet enough to permit adequate distribution of the binder mortar in concrete during mixing and vibratory compaction. (Monteiro et .al)

The speed of construction and the cost effective way of building is the main reasons why this dam type still is very popular. The unofficial world record is a placement of 18 000 m^3 of RCC in one day, this indicates that the method can be extremely effective. However these amounts cannot be expected in Zambia.

Construction of roller compacted concrete dams consists mainly of three basic steps:

- Production and loading of concrete
- Unloading and spreading.
- Compaction

Figure 32 Unloading concrete by dump truck (Monteiro et .al)

Figure 33 Spreading concrete by bulldozer (Monteiro et .al)

Figure 34 Compaction by vibratory roller (Monteiro et .al)

One of the major advantages regarding the construction of the dam is based on its rapid construction. This is possible due to the technique used, and an adaption of the concrete recipe. The concrete is created with a low cement content that minimizes the heat generation. It is also made as a very dry concrete with zero slump. Because of the consistency ordinary concrete trucks are replaced with dump trucks and spreading / compression is done by bulldozers and vibratory rollers as presented in figure 32, 33 and 34. For special projects there have also been utilized conveyors to transport the concrete onto the dam. There is also a reduced use of formwork, which reduces the construction time as well. The placement of the concrete is normally performed with lifts of 0.15-0.9 meters, but a normal rate is approximately 0.3 meters. If the lift is too thick there will be a problem of with adequate compaction, and if the lift is too thin the placement rate will be too small reducing the advantages of RCC. Compaction of the lifts should be performed as soon as possible after spreading. After placing and compacting the concrete it is essential that the concrete is exposed to good curing conditions, otherwise it may cause weaker layers in the construction that may slide. The concrete should be kept moist until the next layer is placed. (Monteiro et .al)

Traditional gravity dams are built in sections and if problems occur in one section, the work effort can easily be moved into another section while the problem is solved. This is not possible when constructing RCC dams, because the raising of the dam is a continuous process.

The spillway is often defined by the choice of dam, and it will often be a severe cost to establish a separate spillway solution. By incorporating the spillway into the dam there may be substantial savings relative to constructing a separate spillway. But a geological assessment of the conditions downstream the dam have to evaluated to see if this is a possible solution.

Certain dam types may require more skilled labor, which may be hard to obtain in rural areas, such as the project area. But the project must be seen in context with the development of the Muchinga project. The plan is that the Muchinga project will be developed first. This means that the expertise in the region has increased. It is expected that much of the labor used on that large project also will be available for the cascade project, minimizing the need of educating new employees.

In Kristoffer S.Hansen’s master thesis he established a cost estimate for concrete to an RCC dam, figure 8, this is considered to be valid for the cascade project as well, and will form the basis for the cost estimate for the dams.

Table 8 Unit cost for concrete (Hansen, 2013)

Cement	36USD/m^3
Aggregates	52USD/m^3
Pozzolans	68USD/m^3
Unit cost concrete	**156USD/m^3**

4.5 Waterways

The different tunnel cross sections are optimized with respect to head loss, but conversations with Mr. Ødegård indicates that it is unlikely that a contractor will utilize a lot of different tunneling and loading equipment. It is therefore unlikely that rail operation will be utilized for the small transfer tunnel of only 1000 meters. The proposed solution is based on unlined high pressure tunnels and shafts. This will reduce the cost associated with tunneling.

There are mainly three different loader types: the excavator, belt/wheel loader and skid steer loader. All with different optimal application, as described in table 9. It is expected that the contractor wants to utilize the same equipment for all the tunnels, this means that there are mainly cross sections larger than 16 m^2 that is applicable. From 16 m2 to 30 m2 it is the small wheel loader that is the optimal loading equipment, and it is in this range the cross section is expected to be.

Table 9 Loading capacity for different loading types (Department of Civil and Transport Engineering NTNU, 2009)

Type of loader	Cross section, m^2	Loading capacity
Excavator	42 →	High
Wheel loader, small	16 →	Low
Wheel loader, large	36 →	Medium
Belt loader, small	24 →	Low
Belt loader, large	30 →	Medium
Skid steer loader / rail operation	6 →	Low- Medium

In the next chapter the waterways in the project is reviewed. The review starts furthest upstream with the transfer tunnel, and continues as the water flows.

4.5.1 Lombwa Transfer Tunnel

Based on the hydrologic modelling conducted, the average discharge from the Lombwa catchment will be 1.26m^3/s. This is not very much, and building a dam to establish a reservoir with 4MCM is considered to be an expensive solution, therefore the transfer tunnel is considered as an option. A solution of transferring the water from the catchment to the Mboshi reservoir to utilize it for power production will be evaluated further in this chapter.

A transfer tunnel is used to lead water from a river into a reservoir or directly into a head race tunnel. The transfer capacity is mainly dependent on the tunnel cross section, the length of the tunnel and the pressure altitude. (Guttormsen, Teknisk- økomomiske betraktninger ved planlegging av vannkraftverk, 1981) A transfer tunnel between the Lombwa and the Mboshi catchments will make it possible to utilize the water from the Lombwa River without building a large dam. This is a solution that will be evaluated against the proposed solution with a dam on the Lombwa River. The proposed solution is presented in figure 35.

There are two options when building this transfer tunnel.

1) Long hole drilling
2) Regular drill and blast

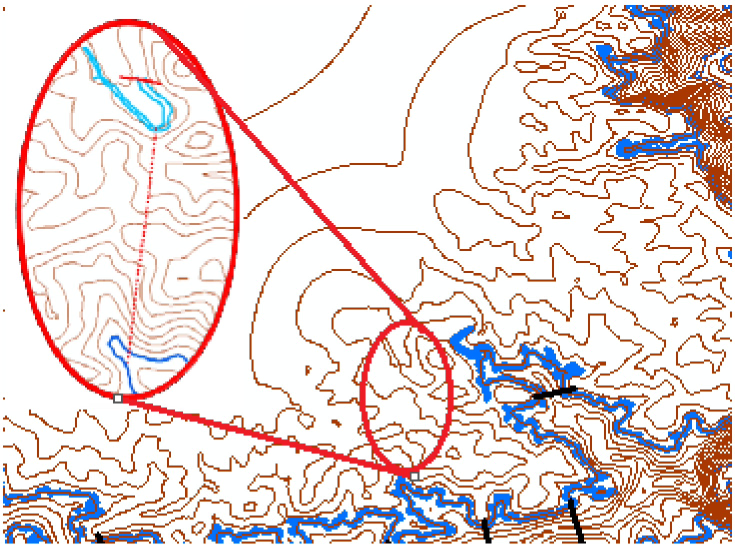

Figure 35 Lombwa transfer tunnel and intake dam

Currently new technology and equipment for long hole drilling is being developed by Norhard a Norwegian contractor and developer. This is mainly focused on directional drilling for small hydro power plants. With the equipment developed so far it is possible to drill stretches up to 1000 meters with a diameter of 700 mm. But there is a continuous process of developing and constructing drill equipment for drilling holes up to 1500 meters and with a diameter of 1200 mm. (Norhard, 2014) This is a method that might have been a good solution for the transfer tunnel, but it is not expected that the knowledge and technology is available in Zambia, and therefore this solution is disregarded. However if it turns out that the method is available in Zambia it should be evaluated further.

The method of regular drill and blast is the preferred method of tunneling and will be recommended for this part. The intake construction is planned on the Lombwa side of the hill. This construction is planned as a small dam with height < 3 meters, and is intended to lead the water into the transfer tunnel. This transfer tunnel also makes the water available for the Mulungushi 2 power plant.

The tunnel is designed as an unlined D-tunnel, with rock support of shotcrete and bolts. The rock support is based on the assumptions that the rock quality is good. There have not yet been conducted any geological investigations in the project area, but an extensive survey has been carried out for the Muchinga project. The conclusion there was that there was mainly good rock quality. Because there are no data available it is assumed that these conditions also apply to this area.

Since the average discharge is not more than 1.26 m^3/s it is likely that the smallest tunnel cross section will be sufficient. But based on the optimization process and costs there may be other factors influencing the final design. This also depends a lot on the equipment the contractor wants to utilize, and as stated it is not likely that tunneling with rails will be utilized.

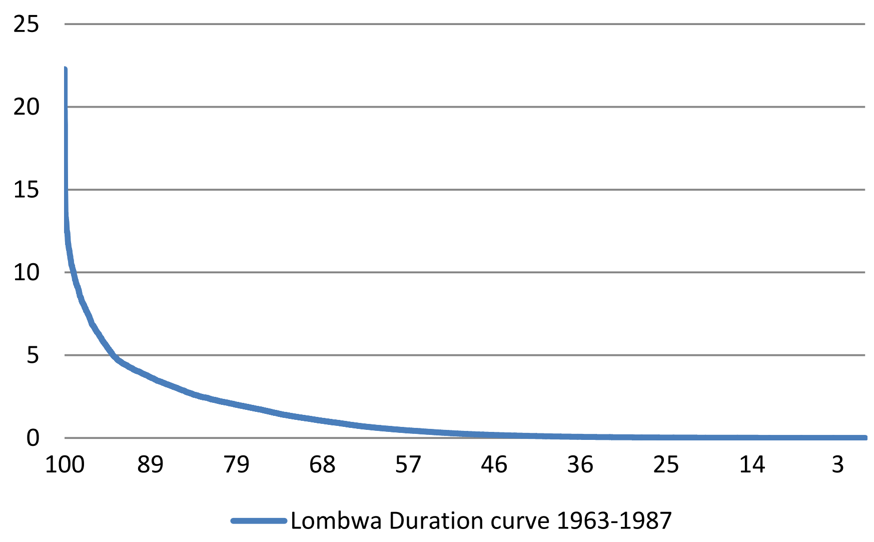

Figure 36 Duration curve Lombwa 1963-1987

The duration curve for the catchment was established based on the simulated data and is illustrated in figure 36. This involves some uncertainty, but gives a good indication of what to expect.

The tunnel will be approximately one kilometer long, with an intake at contour 956 in the Lombwa River and an outlet at contour 940 in the Mboshi reservoir. The proposed design is illustrated in figure 37.

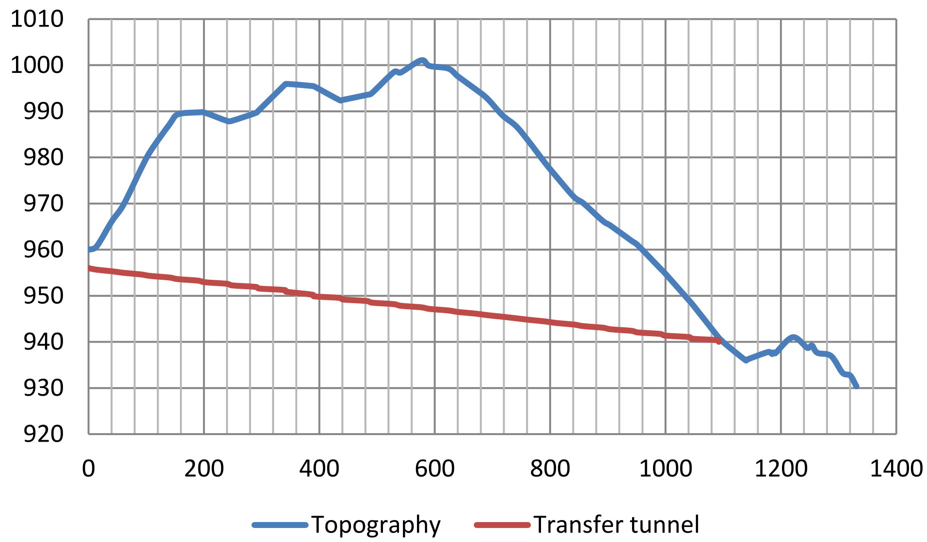

Figure 37 Transfer tunnel design

A tunnel length of 1.1 kilometers and a cross section of 10 m^2, gives a total of 11 000 m^3 to excavate. An estimated cost of the tunnel is based on calculations in TunSim. This gives a cost of 90 $ / m^3 or equally 903 $ / meter tunnel. This gives a total cost of 993 300 USD for the excavation of the transfer tunnel. The cost of excavating the transfer tunnel is quite high per m^3, when excavating small tunnels, the construction machines have to be adapted and a smaller cross section means smaller machines, with less capacity. However if a larger cross section is chosen, and utilization of larger equipment is preferred, then 16 m^2 is applicable. The tunneling cost will then increase to approximately 1070 USD/meter and a total of 1 177 000 USD, but the price for each m^3 will decrease to approximately 67 USD/m^3 This is without rock support, which comes in addition.

The rock support is based on good geological conditions, and the unit price for shotcrete and bolts is obtained from the cost estimate for Muchinga, made by MMD. It is assumed conservatively that shotcrete is used consistently in walls and in the roof of the tunnel. This is unlike Norway, where rock support only is used only when needed, especially in water tunnels. A conservative estimation has been conducted with 90 % of the tunnel covered with a 50mm layer of shotcrete with fibers, and 10 % of the tunnel covered with a 100 mm layer of shotcrete with fibers. This is estimated to cost respectively 60 -and 90 USD/ m2. In addition to this rock bolts are estimated to be used, with a cost of 88 USD / bolt (25 mm diameter x 2.75 m).

The cost of the transfer tunnel is summed up with regard to tunneling method.

Table 10 Transfer tunnel cost

	10 m2	16 m2
Tunneling cost	993 300	1 177 000
Shotcrete	596 277	754 238
Rock bolts	60 403	70 083
Addition 5 %	82 499	100 066
Total (USD)	1 732 480	2 101 387

In addition there is a small intake dam, and the cost for this is calculated to be 39 000 USD.

As outlined this proves to be a more cost efficient solution compared to the Lombwa dam, which is roughly estimated to cost 25 Million USD.

In the next part the proposed solution for the Mboshi waterway will be evaluated.

4.5.2 Mboshi

A solution with a penstock is from a Norwegian point of view an old fashioned way of constructing hydro power plants, especially in the extent provided in this project. It is more common for small hydro power with installation <10 MW. This indicates that another solution than the penstock should be evaluated also. Because of the large mining environment it should not be a problem to get local labour for construction of the tunnels, and they have good knowledge of pilot drilling and reaming shafts.[2] This local knowledge should be utilized to create the overall best solution for the project. A solution with a shaft will be compared to the penstock solution.

4.5.2.1 Penstock

The proposed waterway solution for the Mboshi power plant is a penstock above ground, a solution with a length of 480 meters. The waterway is planned with a horizontal head race tunnel, from the reservoir to the edge of the gorge that descends to the Mulungushi River. A cost basis for the penstock solution is difficult to prepare, because difficult terrain can raise the price significantly. Because the field trip was cancelled, the route of the penstock was hard to evaluate and has been based on maps developed from LIDAR data, and aerial photos. As a basis for comparison a cost estimate based on the unit price of steel USD/ ton will be used.

[2] Communicated by Lars Ødegård 20.04.2014

This solution is in Mott Macdonald's cost estimate, prescribed as a cost of 8250 USD/ton installed. This is considered to be an overestimation, and an impairment of the costs has been recommended by the project manager Lars Ødegård. The new price estimation will be 6500 USD/ton installed. This will be used to evaluate the costs connected to the penstock and to consider the costs compared to constructing a vertical shaft.

A penstock is often built in difficult terrain with expensive components. Therefore the penstock should be as short and steep as possible/practical. This is to minimize the cost of the components. This increases the risk associated with the development and implies that one must have good safety procedures. This is not always something that is associated with development in developing countries. A safe work place is important both for the workers and the construction client. It may therefore be more appropriate to build a shaft, minimizing the uncertainty connected to the penstock. But it is not like shaft construction is undramatic either, but based on the experience from the mining section this is considered to be a more processed work method.

The penstock solution was optimized with regard to the head loss and marginal costs of penstock and the calculations are presented in appendix B. The optimal penstock radius is based on a length of 480 meters and is illustrated in figure 38.

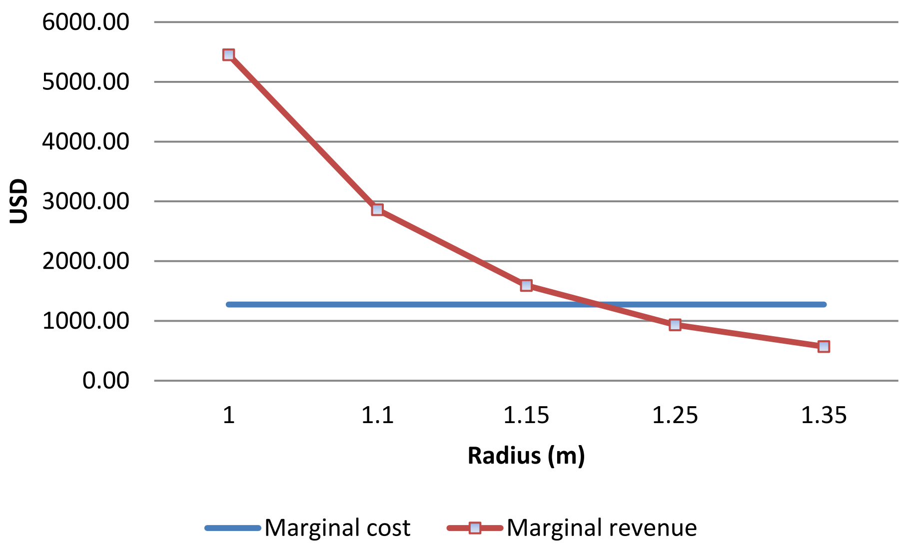

Figure 38 Optimum penstock radius

The optimum penstock radius was calculated to be 1.2 meter. This is based on penstock with an average thickness of 40 mm. This gives a total cost of approximately 15 546 USD per meter just for the penstock, welded on site. As mentioned earlier the cost of installing the penstock may vary a lot depending on the terrain and topography. Therefor the installation costs will be included as a percentage of the whole installation cost. This is solely based on the cost estimate performed for the Muchinga project. In that project the steel penstocks were calculated to be approximate 65 percent of the total costs connected to the penstock. (Mott MacDonald, 2013) This may vary a lot from project to project and a more thorough investigation must be conducted when the final route has been decided, but for further assessments in this thesis this will be the basis. Summarized this leads to a cost of:

- 23 916 USD / meter penstock
- 11.48 Million USD total
- It is important to emphasize that difficult terrain can cause the estimated cost to increase significantly.

4.5.2.2 Shaft

Given the extensive mining in the area, it is assumed that there will not be a problem to obtain labor with the necessary knowledge regarding shaft construction. On this basis, a shaft is considered as a good technical solution, with excellent opportunities for implementation. Due to the lack of data basis for similar projects in Zambia, the Norwegian cost estimate is utilized to create a cost basis. Total cost of shaft construction with an uncertainty of ±30%. It is assumed that the rock quality is good enough to stand without any steel liner and shotcrete / bolts are assumed as rock support.

A shaft may be constructed in different ways:

- Raise drilling
  - Is used to create large drill holes- up to 7.6 meters in diameter. The drilling is performed in two stages, first a small pilot hole is drilled, and then the small drill bit is swapped with a reamer. The reamer is equipped with reels made of hardened metal, which have the same diameter as the final hole. The hole is expanded as the reamer crushes the rock. The method can be utilized on shafts up to 1100 meters in length. Illustration of the technique in figure 39. (Driconeq Production AB, 2012)

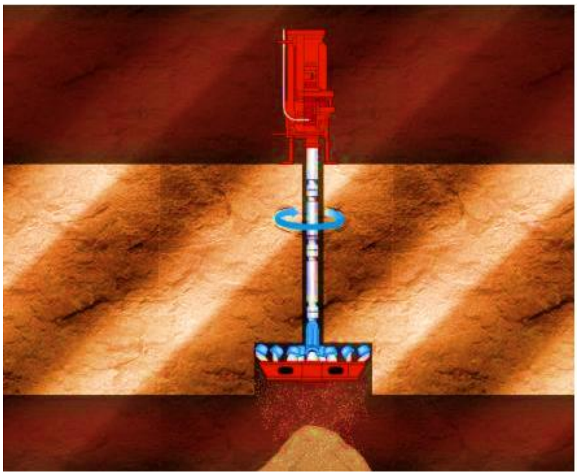

Figure 39 Raise drilling- large holes in two stages (Driconeq Production AB, 2012)

- Conventional operation
    - This means that the shaft is constructed from the bottom and up, using the Alimak method. Rails are mounted along the wall of the shaft, and a work platform brings the workers up to the tunnel face with rail operation. The platform is illustrated in figure 40. (Australian contract mining, 2014)

Figure 40 Alimak working platform (Hardrockminerclothing, 2014)

- It is also possible to combine the two methods. A small hole is drilled, and it is expanded by drill and blast from the top, to the desired cross section.

For further processing it is assumed that the raise drilling method is most applicable in Zambia, it is most suitable in terms of progress and safety and based on communication with Mr. Ødegård it is established that it is a well know method within the mining operations.

Between the shaft and the power plant there will be a plug that is stopping the water from flowing into the power plant, as well as a steel pipe embedded in concrete to lead the water from the shaft to the turbines. This plug is usually from 50-150 meters long dependent on the rock pressure in situ. (Jentoftsen, 2013) A conservative approach is chosen and a solution with an approximately 100 meter long plug that is chosen. The cost of this plug and the embedded steel pipe is calculated based on NVE's cost basis for embedded steel pipes. The cross section is assumed to be the same as the head and tailrace tunnel. The size of the steel pipe is based on that is shall have the same head loss per meter as the shaft.

The cost have been calculated

- Tunnel 1092 USD /m
- Work support: 890 USD/m
- Steel pipe: Radius 1.6 meter / 8 m2
- Cost steel pipe 3367 USD/ m
- Cost plug 1482 USD / m
- Gives a total cost of 6831 USD/ m
- 683 100 USD total.

Calculation of optimal radius for the shaft is given in appendix C, and the result is presented in figure 41.

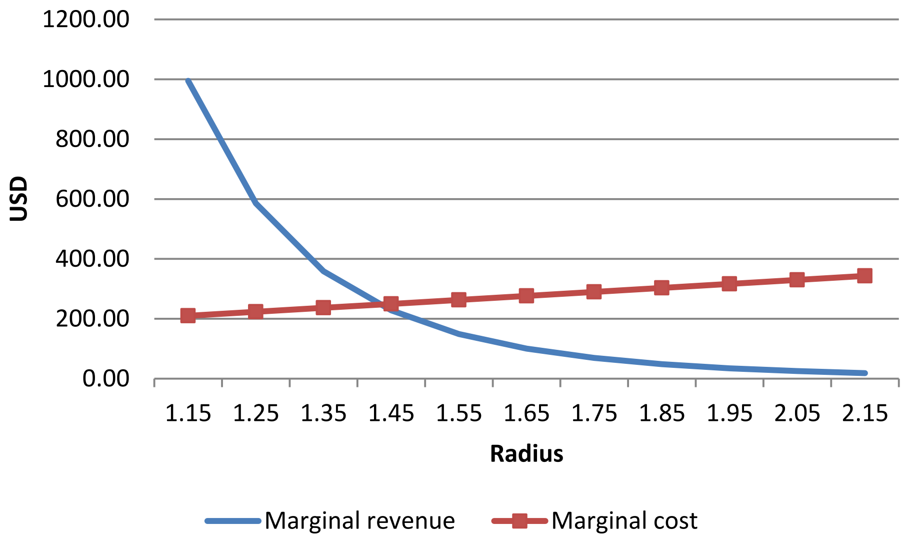

Figure 41 Optimum shaft radius

Specifications shaft:

- 1.45 meter radius
- Cross section 6.6 m^2
- Length 260 meters
- Unit cost of 3667 USD / m
- Steel lined transition: 6831 USD/ m
- This gives an approximate total cost of the shaft 1 636 500 USD.
- This is an estimate with a great deal of uncertainty ±30 %.

Estimated rock support will mainly consist of 100 mm shotcrete with fibers (90 USD/ m2) and systematic bolting (88 USD /bolt). The rock support is implemented in the unit cost.

Even though this rough estimate shows that the shaft solution has potential compared to the penstock solution, all the different parts must be assessed as a whole to make a decision.

4.5.2.3 Headrace- / tailrace- tunnel

There are two main methods of excavating the head and tail race tunnels:

- Tunnel Boring Machine (TBM)
    - There are many pros to using TBM as excavation method, such as: lower friction, good contour, less rock support and good advance rate in good rock conditions but for this project there are some cons which imply that this solution not should be

chosen. At the start of projects utilizing TBM, there is a large investment. This makes the project very vulnerable in terms of difficulties with the machine. The costs could however be reduced by leasing the equipment. The delivery time of a machine like this is long and the logistics to the construction area is poor. In the project there are mainly three different tunnels all with different optimal size and length, this indicates that the machine has to be moved and rigged several times, and this is a time consuming operation. (Department of Civil and Transport Engineering NTNU, 2002)

- Conventional drill and blast (D&B)
  - The advantage of quick commissioning, known methods, and the ability to operate on multiple tunnel faces at the same time, makes this method a safe and good choice. The progress is less dependent on one tunnel face alone, making it less vulnerable to problems. The proposed solution is that the project will be conducted with a conventional drill and blast technique. This technique provides great flexibility regarding tunnel cross section and length.

As stated it is assumed good rock quality, and there is mainly good overburden above the tunnel. This implies good conditions for tunneling. But there is one zone that is critical for the Mboshi head race tunnel, and that is when passing underneath the Lombwa River. This is a zone with low overburden and a geological assessment of the site should be conducted. This is the zone where the most extensive rock support must be expected. To minimize these problems it is possible to place the tunnel axis with a bend so that it crosses the Lombwa River at a convenient point. By a change of route the overburden is calculated to be 27 meters, this should provide good tunneling conditions given good rock conditions. The head race tunnel will be approximately 4800 meters long, and the tailrace tunnel will be approximately 700 meters. The intake will be at contour 900 and the outlet at 640. The route is illustrated on figure 42 and with the topography on figure 43.

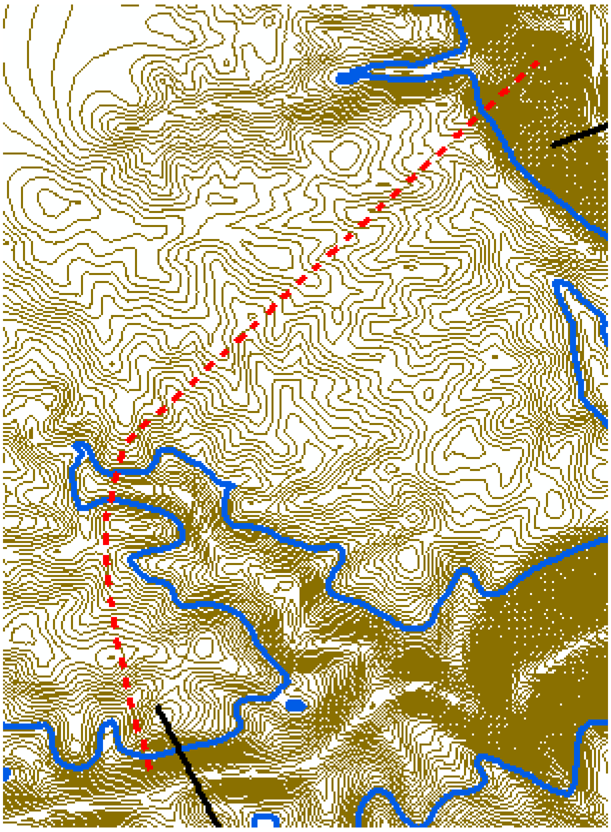

Figure 42 Mboshi head- and tail- race tunnel, marked with red

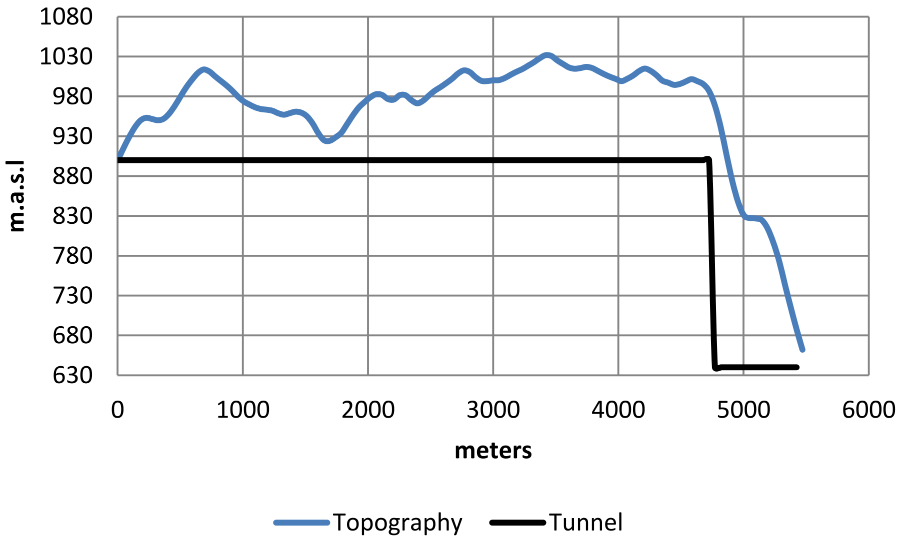

Figure 43 Mboshi headrace tunnel topography

An optimization to find the optimum cross section has been conducted and the calculations are in appendix D. The results are presented in figure 44.

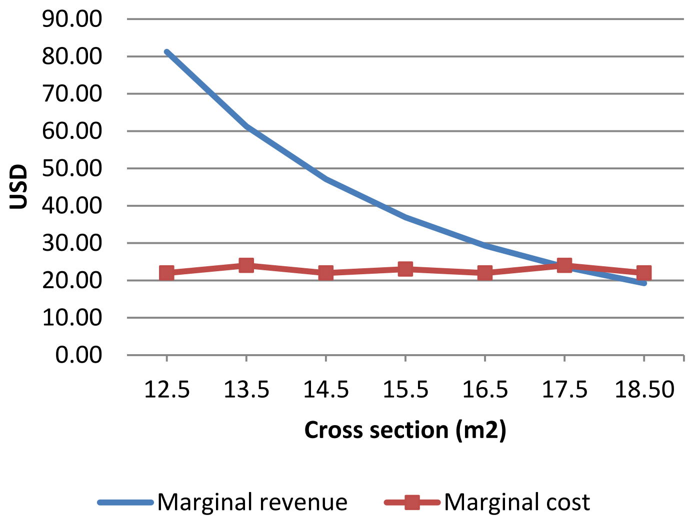

Figure 44 Optimum head- tail race tunnel cross section

Optimized head- and tail race tunnel specifications solely based on tunneling cost and the rock support comes in addition:

- Cross section 17.5m^2
- Unit cost 1092 USD / meter
- 5.24 Million USD (head race)
- 0.76 Million USD (tail race)

The tail race tunnel is designed with the same characteristics as the head race tunnel to ensure sufficient capacity.

Rock support is calculated based on the optimal cross section and consist of a layer of 50 mm shotcrete with fiber, at a cost of 60 USD / m2, and bolts of 25 mm, 2.5 meters 88 USD / piece.

- Shotcrete cost 3.22 M USD (head race)
- Shotcrete cost 0.470 M USD (tail race)
- Bolts 1.21 M USD

The extra effort associated with the tunnel entrance is not taken into account, this site must be evaluated further and a location with good rock conditions is preferable. This operation is often considered to be demanding, and can in poor conditions be a considerable expense.

With three tunnel faces the tunnel is estimated to be completed in approximately one year.

4.5.3 Mulungushi 2

Based on the terrain and topography downstream the Mulungushi 2 dam, the proposed solution from SP is a horizontal head race tunnel, a shaft and an underground power house. Based on the acquired data about the project there is nothing to suggest that another solution would be better fit. Therefore further assessment will be based on the proposed solution with regard to optimizing the design and creating a cost estimate. The headrace tunnel is planned with good overburden along the entire route and with good rock quality as assumed, nothing indicates that there will be major problems with this tunnel, figure 45 shows the tunnel route.

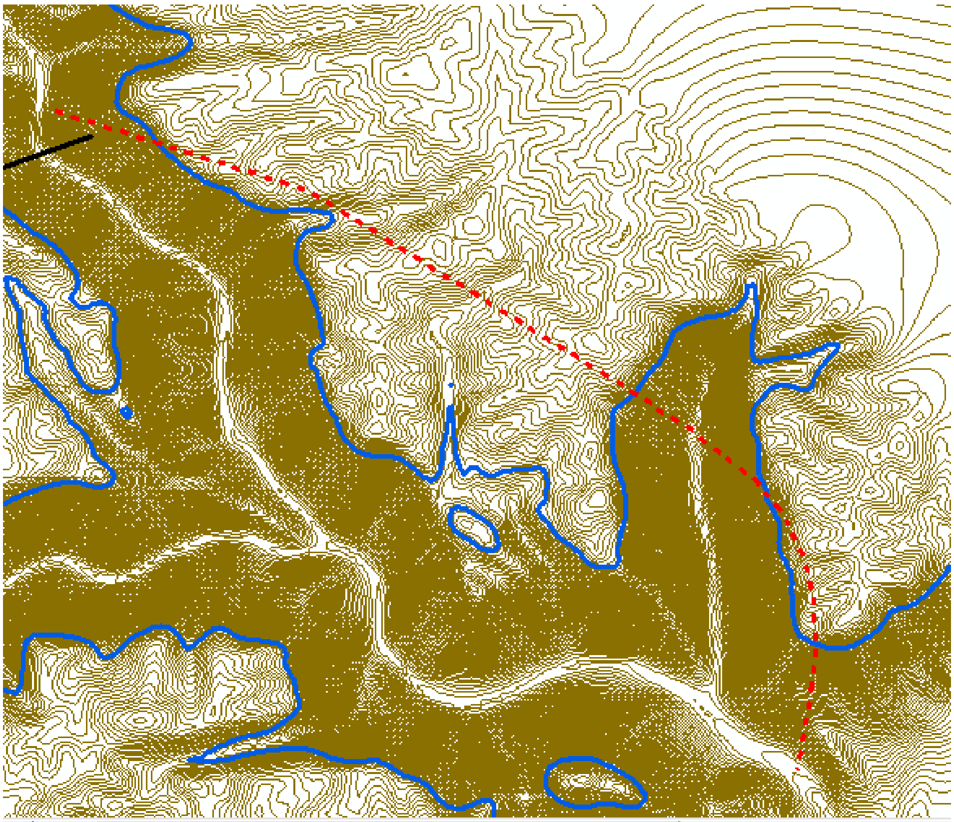

Figure 45 Mulungushi 2 head- and tail- race tunnel route

4.5.3.1 Headrace- / tailrace- tunnel

The head and tailrace tunnel is calculated to respectively 5000 and 3000 meters. And the optimized cross section is illustrated in figure 46.

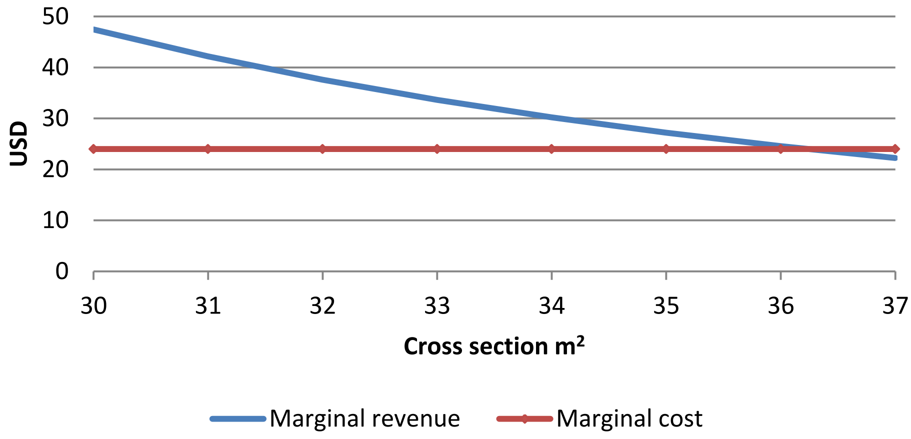

Figure 46 Optimum cross section head- tail- race tunnel

The optimized cross section (appendix E):

- Approximately 36 m^2
- 1441 USD/ meter.
- 40 USD / m^3
- Total cost of 7.2 M USD (headrace tunnel)
- Total cost 4.32 M USD (tailrace tunnel)

Rock support is continuous 50 mm shotcrete with fibers on roof and walls, and rock bolts in places of need. This is a conservative estimate, and it is probably no need to spray the entire tunnel.

- Shotcrete 4.87 M USD (Headrace tunnel)
- Shotcrete 2.92 M USD (tailrace tunnel)
- Rock bolts 1.54 M USD (Total)

This gives cost of 2641 USD/ meter tunnel, for the head- and tail- race tunnel and a total cost of 18.5 M USD.

The tunnel can be excavated from two tunnel faces, and the total excavation time will be approximately 1.5 year. The adit may also be utilized as surge chamber upon completion of project.

4.5.3.2 Shaft

The shaft is designed as a vertical shaft with a length of 123 meters.

The calculations of the optimized radius are presented in appendix F and results are illustrated in figure 47.

The steel lined transition is also here estimated to be approximately 100 meters long. The same cross section is estimated as for the headrace tunnel 36 m2.

- Tunneling: 1441 USD/m
- Work support 1166 USD/m
- Steel pipe: 2.4 m radius, 18 m2
- Cost steel pipe: 5050 USD / m
- Cost plug: 2808 USD/m
- Total cost of 1.04 M USD.

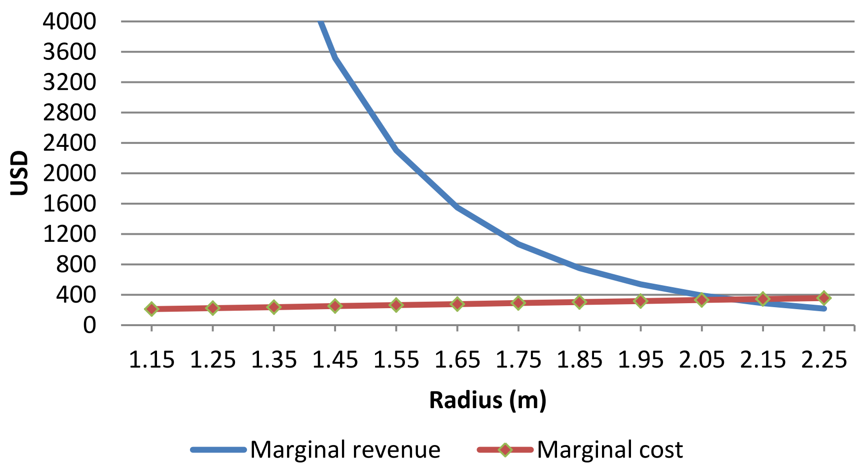

Figure 47 Optimum radius for shaft

The cost of the shaft has been calculated based on the cost base for hydropower plants, and rock support costs from the Muchinga project. The optimal shaft cross section is:

- Radius 2.1 meter
- Cross section 13.85 m^2
- Unit cost: 5661 USD / m
- Steel/concrete transition 1.04 M USD.
- Total cost: 1.74 M USD

4.6 Other components

This early in a project it is not common to optimize all the components in detail. The big picture is essential and the major cost drivers are prioritized. Once this is in place, one can proceed with the detailed design. Due to the limited time and resources, only the main components are evaluated.

4.6.1 Power house

The most common way to build power plants in Zambia is with a surface powerhouse and penstocks, and there is a big difference in what the Norwegians and Zambians perceive as the best approach. In Norway the main method has been unlined pressure shafts / tunnels and an underground power house, since the 60's. This has been possible due to the good rock conditions and favorable tensions. In Norway there are more than 200 underground power houses. (Panthi, 2014) There are several benefits by using the mountain as construction material e.g. good anchoring, the station isn't occupying any surface space which makes the project more environmental friendly, makes the station more secure against both landslides and acts of terror. But it is important to conduct detailed investigation of the ground, especially since the quality of the rocks is assumed to be good. Deviations in the rock mass may lead to substantial additional costs regarding the rock support.

It is possible to draw the comparison between the development taking place in Zambia today with the early period of utilizing hydro power in Norway. The knowledge and expertise was not that well developed, and the access to good equipment was poor. The development started with penstocks and surface power houses, and continued via steel lined shafts to todays practice with unlined pressure tunnels and air cushion chambers.

It is important to understand the Norwegian history and mentality when it comes to planning and executing of hydro power projects. As mentioned by Kristoffer Jentoftsen in his master thesis from the Muchinga project in 2013, his evaluation of the rock quality was that it had enough capacity to be used as construction material for an underground power house, pressure tunnel and an air cushion chamber. The problem was that it would be hard to sell cushion chamber idea to the investors. He writes that the technical personnel at LHPC were unfamiliar with this method of designing waterways. He also concludes that even though the solution may be feasible it would most likely not be the most cost efficient and therefore the solution was not evaluated any further. (Jentoftsen, 2013) As the Muchinga project is a much bigger installation 170 MW than the cascade it is not likely that it will be the most cost efficient solution and is therefore not evaluated further in this thesis.

Underground power house

In the sketch project the proposed solution for Mboshi was a surface power house but the potential of an underground power house is also present and should be evaluated further. There are both positive and negative aspects of both the surface and the underground power house solution, but an important point is that the underground solution reduces the cost associated with the penstock and anchoring, which is regarded as significant costs.

The cost estimation of the underground power house both for the Mboshi and Mulungushi 2 power station is estimated based on volume and quantities obtained from the cost base for hydropower plants. This is considered as a good foundation, because the design of power stations does not vary much. In order to provide a good cost basis, the Norwegian prices have been set aside, and updated unit prices have been obtained. These unit prices have been obtained from the cost estimation for the Muchinga hydropower project (Mott MacDonald, 2013) and from the cost basis developed by Marius Jentoftsen and Kristoffer Hansen during their field trip to Zambia, spring 2013. This means that the cost basis for the underground power house is updated according to Zambian prices.

The overall estimated cost of the underground power house: (see appendix H for calculations)

- Mboshi underground power house 2 308 098 USD
- Mulungushi 2 Underground power house 2 936 778 USD

Surface power house

The Norwegian cost base for hydropower plants is based on low pressure plants, and it is stated that the cost of constructing a surface power station is more dependent on the intake capacity than the installation in MW, because the pressure plays a small part for the civil engineering structures. However this cost base is not intended for high pressure power plants and the project falls outside the specified curves. This indicates that curves have to be extrapolated to get an estimate, but even then it does not give a result to rely on. The cost estimate gives approximately a cost of 841 750 USD. This is considered to be quite low.

Because of the rather scarce data basis, the proposed solution for the Muchinga surface power station has been scaled according to installation. This is not an academic way of preparing a cost estimate, but as a basis for comparing the overall solution with the penstock to the underground power station with shaft, this is assumed to be a good enough solution. The calculations are presented in appendix I.

The total cost of the surface power station is estimated to be 1 820 084 USD. This is a quite rough estimate with a large uncertainty, but when costs for the penstock and the surface power house is combined and compared to the underground solution, this rough assessment is considered to be a valid comparison basis.

4.6.2 Electro technical and mechanical installations

Turbine: For this kind of projects there are mainly two different turbines that are in the range of use. The turbine that is recommended from the sketch is a Francis turbine. There are both positive and negative sides to this choice

Francis turbine (Reaction turbine):

- + Cheaper than Pelton turbine
- + Sharper efficiency curve
- + Can be utilized down to 30% of maximum Q.
- ÷ Chance of cavitation
- ÷ Hard to operate and assemble

Pelton turbine (Impulse turbine)

- + Operates best on high head and low discharge
- + Easy to operate and assemble
- + May be utilized down to 4-5 % of maximum Q.
- + No Cavitation danger
- + Flat efficiency curve
- + Easy availability of spare parts if repair is needed.
- ÷ Increased head loss

  (Sweco Norge AS, 2012)

There is a possibility of increasing the installed capacity to reduce the flood loss, but this will lead to fewer operating hours and the firm power will decrease over the year. This is not an option, as long as firm power is the most important. Also this would require a much larger installation and that is assumed to be disproportionally expensive, and will not be considered further in this thesis.

Figure 48 illustrates the area of application of different Francis turbines, and all the turbines for this project come within the range of standard Francis Turbines.

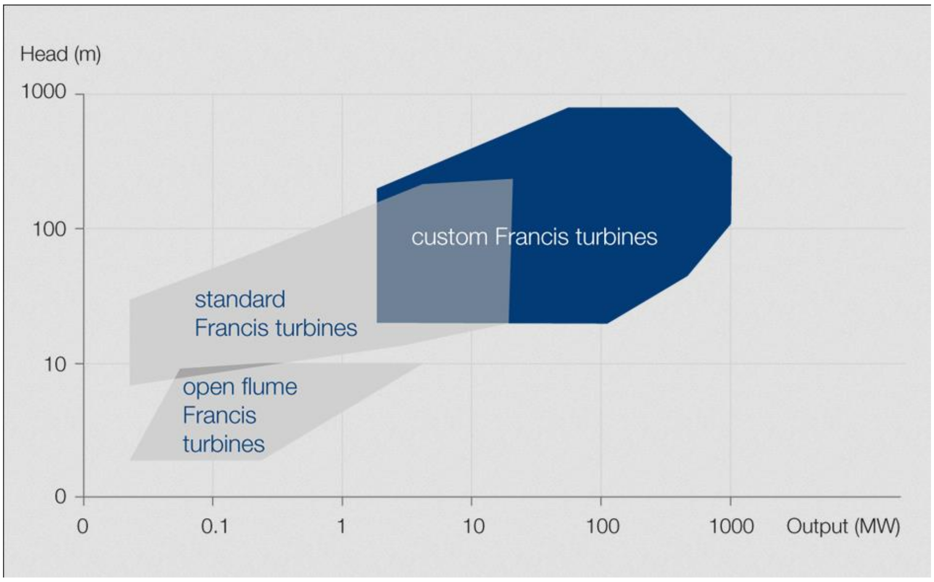

Figure 48 Application of Francis turbine (VOITH, 2013)

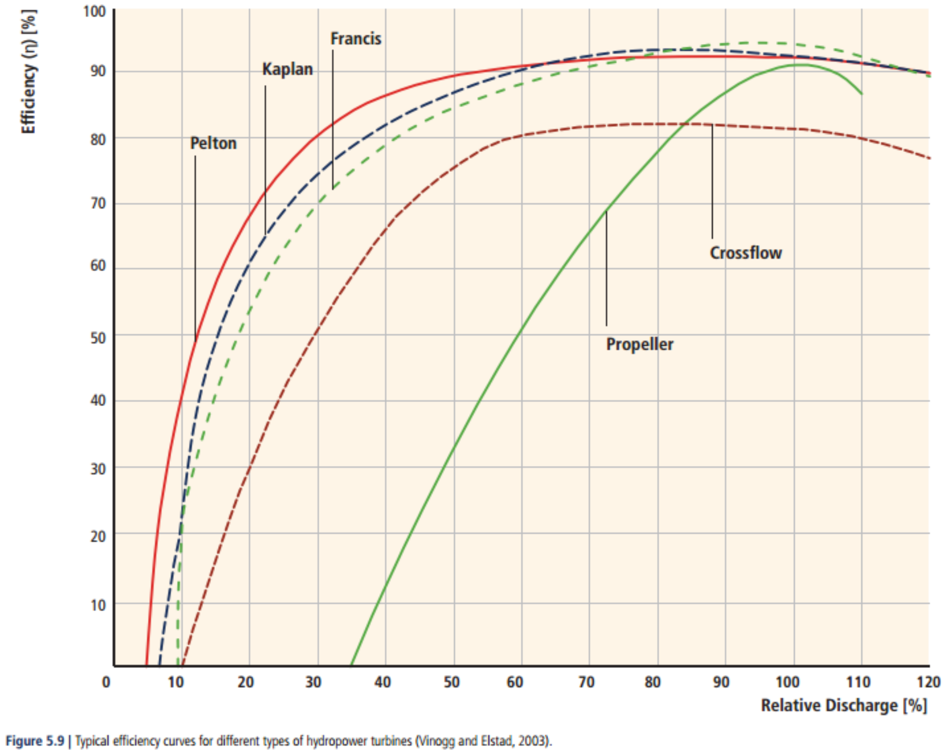

Figure 49 Efficiency curve turbines (Intergovernmental panel on climate change, 2011)

As seen from figure 49 the Francis turbine has a sharper efficiency curve and a higher maximum efficiency point. A high efficiency is optimal for a power plant with an operating time of over 5000 hours/year. That combined with lower investment cost and less head loss makes the Francis turbine the preferred choice.

The cost estimate for Zambia is inadequate, and hence it is necessary to utilize the Norwegian cost estimate made by the Norwegian Water Resources and Energy Directorate. It is assumed that goods traded on the international market, has the same prices both in Norway and in Zambia. On this basis the Norwegian cost basis has been used for a simplified assessment, and the costs have been compared to the Muchinga project. The cost estimate for the Muchinga project estimates that two 85 MW Francis turbines will cost 18 M USD, in the Norwegian cost estimate the two turbines for the Muchinga project would have cost approximately 12 M USD. This is not used further for the calculations for electro technical and mechanical components. This is due to the uncertainty of the basis for comparison with such large differences in installation. Solely the Norwegian cost base is used as foundation with prices adjusted from 2010 level. The cost for electro technical components is based on a total cost estimate curve in the NVE cost base. This gives a total cost for all the electrical components, such as: generator, transformer, switch gear and control system etc. This is a simplification of the cost estimate but considered to be accurate enough for the cost estimation.

A reassessment of the designed solutions gives these specifications:

- Mboshi: 32.5 MW
- Mulungushi 2: 40.5 MW

Mboshi

- Turbine: 3.4 M USD
- Electro technical: 11.8 M USD

Mulungushi 2

- Turbine: 4.16 M USD
- Electro technical: 15 M USD

4.6.3 Access tunnel

Because the overall solution with the underground power station is considered to be the best, it is necessary to construct an access tunnel to the power station for both the Mboshi and the Mulungushi power station. The final design of this tunnel is dependent on the size of the equipment to be installed in the power plant, and a normal cross section is often between 30-40m^2. For the Francis turbine it is normally the transformer that determines the height of the tunnel and the turbine drum will determine the width of the access tunnel. (Sweco, 2012)

The Mboshi access tunnel is calculated to approximately 1 km. This is a rough assessment for a 30 m2 cross section. The cost of the tunnel will be approximately 1.6 M USD.

The Mulungushi 2 access tunnel is not more than approximately 750 meters, but with an inclination of 12 %. The cost of this tunnel will be approximately 1.8 M USD.

4.6.4 Spillway

To ensure that the dams can withstand a flood situation and not be affected of an uncontrolled rise of water level, it is necessary to create good solutions for flood diversion. Both dams will have incorporated spillways into the dam. This is a good and cost efficient solution but a thorough investigation of the ground conditions downstream of the dam is crucial, to validate that they can withstand the water overtopping the dam. There are cases where it has been eroded large pits downstream of the dam, and it is important to be cautious.

Because of the scarce data basis available for the hydrological simulation, and on the basis that the simulated values are considered to be more accurate for average run off than the extreme peaks the design floods will be scaled from the Mkushi river basin. This river basin is located further north, and one can expect that the annual precipitation is greater there, which means that this is a conservative estimate. The simple scaling is based on the Mkushi area 3537km2, the Mboshi / Lombwa area of 3046 km2 and the Mulungushi / East area of 4435.

Table 11 Design floods Mboshi

Return period (Years)	Mkushi dam, Design Floods (m3/s)	Mboshi dam, scaled design floods (m3/s)	Mulungushi 2, scaled design floods (m3/s)
5	115	99	114
10	143	123	179
20	168	145	211
50	202	174	253
100	321	276	402
1000	469	403	588
PMF	1864	1605	2337

The length of the spillways has been calculated in appendix J.

- Mboshi: 110 meters
- Mulungushi 2: 160 meters

4.6.5 Transportation

There are currently no roads connecting the dam sites to the public road network. This has to be established to secure access to the construction site continuously through the year. The road network to the project area is inadequate and a major upgrade is required to ensure transportation to the project area in the wet season. The road from Kabwe to the Mulungushi dam is mainly created from compressed sand, earth fill and gravel and there are not taken any measures for draining it. This implies that the roads, at times, are impassable. For the large Muchinga project, there are plans of upgrading the road network to ensure accessibility for heavy transport and development should be seen in connection with this.

The existing Mulungushi power house is currently without road access. It is only accessible by foot or by a cable way. During the planning of the rehabilitation and upgrading it has been decided that there will be built roads to the power station. This will make it easier to get access to the Mulungushi 2 dam site, and the Mboshi surface power house or the tunnel entrance. There have to be made roads to all the related parts of the project. However these roads will not be assessed further in this thesis and must be evaluated based on the chosen solution.

4.6.6 Power lines

The power line routes from the new power plants will be linked up with the existing Mulungushi power house. This makes the distribution of the power easy, and the cost of connecting the power plants to the power grid minimal. The power lines are planned as 145 kV lines and the costs are directly applied from the Norwegian cost base. This has been done in consultation with Mr. Ødegård. Because the cost evaluation is based on the Norwegian cost estimate, it is considered as a rough assessment and it is expected that the developed solution will cost less. Further work needs local price estimates, but the proposed estimate is considered to be sufficient for this basic assessment.

The terrain is not expected to be a major problem during the construction, but it is not in the category of easy terrain either. This is based on aerial photographs, maps and google earth. A field trip to the area, or contact with the locals will reveal potential problem areas. Based on the available information the cost is set to 151 000 USD / kilometer of power line, but difficult terrain could easily add to the cost of up to 50 percent, and this must be evaluated further. The route of the planned power lines is illustrated in figure 50.

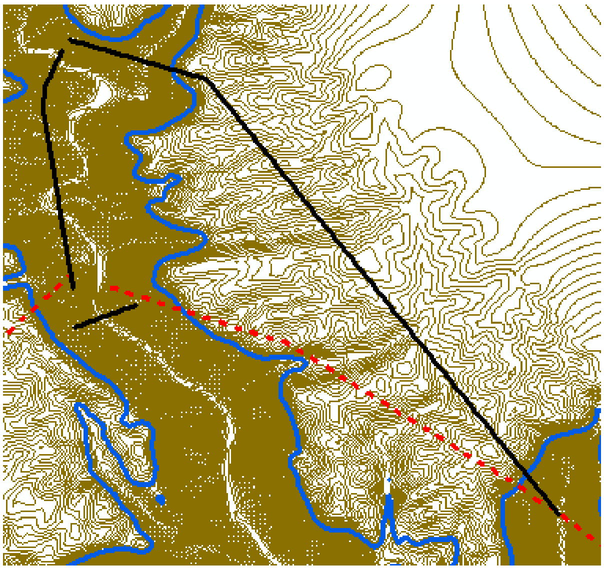

Figure 50 Power line route

- Mboshi- 2 kilometers
- Mulungushi2 –5 kilometers.

This gives a total cost of the power lines to 1.07 M USD. This is a rough estimate and an update with local rates should be performed to get a more accurate estimate.

4.6.7 Sedimentation

There have been performed a desk study for the Muchinga hydropower project, regarding the sediment transport from the rivers and into the planned reservoirs. And the preliminary results were that sedimentation would not be a problem for that project. (Mott MacDonald, 2013) The Muchinga project and the planned Mulungushi cascade is located within the same area (approximately 60km in linear distance), with similar topography and vegetation, this indicates that sediment transport will not be a problem for the planned Mulungushi cascade project either. Based on this, a flushing system for sediments will not be evaluated for this project.

Chapter 5 Power production simulation

In this chapter the optimized technical solutions will be implemented, together with the simulated hydrology, into the simulation software Nmag to assess the production.

5.1 Input

To simulate the power production generated from the two power stations, Mboshi and Mulungushi 2, all the processed data from this thesis have been utilized. The model has been updated in relation to these points:

- Hydrology
  - Time series describing the inflow to the different parts of the project, and evaporation from the reservoirs.
- Structure and technical specifications
  - Overview of the different components in the system (power plants, reservoirs, waterways) and how the water is routed between them. And technical specifications regarding storage, efficiency, loss, maximum discharge etc.
- Operation of power plants and reservoirs
  - Strategy of how the water is released based on regulation of the reservoirs for each time step.
- Energy market
  - The price dependent on supply and demand.

A problem with this simulation is that it is only based on 25 years. This is not much, and a larger time span would have been preferred. As seen from figure 24 the inflow varies widely between the years. And there are several consecutive years with low inflow that makes it hard to produce firm power because of the limited reservoir capacity and that the reservoirs do not fill.

5.1.1 Hydrology

For the hydrological time series two series have been utilized to simulate the power production.

- Simulated runoff based on the HBV model
- Scaled runoff based on the discharge measurements from the Great North Road.

This is to get a comparison basis and because the calibration of the HBV model was not perfect, which indicates that even though a good correlation was found for average runoff, the water may not be accurately distributed over the year with the simulated values.

The series contains as stated data on a daily basis and the advantage of using a daily data series is that the uncertainty regarding flood loss is minimized. The average inflow to the project area for the years (1963-1987) is illustrated in figure 51. Evaporation rates for the reservoirs is also included, this is based on pan evaporation rates for the Mulungushi reservoir, obtained from Dr. Terrence Muir. The pan evaporation rates are scaled with a factor of 0.75, to adapt them to the reservoir.

Table 12 Evaporation from Mulungushi reservoir (Muir T. , 2013)

Surface evaporation (mm/month))											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
111.6	84.0	97.65	112.5	118.575	114.75	118.575	151.125	166.5	223.2	173.25	125.55

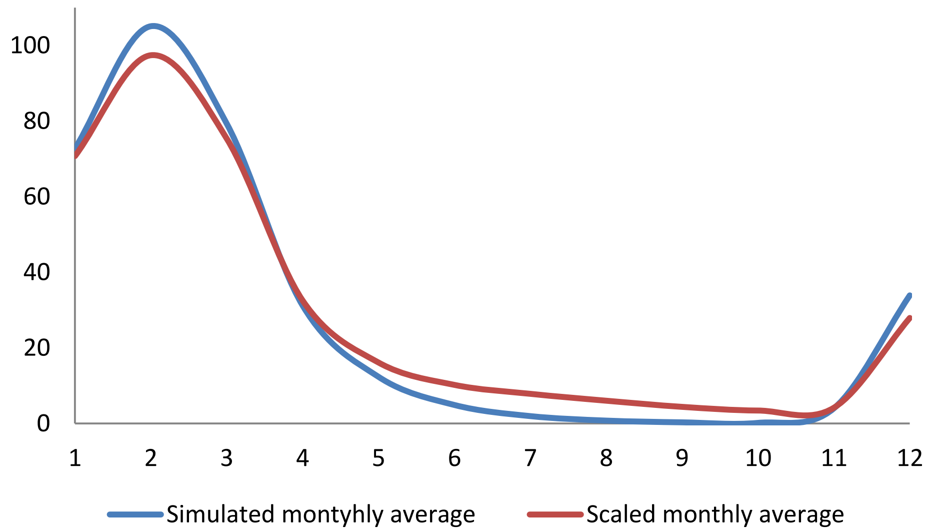

Figure 51 Average inflow to the project area from 1963-1987

The average local inflow is calculated to be:

Simulated (MCM)

- Mboshi: 335.7
- Lombwa: 39.7
- Mulungushi 1: 511.8
- Mulungushi 2: 5.7

Scaled (MCM)

- Mboshi: 335.5
- Lombwa: 39.6
- Mulungushi 1:538.1
- Mulungushi 2: 8.1

As figure 51 shows there is a sharper peak and a lower inflow during the dry season on the simulated hydrograph than the scaled hydrograph.

There is a demand for an environmental flow release from the Mulungushi reservoir of 0.2 m3/s or naturalized flow, whichever is the smallest. It is assumed that this requirement also will apply to the new reservoirs, except from the Lombwa intake reservoir. Therefore a conservative approach have been made and 0.2 m3/ have been incorporated into the model as bypass from Mulungushi (1-2) and Mboshi.

5.1.2 Structure

The model is assembled by using the modules presented in chapter 3 and the technical details for each component are incorporated into the different modules. The entire project area is established within the model, except from one module. It is the Mulungushi 1 power station that has been omitted because it is not a part of the reviews of the new project. The module has however been illustrated in the structure overview in figure 52, but is marked out with an X.

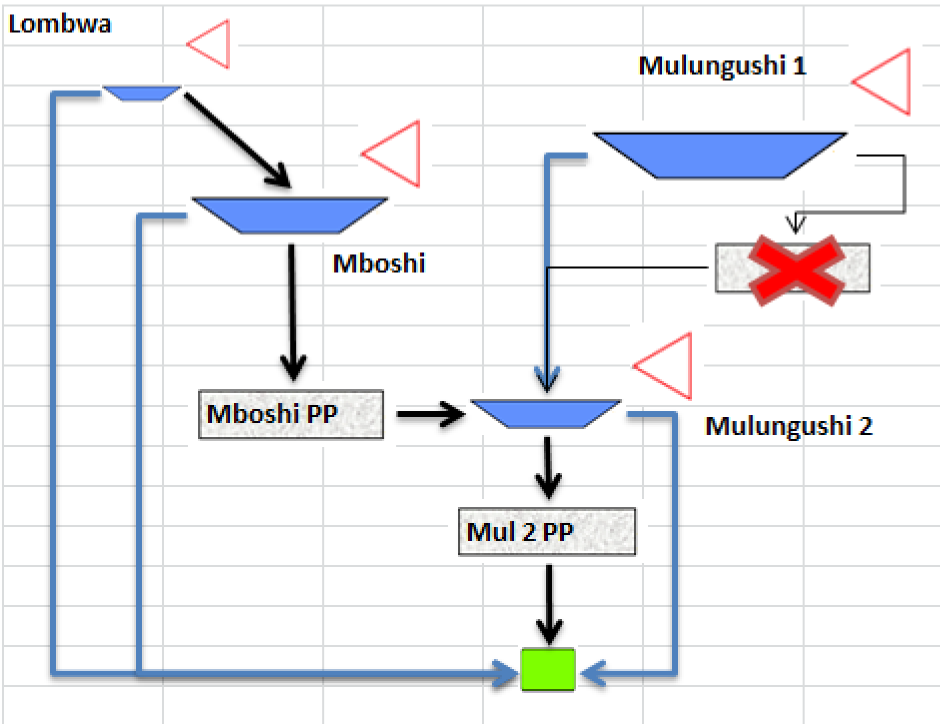

Figure 52Model sketch of the project area

Each component was updated with the parameters established in chapter 4, but some of the main parameters will be listed here as well:

- Mboshi
    - Qmax= 13 m^3/s
    - Energy equivalent 0.694 kWh/m^3
    - Head loss coefficient 0.016 s^2/m^5
    - Reservoir 165 MCM
- Mulungushi 2:
    - Qmax= 34 m^3/s
    - Energy equivalent 0.331kWh/m^3
    - Head loss coefficient 0.0030 s^2/m^5
    - Reservoir 6 MCM

The energy equivalent for the power plant is calculated and given as initial start value for the simulation; however a new equivalent is calculated based on the available head for each time step.

5.1.3 Operation

The nMAG software describes the hydraulic and hydrological conditions in an accurate way, but when it comes to operational strategy and the consumption system it is slightly more simplified. This means that the program is most suitable for calculating new projects, but less suitable for day to day planning of existing power plants. (Killingtveit, 2004) This indicates that the software is suitable for the calculations for this new project. Because the project consists of two power stations with different reservoir size, it is evident that they have to be operated different. The Mulungushi 2 power plant is dependent on release from the reservoirs further upstream to operate. While the Mboshi power plant has a much larger reservoir and operation can vary so that water can be stored for the dry season. The software provides different ways of managing the reservoirs:

Reservoir release specification

This setting makes it possible to specify the release from each reservoir as a percentage of average annual release. This makes it possible to adapt the release to the annual distribution of inflow.

Reservoir guide curve specification

Because the inflow to the reservoirs is approximately the same every year, it is possible to create a curve that describes the optimum reservoir level through the year. This curve follows the hydrological circle and indicates when the reservoir should be filled and when it should be emptied. If the reservoir level is above the curve there will be produced dump power, and if the reservoir is below the curve a curtailment occurs.

To optimize the production and minimize the flood spill a reservoir release specification has been chosen for this model, for the Mboshi and Mulungushi 1 and 2 reservoirs, the Lombwa is specified with automatic reservoir balancing. This gave the best results regarding to power production and firm power production.

5.1.4 Energy market

The development of the energy market in Zambia is related to the increasingly developing of power stations in the country and economic growth. In the long term it is expected that Zambia will utilize its hydropower potential (>6000 MW), to become a large exporter of power. But the current conditions and the deficit of power indicates that it is important to supply constant firm power. This may change in the years to come with more development, but the current situation will be indicative for the simulations that are carried out. It is assumed that the need for firm power is virtually constant over the year, even though this is a slight simplification of the current conditions. The demand will also vary throughout the day, but this is not possible to simulate with this model.

The optimizing criteria for the power production simulation will therefore be based on a firm power production. If the criteria was to only produce as much power as possible regardless of time the operation of the power plants would have been different and the production would have been higher.

This simulation will not be incorporating different peak prices for the produced electricity but simply aim to simulate the firm power production based on demand coverage above 90 %. This means the power that can be delivered with a high reliability in 9 out of 10 years. (Hansen, 2013) Therefore the simulation will be performed based on a constant firm load.

Power that is generated beyond the planned firm power is occasional power. This power is often produced in periods when the inflow is large and demand is low, which means that the price will also be lower. It is often distributed for shorter periods of time.

5.2 Simulation results

The power production simulation has been based on an optimizing of the firm power production through the year. And the regulation of the reservoirs has been fitted to best suit the needs. There have been simulated two scenarios, giving different output as presented in appendix K. But a review of the results is presented below.

Simulated time series:

- Firm power production 245 GWh, with a demand coverage of 98.8%

- Average production of 377 GWh per annum.
- Approximately 60 % utilization of the inflow for each power plant.

Scaled time series:

- Firm power production of 130 GWH, with small deviations with demand coverage of 99.8%.
- Average production of 364 GWh per annum
- Approximately 45 % utilization of inflow to the Mboshi power plant, and 77% from the Mulungushi 2 power plant.

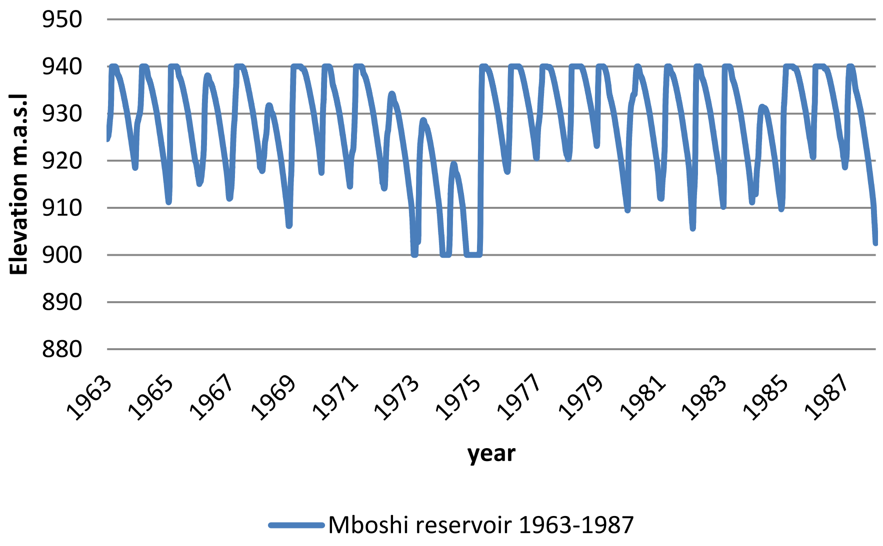

Figure 53 Mboshi operation of reservoir

In figure 53 the operation of the Mboshi reservoir is illustrated and as it shows the whole reservoir is not utilized. This is simply because of the consecutive years with low inflow and the demand for firm power. There are large deviations in the inflow and because of the low reservoir capacity there will be problems of producing the firm power, especially for the years with consecutive low inflow when the reservoirs don't fill. Without the large storage of water, there would simply not be enough water to produce the firm power in the dry years and this would mean large costs. However this high regulation level indicates that there will be a lot of spill from the reservoir. If the criterion for firm power was lower, the operation of the reservoir could have been adapted better to increase the annual production.

5.2.1 Spill

As expected a large amount of the available water was lost as flood spill. This flood loss was expected due to the limited capacity for water storage, but because of the high regulation level through the year it was amplified. There is little to do with this except from adapting the guide curve better to optimize the operation of the power plants, or reducing the firm power. One can also increase the installed capacity in the power stations or increase the regulation of the reservoirs. But it is not realistic to avoid flood loss. An increased installation would in addition to cost more, most likely result in lower operating time, which is not consistent with distributing firm power over the year.

The spill from the reservoirs from the two scenarios:

- Simulated approximately 264 MCM, (30 % of total)
- Scaled approximately 246 MCM, (27% of total)

5.2.2 Evaluation of the results

Because of the demand for firm power production, it is not possible to run the power plant optimal and a lot of the inflow is lost as flood spill. With a better optimization with regard to the day to day regulation of the reservoirs it is expected that the spill is reduced and average annual production and firm power production will increase. Based on the uncertainty regarding the simulated hydrological inflow there was performed a power production simulation for the scaled time series as well and even though the output from the two series was quite similar with regard to yearly average production (≈370 GWh), there was a large deviation in the firm power production. The total output was far from the expected production from the sketch project (595 GWh). This discrepancy is mainly based on that the operation of the power plant is optimized for firm power production and not maximum output. It is also a result of the extensive flood loos from the reservoirs.

Chapter 6 Conclusions

6.1 Proposed design for the Mulungushi cascade

The optimized overall solution for the Mulungushi cascade is presented below.

Lombwa:

- 1100 meter transfer tunnel, (16 m^2)
- Small threshold < 3 meters, 250 m^3

Mboshi

- RCC dam, 79.5 meters high, 0.437 MCM
- Reservoir, 165 MCM
- Headrace tunnel, 4800 meters, 17.5 m^2
- Tailrace tunnel, 700 meters, 17.5 m^2
- Shaft, 260 meters, 1,45 m radius
- Underground power station
- Installed capacity. 32.5 MW
- Power lines, 2 kilometers

Mulungushi 2

- RCC dam, 47 meters high, 0.1 MCM
- Reservoir, 6 MCM
- Headrace tunnel, 5000 meters, 36 m^2
- Tailrace tunnel, 3000 meters, 36m^2
- Shaft, 123 meters, 2.1 meter radius
- Underground power station
- Installed capacity, 40 .5 MW
- Power lines, 5 kilometers

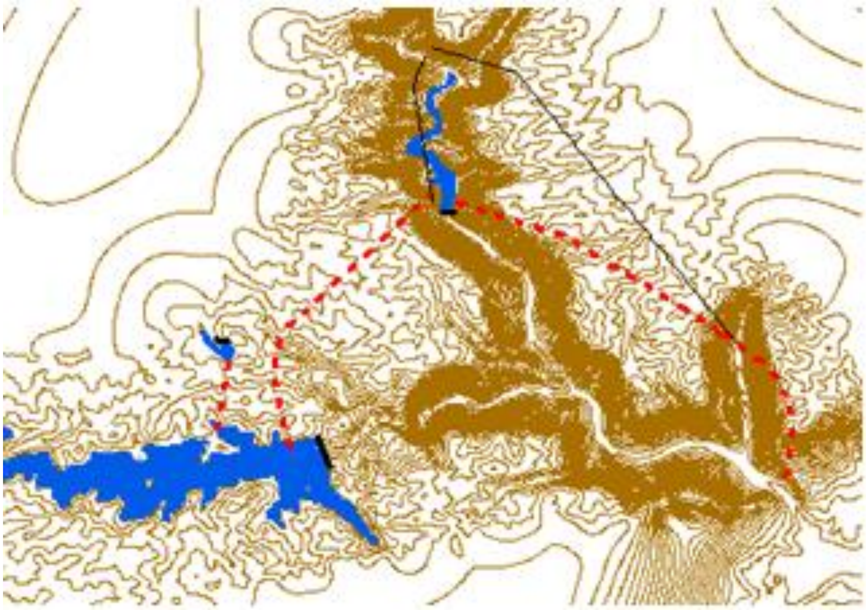

Figure 54 Proposed new design for the Mulungushi cascade

Costs

Lombwa	**Mboshi**	**Mulungushi**
• Threshold: 0.039 M USD • Transfer tunnel: 2.1 M USD (16 m2)	• RCC dam: 68.2 M USD (1:0.7) • Head- / tail- race tunnel: 10.9 M USD • Shaft : 1.63 M USD • Underground power house: 2.3 M USD • Electro/ Mechanical: 15.2 M USD • Access tunnel: 1.6 M USD • Power Lines: 0.3 M USD	• RCC dam: 15.6 M USD (1:0.75) • Head- / tail- race tunnel: 20.85 M USD • Shaft: 1.74 M USD • Underground power station: 2.94 M USD • Electro / Mechanical: 19.16 • Access tunnel: 1.8 M USD • Power lines: 0.75 M USD

Lombwa

Construction of the transfer tunnel and threshold is a good investment compared to the solution with a large dam and it provides a reduced development cost of 22.8 M USD.

Mboshi

The solution with the shaft and the underground power station is considered to be approximately 5 M USD cheaper than the proposed solution with a penstock and a surface power station. This could potentially be more based on the penstock route, and the uncertainty connected to the surface power station does not influence the decision that much. This gives a total cost of 100.13 M USD. This is an estimate of the major components and a more detailed assessment must be conducted for further evaluations. The head loss has been calculated to 2.72 meters (appendix G), giving a net head for power production to be 297.28 meters. This indicates that the installation should be increased from 30 to 32.5 MW.

Mulungushi 2

The installed capacity is reduced from 50 MW to 40. 5 MW and the water level in the reservoir have been lowered from 680 to 660 meter above sea level. The head loss is calculated to 3.52 meters (Appendix G) giving a net head for power production to be 139.48 meters.

Total costs for the solutions addressed in this thesis:

Lombwa	2.14 M USD
Mboshi	100.13 M USD
Mulungushi 2	62.84 M USD
Total	165.11 M USD

Even though all the parts of the development has not been been considered in this thesis there are indications that this is a very promising project.

6.2 Recommendations for further work

Establishing gauging station at Mboshi

The planned gauge upstream the Mboshi dam should be deployed and a rating curve prepared. The project will most likely not be initiated before the large Muchinga project is completed, and this gives a few years of collecting data. If a discharge and/or a precipitation station are established in this catchment, there may be several years of good records to control the assumptions that were made when conducting this thesis and improve it. Since the station already is planned and a suited location have been found upstream the Mboshi dam, the effort of installing the station and monitoring the precipitation and runoff should be carried out.

Prepare a revised hydrological basis

The conditions for hydrological modelling have been difficult, which can be related to the models that have been used. Use of a different hydrological model, and maybe incorporating the TRMM data, to establish a more certain hydrological basis is advised.

Update the costs

Several of the components have been evaluated with a Norwegian approach and based on a Norwegian cost base, adapted to Zambian conditions. There is a large uncertainty in this approach and local costs should be obtained to minimize the uncertainty.

Geological survey of the project area

The dam site, tunnel route and the underground power stations are dependent on a thorough investigation of the conditions on the site. This thesis is solely based on assumptions regarding the geological conditions and deviations can result in extra expenses for rock support and tunneling.

Evaluate the power production possibilities further

The power production simulation showed that there were large problems of maintaining a constant firm power through the year because of the large deviations in inflow and the small reservoir capacity. Based on this an evaluation of the power market and future developments should be carried out.

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Appendix

Appendix A

Optimized parameters HBV Model

Name:	PARAMETER	LOWER	UPPER
PKORR:	1.0100	1.0000	1.2000
SKORR:	1.1368	1.0000	1.5000
HPKORR:	12.7080	5.0000	15.0000
TX:	-0.6176	-1.0000	2.0000
TS:	1.8609	-1.0000	2.0000
CX:	4.8556	1.0000	5.0000
CPRO%:	4.3526	0.0000	10.0000
PRO%:	6.1002	5.0000	15.0000
FC:	206.6927	100.0000	300.0000
BETA:	1.5537	1.0000	3.0000
LP%FC:	71.7383	50.0000	100.0000
KUZ2:	0.1037	0.1000	0.5000
KUZ1:	0.0507	0.0500	0.2000
UZ1:	24.3754	5.0000	30.0000
PERC:	1.4471	0.2000	1.5000
KLZ:	0.0298	0.0200	0.1000
GCX:	1.0000	1.0000	1.0000
Tlp:	-0.4770	-0.4000	-0.7000
Tlo:	-0.8118	-0.4000	-1.0000
SM0:	60.0000	60.0000	60.0000
UZ0:	16.0000	16.0000	16.0000
LZ0:	10.0000	10.0000	10.0000
hpk0:	0.8653	0.8653	0.8653
hpk1:	0.8793	0.8793	0.8793
hpk2:	0.8894	0.8894	0.8894
hpk3:	0.8983	0.8983	0.8983
hpk4:	0.9060	0.9060	0.9060
hpk5:	0.9136	0.9136	0.9136
hpk6:	0.9250	0.9250	0.9250
hpk7:	0.9441	0.9441	0.9441
hpk8:	0.9708	0.9708	0.9708
hpk9:	1.0470	1.0470	1.0470
NiMt:	1.0000	1.0000	1.0000

SAVING: C:\HBV_Calib\hbvopt\Free_Par.txt.OUT
Free Parameters... DONE

Appendix B

Calculations of penstock

The calculation is based on a steel weight of 7847 kg/m3.

And a cost of 6500 USD /ton steel

L	480	meters
Hlosscoeff	5000	hours
Q	13	m3/s
Pefficiency	0.85	
Price	0.09	USD/ kWh
PVF	6.57	
Interest	15	%
k	0.045	mm
Life expectancy	30	years
ρ	1000	kg/m3
vicosity	0.000001	

A m^2	r m	Re	Friction coefficient	Head loss	Lost energy W/m	Present value USD/m	Total cost	Marginal cost	Marginal revenue
2.5	0.9	9195618	0.05309	18.83	4252	12573	11723		
								1274	5452
3.1	1	8276057	0.05092	10.67	2408	7121	12997		
								1274	2860
3.8	1.1	7523688	0.04907	6.38	1441	4261	14271		
								1274	1593
4.5	1.2	6896714	0.04607	4.0	902	2668	15546		
								1274	932
5.3	1.3	6366197	0.04482	2.6	586	1735	16820		
								1274	569
6.1	1.4	5172535	0.04371	1.75	394	1165	18094		

Appendix C

Calculation of Mboshi shaft

M	60	m^1/3/s
L	260	m
Hlosscoeff	5800	h
Q	13	m3/s
Pefficiency	0.85	
Price	0.09	USD
PVF	6.57	
Interest	15	%
Life expectancy	30	years
ρ	1000	kg/m3

Area (m)	**Radius (m)**	**Velocity m/s**	**Rh (m)**	**Total head loss (m)**	**Lost energy W/m**	**Present Value USD/m**	**Total cost USD/m**	**Marginal cost**	**Marginal revenue**
3.8	1.1	3.4	0.55	1.87	781.5	2680.18	2874.83		
								209.85	995.08
4.52	1.2	2.8	0.6	1.18	491.35	1685.1	3084.69		
								223.19	585.52
5.31	1.3	2.4	0.65	0.77	320.62	1099.58	3307.87		
								236.52	358.99
6.16	1.4	2.1	0.7	0.52	215.94	740.59	3544.39		
								249.85	227.99
7.07	1.5	1.8	0.75	0.36	149.46	512.59	3794.24		

Appendix D

Calculation of Mboshi head-/ tailrace tunnel

Calculation is performed for the head race tunnel, this is the longest one, but the same cross section will be used for both head and tail race tunnel to ensure adequate runoff.

M	34	m^1/3/s
L	4800	m
Hlosscoeff	5800	Hydraulic radius (m)
Q	13	m3/s
Pefficiency	0.85	
Price	0.09	USD
PVF	6.56597964	
Interest	0.15	%
Life expectancy	30	years
ρ	1000	kg/m3

Area (m)	**Velocity m/s**	**Rh (m)**	**Total head loss (m)**	**Lost energy W/m**	**Present Value USD/m**	**Total cost USD/m**	**Marginal cost**	**Marginal revenue**
13	1	0.96	4.41	99.64	341.52	1001		
							61.24	24
14	0.93	0.99	3.62	81.78	280.28	1025		
							47.1	22
15	0.87	1.03	3.01	68.03	233.18	1047		
							36.87	23
16	0.81	1.06	2.54	57.28	196.31	1070		
							29.3	22
17	0.76	1.09	2.16	48.73	167.01	1092		
							23.61	24
18	0.72	1.12	1.85	41.84	143.4	1116		

Appendix E

Calculations of Mulungushi 2 Head- tail- race tunnel

Calculation is performed for the head race tunnel, this is the longest one, but the same cross section will be used for both head and tail race tunnel to ensure adequate runoff.

M	34	m^1/3/s
L	5000	m
Hlosscoeff	5000	
Q	34	m3/s
Pefficiency	0.85	
Price	0.09	USD
PVF	6.57	
Interest	15	%
Life expectancy	30	years
ρ	1000	kg/m3

Area (m)	Velocity m/s	Rh (m)	Total head loss (m)	Lost energy W/m	Present Value USD/m	Total cost USD/m	Marginal cost	Marginal revenue
32	1.06	1.5	2.85	161.38	477.11	1345.00		
							37.59	24
33	1.03	1.52	2.62	148.66	439.52	1369.00		
							33.63	24
34	1.0	1.55	2.42	137.29	405.89	1393.00		
							30.19	24
35	0.97	1.57	2.24	127.07	375.70	1417.00		
							27.19	24
36	0.94	1.59	2.08	117.88	348.51	1441.00		
							24.56	24
37	0.92	1.61	1.93	109.57	323.95	1465.00		
							22.24	24
38	0.89	1.63	1.80	102.05	301.71	1487.24		

Appendix F

Calculations of Mulungushi 2 Shaft

M	60	m^1/3/s
L	123	m
Hlosscoeff	5000	h
Q	34	m3/s
Pefficiency	0.85	
Price	0.09	USD
PVF	6.57	
Interest	15	%
Life expectancy	30	years
ρ	1000	kg/m3

Area (m)	**Radius (m)**	**Rh (m)**	**Total head loss (m)**	**Lost energy W/m**	**Present Value USD/m**	**Total cost USD/m**	**Marginal cost**	**Marginal revenue**
10.18	1.8	0.9	0.44	1011.21	2990	4711.7		
							748	303
11.34	1.9	0.95	0.33	757.9	2241	5014.9		
							536	317
12.57	2	1	0.25	576.5	1704	5331.4		
							390.5	330
13.85	2.1	1.05	0.19	444.42	1314	5661.2		
							288.7	343
15.21	2.2	1.1	0.15	346.77	1025	6004.4		

Appendix G

Head loss

The head loss of the tunnel and shaft has been calculated from the Manning formula

$$hf = \frac{L*Q^2}{A^2 M^2 R^{4/3}} \qquad \text{formula 5}$$

L= Length (meters)

Q= Discharge (m3/s)

A= Cross section (m2)

M= Manning's number

R= Hydraulic radius (m)

And the penstock has been calculated from the Darcy Weissbachs formula:

$$hf = \frac{L*Q^2}{D*2g*A^2} * f \qquad \text{Formula 6}$$

Where:

L= Length

Q= Discharge (m3/s)

D= Diameter (m)

g=Gravity (9.82 m/s^2)

A= Cross section (m^2)

The friction factor is calculated based on the Colebrook-White equation, (7)

$$f = \left(\frac{1}{-2\log\left(\frac{k}{3.7D}+\frac{5.1286}{Re^{0.89}}\right)}\right)^2 \qquad \text{Formula 7}$$

$$Re = \frac{D*V}{v} \qquad \text{Formula 8}$$

D= Diameter (m)

V= Velocity (m/s)

v= Kinematic viscosity

A slight simplification has been made to establish the total head loss through the waterways. This is based on that the singular losses from intake, trash rack, niche expansions, and so on are considerably smaller than the loss due to friction in the waterways. Therefore the minor losses are disregarded from the calculations in this thesis.

Total head loss

Mboshi

Option 1	Shaft		Option 2	Penstock	
Head race tunnel	2.0	m	Head race tunnel	2.0	m
Shaft	0.43	m	Penstock	4.0	m
Steel lined transition	0.15	m			
Tailrace tunnel	0.29	m			
Total	2.87	m	Total	6.0	m

Mulungushi

Head race tunnel	2.08	m
Shaft	0.19	m
Steel lined transition		
Tailrace tunnel	1.25	m
Total	3.52	m

Appendix H

Underground power station

The volume of the different parts has been calculated using the cost basis for power plants, published by NVE. The unit prices have been obtained from the cost estimate for the Muchinga project, together with unit prices obtained by Kristoffer Sandstad and Marius Jentoftsen during their field work in Zambia, spring 2013.

Blasted rock V = 78 x H^0.5 x Q^0.7 x n^0.1   formula 9
h=head, Q=discharge, n=number of units

Concrete 20 % of blasted volume

Rebar 60 kg/ m3 concrete

Formwork 2.1 m2/m3 concrete

Rock support 15 % of cost of blasting

Masonry work 5% of blasting and concrete works

Decor 10 % of % of blasting and concrete works

Unforseen 10 % of the aforementioned works

Rig and operation 25-30 % of the aforementioned works

Electrical 168 000-420 000 $

Ventilation / Air condition :336000-1000000 $

Cost estimate Mboshi Underground Power station			
	Volume (m3)	Unit price (USD)	Total USD
Blasted rock	8 720.04	50.00	436 002.10
Concrete	1 744.01	156.00	272 065.31
Rebar (tons)	104.64	1 800.00	188 352.91
Formwork	3 662.42	33.67	123 313.60
Rock support		0.15	65 400.31
Masonry work		0.05	35 403.37
Decor		0.10	70 806.74
Unforseen expenses		0.10	119 134.43
Rigging and operation		0.25	327 619.69
Electrical			200 000.00
Heating, Ventilation and Air Conditioning			470 000.00
Total costs		USD	2 308 098.47

Cost estimate Mulungushi 2Underground Power station			
	Volume (m3)	Unit price (USD)	Total USD
Blasted rock	11 800.51	50.00	590 025.62
Concrete	2 360.10	156.00	368 175.98
Rebar (tons)	141.61	1 800.00	254 891.07
Formwork	4 956.22	33.67	166 875.77
Rock support		0.15	88 503.84
Masonry work		0.05	47 910.08
Decor		0.10	95 820.16
Unforseen expenses		0.10	161 220.25
Rigging and operation		0.25	443 355.69
Electrical			220 000.00
Heating, Ventilation and Air Conditioning			500 000.00
Total costs			2 936 778.46

Appendix I

Mboshi Above ground power station

Calculations are solely based on the proposed cost estimate for the Muchinga. The costs have been scaled due to lack of better cost basis. The estimate in the Norwegian cost basis is not applicable here, but just for a comparison this is extrapolated and calculated to be 2.5 M USD. The scaled costs are most likely more real and will be used as comparison basis and this is calculated to 1.8 M USD.

Power house structure	**Unit**	**Rate**	**Quantity**	**Muchinga**	**Mboshi**
Soft excavation & disposal to soil	m3	12	35000	420000	55263
Rock excavation & disposal to stockpile for reuse	m3	27	20000	540000	71052
Type 1 Granular fill	m3	24	8000	192000	25263
Structural fill	m3	20	4200	84000	11052
Foundation Preparation to receive concrete	m2	24	500	12000	1578
Structural concrete (C32/40 & 20mm Aggregate size)	m3	252	19000	4788000	630000
Mass Concrete (C20 & 20 mm aggregate size)	m3	210	100	21000	2763
Blinding concrete (C20 & 20 mm aggregate size)	m3	228	100	22800	3000
Shotcrete	m3	750	100	75000	9868
Rebar	TN	1800	1750	3150000	414473
Formwork (vertical)	m2	78	15000	1170000	153947
Formwork (Horizontal)	m2	168	2000	336000	44210
Formwork (Curved)	m2	132	1200	158400	20842
Backfill (Soft excavation)	m3	12	1500	18000	2368
Structural steel	TN	3600	150	540000	71052
				11527200	1516736
Unmeasured items	%	20	11527200	2305440	303347
Total costs				13832640	1820084

Appendix J

The spillway capacity is based on the formula:

$$Q = c * L_{eff} * H_0^{3/2}$$ (Norges vassdrags- og energidirektorat, 2005) formula 10

Q= Total capacity (m3/s)

C= Overflow coefficient ($m^{1/2}$/s)

Leff= Effective length of spillway

H_0= Dimensioning overflow height

For the calculations c=2 and H_0=1.5.

Appendix K

Power production simulation based on simulated timeseries from HBV model

SIMULATION MODEL n N M A G 2004
DATASET : one year. File: C:\nmag2004\Cascade.set
RUN : Mulungushi Cascade
SIMULATION FOR 1963 TO 1987

YEAR	FIRM	PSUM	COST	DEFICIT	PSEASON1	PSEASON2
1963	245.00	383.23	-2.4383	0.00	192.62	190.61
1964	245.00	379.40	-1.3689	0.00	206.36	173.04
1965	245.00	386.20	-2.1658	0.00	205.34	180.86
1966	245.00	379.65	-1.7896	0.00	200.38	179.27
1967	245.00	393.77	-3.1342	0.00	202.37	191.40
1968	245.00	379.06	-1.2363	0.00	195.90	183.15
1969	245.00	395.03	-2.8810	0.00	207.02	188.01
1970	245.00	391.17	-1.8722	0.00	206.90	184.27
1971	245.00	386.91	-2.1166	0.00	206.53	180.39
1972	245.00	364.12	11.6834	3.45	199.98	164.14
1973	245.00	328.18	65.1898	18.54	182.65	145.53
1974	245.00	266.95	184.6255	53.81	145.76	121.19
1975	245.00	350.79	-0.5833	0.21	162.39	188.40
1976	245.00	399.77	-3.4642	0.00	203.22	196.55
1977	245.00	399.32	-3.4088	0.00	206.24	193.08
1978	245.00	417.04	-4.2758	0.00	204.74	212.30
1979	245.00	374.26	-0.3839	0.00	207.20	167.07
1980	245.00	381.66	-1.6371	0.00	206.21	175.45
1981	245.00	379.92	-1.9909	0.00	200.70	179.22
1982	245.00	366.51	-1.3228	0.00	190.52	176.00
1983	245.00	372.85	-1.2489	0.00	199.71	173.14
1984	245.00	391.67	-2.1954	0.00	198.09	193.59
1985	245.00	400.56	-3.2973	0.00	207.18	193.38
1986	245.00	397.07	-3.0932	0.00	207.37	189.70
1987	245.00	365.67	-0.0638	0.00	204.52	161.15
MID	245.00	377.23	8.6212	3.04	198.00	179.23

MAIN SYSTEM DATA
DATASET : one year. File: C:\nmag2004\Cascade.set
RUN : Mulungushi Cascade
SIMULATION FOR YEARS 1963 TO 1987

NO	NAME	R e	P p	I t	C o	RESVOL Mm3	PMAX MW	QMAX m3/s	EEKV kWh/m3	ADR. 1 2 3	PROD GWH	UTIL %
1	Mboshi PP	X	X			165.0	33.351	13.0	0.674	32424	185.3	61.3
3	Mulu 2 Pow	X	X			6.0	40.948	34.0	0.333	242424	191.9	64.9
4	Intake	X				0.0	0.000	10000.0	0.000	122424	0.0	0.0
5	Mulungushi	X				233.6	0.000	10000.0	0.000	3 3 3	0.0	0.0
12	Interbasin			X		0.0	0.000	20.0	0.000	124 1	0.0	0.0
24	Utløp				X	0.0	0.000	10000.0	0.000	0 0 0	0.0	0.0
25	KP Mul DAM				X	0.0	0.000	10000.0	0.000	5 5 5	0.0	0.0

```
WATER BUDGET FOR EACH MODULE IN THE SYSTEM:
DATASET :  one year.  File: C:\nmag2004\Cascade.set
RUN      : Mulungushi Cascade
SIMULATION FOR YEARS 1963 TO 1987
     MODULE                  QLOCAL  QTOTAL  THROUGH  BYPASS   SPILL   SPILL
NO   NAME                      Mm3     Mm3      Mm3     Mm3     Mm3       %

 4   Intake                   39.0    39.0     39.0     0.0     0.0     0.0
12   Interbasin transf        39.0    39.0     39.0     0.0     0.0     0.0
 1   Mboshi PP               335.5   374.5    275.0     6.2    88.8    24.0
25   KP Mul DAM              511.8   511.8    511.8     0.0     0.0     0.0
 5   Mulungushi Reserv       511.8   511.8    473.2     6.3     0.0     0.0
 3   Mulu 2 Power Plan         5.7   760.2    576.8     6.3   176.4    23.2
24   Utløp                     0.0   854.5    854.5     0.0     0.0     0.0


STATISTICS OF DEFICIT:
======================

DATASET :  one year.  File: C:\nmag2004\Cascade.set
RUN      : Mulungushi Cascade

SIMULATION FOR YEARS 1963 TO 1987

YEAR / VOLUME OF DEFICIT:
 1974    53.81
 1973    18.54
 1972     3.45
 1975     0.21
 1963     0.00

AVERAGE DEFICIT     =    3.0 GWh/yr
DEMAND COVERAGE     =  98.8 %
```

Power production simulation based on timeseries scaled from Great North Road

```
SIMULATION MODEL n N M A G 2004
DATASET :  one year.  File: C:\nmag2004\cascade_scaled.set
RUN      : Mulungushi Cascade
SIMULATION FOR 1963 TO 1987
 YEAR    FIRM     PSUM     COST   DEFICIT  PSEASON1 PSEASON2

 1963   130.00   424.05  -6.5187    0.00    194.64   229.41
 1964   130.00   350.97  -3.3516    0.00    187.62   163.35
 1965   130.00   192.37   0.0362    0.00    111.88    80.48
 1966   130.00   141.63   4.3665    1.41     66.99    74.63
 1967   130.00   199.94   2.6883    1.30    100.01    99.93
 1968   130.00   155.16  10.7174    3.49     77.30    77.86
 1969   130.00   468.68  -8.8094    0.00    190.30   278.38
 1970   130.00   399.58  -6.2636    0.00    184.91   214.67
 1971   130.00   354.87  -5.8660    0.00    180.13   174.74
 1972   130.00   408.68  -6.8757    0.00    200.64   208.04
 1973   130.00   196.25  -3.2907    0.00     88.87   107.38
 1974   130.00   513.33  -9.1207    0.00    202.12   311.22
 1975   130.00   477.96  -8.9703    0.00    203.39   274.57
 1976   130.00   517.35  -9.1368    0.00    201.97   315.39
 1977   130.00   413.16  -6.7924    0.00    194.99   218.16
 1978   130.00   560.78  -9.3105    0.00    207.56   353.21
 1979   130.00   430.97  -7.2464    0.00    194.89   236.08
 1980   130.00   504.04  -9.0835    0.00    203.91   300.13
 1981   130.00   518.20  -9.1402    0.00    207.49   310.71
 1982   130.00   362.51  -5.9148    0.00    178.96   183.55
 1983   130.00   295.68  -4.3978    0.00    165.78   129.91
 1984   130.00   192.50  -1.8470    0.01     93.31    99.19
 1985   130.00   415.27  -6.4059    0.00    194.36   220.91
 1986   130.00   440.51  -7.6264    0.00    206.51   234.00
 1987   130.00   188.67   0.1178    0.26    105.38    83.29

  MID   130.00   364.92  -4.7217    0.26    165.76   199.17
```

MAIN SYSTEM DATA
DATASET : one year. File: C:\nmag2004\cascade_scaled.set
RUN   : Mulungushi Cascade
SIMULATION FOR YEARS 1963 TO 1987

NO	NAME	R e	P p	I t	C o	RESVOL Mm3	PMAX MW	QMAX m3/s	EEKV kWh/m3	ADR. 1 2 3	PROD GWH	UTIL %
1	Mboshi PP	X	X			165.0	33.351	13.0	0.701	32424	144.7	48.4
3	Mulu 2 Pow	X	X			6.0	40.948	34.0	0.346	242424	220.2	76.8
4	Intake	X				0.0	0.000	10000.0	0.000	122424	0.0	0.0
5	Mulungushi	X				233.6	0.000	10000.0	0.000	3 3 3	0.0	0.0
12	Interbasin			X		0.0	0.000	20.0	0.000	124 1	0.0	0.0
24	Utløp				X	0.0	0.000	10000.0	0.000	0 0 0	0.0	0.0
25	KP Mul DAM				X	0.0	0.000	10000.0	0.000	5 5 5	0.0	0.0

WATER BUDGET FOR EACH MODULE IN THE SYSTEM:
DATASET : one year. File: C:\nmag2004\cascade_scaled.set
RUN   : Mulungushi Cascade
SIMULATION FOR YEARS 1963 TO 1987

NO	MODULE NAME	QLOCAL Mm3	QTOTAL Mm3	THROUGH Mm3	BYPASS Mm3	SPILL Mm3	SPILL %
4	Intake	39.6	39.6	39.6	0.0	0.0	0.0
12	Interbasin transf	39.6	39.6	39.6	0.0	0.0	0.0
1	Mboshi PP	335.5	375.1	206.4	6.3	153.1	41.8
25	KP Mul DAM	538.1	538.1	538.1	0.0	0.0	0.0
5	Mulungushi Reserv	538.1	538.1	515.9	5.5	0.0	0.0
3	Mulu 2 Power Plan	8.1	736.0	635.6	6.3	93.7	12.7
24	Utløp	0.0	895.0	895.0	0.0	0.0	0.0

YEAR / VOLUME OF DEFICIT:

1968	3.49
1966	1.41
1967	1.30
1987	0.26
1984	0.01

AVERAGE DEFICIT   =   0.3 GWh/yr
DEMAND COVERAGE   = 99.8 %