UPPSALA
UNIVERSITET

UPTEC-W13020
Examensarbete 30 hp
Augusti 2013

Rating of discharge at monitoring station affected by backwater effects – El Deim Station in the Blue Nile

---

Mattis Hansson

ABSTRACT

Rating of discharge at monitoring station affected by backwater effects – El Deim station in the Blue Nile

Mattis Hansson

On the Blue Nile in Sudan, near the Ethiopian border, there is a measurement station named El Deim. The discharge assessments carried out at this station are crucial for the water resource management in Sudan. Due to changed conditions, caused by a heightening of the downstream-located Roseires dam, new methods for discharge assessment are needed. The objective of the present study was to examine possibilities and methodologies to assess the discharge at this station. The flow dynamics was examined through steady state as well as dynamic hydraulic modeling by use of the Mike 11 modeling software package. By simulating possible future scenarios, in the aspect of discharge variations in the Blue Nile and water level variations in the reservoir, the effects from the raised dam on El Deim could be studied. The model was based on bathymetrical data in form of cross sections. As boundary conditions for the simulation, measured and synthetic data series of discharge and water levels were used. The known measured water levels at El Deim were compared with the simulated water levels at El Deim for the same discharge scenarios. The modeled value corresponds well to the measured values. The existing discrepancies between the simulated and measured values are likely caused by insufficient bathymetrical data.

Simulation results show that the flow dynamics at El Deim are highly dependent on the water level of the reservoir and the discharge's rate of variation. Accordingly, rating curves were created for a range of water levels at the reservoir. With the use of these curves, and tables/equations based on them, the discharge can be rated by knowing the water level at the Roseires dam and El Deim. However, the results from this study are more a description of the principles of how the discharge ratings could be performed. If the methodology and rating tools from this study are planned to be implemented the model must be improved with more bathymetrical data. The improvements are needed to create more accurate curves, tables and equations for discharge rating. Discharge ratings can then be produced and enable better operation of Roseires dam and a more efficient use of the valuable water resources in Sudan. In order to test the applicability of the created model and produced rating tools they should be compared with new measurement data from El Deim with the heightened Roseires dam fully implemented.

It is possible to assess the discharge at El Deim even when backwater effects affect the station. The methodology developed in this thesis would be applicable for similar studies at other locations.

Keywords: Hydrology, Mike 11, backwater, flow dynamics, El Deim, Blue Nile, Sudan

Department of Earth Sciences, Program for Air, Water and Landscape Sciences.
Uppsala University. Villavägen 16, SE-752 36 UPPSALA
ISSN 1401-5765

REFERAT

Bestämning av vattenföring vid en mätstation påverkad av dämning – Mätstationen El Deim vid Blå Nilen

Mattis Hansson

Vid den Blå Nilen i Sudan, nära den Etiopiska gränsen, ligger en mätstation som heter El Deim. Vattenföringsbestämningarna som utförs vid denna station är av högsta vikt för vattenresurshanteringen i Sudan. På grund av förändrade hydrologiska förhållanden, orsakade av en höjning av den närliggande Roseires dammen, behöver det utvecklas nya metoder för vattenföringsbestämning vid stationen. Detta arbete syftar till att undersöka möjligheten och metodik för vattenföringsbestämning vid denna station. Flödesdynamiken undersöktes med hjälp av statisk och dynamisk simulering i Mike 11. Genom att simulera olika möjliga framtida scenarier, med varierande vattenföring i Blå Nilen och vattenstånd vid reservoaren, kunde effekterna av höjda nivåer i Roseires reservoar studeras. Modellen skapades med hjälp av batymetriska data i form av tvärsektioner. Som gränsvärden för simuleringarna användes uppmätta och skapade dataserier med vattenföring och vattenstånd. De kända mätvärdena av vattenståndet vid El Deim jämfördes med de simulerade vattenstånden vid stationen. Det modellerade värdena överensstämmer väl med de uppmätta vattennivåerna. Den diskrepans som finns mellan simulerade och de uppmätta värdena är troligen en effekt av otillräcklig information om flodens batymetri.

Simuleringar visade att vattenföringens dynamik vid mätstationen i högsta grad påverkas av nivån i Roseires reservoar samt av hur snabba eventuella flödesförändringar är. Resultat från simuleringar med de nya högre reservoarnivåerna användes för att skapa ett antal olika avbördningskurvor, från vilka tabeller och ekvationer för att skatta vattenföringen togs fram. Med hjälp av dessa kan vattenföringen fastställas genom att veta vattennivån vid mätstationen samt reservoaren. Resultaten från denna examensuppsats bör ses som en principiell möjlighet till att skatta vattenföringen. Om metoder och verktyg utvecklade under detta examensarbete skall implementeras bör den hydrauliska modellen förbättras med mer data över batymetrin. Denna förbättring är nödvändig för att öka noggrannheten i skapade tabeller, ekvationer och kurvor för skattning av vattenföringen. Vattenföringsskattningar från dessa möjliggör bättre styrning av Roseires dammen och ett mer effektivt utnyttjande av Sudans viktiga vattenresurser.

Det är möjligt att skatta vattenföringen vid mätstationen El Deim även vid påverkan av dämningseffekter. Metodiken vilken använts för denna studie bör vara tillämpbar för andra studier av liknande karaktär.

Nyckelord: Hydrologi, Mike 11, dämningseffekter, flödesdynamik, El Deim, Blå Nilen, Sudan

Institutionen för geovetenskaper, Luft-, vatten- och landskapslära.
Uppsala Universitet. Villavägen 16, SE-752 36 UPPSALA
ISSN 1401-5765

PREFACE

This report for my master thesis is the final part in my Master of Science degree in Aquatic and Environmental Engineering at Uppsala University. It is a thesis written during one semester (30 hp) and it was executed at Sweco Infrastructure AB in Stockholm. Supervisor has been Carsten Staub, Area Manager-Eastern Africa, at Sweco Infrastructure and the subject reviewer has been Professor Allan Rodhe at the Department of Earth Sciences, Air, Water and Landscape science, Uppsala University.

I want to thank both Allan and Carsten for the time and effort they invested in this master thesis. I also want to thank them for good discussions and inputs along the way.

Many thanks to Dr. Ahmed and other people involved from Dams Implementation Unit (DIU) in Sudan for making this master thesis possible. Thanks for giving me the data that I needed for this study.

The examiner of this study was Fritjof Fagerlund at the Department of Earth Sciences, Air, Water and Landscape science, Uppsala University. Thank you Fritjof for good comments on the report.

I also want to thank Karen Kemling and Joakim Holmbom at Sweco Infrastructure for guidance and support.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Bestämning av vattenföring vid en mätstation påverkad av dämning – Mätstationen El Deim vid Blå Nilen

Mattis Hansson

I länder med korta men intensiva regnperioder finns det ett stort behov av att kunna spara vatten till perioder med torka. Vattnet kan då användas till bevattning av områden vilka annars skulle vara obrukbara samt till energiproduktion genom vattenkraft. Ett sätt att bevara vatten är genom att bygga dammar. Ovanför dammen skapas då en reservoar, vilken kan lagra stora mängder vatten.

Genom Sudan rinner den mytomspunna Nilen, vilken är och har genom historien varit en källa till liv för både djur och människor, i ett annars ofta torrt klimat. För att kunna nyttja Nilens vatten under en större del av året har flera dammar byggts längs dess väg. Dammar vilka producerar el och möjliggör utnyttjande av vattenresurser under de återkommande torrperioderna. För att kunna utnyttja dessa dammar på ett effektivt sätt bör information om aktuella och kommande flöden vara så tillförlitliga som möjligt. På detta sätt kan rätt mängd vatten utnyttjas och ledas ut för bevattning och dammen hållas på en lämplig nivå.

Vattenföringen i den Blå Nilen kännetecknas av en koncentrerad flödestopp under augusti-september, vilken uppkommer på grund av en kort och intensiv regnperiod i det branta Etiopiska höglandet, där Blå Nilen har sin källa. I den Blå Nilen, nära den Etiopiska gränsen, ligger en mätstation som heter El Deim. Flödesbestämningarna som utförs vid denna station är av högsta vikt för vattenresurshanteringen i Sudan. Tidigare har vattenföringen bestämts genom en enskild avbördningskurva, där varje vattennivå vid mätstationen motsvarar ett unikt vattenflöde. På grund av förändrade hydrauliska förhållanden, skapade till följd av en höjning av den nedströms liggande Roseires dammen, önskar Sudans Dam Implementation Unit (DIU) att det utvecklas nya metoder för vattenföringsbestämning vid stationen. Nivån vid mätstationen beror nu inte längre endast på vilket flöde som rinner i Blå Nilen utan även på nivån i reservoaren.

Detta examensarbete syftade till att undersöka möjligheten samt metoder för att skatta vattenföringen vid stationen El Deim. Genom att skapa en modell i simuleringsprogrammet Mike 11 kunde flera olika flödesscenarier undersökas. Både simuleringar med verkliga serier av mätdata och hypotetiska scenarier studerades. Modellen skapades med hjälp av information från DIU. Informationen bestod av tvärsektioner över bottens utseende samt mätningar av vattenföringen och vattennivåer i Blå Nilen. Mätningarna hade utförts vid El Deim och Roseires dammen mellan 1965-2012. Kalibrering och validering av den hydrauliska modellen genomfördes mot historiska data. Under kalibreringen ändrades ingående parametrar som Mannings tal för att ge en så verklighetsöverstämmande simulering som möjligt. Simulerat vattenstånd jämfördes mot historiska uppmätta data. Resultaten från olika simulerade flödesscenarier visar att simuleringarna nästan ger samma värden som de uppmätta. Detta indikerar på att modellen kan användas för att uppskatta vattenföring, både av statisk samt dynamisk karaktär, i Blå Nilen. Även statistiska analyser av den hydrauliska modellens förmåga att simulera vattenståndet visar goda resultat.

Modellens Nash-Sutcliffe (NS) värde för valideringsperioden 2012 var cirka 0,993. Ett NS värde på 1 indikerar att det simulerade värdet överensstämmer exakt med det observerade. Vissa skillnader mellan de simulerade och de uppmätta värdena finns dock och en möjlig orsak till detta är otillräcklig mängd information om bottens utseende.

Resultaten från simuleringarna visar att vattennivån vid mätstationen El Deim i högsta grad påverkas av nivån i Roseires reservoar samt av hur snabba eventuella flödesförändringar är. På grund av detta behövde avbördningskurvor skapas för olika vattennivåer i Roseires dammen. Från dessa avbördningskurvor kan tabeller samt ekvationer över relationen mellan flödet och vattennivåerna skapas. Med hjälp av dessa kan vattenföringen fastställas ur vattennivån vid mätstationen och reservoaren.

Resulterande avbördningskurvor, tabeller samt ekvationer, för skattning av flödet i El Deim, bör användas med försiktighet innan det är väl studerat hur väl de överensstämmer mot nya mätdata. Framtagen metod för att ta fram och utföra vattenföringsskattningar vid El Deim bör ses som en principiell möjlighet. Om den hydrauliska modellen förbättras med mer batymetriska data och återigen kalibreras kan mer korrekta avbördningskurvor, ekvationer och tabeller tas fram.

Det är möjligt att fastställa vattenföringen vid mätstationen El Deim, med en rimlig noggrannhet, med framtagna avbördningskurvor, tabeller och ekvationer för ett brett spektrum av flödesscenarier. Dessa verktyg möjliggör, att på ett snabbt och enkelt sätt kunna skatta vattenföringen, genom att mäta nivån vid mätstationen och dammen. En god skattning av vattenföringen är en förutsättning för en effektiv reglering av Roseires dammen och därigenom en förutsättning för ett effektivt utnyttjande av Sudans livsnödvändiga vattenresurser. Metodiken vilken använts för denna studie bör vara tillämpbar för andra studier av liknande karaktär.

DEFINITIONS

Backwater effects: Effects from a downstream control section on the flow characteristics upstream

Wetted perimeter, P (m): The perimeter along the cross section that is in contact with water

Hydraulic radius, R (m): The ratio between the cross sectional area of the flowing water (A) and the wetted perimeter (P), A/P

Steady flow: The velocity of the water flow does not change with time

Uniform flow: The velocity is constant in the direction of the flow

Quasi-steady flow: The flow variations are so slow that the flow for certain study purposes can be assumed to be steady. For a given flow the quasi steady flow results in approximately the same water level as for a steady state situation

Subcritical flow: Tranquil flow (Froude’s number <1)

Bathymetry: The underwater equivalent to topography

TABLE OF CONTENTS

1 INTRODUCTION

It is important for many reasons to have detailed knowledge of river discharges, under both normal and extreme conditions. The surface water is a limited and very valuable resource for domestic use as well as irrigation and for generating hydropower (Sutcliffe and Park, 1999). Extreme high and low flows may cause floods and droughts with large economical and humanitarian impact to surrounding communities. With more knowledge about these events and the possibility to forecast them, it is possible to be prepared. Action plans to protect communities, infrastructure and other economic values can be developed and implemented.

The short rain period in the steep topography of Ethiopia gives a high and concentrated runoff in the Blue Nile, named Abbay River in Ethiopia. The need for dams to store water for irrigation and power generation during dry periods is therefore high (Sutcliffe & Parks, 1999). Operation of dams built to regulate the flow and utilize the water should be based on reliable information about the present and future predicted flows (Chanson, 2004).

On the Blue Nile in Sudan near the Ethiopian border there is a measurement station named El Deim. A recent heightening by 10 meters of the Roseires dam, some 100 km downstream of El Deim, causes backwater effects in the form of increased water level at the station. The magnitude of the backwater effect at El Deim depends on the water level in Roseires reservoir and the flow variations. The backwater causes a changed and non-unique relationship between discharge and water level at El Deim, making the rating curve used for determining the flow from water level readings non valid. The normal way to deal with this kind of problem would be to move the station upstream. In this case the border of Ethiopia makes that impossible. For the water resource management for the Nile in Sudan the need of knowing the inflow, from Ethiopia through the Blue Nile, is very important (Wilson, 2008). Therefore, there is a wish from the Dams Implementation Unit (DIU) in Sudan to find new ways to assess the discharge at El Deim in spite of the fact that it is not an ideal location for measurement. The new conditions at El Deim make the assessment more complex than normal at a discharge station.

1.1 OBJECTIVE

The overall objective for this master thesis was to assess the possibility and methodologies to generate time series of rated discharge at monitoring stations suffering from backwater effects. The specific objective was to assess such possibility and methodologies at the El Deim monitoring station in Sudan. The assessment should consider both steady and realistic dynamic conditions.

1.2 DELIMITATIONS

In this master thesis following delimitations were made:

- The study takes no consideration of the Blue Nile's morphology upstream the Ethiopian border.

- Only the water from the Blue Nile entering from Ethiopia is included in the modelling, i.e. any inflow from small tributaries between El Deim and Roseires reservoir is neglected.

2 BACKGROUND AND THEORY

2.1 AREA OF INTEREST

Sudan is located in the north east of Africa. The climate is very dry and the water access varies a lot, both with season and over different parts of Sudan. This study considers the monitoring station El Deim located in the South East of Sudan very close to the Ethiopian boarder (Figure 1)

2.1.1 The Nile system in Sudan

The Nile River system in Sudan includes the White Nile, the Blue Nile and Atbara River, with tributaries (Figure 1). The first two rivers have their confluence at Khartoum, and the Atbara joins the Nile 325 km north of Khartoum at the city of Atbara. There are other tributaries but the contribution from these rivers is negligible compared to the total flow of the Nile. The White Nile has its origin at Lake Victoria and flows through Uganda and South Sudan before entering Sudan. Most of the water in the Blue Nile basin has its source in the highland of Ethiopia (at an elevation of 2,000-3,000 m). Therefore it is the climatological situation in Ethiopia, not Sudan that affects the flow the most (Sutcliffe & Parks, 1999). The short rain period, July to October, gives a high and concentrated runoff in the Blue Nile with maximum flow in August-September. The need for dams to store water for irrigation and power generation during dry periods is therefore high (Sutcliffe & Parks, 1999). As the Blue Nile flows in deep valleys and canyons from the humid and green Ethiopian highlands down to the lowlands the evaporation and temperature change considerably. The air temperature increases from 15-18 °C in the highlands to a mean daily temperature of 30°C in the southern Sudan. This temperature increases the water loss through evaporation considerably (Block et al. 2007). The Blue Nile basin in total has an average annual rainfall of 1,600 mm (Sutcliffe & Park, 1999) with most of the precipitation in Ethiopia. In the Sudan part of the Blue Nile basin the precipitation is much lower (Block et al, 2007).

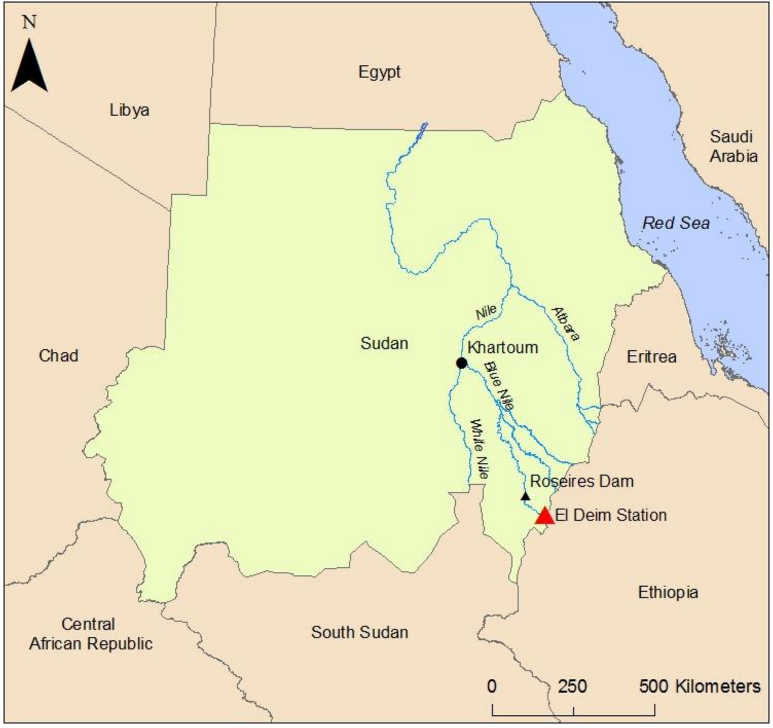


Figure 1 The Nile River system in Sudan. The study site, El Deim, is located on the border between Sudan and Ethiopia upstream of Roseires dam.

2.1.2 Roseires dam

The Roseires dam is located 550 km southeast of Khartoum (Figure 1). It was established 1961-1966 by the Sudanese Government to meet the growing need of water for electricity generation and irrigation (Sutcliffe & Parks, 1999). It was constructed to generate 280 MW and have a storage capacity of 3,100 Mm^3 (Yagoub, 2012). In order to make it possible to extend the irrigation systems connected to the dam and increase the hydropower generation the reservoir capacity had to be increased. The dam was therefore heightened by ten meter. The new dam was completed in late 2012. The Roseires dam is at the time of writing the longest dam in the world, with a reach of 25 km. The reservoir increased, due to the heightening, to a storage capacity of 7,400 Mm^3. By this heightening the plan is to intensify agriculture over 1.7 Mha of irrigated land. The heightening is also supposed to increase the hydropower production by 68 MW (AFESD, 2012). The new full storage level and lower level at the reservoir are 493 respectively 485 m a.s.l. (Pietrangeli et al., 2013).

2.1.3 El Deim monitoring station

One of the key monitoring stations of the Nile, El Deim, is located close to the border of Ethiopia. At this station the staff measures sediment transport, discharge and water level (Figure 2). The station was moved from the Roseires village to its existing location in 1962 when Roseires dam was under construction (Sutcliffe & Parks, 1999). Measurements from the station are crucial for operation of Roseires dam and for flood forecasting along the Blue Nile (Yagoub, 2012). Before the heightening of the dam the station was not affected by backwater effects from the reservoir. However, with the new dam and higher reservoir levels the backwater effect was expected to affect El Deim station (Wilson, 2008). Measurements made in 2007 by DIU at Fammaka (15 km downstream of El Deim) confirmed that the rating curve at El Deim still was correct and that the El Deim river site is morphologically stable (Mohamed, 2010). Sutcliffe and Park (1999) also described the El Deim station as stable and stated that ratings from this station are reliable and precise.

Figure 2 Right bank tower of the cable way at El Deim station. (Wilson, 2008)

2.1.4 The Nile basin initiative

In 1959 an agreement about the Nile water resource distribution was made. Egypt was allotted 55.5 and Sudan 18.4 billion m^3 water per year, while all other riparian states were given no allotment. The amount allotted between Egypt and Sudan was, at that time, in proportion to the population of the countries (Sutcliffe & Parks, 1999). The allocation of the Nile water is, and has been for decades, a controversial topic. With more independent countries claiming their right to the resource and pronouncing the Agreement of 1959 no longer valid, the topic gets even more delicate. The Nile Basin Initiative was created in 1998 to enhance a fair and amicable cooperation between all countries in the Nile Basin, in the aspect of usage of the water resource (Block et al. 2007). To have control of the amount of water that each country has access to discharge assessments are needed. The discharge assessment at El Deim is therefore, also in a political aspect, important because it assess the amount of water entering Sudan through the Blue Nile.

2.2 THE NEED OF MEASUREMENTS

For better water resource management there is a need of good discharge data. There are many monitoring stations along the Nile (Mohamed, 2010). Of these some stations were established early in the 20th century. Unfortunately, the quality of the instruments and stations has deteriorated over time, which causes more inadequate measurement results. The number of measurements and the intensity of updating rating-curves have also declined the last decades. Another issue is that the instruments regularly need calibration. The lack of calibration facilities in Sudan forces the staff to send the instruments abroad. Many monitoring stations do not have any extra equipment, which results in periods of no data when instruments are broken or sent to re-calibration (Mohamed, 2010).

2.2.1 Measurement methods

Measuring the discharge is often complicated and time consuming. A way to generate time series of discharge is to establish an empirical relationship between the discharge and the water level (so-called rating curve). In order to establish an accurate rating curve measurements of both water level and corresponding discharge are needed at different times to cover the range of variations over the year. When the rating curve is established the only measurement needed to get the discharge is the water level and the discharge can be rated by looking at the existing empirical relationship. There are many ways do determine the water level, or stage as it is sometimes called. At stations along the Nile masonry gauges are often used (Figure 3). The frequency of manual water level measurements varies with season and location, from the most common 3 times a day up to every hour (Mohamed, 2010). The gauge is usually read manually but automatic gauge recorders have been tested, at for example Sennar and Dongola, but the results have not been reliable enough. One problem is that the automatic gauges have faced maintenance problems (Mohamed, 2010). When measurements are made manually there is always a risk that some flow fluctuations don't get captured. There can be many reasons for this, few or no measurements during the night, or other issues like problems to reach a station affected by high flows.

Figure 3 Masonry gauge in Sudan at measurement station. Photo: Hansson, M., Sudan, 2012.

At El Deim station a cableway over the Blue Nile River is used for discharge measurement (Figure 2). The method used up till now is about the same as the method used by the British and Egyptians in the beginning of the 20th century. The velocity is measured with current meter at half depth where three readings of 30 seconds are made and the mean velocity at each point is calculated. The total discharge is calculated by the mean section method (Mohamed, 2010).

2.3 RATING CURVES FOR DETERMINING DISCHARGE

With a morphologically stable measurement site, a relationship between the water level and discharge can be used to get the discharge only by reading the water level (gauge level). To be able to find this relationship, discharge measurements are plotted against water level, giving a so-called rating curve. The more measurements the rating curve contains, the more accurate the conversion from water level to discharge. The morphology almost always changes, but sometimes in a very slow pace. By renewing the rating curve annually, accurate rated discharge can be produced. An example of a rating curve from El Deim station 1967 can be seen in Figure 4. The rating curve is expressed mathematically as a rating equation.

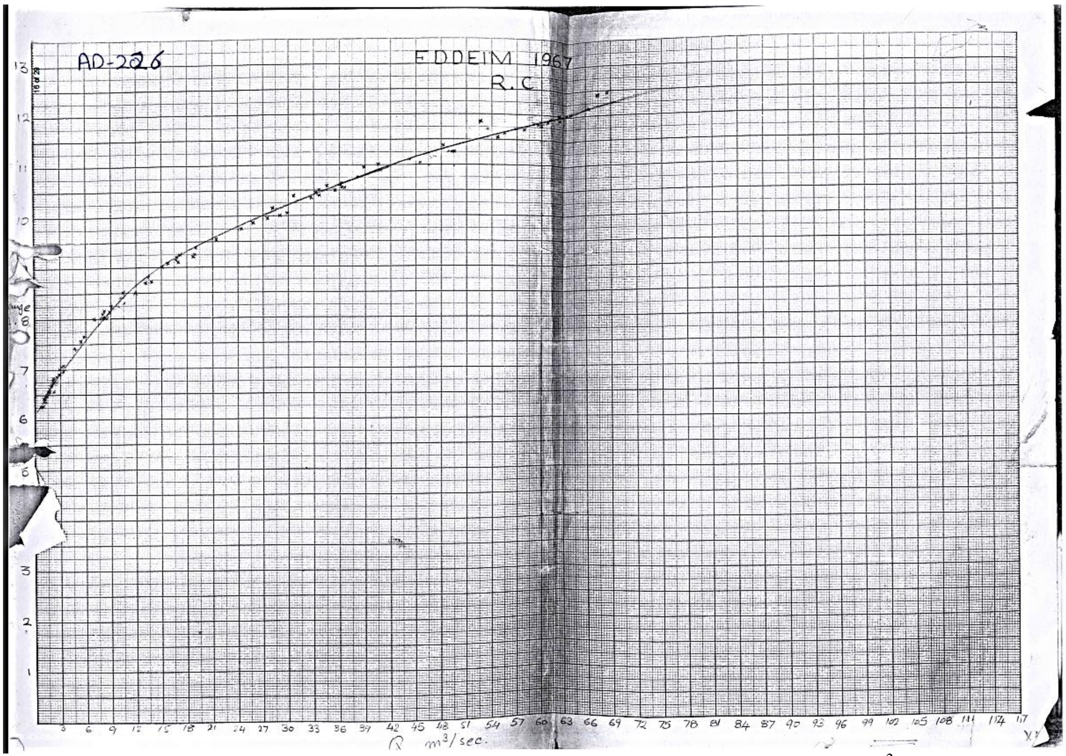


Figure 4 Rating curve used at El Deim station during 1967. Discharge (Q) in m^3/s on the x-axis and gauge level in meters on the y-axis (Ahmed, pers. com., 2013).

To be sure that the morphological characteristics have not changed the rating curves need to be updated frequently to ensure trustworthy results. The conditions for making rating curves at El Deim have historically been ideal thanks to a morphologically stable cross section. But the backwater effects from the heightened Roseires dam make the situation more difficult. There are no longer a unique correlation between water level and discharge at the station. The new factor is the water level at the Roseires dam, when it changes it affects the water level at El Deim.

A phenomenon that can complicate the making of an accurate rating curve is hysteresis. In a situation with hysteresis the equilibrium state depends on the history of the physical system (Hendriks, 2010) Hysteresis can also be described as a deviations between the water level when the flow increases and decreases for a specific discharge.

2.4 BACKWATER EFFECTS

In subcritical flow (Froude's number <1) the longitudinal flow profile is affected by flow conditions downstream. Control structures, obstacles or morphological changes downstream may induce backwater effects (Chanson, 2004). One of the backwater effects is that the hydraulic condition changes (Munier et al., 2008).

2.5 THE EFFECT BY WIND ON RESERVOIRS

Water level affected by other factors than backwater effect is a source of error in this study. High wind speed causes the water in the reservoir to drift in the wind direction. The water level may therefore rise in one end of the reservoir and fall in the other. Water level measurements will be affected by this phenomenon. In this study the water level was of most importance and errors may lead to inaccurate conclusion regarding the flow dynamics. Adding the wind into the modelling or not using data affected by high wind speeds could minimize this problem.

2.6 HYDRAULIC MODELING

For studying the effects from hypothetical hydraulic events like floods and, as in this study, changed flow dynamics hydraulic modelling is a strong tool (Chanson, 2004). For this study it was important to choose a powerful and advanced modelling program that could model both dynamic and static flows. A model that operates in a similar manner as the actual system can be used for predictions of the real system at different scenarios. To get a useful simulation result it is of most importance that the model is calibrated and validated against accurate discharge measurements.

2.6.1 Choice of hydraulic model

The choice of hydraulic model affects the result. Depending on the available data and the size of the river, different models are more or less suitable. Two- and three-dimensional modelling is more complex and need more data to be accurate than a one-dimensional model. The dimension of the model to use should be based on the purpose of the study and data availability. For hydraulic modelling of large rivers one-dimensional models have been proven more successful (Brandt, 2009). With increasing data power and more frequent and accurate data the two- and three-dimensional models might give better results in the future. Three-dimensional models have so far only given accurate results for very small systems (Brandt, 2009). Because of limited data of bathymetry and flow characteristics the one-dimensional model Mike 11 was selected for this study.

2.6.2 Introduction to Mike 11

The hydraulic modelling program Mike 11 can be used for simulations of water quality, discharge and transportation of sediment in channels, rivers, irrigation systems and more. Mike 11 is an advanced program for modelling of both dynamic and static scenarios. The following description is based on the Mike 11 manual (DHI, 2012a) and tutorial (DHI, 2012b).

If cross section data are available Mike 11 can use Saint Venant’s equation for integration calculation. When cross section data are missing routing can be used. The Saint Venant’s equation is solved under following presumptions: the water is incompressible with constant density, the slope of the river is limited, the flow direction is parallel to the bottom at all depth and the flow is subcritical.

Mike 11 contains a number of editors that can be edited independently. Important editors for this study are; Simulation editor, Network editor, Cross Section editor, HD Parameter editor, Time Series editor and Boundary editor (Figure 5). These editors will shortly be described below.

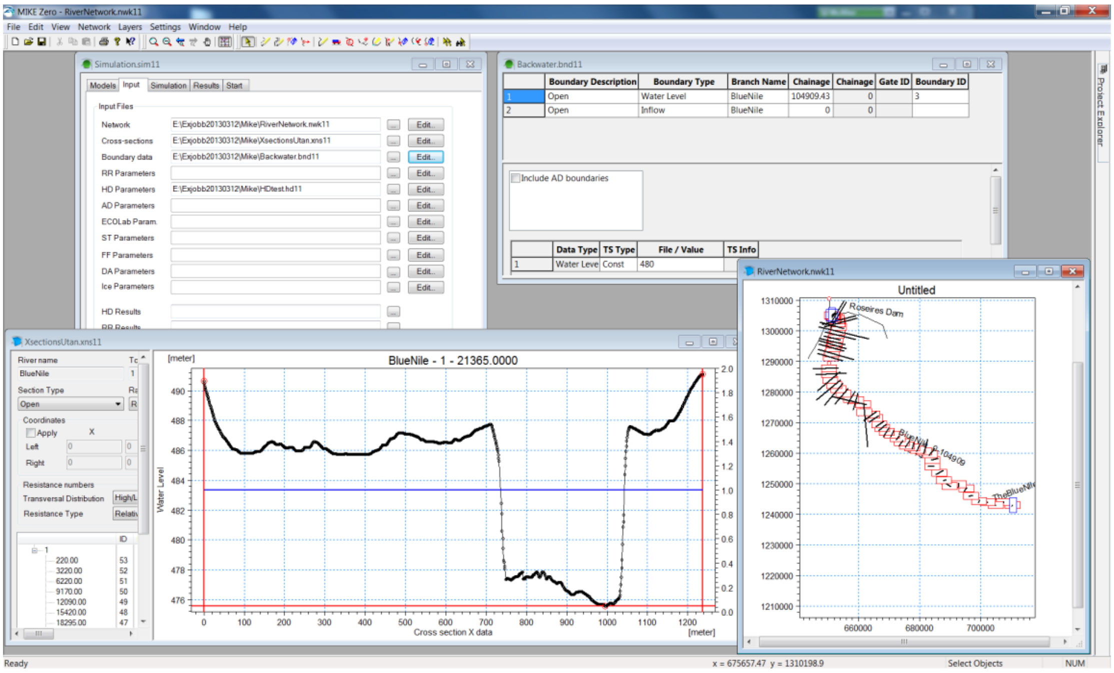
In the Simulation editor the user can create the link between the individual editors needed to perform a simulation. Control parameters for computation and simulation are set in the Simulation editor.

The Network editor has a table view and a graphical view, were the information from other editors can be viewed. The graphical view contains facilities for presentation and editing of the river network. It also provides editing facilities for data of the river, like definition of hydraulic structures, definition of the catchment and digitizing of river branches.

The boundary conditions are defined in two editors: Time Series editor and Boundary editor. In the Time Series editor time series for inflow, water levels etcetera are defined and the Boundary editor defines the boundary conditions at the inlet/inlets and outlet/outlets.

To specify the initial values for the hydraulic modelling, like water level and discharge, the HD Parameter Editor is used. It is also used to define other variables like Manning's number (n) and to set the different types of maps that should be displayed after modelling.

The bathymetrical raw data, in the form of cross sections, can be added manually in the Cross-section Editor. The roughness along the cross-section can also be varied if needed. Mike 11 linearly interpolates between the cross sections to recreate the bathymetry of the river.



Network: E:\Exjobb20130312\Mike\RiverNetwork.nwk11
Cross-sections: E:\Exjobb20130312\Mike\XsectionsUtan.xns11
Boundary data: E:\Exjobb20130312\Mike\Backwater.bnd11
RR Parameters:
HD Parameters: E:\Exjobb20130312\Mike\HDtest.hd11
AD Parameters:
ECOLab Param.:
ST Parameters:
FF Parameters:
DA Parameters:
Ice Parameters:
HD Results:

	Boundary Description	Boundary Type	Branch Name	Chainage	Chainage	Gate ID	Boundary ID
1	Open	Water Level	BlueNile	104909.43	0		3
2	Open	Inflow	BlueNile	0	0		

☐ Include AD boundaries

	Data Type	TS Type	File / Value	TS Info
1	Water Leve	Const	480	

River name: BlueNile
Section Type: Open
Coordinates: ☐ Apply
Left: 0 0
Right: 0 0
Resistance numbers
Transversal Distribution: High/L
Resistance Type: Relativ

1	ID
220.00	53
3220.00	52
6220.00	51
9170.00	50
12090.00	49
15420.00	48
18295.00	47

Figure 5 A screen shoot of Mike 11 during the working process showing the Simulation editor, Boundary editor Cross section editor and the Network editor.

2.6.3 Data needed to model in Mike 11

To be able to model the flow of the Blue Nile in Mike 11 data of the bathymetry are needed in the form of cross sections. The data must have the same reference level. The cross sections should preferably be perpendicular to the river flow and consist of depth data points across the river from one side to the other (Figure 5). To enable modelling of extreme events the cross sections should preferably be extended above highest expected water level. Cross sections should be frequent along the studied river, especially at narrow parts of the river. The cross sections are set based on their location along the river, their chainage, all measured points have a distance (from the uttermost point) and a depth. These raw data are usually obtained from riverbed surveys. Mike 11 can from these data create a surface model by interpolating between the added cross sections (DHI, 2012a).

The velocity of the water is affected by the roughness of the bottom surface, gravity and inertia. In the modelling the roughness is represented by Manning's number (n) with the unit s/m$^{1/3}$ (DHI, 2012a). The Manning's number is essential for flow velocity calculations. Surfaces with more roughness have a larger n, which imply that they slow the water more (Equation 1) (Chow et al., 1988).

$$v = \frac{R^{\frac{2}{3}} \cdot S_f^{\frac{1}{2}}}{n} \qquad (1)$$

where the velocity (v) is in m/s, the hydraulic radius (R) in m and the slope (S_f) is dimensionless (m/m) (Hendriks, 2010). Often the roughness varies over the cross section (Pietrangeli et al., 2013). Guidelines to what actual value to use as Manning's number can be found in tables, were the number is chosen based on the river bottoms characteristics, but preferably the Manning's number should be set after a conveyance study of the river. The Manning's number can also be set through calibration of the model or after another calibrated model based on similar conditions. During calibration of a model Manning's number is a significant parameter to look at (DHI, 2012a).

The modelling processes must have defined boundary conditions. These boundary conditions can for example be time series of discharge (Q) and water level data (h) (DHI, 2012a).

2.6.4 Visualisation of results in Mike View

Mike View is used as the result viewer for Mike 11. Mike View contains a variety of functions and features for analysing and viewing the results from simulations. Animations of longitudinal profiles and water levels at cross sections, producing Q-h and time series plots are just some of the features in Mike View (Figure 6). The different animations can be synchronized and the user allows: to stop, play or step-by-step walk through one or more simulation (DHI, 2012a).

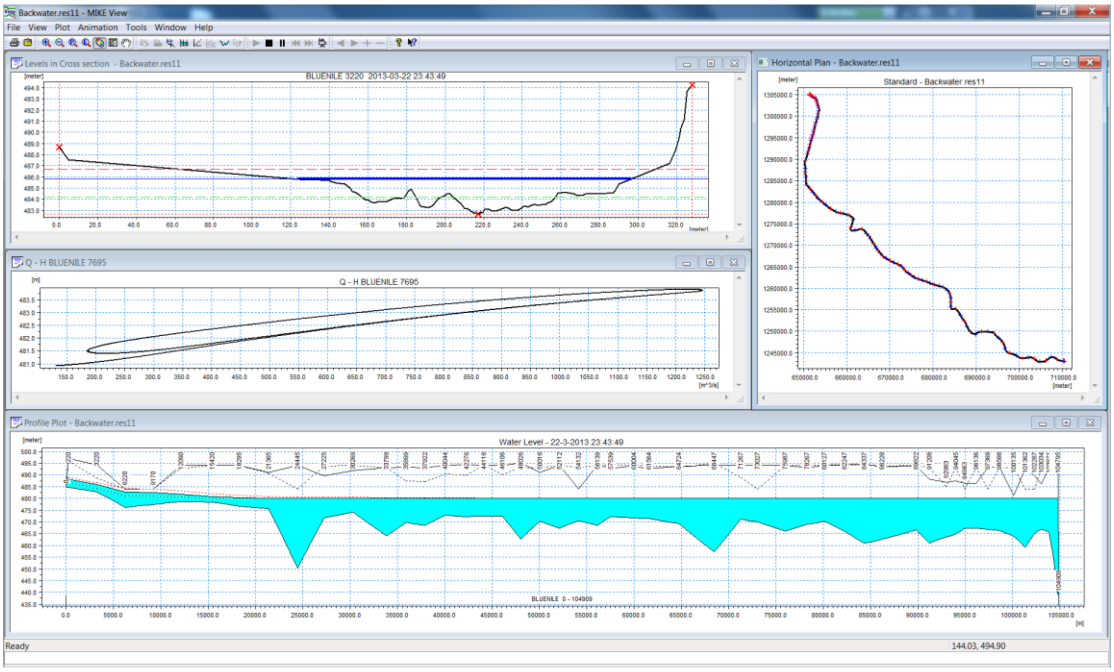


Figure 6 Animations and plots in Mike View of the results from a run in Mike 11. The longitudinal profile and water level animations, Q-h plot, and the river overview are displayed.

3 METHODS AND MATERIALS

The work done during the study can be divided into different work processes, all depending on the previous. A literature study was the first step, and included collecting the data and information needed for this study. Data were received from DIU and processed to get an overview of the quality and range of the data. Processed data were used to set up and run the hydraulic model in Mike 11. The model was calibrated and validated against different data sets and later used for simulating various flow scenarios and Q-h relationships. The program Mike View was used to study the results.

3.1 LITERATURE STUDY

To get more knowledge of related previous studies, the Blue Nile and measurement techniques used in the area a literature study was carried out. Books like The Hydrology of the Nile (Sutcliffe et al., 1999) and Water Resources In Sudan: Planning and Management (Yagoub, 2012) were valuable in the process of understanding the hydrological situation in the area. Almost no previous studies about similar situations were found during the literature study. Study related authorities, like the Swedish Meteorology and Hydrology Institute (SMHI) were contacted in hope of guidance about the complex situation at El Deim. The answer from SMHI was that measurement stations affected by backwater were considered useless (Losjö, pers.com., 2013).

3.2 AVAILABLE DATA

The data needed for this study were obtained from DIU. It included time series of water level (h), daily discharge (Q) at both El Deim and Roseires and bathymetrical data with coordinates. Data used for the hydraulic boundary conditions of the model in this study were these time series of daily discharges and daily water levels at El Deim station and Roseires dam. Bathymetrical data in form of cross sections were used for setting up the hydraulic model in Mike 11. To be able to relate the different data points to each other and enable the use of that data in the modeling process all water level data needed to have the same reference level. With no data about the wind conditions at the time of measurements the wind was not taken into account in the performed simulations.

3.2.1 Cross sections

The total distance from El Deim to Roseires is about 105 km. Along this distance data of 53 cross sections at around 1-3 km distance from each other were obtained. The cross sections are more frequent in the reservoir (Figure 7). The cross sections totally contained more than 200,000 points, all with known longitude, latitude and altitude. To be able to add these cross sections into Mike 11 the internal distance between the first point and all other points needed to be calculated for each cross section.

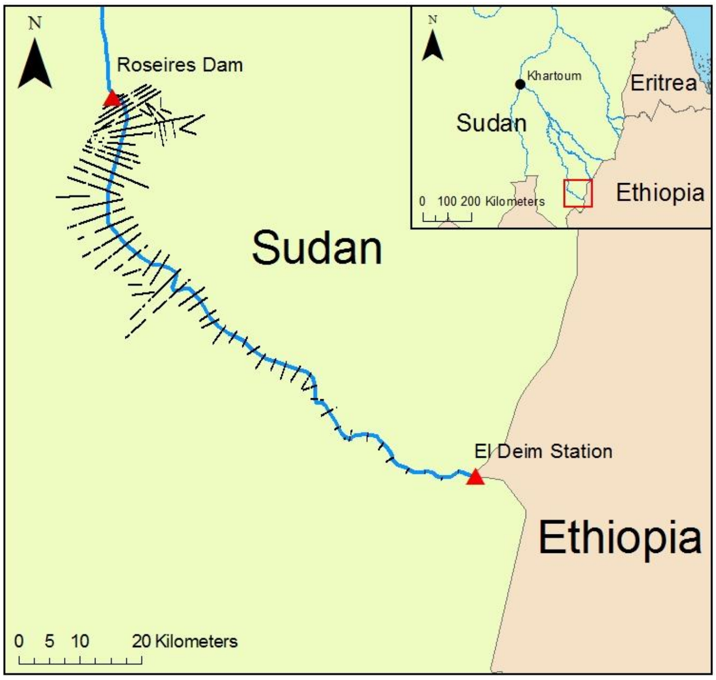


Figure 7 Map over the locations for cross sections between El Deim station and Roseires dam. The blue line in the large map visualizes the reach of the Blue Nile from El Deim and downstream to Roseires dam. The black lines crossing the river are visualized cross sections.

3.2.2 Discharge and water level data

Daily discharge data at El Deim from 1965-2012 were available for this study (Figure 8). The data from 2012 did not seem to be affected by the dam heightening project. The water level data available for this study were also daily values for the same periods as for the discharge (Figure 9 and Figure 10). For the discharge and water level data at El Deim there is a long period (1997-2002) with no data. The data set from Roseires dam are almost continuous with only a few days with missing data. The discharge data for the years 1978-2012 from El Deim seem to be not measured, but rated discharges from a rating curve (Figure 11). Zero gauge level for El Deim is 481.2 m a.s.l. (Ahmed, pers.com., 2013). For all plots in the rest of the report with the water level at El Deim defined in the unit m, a zero gauge level of 481.2 m a.s.l. is used.

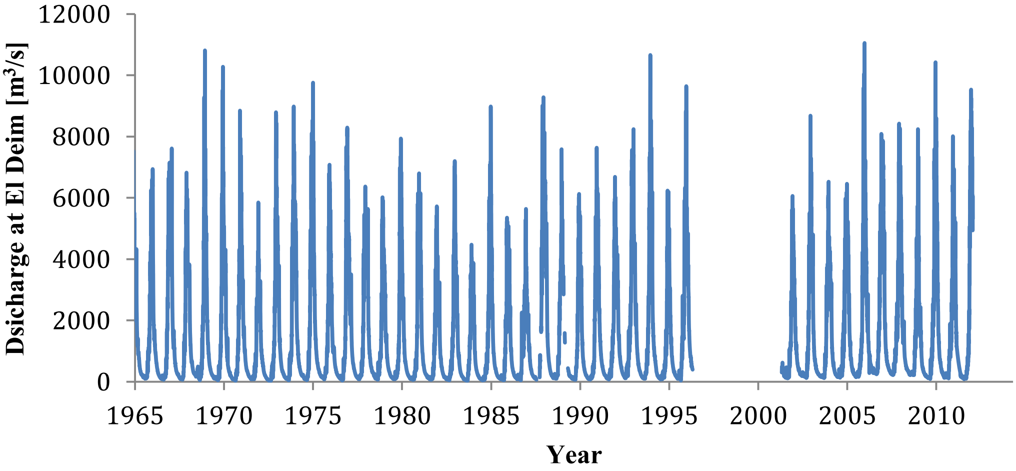


Figure 8 The discharge data from El Deim station (1965-2012).

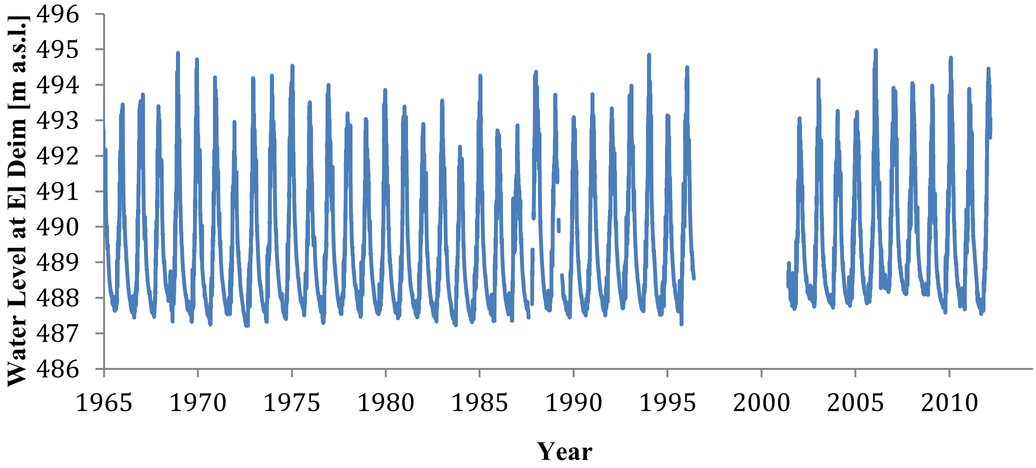


Figure 9 The water level at El Deim (1965-2012).

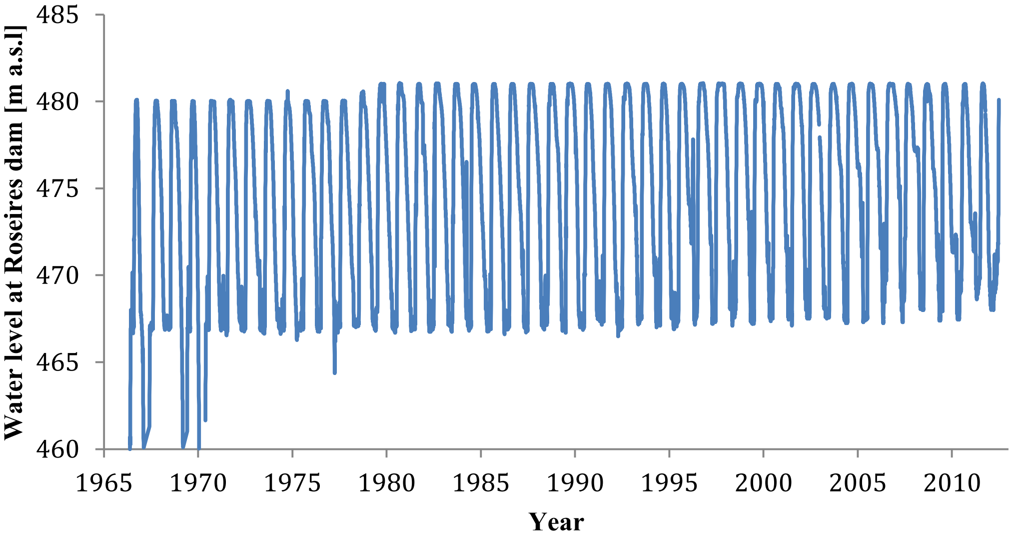


Figure 10 The water level data from Roseires dam (1966-2012).

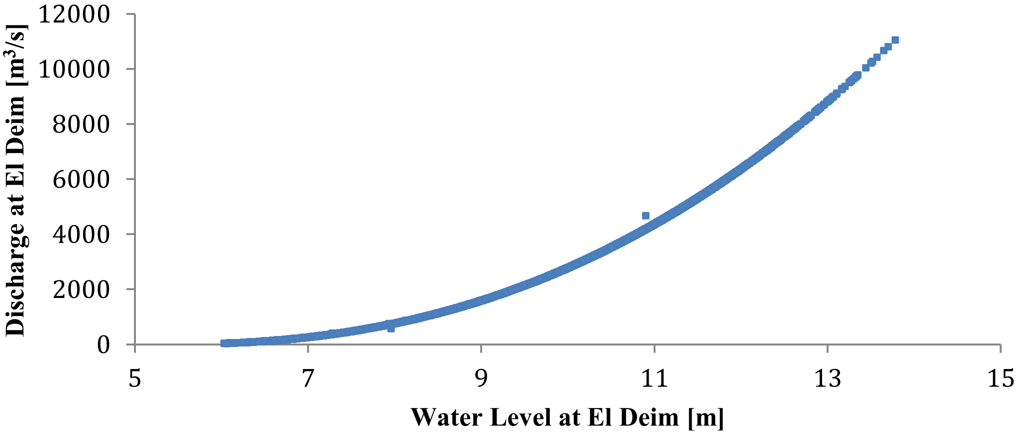


Figure 11 All discharge data at El Deim from 1965-2012. The daily water level data [m] plotted against daily discharge data [m^3/s] at El Deim station. The few point that do not follow the pattern are most likely errors.

3.2.3 Calibration data

The goal with the calibration was to create a model with the least average deviation between the simulated and measured water level at El Deim. Backwater effects from the reservoir did not seem to affect the data for calibration or validation. The data used for calibration were water level and discharge data from El Deim and Roseires dam from 2011. Data from year 2011 were chosen because it is the latest complete year with data records of both water level and discharge at El Deim and Roseires reservoir. The calibration data set was extended with a few days of extreme high flows from 2010 to get a wider range of flows.

The calibration period contained 52 different daily values of discharge and water level at El Deim. The discharge varied from about 100 to 10,400 m^3/s and the water level from 6.5 to 13.6 m (487.7 to 494.8 m a.s.l.).

3.2.4 Validation data

Water level and discharge data from 2012 were used for the validation of the model. This year was chosen because it was the most recent year with available data. The bathymetric conditions in 2012 are also likely to be similar to the conditions in 2011. Validation of the model against very old data could cause an additional error due to changed bathymetry. The validation data series comprised 43 daily values of varied discharge and water level from El Deim. The range of discharge in the validation data set was from 80-9,500 m^3/s.

3.3 MODELING APPROACH

The model setup contained a few steps in Mike 11. The location of the river was set by adding the reach of the river, extracted from Google earth (2013) into Mike 11. When the river was in place its bathymetrical characteristics needed to be defined. By adding cross section data, Mike 11 interpolates the elevation between the cross sections and in this way the model creates the expected bathymetry of the river. To start a simulation a Mike 11 model needs boundary conditions defined by the user. In this case the model was set to only have one inflow and one outflow. Therefore it only needed one boundary condition, discharge time series, at the inlet and one, water level time series, at the outlet. In the simulation process the boundary at the inlet was set as the discharge at El Deim and the outlet boundary conditions as the water level at Roseires dam. To get accurate simulation results the model needed to be calibrated and validated.

3.3.1 Calibration

Using a known discharge at El Deim as upstream boundary condition and setting the reservoir level, from the same day, as downstream boundary condition, realistic simulations could be performed. These simulations contained time series were the conditions changed step-by-step between the chosen calibration values. By setting long duration at each of the 52 calibration values the simulation results can be considered the same as for stationary conditions. The known water level at El Deim was compared with the corresponding water level from the simulation results. Calibration of Manning´s number was done, until the simulated water level corresponded well to the measured water level. The way this fit was controlled was by minimizing the average deviation from the 52 compared values. More important was to get a good match for the most frequent flows. The simulation deviations in absolute, average and maximum values were computed in Excel.

Manning's number was an important parameter in the calibration process. It is a physical parameter and must therefore be calibrated in the range of its natural variations. A study of the conveyance characteristics of the Blue Nile at the Ethiopian/Sudanese border shows that the Manning's number is between 0.05 and 0.1 $s/m^{1/3}$ for ordinary wet-season flows. For more shallow flows, more irregularities get exposed which increases the water resistance. The parameter therefore often decreases with increasing water level (Pietrangeli et al., 2013). The river bottom in parts of the Blue Nile close to El Deim contains of a narrow and steep canal. It is carved out of rock masses by the erosive force of the river. The riverbank in the same area is often flooded in the rainy season and is characterized by irregular rock-masses, very large boulders and massive gneiss (Figure 12) (Pietrangeli et al., 2013).

Figure 12 Picture of Blue Nile river bottom. Emerging rock pillars in the left picture and dry season sand deposits in the right picture (Pietrangeli et al., 2013).

To capture these natural variations in roughness the Manning's number was set for different zones of the cross section. This method is called the triple zone division (Figure 13) (DHI, 2012b). To separate the zones 1-3 the cross section data were investigated along the river reach. The separation levels were set at altitudes where the form of the cross section changed. To get as accurate values of the roughness parameters as possible simulations were first performed with low flows. When the model was calibrated for low flows, simulations started with high-level flows, and the two other roughness parameters, for zone 2 and zone 3, were obtained from calibration. The calibrations were executed to give the result with the least deviation possible between the simulated and the measured value.

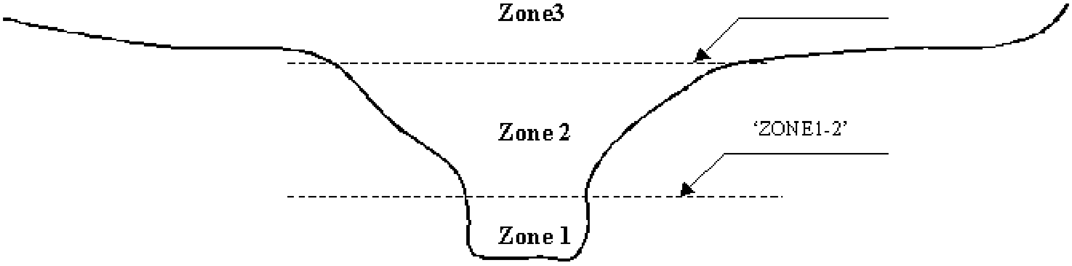


Figure 13 Sketch of the triple zone divisions of cross sections. (DHI, 2012b)

The most reliable model from the calibration was simulated against all the data from 2011 to see how well the model followed the natural flow dynamics (Figure 14). The result was studied in Mike View and data imported to Excel. The longitudinal profiles from the simulations were controlled to determine if the flow event looked realistic. When the model was calibrated the model had to be validated to see if the simulations are accurate for other scenarios.

3.3.2 Validation

The validation data cannot be the same as the data used for calibration. The validation process contained dynamic modelling and result comparisons for all the data of 2012 as well as a separate simulation of 43 chosen dates with varying water levels. To assess the predictive power of the model the Nash-Sutcliffe model efficiency coefficient (NS) was computed for the simulated values from 2012. The Nash-Sutcliffe value is defined as described in equation 2:

$$NS = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \qquad (2)$$

where Q_m^t is modelled value and Q_o^t is the observed value at time t. $\overline{Q_o}$ is the average observed value. The NS can range from $-\infty$ to 1. A perfect match between the modelled and observed data gives a NS value of 1. The linearity between the measured and simulated water levels for the whole period of 2012 was also studied through a linear regression.

The simulation results were studied in Mike View and data imported to Excel. The simulation deviation, calculated from comparison between the simulated and measured water levels for the 43 dates, were computed in absolute, average and maximum values. The parameter setup with the least deviation was used also for validation against the measured data from 1965-1977. This simulation enables a comparison of how close the simulated values are real measured data, which contain natural flow dynamics. After the validation process the flow characteristics can be studied through dynamic simulations.

3.3.3 Simulations

To investigate the hydraulics of the river, both before and after the heightening of the dam, simulations with the calibrated model were performed in Mike 11. The discharge was specified as upstream boundary condition and the water level at Roseires as downstream boundary condition. The magnitude and variation of the discharge and water level was set after the purpose of each simulation. The simulation results were studied in Mike View and data from the simulations were imported to excel for analysis. The simulation process in this study was divided into three parts.

The first part had the purpose of looking at critical reservoir levels and discharges for which the backwater effects reached El Deim station. This is important because it can give important information for if/when the flow at El Deim is not affected by backwater effects caused by the water level in the Roseires Reservoir. If El Deim is not affected the old rating curves can be used. The way used to determine these levels was to set a constant inflow and slowly increase the water level at the reservoir. When a significant change in water level can be seen at the station, in this study defined as 2 cm rise of water level, in the simulation result the critical level has been found for that specific discharge. Several simulations with this method were executed to find out how the water level and discharge affected the presence of backwater effects at El Deim. The reason to define a significant change in water level to 2 cm was that the measurement method of reading the level from a masonry gauge at El Deim is not very precise but it is likely that a change by 2 cm would be noticeable.

The second part of the simulation process had the purpose of investigating a possible occurrence of hysteresis caused by rapid flow variations. To simulate this in a realistic way, the natural discharge rates of variation are needed. These natural flow dynamics were found through frequency analysis of the discharge rates of variation at El Deim. When knowing the range of natural flow dynamics, synthetic data sets of well-defined statistical characteristics can be created. Simulations can then be executed with the synthetic data sets as upper boundary condition and a constant water level at Roseires dam as lower boundary condition. A Q-h plot of the simulation result can be presented in Mike View to conclude whether or not the simulated rate of variation induces a dynamic or quasi-steady state situation. The flow dynamics can be seen as quasi-steady if the Q-h plot shows only negligible signs of hysteresis. The way to see if there is a hysteresis effect is to look for differences between the water level when the flow increases and decreases for a specific discharge. A difference would indicate that a downstream control section affects the flow. By performing several simulations in Mike 11, with varying discharge rates of variation, the hysteresis effects from truly dynamic to quasi-steady flow scenarios can be determined.

The third part includes the making of the final rating curves, based on simulations with slowly increasing discharge from the lowest to the highest realistic flow. The discharge magnitudes should range from the lowest to the highest occurring value to enable making of rating curves that cover all flow variations, during both dry and rainy periods. The simulations need to have a static water level at Roseires and a well-defined rate of change in discharge, so that the conditions for when the resulting rating curve can be used are well defined. Tables and equations for discharge rating at El Deim can be produced based on these curves.

3.3.4 Conveyance analysis

The conveyance of the different cross sections was studied to locate possible cross sections with unrealistic flow resistance. The conveyance for all cross sections and water levels were studied in Mike View. The conveyance is defined as seen in equation 3.

$$Conveyance = A \cdot R^{\frac{2}{3}} \qquad (3)$$

where A is the cross sectional area of the flowing water and R is the hydraulic radius. To capture the conveyance variations with water level the simulation contained the full spectra of expected discharges. The cross section with the lowest conveyance can be seen as the control section, which has a large impact on the flow. Low conveyance causes the water level to rise more quickly than if the conveyance is high. Low conveyance can be caused by natural variations in the cross section, but also in the situation of not enough data in the cross section. If the water level rises above the upper limit of cross section data Mike 11 extrapolates a vertical line for the remaining cross section. Cross-sections that have a low value due to lack of cross section data can be removed to see if the simulated flow becomes more accurate.

4 RESULTS AND DISCUSSION

The purpose of doing simulations was to create a way to examine the influence of the raised water level in Roseires reservoir on the water level at El Deim. Results from simulations, of both real and synthetic flow scenarios, can be used to investigate how the water level at Roseires reservoir and discharge variations affects the water level at El Deim. The goal was to assess the possibilities and methodologies to generate time series of rated discharge that can be used to rate the discharge at El Deim. An important aspect of the quality of the simulation results is that most of the discharge data (1978-2012) are not actual measurements at El Deim, but rated discharges from water level measurements. The data analysis, when the discharge and water level data at El Deim were plotted, showed an unrealistically clear relationship without almost any variations (Figure 11). This clearly indicates that these data were rated discharges and implies that all that discharge data have been rated with the same empirical relationship (rating curve). Therefore, the calibration/validation of that period does not say how well the hydrodynamic model describes the dynamic effects of the system (natural deviations from the rating curve), but how well the model can answer to other discharges based on the same empirical relationship as before. Validation against the time series with only measured values (1965-1977) was also executed.

4.1 CALIBRATION

During the process of calibration it became clear that the most accurate simulation result was obtained when changing the levels that separated the different roughness zones (see triple zone division in chapter 3.3.1). Therefore, two alternative parameter setups were created, one where the roughness zones are fixed after the characteristics of the cross sections (First parameter setup) and one were the parameters could be calibrated more freely (Second parameter setup) (Table 1). The zones should theoretically be fixed after the characteristics of the cross section, but due to few, and sometimes irregular, cross sections the levels were hard to define for the majority of the river reach. This might be a reason why the second setup gave more accurate calibration results (Table 1).

Table 1 The two produced parameter setups and the deviation of their simulations to the measured values in average, maximum and minimum values.

Parameter setup	First	Second
Zone 1	n=0.076	n=0.109
Zone 2	n=0.055	n=0.060
Zone 3	n=0.033	n=0.032
Average deviation [m]	0.45	0.13
Maximum deviation [m]	0.87	0.50
Minimum deviation [m]	0.03	0.00

The most accurate result appeared when the model parameters were calibrated more freely. The best parameter setup has an average deviation of 0.13 m and a maximum deviation of 0.50 m when the simulated water levels were compared with the measured water levels at El Deim. During the calibration of the model the accuracy for more common flows were considered to be more important. Therefore, the lowest accuracy appears for flows larger than 10,000 m^3/s. The Manning's numbers in the second parameter set for zone 1 and zone 3 are outside the range of the numbers (n=0.05-0.10) that the conveyance study concluded for wet-season flow (Pietrangeli et al., 2013). However, these Manning's numbers are supposed to be valid for the whole cross section and for large flows. The model was calibrated for low and high flows with triple zone division. It is therefore not surprising that the lowest part, zone 1, has a higher roughness (n=0.109) due to the fact that roughness often increases with decreased water level. The low roughness parameter in zone 3 can be explained with the same reasoning. The good calibration result for the second parameter setup might also be explained by the fact that other possible error factors, like inaccuracies in the data and unknown bathymetrical conditions, are absorbed by the calibration. To examine how well the model follows the true flow dynamics a simulation with all the data from 2011 was executed. The result shows that the simulated values correspond well to the measured values at El Deim (Figure 14).

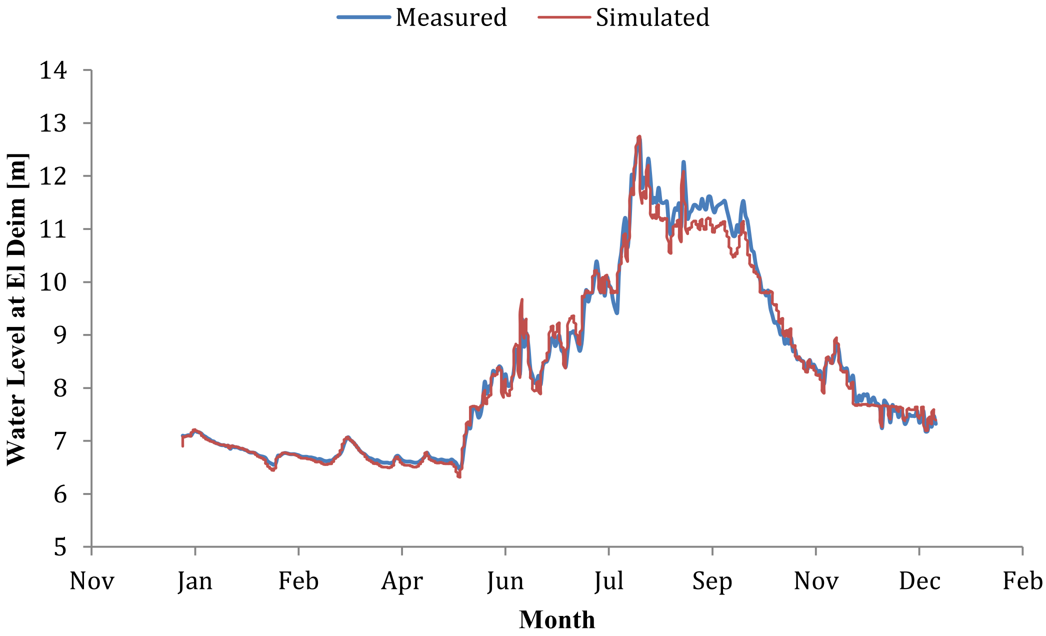


Figure 14 Simulated and measured water levels at El Deim during the calibration period (2011). Simulation executed with the second parameter setup.

4.2 VALIDATION

The two different parameter setups had different accuracy for the validation period of 2012. The first parameter setup has an average deviation of 0.40 m between the simulated and the measured water levels at El Deim and the average deviation for the second parameter setup was 0.16 m. Simulations with the two models were also performed with continuous data for 2012 (Figure 15 and Figure 16). The second parameter setup gave clearly a more accurate simulation result of the water level at El Deim, and is therefore the one that has been used in this study. Comparisons between the simulated values and the actual measured values for the period of 1965-1977 show that the model results most often lie within the deviation caused by natural dynamics (Figure 17). A computed NS-value of 0.9927 and R^2-value of about 0.994 (Figure 18) for the validation period of 2012 indicates that the accuracy of the model is high.

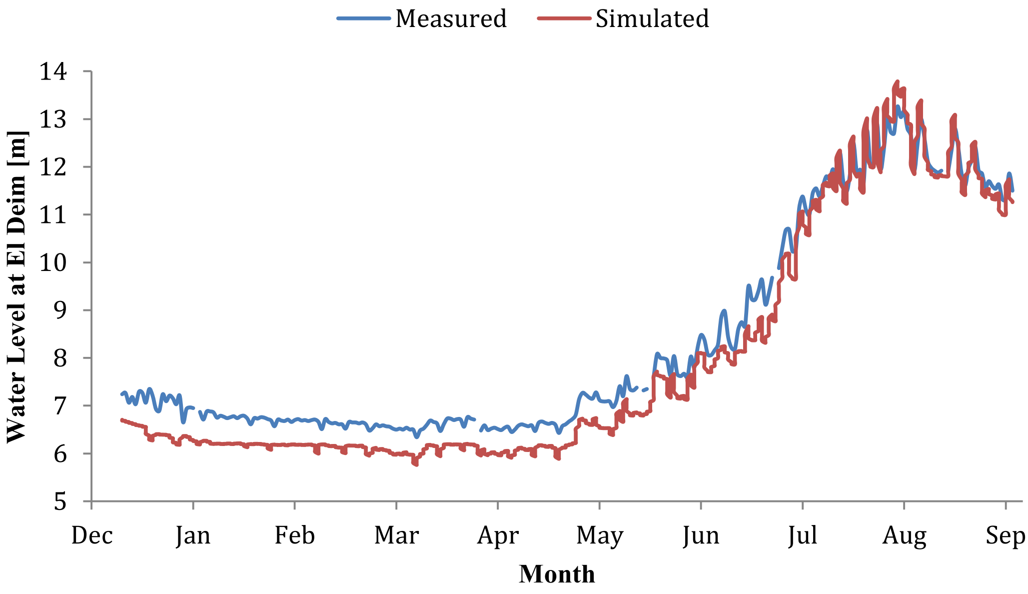


Figure 15 Validation of the first parameter setup. Measured and simulated water level at El Deim for 2012.

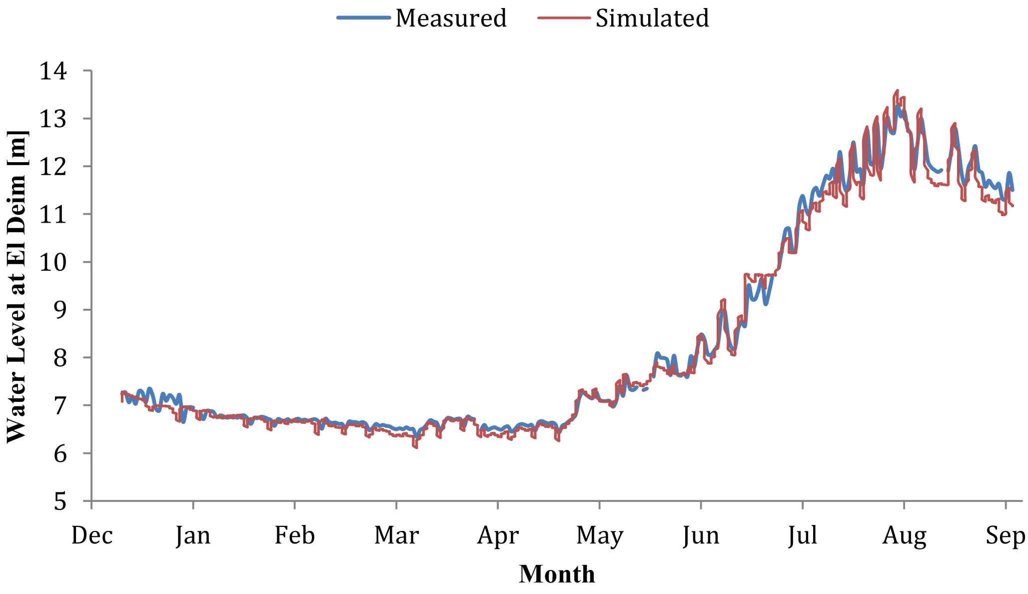


Figure 16 Validation of the second parameter setup. Measured and simulated water level at El Deim for 2012.

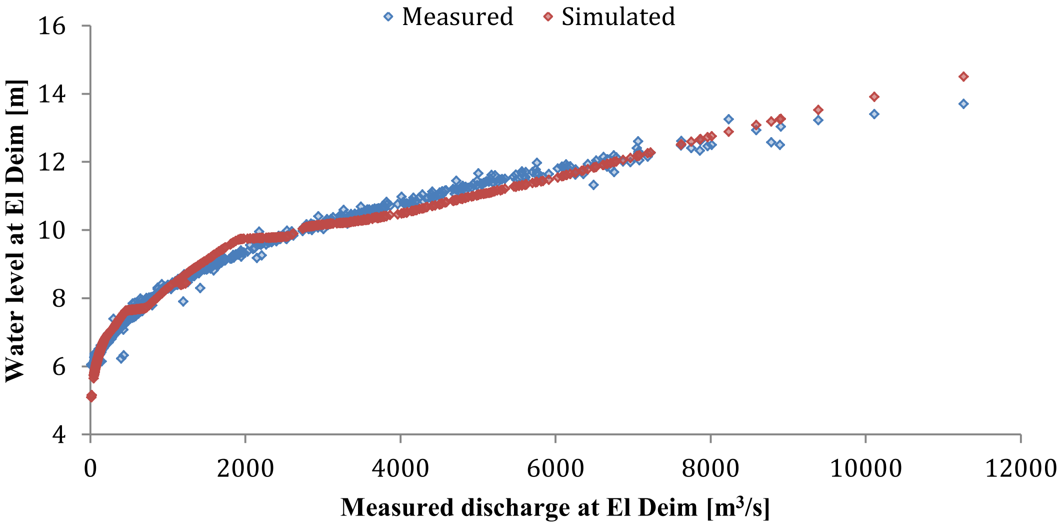


Figure 17 Simulated and measured water levels for El Deim from 1965-1977.

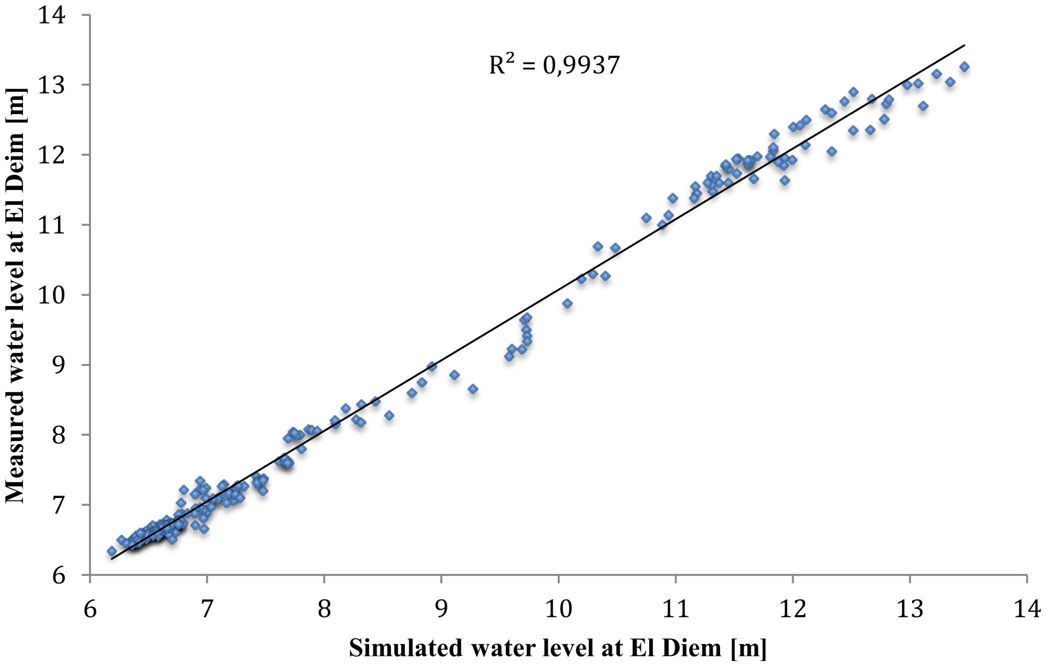


Figure 18 Linearity analysis of simulated and measured water level at El Deim for the validation period.

In both the calibration and validation the quality of the model was rated after the deviation of the simulations between the simulated water level and the rated water level at El Deim. To have in mind when looking at the validation and calibration result is that the real measurements also deviate from the rated values. The level of average deviation was found to be 0.14 m for the period of 1965-1977 between the measured and the, from the rating curve (Figure 11), rated water level. This deviation is only 0.02 m less than the deviation of the water level simulations during the validation period. The fact that the real measurements have almost the same deviation as the simulated values indicates that the model is quite accurate. The deviation for the measured data was found by comparisons between the water level computed with the rating curve equation and the measured water level for the same discharge.

4.3 CONVEYANCE ANALYSIS

The conveyance varies, both between the different cross sections and depending on the water level. However, the result showed no cross section with any significantly lower conveyance than the other sections. This indicates that a removal of the cross section with the lowest conveyance would not significantly lower the longitudinal profile of the river.

4.4 NATURAL DISCHARGE AND WATER LEVEL RATES

For some simulations it is important that the simulations with the hydraulic model in Mike 11 are based on the data that follows the natural behaviour of the river. In order to get an idea of how the discharge varies naturally with time a frequency analysis of the rate of variation was performed. Median, high and extreme rates of discharge variation over time were calculated. The results from the analysis of the discharges rates of variation from 1968 to 2010 are presented in Table 2. In Figure 19 and Figure 20 the distribution of all rates from the frequency analysis are presented. The analysis was performed with daily data, and the resulting rates might therefore be underestimated since rapid variations might occur in the long periods between the daily measurements. Simulation results based on these rates might also be misleading if the actual rates are higher. Therefore, it is important to look at the frequency analysis and resulting simulations based on these values as guidelines for the realistic flow fluctuations.

Table 2 Results from the frequency analysis of the median and maximum fall respectively rise for the discharge at El Deim. Data used in the frequency analysis are rates of variation from 1968 to 2010 at El Deim.

	Discharge [m^3/s/day]
Median fall	-13
High fall	-500
Maximum fall	-3554
Median rise	82
High rise	1000
Maximum rise	3441

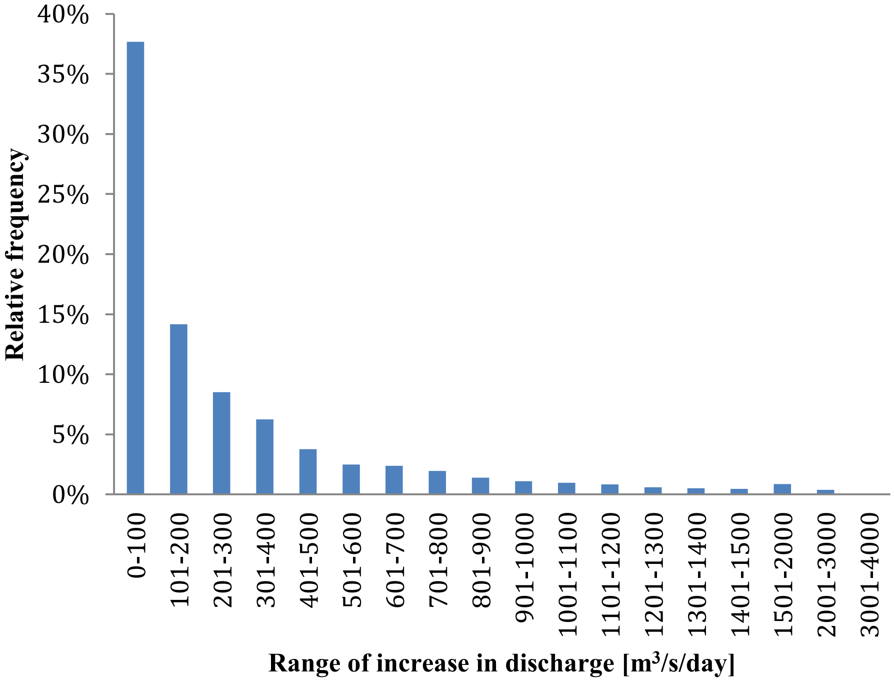


Figure 19 Frequency distribution for daily discharge increase [m^3/s/day].

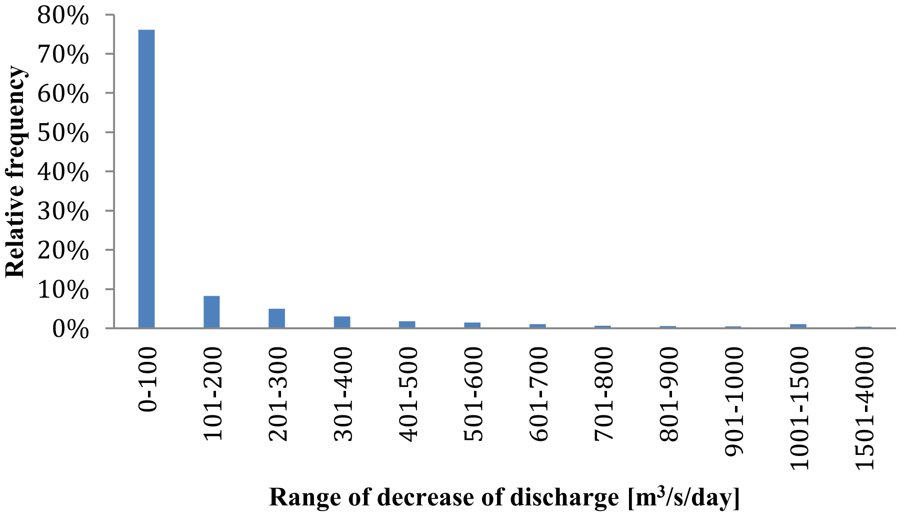


Figure 20 Frequency distribution for daily discharge decrease [m^3/s/day].

4.5 SIMULATIONS

Mike 11 has the features and facilities to complete the simulations needed in this study. The study focussed on simulation of dynamic scenarios, with varying water level and discharge. The simulation results corresponded well to the measured or rated data which imply that the hydraulic model can be used to simulate both static and dynamic scenarios at El Deim monitoring station.

4.5.1 Backwater simulations

The situations when backwater effect occurs, due to raised water level in Roseires reservoir, were studied. Each simulation had a constant inflow as input boundary condition and the Roseires water level was raised until backwater effects reached the El Deim station (Figure 21). Simulations were produced for different discharges, from

250 to 8,000 m^3/s, with an increase of 250 m^3/s between every simulation. The water levels at Roseires that induced backwater effects for different discharges are presented in Figure 22. Simulations for flows up to 3,000 m^3/s resulted in a cluster of points from which it is difficult draw any conclusions. This result was not expected and the reason for these simulated results has not been determined. This should be investigated in later studies.

The level in Roseires reservoir that resulted in backwater effects varied depending on the magnitude of the discharge. However, these results indicate that for low discharges (0-2,000 m^3/s) and high discharges (6,000-8,000 m^3/s) backwater effect are visible for reservoir levels around 485-486 m a.s.l.. For other discharge magnitudes the level varied from about 485-490 m a.s.l.. These results indicate that after the heightening the El Deim monitoring station will for almost all discharges be affected by backwater effects. To be compared to the situation before the heightening, were the reservoir level only reached just above 480 m a.s.l. (Figure 10). Some discharge events might result in no backwater effect if the reservoir is at its lowest allowed level (485 m a.s.l.). Assuming that these results are accurate, the old rating curves at El Deim can only occasionally be used for discharge assessment after the heightening. If the backwater effect does not reach the El Deim station, normal rating curves can be used for steady and quasi-steady flows.

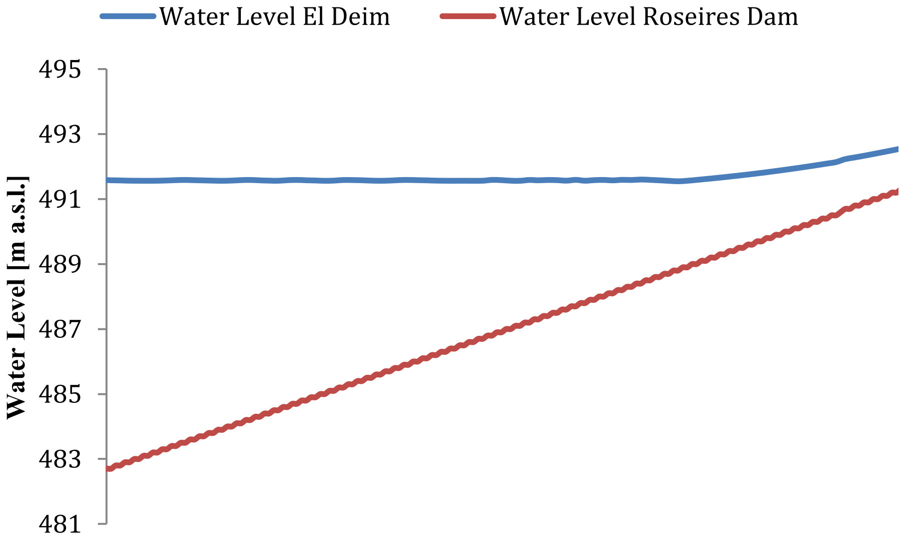


Figure 21 Visualisation of the water level changes at El Deim when the water level at Roseires is increased. The discharge was set to 4000 m^3/s during this simulation.

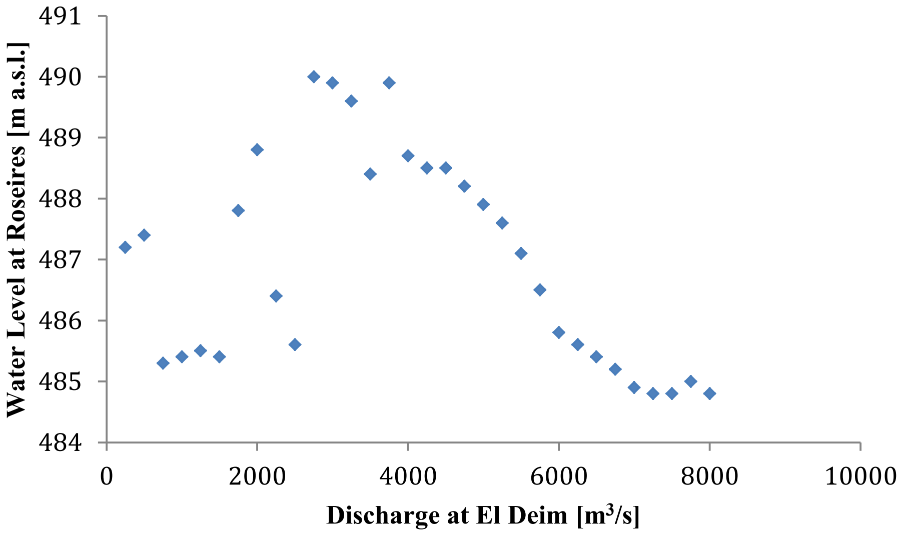


Figure 22 Simulation for water levels at Roseires dam resulting in backwater effects at El Deim. The points present the water level at Roseires dam for which backwater effects occur at El Deim for different discharges.

4.5.2 Natural flow dynamics

Simulations with discharge variations that follow the median rate for both rise and fall show no signs of hysteresis (Figure 23). This indicates that the modelled flow is in quasi-steady state for these rates of variation. This simulation was set to four days of median water rise and 26 days of median fall to start and end on the same discharge magnitude. The results from simulations that follow the maximum rate for both rise and fall show, not surprisingly, clear signs of hysteresis (Figure 24). The difference in water level for the same discharge in rise and fall is sometimes more than 0.2 m. An issue when drawing conclusions from the results from these simulations is that the history of the hydraulic system affects the system's response of a certain discharge variation. The same discharge variation might result in different flow dynamics depending on the properties of the system at the start of the simulation. For example, the flow shows a different behaviour at El Deim depending on the level at Roseires dam during the simulation of a period with discharge variation. Results from a simulation with maximum rates show that an increased water level at Roseires dam (with 5 m) results in less hysteresis than if the reservoir level is low (compare Figure 24 and Figure 25).

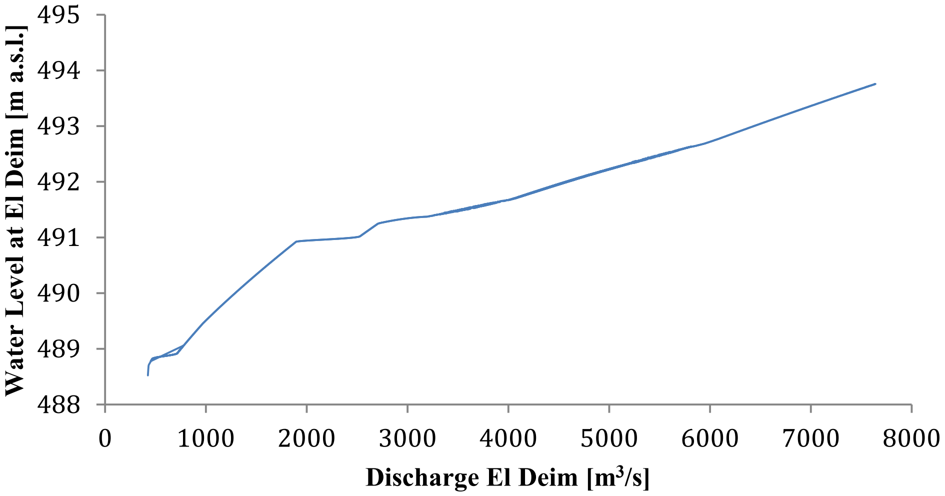


Figure 23 Simulation of water level at El Deim with discharge that increases and decreases with the median rate. The reservoir level was set to 485 m a.s.l.

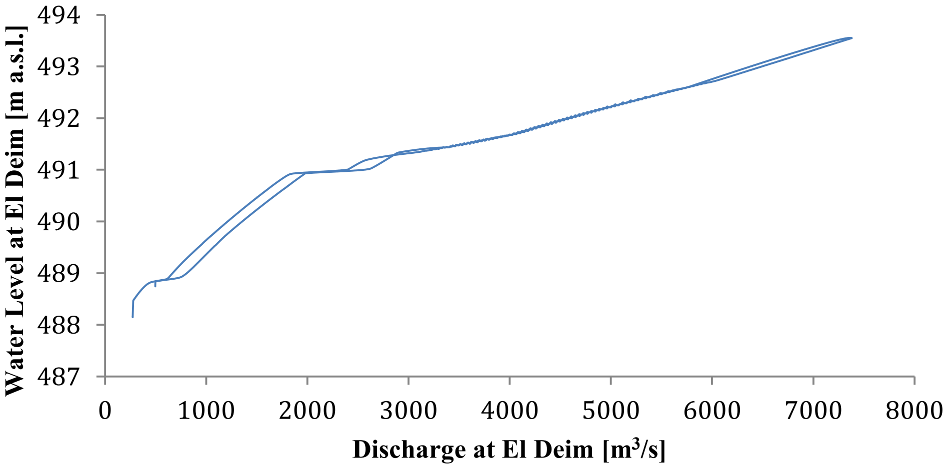


Figure 24 Simulation of water level at El Deim with discharge that increases and decreases with the maximum rate. The Reservoir level was set to 485 m a.s.l.

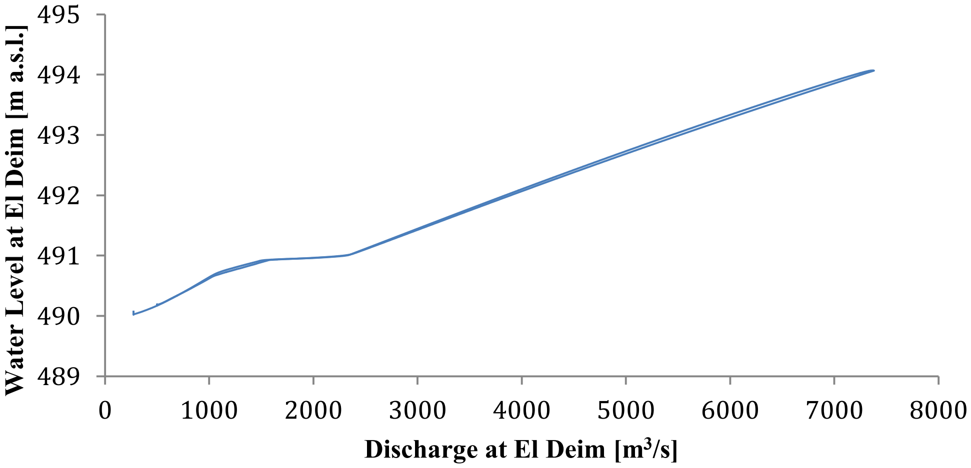


Figure 25 Simulation of the water level at El Deim with discharge that increases and decreases with the maximum rate. The Reservoir level was set to 490 m a.s.l.

Results from the frequency analysis show that the probability of different flow variations varies considerably. Lower rates of variation are much more common than the higher rates. This result is not so surprising considering the long period with low flow in Sudan. The probability of rate variation in the magnitude of 3,000-4,000 m^3/s/day is extremely low. Only four days in the data period from 1965-2012 have events with these magnitudes of flow increase. Based on the frequency analysis (Figure 19) the rates of the discharge variations were set to capture the most common variations. The high flow variation limit of rise and fall was set to 1,000 m^3/s/day respectively 500 m^3/s/day. More than 94% of the daily rates are lower than these values. Simulations with these, and lower rates, were executed to investigate how the flow dynamics changed at El Deim. These dynamic simulations showed that a higher rate of increase and decrease induces more hysteresis effect, therefore the hysteresis effect of more than 94% of the daily changes are covered by the resulting rating curve. In Figure 26 it can be seen that all simulations with lower rates of variation have less hysteresis effects than the blue line, which represents the highest rates of variation. These simulations are executed with the same downstream boundary condition and the same range of flows for the upstream boundary, but with different rates of variation.

To study the effect of changed water level in Roseires reservoir simulations were executed for the new expected reservoir levels, from the lowest (485 m a.s.l.) to the highest (493 m a.s.l.) (levels according to Pietrangeli et al., (2013)). The water level changes at El Deim caused by a higher water level in Roseires reservoir turned out to be considerable. Therefore, rating curves for different water levels at Roseires dam must be created to capture the unique flow dynamics for respective level. In this master thesis only a few rating curves with defined rating equations and tables were produced. More rating curves could preferably be produced if these ones are proven accurate against new measurement data from El Deim.

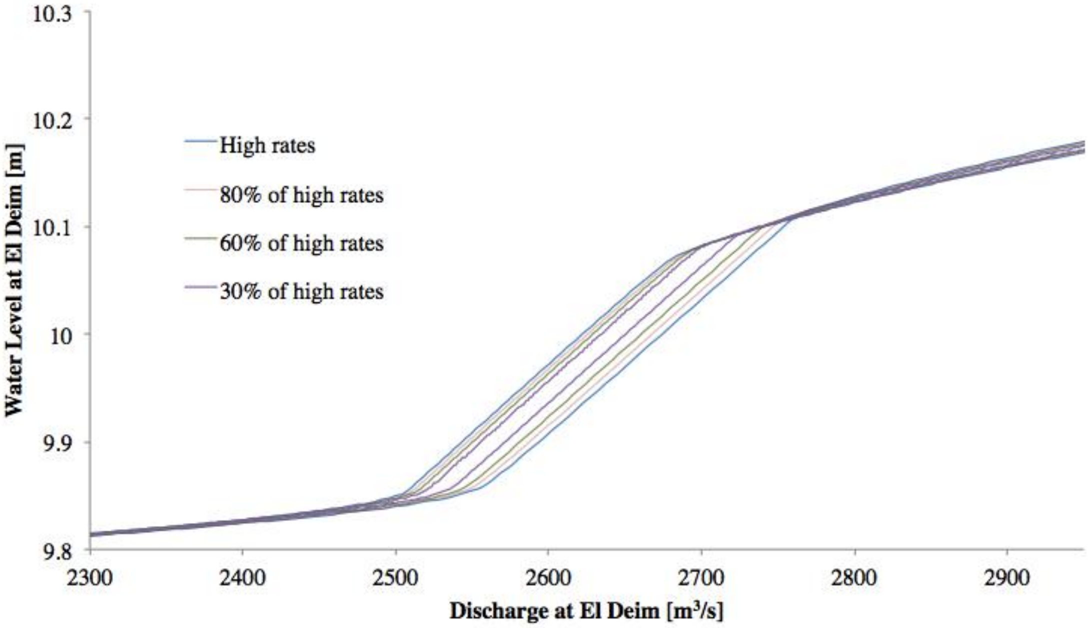


Figure 26 Simulation results for El Deim at a constant water level of 485 m a.s.l. at Roseires dam. Graf shows simulation results for different rates of variation.

4.5.3 Simulations of quasi-steady and truly dynamic flow variations

Except of the discharge rate at El Deim and water level at Roseires dam, it is also important to know how the flow dynamic changes depend on the duration of the flow variation and the duration of the peak flow. Simulation with the high rates show that an extended time of increase and decrease of the same rate does not affect the hysteresis effect if water level at Roseires dam is kept at constant level. A longer duration of the flow peak (3 days) resulted in the same hysteresis effect as a shorter flow peak (1 day).

Flow simulations with increased inflow were processed in order to study possible correlations between the discharge magnitude at the start of the simulation, and the hysteresis effects. These results did not indicate that a larger inflow would cause more hysteresis effects.

4.6 DISCHARGE ASSESSMENT AT EL DEIM MONITORING STATION

Rating curves can be created for different water levels at Roseires reservoir assuming that the water level of the reservoir can be seen as constant during a flow event. This assumption is applicable if the volume of the water flow event only has a small effect on the level of the great reservoir of Roseires. These rating curves can then be used to assess the discharge at El Deim station, knowing only the water level at the reservoir and the station.

The results from the simulations in Mike 11, of the hydrological dynamics in the Blue Nile from the border of Ethiopia to Roseires dam, indicates that the state of the flow is strongly dependent on the intensity of the flow variations. A flow with a fast variation induces a hysteresis effect while slow variations result in a quasi-steady flow (Figure 23 and Figure 24). Different rating curves for all different scenarios concerning water levels at Roseires dam and discharge rates could be created. This would result in many rating curves, each with a very specific interval of usability. More convenient would be to have a single rating curve for each level at Roseires dam which covers a range of rates of variation, a rating curve that could be used for a wider range of hydraulic scenarios. Well-defined simulations with specific conditions, concerning the water level at Roseires and discharge variation rates at El Deim, were performed to create these rating curves. The results from simulations for a specific water level at Roseires can be presented in the same Q-h plot and from this plot rating equations and tables can be created. Because of hysteresis effects the rating curve became wide for some parts. This gives the gauge reader a discharge interval corresponding to that water level.

The maximum rate of discharge increase for El Deim was set to 1,000 m^3/s/day. For the maximum decrease 500 m^3/s/day was chosen. More than 94% of the daily changes are smaller than these specific rates (Figure 19 and Figure 20). Dynamic simulations showed that a higher rate of increase and decrease induces more hysteresis. Therefore, 94% of the daily changes are covered by this rating curve. A rating curve for every meter at Roseires dam, from 485 m to 493 m, was computed from simulation results. The result that the simulation with the highest rates of change in discharge gave the most hysteresis effect indicates that only the maximum changing rates need to be modelled for every level at Roseires dam.

4.6.1 Comparison between the simulated and old rating curve

To get an idea of how well the rating curves from the simulations correspond to the rating curve used at El Deim a comparison was made. A rating curve from a simulation with no backwater effect (low water level at Roseires dam) was compared with the used rating curve at El Deim. The simulated increase in the flow was set to a very slow change to avoid disturbance due to rapidly increased water level. Two almost identical curves would indicate that the simulated flow follows the empirical relationship found at the station. The rating curve used to rate the discharges in the given data set (1977-2012) was used for comparison to the simulated curve (Figure 27). The two rating curves follow the same main trends. There are a few parts were the two curves are different. At the water level interval 8.5-9.5 m (approximately flow interval 1,700-2,200 m^3/s) the simulated curve underestimates the flow compared to the old rating curve. The difference is also significant for water levels above 12.5 m (corresponds to a flow of about 8,000 m^3/s or more). A possible explanation is that these differences might occur because of the bathymetry of the simulated model is inadequate. The extensions of the cross sections, of which the bathymetry of the model is based on, do not always reach above the water level in the simulations. In these cases, when the water level is higher than there is info about the cross section, Mike 11 extrapolates the cross section as vertical planes (Figure 28). Vertical cross sections cause the water level to rise more rapidly than cross sections with sides that are not as steep. This induces an underestimation of the discharge at these water levels. This scenario might be the reason for the significant deviations between the rating curves for flows about 2,000 m^3/s and over 8,000 m^3/s (Figure 27).

The expected behaviour of a rating curve relationship is that the water level should rise with increased discharge. The simulation of the model shows some parts with almost no change in water level when the discharge increases. A possible explanation for these flow dynamics is that these flat parts are the result of the natural shape of the cross sections. They often have a certain level with a rapid and significant widening (cross section in Figure 5). The part of the simulated rating curve that is below the old rating curve, overrating the discharge, might be an effect caused by the calibration. To produce a more accurate hydraulic model the bathymetrical information in form of cross sections must be more frequent and reach further up the riversides. That would minimize the risk of errors due to erratic bathymetry.

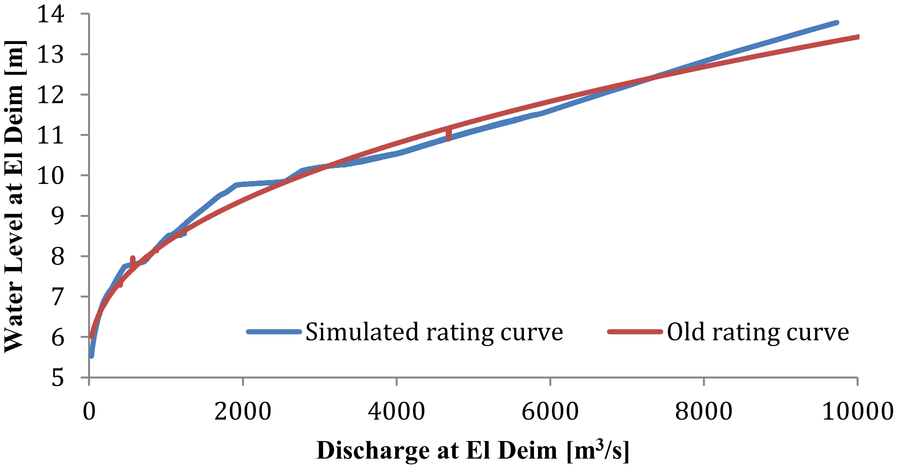


Figure 27 Comparison between the used rating curve and the simulated. Backwater effects do not affect the water level during this simulation due to a water level of 475 m a.s.l. at Roseires dam.

Figure 28 The cross section data for the cross section 6 km downstream of El Deim. The blue line illustrates the current water level, the red dotted line the maximum water level and the green dotted line the lowest water level during an on-going result simulation.

4.6.2 Rating curves for El Deim monitoring station

Simulations with the high discharge rates of variation (Table 2) from 30-10,000 m^3/s for different levels at Roseires dam resulted in rating curves. These rating curves should be adequate to use for a wide range of dynamic scenarios. Daily discharge variations from an increase of 1,000 $m^3/s/day$ to a decrease of 500 $m^3/s/day$ are covered by these curves, which cover the majority of the daily variations at El Deim (Figure 19 and Figure 20). These curves should not be used for events of higher rates of change. This interval of variation rates covers scenarios affected by hysteresis effects. Therefore, the rating curves have wider parts at levels affected by hysteresis. Due to the large range of discharge and water level that the rating curves are based on it is complicated to see the actual influence of hysteresis on the rating curves presented in Figure 29. To simplify this and to make it easier to find a more precise rated discharge tables and equations, based on the rating curves, were produced (Appendix A.1 and A.2).

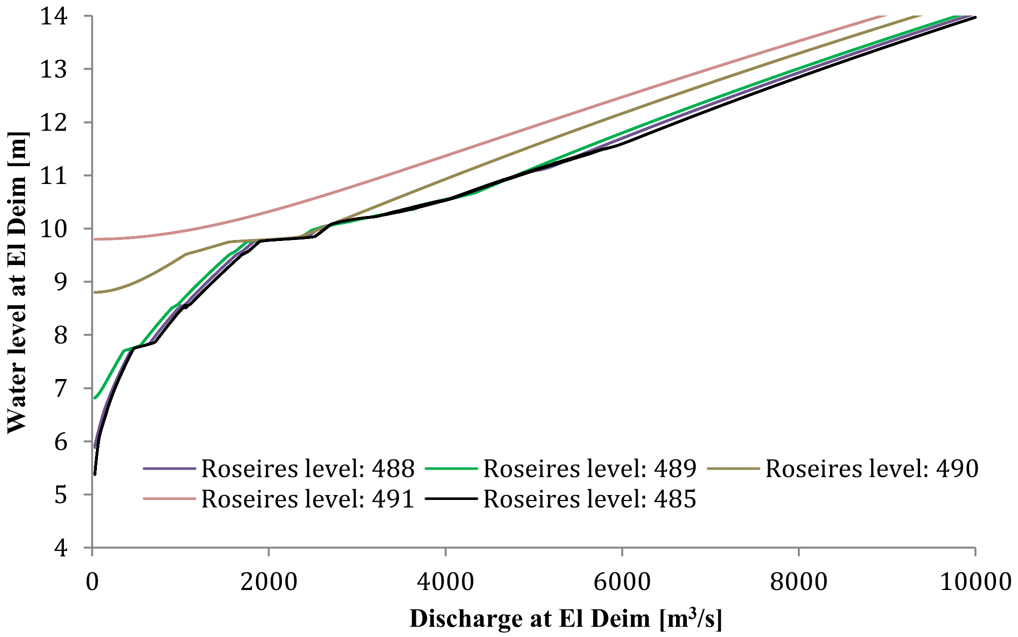


Figure 29 Produced rating curves for El Deim monitoring station. Zero water level at El Deim is 481.2 m a.s.l.. Roseires water level given in m a.s.l..

4.6.3 Equations for rating discharge at El Deim

To simplify the discharge rating equations can be computed in Excel, from the best-fit trend line based on the produced rating curves. The equations of these resulting trend lines can then be used for the assessment of the discharge. For produced equations see Appendix A.2.

4.6.4 Tables for rating discharge at El Deim

Tables, based on the rating curves, were produced to simplify the discharge rating at El Deim. With these tables the discharge, for every 0.1 m, can be rated without any calculations. One table for each curve has been produced. The validity of these tables is the same as for the rating curves and equations. They should only be used if the discharge variation is in the specified range of variation.

4.7 UNCERTAINTIES

4.7.1 Discharge rating with rating curve

It is possible to use the produced rating curve directly for rating discharge but it is not very convenient. Since the whole rating curve is presented in one plot it is hard to see the hysteresis effects and to do precise readings of the discharge. To be able to more exact readings the rating curve need to be divided into sections. Each section would then have a more precise scale on the x-axis and the hysteresis effects would be easier to see.

4.7.2 Discharge rating with equation

By the use of rating equations the discharge is easy to compute for a known water level. But the accuracy of the computed best-fit equations varies a lot. They often have a significant deviation to the simulated rating curve. Therefore, assessments with these equations will give only a rough approximation of the discharge. The accuracy of the approximation also depends on the discharge rate of variation at the time of measurement at El Deim. A high rate of variation causes more hysteresis effects and thereby a higher risk of deviation from discharge computed with the rating equation.

The trend line that represents the equation has most often a larger deviation compared to the rating curve than the deviation caused by the hysteresis. It is therefore, in most cases, better to use the table for rating the discharge.

4.7.3 Discharge rating with table

The tables made for discharge rating are not continuous. They present the discharge for every 0.1 m water level at El Deim. Therefore, when using the tables, water level measurements need to be adapted to the closest existing value. This gives a rated discharge that not always corresponds to the exact measured water level, but still a good approximation of the flow.

4.7.4 Simulation results

In this study simulations were executed with the one-dimensional hydrological program Mike 11. Mike 11 simulates the flow as one-dimensional, which is a considerable simplification. The Blue Nile has many turns and the flow is affected by turbulence. Results from the modelling could preferably be compared with results from the same scenarios modelled with another suitable modelling program, for example Hec-Ras. This could give more data to confirm or repudiate the result of this study.

4.7.5 Measurement and data liability

The study is based on measurement data. In all measurements there are measurement errors. As described under chapter 2.3 the equipment is not 100% correct even if it is well maintained and used correctly. The actual error in the data used in this study might be higher than the known errors of the equipment. A few possible reasons to this are described below:

For water level measurements at El Deim masonry gauge is used. This solid installation has many advantages. It is stationary and therefor no additional errors or problems with its reference level to the datum, which is the case with mobile rulers. At El Deim the Blue Nile is about 500 m wide. Because of this it is extremely important to read the gauge as precise as possible. Only a minor error will result in a considerable error in the discharge calculation. Wind and high floods might also make it difficult for the gauge readers to do their job.

A possible error in the discharge data is that they often are calculated from the equations based on rating curves. Even if the rating curves are made from many measurements at different water levels they are not precise. The characteristics of the bathymetry might change with time, a change caused by erosion, sedimentation and flood events. To be accurate, a new rating curve should be made when the physical characteristics of the river changes. However, the cross section at El Deim is known to be stable which indicates that this error hopefully is quite small for discharge measurements at the station.

The number of measurements is also a crucial aspect of the quality of a study based on measurement results. More data, given that the data are based on accurate measurements, gives a more trustworthy result. Longer time series gives a higher possibility that the data cover the natural fluctuations of for example discharge. Most often the measurements are taken during the day, in best case from early morning until nightfall. Variations occurring during the night then get missed due to this timely distribution of the measurements. This study complicates by the fact that there is no accessible data for the period after the heightening. Therefore, it is impossible to calibrate the Mike 11 model against the new situation with the Roseires dam fully implemented.

Even if the data might contain a lot of errors it is the data available. Therefore, it is essential information to use for this study.

In the calibration process important parameters like Manning's number and the limits in the triple zone division are adjusted to get a model with as little deviation as possible. A small change in Manning's number (n) causes large effects on the modelled flow velocity. A doubled n results in half the flow velocity (equation 1).

4.7.6 Delimitations

This study has been processed under two delimitations. The first one is that no consideration is taken about the morphology upstream of the Ethiopian border, and the second one is that no additional source of water is taken into account except the Blue Nile. These delimitations should not affect the accuracy of the simulation results considerably. It is only the water level at El Deim that is taken under consideration during calibration and validation. More cross section data upstream would likely not affect the water level at the station. The discharges in the other tributaries to the Blue Nile are negligible compared to the flow in the Blue Nile. Therefore, simulations with these tributaries included would likely give similar results. For these reasons, the delimitations do not make the results of this master thesis less useful.

4.8 IMPROVEMENTS

The accuracy of the results could have been better if more data were accessible. With more frequent cross sections, with extended reach, between El Deim and Roseires dam the rivers bathymetry would be captured in a better way. This would prevent errors appearing in the simulations caused by non-satisfying bathymetrical data and result in more accurate simulations for both high and low flows.

The resulting tables and equations of this study should be compared with new measurements at El Deim and Roseires after the heightening, to see if the flow dynamics fits the modelling results of this study. The data available for this study were daily values. This makes it hard to study the short-term natural variation of the flow. A new frequency analysis with continuous data series of discharge variations should be produced to control the accuracy of the frequency analysis in this study. It is important to control this because the validity of the produced rating curves and tables are based on that analysis.

4.9 RESULT AND DISCUSSION SUMMARY

After calibration and validation a hydraulic model was developed that could simulate the water level at El Deim given the discharge in the Blue Nile and the water level at Roseires dam. The model's Nash-Sutcliffe value for the validation period was 0.9927, which strongly indicates that the predictive power of the model is high. No cross section was found in the conveyance analysis that individually can be seen as the dominating control section for the flow. The discrepancies between the simulated and measured values are therefore not likely caused by a cross section with unrealistically low conveyance. The water level at Roseires reservoir and the discharge rate of variation are two factors that significantly affect the flow dynamics at El Deim. The new levels of the reservoir will most likely induce backwater effects at El Deim for levels above 485 m a.s.l.. If this result is accurate the old rating curves cannot be used after the heightening. Several rating curves for the full range of expected discharges were therefore created. They were created from the results from dynamic simulations in Mike 11. The rates of change of discharge in the simulation of the rating curves were based on a frequency analysis to cover almost all the natural variations. Equations and tables were developed from the rating curves to simplify the discharge rating procedure. These discharge rating tools are likely less accurate for high levels in Roseires reservoir due to the large distance between some cross sections and the cross sections lack of extensive reach. The rating curves, rating equations or tables should not be implemented before they have been validated against new measured data from El Deim. More rating curves could preferably be produced if the rating curves, produced in this study, are proven accurate. In the case of an inaccurate rating curve the model must be improved with more bathymetrical data. The model should be recalibrated and validated once more against new discharge and water level data. If this is done, the possibilities are good that discharge ratings can be performed at El Deim even if backwater and hysteresis effects affect the water level.

5 CONCLUSIONS

5.1 DISCHARGE ASSESSMENT AT EL DEIM MONITORING STATION

For both steady flow and realistic dynamic flow conditions the simulations with the hydraulic model correspond well to the measured data. Simulation results indicate that backwater effects caused by new higher reservoir levels likely will reach El Deim station. The study has resulted in rating curves, rating equations and tables useful for discharge assessments for a wide range of dynamic scenarios. These curves can be used even if the station is affected by both backwater and hysteresis effects. The actual accuracy for these rating tools needs to be studied through comparisons with new measurement data from El Deim. The most efficient method to rate the discharge at El Deim is likely to use the tables developed from the simulated rating curves (APPENDIX A.1). They capture the variations caused by hysteresis and can be used without any calculations.

If the methodology and rating tools from this study are planned to be implemented the model must be improved with more bathymetrical data. The improvements are needed to create more accurate curves, tables and equations for discharge rating. Discharge ratings can then be produced, and enable better operation of Roseires dam and a more efficient use of the valuable water resources in Sudan.

5.1.1 Methods to rate discharge

Even after the heightening of the Roseires dam there are ways to rate the discharge at El Deim. The produced tables and equations of rating curve relationships (Appendix A.1 and A.2) can be used to rate the discharge only from knowing the water level at El Deim and Roseires dam. They are both easy methods to rate the discharge. By using the tables no calculation is needed. The procedure of rating discharge using these tables or equations can be divided into three steps. First the gauge reader measures the water level at El Deim station and reports this to the operators of the Roseires dam. Second the operators control the present water level in the dam and then the third step is to use the table or equation that represents the discharge-water level relationship for that specific level at Roseires dam. The operators can look at the table or use the equation to get the rated discharge corresponding to the present water level at the El Deim station.

5.2 METHODOLOGY

The methodology used in this study should be applicable to studies of backwater effect and flow dynamics at other sites. There are other programs than Mike 11 possible to use for hydraulic modelling and the choice of program should be based on data availability and the objective of the study. The goal to produce an accurate and useful hydraulic model is much more likely to be fulfilled if based on extensive and adequate studies and measurements from the study site. In the study of El Deim the conveyance study of the riverbed was of great importance. That study concluded the range of roughness of parts of the Blue Nile. With more knowledge about the study site the calibration of the model parameters can be defined after true conditions instead of approximations. By keeping physical parameters realistic the model result are more reliable.

6 REFERENCES

AFESD, Arab Fund for Economic and Social Development, 2012. *Heightening of Roseires Dam*. [online] Accessible: http://www.arabfund.org/Default.aspx?pageId=359&pId=558 [Collected 2013-01-09].

Block, P. J., Strzepek, K., Rajagopalan, B., 2007. *Integrated Management of the Blue Nile Basin in Ethiopia, Hydropower and Irrigation Modelling*. Washington, DC: International Food Policy Research Institute.

Brandt, S.A, 2009. *Betydelse av höjdmodellers kvalitet vid endimensionell översvämningsmodellering*. Gävle: Högskolan i Gävle. FoU-rapport Nr 35.

Chanson, H., 2004. *Hydraulics of Open Channel Flow: An introduction* Australia: University Of Queensland

Chow, V. T., Maidment, D. R., Mays, L. W., 1988. *Applied Hydrology*. Singapore: McGraw-Hill Book Co.

DHI, 2012a. *Mike 11-a Modeling System for Rivers and Channels. Tutorial Version 2012*. Denmark: DHI

DHI, 2012b. *Mike 11- a Modeling System for Rivers and Channels. User Guide.* Denmark: DHI

Google Earth 5.1. 2013. *Coordinates for Blue Nile in Sudan*. [online] Program available through: http://www.google.com/earth/index.html [Accessed 2 March 2013]

Göransson, B., 2013. *Observation unit at SMHI.* [email] (Personal communication, 4th of April 2013).

Hendriks, M. R., 2010. *Introduction to Physical Hydrology*. USA: Oxford University Press.

Mohamed, Y. A., 2010. *Sediment & Water Quality Monitoring for the EN Basin*. Sudan: Eastern Nile Technical Region Office.

Munier, S., Litrico, X., Belaud, G., Malaterre, P., 2008. *Distibuted approximation of open-channel flow routing accounting for backwater effects*. Elsevier. Advances in Water Resources.

NE (Nationalencyklopedin), 2013. *Blå Nilen*. [online] Accessible: http://www.ne.se/lang/blå-nilen. [Collected 2013-02-11].

Pietrangeli, G., Mario, B., Gian, M. V., 2013. *Characterization of Blue-Nile (Abbay) conveyance at Ethiopian/Sudanese border*.

Sutcliffe, J. V., Parks, Y. P., 1999. *The hydrology of the Nile*. Oxford: International Association of Hydrological Science.

Tesemma, Z. K., 2009. *Long term hydraulic trends in the Nile Basin.* New York: Cornell University

Wilson, S., 2008. *Blue Nile (Abbay) Basin: Rapid Assessment Of Hydrological Monitoring Needs*. Addis Abeba: Eastern Nile Regional Projects

Yagoub, S. M., 2012. *Water Resources In Sudan. Planning and management*. Khartoum

PERSONAL COMMUNICATION

Ahmed, E. T., 2013. *Ministry of Electricity and Dams*. [email] (Personal communication, 28th of March 2013)

Losjö, K., 2013. *Hydrological Modelling Expert. SMHI.* [email] (Personal communication, 15th of February 2013)

Staub, C., 2013. *Area Manager – Eastern Africa. SWECO.* [email] (Personal communication, 25 March 2013).

APPENDIX

A.1 TABLES FOR DISCHARGE RATING AT EL DEIM STATION

Tables produced for rating discharge at El Deim contain values from the simulated rating curve. The tables also present the maximum and minimum flow for eventual hysteresis events. The tables are most likely better to use than the discharge rating equations. Each table are valid to use for a specific water level at Roseires reservoir. These tables should not be used in case of a discharge increase over 1000 m^3/s/day or discharge decreases over 500 m^3/s/day. Rated discharges based on these tables should be seen as rough approximations of the real discharge.

Table A.1.1 Discharge at El Deim [m^3/s]: Water level at Roseires 485 m a.s.l.

Meter	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
5					34	40	41	47	53	61
6	77	80	97	119	135	158	227	186	210	227
7	255	282	308	336	363	393	424	452	574	723
8	771	819	870	912	971	1013	1133	1178	1244	1301
9	1361	1431	1493	1561	1626	1698	1791	1853	2163	2561
10	2638	2750	3047	3375-3431	3631-3662	3886-3910	4123	4274	4460	4613
11	4812	4987	5206	5369-5412	5573-5622	5782	6010	6165	6316	6462
12	6615	6782	6352	7086	7275	7422	7601	7757	7945	8093
13	8308	8446	8640	8794	9005	9147	9369	9501	3711	9877
14	10000									

Table A.1.2 Discharge at El Deim [m^3/s]: Water Level at Roseires dam 488 m a.s.l.

Meter	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
5										31
6	41	49	81	88	97	123	141	164	187	210
7	233	264	289	330	344	372	405	437	581	679
8	733	770	817	874	954	977	1074	1130	1187	1246
9	1309	1366	1431	1494	1558	1597	1726	1794	2133	2485
10	2573	2790	3109	3379-3407	3627-3660	3878-3899	4114-4130	4278-4324	4449	4627
11	4829	5004	5247	5405	5583	5682	5904	6007	6322	6315
12	6458	6639	6790	6942	7112	7285	7440	7617	7777	7977
13	8129	8316	8460	8667	8819	9002	9173	9364	9537	9731
14	9930									

Table A.1.3 Discharge at El Deim [m^3/s]: Water Level at Roseires dam 489 m a.s.l.

Meter	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
6										88
7	148	151	190	218	277	287	302	372	554	619
8	653	691	737	790	845	898	995	1045	1103	1161
9	1220	1290	1348	1415	1479	1545	1650	1716	2125	2426
10	2560	2836	3160	3333	3674	3875-3940	4150	4375	4515	4655
11	4790	4855	5105	5240	5402	5536	5705	5850	6005	6152
12	6297	6487	6652	6800	6974	7139	7315	7465	7643	7820
13	7983	8169	8330	8523	8681	8877	9055	9247	9419	9603
14	9750	9935								

Table A.1.4 Discharge at El Deim [m^3/s]: Water Level at Roseires dam 490 m a.s.l.

Meter	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
8									97	343
9	494	636	746	856	944	1034	1235	1445	1967	2449
10	2589	2750	2882	3024	3176	3339	3492	3650	3807	3951
11	4119	4269	4425	4583	4735	4908	5055	5218	5400	5553
12	5715	5888	6072	6231	6403	6576	6755	6927	7109	7296
13	7463	7659	7838	8017	8194	8386	8584	8761	8950	9147
14	9344	9545	9726	9930						

Table A.1.5 Discharge at El Deim [m3/s]: Water Level at Roseires dam 491 m a.s.l.

Meter	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
9									107	803
10	1162	1481	1722	1969	2181	2392	2580	2765	2955	3340
11	3340	3514	3712	3878	4075	4246	4419	4613	4771	4975
12	5131	5319	5512	5680	5866	6065	6233	6421	6603	6793
13	6992	7200	7363	7560	7753	7951	8144	8340	8540	8740
14	8940	9139	9344	9547	9758	9962				

A.2 EQUATIONS FOR RATING DISCHARGE AT EL DEIM STATION

Produced equations for rating discharge at El Deim are likely not very accurate. They only give a rough approximation for the flow. Before using these equation they need to be validated against new measurement data at El Deim. The different equations are valid for a specific water level at Roseires dam and over the specified water level at El Deim. x in the discharge rating equations stands for water level in m and y is the discharge in m^3/s.

Table A.2.1 Equations for rating discharge at El Deim station. R^2 is the mean square error between the line based on the equation and the simulated value.

Water level at Roseires Dam [m a.s.l.]	Discharge rating Equations	R^2	Validity for water levels at El Deim [m]
485	$y = 130.63x^2 - 1302x + 2986$	0.9921	Over 6.8 m
488	$y = 123.26x^2 - 1168.6x + 2356$	0.9923	Over 6.5 m
489	$y = -26.361x^3 + 938.55x^2 - 9291.3x + 28217$	0.9973	Over 7 m
490	$y = -1.1367x^2 + 1795.5x - 15584$	0.9988	Over 8.8 m
491	$y = -74.519x^2 + 3823.7x - 29940$	0.9966	Over 9.8